MINNESOTA GEOLOGICAL SURVEY

PAUL K. SIMS, *Director*

SEISMIC STUDIES OVER THE MIDCONTINENT GRAVITY HIGH IN MINNESOTA AND NORTHWESTERN WISCONSIN

Harold M. Mooney, Paul R. Farnham,
Stephen H. Johnson, Gary Volz, and Campbell Craddock

Report of Investigations 11

UNIVERSITY OF MINNESOTA

MINNEAPOLIS • 1970

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ABSTRACT

Seismic refraction data from 87 profiles contribute to the delineation of the geologic structures which cause gravity and magnetic anomalies associated with the northern part of the Midcontinent Gravity High. Interpretations of the seismic data provide knowledge about structure within the sedimentary section as well as depth to the igneous basement, which reaches a maximum of about 10,000 feet in this area.

The area investigated extends from the Minnesota-Iowa border on the south to Lake Superior on the north, and includes parts of eastern Minnesota and northwestern Wisconsin. Gravity and magnetic maps compiled from published data and 12,000 additional gravity stations occupied as part of the present investigation were used in combination with geologic control from outcrops and drill holes as a guide in the location and later interpretation of the seismic profiles. The seismic data were obtained by shooting across a fixed geophone spread for shot distances up to a maximum of eight miles.

Results for each profile are presented separately and include observed seismic travel-time data, an inferred geologic structure section, and a discussion. The discussion describes the geologic setting and purpose of the seismic profile, the reliability of the seismic interpretation, and the correlation of the seismic results with gravity, magnetic, and geologic control.

Tabulated values for the observed seismic velocities fall in the range of 9,000-23,000 feet/second. The velocities can be assigned to seven groups of geologic strata, corresponding to Paleozoic, upper, middle, and lower Upper Keweenawan sedimentary strata, Middle Keweenawan volcanics, pre-Keweenawan felsic intrusives, and pre-Keweenawan mafic intrusives. Good velocity correlations can be established between similar strata in different geologic provinces.

A second paper (Mooney and others, 1970) synthesizes data reported here into a regional geologic picture in the form of six structural cross-sections across the Midcontinent Gravity High.

INTRODUCTION

The St. Croix horst forms the northern end of one of the major tectonic features of North America. This linear structural feature, at least at its northern end, consists of uplifted mafic igneous rocks flanked by thick wedges of sedimentary rock, both Late Precambrian in age. The structure forms a belt only a few tens of miles wide.

The total feature is most clearly revealed by a major gravity anomaly that extends in a sinuous pattern from its northern end at Lake Superior, across northwestern Wisconsin, eastern Minnesota, central Iowa, southeastern Nebraska, and central Kansas, a distance of nearly 1,000 miles. The name Midcontinent Gravity High is commonly given to the gravity anomaly and is extended by some to the associated tectonic feature. The anomaly includes both positive and negative Bouguer values. The high-density uplifted igneous rocks produce positive Bouguer anomalies of as much as +60 mg, and the flanking low-density sedimentary rocks produce negative anomalies to -100 mg. The maximum gravity relief exceeds 160 mg over a distance of less than 25 miles in northern Iowa; relief in excess of 100 mg occurs over a similar distance at several localities in Minnesota and western Wisconsin. A gravity contour map delineating the entire feature may be found in Coons and Woollard (1967); a map for the northern part is given in this paper.

Except at its northernmost end, geologic knowledge concerning the Midcontinent Gravity High is sparse and incomplete. Flat-lying Paleozoic sedimentary rocks cover all but the northern end of the structure to depths of as much as several thousand feet, and only widely-scattered drill holes have penetrated this cover. The Paleozoic rocks terminate north of latitude 45°45′, in east-central Minnesota. North of this latitude, the Precambrian rocks are exposed locally and are known from drilling at several localities. Still further north, adjacent to Lake Superior, outcrops are moderately common and their geology has been studied intensively for decades.

Several approaches have been utilized in studies attempting to define the structure associated with the Midcontinent Gravity High, particularly at the northern end where some geologic control is available. Thiel (1956), working with gravity data in Minnesota and Wisconsin, was the first to show clearly that the positive gravity anomalies correlate with uplifted mafic volcanics and gabbros of Middle Keweenawan age and that the negative anomalies correlate with thick sequences of Upper Keweenawan sedimentary rocks. This work was extended to southern Minnesota by Craddock and others (1963), who presented hypothetical structure sections across the high which satisfied observed gravity anomalies as well as the limited geologic constraints. Coons (1968) carried out extensive analyses of gravity data along the entire length of the gravity high. However, in the absence of good geologic control, the interpretation of gravity data is at best ambiguous; therefore no unique solution can be demonstrated or was claimed by these authors.

An alternative approach to determining structure makes use of seismic refraction techniques. Long seismic profiles designed to yield data on structure of the deep crust and upper mantle have been reported for various localities on or adjacent to the Midcontinent Gravity High. Tuve (1953) has presented results for a single profile in northeastern Minnesota. Cohen (1966) and Cohen and Meyer (1967) have described profiles in northwestern Wisconsin and central Iowa.

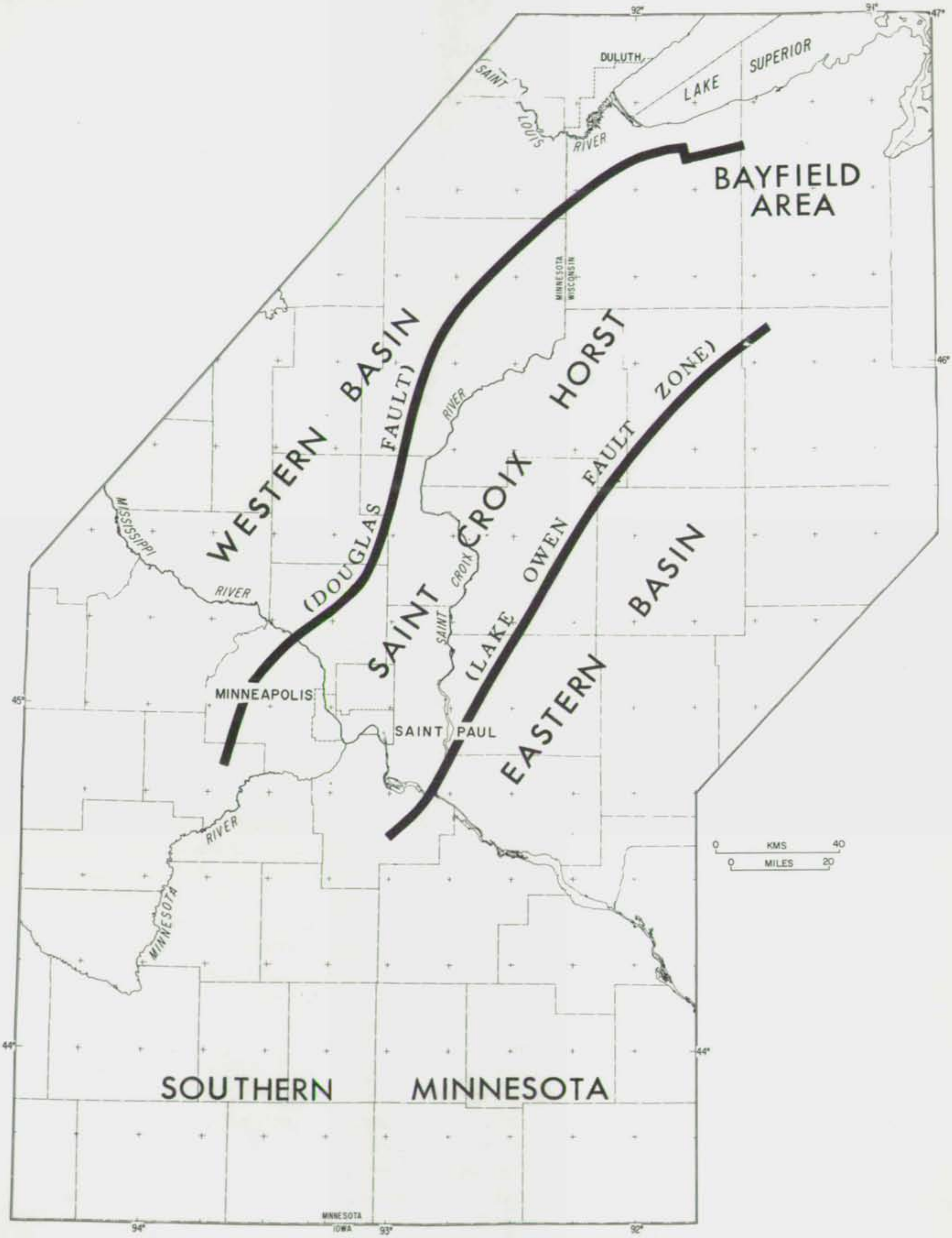


Figure 1 – Location map and tectonic divisions for the area of investigation.

To a first approximation, these refraction data from the deep crust are irrelevant to defining the structure that produces the Midcontinent Gravity High, for the observed steep gravity and magnetic gradients establish clearly that the cause must be sought within the uppermost few miles of the crust. Shorter refraction profiles yield relevant data, but very few of these have been reported. Steinhart and Meyer (1961) described a single short profile in the Apostle Islands, slightly beyond the northern terminus of the main gravity high. Cohen (1966) described five profiles over the western gravity low in Iowa.

The work reported here is an attempt to define the regional structure of the northern part of the Midcontinent Gravity High by means of shorter seismic refraction profiles. The area studied (figure 1) extends for 250 miles northeastward from the Minnesota-Iowa border to the southwestern tip of Lake Superior. This northern part of the Midcontinent Gravity High offers certain advantages for a study of this type. Most importantly, rock exposures and drill data provide essential geologic control. The geology of eastern Minnesota and northwestern Wisconsin has been actively investigated and well described, notably by the Minnesota Geological Survey and the Wisconsin Geological and Natural History Survey. The geologic data have enabled us to check seismic depth determinations and to correlate seismic velocities with specific rock formations. Accordingly, we can proceed more confidently to interpret seismic data beyond the control points to greater depths, either beneath the glacial drift or southward beneath the Paleozoic cover. In turn, the seismic results have contributed to the solution of several local geologic problems as well as to the principal goal of determining regional structure.

A second advantage of studying the northern part of the gravity high is the availability of detailed gravity and magnetic maps for the area. Generalized contours taken from these maps (see figure legends for sources) are presented as Figures 2 and 3. These data provided essential guidance for placing the seismic profiles in areas of geologic significance. A regional gravity map of the area has been available since the work of Thiel (1956) and Adams (1957); we found it necessary, however, to precede the seismic program with an additional 12,000 gravity stations (Craddock and others, 1970) in order to delineate the pattern in more detail. Aeromagnetic coverage is available for eastern Minnesota through a cooperative program between the United States Geological Survey and the Minnesota Geological Survey. Patenaude (1966) has compiled a generalized aeromagnetic map of Wisconsin. We found this valuable for reference, but it has not been incorporated into Figure 3 because of differences in scale and flight elevation from the U. S. Geological Survey aeromagnetic maps.

The northern part of the Midcontinent Gravity High has particular interest because the structure appears to change in character from north to south. The central part of the area shown in Figure 1 illustrates many of the features considered representative of the entire Midcontinent Gravity High. These include a broad central gravity maximum, steep gradients dipping down into symmetrical deep flanking gravity lows, and a gradual return outward to normal gravity values. A similar pattern extends southwestward from the Minnesota-Iowa border beyond the lower edge of Figure 1, but this belt is offset laterally by about 80 miles from the one to the north. We designate this region of offset, identified as southern Minnesota in Figure 1, as a second structural segment within the northern part of the Midcontinent Gravity High. A third segment, labelled Bayfield area in Figure 1, coincides with a major gravity low in Figure 2. In this region, the St. Croix horst appears to plunge beneath a deep sedimentary basin.

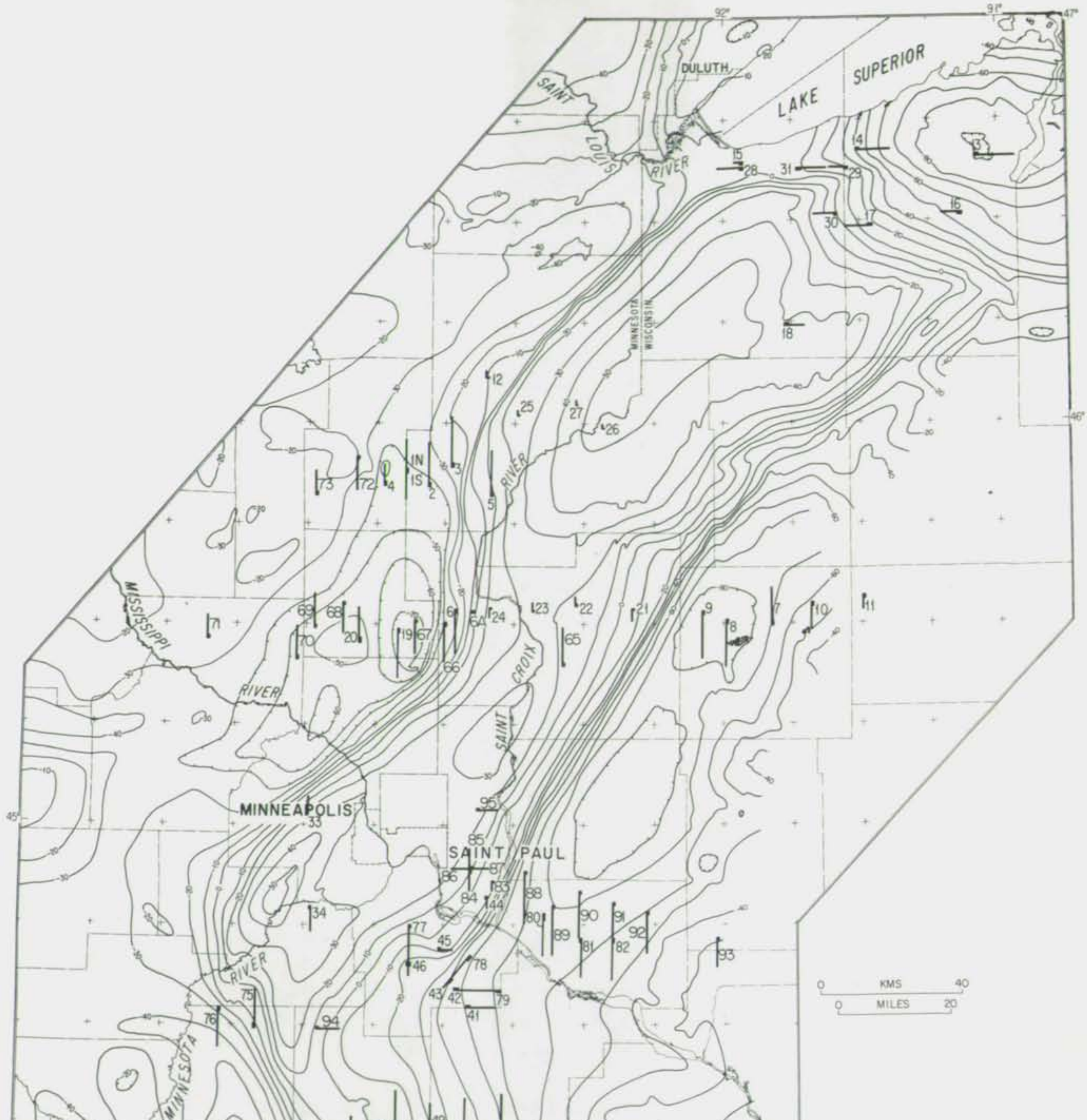


Figure 2 – Bouguer gravity map, showing location of all seismic profiles. (Gravity data from Craddock and others, 1970.)

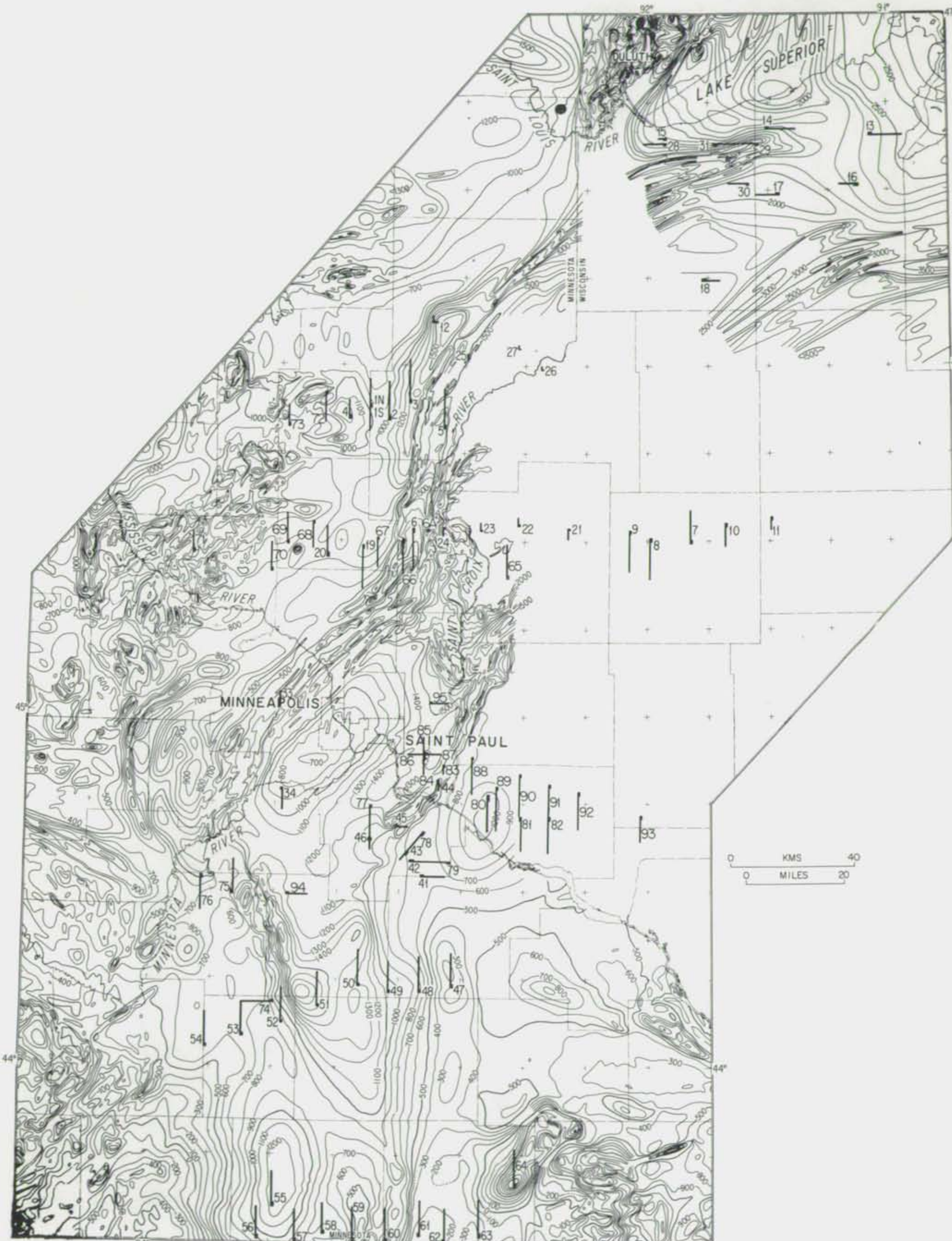


Figure 3 – Aeromagnetic contour map, showing location of all seismic profiles. (Magnetic data from U.S. Geological Survey, Geophysical Investigations Maps GP-474, GP-556, GP-559, and GP-563.)

The seismic field work was carried out from 1964 to 1967. Seismic party chiefs were Paul R. Farnham in 1964 and 1965, Stephen H. Johnson in 1966, and Gary Volz in 1967. A total of 87 seismic profiles was obtained. Their locations are shown in Figures 2 and 3, superposed on regional gravity and magnetic contour maps.

Results of the seismic investigation are given in two publications. In this paper, we present the basic analysis for the seismic profiles on a line-by-line basis. The three following sections describe the field procedures, tabulate the measured seismic velocities, and present the probable correlation of velocities with known or inferred geologic formations. A chart that gives the stratigraphic succession for all areas within the region of study appears as Figure 4. For each seismic profile, data are given in the Appendix showing travel-time observations, an interpretation of the structure, and a discussion of the interpretation and its geologic control.

A second paper (Mooney and others, 1970) attempts to synthesize results from the individual profiles into general conclusions with respect to regional structure and stratigraphy. The conclusions are presented in the form of six structural cross sections.

The seismic studies form part of a larger investigation of the Keweenawan rocks of eastern Minnesota and western Wisconsin supported by National Science Foundation Grant GA-507 to Harold M. Mooney and Campbell Craddock. A program of detailed gravity measurements over the northern half of the area shown in Figure 1 has been completed. The results have been included in a gravity map of Minnesota and northwestern Wisconsin (Craddock and others, 1970) published by the Minnesota Geological Survey.

FIELD PROCEDURES AND METHODS OF INTERPRETATION

A description of field procedures and of methods of interpretation are given in a separate publication (Mooney and others, 1970). Certain points are summarized here. Seismic measurements were taken by shooting across a fixed spread of geophones, the arrangement of which is shown in Figure 5. Seven geophones were laid out along a total spread length of either 3,000 or 4,000 feet. Shot points were placed at approximately 1/2, 1, 1 1/2, and 2 miles, and at 1-mile intervals beyond the 2-mile point. Maximum shot distance varied, depending upon the purpose of the profile, but never exceeded eight miles. A separate in-line profile was taken at each location to yield data on the shallow structure. As shown in Figure 5, the in-line spread typically used 10 geophones along a total spread of 750 feet, with shots at both ends to provide reversed coverage.

Shots were placed in holes drilled into the glacial drift at depths of 5 to 30 feet. Charge size ranged from 1 to 30 pounds of Nitramon detonated by seismic caps. Shot instant was transmitted by radio using a 1,000-hertz tone. Two geophone types were used, Hall Sears HS-10 2-hertz units for the first three seasons and Mark Products L-1 3 1/2-hertz for the last. The recording equipment was based upon a Dynatronics FM-71, reflection-refraction system. The amplifiers were operated without external low-cut filters; their response extended below that of the geophones, hence the latter established the low-frequency limit. High-cut filtering ranged from 150 hertz at the shortest shot distances to 61 hertz at the longest. Two oscillographs were used, a Southwestern Industrial Electronics unit during the first part of the program and a Magnolia unit during the last. All seismograms were recorded simultaneously at two gain levels separated by 12 decibels.

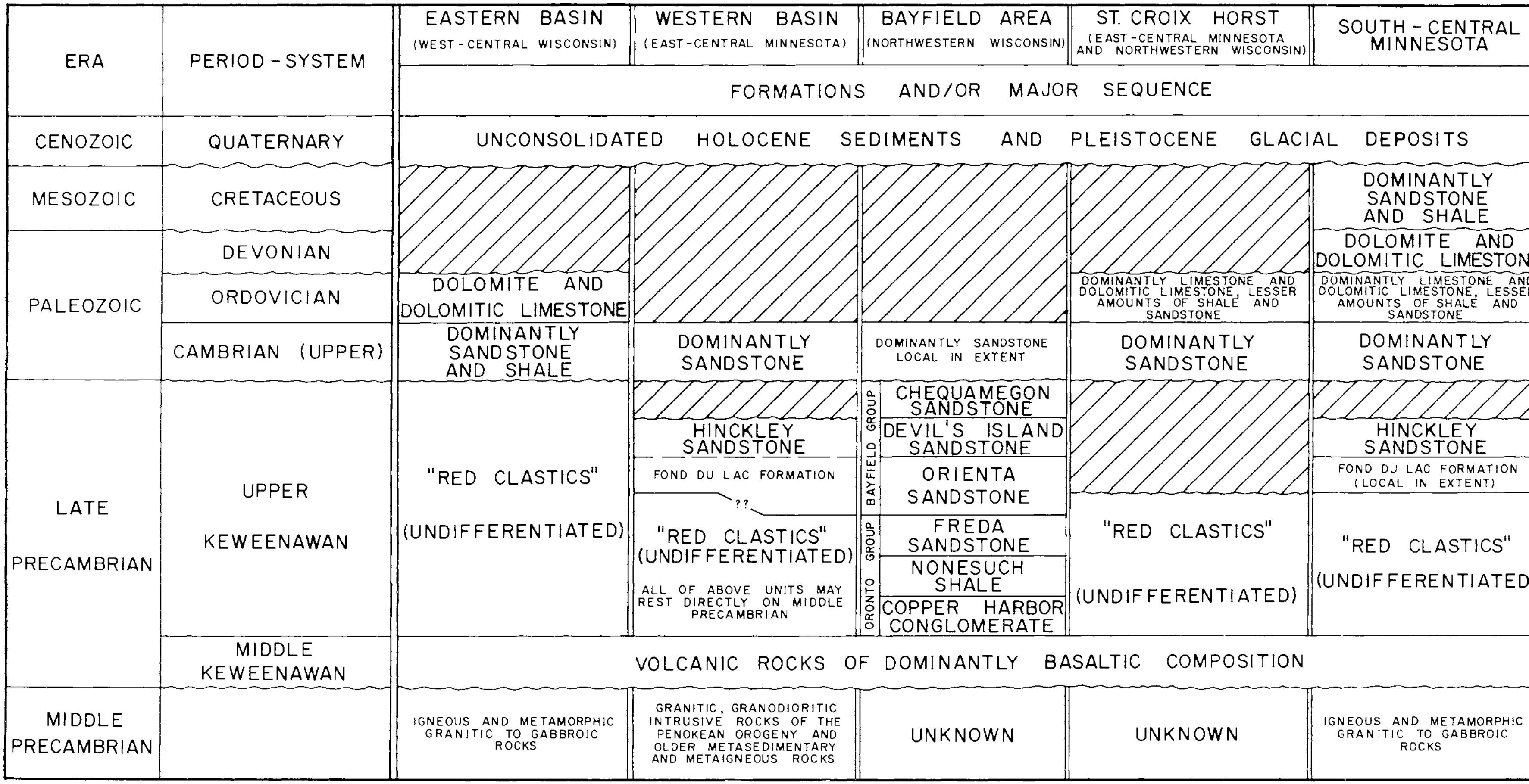


Figure 4 — Stratigraphic relationships for tectonic divisions defined in Figure 1. Sources: Eastern basin, Farnham (1967); Western basin, Thiel (1944), Goldich and others (1961), Kirwin (1963); Bayfield area, Thwaites (1912), Hamblin (1961), Hite (1967); St. Croix horst, Hall (1901), Hamblin (1961); South-central Minnesota, Thiel (1944), Kirwin (1963).

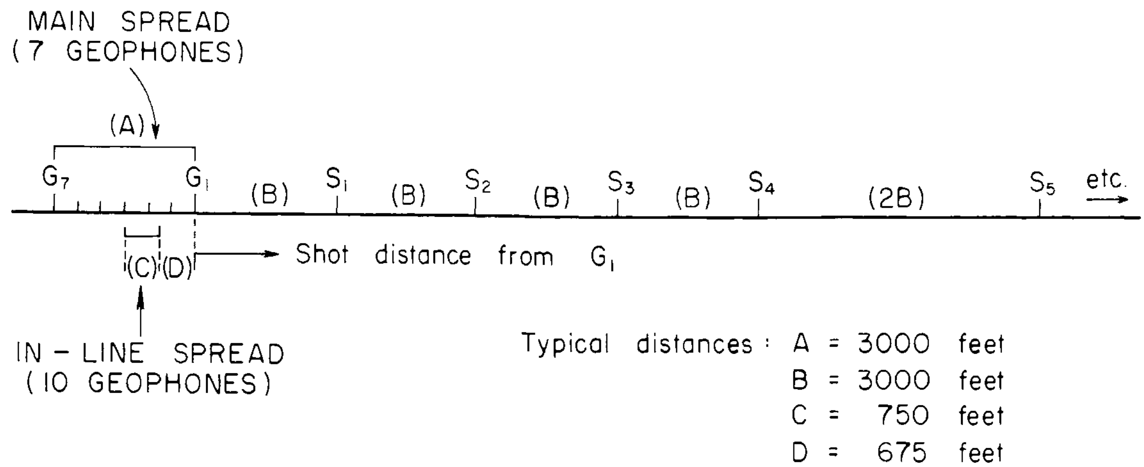


Figure 5 – Representative geophone spread and shot locations.

Profiles were taken along country roads wherever possible. Shot holes were placed in ditches or woodlots. The availability of excellent topographic maps eased the problem of accurate locations. Shot distances were measured by a device incorporating a bicycle wheel and cyclometer, calibrated against control distances.

The first step in seismic interpretation was to pick the seismic arrivals. Since this formed the foundation for all subsequent steps, two individuals carried it out independently and the results were combined. Seismic arrivals at the seven geophones were graphed for each shot in order to determine both arrival time and apparent velocity across the geophone spread. Information transferred to the graphs included not only first breaks but also succeeding peaks, troughs, and phase changes for several hundred milliseconds. The latter often revealed new arrivals not recognizable as first breaks, in addition to confirming arrival times and apparent velocities.

As a second step in interpretation, data for all shots along a given seismic profile were transferred to a travel-time graph. A structural model was then devised which appeared best capable of accounting for the observations. Theoretical travel times computed from this model were superposed onto the travel-time graph to show the degree of correspondence. Where available, geologic control was taken into account.

A compilation of individual travel-time graphs and structure sections is presented in the Appendix.

VELOCITY CORRELATIONS

General Remarks

The correlation between seismic velocities and individual geologic formations constitutes one of the more important results of this investigation. The correlation may not always be unique or unambiguous, because any given formation shows a range of velocity values and the ranges for different formations may overlap. Nevertheless, the results have proved useful. Individual formations can be correlated between seismic profiles and even from one geologic province to another. Layers unknown from drilling or outcrop data can be identified.

In the remainder of this section, we present a detailed analysis of our velocity measurements. They have been placed in the context of accepted stratigraphic relationships (figure 4) for the five regions shown in Figure 1.

Figure 6 shows an analysis of the observed velocities on a line-by-line basis, together with our interpretation of the geologic formations to which they should be assigned. Where a range of velocities was observed, a horizontal line is used. This range should not be interpreted as having statistical significance, however. A circle, not necessarily at the midpoint of the line, shows the preferred value.

Numerical velocities for individual seismic profiles, grouped according to inferred geologic units, are given below. Particular attention has been given to obtaining information from outcrops or well logs to support identification of units. A rating of good, fair, or poor has been assigned to indicate the quality of the seismic data upon which the velocities are based. Analysis of these velocity correlations in terms of their geologic implications is presented in a separate publication (Mooney and others, 1970).

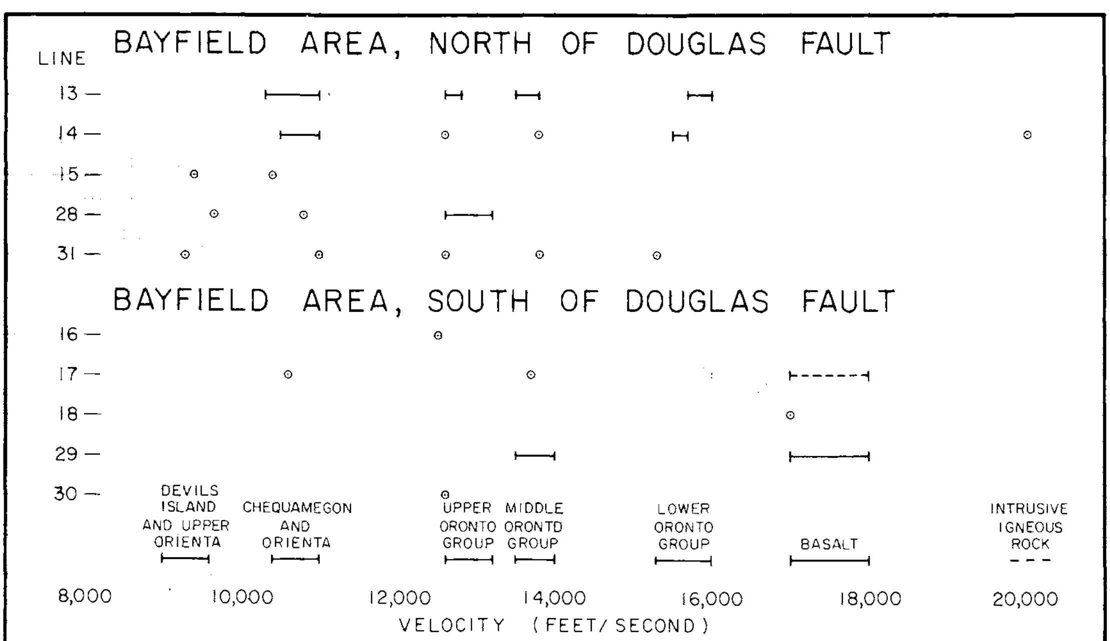
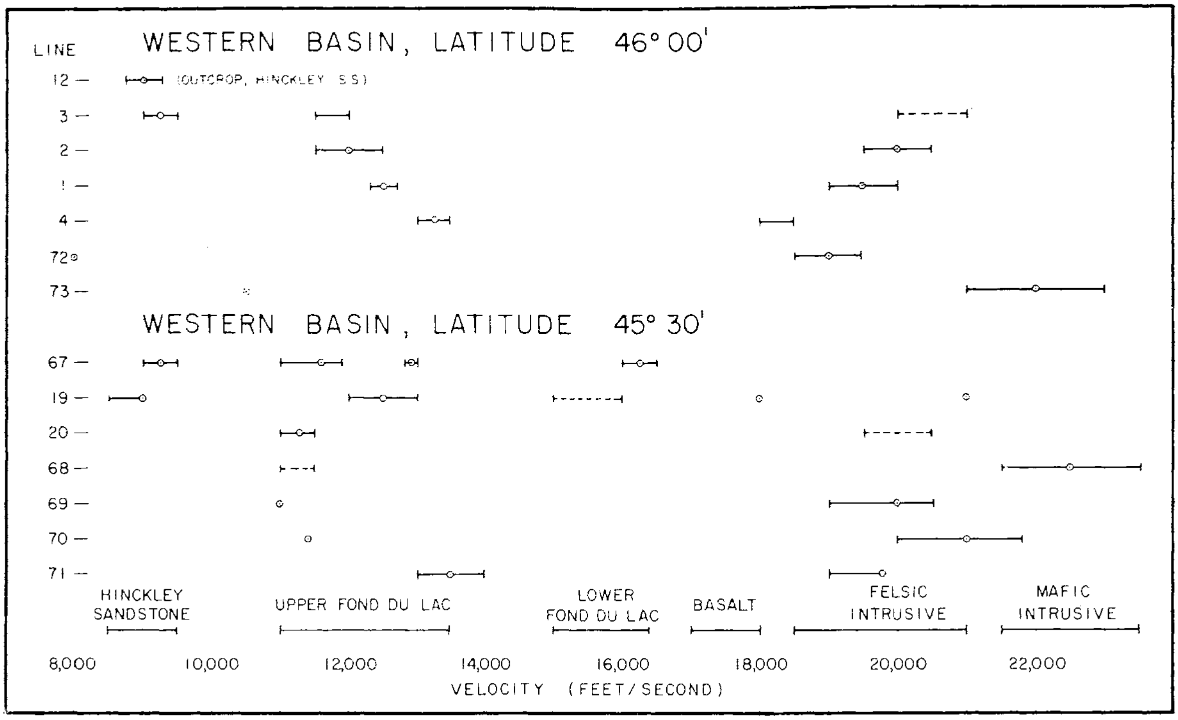


Figure 6 – Observed velocity values with geologic correlations for tectonic divisions defined in Figure 1. Figure 6A – Bayfield area; Figure 6B – Western basin; Figure 6C – Eastern basin; Figure 6D – St. Croix horst; Figure 6E – Southern Minnesota.



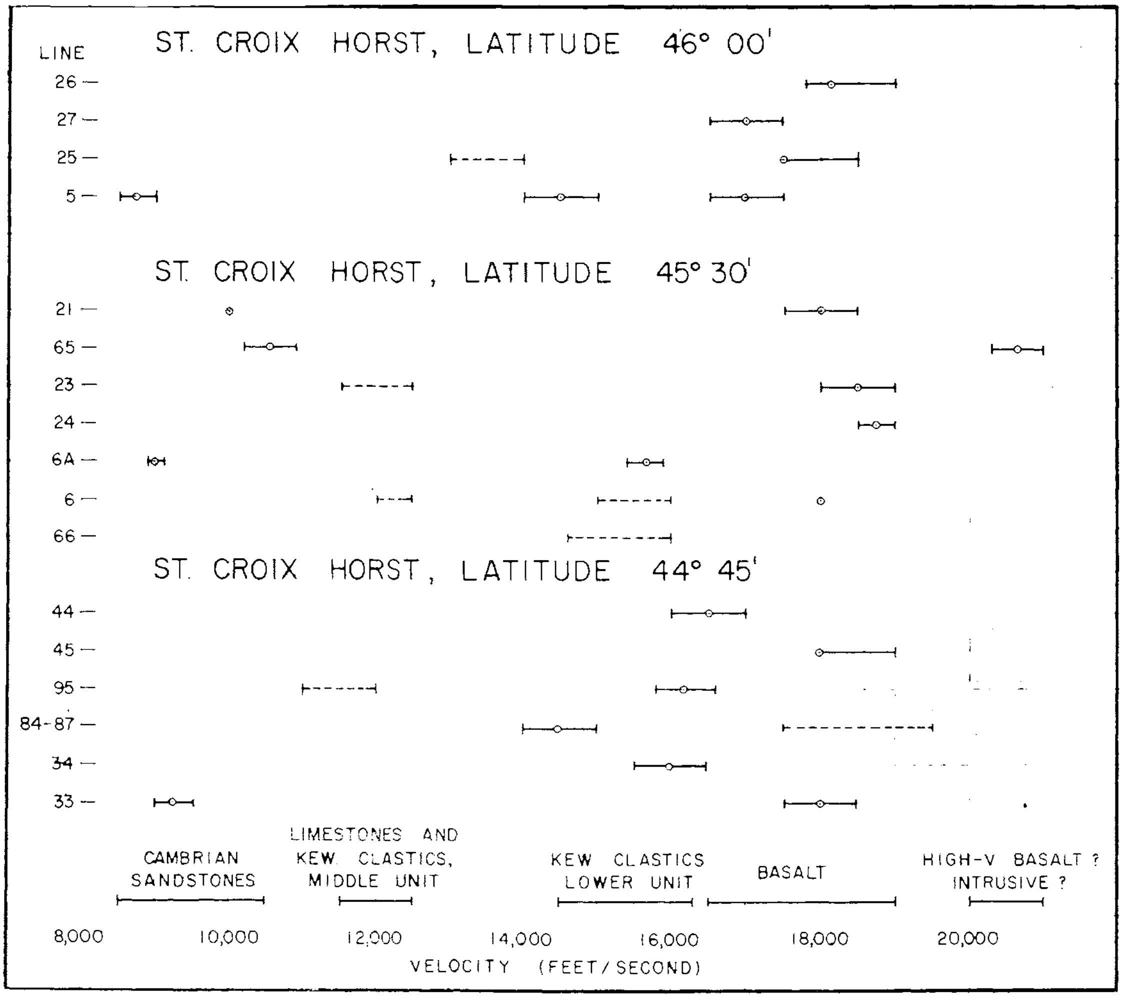
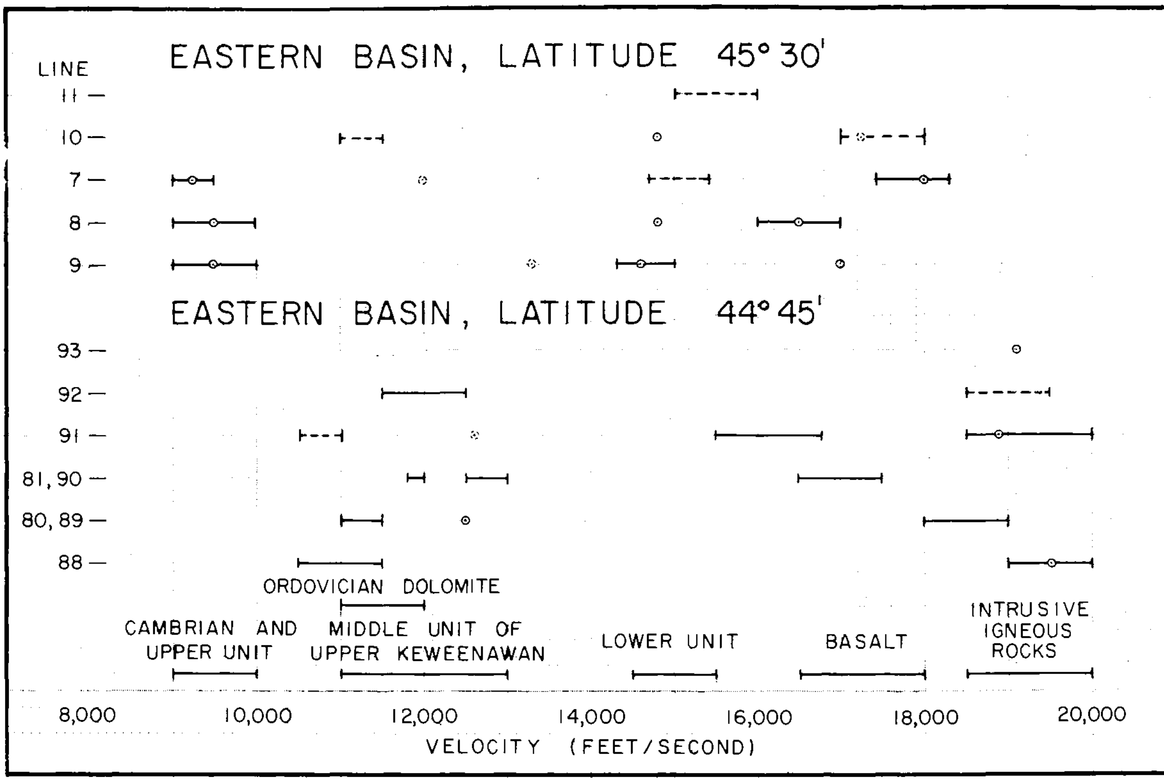


Figure 6 (continued)



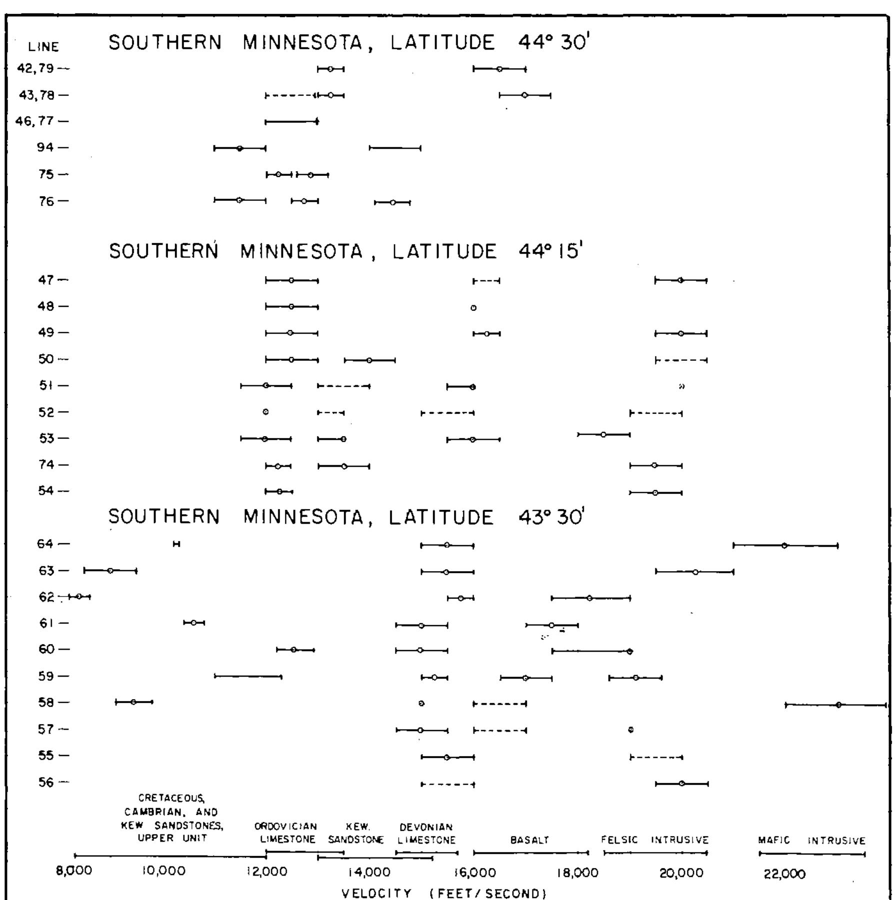


Figure 6 (continued)

Bayfield Area

1. Chequamegon Sandstone (Bayfield Group) – 10,500-11,000 feet/second.

Type area for the Chequamegon Sandstone is along the lake shore a few miles east of Line 13.

Line 13	10,500, good in-line data.
14	10,500, only a single point and poor data, but the travel time agrees well with Line 13.

2. Devils Island Sandstone and/or upper Orienta Formation (Bayfield Group) – 9,000-9,500 feet/second.

Excellent seismic data show this velocity to be present immediately beneath the glacial drift at Lines 15, 28, and 31. Thwaites (1912) shows Orienta Formation to be present beneath the drift at these localities.

Line 15	9,250, excellent in-line data with confirmation from one along-line shot.
28	9,650, same.
31	9,300, excellent but unreversed in-line data.

3. Orienta Formation (Bayfield Group) and possibly upper Freda Sandstone (Oronto Group) -- 10,500-11,000 feet/second.

This velocity was assigned to known (?) Chequamegon Sandstone on Lines 13 and 14, but on the basis of Thwaites' (1912) map it is assigned to the Orienta Formation on Lines 15, 28, and 31. The velocity layer may include part of the Freda Sandstone, which in the field cannot be distinguished with confidence from the Orienta Formation. The data for Line 17 suggest the presence of the Bayfield Group south of the Douglas fault but the evidence is weak.

North of Douglas fault	
Lines 15, 28	10,800, an excellent velocity determination for Line 28; confirmed by a single good point on Line 15.
31	11,000, a good fit to two shot points; agrees with Lines 15 and 28.
South of Douglas fault	
Line 17	10,500, questionable data.

4. Freda Sandstone (Oronto Group) – 12,500-13,000 feet/second.

Well-defined velocities in this range are found on both the north and south sides of the Douglas fault. Geologic correlation with the Freda Sandstone is reasonably good only for the three lines south of the fault. Identification of the Freda Sandstone on the north side of the fault is based entirely upon velocities and must be considered speculative.

North of Douglas fault		
Line 13		12,600, based on two good arrivals, although across-spread velocities are slightly lower.
	14	12,600, based on a good fit to three shot points as well as agreement with Line 13.
	28	12,600, but poorly defined by only a single shot point.
	31	12,600, based on a good fit to two shot points and possibly to a third.
South of Douglas fault		
Line 16		13,200, based on four good points, but the across-spread velocities are only 10,500 feet/second.
	17	12,800, based on two good points, but the across-spread velocities are only 11,000 feet/second.
	30	12,400, based on three points, but the across-spread velocities are lower.
		The discrepancy with the across-spread velocities on all three of these lines suggests that the true velocity may be somewhat less than 12,000 feet/second.

5. Middle Oronto Group -- 13,500-14,000 feet/second.

No geologic correlation is available for this velocity. It may include the Nonesuch Formation and possibly the lower part of the Freda Sandstone.

North of Douglas fault		
Line 13		13,800, based on two good arrivals as well as a third arrival of lower quality.
	14	13,800, a single arrival with good across-spread velocity.
	31	13,800, a single arrival with good across-spread velocity.
South of Douglas fault		
Line 17		13,800, excellent fit to three good points.
	30	13,800, questionable data.

6. Lower Oronto Group -- 15,300-16,000 feet/second.

No geologic correlation is available for this velocity. It may include the Copper Harbor Conglomerate and possibly part or all of the Nonesuch Formation.

North of Douglas fault		
Line 13		16,000.
	14	15,700.
	31	15,700.
		On each of the three lines, only a single shot gives this across-spread velocity, but the data are good.

7. Middle Keweenawan volcanics -- 16,500-18,000 feet/second.

Line 17	17,000-18,000, based on a large arrival at shot 5 and a correlation at shot 4. Across-spread velocities are lower, however.
18	17,000-18,000, good velocity.
29	17,000-18,000, fair velocity.

8. Pre-Keweenawan basement -- 20,000 feet/second.

Evidence for this velocity appears on only a single line and must be regarded as weak.

Line 14	20,000, based on two fair arrivals.

Note: The following velocity values for this area have been kindly supplied by Kennecott Copper Company:

Freda Sandstone — 11,000-13,000 feet/second.

Copper Harbor Conglomerate -- 14,700 (14,000-15,400) feet/second.

Volcanics --- 16,000-18,000 feet/second.

Western Basin

1. Glacial drift -- 5,000-6,500 feet/second.

Line 20	6,250, good velocity determination.
67	5,000, good velocity.
68	6,000, good velocity.
70	6,000, good velocity.
73	6,600, fair velocity.

2. Cambrian sandstone and/or upper unit of Upper Keweenawan (Hinckley Sandstone) -- 9,000 (8,500-9,500) feet/second.

Line 3	9,000-9,500, good velocity; Northern Pacific Railroad well in Pine City, 2 miles southeast, penetrated 470 feet of Hinckley Sandstone directly beneath the glacial drift.
12	9,000±300, good velocity. Measurements were taken on a quarry face of Hinckley Sandstone at Sandstone, Minnesota, 13 miles northeast of Line 3.
19	8,500-9,000, good velocity. Cambrian sandstone encountered within 5 miles at well Is-2.
67	9,000-9,500, based on a single shot point.
72	7,700, good velocity. Glacial drift or weathered sandstone (?).

3. Middle unit of Upper Keweenawan -- 12,000 (11,000-13,500) feet/second.

This unit, the Fond du Lac Formation, is thought to be widespread and thick in the western basin. The seismic evidence shows a velocity inversion within the section, hence the measured velocity values represent an upper limit corresponding to a cap layer that has a maximum thickness of a few hundred feet. True velocities within the main part of the section may be substantially lower than 12,000 feet/second, possibly 11,000.

Line 1	12,500 (12,300-12,700), good velocity determination.
2	12,000 (11,500-12,500), good velocity, considerable thickness.
3	11,500-12,000, fair velocity, considerable thickness.
4	13,000-13,500, good velocity, thin layer with lower velocity beneath. Fond du Lac Formation outcrops 4 miles west.
19	12,500 (12,000-13,000), good velocity.
20	11,000-11,500, fair velocity.
67	11,600, fair velocity; 13,000, fair velocity.
69	11,000, based on a single shot point.
70	11,400, fair velocity, thin layer. Fond du Lac Formation encountered in a well 5 miles southwest.
71	13,500 (13,000-14,000), fair velocity.

4. Lower unit of Upper Keweenawan -- (15,500-16,500 feet/second).

This unit, if present, may be the lower part of the Fond du Lac Formation. Evidence for it appears only on Lines 19 and 67, located 7 and 4 miles west of the Douglas fault at latitude 45°30′; the formation at Line 67 could possibly be basalt.

Line 19	15,000-16,000, based on a single shot point.
67	16,000-16,500, fair velocity determination.

5. Middle Keweenawan volcanics -- (18,000 feet/second).

Line 19	18,000, fair velocity determination.

6. Pre-Keweenawan crystalline basement rocks. Felsic intrusive rocks -- 19,000-21,000 feet/second. Mafic intrusive rocks -- 21,500-23,500 feet/second.

An intrusive complex is exposed along the western edge of the basin and presumably extends eastward beneath the sedimentary section. Velocity values for this complex were obtained on 10 lines, although correlation with individual rock units remains tentative.

Line 1	19,500 (19,000-20,000), good velocity determination.
2	20,000 (19,500-20,500), good velocity.
3	20,000-21,000, poor velocity.
4	18,000, fair velocity; probably Warman Quartz Monzonite.

20	19,500-20,500, poor velocity.
68	21,500 or higher, poor velocity.
69	20,000 (19,000-20,500), good velocity; possibly St. Cloud Gray Granodiorite.
70	20,000 or higher, fair velocity; probably St. Cloud Gray Granodiorite, which was encountered in a well 5 miles southwest.
71	19,000-19,800, fair velocity; probably St. Cloud Gray Granodiorite.
72	18,500-19,500, fair velocity; probably Warman Quartz Monzonite, which crops out 2 miles west.
73	22,000-23,000, good velocity; possibly a gabbroic intrusion. The line lies close to the mapped (Woyski, 1949) contact between the Warman Quartz Monzonite and the Stearns magma series.

St. Croix Horst

1. Glacial drift -- 5,000-6,000 feet/second.

No attempt was made to resolve velocity distinctions within the drift nor to correlate velocities with specific horizons. The following values were obtained:

Line 6A	5,800, excellent velocity determination.
21	5,700, good velocity.
23	6,000, good velocity.
24	6,000, fair velocity.
26	7,500, fair velocity, but material could be weathered sandstone.
33	5,500, fair velocity.
45	4,500, poor velocity.

2. Ordovician dolomite -- (11,000-12,000 feet/second).

Line 34	12,000, poor velocity.
95	11,000, poor velocity.

3. Cambrian sandstone and upper unit of Upper Keweenawan sedimentary section -- 9,000 (8,500-10,500) feet/second.

These units appear to be absent or very thin (a few tens of feet) over the central and northern parts of the St. Croix horst. Reliable detection requires close geophone spacing such as was used for Line 6A.

Line 5	8,500-9,000, poor velocity from in-line shots.
6A	9,000, excellent velocity; good geologic control from well 2 miles away.
21	10,000, based only on second seismic arrival data.
33	9,000-9,500, questionable in-line data.
44	9,000, questionable velocity.
65	10,200-10,900, poor velocity; geologic correlation from nearby well.

4. Middle unit of Upper Keweenawan -- 12,000 (?) feet/second.

The existence of this unit in the central and northern parts of the St. Croix horst is questionable. Line 6 yielded a velocity of 12,500 feet/second and Line 23 of 12,000 feet/second, but both values were of poor quality.

5. Lower unit of Upper Keweenawan -- 15,500 (14,500-16,000) feet/second.

The presence of this member is documented in several wells along the central and southern parts of the St. Croix horst, where it is logged as Keweenawan Red Clastics.

Line 5	14,000-15,000, fair velocity determination but poor geologic control.
6	15,000-16,000, based on a single arrival; material could be basalt and interbedded sedimentary rocks.
6A	15,700, excellent velocity; Keweenawan Red Clastics are reported in a well 2 miles away (see figure 7A), although magnetic data suggest a major fault between the horst and the well.
34	16,000 (15,500-16,500), fair velocity; a well 5 miles away reports Keweenawan Red Clastics. Magnetic data show igneous rocks to be absent or deep.
84	14,000 (14,000-15,000), fair velocity; Keweenawan Red Clastics in well 6 miles west.
95	16,400, good velocity; Keweenawan Red Clastics in well 2 miles away.

6. Middle Keweenawan volcanic rocks - 17,800 (16,500-19,000) feet/second.

Good velocity determinations for basalt have been obtained on many lines, with good agreement from line to line. Geologic correlation is available from outcrops near Line 23 and from well logs near Lines 21-24, 26, 33, and 45. The basalt also produces a distinctive magnetic pattern that permits extrapolation away from control points.

Line 5	17,000 (16,500-17,500), excellent velocity determination; no geologic control on Lines 5 and 6, except that magnetic data show the lines to overlie a structural depression.
6	18,000, fair velocity.
21	18,000 (17,500-18,500), good velocity; good geologic correlation from nearby wells on Lines 21-24.
23	18,000 or slightly higher, good velocity; basalt crops out 10 miles south.
24	19,000 (18,500-19,000), good velocity.
25	17,400-18,500, uncertain velocity due to higher values for spread velocities; magnetics show shallow basalt on Lines 25-27.
26	17,800-19,000, fair velocity; basalt in well 10 miles south.
27	17,000 (16,200-17,500), fair velocity.
33	18,000 (17,500-18,500), fair velocity; good geologic control from well 5 miles away.
44	16,500 (16,000-17,000), fair velocity; presence of basalt inferred from magnetics.
45	18,200, good velocity but spread velocities are higher; geologic control from two wells within a mile of the line.
65	20,600, good velocity; this value is too high for Middle Keweenawan volcanics; it may represent an intrusive or a more basic basalt. No geologic control is available, but magnetic data show mafic rock at shallow depth.
66	14,600-16,000, fair velocity; no geologic control is available. Magnetic data suggest mafic rock. The low velocity value suggests basalt and interbedded sedimentary rock.

Eastern Basin

1. Glacial drift – 5,500 feet/second.

Line 90	5,500, fair velocity determination.
93	5,600, good velocity.

2. Ordovician dolomite -- 10,500-12,000 feet/second.

Dolomite is known to occur locally as a thin layer that caps the Cambrian sandstones.

Line 80, 89	11,000-11,500, fair velocity.
88	10,500-11,500, poor velocity; 250 feet of dolomite penetrated in well 3 miles west.
90	11,800, fair velocity.
91	10,500-11,000, poor velocity; nearby well shows Cambrian sandstone beneath drift, hence dolomite is assumed to be thin at seismic location.

3. Cambrian sandstone and/or upper unit of Upper Keweenawan -- 9,000-9,500 feet/second.

Cambrian sandstone is known to be widespread in the vicinity of Lines 7-11; all wells in Barron County, Wisconsin bottom in it.

Line 7	9,000-9,500, good velocity.
8	9,500 (9,000-10,000), good velocity.
9	9,500 (9,000-10,000), fair velocity.

4. Middle unit of Upper Keweenawan -- 12,000 (11,000-13,000) feet/second.

Velocity data are variable and relatively poor. No geologic control is available.

Line 7	12,000, based on a single shot point.
9	13,300, based on a single shot point.
10	11,000-11,500, fair velocity.
80, 89	12,500, fair velocity.
81, 90	12,500-13,000, fair velocity.
91	12,500, poor velocity.

5. Lower unit of Upper Keweenawan -- 14,500-15,000 feet/second.

The only geologic control is an outcrop of Barron Quartzite near Line 11. Possibly this formation constitutes the lower unit of the Upper Keweenawan throughout the Eastern basin.

Line 7	15,000, based on a single shot point.
8	14,500-15,000, fair velocity.
9	14,600 (14,300-15,000), fair velocity.
10	14,800, good velocity.
11	15,000-16,000, poor velocity; near outcrop of Barron Quartzite.

6. Middle Keweenawan volcanics -- 17,000-18,000 feet/second.

These velocities are correlated with Middle Keweenawan volcanics on the basis of similar velocities in nearby areas.

Line 7	18,000 (17,400-18,300), good velocity.
8	16,000-17,000, fair velocity.
9	17,000, fair velocity.
10	17,000-18,000, based on a single shot point.
81	17,000, fair velocity.
90	16,500-17,500, good velocity.

7. Pre-Keweenawan crystalline rocks -- 19,000 feet/second.

These velocities are correlated with felsic igneous rocks on the basis of drillhole samples near Line 93 and on similar correlations in the Western basin.

Line 88	19,000-20,000, poor velocity.
89	18,000-19,000, fair velocity.
91	19,000, good velocity.
92	18,500-19,500, fair velocity but across-spread velocities are lower.
93	19,100, good velocity. Precambrian pink granite penetrated in well 2 miles east.

Southern Minnesota

1. Glacial drift -- 5,000-6,000 feet/second.

Line 46	5,300, good velocity determination.
48	6,000, good velocity.
49	5,600, good velocity.
50	6,200, poor velocity.
52	6,150, fair velocity.
53	5,400, good velocity.
54	6,000, good velocity.
55	5,500, good velocity.
56	5,100, good velocity.
74	5,300, good velocity.
75	5,800, good velocity.
76	5,200, fair velocity.
94	4,300, fair velocity.

2. Devonian limestone and dolomite (Cedar Valley Formation) -- 15,500 (15,000-16,000) feet/second.

The presence of flat-lying Cedar Valley Formation throughout the area of Lines 55-64 is documented from numerous wells.

Line 55	15,000-16,000, good velocity.
56	15,000-16,000, poor velocity.
57	15,000 (14,500-15,500), fair velocity.
58	15,000, poor velocity.
60	15,500 (14,500-15,500), good velocity.
61	15,500 (14,500-15,500), good velocity.
62	15,500-16,000, good velocity.
63	15,000-16,000, fair velocity.
64	16,000 (15,000-16,000), fair velocity.

3. Ordovician limestones and dolomites -- 12,500 (12,000-13,000) feet/second.

The presence of Ordovician limestone and dolomite is known from numerous wells in the area of Lines 47-54.

Latitude 44° 15′ North

Line 47	12,500 (12,000-13,000), fair velocity determination.
48	12,500 (12,000-13,000), fair velocity; limestone known from well 3 miles west.
49	12,500 (12,000-13,000), fair velocity; limestone known from well 3 miles east.
50	12,500, based on a single shot point.
51	12,000 (11,500-12,500), good velocity.
53	12,000 (11,500-12,500), good velocity.
54	12,000, based on a single shot point.
74	12,000-12,500, poor velocity; 200 feet of Shakopee Dolomite in well 1 mile away.

Latitude 44° 30′ North

Line 42, 79	12,000-13,500, fair velocity.
43, 78	13,000-13,500, good velocity.
46, 77	12,000-13,000, fair velocity.
75	12,000-12,500, good velocity; Ordovician dolomite in wells 5 and 11 miles east.
76	11,000-12,000, poor velocity.

4. Cambrian sandstone and upper unit of Upper Keweenawan -- (11,000 feet/second?)

Despite the known widespread occurrence of these units from well data, no velocity determinations were obtained due to the presence of a higher-velocity dolomite cap layer. The dolomite velocity of 11,600 feet/second from Line 94 establishes an upper limit for the underlying sandstones. A lower limit would be the 9,000 feet/second value obtained in the Western basin. We have tentatively taken 11,000 feet/second for purposes of calculation; a lower value would decrease computed depths slightly. The velocity inversion associated with these units is clearly visible on nearly all seismic lines in south-central Minnesota.

5. Middle and/or lower unit of Upper Keweenawan -- 14,000 (13,500-14,500) feet/second.

Latitude 44° 15′ North

Line 49	14,000, based on a single shot point.
50	14,000 (13,500-14,500), excellent velocity.
51	13,000-14,000, poor velocity.
52	13,000-13,500, poor velocity.
53	13,500 (13,000-13,500), good velocity.
74	13,600 (13,000-14,000), excellent velocity.

Latitude 44°30′ North	
Line 75	12,800 (12,600-13,200), excellent velocity.
76	12,500-13,000, good velocity; 14,500, fair velocity.
94	14,000 (14,000-15,000), good velocity but the across-spread velocities are higher. Lower unit of Upper Keweenawan sandstone in well 1/2 mile away, from depth of 1,025 feet to well bottom at 2,900 feet.

6. Middle Keweenawan volcanics -- 17,000 (16,000-17,500) feet/second.

Latitude 43°30′ North	
Line 57	16,000-17,000, poor velocity.
59	17,000 (16,500-17,500), excellent velocity.
60	19,000 (17,500-19,000), good velocity; velocity value is higher than would be expected for basalt, but across-spread velocities are lower.
61	17,000-18,000, poor velocity.

Latitude 44°15′ North	
Line 47	16,000-16,700, based on single shot point.
48	16,000, fair velocity.
49	16,000-16,500, good velocity.
51	16,000 (15,500-16,000), good velocity.
52	15,000-16,000, poor velocity.
53	16,000 (15,500-16,500), fair velocity.

Latitude 44°30′ North	
Line 42, 79	16,000-17,000, fair velocity; identification as basalt is questionable.
43, 78	17,000 (16,500-17,500), fair velocity.
75	17,000-18,000, based on a single shot point.

7. Pre-Keweenawan igneous rocks, felsic -- 20,000 (19,500-20,500) feet/second.

Latitude 43°30′ North	
Line 55	19,000-20,000, poor velocity.
56	20,000 (19,500-20,500), good velocity.
57	19,000, poor velocity.
59	19,000, based on a single shot point.
62	17,500-19,000, fair velocity; material could consist of basalt.
63	20,000 (19,500-21,000), good velocity.

Latitude 44° 15′ North	
Line 47	20,000 (19,500-21,000), fair velocity.
49	20,000 (19,500-20,500), fair velocity.
50	19,500-20,500, poor velocity.
51	20,000, poor velocity.
53	18,000-19,000, fair velocity.
54	19,000-20,000, fair velocity.
74	19,000-20,000, poor velocity.

8. Pre-Keweenawan igneous rocks, mafic -- 22,000-23,000 feet/second.

Line 58	23,000 (22,000-24,000), good velocity.
64	22,000 (21,000-23,000), good velocity; gabbro was encountered in a well 30 miles east.

INTERPRETATION OF SEISMIC PROFILES

The basic data obtained from the seismic investigation consist of seismic travel-time graphs and geologic interpretation of the graphs. These data appear in the Appendix. This section contains some explanatory comments.

For each seismic profile, the travel-time graph appears on the left page and the geologic interpretation on the right. Each seismic arrival on the travel-time graph is represented by a circled point and by a numerical value for the across-spread velocity. The point shows shot distance versus travel-time for geophone G1 (see figure 5). The numerical value represents the apparent velocity across the spread of geophones. Comments on reliability of the velocity determination and on the character of the seismic arrival are included.

Straight lines have been fitted to the travel-time data. These form the basis for our interpretation. They have been drawn to pass as closely as possible through the individual points, and are subject to the constraint that all points on a given line must have similar across-spread velocities. Each line has been characterized by an equation to give slope and intercept time.

Some of the travel-time lines are terminated by "X". This represents the point of critical reflection as computed from the structure section shown on the facing page. At this shot distance, the refraction arrival should merge with the reflection arrival to form a signal of large amplitude. Only reflection arrivals could be observed at lesser shot distances.

Supplementary data on each travel-time graph include an in-line seismic profile, a graph of across-spread velocities versus shot distance, and a location map. The in-line profile provides information on the shallow structure. The field arrangement is shown in Figure 5. The graph of across-spread velocities is used as a guide in drawing the travel-time lines. The location map shows geophone spread and shot line with reference to local roads as well as to latitude and longitude.

The right-hand page for each profile gives an interpretive geologic section and a discussion of the purpose and results of each. The section represents the simplest interpretation capable of accounting for the lines drawn onto the travel-time graph. In most cases, the structure consists of constant-velocity layers separated by plane-dipping boundaries; more complex structures are required in some cases. Velocities are designated on the geologic section, along with proposed identifications of the formations. An interpretation of the in-line profile is given separately.

In the discussion, we indicate why the profile was placed at its particular location and what geologic purpose it was intended to serve. Drill data and outcrop control are tabulated, if available, together with surface elevation at the seismic profile. Under "Results", we explain the seismic interpretation and present some geologic conclusions.

A few of the seismic profiles presented in the Appendix require special comment. Figure 7A shows a sequence of profiles across the Western basin at latitude 45°30′. As noted in the discussion accompanying individual profiles, the western margin of the St. Croix horst at this latitude appears geologically complex. This margin occurs between Lines 24 and 67. Figure 7A shows the seismic profiles in relation to the magnetic contours, the inferred geology, and a shallow well referred to under Line 6. The lighter part of the map shows the sedimentary rocks of the Western basin. The northernmost extent of the Paleozoic sedimentary rocks appears as a hachured line passing through Lines 68-70. The darker portion on the left represents an exposed complex of metamorphic and intrusive igneous rocks of Precambrian age. The darker portion on the right shows the Keweenawan volcanics of the St. Croix horst. A down-faulted (?) sediment-filled depression within the horst appears near its western margin as a light-colored elongate feature. The inferred position of the Douglas fault is shown by a dashed line which passes between Lines 66 and 67.

Figure 7B presents another part of the same magnetic map, to show the location of seismic profiles near the southeastern end of the St. Croix horst. The area extends east and south from Minneapolis-St. Paul. The horst is wider at this latitude than it is to the north, and includes a structural depression known as the Twin Cities basin.

Figure 8 shows the location of Lines 75 and 76 with respect to magnetic contours and to three drill holes. Two of these drill holes encountered basalt at depths of about 800 feet. The seismic profiles were intended as calibration lines close to the wells. The proximity of a major fault was not recognized when the lines were laid out, but the seismic results show a fault present between Line 75 and the wells. The magnetic contours support this conclusion.

Figure 9 shows densities determined on samples from a deep cored drill hole near Lonsdale in southern Minnesota. The data were made available by Rodney J. Ikola of the Minnesota Geological Survey. Line 94 was placed near the drill hole for calibration purposes. As noted in the discussion under Line 94, the drill hole provides access to samples of the lower part of the Upper Keweenawan sequence, which was penetrated from a depth of 944 feet to the bottom at 2,840 feet. The interval from 944 to 1,180 feet consists predominantly of shale and siltstone and possibly represents a zone of ancient weathering. The underlying section is interbedded shale and sandstone.

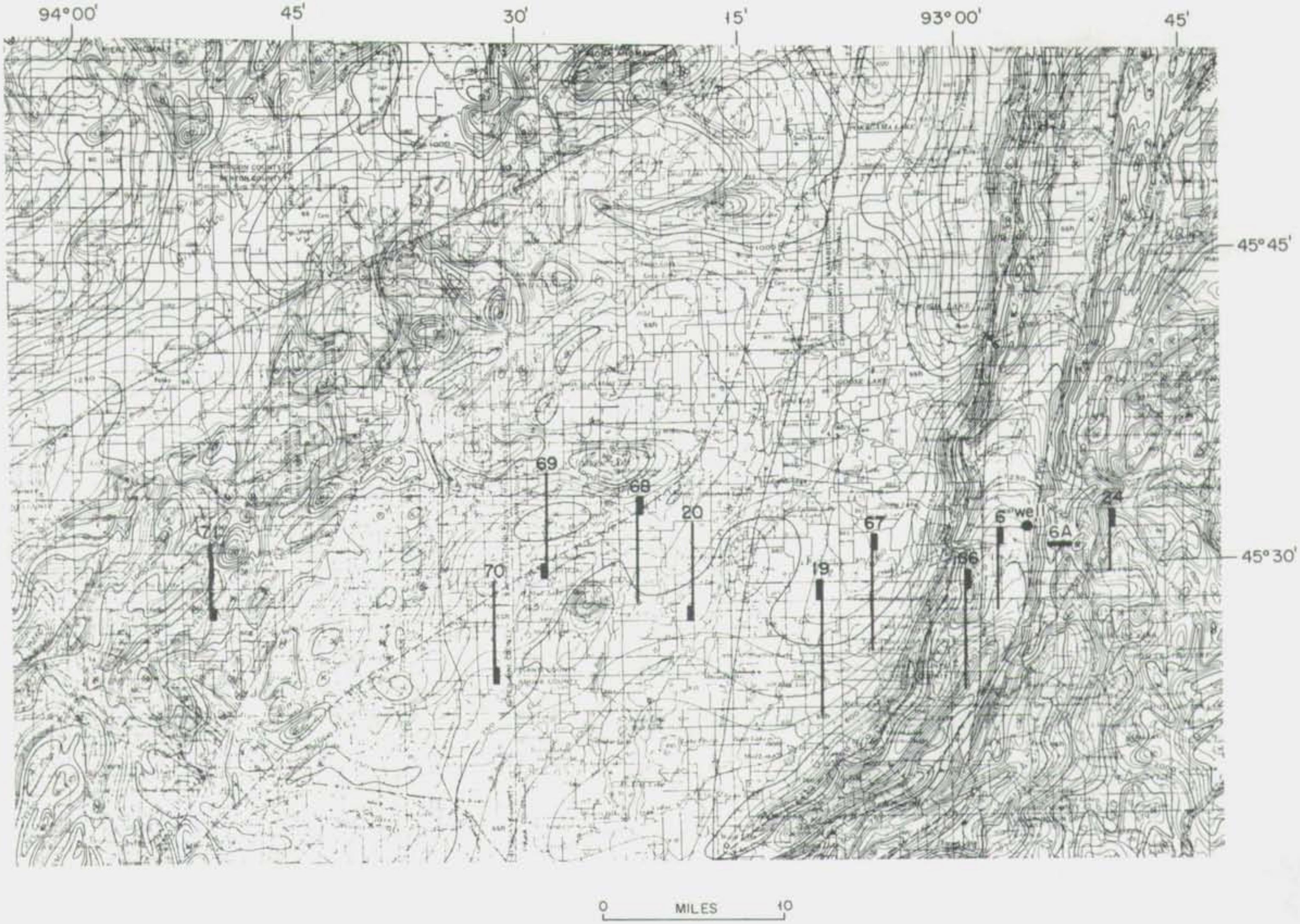


Figure 7A – Aeromagnetic contour map showing location of seismic profiles and a drill hole near Cambridge, Isanti County, Minnesota. (Magnetic data from U.S. Geological Survey, Geophysical Investigations Map GP-563.)

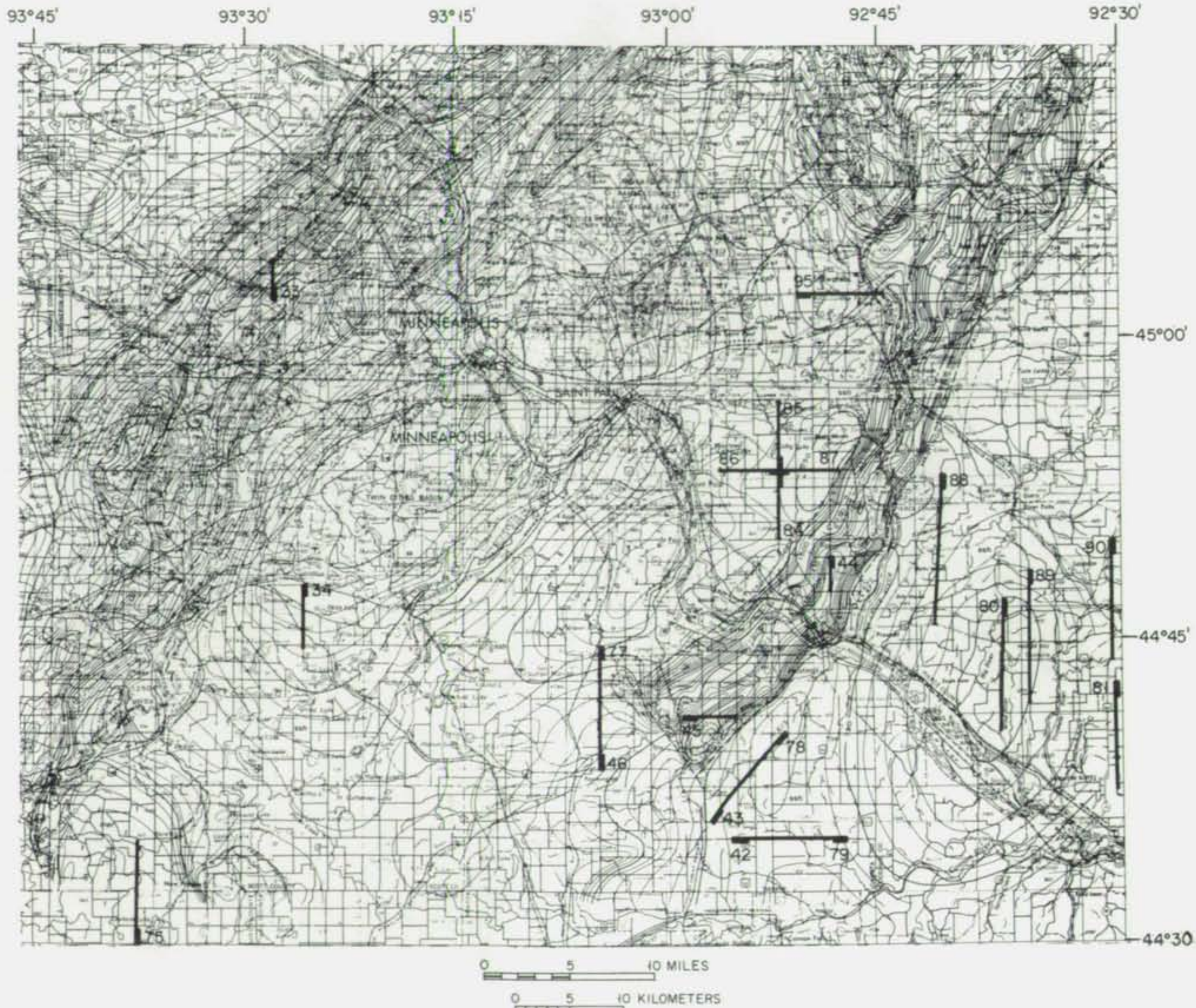


Figure 7B – Aeromagnetic contour map showing location of seismic profiles southeast of St. Paul, Minnesota. (Magnetic data from U.S. Geological Survey, Geophysical Investigations Map GP-563.)

The high density (2.70-2.76 grams/cc) of the sandstone shown in Figure 9 results from compaction coupled with the presence of numerous mafic volcanic rock fragments. The seismic data, indicating a velocity of 14,000-14,500 feet/second, confirm the unusual character of the sandstone. This velocity correlation has proved useful for interpretation of seismic lines throughout southern Minnesota.

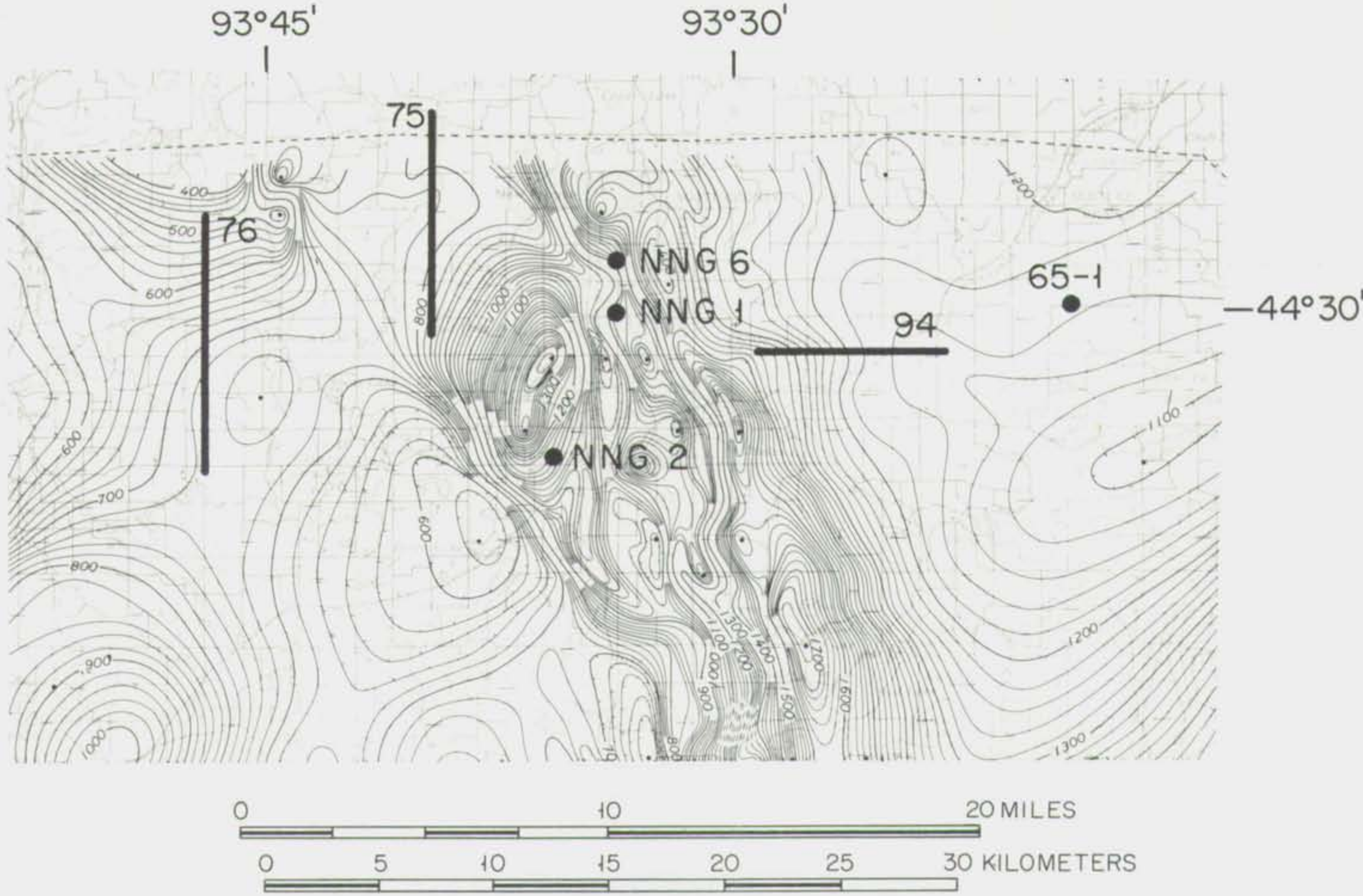


Figure 8 – Aeromagnetic contour map, showing location of seismic profiles with respect to four drill holes near New Prague, Scott County, Minnesota. (Magnetic data from U.S. Geological Survey, Geophysical Investigations Map GP-559. Faribault, Minnesota lies 27 miles ESE of well NNG-2.)

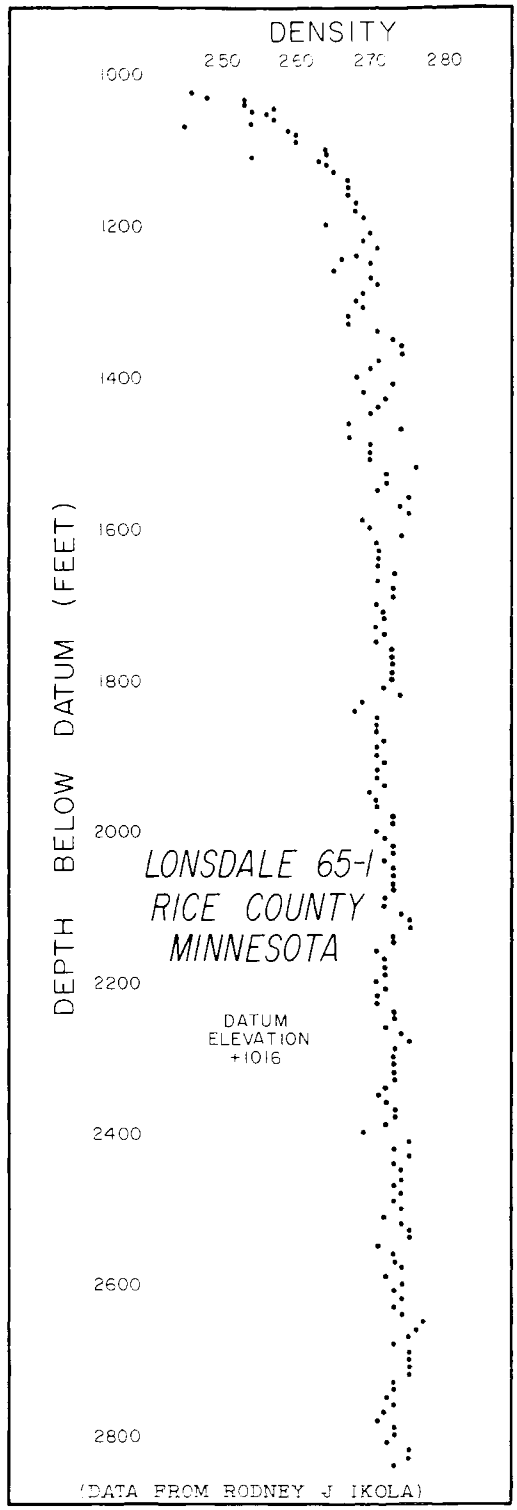


Figure 9 – Density measurements on Upper Keweenawan Red Clastics from Lonsdale 65-1 well (see Figure 8 for location).

ACKNOWLEDGMENTS

Grateful acknowledgment is made to W. D. Lacabanne, Willard Blake, James Knopick, and Thomas Lynch for assistance in field work, and to Robert Meyer and Theodore Cohen for guidance in planning. Richard Darling drafted most illustrations. G. B. Morey contributed substantially to Figure 4; both he and George Austin provided geologic information. This work was supported by the National Science Foundation under grant GA-507.

REFERENCES

Adams, B. B., 1957, Regional gravity and geologic structure in east-central Minnesota: Unpublished Ph.D. Thesis, Univ. Wisconsin, 106 pp.

Cohen, T. J., 1966, Explosion seismic studies of the midcontinent gravity high: Unpublished Ph.D. Thesis, Univ. Wisconsin, 350 pp.

Cohen, T. J., and R. P. Meyer, 1966, The midcontinent gravity high: gross crustal structure; in, The Earth Beneath the Continents, American Geophys. Union, p. 141.

Coons, R. L., 1968, Precambrian basement geology and Paleozoic structure of the midcontinent gravity high: Unpublished Ph.D. Thesis, Univ. Wisconsin, 296 pp.

Coons, R. L., and G. P. Woollard, 1967, Structural significance and analysis of the midcontinent gravity high: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2381.

Craddock, C., E. C. Thiel, and B. Gross, 1963, A gravity investigation of the Precambrian of southeastern Minnesota and western Wisconsin: Jour. Geophys. Res., v. 68, p. 6015.

Craddock, C., H. M. Mooney, and V. Kolehmainen, 1970, Bouguer gravity map of Minnesota and northwestern Wisconsin: Minn. Geol. Survey Map M-10.

Farnham, P. R., 1967, Crustal structure in the Keweenawan province of east-central Minnesota and western Wisconsin: Unpublished Ph.D. Thesis, Univ. Minnesota, 464 pp.

Goldich, S. S., A. O. C. Nier, and H. Baadsgaard, 1961, The Precambrian geology and geochronology of Minnesota: Minn. Geol. Survey Bull. 41, 193 pp.

Hall, C. W., 1901, Keweenawan area of eastern Minnesota: Geol. Soc. America Bull. v. 12, p. 313.

Hamblin, W. K., 1961, Paleogeographic evolution of the Lake Superior region from Late Keweenawan to Late Cambrian time: Geol. Soc. America Bull., v. 72, p. 1.

Hite, D. M., 1967, Sedimentology of the Upper Keweenawan sequence of northern Wisconsin and adjacent Michigan: Unpublished Ph.D. Thesis, Univ. Wisconsin, 217 pp.

Johnson, S. H., 1967, Seismic investigation of the midcontinent gravity high in southeastern Minnesota: Unpublished M.S. Thesis, Univ. Minnesota, 118 pp.

Kirwin, P. H., 1963, Subsurface stratigraphy of the Upper Keweenawan redbeds in southeastern Minnesota: Unpublished M.S. Thesis, Univ. Minnesota, 74 pp.

Mooney, H. M., C. Craddock, P. R. Farnham, S. H. Johnson, and G. Volz, 1970, Geophysical investigations of the northern midcontinent gravity high: Jour. Geophys. Res. (in press).

Patenaude, R. W., 1966, A regional aeromagnetic survey of Wisconsin; *in,* The Earth Beneath the Continents, American Geophys. Union, p. 111.

Steinhart, J. S., and R. P. Meyer, 1961, Explosion studies of continental structure: Carnegie Inst., Washington, Publ. 622, 409 pp.

Thiel, E. C., 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota: Geol. Soc. America Bull., v. 67, p. 1079.

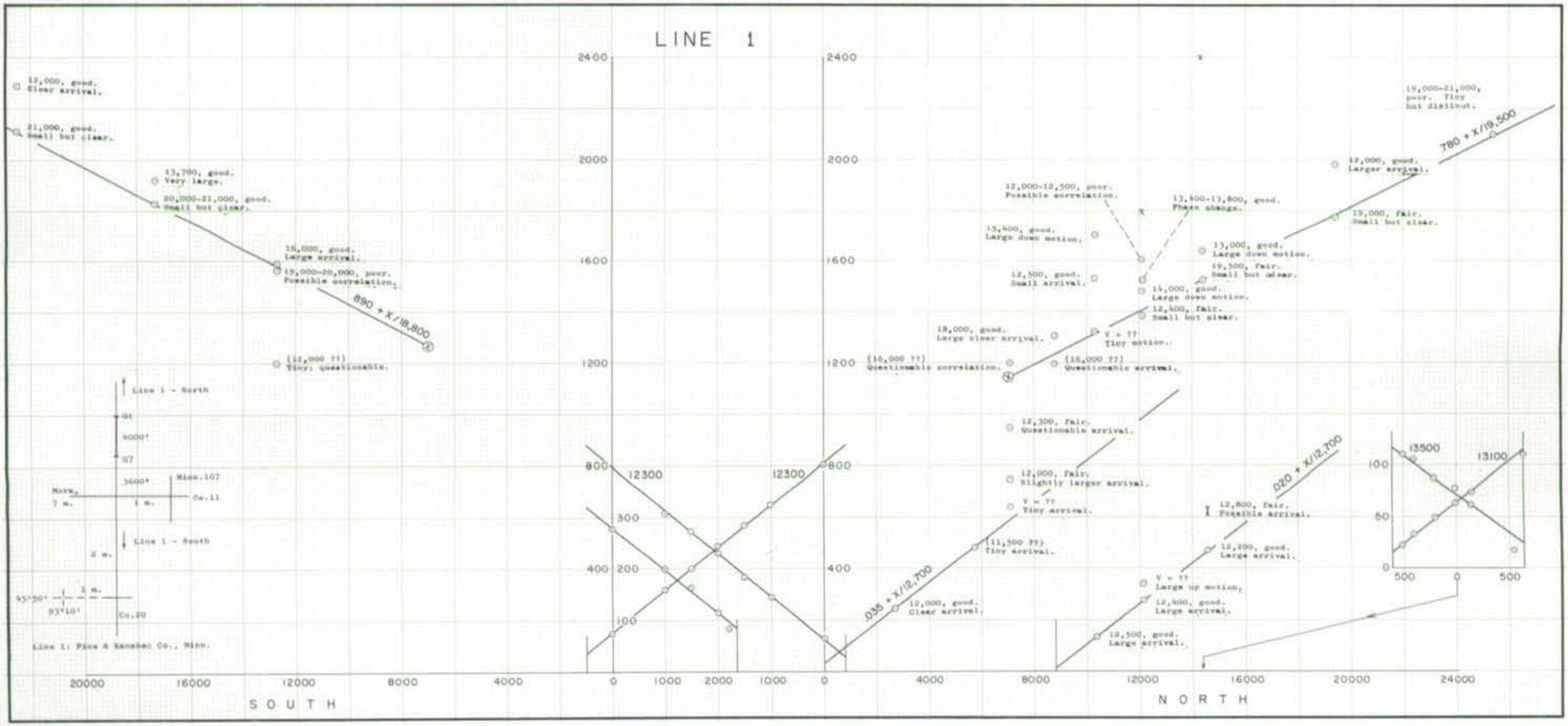
Thiel, G. A., 1944, The geology and underground waters of Southern Minnesota: Minn. Geol. Survey Bull. 31, 506 pp.

Thwaites, F. T., 1912, Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geol. and Nat. Hist. Survey Bull. 25, 117 pp.

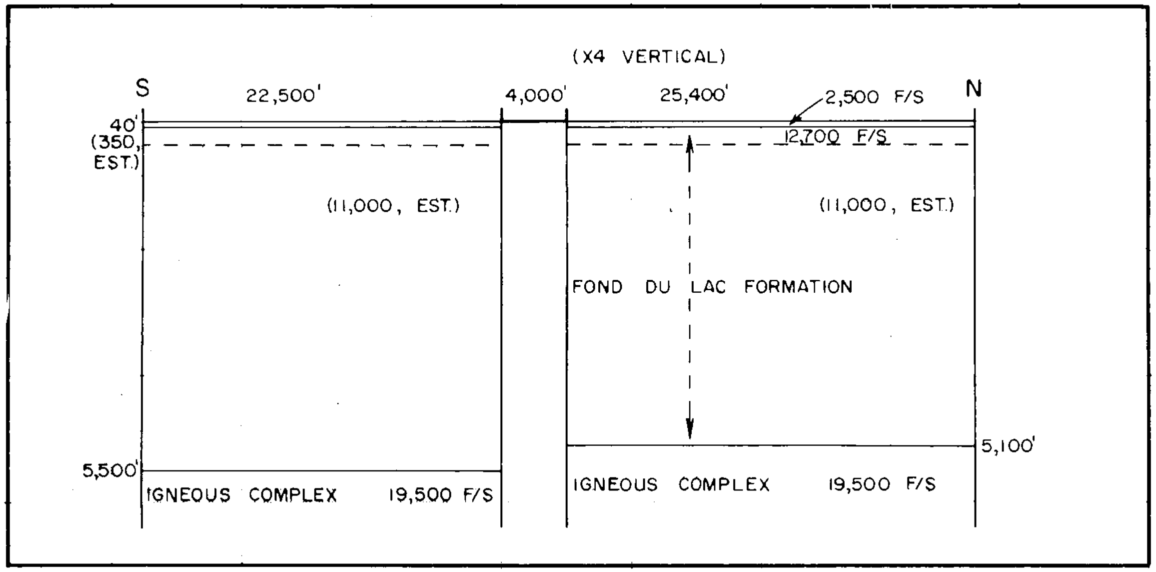
Tuve, M. A., 1953, The earth's crust: Carnegie Inst., Washington, Yearbook 52, p. 103.

Volz, G., 1968, Seismic investigation of the River Falls basin in western Wisconsin and part of the St. Croix horst in southeastern Minnesota: Unpublished M.S. Thesis, Univ. Minnesota, 140 pp.

Woyski, M., 1949, Intrusives of central Minnesota: Geol. Soc. America Bull., v. 60, p. 999.



LINE 1
SOUTH
NORTH
12,000, good. Clear arrival.
21,000, good. Small but clear.
13,700, good. Very large.
20,000-21,000, good. Small but clear.
16,000, good. Large arrival.
19,000-20,000, poor. Possible correlation.
890 + X/18,800
(12,000 ??) Tiny; questionable.
12,000-12,500, poor. Possible correlation.
13,400-13,800, good. Phase change.
15,400, good. Large down motion.
12,500, good. Small arrival.
18,000, good. Large clear arrival.
(16,000 ??) Questionable correlation.
(16,000 ??) Questionable arrival.
12,300, fair. Questionable arrival.
12,000, fair. Slightly larger arrival.
(11,500 ??) Tiny arrival.
12,000, good. Clear arrival.
.035 + X/12,700
12,800, fair. Possible arrival.
12,200, good. Large arrival.
12,400, good. Large arrival.
12,500, good. Large arrival.
.020 + X/12,700
13,000, good. Large down motion.
19,500, fair. Small but clear.
14,000, good. Large down motion.
12,400, fair. Small but clear.
12,000, good. Larger arrival.
19,000, fair. Small but clear.
19,000-21,000, poor. Tiny but distinct.
780 + X/19,500
12300
13500
13100
Line 1 - North
Line 1 - South
Line 1: Pine & Kanabec Co., Minn.

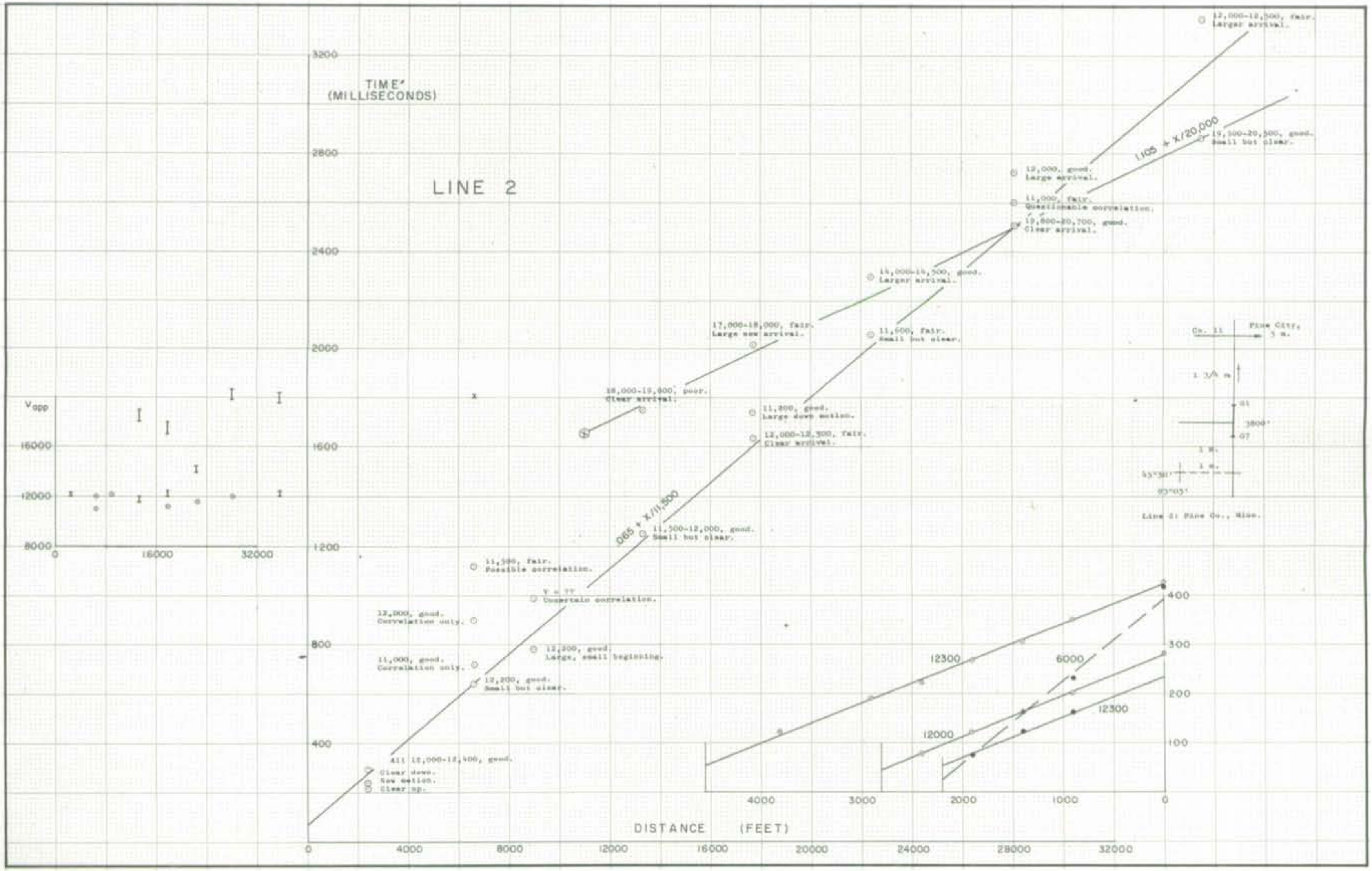


LINE 1

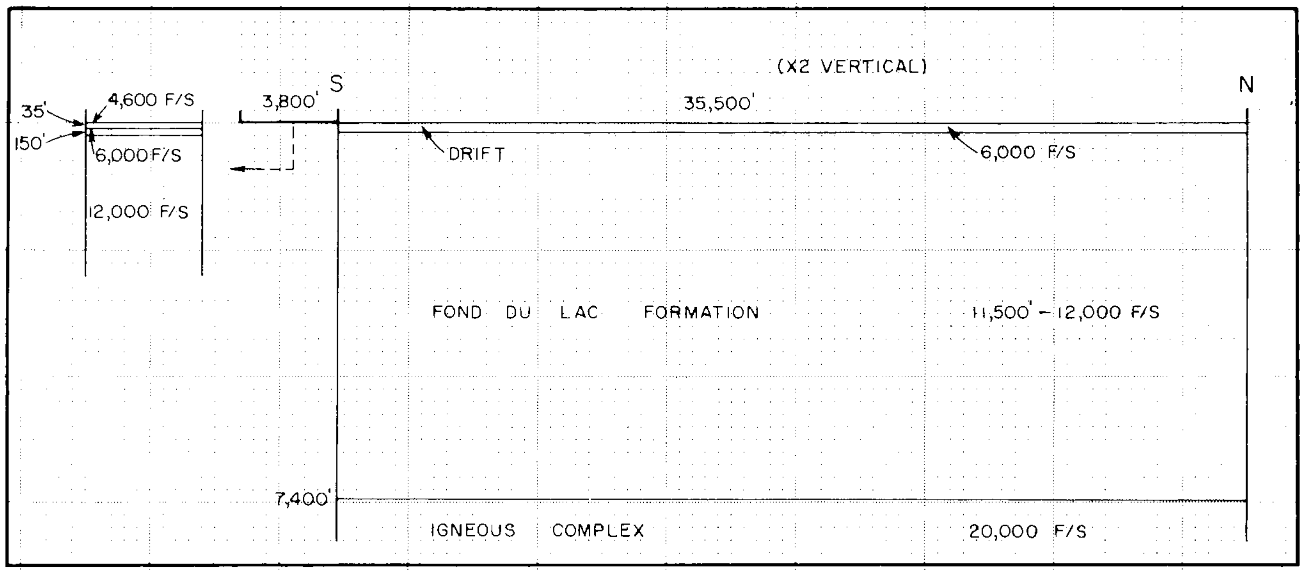
PURPOSE: Lines 1-4 and 72-73 are located to provide structure in the western basin at latitude 45°55′. Proceeding westward from Line 3, which is approximately 3 miles west of the Douglas Fault, gravity values are: Line 3, -25 mg; 2, -35 mg; 1, -40 mg; 4, -40 mg; 72, -30 mg; 73, -25 mg. Mean surface elevation is 1,025 feet.

RESULTS: A large offset of the travel time graph, combined with rapid attenuation of the earlier 12,000 feet/second arrival, is interpreted as due to a velocity inversion within the sedimentary section. Several short seismic lines were taken at adjacent locations to eliminate the possibility that the offset can be accounted for by lateral variations.

Using an assumed velocity value of 11,000 feet/second for the low velocity layer, basement depth along the north line is computed as 5,100 feet. Reducing the assumed value to 10,000 feet/second would decrease this depth to 4,600 feet. Basement depth along the south line appears to be about 400 feet greater than along the north line.



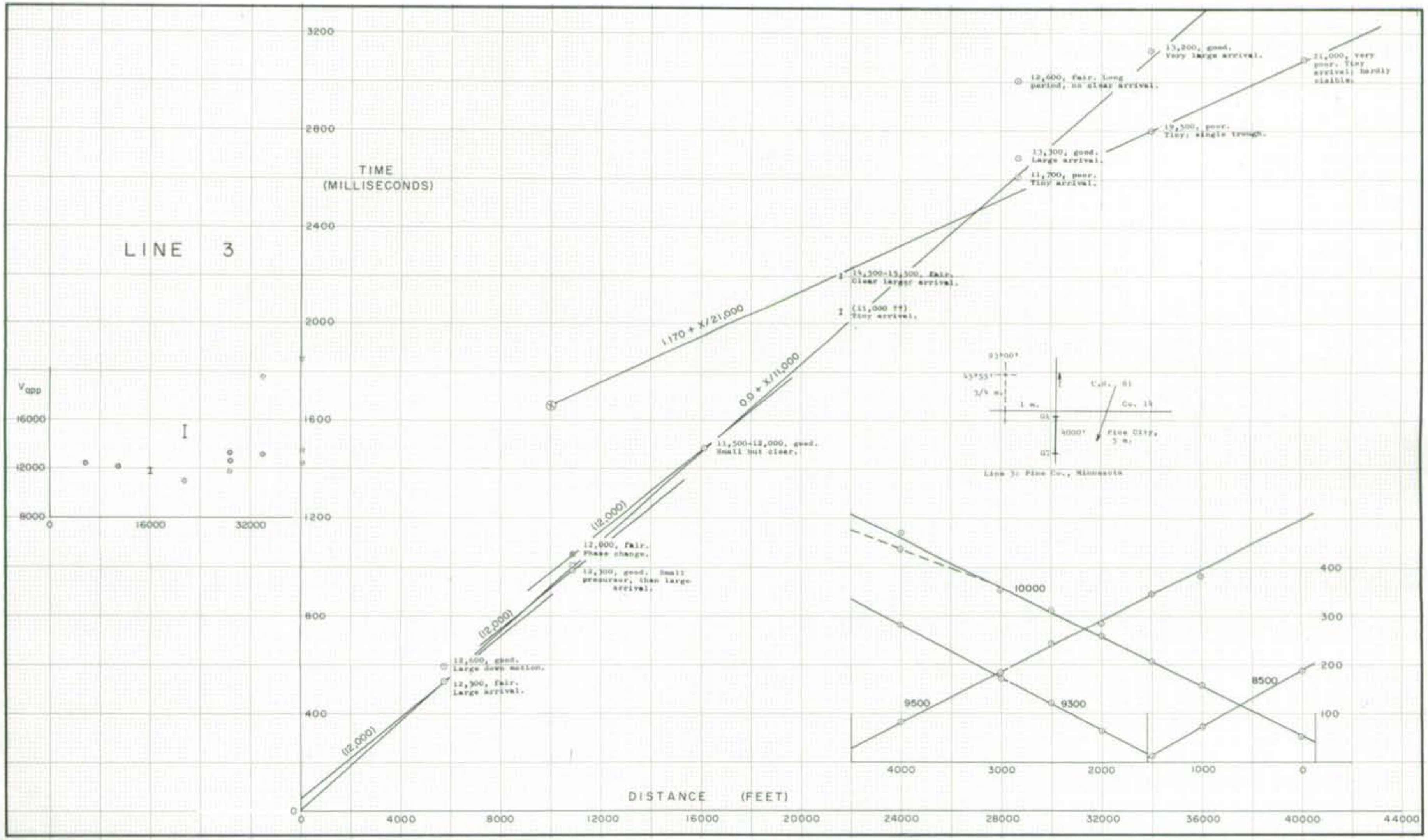
LINE 2
TIME' (MILLISECONDS)
DISTANCE (FEET)
3200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
V_{app}
16000
12000
8000
0
16000
32000
12,000-12,500, fair. Larger arrival.
19,500-20,500, good. Small but clear.
.1105 + X/20,000
12,000, good. Large arrival.
11,000, fair. Questionable correlation.
19,800-20,700, good. Clear arrival.
14,000-14,500, good. Larger arrival.
17,000-18,000, fair. Large new arrival.
11,600, fair. Small but clear.
18,000-19,800, poor. Clear arrival.
11,200, good. Large down motion.
12,000-12,300, fair. Clear arrival.
.065 + X/11,500
11,500-12,000, good. Small but clear.
11,500, fair. Possible correlation.
V = ?? Uncertain correlation.
12,000, good. Correlation only.
11,000, good. Correlation only.
12,200, good. Large, small beginning.
12,200, good. Small but clear.
All 12,000-12,400, good.
Clear down.
New motion.
Clear up.
Co. 11
Pine City, 3 m.
1 3/4 m
01
3800'
07
1 m.
1 m.
Line 2: Pine Co., Minn.
12300
6000
12000
12300
400
300
200
100
4000
3000
2000
1000
0



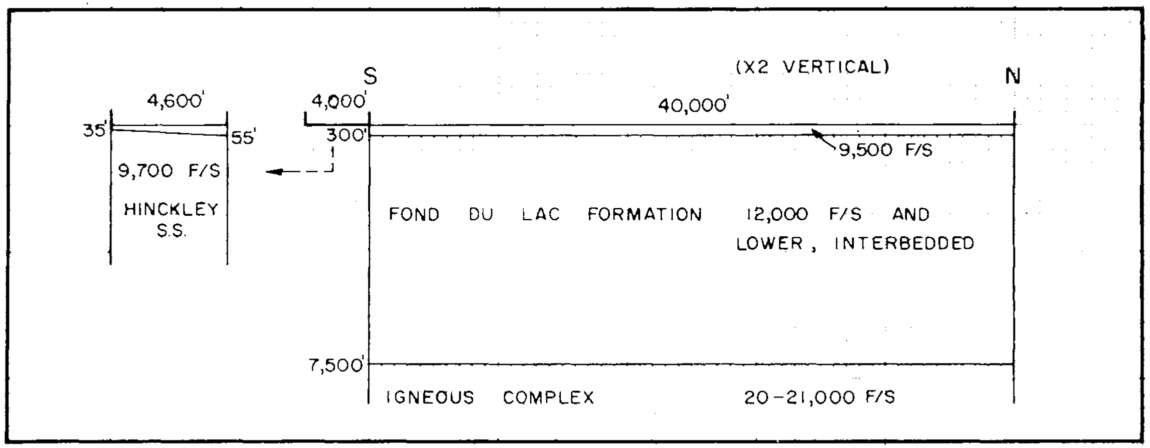
LINE 2

PURPOSE: See Line 1. Mean surface elevation is 1,000 feet.

RESULTS: The seismic data indicate a great thickness of material with velocity not greater than 11,500-12,000 feet/second. Depth to igneous basement is computed as 7,400 feet. By contrast with Lines 1 and 4 to the west, Line 2 shows no evidence of a velocity inversion; if an undetected inversion exists, depth to basement would be slightly less than the above value.



LINE 3
TIME (MILLISECONDS)
DISTANCE (FEET)
V_{app}
1170 + X/21,000
0.0 + X/11,000
(12,000)
(12,000)
(12,000)
12,300, fair. Large arrival.
12,600, good. Large down motion.
12,300, good. Small precursor, then large arrival.
12,000, fair. Phase change.
11,500-12,000, good. Small but clear.
(11,000 ??) Tiny arrival.
14,500-15,500, fair. Clear larger arrival.
11,700, poor. Tiny arrival.
13,300, good. Large arrival.
12,600, fair. Long period, no clear arrival.
13,200, good. Very large arrival.
19,500, poor. Tiny; single trough.
21,000, very poor. Tiny arrival; hardly visible.
Line 3: Pine Co., Minnesota
Pine City, 5 m.
Co. 14
1 m.
10000
9500
9300
8500



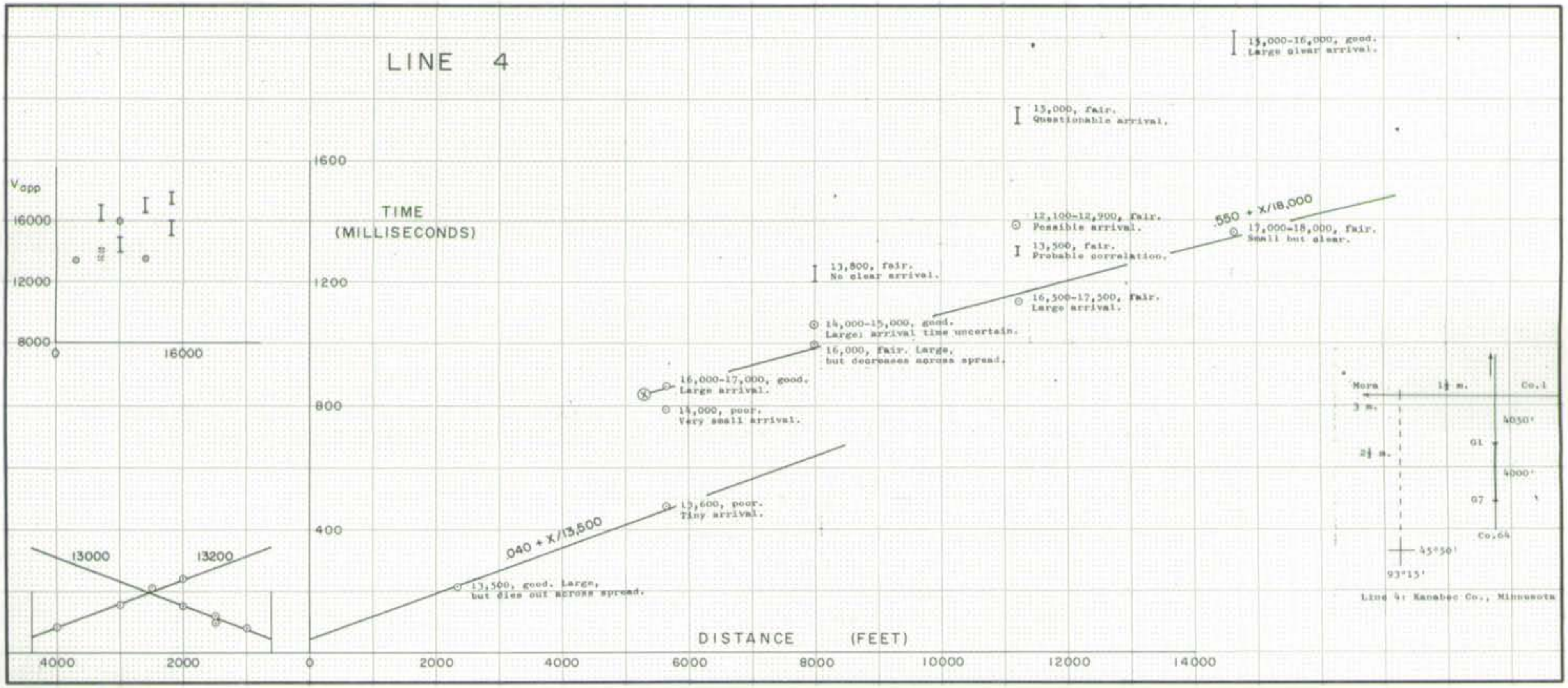
LINE 3

PURPOSE: See Line 1. Mean surface elevation is 960 feet.

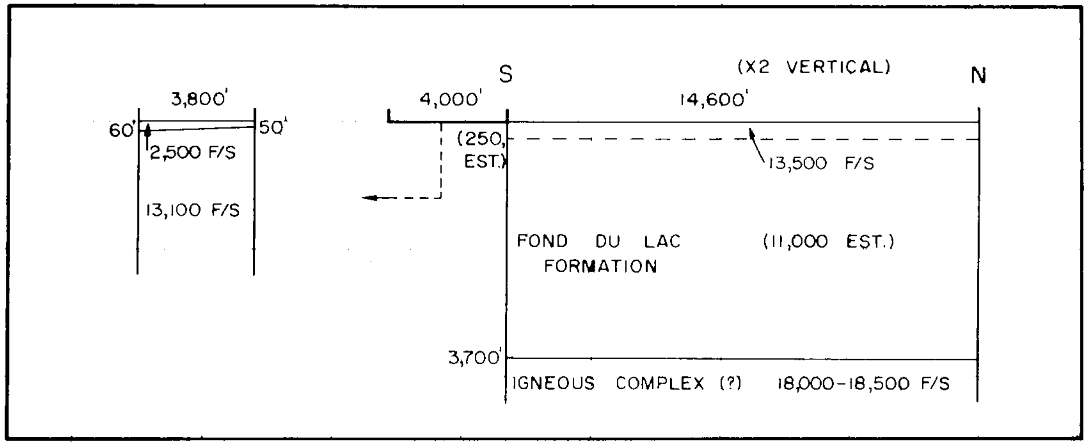
RESULTS: The principal results are clear, namely a considerable thickness of material with velocity not exceeding about 12,000 feet/second underlain by basement with velocity 20,000-21,000 feet/second. A thin (250 feet) layer of Hinckley Sandstone lies immediately below the drift.

The seismic arrivals fit surprisingly well to a single line with intercept 0 and apparent velocity 11,000 feet/second. A zero intercept is not acceptable on geological grounds, however; in addition, the across-spread velocities are slightly higher, 12,000 feet/second, and at the larger distances 13,000 feet/ second. We interpret these results to indicate an interbedding of 12,000 feet/ second material with layers of lower velocity.

Basement depth is about 7,500 feet, using a single 11,000 feet/second line for the sedimentary section. Interbedding of the lower velocity material would decrease this depth slightly.



LINE 4
TIME
(MILLISECONDS)
DISTANCE (FEET)
V_{app}
16000
12000
8000
0
16000
4000
2000
13000
13200
1600
1200
800
400
0
2000
4000
6000
8000
10000
12000
14000
.040 + X/13,500
.550 + X/18,000
13,500, good. Large, but dies out across spread.
13,600, poor. Tiny arrival.
16,000-17,000, good. Large arrival.
14,000, poor. Very small arrival.
14,000-15,000, good. Large; arrival time uncertain.
16,000, fair. Large, but decreases across spread.
13,800, fair. No clear arrival.
16,500-17,500, fair. Large arrival.
13,500, fair. Probable correlation.
12,100-12,900, fair. Possible arrival.
17,000-18,000, fair. Small but clear.
15,000, fair. Questionable arrival.
15,000-16,000, good. Large clear arrival.
Mora
1½ m.
Co.1
3 m.
4030'
01
2½ m.
4000'
07
Co.64
45°50'
93°15'
Line 4: Kanabec Co., Minnesota



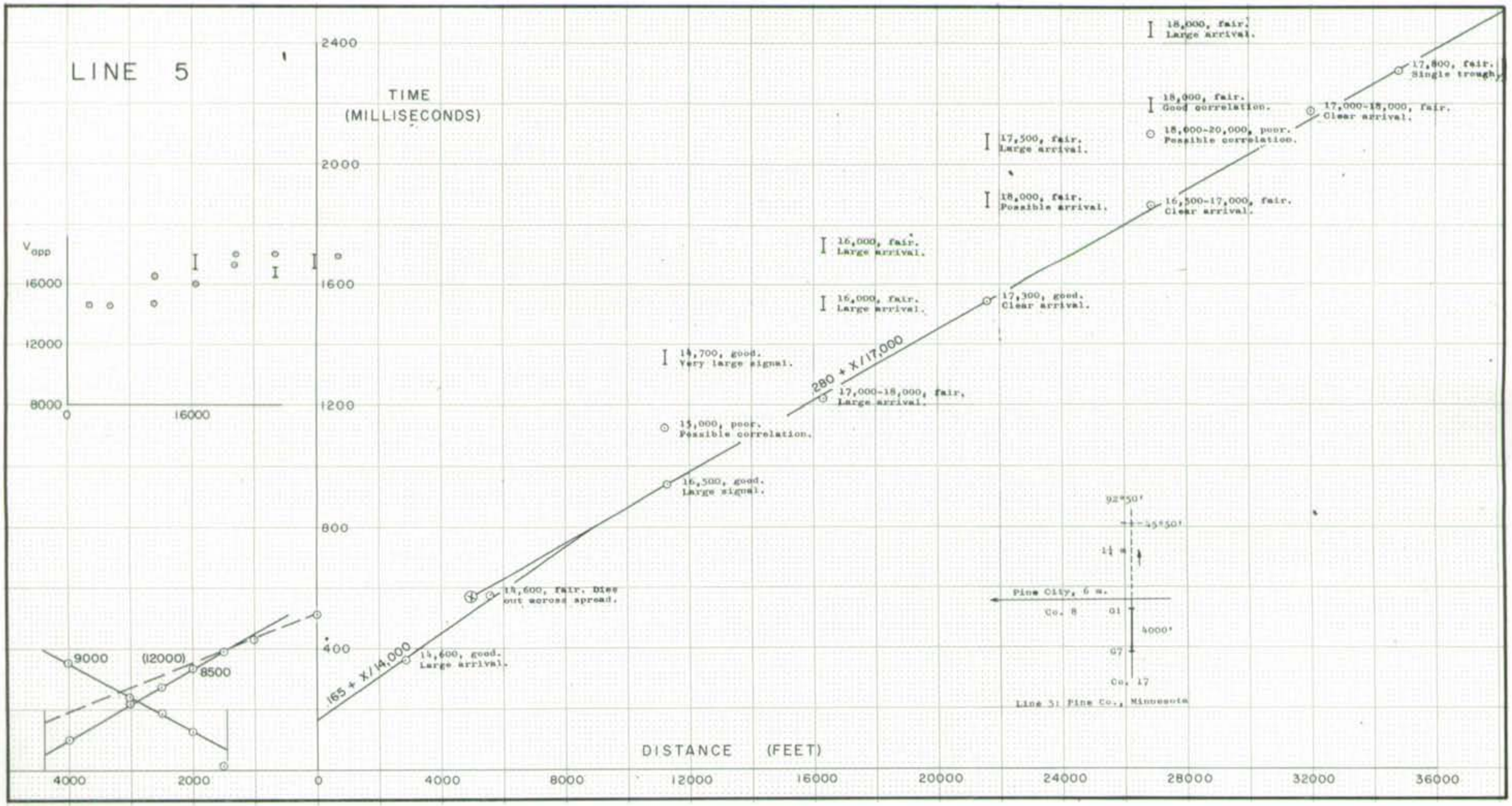
LINE 4

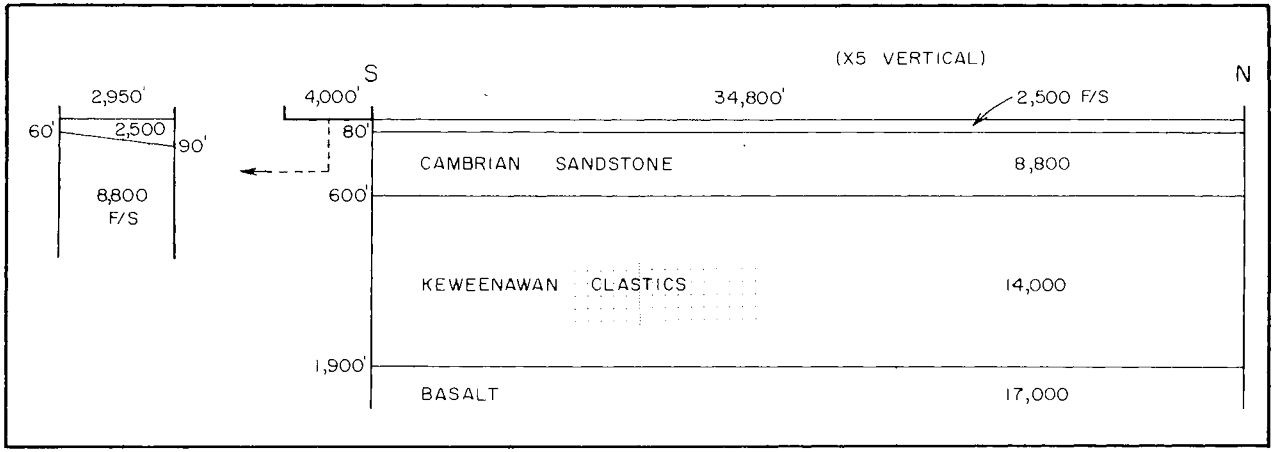
PURPOSE: See Line 1. Fond du Lac Formation crops out 4 miles to the west, near Mora, Minnesota. Mean surface elevation is 1,050 feet.

RESULTS: As on other lines in the western basin, we interpret the large offset of the travel time graph coupled with rapid attenuation of the earlier arrival to be produced by a velocity inversion. The high velocity layer beneath about 50 feet of drift shows a well-defined velocity of 13,500 feet/second. Assuming a thickness of about 200 feet for this layer and a velocity of 11,000 feet/ second in the underlying material, depth to basement is approximately 3,700 feet. Assumed velocities of 10,000 or 12,000 feet/second would yield depths 400 feet smaller or larger, respectively.

The best-fitting straight line to the basement arrivals is 18,000-18,500 feet/second; lower values for the across-spread velocities suggest that the true value may be slightly less. From geologic considerations and from the magnetic pattern, we identify the basement rocks as felsic intrusives, but the velocity is more indicative of basalt.

Shot 2 is located at approximately the critical reflection distance for the basement arrival. Consistent with this interpretation, a large arrival is observed.


LINE 5
TIME
(MILLISECONDS)
2400
2000
1600
1200
800
400
0
DISTANCE (FEET)
4000
2000
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
V app
16000
12000
8000
0
16000
9000
(12000)
8500
165 + X/14,000
280 + X/17,000
14,600, good.
Large arrival.
14,600, fair. Dies
out across spread.
16,500, good.
Large signal.
15,000, poor.
Possible correlation.
14,700, good.
Very large signal.
17,000-18,000, fair.
Large arrival.
16,000, fair.
Large arrival.
16,000, fair.
Large arrival.
17,300, good.
Clear arrival.
18,000, fair.
Possible arrival.
17,500, fair.
Large arrival.
16,500-17,000, fair.
Clear arrival.
18,000-20,000, poor.
Possible correlation.
18,000, fair.
Good correlation.
18,000, fair.
Large arrival.
17,000-18,000, fair.
Clear arrival.
17,800, fair.
Single trough.
92°50'
45°50'
1¼ m
Pine City, 6 m.
Co. 8
01
4000'
07
Co. 17
Line 5: Pine Co., Minnesota

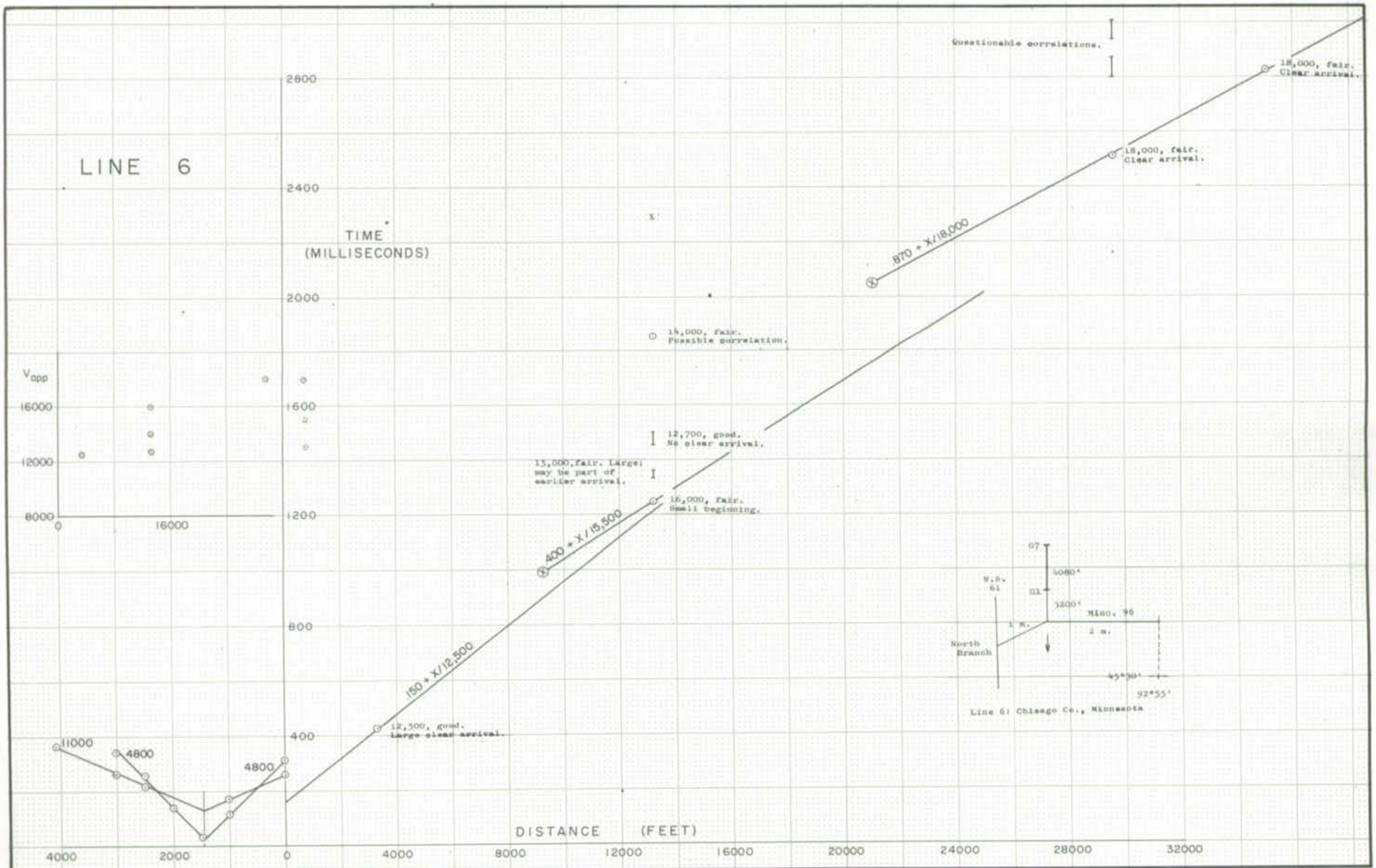


LINE 5

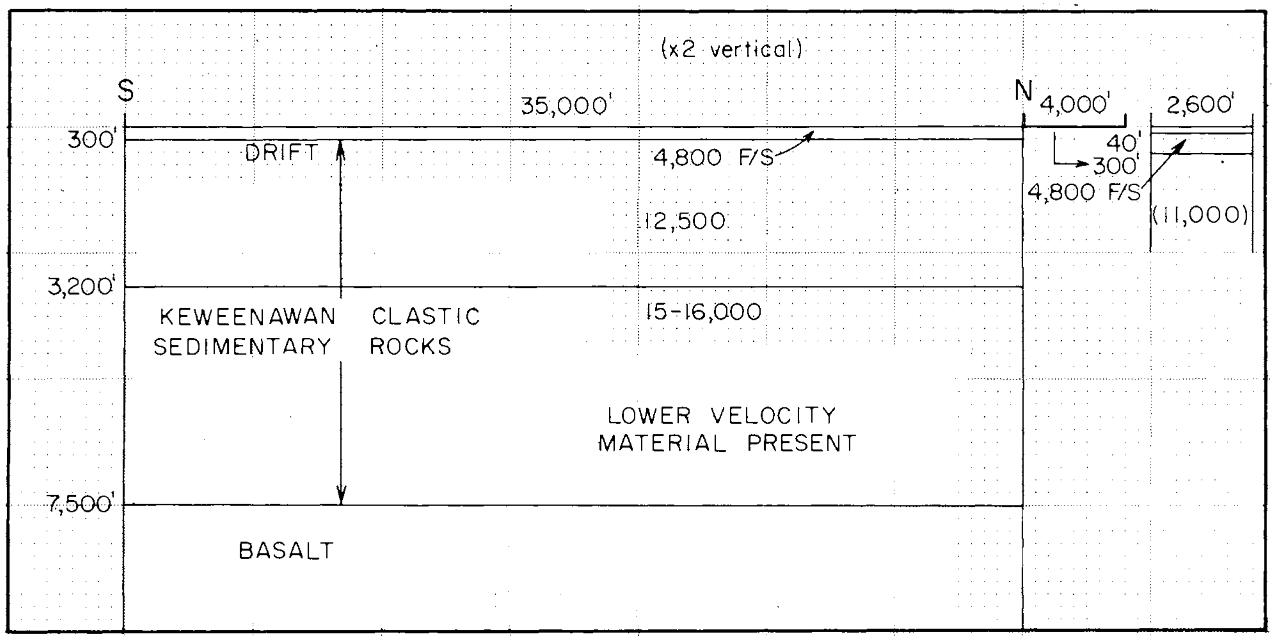
PURPOSE: Lines 5 and 6 lie about 3 miles east of the Douglas Fault, at the north and south ends respectively of a sediment-filled depression on the top of the St. Croix Horst. From magnetic data, the depression appears to be about 35 miles long and 4 miles wide. The seismic lines are intended to supply more specific information on the structure. Mean surface elevation is 950 feet.

RESULTS: The basalt surface appears to be essentially horizontal along the line, with a well-defined velocity of 17,000 feet/second. Depth to the top surface is about 2,000 feet. The seismic data do not exclude a component of dip perpendicular to the profile.

The overlying section includes 9,000 feet/second material, presumably Cambrian sandstone, to a depth of about 600 feet, and an intermediate section of 14,000-15,000 feet/second Keweenawan clastics. The amplitude of the latter arrival appears to be decreasing with distance; this suggests the possibility of a velocity inversion hence a lower velocity layer overlying the basalt, although we have not included it in the section. On the basis of similar apparent velocities, secondary arrivals are assumed to be converted waves.



LINE 6
TIME (MILLISECONDS)
DISTANCE (FEET)
2800
2400
2000
1600
1200
800
400
4000
2000
0
4000
8000
12000
16000
20000
24000
28000
32000
V_{app}
16000
12000
8000
0
16000
11000
4800
4800
150 + X/12,500
400 + X/15,500
870 + X/18,000
12,500, good. Large clear arrival.
16,000, fair. Small beginning.
13,000, fair. Large; may be part of earlier arrival.
12,700, good. No clear arrival.
14,000, fair. Possible correlation.
18,000, fair. Clear arrival.
18,000, fair. Clear arrival.
Questionable correlations.
North Branch
4080'
3200'
Misc. 96
2 m.
1 m.
92°55'
Line 6: Chisago Co., Minnesota



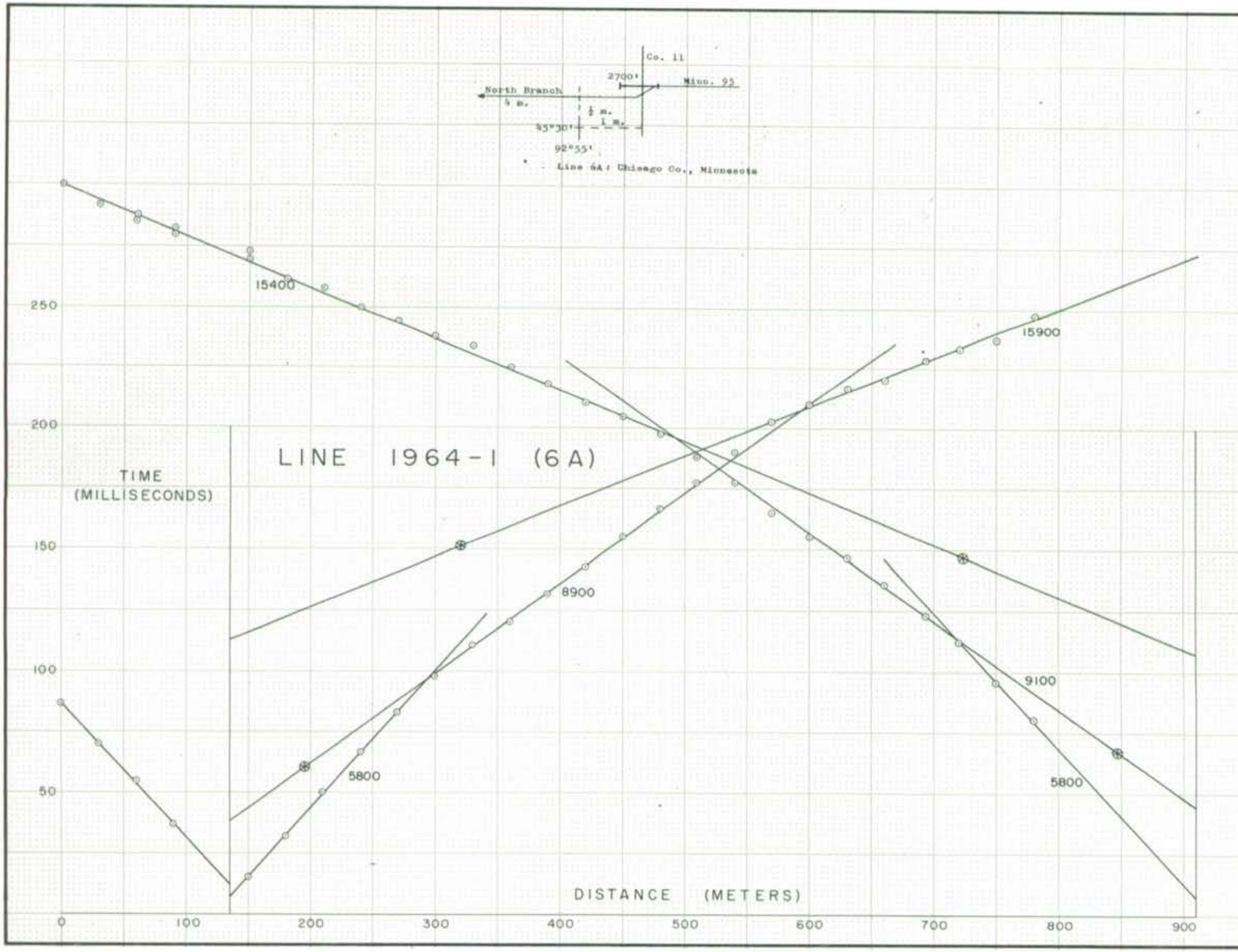
LINE 6

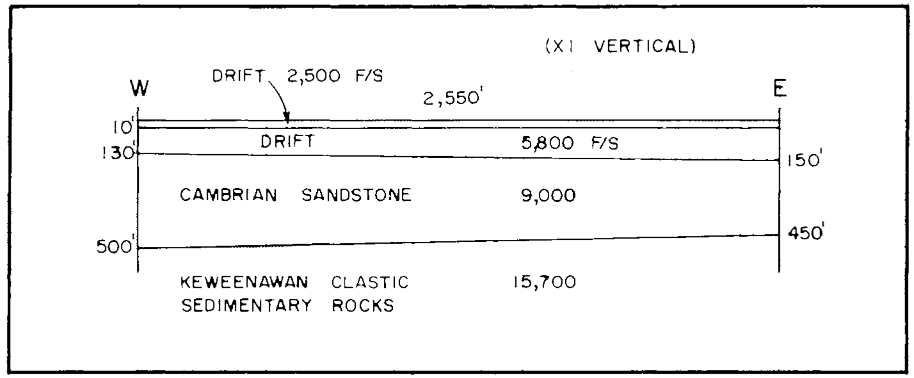
PURPOSE: See Line 5. An "oil" well 2 miles northeast encountered 258 feet of drift, 66 feet of Cambrian sandstone, 24 feet of Hinckley Sandstone, and Keweenawan clastic sedimentary rocks to bottom at 675 feet. Mean surface elevation is 950 feet.

RESULTS: Arrivals were recorded from only four shot points, so the interpretation must be considered tentative. The in-line data show about 300 feet of glacial drift overlying Keweenawan clastic sedimentary rocks. Cambrian sandstones if present are too thin to have been detected with this shot spacing. Taking into account both in-line and along-line data, the preferred velocity is 12,000-12,500 feet/second. This value would be compatible with correlating the material with Freda Sandstone (upper Oronto Group) of the Bayfield area or Fond du Lac Formation of the Western Basin.

A single seismic arrival indicates 15,000-16,000 feet/second material, correlable on the basis of velocity with the Lower Oronto Group of the Bayfield area. This velocity could also be interpreted as basalt with interbedded sediments.

The final velocity layer is well defined at 18,000 feet/second by two arrivals. This is interpreted as Middle Keweenawan basalt. The travel-time line is delayed by at least 250 ms with respect to the preceding one, however, which suggests a velocity inversion overlying the basalt. We have no suggestions as to what this might represent geologically.


LINE 1964-I (6A)
TIME
(MILLISECONDS)
DISTANCE (METERS)
15400
15900
8900
9100
5800
5800
Co. 11
2700'
Minn. 95
North Branch
4 m.
½ m.
1 m.
45°30'
92°55'
Line 6A: Chisago Co., Minnesota
0
100
200
300
400
500
600
700
800
900
50
100
150
200
250

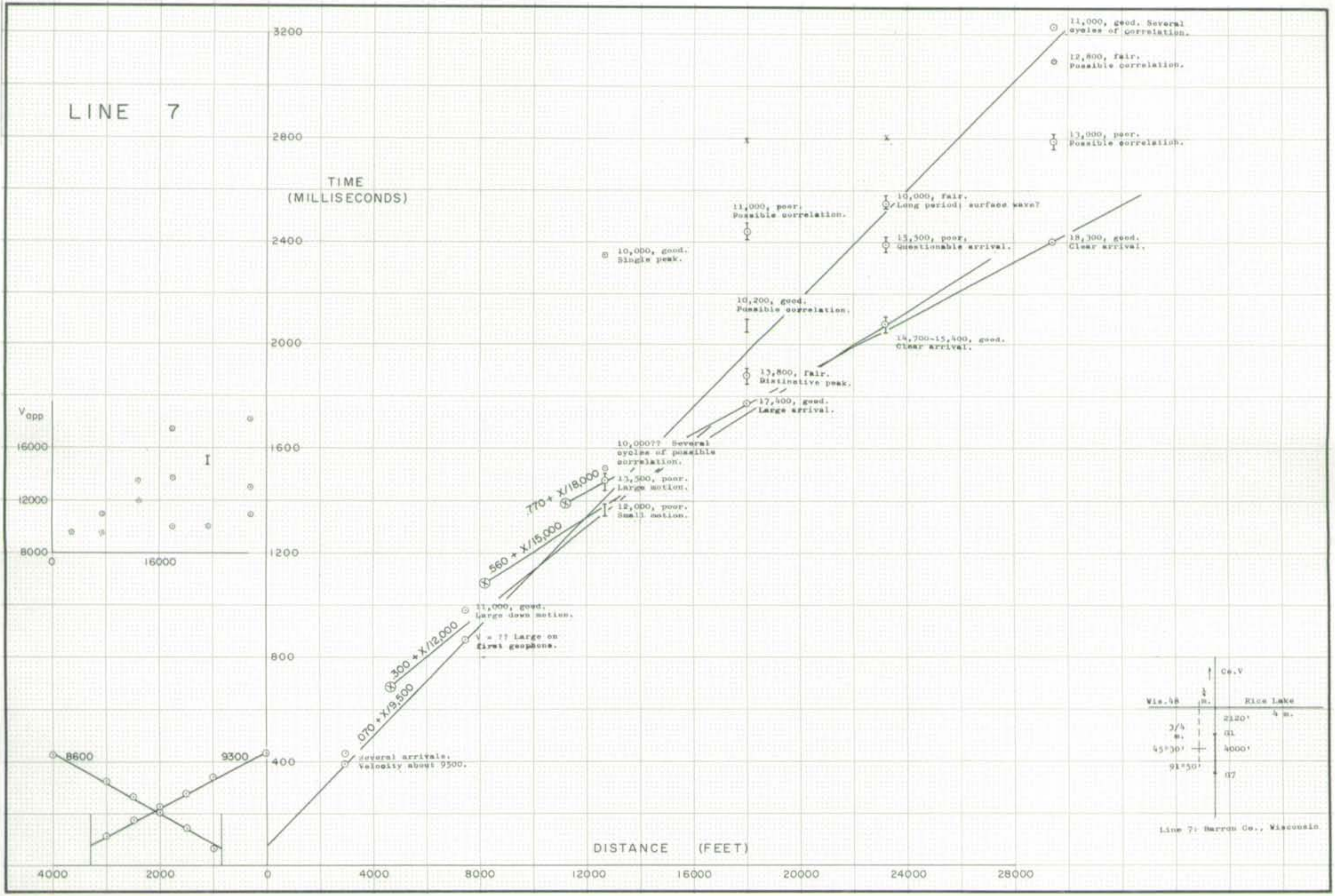


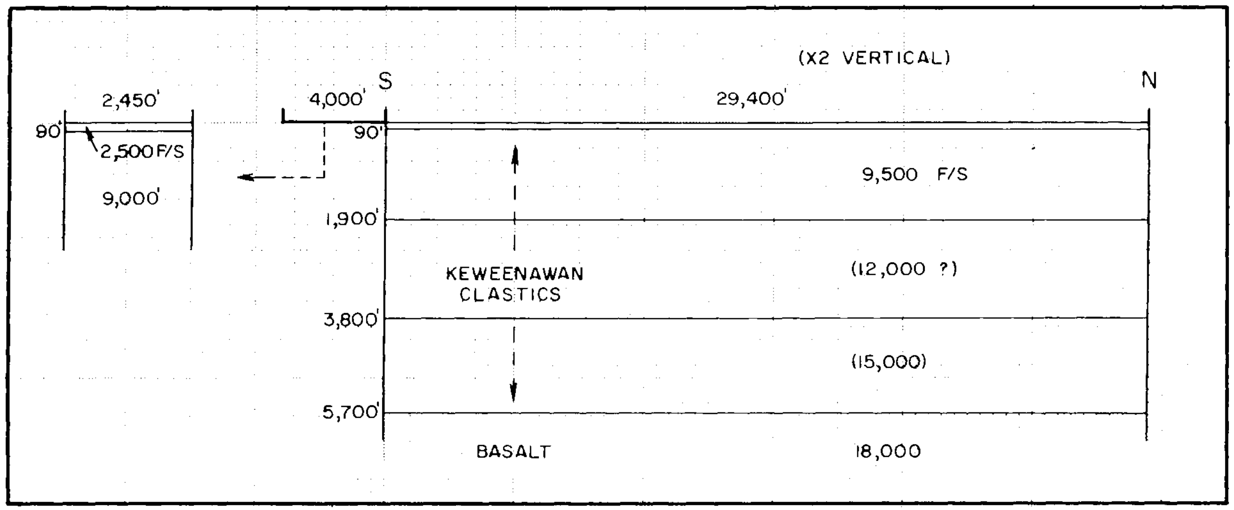
LINE 6A

PURPOSE: This short completely reversed line lies over the St. Croix Horst, close to (but one mile east of) a structural depression revealed by magnetics (see Figure 7). The "oil" well noted under the discussion of Line 6 lies 2 miles to the northwest, but within the structural depression. Mean surface elevation is 950 feet.

RESULTS: The data are excellent and consistent. The points show little scatter, indicating plane although not quite horizontal surfaces.

Drift thickness is approximately 140 feet. Two well-defined velocities exist beneath the drift. The velocity of 9,000 feet/second is characteristic of a soft sandstone, probably the basal Cambrian sandstone. The velocity of 15,700 feet/second is identified here with a Keweenawan clastic sedimentary rock.


LINE 7
TIME
(MILLISECONDS)
3200
2800
2400
2000
1600
1200
800
400
DISTANCE (FEET)
4000
2000
0
4000
8000
12000
16000
20000
24000
28000
V app
16000
12000
8000
0
16000
8600
9300
070 + X/9,500
300 + X/12,000
560 + X/15,000
770 + X/18,000
Several arrivals.
Velocity about 9300.
V = ?? Large on
first geophone.
11,000, good.
Large down motion.
12,000, poor.
Small motion.
13,500, poor.
Large motion.
10,000?? Several
cycles of possible
correlation.
10,000, good.
Single peak.
17,400, good.
Large arrival.
13,800, fair.
Distinctive peak.
10,200, good.
Possible correlation.
11,000, poor.
Possible correlation.
14,700-15,400, good.
Clear arrival.
13,500, poor.
Questionable arrival.
10,000, fair.
Long period; surface wave?
18,300, good.
Clear arrival.
13,000, poor.
Possible correlation.
12,800, fair.
Possible correlation.
11,000, good. Several
cycles of correlation.
Co.V
Wis.48
Rice Lake
2120'
3/4 m.
4000'
45°30'
91°50'
Line 7: Barron Co., Wisconsin



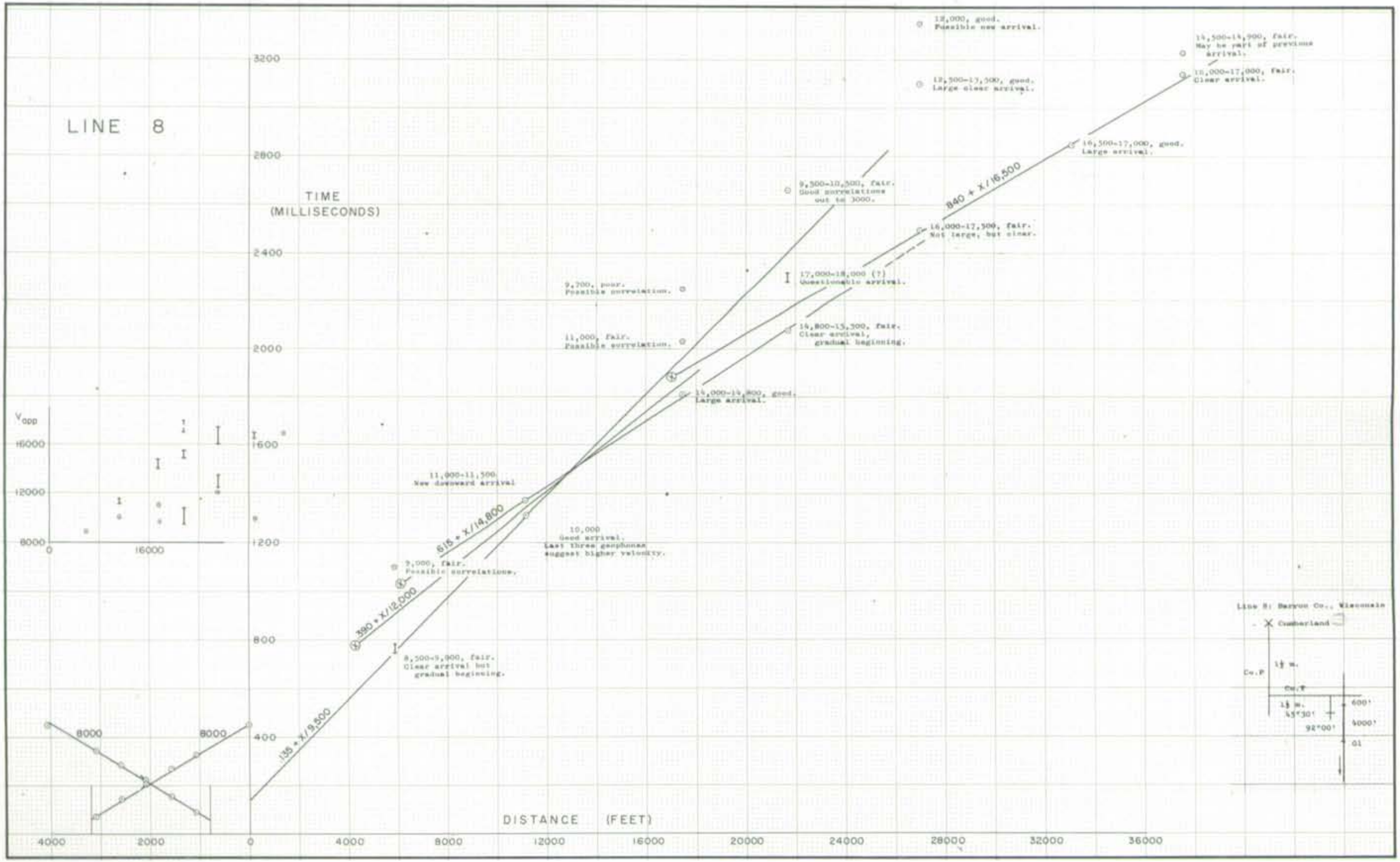
LINE 7

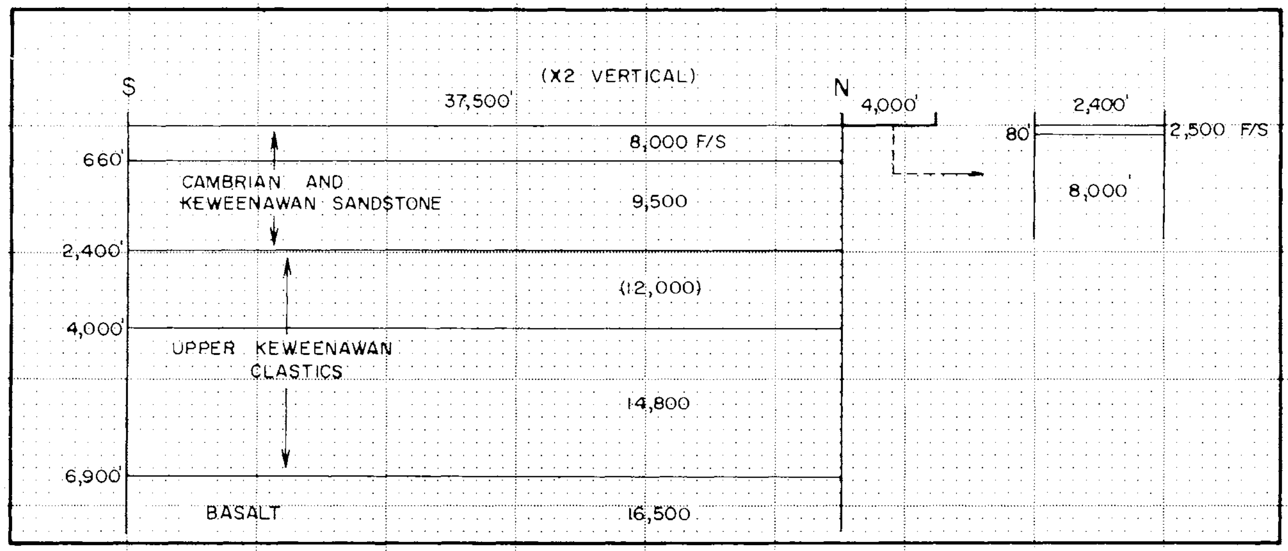
PURPOSE: Lines 7-11 cover the eastern end of the structure section along latitude 45°30′. They lie east of the Lake Owen Fault Zone within the eastern flanking basin. Gravity values are: Line 7, -75 mg; 8, -85 mg, 9, -85 mg, 10, -55 mg; 11, -45 mg. Line 8 lies at the gravity minimum. Mean surface elevation is 1,250 feet.

RESULTS: Beneath about 100 feet of drift, the top of the sedimentary section consists of Cambrian or Keweenawan sandstone with a velocity of 9,000-9,500 feet/second.

The intermediate layering in the section is not clear from the seismic data. We prefer the interpretation shown above, which includes 12,000 and 14,500-15,000 feet/second materials: both of these values are based upon a single seismic arrival, but they are confirmed from adjacent lines. Several secondary arrivals suggest the presence of 13,000-14,000 feet/second material.

The basement rock yields a velocity of about 18,000 feet/second, hence is interpreted as basalt. Depth to basement is shown as 5,700 feet, but alternative interpretations for the overlying section would permit depths between 5,000 and 6,000 feet.


LINE 8
TIME (MILLISECONDS)
DISTANCE (FEET)
V_{app}
135 + X/9,500
390 + X/12,000
615 + X/14,800
840 + X/16,500
12,000, good. Possible new arrival.
14,500-14,900, fair. May be part of previous arrival.
12,500-13,500, good. Large clear arrival.
16,000-17,000, fair. Clear arrival.
16,500-17,000, good. Large arrival.
9,500-10,500, fair. Good correlations out to 3000.
16,000-17,500, fair. Not large, but clear.
9,700, poor. Possible correlation.
17,000-18,000 (?) Questionable arrival.
11,000, fair. Possible correlation.
14,800-15,500, fair. Clear arrival, gradual beginning.
14,000-14,800, good. Large arrival.
11,000-11,500 New downward arrival
10,000 Good arrival. Last three geophones suggest higher velocity.
9,000, fair. Possible correlations.
8,500-9,900, fair. Clear arrival but gradual beginning.
Line 8: Barron Co., Wisconsin
Cumberland
Co.P
1½ m.
45°30'
92°00'
600'
4000'
G1



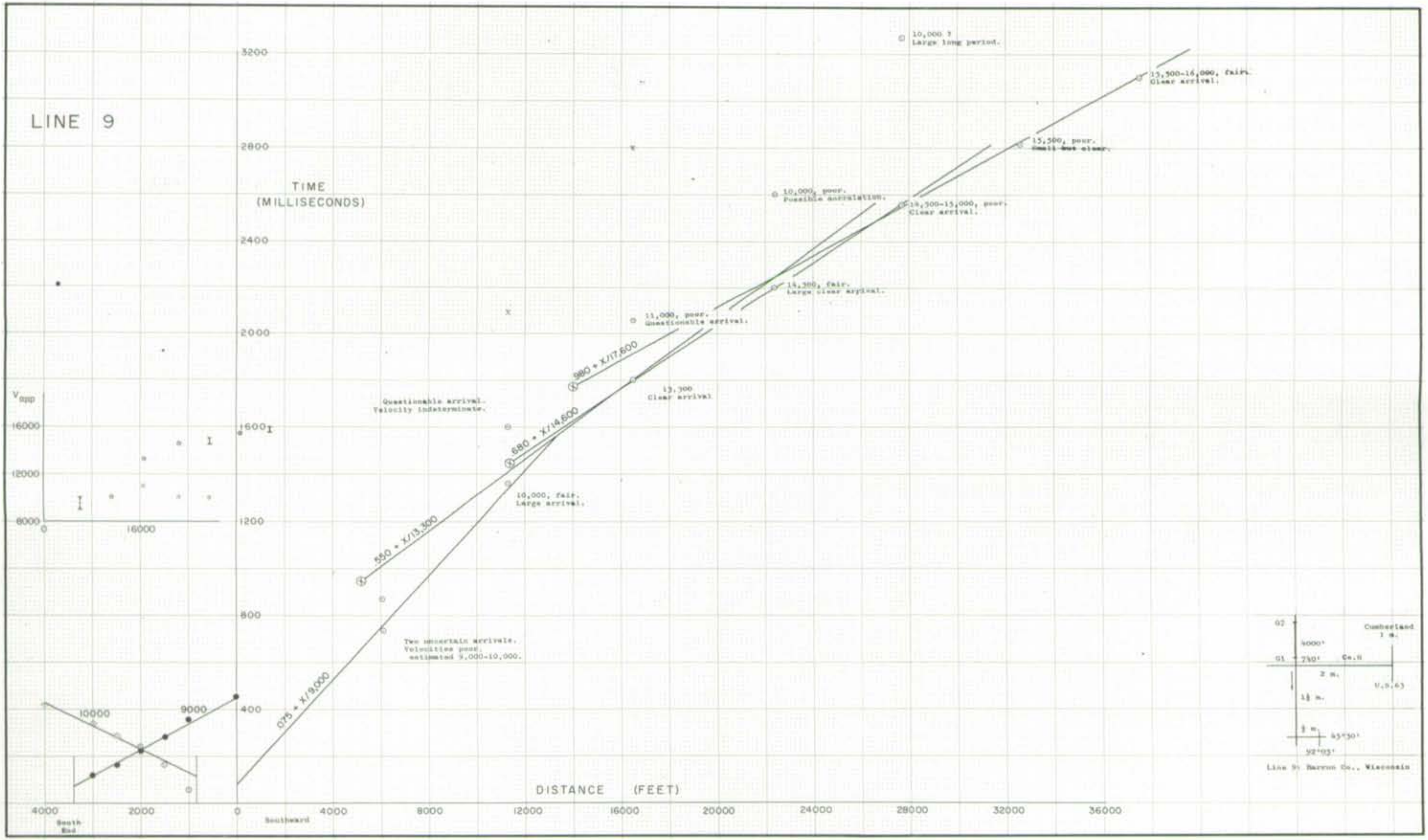
LINE 8

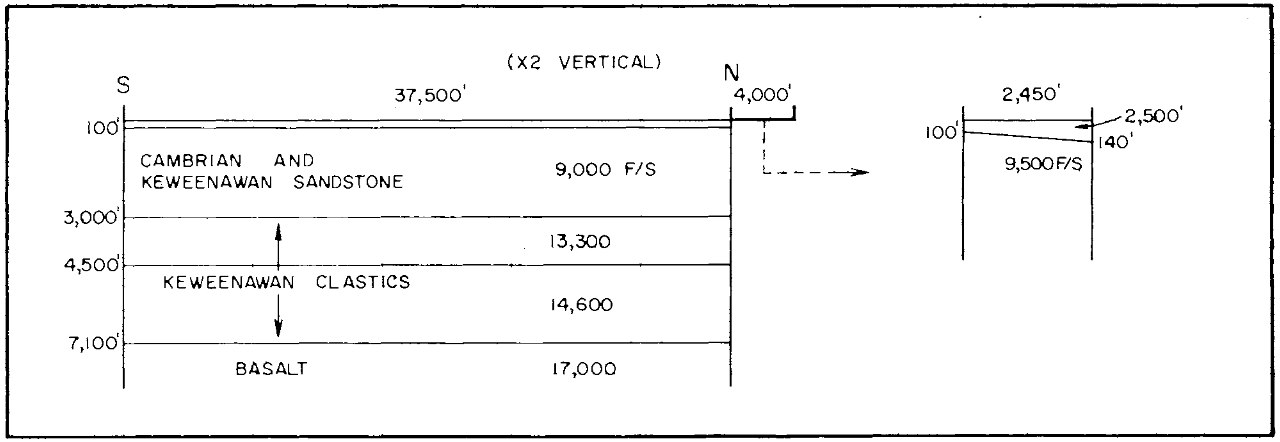
PURPOSE: See Line 7. Line 8 is located close to the gravity minimum. All wells in Barron County (Lines 7-10) bottom in Cambrian sandstone beneath drift thicknesses ranging from 30 to 300 feet. Mean surface elevation is 1,250 feet.

RESULTS: The in-line data show a thin section of 8,000 feet/second material, presumably Cambrian sandstone, overlying about 2,000 feet of 9,500 feet/second Cambrian and/or Keweenawan sandstone.

A layer of 12,000 feet/second material is included in the section on the basis of a single second arrival together with evidence from adjacent lines. The lower unit of the Upper Keweenawan clastics is indicated by two clear arrivals with velocity of 14,800 feet/second.

Depth to basement is about 7,000 feet. The basement velocity of 16,500-17,000 feet/second is characteristic of basalt. The basement arrivals are slightly offset from the extension of the 14,800 feet/second line, suggesting the presence of a lower velocity material just above the basement. Calculations for an extreme case would decrease basement depth by about 500 feet.


LINE 9
TIME
(MILLISECONDS)
3200
2800
2400
2000
1600
1200
800
400
DISTANCE (FEET)
4000
2000
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
South End
Southward
V app
16000
12000
8000
0
16000
10000
9000
075 + X/9,000
550 + X/13,300
680 + X/14,600
980 + X/17,600
Two uncertain arrivals.
Velocities poor,
estimated 9,000-10,000.
Questionable arrival.
Velocity indeterminate.
10,000, fair.
Large arrival.
13,300
Clear arrival
11,000, poor.
Questionable arrival.
14,300, fair.
Large clear arrival.
10,000, poor.
Possible accrulation.
14,500-15,000, poor.
Clear arrival.
10,000 ?
Large long period.
15,500, poor.
13,500-16,000, fair.
Clear arrival.
G2
G1
4000'
750'
Co.H
2 m.
Cumberland
1 m.
U.S.63
1½ m.
45°30'
92°03'
Line 9: Barron Co., Wisconsin



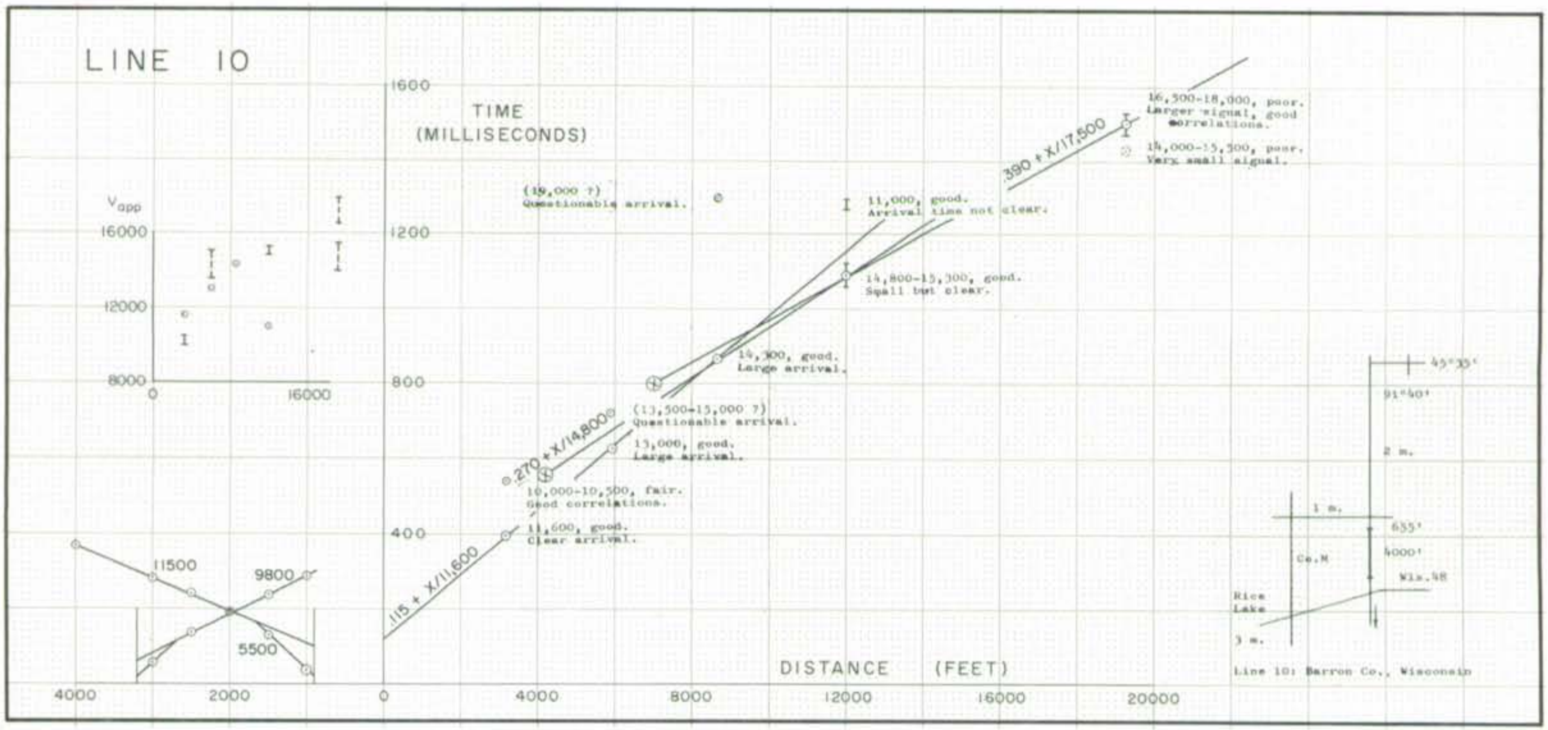
LINE 9

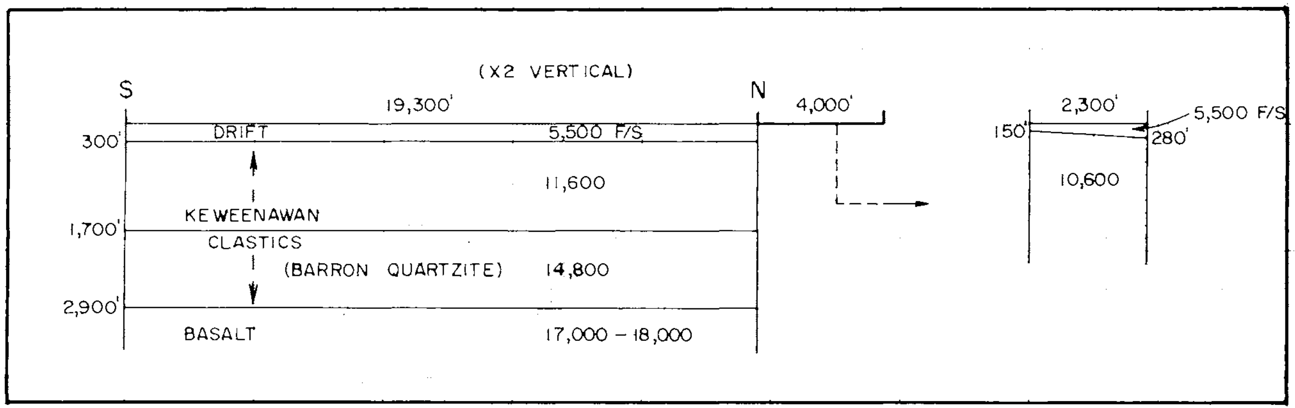
PURPOSE: See Line 7. Mean surface elevation is 1,300 feet.

RESULTS: The data clearly show a thick section of sedimentary rocks lying beneath about 100 feet of drift. The top layer gives a well-defined velocity of 9,000-9,500 feet/second, extending to a depth of about 3,000 feet. Beneath this, we infer layers with velocities 13,300 and 14,600 feet/second although the former is based on a single point.

The two most distant shots give across-spread velocities of 15,500-16,000 feet/second, but the line segment which joins them corresponds to 17,700 feet/second. We interpret the true velocity to be 17,000 feet/second or greater and the across-spread velocity to be local to the geophone spread. Any other interpretation leads to either a geologically improbable structure or to predicted arrivals for the earlier shots which do not appear on the seismograms.

By this interpretation, the basement rock in this area is basalt, at a depth of about 7,000 feet.


LINE 10
TIME
(MILLISECONDS)
1600
1200
800
400
DISTANCE (FEET)
4000
2000
0
4000
8000
12000
16000
20000
Vapp
16000
12000
8000
0
16000
11500
9800
5500
.115 + X/11,600
.270 + X/14,800
390 + X/17,500
11,600, good.
Clear arrival.
10,000-10,500, fair.
Good correlations.
13,000, good.
Large arrival.
(13,500-15,000 ?)
Questionable arrival.
14,300, good.
Large arrival.
14,800-15,300, good.
Small but clear.
11,000, good.
Arrival time not clear.
(19,000 ?)
Questionable arrival.
16,500-18,000, poor.
Larger signal, good
correlations.
14,000-15,500, poor.
Very small signal.
45°35'
91°40'
2 m.
1 m.
635'
4000'
Co.M
Wis.48
Rice
Lake
3 m.
Line 10: Barron Co., Wisconsin



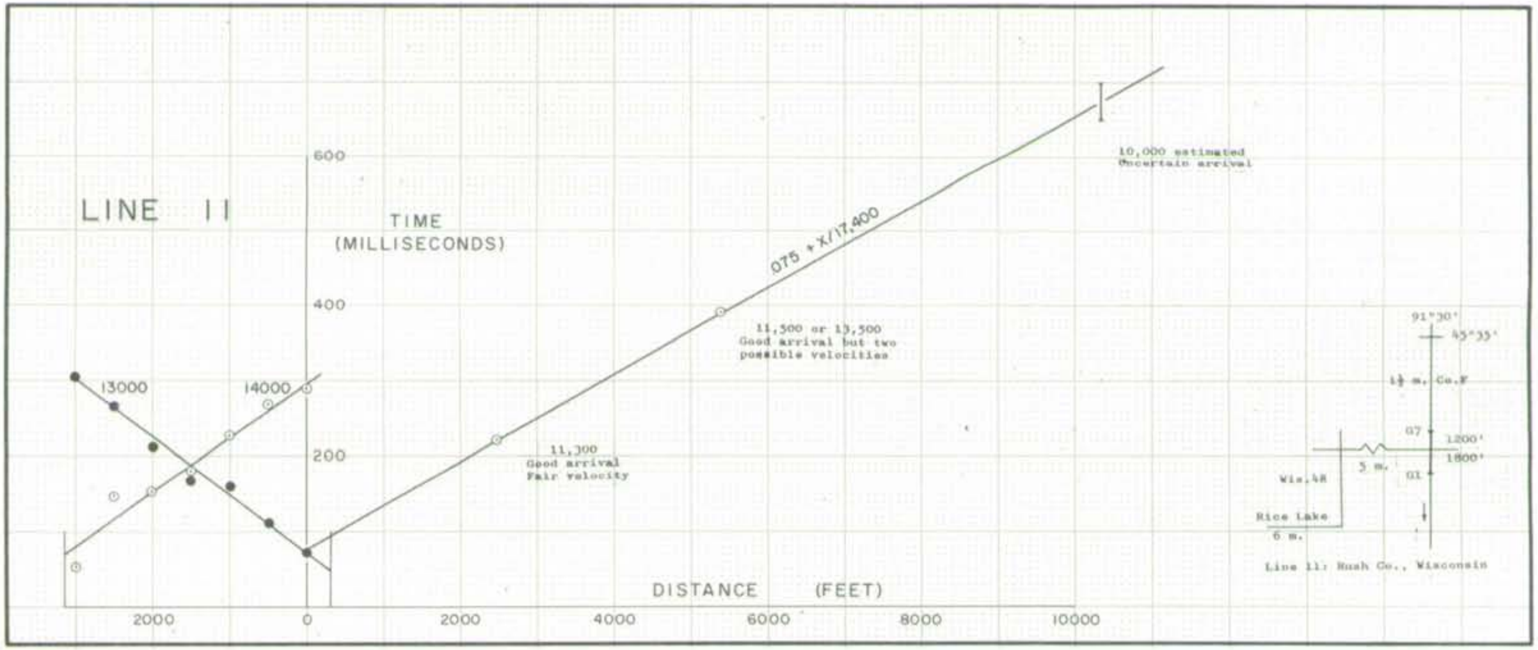
LINE 10

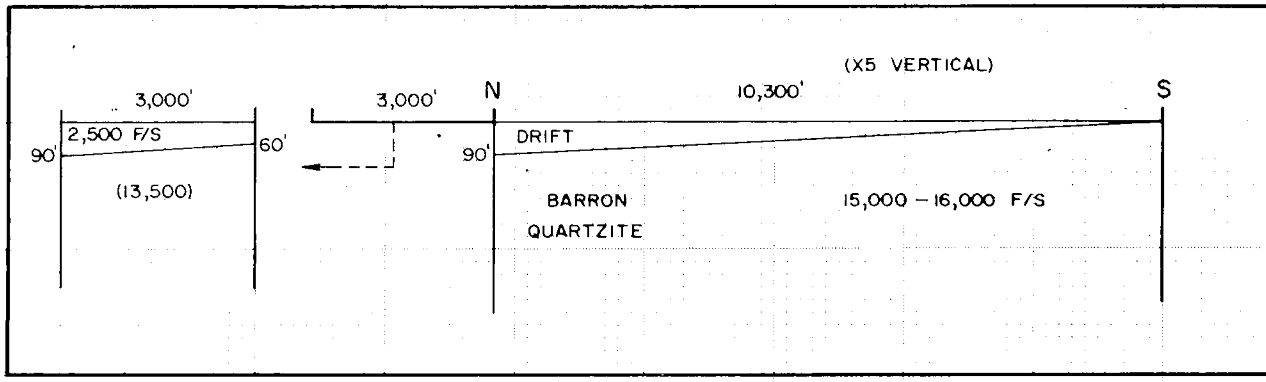
PURPOSE: See Line 7. Mean surface elevation is 1,150 feet.

RESULTS: The general structure is clear, but the details permit alternative interpretations. We identify the 10,600 feet/second arrival from the in-line shots with the 11,600 feet/second arrival along the line, due to similar intercept times. The 13,000 feet/second arrival at shot 2 is also identified with this refractor because the only permissible line through this point which does not conflict with shots 1 or 3 has velocity 11,700 feet/second. This refractor is almost certainly to be identified with the 12,000 feet/second material found on adjacent lines. The 9,500 feet/second sandstones found on Lines 7-9 appear to be absent here, however.

The presence of the 17,000-18,000 feet/second basement arrival on shot 5 is clear; the precise velocity is uncertain, however, because this arrival does not appear on any of the earlier shots. A small precursor appears on the seismogram for shot 5; it may form part of the basement arrival (in which case basement depth is slightly less than shown), although the spread velocity appears to be somewhat too low.

An intermediate layer with velocity 14,800 feet/second is defined by two good first arrivals. This probably represents the Barron Quartzite, although data from the outcrop area at Line 11 would call for a slightly higher velocity.


LINE 11
TIME
(MILLISECONDS)
600
400
200
13000
14000
075 + X/17,400
10,000 estimated
Uncertain arrival
11,500 or 13,500
Good arrival but two
possible velocities
11,300
Good arrival
Fair velocity
DISTANCE (FEET)
2000
0
2000
4000
6000
8000
10000
91°30'
45°35'
1½ m. Co.F
07
1200'
1800'
01
5 m.
Wis.48
Rice Lake
6 m.
Line 11: Rush Co., Wisconsin



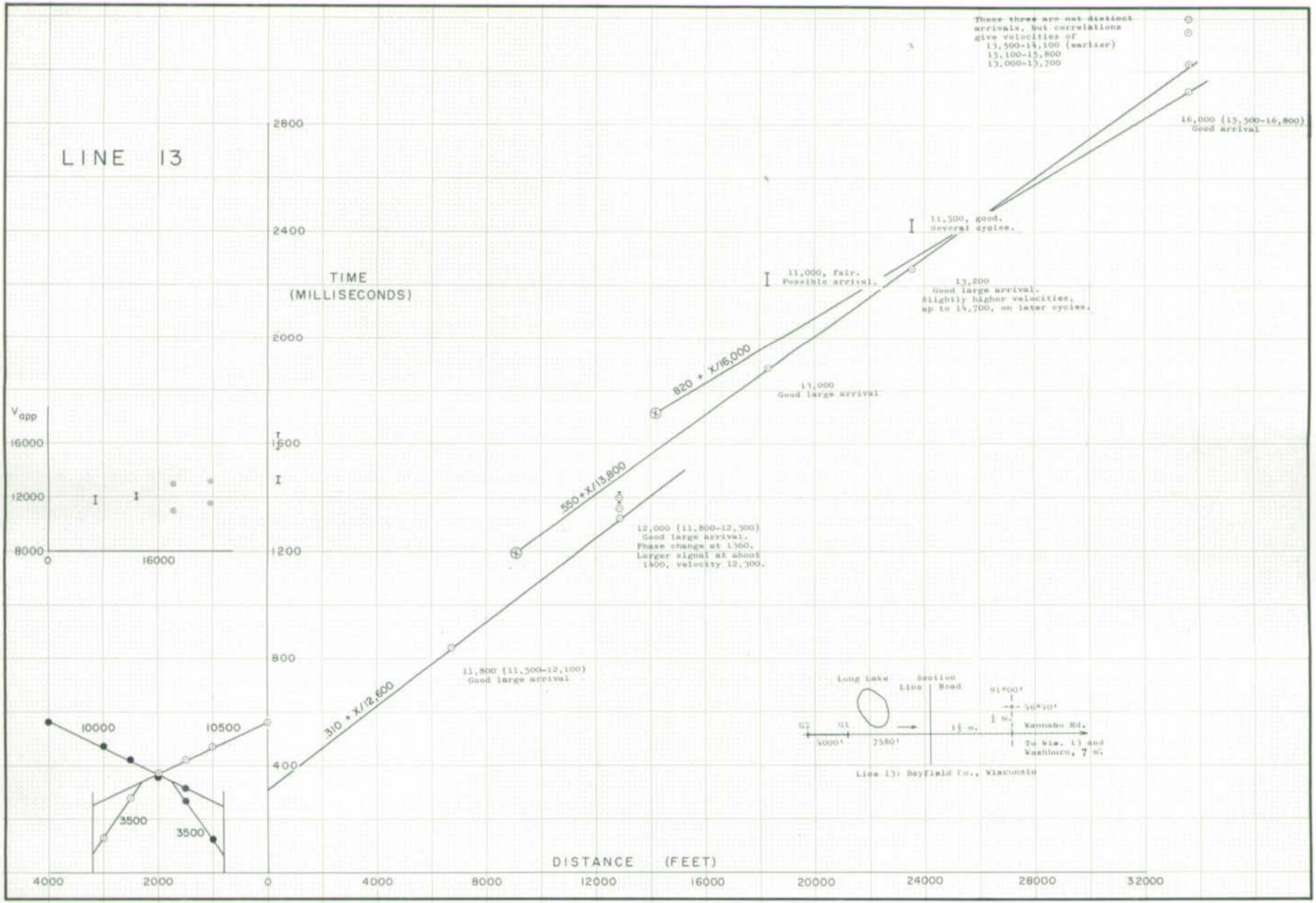
LINE 11

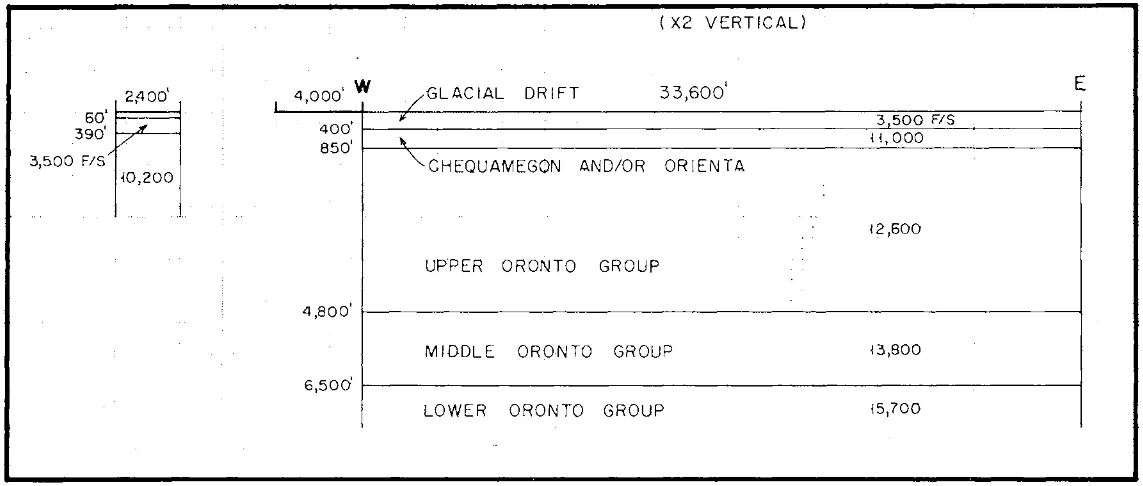
PURPOSE: Line 11 was designed to obtain a characteristic velocity for the Barron Quartzite. Correlation of the Barron Quartzite with other formations has been an unsolved geological problem. It was hoped that a velocity correlation might be achieved. The quartzite crops out about ½ mile south of the most distant shot point. Mean surface elevation is 1,500 feet.

RESULTS: The in-line data reveal local irregularities under the geophone spread. Arrivals on geophones 1-3 are 30-40 ms later than on 4-7, suggesting abrupt thickening of the drift at the north end.

The spread velocities of about 11,000 feet/second can only be interpreted as due to locally increasing dip under the geophone spread. If the main line data were interpreted as a dipping plane layer, the across-spread velocity would have to be 15,000 feet/second or greater to keep the interface from reaching the surface at the south end.

In view of these uncertainties, we conclude that the velocity value for the Barron Quartzite cannot be less than 15,000 feet/second, that it is probably closer to 16,000, and that the quartzite surface dips downward to the north along this line.


LINE 13
TIME (MILLISECONDS)
DISTANCE (FEET)
V_{app}
310 + X/12,600
550+X/13,800
820 + X/16,000
10000
10500
3500
3500
These three are not distinct arrivals, but correlations give velocities of
13,500-14,100 (earlier)
15,100-15,800
13,000-13,700
16,000 (13,500-16,800) Good arrival
11,300, good. Several cycles.
11,000, fair. Possible arrival.
13,200 Good large arrival. Slightly higher velocities, up to 14,700, on later cycles.
13,000 Good large arrival
12,000 (11,800-12,300) Good large arrival. Phase change at 1360. Larger signal at about 1400, velocity 12,300.
11,800 (11,300-12,100) Good large arrival
Long Lake
Section Line Road
91°00'
46°40'
1/2 m.
1 1/2 m.
G2
G1
4000'
7580'
Wannabo Rd.
To Wis. 13 and Washburn, 7 m.
Line 13: Bayfield Co., Wisconsin



LINE 13

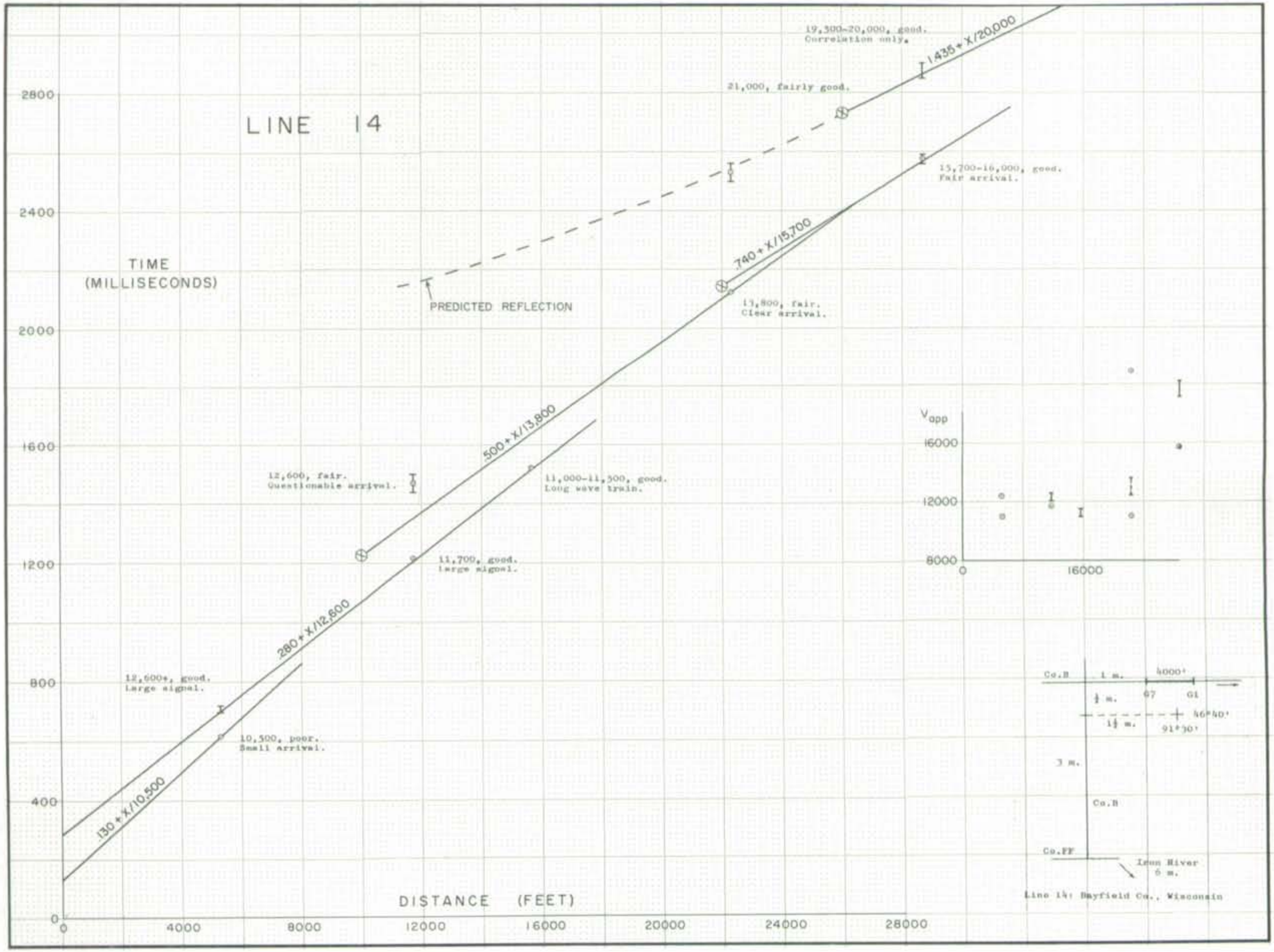
PURPOSE: The line is located over the -90 mg gravity low northwest of Ashland, Wisconsin. Chequamegon Sandstone crops out at its type locality along the lakeshore a few miles to the east. Mean surface elevation is 970 feet.

RESULTS: The in-line data show about 400 feet of drift overlying material with velocity 10,300 feet/second. Along-line data suggest a slightly higher value of 11,000 feet/second. We identify this formation as Chequamegon Sandstone on the basis of nearby outcrops, although the same velocity value is identified with Orienta Formation to the west at Lines 28 and 31. The two formations are difficult to distinguish geologically.

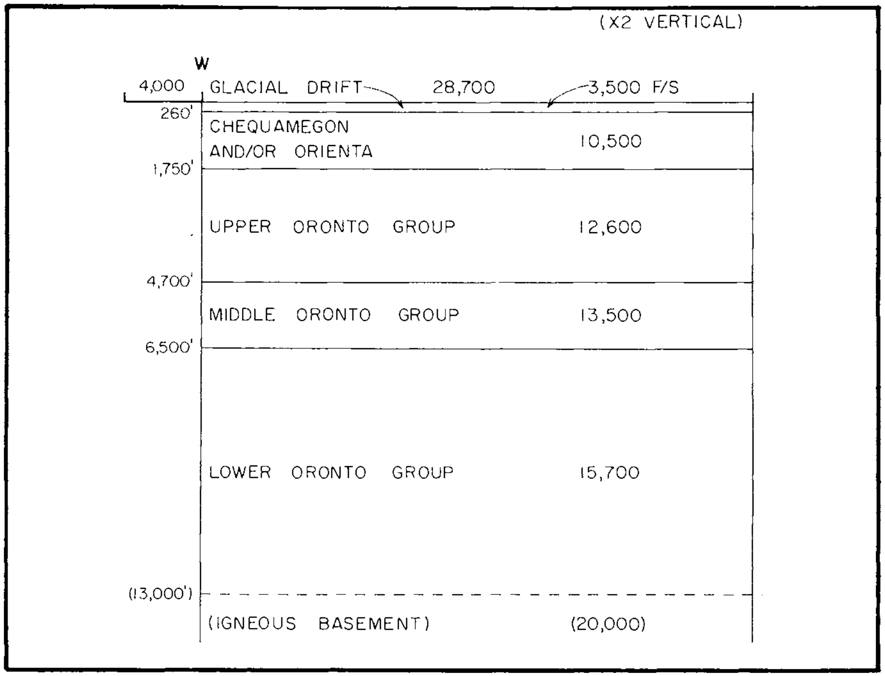
Good seismic data, confirmed by Line 14 to the west, show the next deeper layer to have velocity 12,600 feet/second. This velocity suggests the Freda Sandstone. If the stratigraphic section is complete at this location, however, the Devil's Island Sandstone (9,500 feet/second) and the Orienta Formation (11,000 feet/second) lie between the Chequamegon and the presumed Freda. This possibility does not violate the seismic data because they would present an undetectable velocity inversion. We have recalculated the depths on the assumption that these formations are present and find (a) total thickness for the three Bayfield formations can hardly exceed a few hundred feet, and (b) depth to the Freda is thereby decreased from 850 to a minimum of 550 feet. Depths to deeper layers are affected only slightly.

We are left with these alternative explanations: (a) Chequamegon lies directly on the Freda, in which case both Devil's Island and Orienta have pinched out somewhere between Line 31 and Line 13, or (b) Devil's Island and/or Orienta exist with a total thickness of a few tens of feet at Line 13, or (c) material identified in outcrop as Chequamegon is really Orienta, in which case Devil's Island has pinched out or been eroded away somewhere between Line 31 and Line 13, or (d) the 12,600 feet/second layer includes some Orienta Formation, suggesting a possible facies and velocity change. A final decision must await further geologic study.

Two deeper layers with velocities 13,800 and 15,700 feet/second appear on Line 13. The first is supported by two good points plus a weak third, the second by only one good point. Both are supported by data from adjacent Line 14. We associate the 15,700 feet/second velocity with the lowest formation of the Oronto Group, although this value approaches that identified elsewhere with basalt. We prefer to reject this possibility on the basis of gravity and magnetic data, which suggest great depth to igneous basement.



LINE 14
TIME
(MILLISECONDS)
DISTANCE (FEET)
0
400
800
1200
1600
2000
2400
2800
4000
8000
12000
16000
20000
24000
28000
130 + X/10,500
280 + X/12,600
500 + X/13,800
740 + X/15,700
1435 + X/20,000
PREDICTED REFLECTION
12,600+, good. Large signal.
10,500, poor. Small arrival.
12,600, fair. Questionable arrival.
11,700, good. Large signal.
11,000-11,500, good. Long wave train.
13,800, fair. Clear arrival.
21,000, fairly good.
19,500-20,000, good. Correlation only.
15,700-16,000, good. Fair arrival.
V_{app}
16000
12000
8000
0
16000
Co.B
1 m.
4000'
G7
G1
½ m.
46°40'
1½ m.
91°30'
3 m.
Co.B
Co.FF
Iron River 6 m.
Line 14: Bayfield Co., Wisconsin



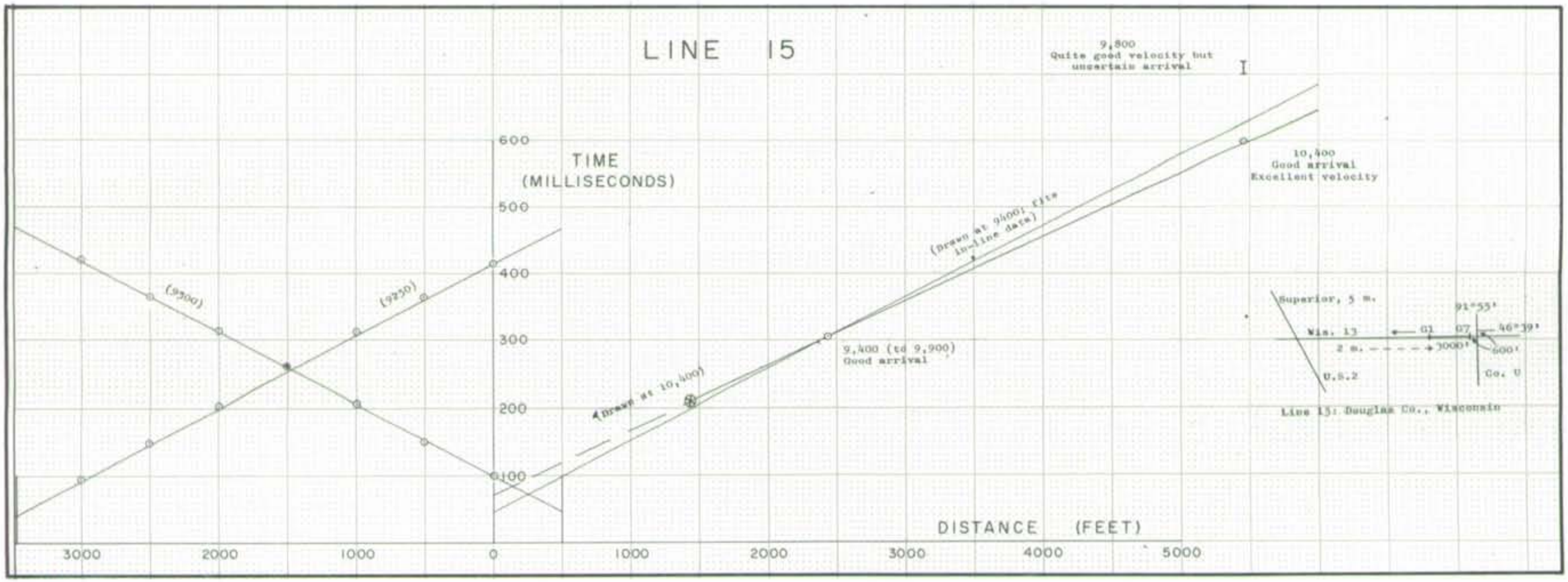
LINE 14

PURPOSE: The line lies on the north side of the Douglas Fault in Bayfield County, Wisconsin, about 12 miles west of the -90 mg gravity minimum. The gravity value decreases from -40 mg at the west end to -65 mg at the east end of Line 14. Thwaites' map shows Upper Oronto Group at this location. Mean surface elevation is 1,015 feet.

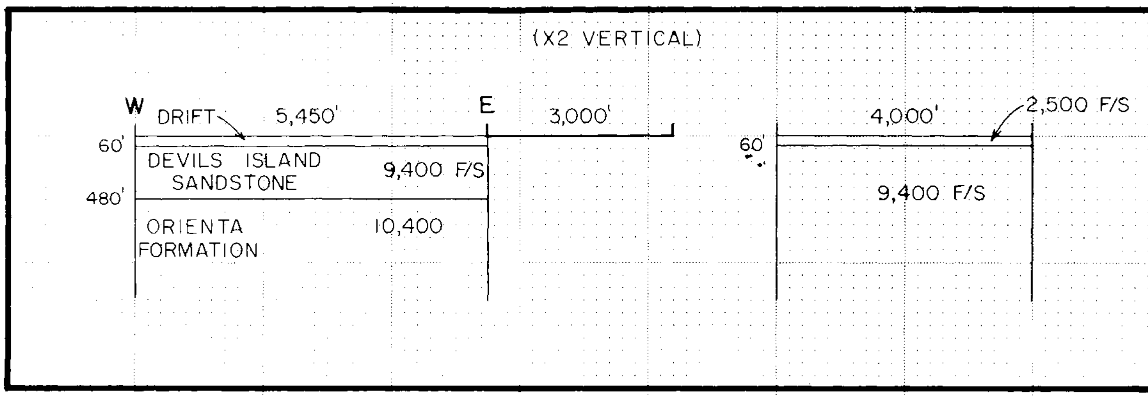
RESULTS: Data for Line 14 agree well with both Line 31 to the west and Line 13 to the east. The 9,500 feet/second velocity of Devil's Island Sandstone observed on Line 31 appears to be absent at Line 14, although failure of the in-line shots leaves open the possibility that a few tens of feet of it could be present. The sub-drift velocity of 10,500 feet/second is defined by only a single point but confirmed from both adjacent lines. Identification of this material is subject to the same alternative possibilities as for Line 13.

Presumed Freda Sandstone with velocity 12,600 feet/second is well defined by three arrivals on Line 14. Two deeper layers with velocities 13,500 and 15,700 feet/second are given by only one point each, but the data are good, the spread velocities confirm them, and the results agree with both Lines 13 and 31.

A possible basement arrival appears as a later arrival from the two most distant shots. The data permit only a tentative conclusion, but the inferred depth would be about 13,000 feet. The velocity of 20,000 feet/second would be too high for basalt based upon our results in nearby areas. If the value is correct, then a different type of basalt or an intrusive rock is indicated.



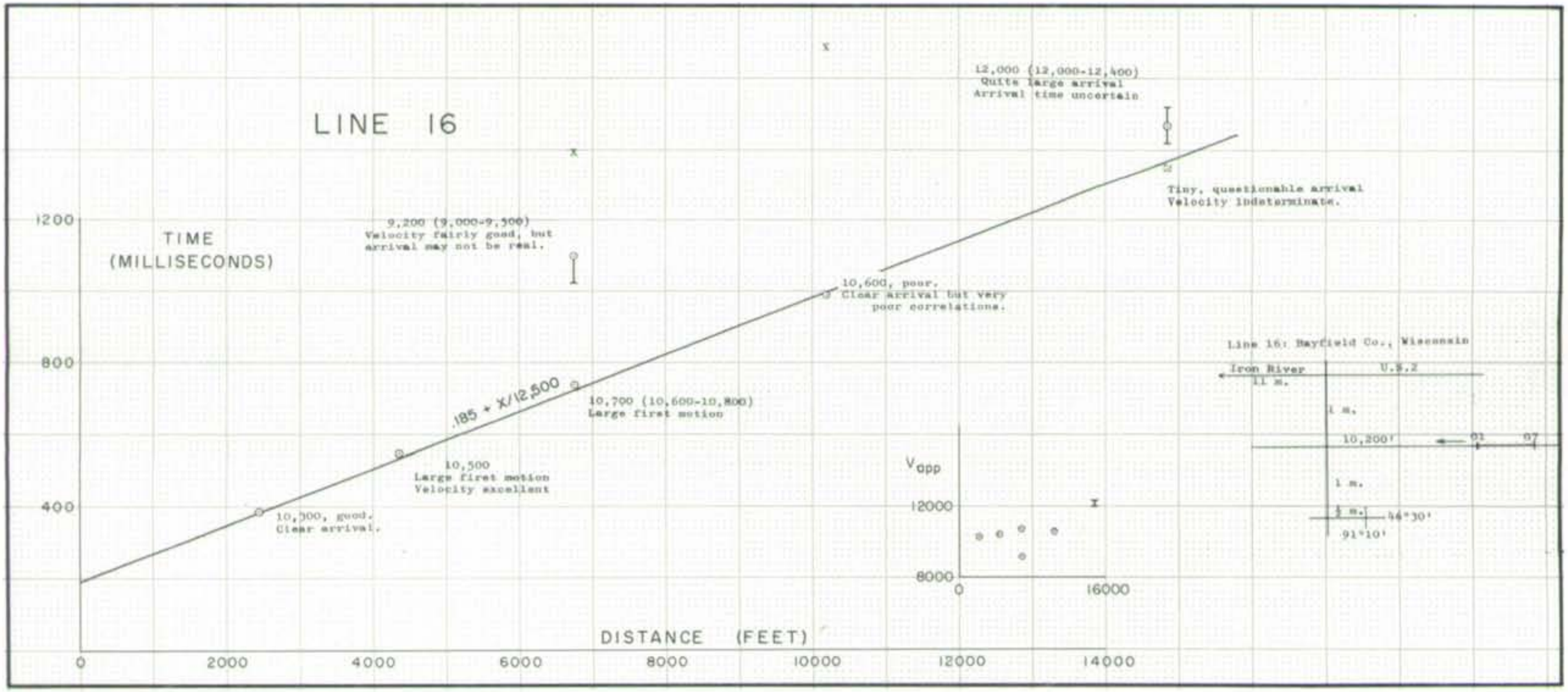
LINE 15
TIME
(MILLISECONDS)
600
500
400
300
200
100
(9500)
(9250)
(Drawn at 10,400)
9,400 (td 9,900)
Good arrival
(Drawn at 9400; fits in-line data)
9,800
Quite good velocity but
uncertain arrival
10,400
Good arrival
Excellent velocity
Superior, 5 m.
Wis. 13
U.S.2
2 m.
01
07
3000'
600'
91°55'
46°39'
Co. U
Line 15: Douglas Co., Wisconsin
DISTANCE (FEET)
3000
2000
1000
0
1000
2000
3000
4000
5000

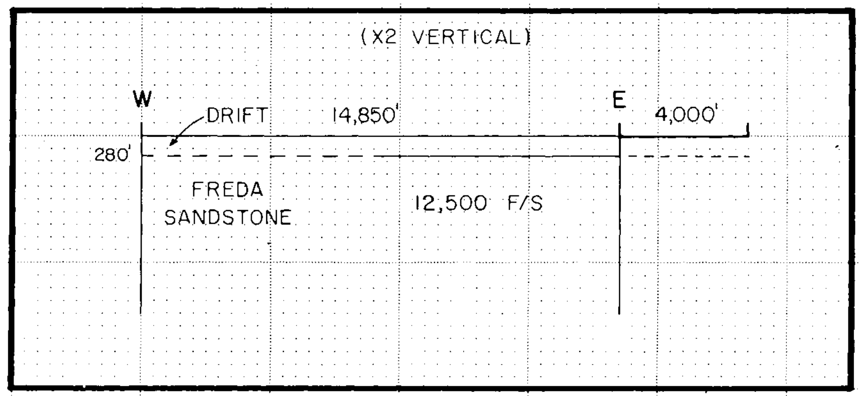


LINE 15

PURPOSE: See Line 28. According to Tyler *et al,* the sub-drift material should be the Orienta Formation (lower Bayfield). Mean surface elevation is 750 feet.

RESULTS: Excellent in-line data show 9,400 feet/second material beneath about 60 feet of glacial drift. This velocity value identifies it with the Devil's Island Sandstone and possibly the upper Orienta Formation, correlative with the Hinckley Sandstone of western Minnesota. A single arrival suggests slightly higher velocity at a depth of about 500 feet. Taken alone, this arrival would have questionable significance, but the interpretation is strengthened by nearly identical results on Line 28, one mile to the south. The 10,400 feet/second velocity is thus identified as Orienta Formation.

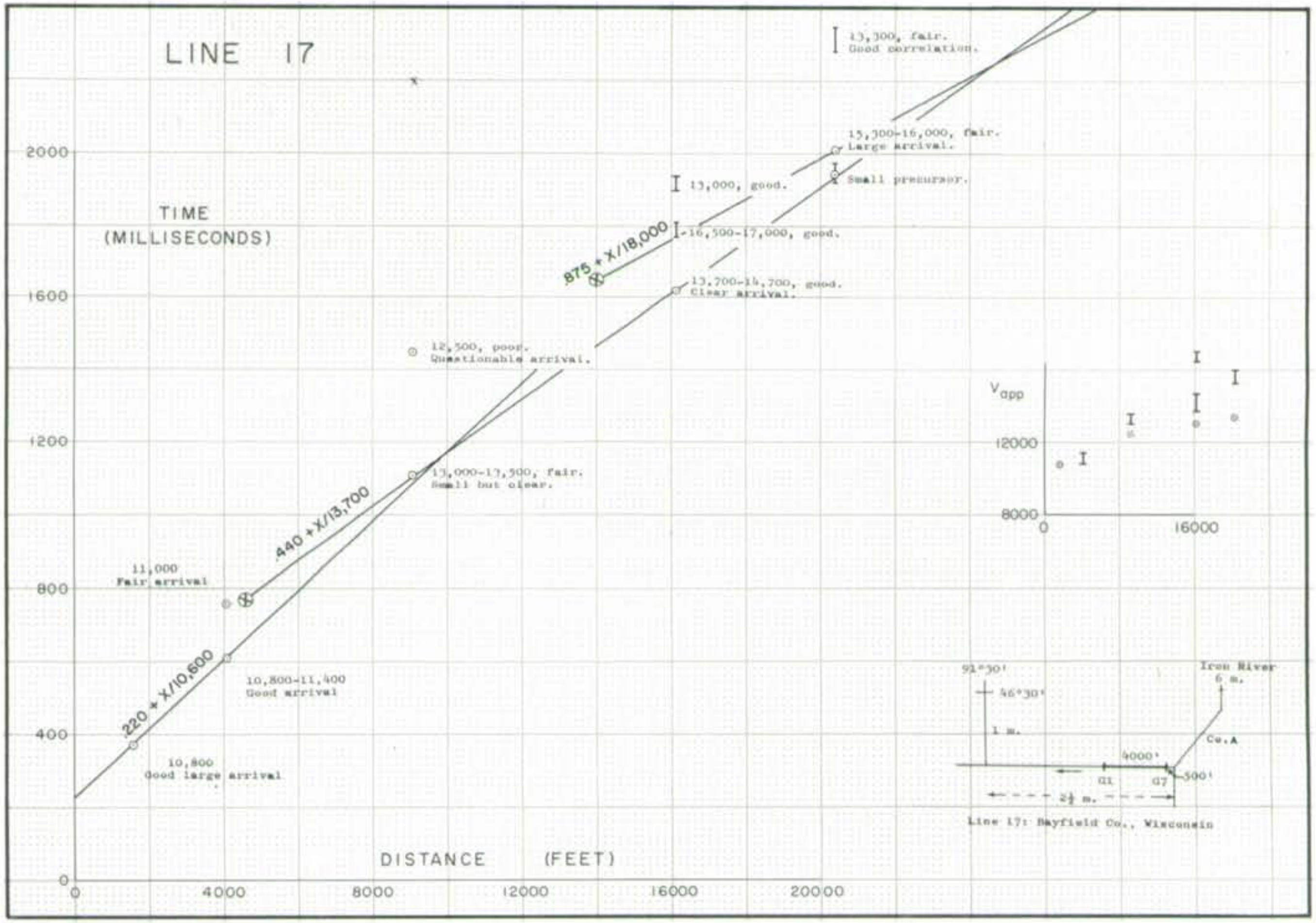

LINE 16
TIME
(MILLISECONDS)
1200
800
400
0
2000
4000
6000
8000
10000
12000
14000
DISTANCE (FEET)
.185 + X/12,500
10,300, good.
Clear arrival.
10,500
Large first motion
Velocity excellent
10,700 (10,600-10,800)
Large first motion
9,200 (9,000-9,300)
Velocity fairly good, but
arrival may not be real.
10,600, poor.
Clear arrival but very
poor correlations.
12,000 (12,000-12,400)
Quite large arrival
Arrival time uncertain
Tiny, questionable arrival
Velocity indeterminate.
V_{app}
12000
8000
0
16000
Line 16: Bayfield Co., Wisconsin
Iron River
11 m.
U.S.2
1 m.
10,200'
01
07
1 m.
½ m.
46°30'
91°10'



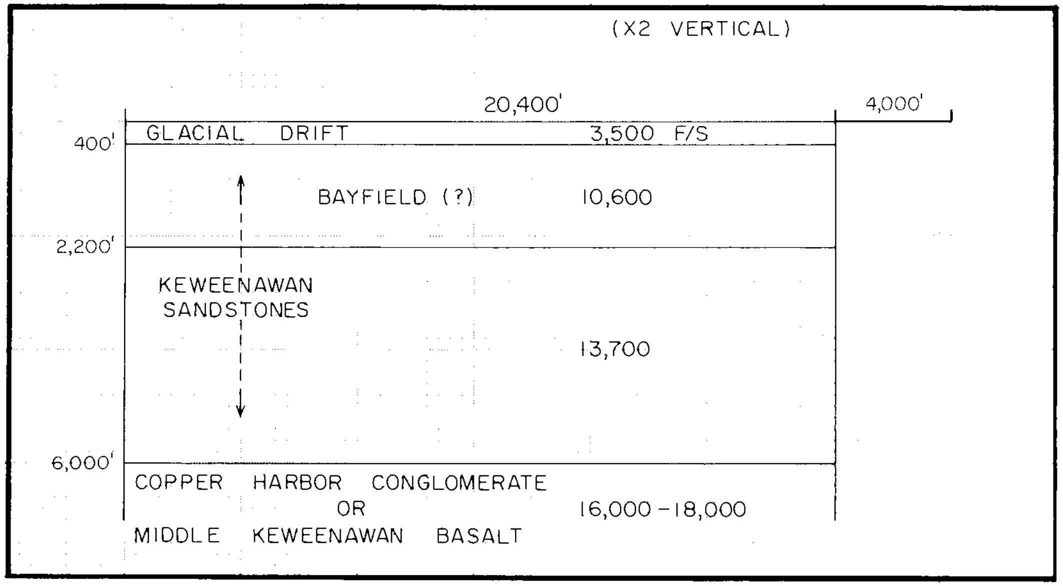
LINE 16

PURPOSE: The line lies eastward from the supposed termination of the Douglas Fault in Bayfield County, Wisconsin, approximately 12 miles SSW of the -90 mg gravity minimum. The gravity value here ranges from -50 to -55 mg. The Freda sandstone is known to occur within a few hundred feet of the surface at this location. Mean surface elevation is 1,250 feet.

RESULTS: The section consists of several thousand feet of material with velocity values not greater than 12,500-13,000 feet/second. Drift thickness is about 280 feet. Apparent velocities across the geophone spread are well determined for four shot points at 10,300-10,800 feet/second. We attribute this to a slight change in dip near the geophone spread because interpretation as a dipping plane surface leads to an impossible structure. Thus the true velocity is taken as about 12,500 feet/second which identifies the material as Freda sandstone (Upper Oronto Group) and possibly some lower Orienta Formation.



LINE 17
TIME
(MILLISECONDS)
DISTANCE (FEET)
0
400
800
1200
1600
2000
0
4000
8000
12000
16000
20000
220 + X/10,600
440 + X/13,700
875 + X/18,000
13,300, fair.
Good correlation.
15,300-16,000, fair.
Large arrival.
Small precursor.
13,000, good.
16,500-17,000, good.
13,700-14,700, good.
Clear arrival.
12,500, poor.
Questionable arrival.
13,000-13,500, fair.
Small but clear.
11,000
Fair arrival
10,800-11,400
Good arrival
10,800
Good large arrival
V_{app}
12000
8000
0
16000
91°30'
46°30'
1 m.
Iron River
6 m.
Co.A
4000'
G1
G7
500'
2½ m.
Line 17: Bayfield Co., Wisconsin



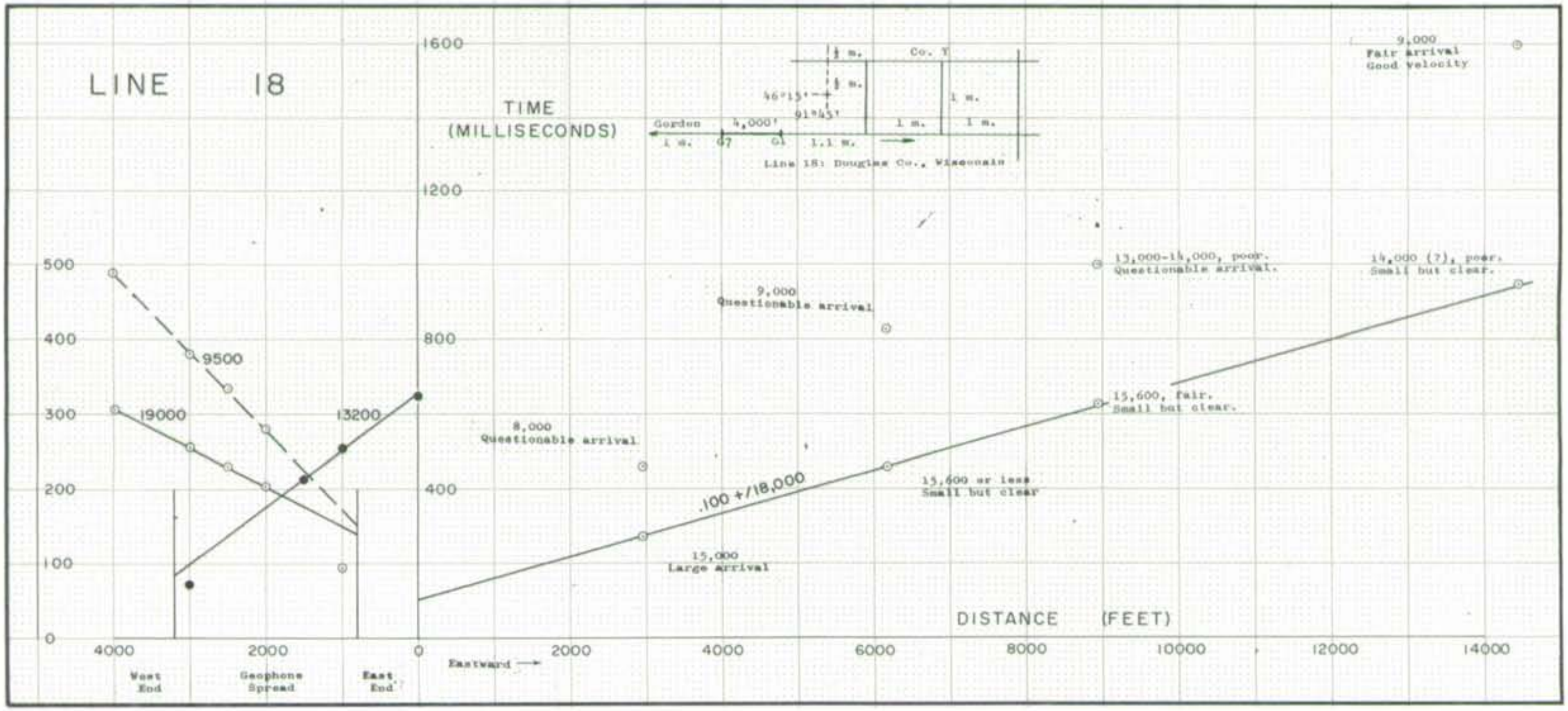
LINE 17

PURPOSE: Lines 17 and 30 lie south of the Douglas Fault in Bayfield and Douglas Counties, Wisconsin. Presumably they lie over the St. Croix Horst, although the geologic evidence suggests that the horst either terminates or plunges sharply downward a few mile to the east of these lines. Gravity values at Line 17 range from +20 to -20 mg and decrease rapidly to the northeast. Thwaites shows the sub-drift material to be Upper Oronto Group. Mean surface elevation is 1,200 feet.

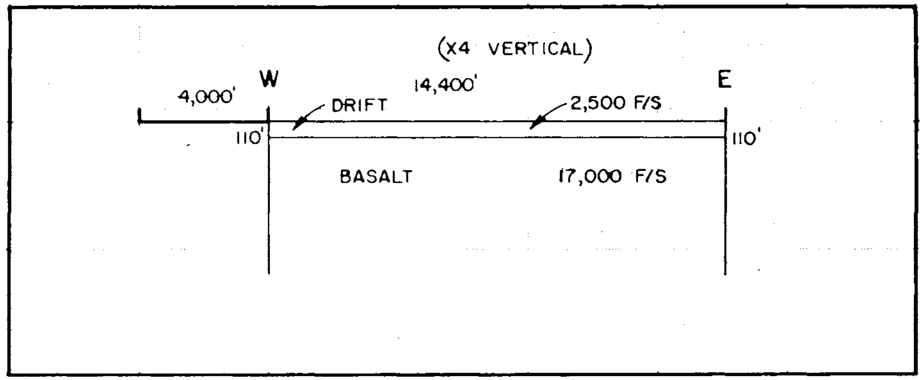
RESULTS: Sub-drift material shows a velocity of 10,600 feet/second; this value rests upon two good arrivals on the main spread plus weak confirmation from poor-quality in-line data. We have difficulty in reconciling the velocity with expected Freda Sandstone at this location, since Freda was tentatively associated with 12,600 feet/second values on the north side of the Douglas Fault. It is possible that that identification was incorrect, or that the Freda has changed slightly on the south side of the fault, but a straight velocity correlation would identify this as Orienta Formation (Lower Bayfield Group).

The next velocity layer of 13,700 feet/second also looks fairly well defined; the travel-time line fits three points, and all three points give across-spread velocities in this range. If correlations from the north side of the Douglas Fault are accepted, this would be the middle member of the Oronto Group.

The deepest velocity layer is based upon two second arrivals. The first is a large arrival at shot 5 with spread velocity of 16,000 feet/second or less. The second is a correlation at shot 4 with well-determined spread velocity of 16,500-17,000 feet/second. The lowest velocity line which can be drawn through these arrivals is about 18,000 feet/second. Depth to the material is about 6,000 feet. Taking into account geologic considerations and the uncertainty in the velocity value, we tentatively identify the material as Copper Harbor Conglomerate, but it could also be Middle Keweenawan basalt.



LINE 18
TIME (MILLISECONDS)
1600
1200
800
400
500
400
300
200
100
0
9500
19000
13200
Co. Y
½ m.
½ m.
46°15'
91°45'
1 m.
Gordon
4,000'
1 m.
1 m.
1 m.
67
61
1.1 m.
Line 18: Douglas Co., Wisconsin
9,000
Fair arrival
Good velocity
9,000
Questionable arrival
13,000-14,000, poor.
Questionable arrival.
14,000 (?), poor.
Small but clear.
8,000
Questionable arrival
15,600, fair.
Small but clear.
.100 +/18,000
15,600 or less
Small but clear
15,000
Large arrival
DISTANCE (FEET)
4000
2000
0
2000
4000
6000
8000
10000
12000
14000
West End
Geophone Spread
East End
Eastward →

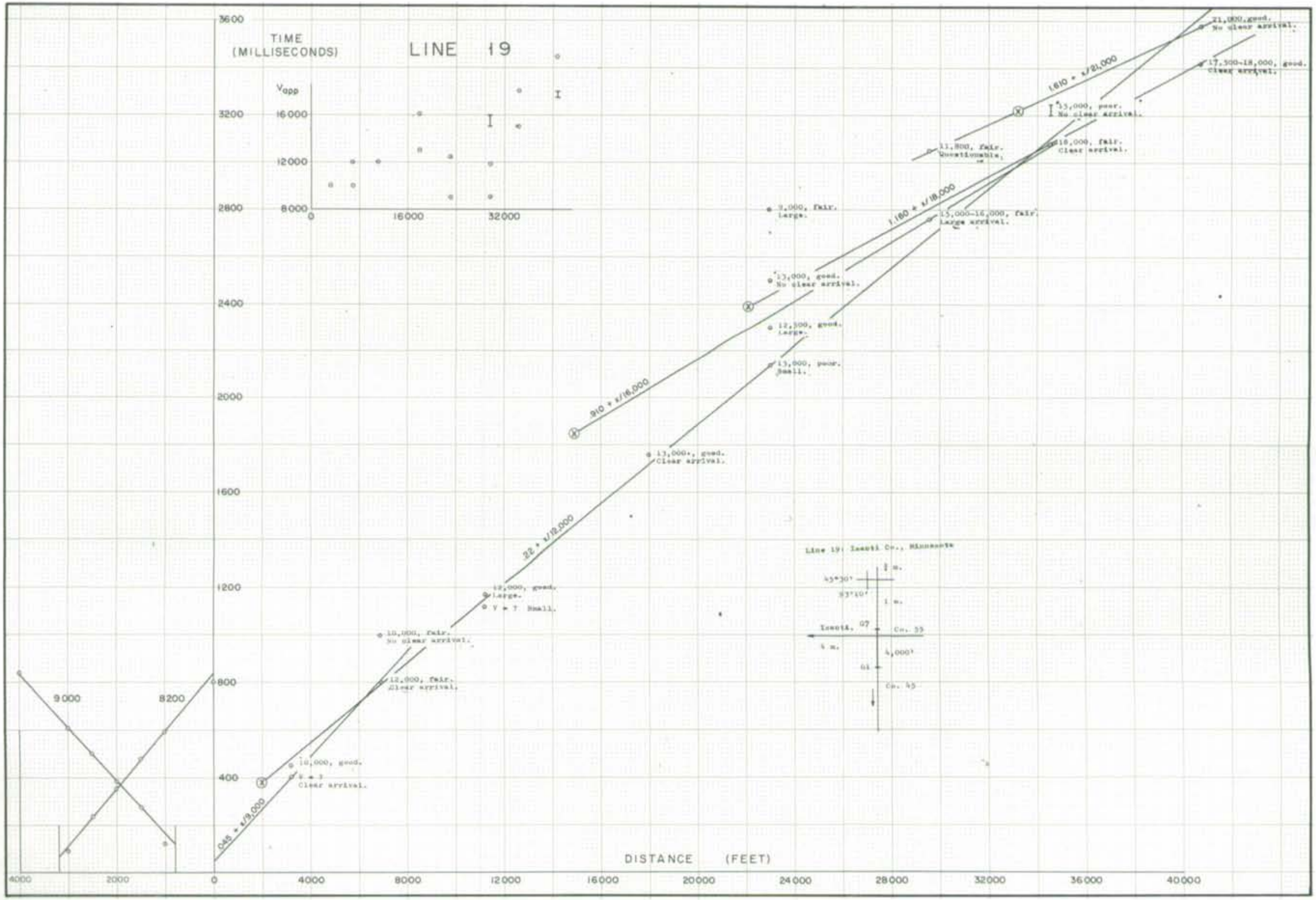


LINE 18

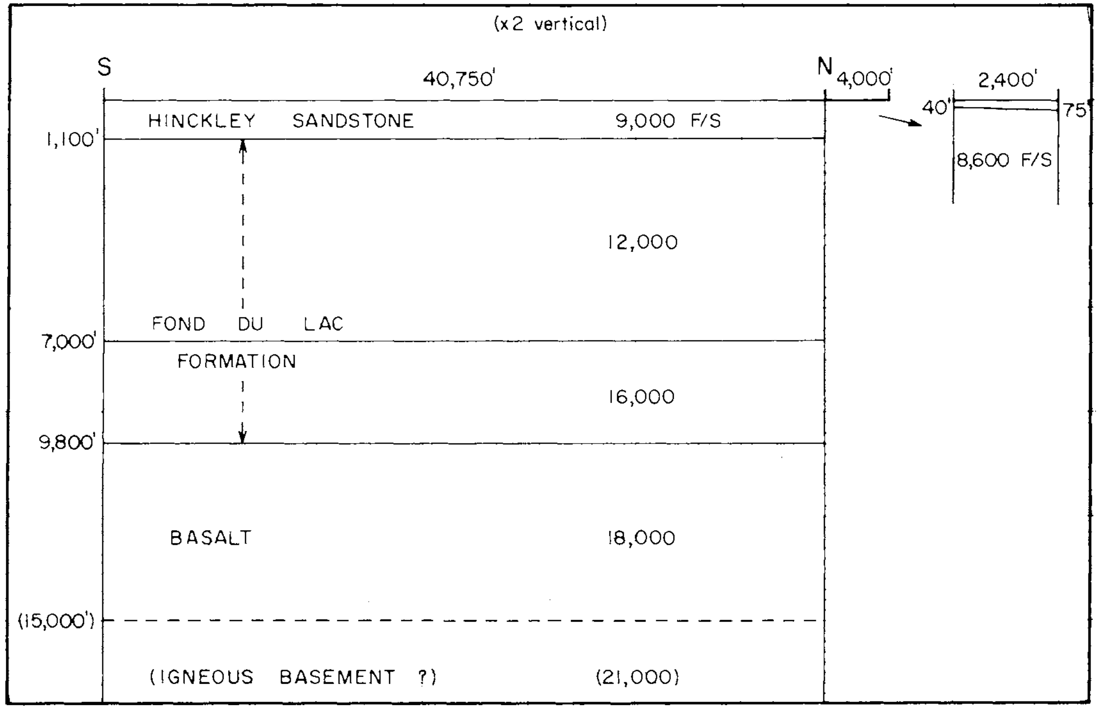
PURPOSE: Line 18 is over the St. Croix Horst in Douglas County, Wisconsin. The gravity value in this area is about +40 mg. Thwaites shows basalt is the sub-drift material. Mean surface elevation is 1,100 feet.

RESULTS: We interpret these data to indicate basalt underlying about 100 feet of drift.

The in-line shots do not permit a clear-cut interpretation but suggest the presence of local irregularities under the geophone spread. Taking this into account, we attach greater weight to the velocity value of 17,000 feet/second for basalt than to the spread velocities of about 15,600 feet/second. The basalt surface appears to be relatively plane and probably horizontal.



TIME
(MILLISECONDS)
LINE 19
DISTANCE (FEET)
V app
.045 + x/9,000
.22 + x/12,000
.910 + x/16,000
1.160 + x/18,000
1.610 + x/21,000
10,000, good.
V = ? Clear arrival.
12,000, fair. Clear arrival.
10,000, fair. No clear arrival.
12,000, good. Large.
V = ? Small.
13,000+, good. Clear arrival.
13,000, poor. Small.
12,500, good. Large.
13,000, good. No clear arrival.
9,000, fair. Large.
15,000-16,000, fair. Large arrival.
11,800, fair. Questionable.
18,000, fair. Clear arrival.
13,000, poor. No clear arrival.
17,500-18,000, good. Clear arrival.
21,000, good. No clear arrival.
9000
8200
Line 19: Isanti Co., Minnesota
45°30'
93°10'
½ m.
1 m.
Isanti, 4 m.
Co. 55
4,000'
Co. 45



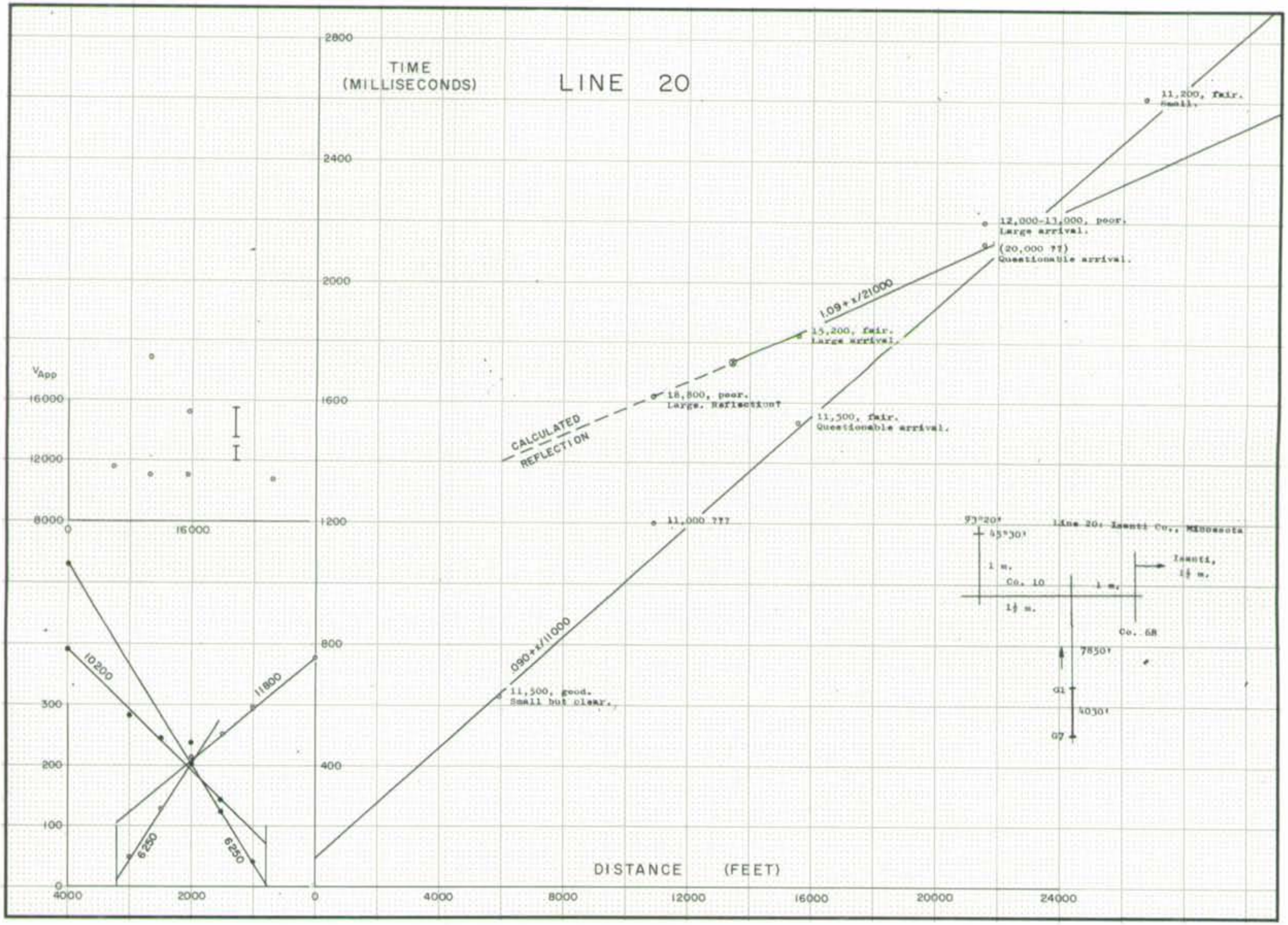
LINE 19

PURPOSE: Lines 19-20 and 67-71 lie along latitude 45°30′ in the western basin, extending westward from the Douglas Fault to a maximum distance (line 71) of 45 miles. The gravity minimum has its greatest width at this latitude. Approximate Bouguer gravity values are: Line 67, -70 mg; 19, -70 mg; 20, -50 mg; 68-70, -50 mg. Mean surface elevation is 950 feet.

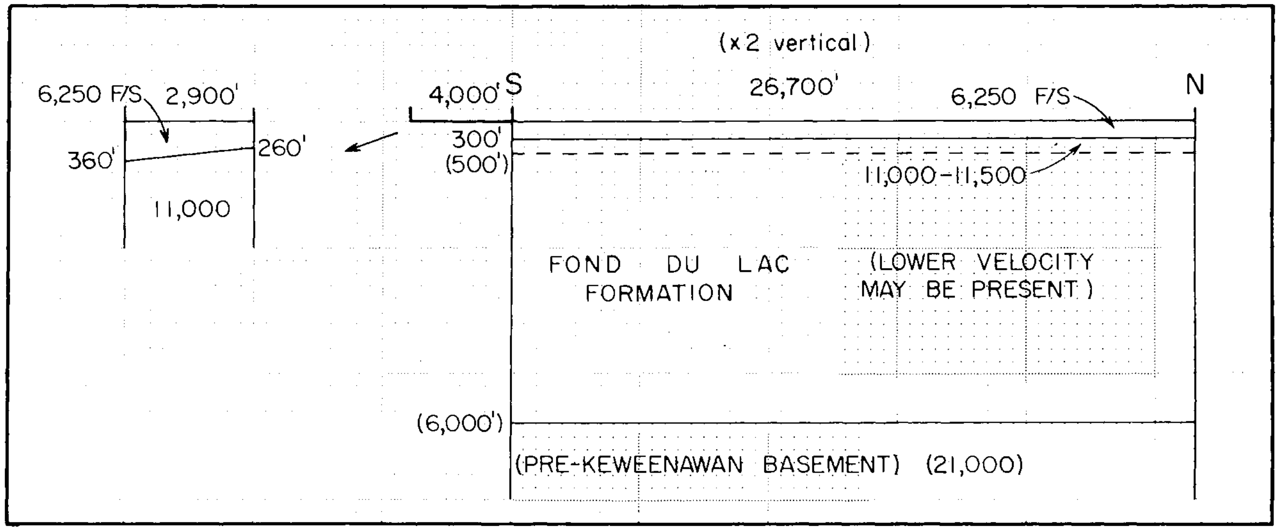
RESULTS: Lines 19 and 67, 3 miles to the east, were interpreted together as well as separately and confirmed each other.

The uppermost layer, Hinckley or possibly Dresbach (Cambrian) Sandstone, yields a velocity of 8,500-9,000 feet/second from in-line shots as well as several secondary arrivals.

12,000 feet/second material is well defined. Presumably this is the Fond du Lac Formation which yields 11,000 feet/second on Lines 20 and 68-70 to the west, although the velocity difference appears real. We have inferred the presence of 16,000 feet/second material on the basis of one arrival on Line 19 and two on Line 67; this represents the lowermost part of the Fond du Lac Formation. 18,000 feet/second material, presumably basalt, is defined by two first arrivals on Line 19, corresponding to a depth of about 9,800 feet. A single good secondary arrival with velocity of 21,000 feet/second may represent pre-Keweenawan igneous or metamorphic basement at about 15,000 feet depth, but confirmation from other shots and from Line 67 is lacking.



LINE 20
TIME
(MILLISECONDS)
DISTANCE (FEET)
11,200, fair.
12,000-13,000, poor.
Large arrival.
(20,000 ??)
Questionable arrival.
1.09+x/21000
15,200, fair.
Large arrival.
18,800, poor.
Large. Reflection?
11,500, fair.
Questionable arrival.
CALCULATED
REFLECTION
11,000 ???
.090+x/11000
11,500, good.
Small but clear.
10200
11800
6250
6250
16000
Line 20: Isanti Co., Minnesota
Isanti,
Co. 10
Co. 68



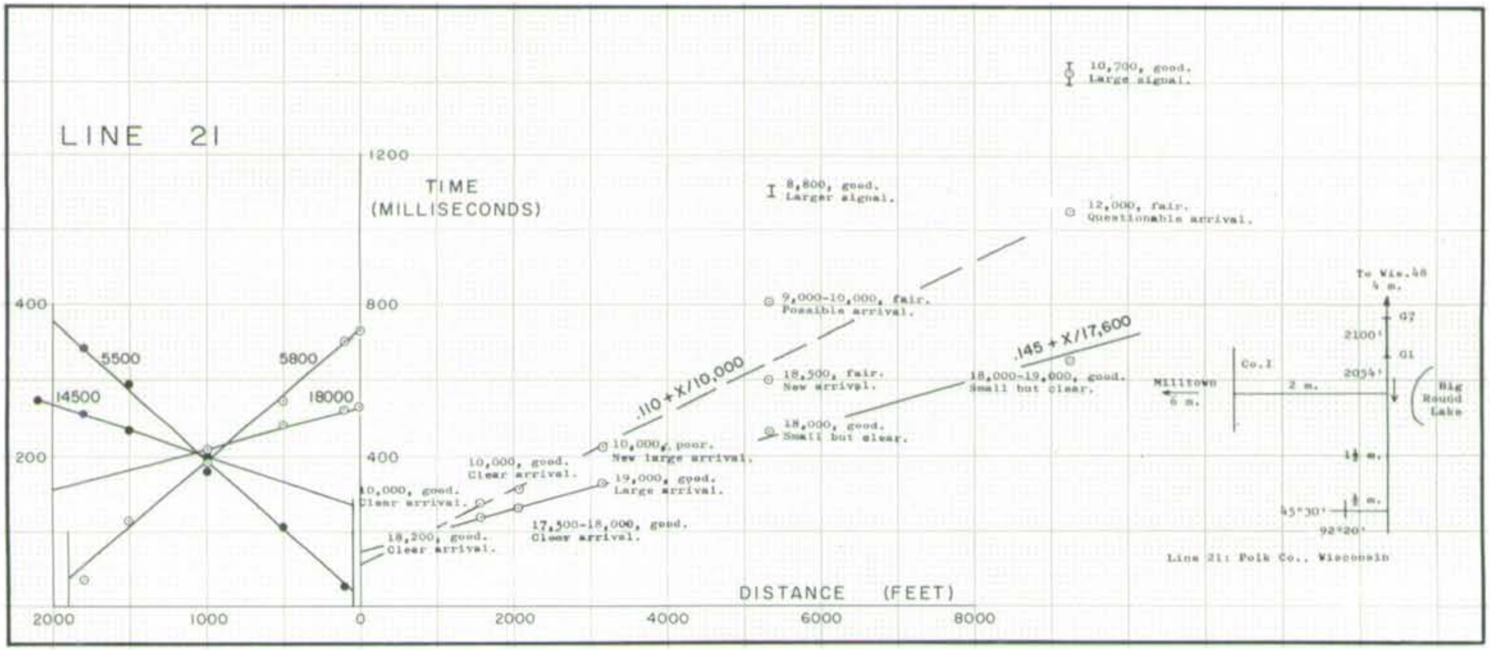
LINE 20

PURPOSE: See Line 19. A well 5 miles northeast of the geophone spread found Cambrian sandstone beneath 88 feet of drift, continuing to well bottom at 290 feet. Mean surface elevation is 950 feet.

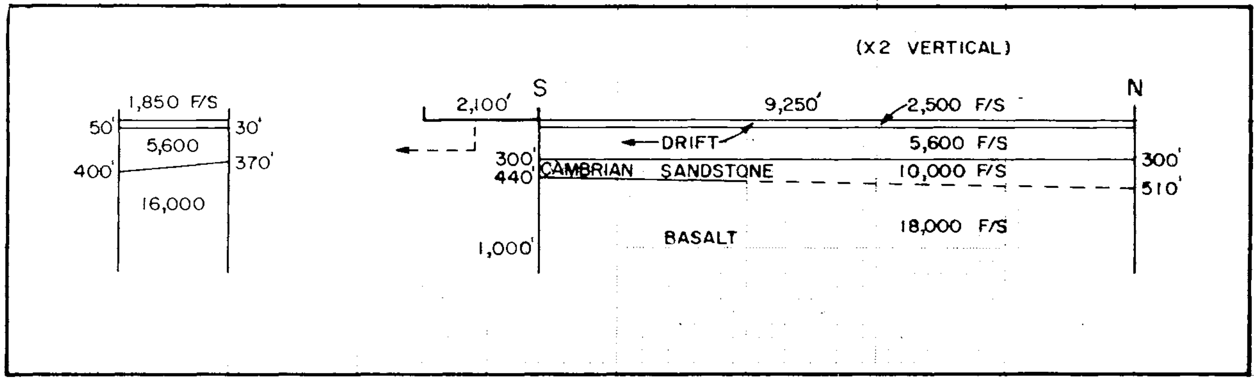
RESULTS: The near-surface material consists of about 300 feet of glacial drift with velocity 6,000 feet/second. The underlying material with velocity 11,000-11,500 feet/second produces seismic arrivals to large distances hence must extend to considerable depth. The material is presumably the Fond du Lac Formation, although the velocities are slightly lower here than elsewhere. We see no trace of the 9,000-9,500 feet/second velocities which would be expected if Cambrian and/or Hinckley Sandstone were present.

We have included a slight velocity inversion on the basis of adjacent Lines 68-70, although the data for Line 20 do not require it. Omission of the velocity inversion would increase depth to basement by 600 feet.

Secondary seismic arrivals provide sketchy evidence for deeper horizons. We have chosen to fit the data with a 21,000 feet/second layer at a depth of 6,000 feet.



LINE 21
TIME
(MILLISECONDS)
1200
800
400
400
200
5500
5800
14500
18000
10,700, good.
Large signal.
8,800, good.
Larger signal.
12,000, fair.
Questionable arrival.
9,000-10,000, fair.
Possible arrival.
.110 + X/10,000
.145 + X/17,600
18,500, fair.
New arrival.
18,000-19,000, good.
Small but clear.
18,000, good.
Small but clear.
10,000, poor.
New large arrival.
10,000, good.
Clear arrival.
19,000, good.
Large arrival.
10,000, good.
Clear arrival.
17,500-18,000, good.
Clear arrival.
18,200, good.
Clear arrival.
DISTANCE (FEET)
2000
1000
0
2000
4000
6000
8000
To Wis.48
4 m.
G7
2100'
G1
2054'
Co.I
Milltown
6 m.
2 m.
Big
Round
Lake
1½ m.
½ m.
45°30'
92°20'
Line 21: Polk Co., Wisconsin



LINE 21

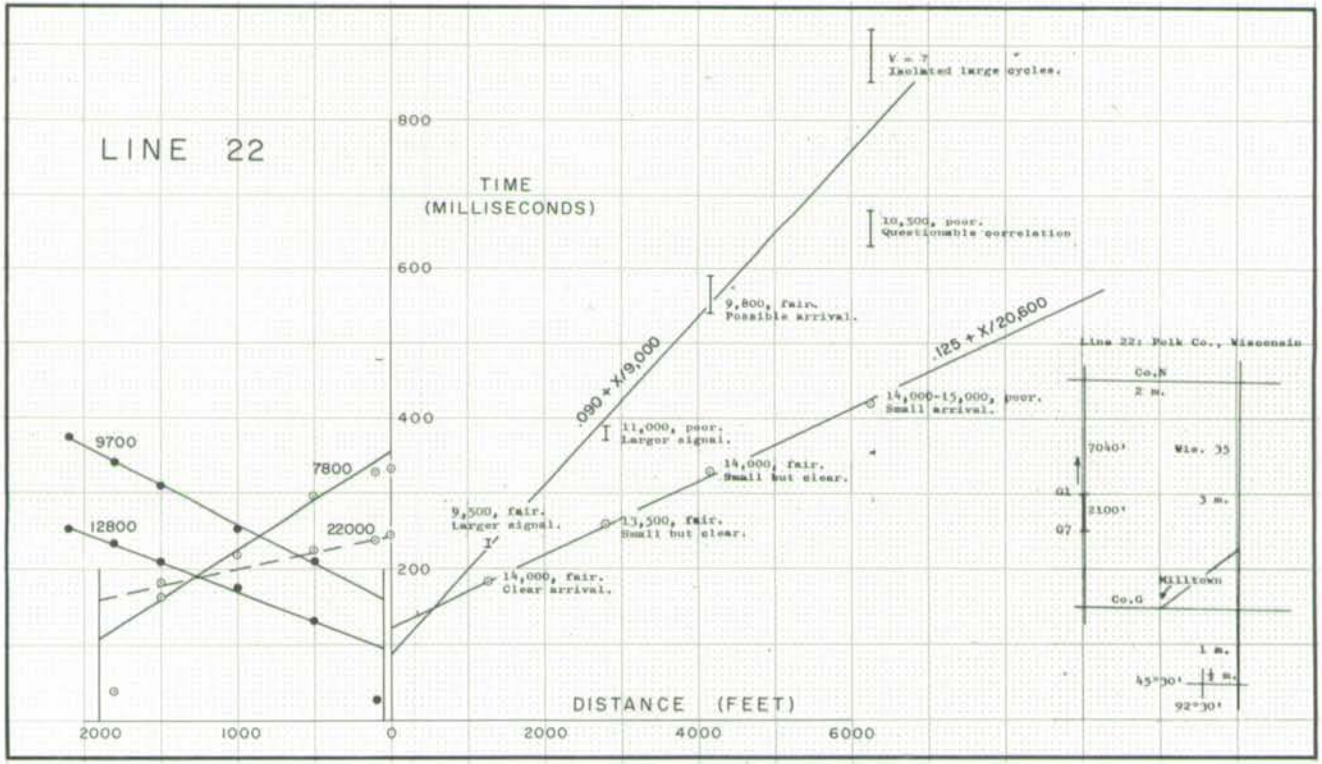
PURPOSE: Lines 21-24 overlie the St. Croix Horst along latitude 45° 30′. The distance from Line 21 on the east to Line 24 on the west is approximately 30 miles. Line 24 is still 3-5 miles east of Lines 6 and 6A and of the structural depression on the top of the horst.

Several shallow drill holes in the vicinity of Lines 21-24 suggest 30-100 feet of drift and a few tens of feet of Cambrian sandstone overlying the basalt. Mean surface elevation is 1,200 feet.

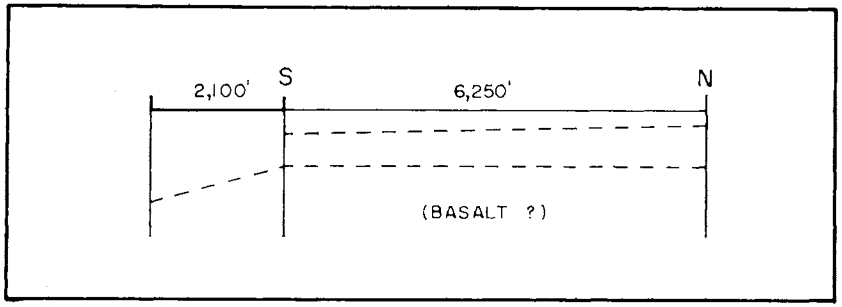
RESULTS: The refraction arrival from the basalt at a depth of about 400 feet is clear, with a well-determined velocity of 18,000 to 18,500 feet/second. The basalt surface appears to be nearly horizontal but somewhat rough, as evidenced by a slight scatter of the points on the travel-time graph.

The presence of a 10,000 feet/second layer is shown by second arrivals on the main spread, but does not appear on the in-line shots. This material if present would be Cambrian sandstone. If this layer were excluded from the interpretation, depth to the basalt in the above section would be reduced by about 50 feet.

The inferred depth to basalt at the north end of the line is less certain than at the south, since it depends upon the apparent velocity across the spread. A depth of as much as 600 feet at the north end would not be incompatible with the data.



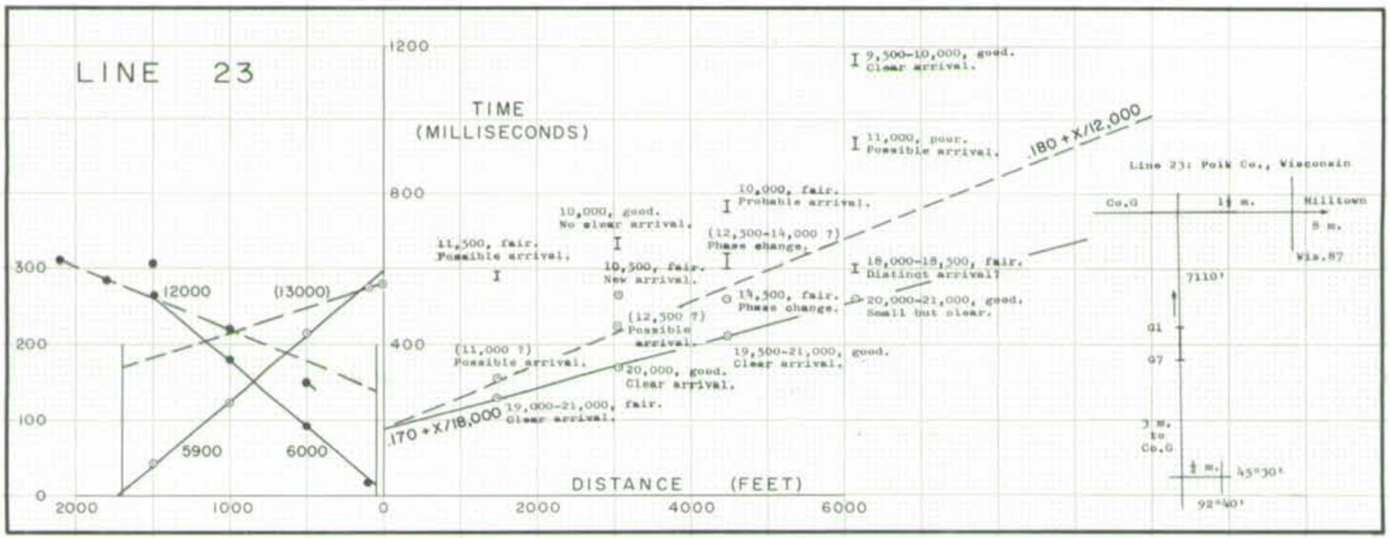
LINE 22
TIME
(MILLISECONDS)
800
600
400
200
9700
12800
7800
22000
V = ?
Isolated large cycles.
10,500, poor.
Questionable correlation
9,800, fair.
Possible arrival.
.090 + X/9,000
.125 + X/20,600
11,000, poor.
Larger signal.
14,000-15,000, poor.
Small arrival.
14,000, fair.
Small but clear.
9,500, fair.
Larger signal.
13,500, fair.
Small but clear.
14,000, fair.
Clear arrival.
DISTANCE (FEET)
2000
1000
0
2000
4000
6000
Line 22: Polk Co., Wisconsin
Co.N
2 m.
7040'
Wis. 35
01
2100'
07
3 m.
Milltown
Co.G
1 m.
45°30'
92°30'

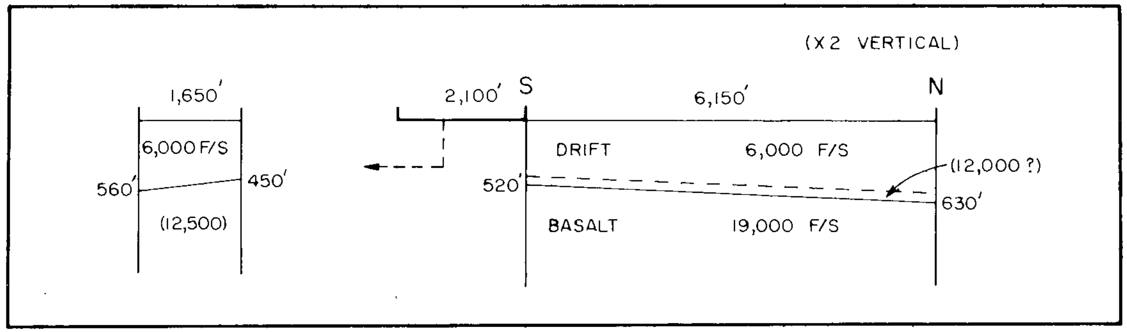


LINE 22

PURPOSE: See Line 21. Mean surface elevation is 1,330 feet.

RESULTS: We are unable to arrive at a satisfactory quantitative interpretation of this line compatible with reciprocity, on the basis of available data. The presence of a high velocity refractor, presumably basalt, is clear. Depth is estimated at 200-400 feet. As suggested by the above cross section, however, a strong component of southward dip on one or both of the refractors appears to exist beneath the geophone spread. Evidence for this appears from the in-line shots and also in the abnormally small apparent velocities across the spread for the main line of shots.


LINE 23
TIME
(MILLISECONDS)
1200
800
400
300
200
100
0
2000
1000
0
2000
4000
6000
DISTANCE (FEET)
12000
(13000)
5900
6000
.170 + X/18,000
.180 + X/12,000
9,500-10,000, good.
Clear arrival.
11,000, pour.
Possible arrival.
10,000, fair.
Probable arrival.
10,000, good.
No clear arrival.
(12,500-14,000 ?)
Phase change.
11,500, fair.
Possible arrival.
10,500, fair.
New arrival.
18,000-18,500, fair.
Distinct arrival?
14,500, fair.
Phase change.
20,000-21,000, good.
Small but clear.
(12,500 ?)
Possible
arrival.
19,500-21,000, good.
Clear arrival.
(11,000 ?)
Possible arrival.
20,000, good.
Clear arrival.
19,000-21,000, fair.
Clear arrival.
Line 23: Polk Co., Wisconsin
Co.G
Milltown
Wis.87
7110'
G1
G7
45°30'
92°40'



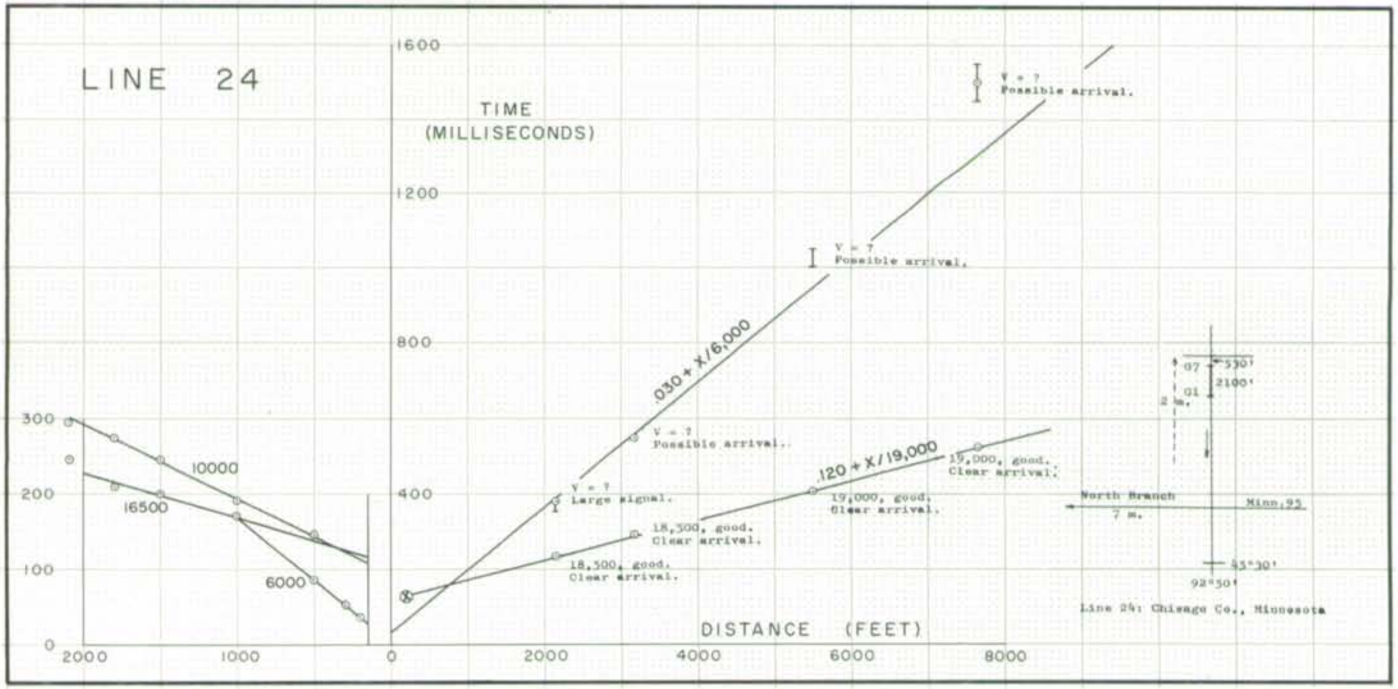
LINE 23

PURPOSE: See Line 21. Mean surface elevation is 1,060 feet.

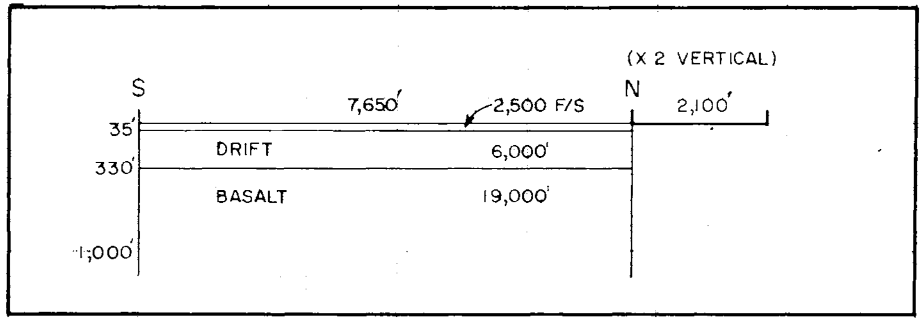
RESULTS: Excellent seismic data show the presence of basalt at a depth of about 500 feet. The surface appears to be approximately plane and nearly horizontal. Basalt velocity is 18,500-19,000 feet/second.

The near-surface drift yields a well-determined velocity of 6,000 feet/second. Thickness of the drift is about 500 feet.

A thin layer of clastics with velocity about 12,000 feet/second may overlie the basalt, although the data do not permit a definite conclusion on this point.



LINE 24
TIME
(MILLISECONDS)
1600
1200
800
400
300
200
100
0
10000
16500
6000
2000
1000
0
2000
4000
6000
8000
DISTANCE (FEET)
.030 + X/6,000
.120 + X/19,000
V = ?
Possible arrival.
V = ?
Possible arrival.
V = ?
Possible arrival.
V = ?
Large signal.
18,500, good.
Clear arrival.
18,500, good.
Clear arrival.
19,000, good.
Clear arrival.
19,000, good.
Clear arrival.
07
530'
2100'
01
2 m.
North Branch
7 m.
Minn.95
45°30'
92°30'
Line 24: Chisago Co., Minnesota



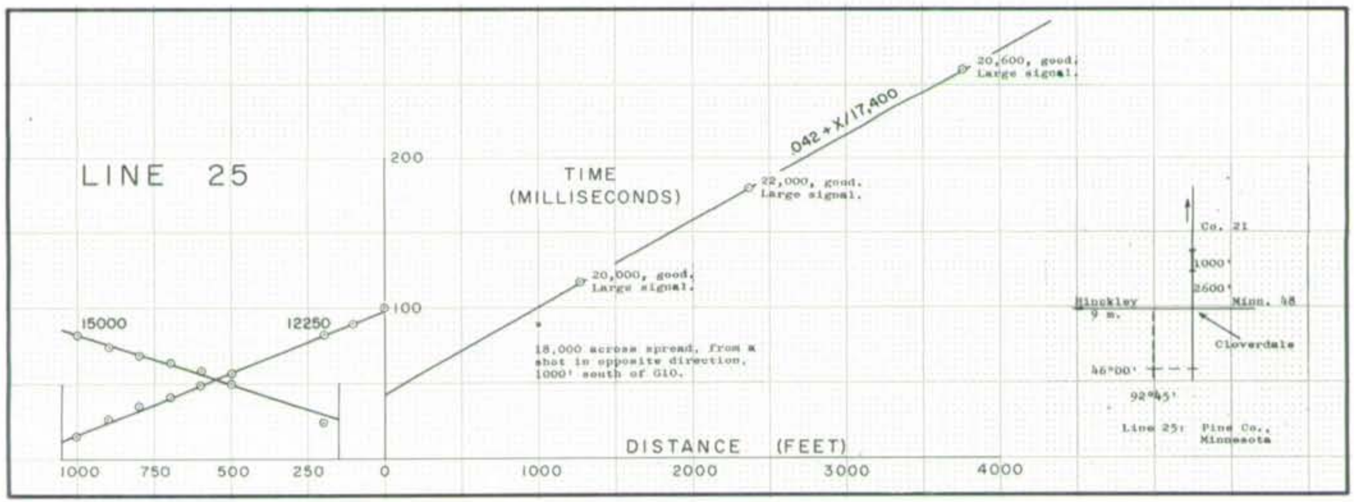
LINE 24

PURPOSE: See Line 21. Mean surface elevation is 950 feet.

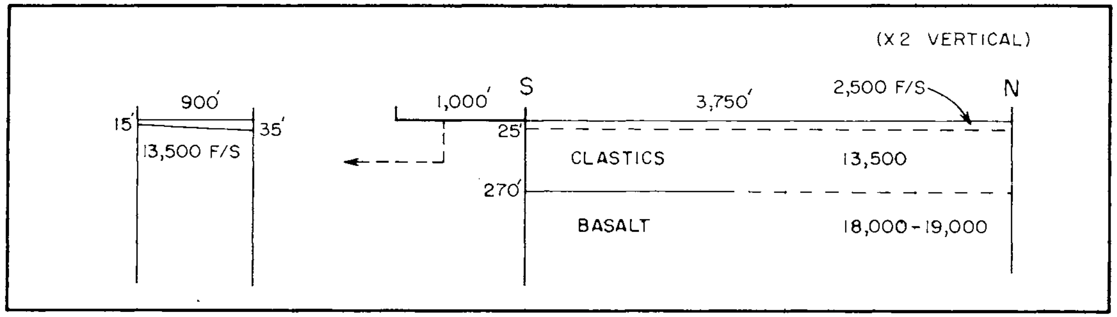
RESULTS: Basalt, with a well-established velocity of 19,000 feet/second, lies at a depth of about 300 feet. The surface is relatively smooth and nearly horizontal.

The in-line shots suggest a slightly lower velocity for the basalt, but the data points are relatively few and scattered. Second arrivals on the in-line shots suggest also a 10,000 feet/second arrival; this is not confirmed by the main line of shots and an interpretation based upon it leads to an impossible structure.

The drift velocity of 6,000 feet/second is well defined by the in-line shots and is consistent with some later arrivals of undetermined velocity on the main line of shots.



LINE 25
TIME
(MILLISECONDS)
200
100
15000
12250
.042 + X/17,400
20,600, good.
Large signal.
22,000, good.
Large signal.
20,000, good.
Large signal.
18,000 across spread, from a
shot in opposite direction,
1000' south of G10.
Co. 21
1000'
2600'
Hinckley
9 m.
Minn. 48
Cloverdale
46°00'
92°45'
Line 25: Pine Co.,
Minnesota
DISTANCE (FEET)
1000
750
500
250
0
1000
2000
3000
4000

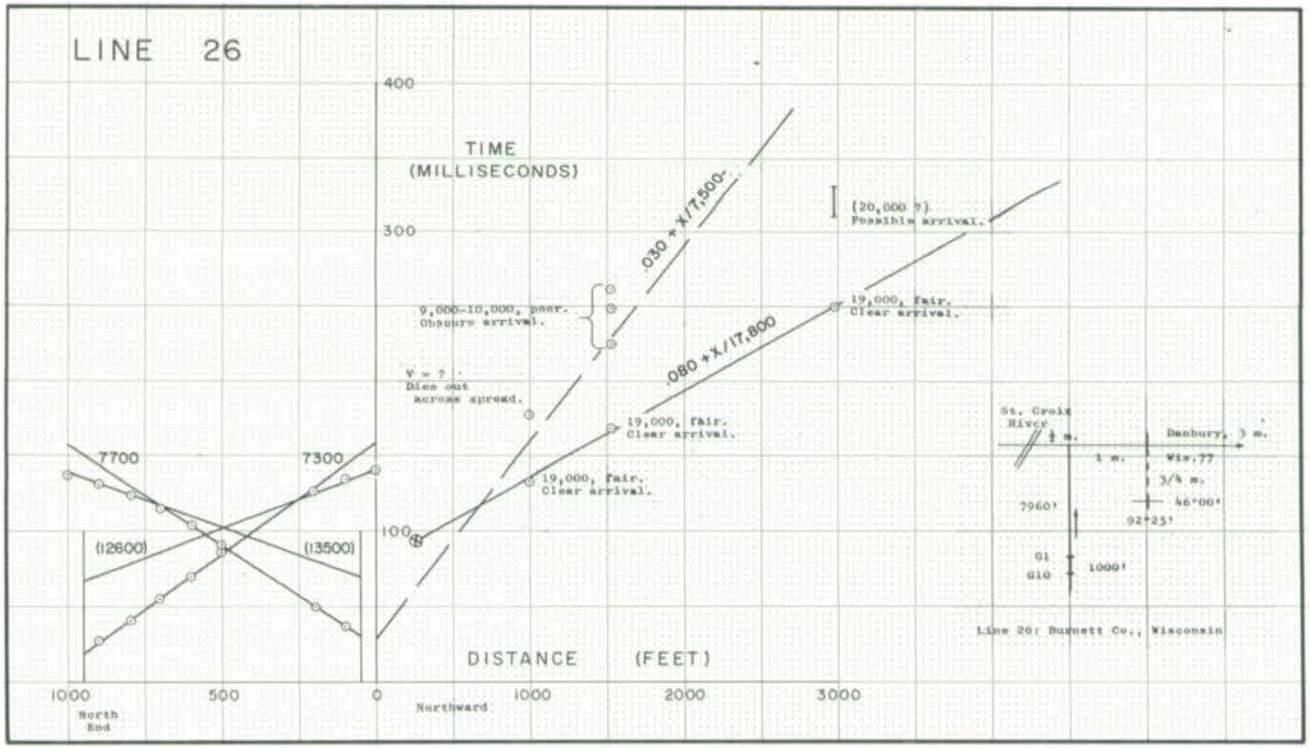


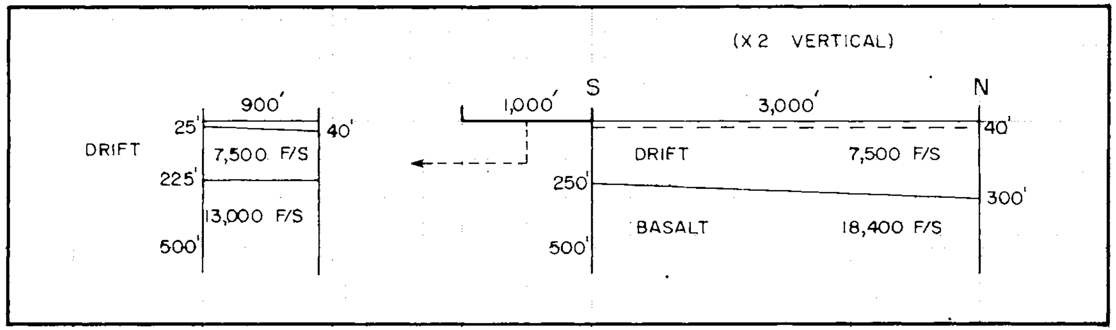
LINE 25

PURPOSE: Lines 25-26-27 are located on top of the St. Croix Horst along the sequence of profiles at 46° north latitude. They are intended to establish depth to the top of the basalt, velocity of the basalt, and the nature of the overlying materials. Mean surface elevation is 1,000 feet.

RESULTS: Basalt is clearly present at a depth less than 300 feet, but there is some question as to whether it is overlain by a thin layer of Keweenawan clastics. The in-line shots suggest the latter, with a slight down-dip to the north. This local dip would also explain the high apparent velocities observed on the main shot line; the true basalt velocity would then be closer to 18,000 feet/second.

If the 13,500 feet/second layer is omitted from the interpretation, then depth to basalt is on the order of 100 feet. Nearby drill data show no evidence of clastics overlying the basalt, hence this interpretation is probably to be preferred.

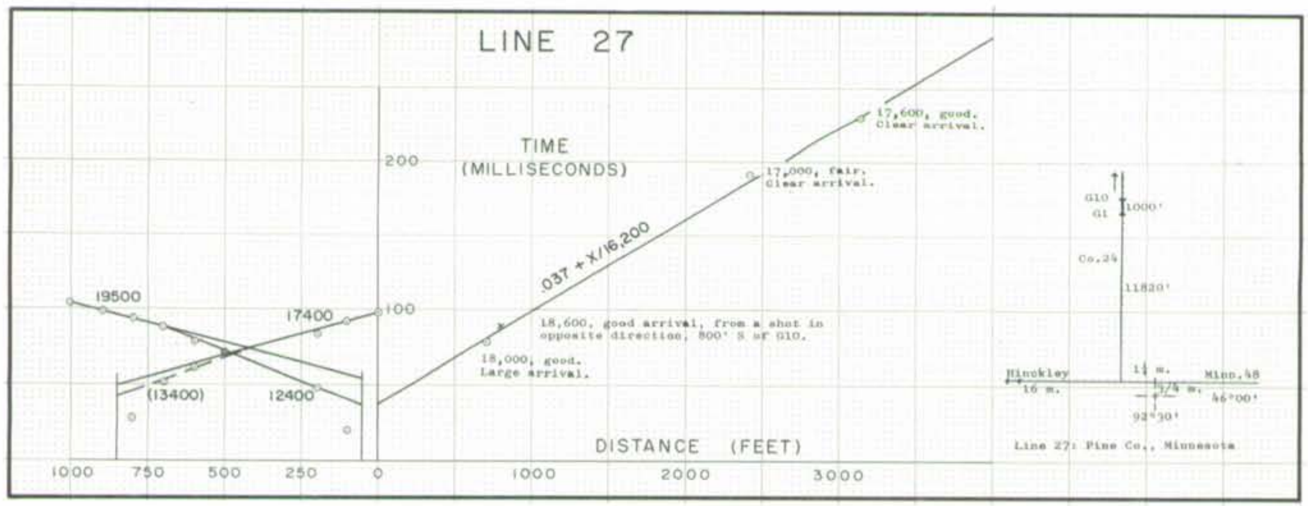

LINE 26
TIME
(MILLISECONDS)
400
300
100
.030 + X/7,500
.080 + X/17,800
(20,000 ?)
Possible arrival.
9,000-10,000, poor.
Obscure arrival.
19,000, fair.
Clear arrival.
V = ?
Dies out
across spread.
19,000, fair.
Clear arrival.
19,000, fair.
Clear arrival.
7700
7300
(12600)
(13500)
St. Croix
River
Danbury, 3 m.
Wis.77
3/4 m.
46°00'
92°25'
7960'
1000'
G1
G10
Line 26: Burnett Co., Wisconsin
DISTANCE (FEET)
1000
500
0
1000
2000
3000
North
End
Northward

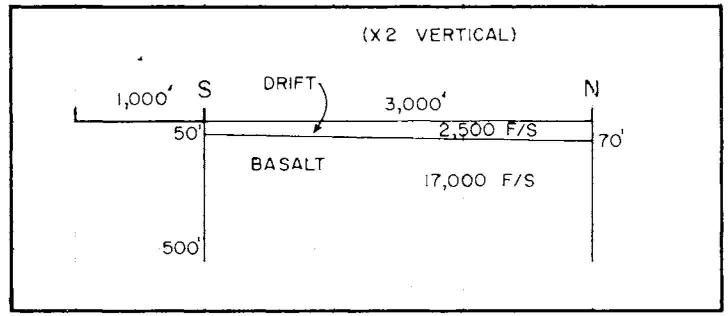


LINE 26

PURPOSE: See Line 25. Mean surface elevation is 1,000 feet.

RESULTS: The presence of basalt is clearly evident on the long shot line, with a reasonably good velocity determination of 18,400 feet/second and a depth varying between 250 and 300 feet. The in-line data show approximately 225 feet of high-velocity drift (7,500 feet/second), but the underlying material appears to have a velocity of only about 13,000 feet/second. We interpret this as a thin weathered layer on top of the basalt; an alternative interpretation would be to identify it as a thin (order of 50 feet) layer of Keweenawan sandstone. By this interpretation, depth to the top of the basalt would be slightly greater than shown on the above section.

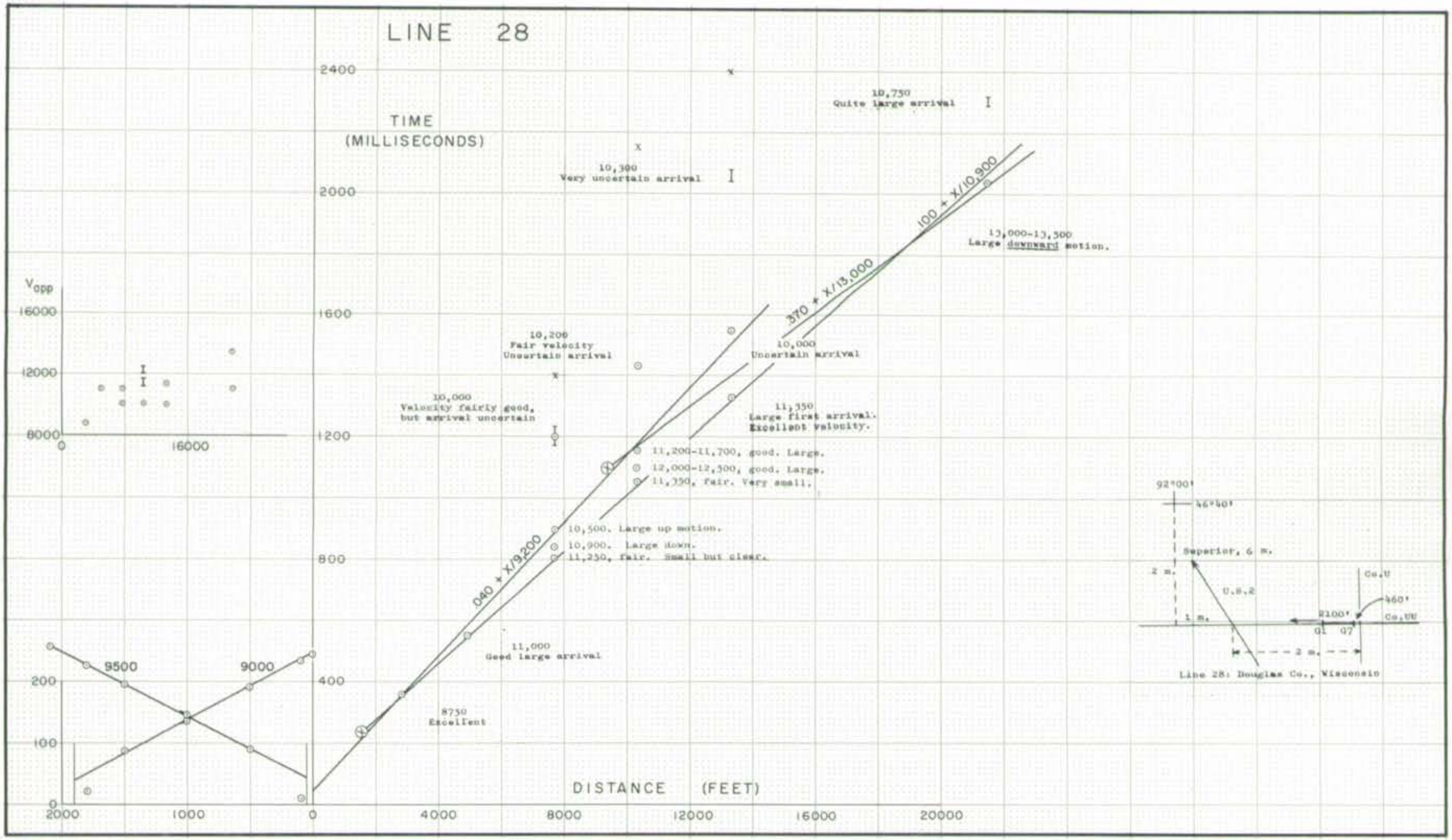

LINE 27
TIME
(MILLISECONDS)
200
100
19500
17400
(13400)
12400
.037 + X/16,200
18,600, good arrival, from a shot in opposite direction, 800' S of G10.
18,000, good. Large arrival.
17,000, fair. Clear arrival.
17,600, good. Clear arrival.
G10
G1
1000'
Co.24
11820'
Hinckley
16 m.
1½ m.
Minn.48
3/4 m.
46°00'
92°30'
DISTANCE (FEET)
1000
750
500
250
0
1000
2000
3000
Line 27: Pine Co., Minnesota



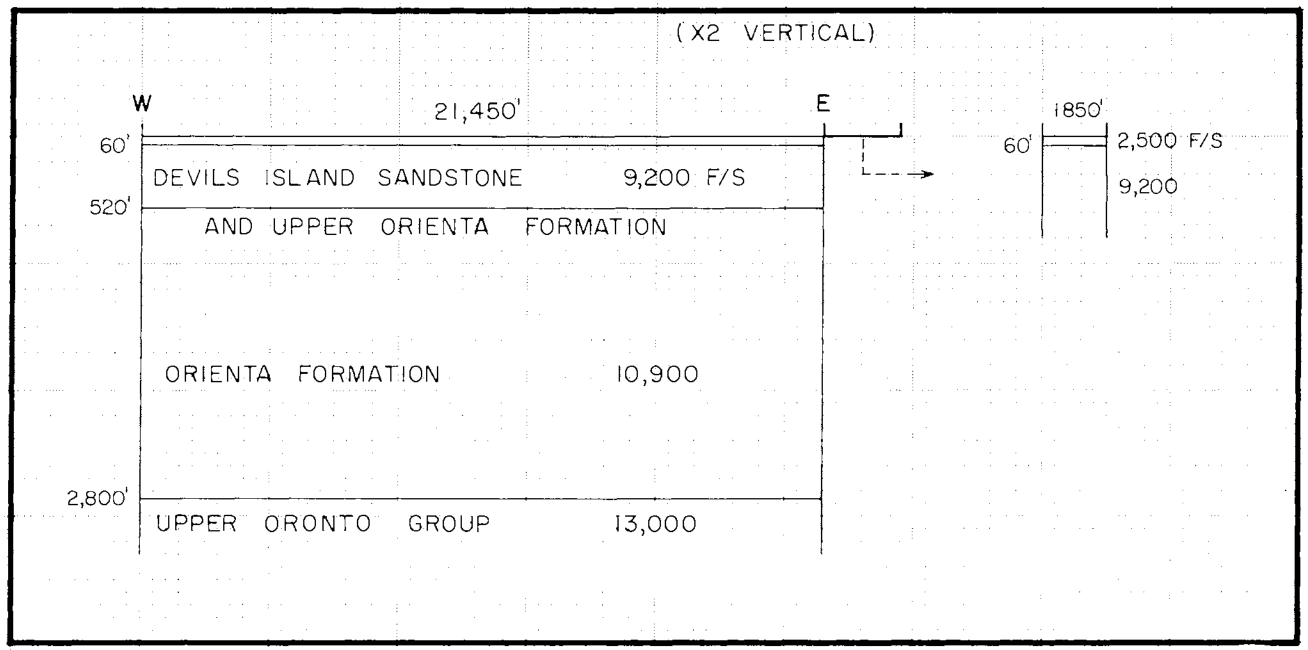
LINE 27

PURPOSE: See Line 25. Mean surface elevation is 1,000 feet.

RESULTS: The basement rock, presumably basalt, occurs at a depth of approximately 50 feet. It yields a velocity of about 17,000 feet/second. The in-line shots suggest the possibility of a very thin intermediate-velocity layer.



LINE 28
TIME
(MILLISECONDS)
2400
2000
1600
1200
800
400
10,750
Quite large arrival
10,300
Very uncertain arrival
100 + X/10,900
13,000-13,500
Large downward motion.
370 + X/13,000
10,200
Fair velocity
Uncertain arrival
10,000
Uncertain arrival
10,000
Velocity fairly good,
but arrival uncertain
11,350
Large first arrival.
Excellent velocity.
11,200-11,700, good. Large.
12,000-12,500, good. Large.
11,350, fair. Very small.
10,500. Large up motion.
10,900. Large down.
11,250, fair. Small but clear.
040 + X/9,200
11,000
Good large arrival
8730
Excellent
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
V app
16000
12000
8000
0
16000
9500
9000
200
100
0
2000
1000
0
92°00'
46°40'
Superior, 6 m.
2 m.
U.S.2
Co.U
460'
2100'
Co.UU
1 m.
Q1
Q7
2 m.
Line 28: Douglas Co., Wisconsin

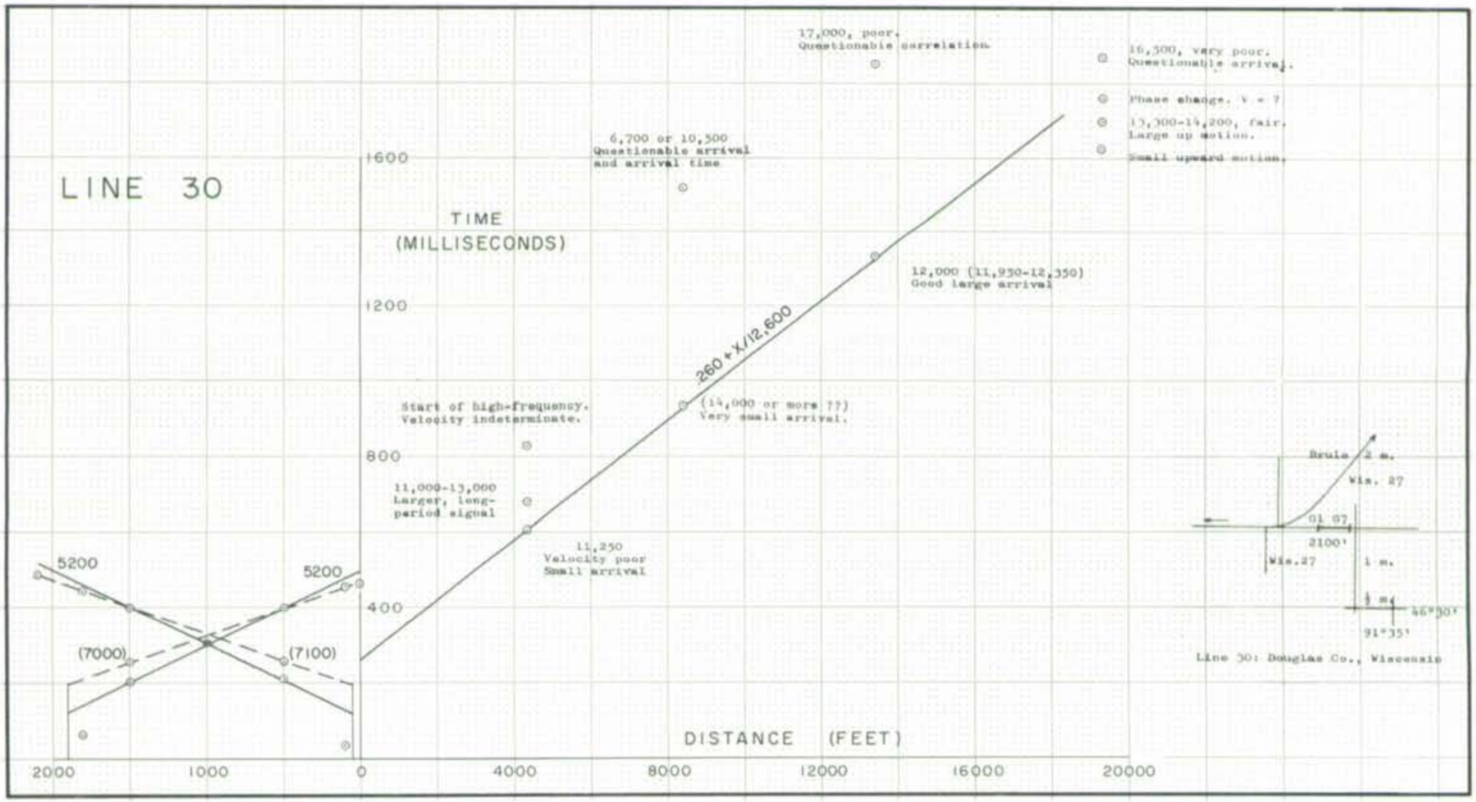


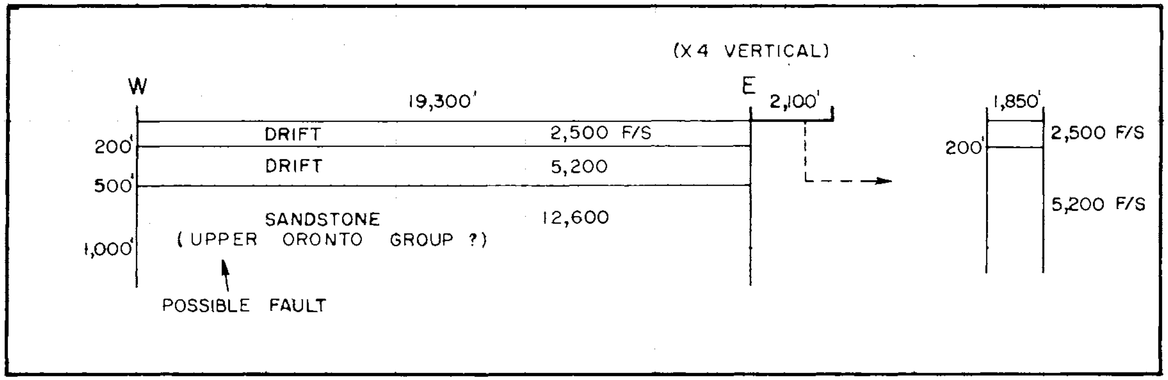
LINE 28

PURPOSE: Lines 15 and 28 lie one mile apart. They are located just north of the Douglas Fault about 15 miles southeast of Superior, Wisconsin, in what would appear to be a positive saddle in the gravity contours. Gravity values here are about 0 mg and become more negative to both east and west. Presumably this indicates shallowing of the igneous basement surface. Thwaites shows Orienta Formation (lower Bayfield) as the sub-drift material. Mean surface elevation is 750 feet.

RESULTS: Excellent reversed profiles show the presence of 9,000-9,500 feet/second material beneath the glacial drift to a depth of about 500 feet. This velocity is associated with Devil's Island Sandstone and/or the upper Orienta Sandstone, which we correlate with the Hinckley Sandstone of eastern Minnesota. Four seismic arrivals define well a 10,800 feet/second horizon, with confirmation from adjacent Lines 15 and 31. We identify this with the lower Orienta Formation. A third velocity segment of 13,000 feet/second is defined by a large seismic arrival from only a single shot point; presumably this is the 12,600 feet/second layer observed on the three lines to the east.

No arrivals were observed representing any higher velocities. A minimum depth to 17,000 feet/second material can be assigned using a minimum arrival time of 2.2 seconds on the most distant shot. This yields a value of 7,000 feet; the true depth may be any larger value. Such a conclusion is somewhat unexpected because the relatively positive gravity values suggest a thinner sedimentary section at this location. The seismic results suggest an alternative explanation for the gravity maximum, either the presence of thicker mafic volcanics or large gabbroic bodies under the sedimentary rocks, or the effect of high-density intrusives on the south side of the Douglas Fault.


LINE 30
TIME
(MILLISECONDS)
1600
1200
800
400
DISTANCE (FEET)
2000
1000
0
4000
8000
12000
16000
20000
5200
5200
(7000)
(7100)
260 + X/12,600
17,000, poor.
Questionable correlation.
16,500, very poor.
Questionable arrival.
Phase change. V = ?
13,300-14,200, fair.
Large up motion.
Small upward motion.
6,700 or 10,500
Questionable arrival
and arrival time
12,000 (11,930-12,350)
Good large arrival
Start of high-frequency.
Velocity indeterminate.
(14,000 or more ??)
Very small arrival.
11,000-13,000
Larger, long-
period signal
11,250
Velocity poor
Small arrival
Brule
2 m.
Wis. 27
01 07
2100'
Wis.27
1 m.
½ m.
46°30'
91°35'
Line 30: Douglas Co., Wisconsin



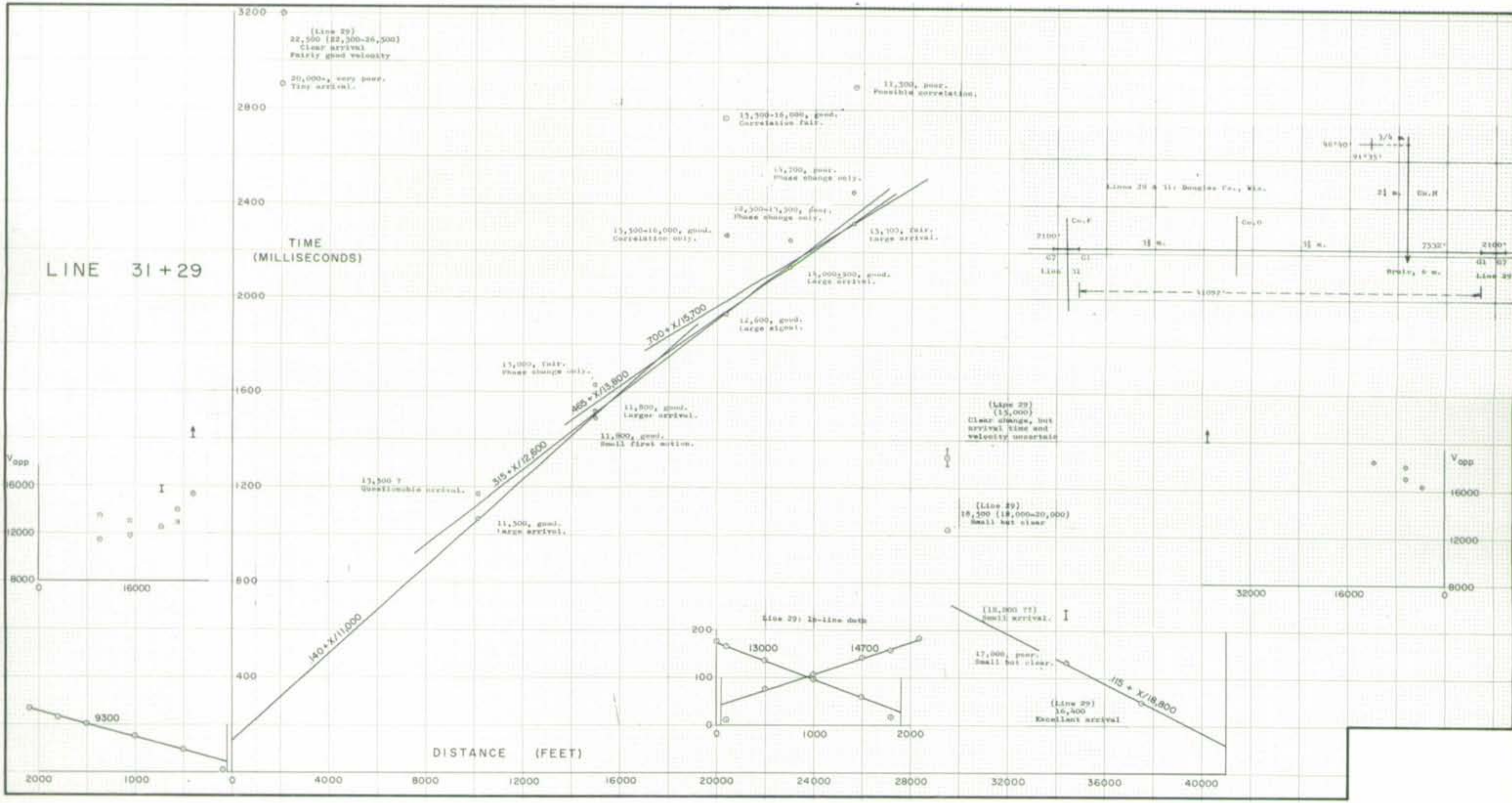
LINE 30

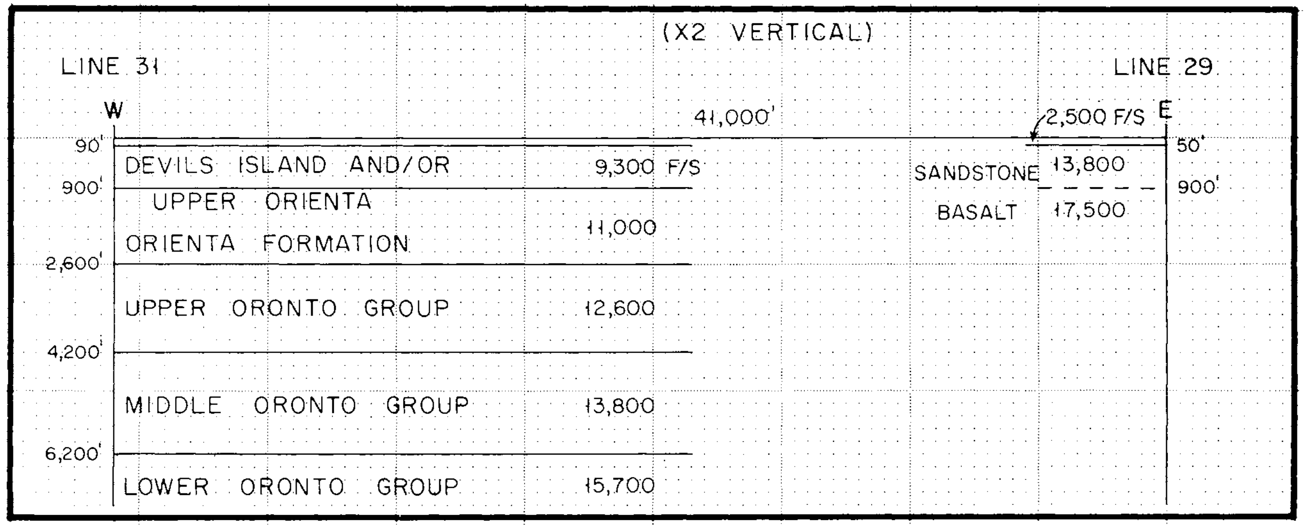
PURPOSE: Line 30 lies 6 miles WNW of Line 17 and similar comments apply. Mean surface elevation is 1,200 feet.

RESULTS: The in-line shots suggest differentiation within the glacial drift. The near-surface layer appears to extend to a depth of about 200 feet and to be underlain by 5,200 feet/second drift to about 500 feet.

Interpretation for the sedimentary column is not entirely satisfactory. The first three shots yield arrivals which fit nicely to a 12,600 feet/second line; north of the Douglas Fault, this velocity value would be identified with the Freda Sandstone (Upper Oronto Group). Spread velocities for the first two of the shots differ substantially from 12,600 feet/second, however. Further uncertainties exist in associating the arrivals from shots 1 and 2 with the same refractor as from shot 3: amplitudes are much smaller for shots 1 and 2, and for these shots (but not for shot 3) arrivals at the two most distant geophones appear to be delayed about 20 ms compared with the remaining five. The proposed interpretation must be considered subject to considerable uncertainty.

The most distant shot gives arrivals which appear to be 170 ms too early. No horizontally layered structure can accommodate the data, hence we infer the presence between shots 3 and 4 of one of the major faults known to exist in the area. The single 14,000 feet/second arrival at shot 4 would be consistent with material of this velocity at a depth of about 3,000 feet.


LINE 31 + 29
TIME
(MILLISECONDS)
DISTANCE (FEET)
140 + X/11,000
315 + X/12,600
465 + X/13,800
700 + X/15,700
115 + X/18,800
Line 29: In-line data
13000
14700
9300
Vapp
Lines 29 & 31: Douglas Co., Wis.
(Line 29)
22,500 (22,300-26,500)
Clear arrival
Fairly good velocity
20,000+, very poor.
Tiny arrival.
11,300, poor.
Possible correlation.
15,500-16,000, good.
Correlation fair.
13,300 ?
Questionable arrival.
11,300, good.
Large arrival.
11,800, good.
Larger arrival.
11,800, good.
Small first motion.
12,600, good.
Large signal.
15,000,300, good.
Large arrival.
(Line 29)
16,400
Excellant arrival
17,000, poor.
Small but clear.
(Line 29)
18,500 (18,000-20,000)
Small but clear
(Line 29)
(15,000)
Clear change, but
arrival time and
velocity uncertain



LINES 31 and 29

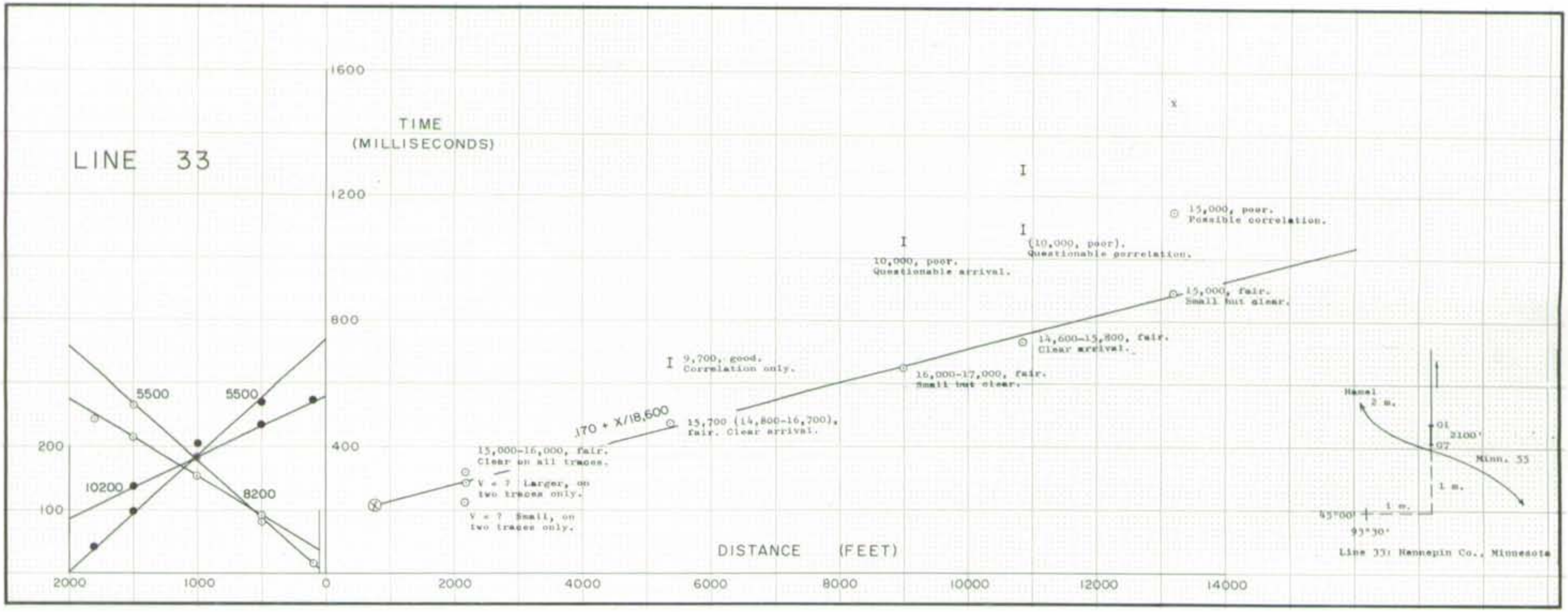
PURPOSE: These lines were intended to provide a long reversed profile just north of the Douglas Fault in Douglas County, Wisconsin. Thwaites shows Orienta Formation (Lower Bayfield) as the subdrift material at this location. Mean surface elevation is 900 feet.

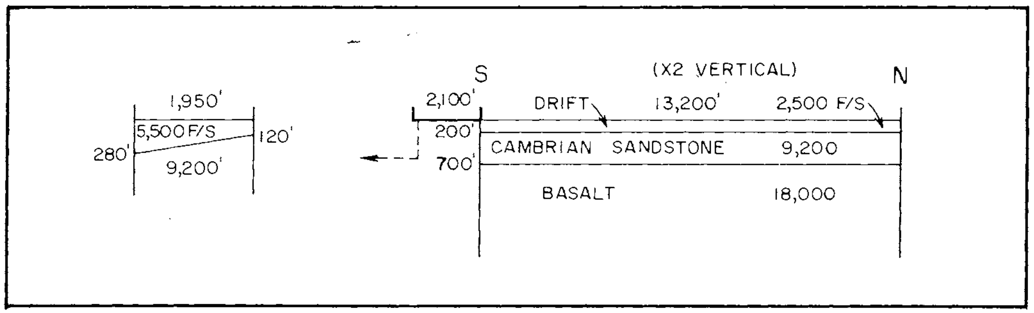
RESULTS: Data for Line 31 show that it lies well north of the Douglas Fault. Excellent but unreversed in-line readings show 9,300 feet/second material immediately beneath the drift, to a depth of about 900 feet. We identify this as Devil's Island Sandstone or upper Orienta Formation, with confirmation from Lines 15 and 28 to the west. The next deeper layer with velocity 11,000-11,500 feet/second is defined by only two points on Line 31, but again the data agree with Line 15 and 28 to the west and Line 14 to the east. This material is presumably the lower Orienta Formation (lower Bayfield Group).

Two deeper layers are recognized by arrivals from only a single shot each, so by itself the evidence would be weak. Each of the arrivals is large, however, the spread velocities are well-defined, and the same velocities are observed on both Lines 13 and 14 to the east. We therefore identify these as the two lower members of the Oronto Group.

Results for Line 29 are entirely different. They show basalt within about 1,000 feet of the seismic profile. By one interpretation, Line 29 lies south of the Douglas Fault, with the fault crossing the seismic line between shots 2 and 3. Since geophone 1 is 7,500 feet east of County Road H (and about ¼ mile south of Waino) and shots 2 and 3 are at distances of 6,700 and 11,600 feet, the fault is crossed on this east-west road somewhere within ¾ mile west of Waino. This would move the fault location about ½ mile north from the position given by Thwaites.

We prefer a second interpretation, however, which leaves the fault location essentially as given by Thwaites. In this, the refracted basalt arrival comes from the steeply-dipping fault surface whose trace runs essentially parallel to the seismic line. Line 29 then lies about 1,000 feet north of the fault.

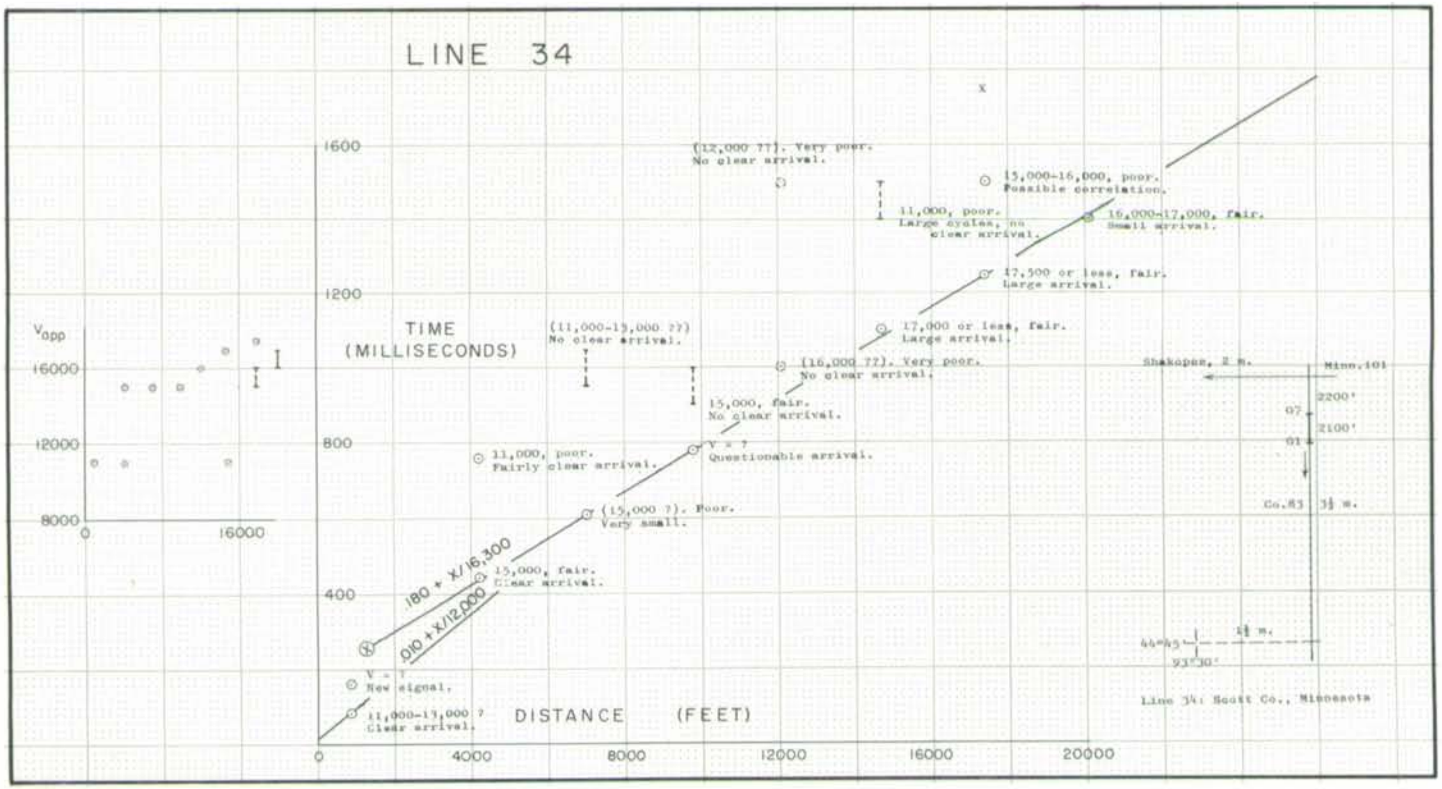

LINE 33
TIME
(MILLISECONDS)
1600
1200
800
400
200
100
5500
5500
10200
8200
170 + X/18,600
15,000-16,000, fair.
Clear on all traces.
V = ? Larger, on
two traces only.
V = ? Small, on
two traces only.
15,700 (14,800-16,700),
fair. Clear arrival.
9,700, good.
Correlation only.
16,000-17,000, fair.
Small but clear.
10,000, poor.
Questionable arrival.
14,600-15,800, fair.
Clear arrival.
(10,000, poor).
Questionable correlation.
15,000, fair.
Small but clear.
15,000, poor.
Possible correlation.
DISTANCE (FEET)
2000
1000
0
2000
4000
6000
8000
10000
12000
14000
Hamel
2 m.
01
2100'
07
Minn. 55
1 m.
1 m.
45°00'
93°30'
Line 33: Hennepin Co., Minnesota



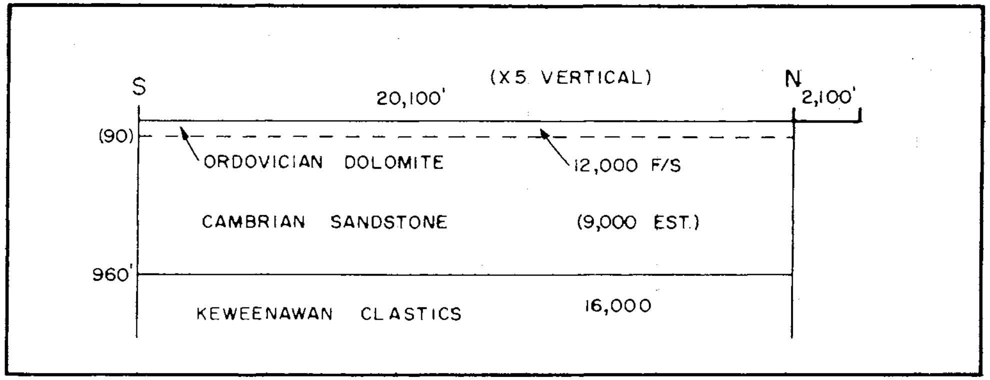
LINE 33

PURPOSE: The line lies west of the Twin Cities Basin and east of the Douglas Fault, in an area where the magnetic results indicate shallow basalt. A well 5 miles east encountered 300 feet of drift, 400 feet of Cambrian sandstone, then basalt. Mean surface elevation is 880 feet.

RESULTS: The in-line shots show about 200 feet of 5,500 feet/second drift overlying the 9,000 feet/second Cambrian sandstone surface dipping gently southward. The main line of shots shows a somewhat irregular basalt surface at a depth of about 700 feet. We interpret the low across-spread velocities as originating in local dip at the spread position, consistent with the in-line data.



LINE 34
TIME
(MILLISECONDS)
DISTANCE (FEET)
V_{app}
16000
12000
8000
0
16000
1600
1200
800
400
0
4000
8000
12000
16000
20000
180 + X/16,300
010 + X/12,000
11,000-13,000 ? Clear arrival.
V = ? New signal.
15,000, fair. Clear arrival.
11,000, poor. Fairly clear arrival.
(15,000 ?). Poor. Very small.
V = ? Questionable arrival.
(11,000-13,000 ??) No clear arrival.
15,000, fair. No clear arrival.
(16,000 ??). Very poor. No clear arrival.
(12,000 ??). Very poor. No clear arrival.
17,000 or less, fair. Large arrival.
17,500 or less, fair. Large arrival.
11,000, poor. Large cycles, no clear arrival.
15,000-16,000, poor. Possible correlation.
16,000-17,000, fair. Small arrival.
Shakopee, 2 m.
Minn.101
2200'
2100'
Co.83 3½ m.
93°30'
Line 34: Scott Co., Minnesota

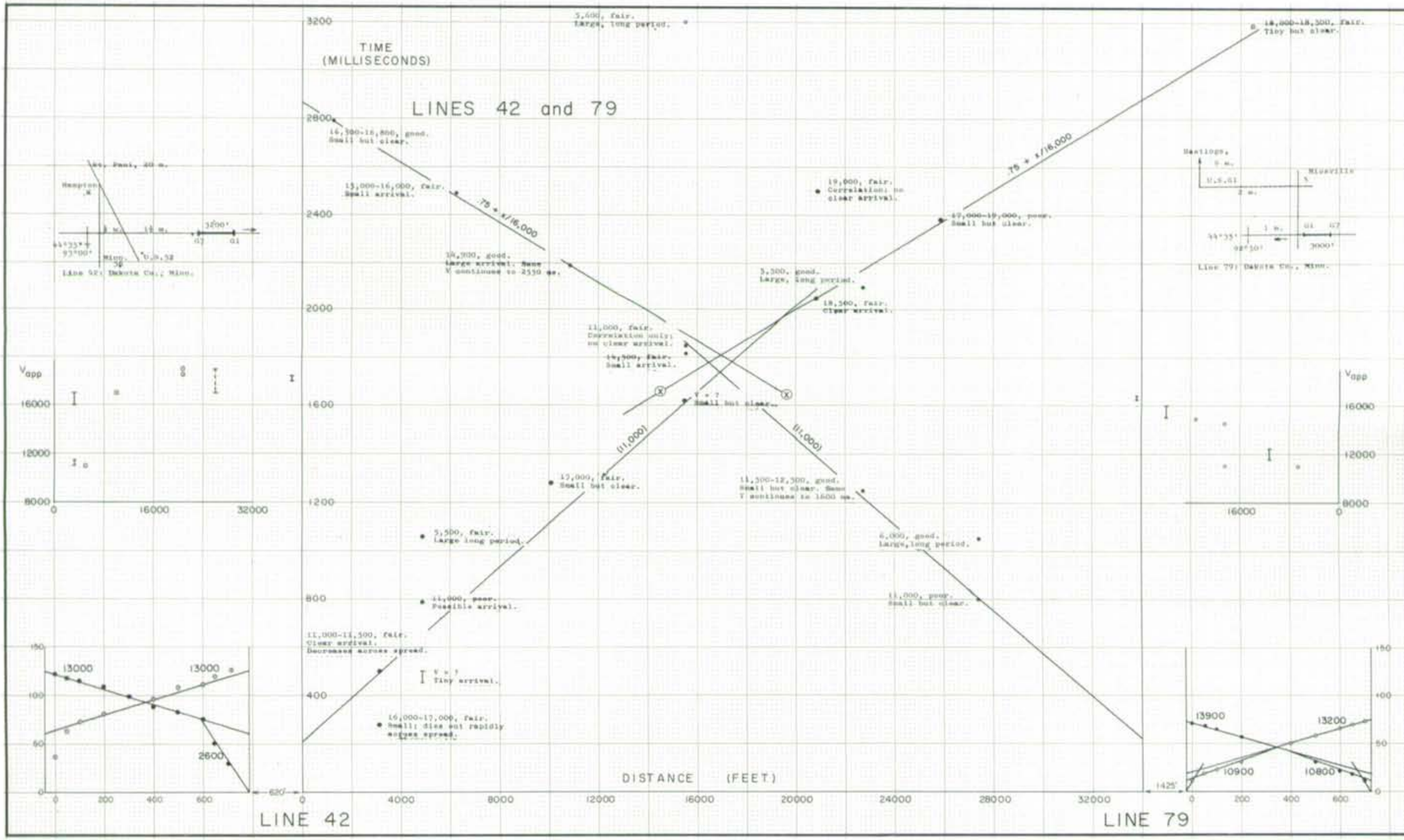


LINE 34

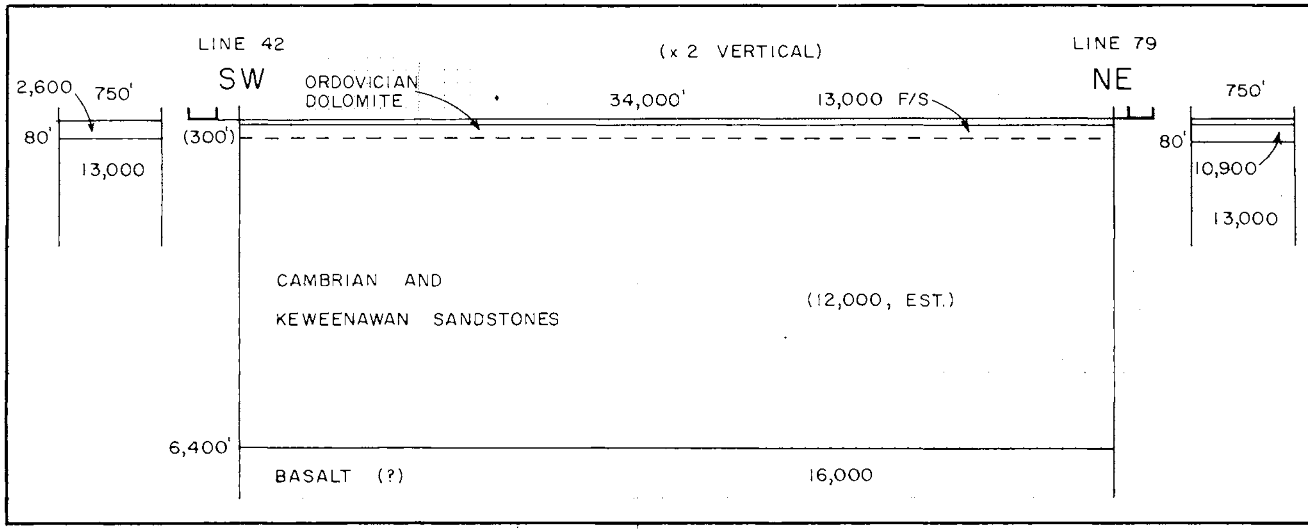
PURPOSE: Line 34 is located near the center of the Twin Cities basin. A well 5 miles to the west encountered Ordovician dolomite to a depth of 92 feet, Cambrian sandstones to 708 feet, and bottomed at 713 feet in Keweenawan Red Clastics. The dolomite also crops out along this line. Mean surface elevation is 800 feet.

RESULTS: The dolomite velocity is poorly determined but is estimated at about 12,000 feet/second. Rapid attenuation of dolomite arrival confirms that the layer is thin; we have assumed a 90-foot thickness on the basis of the nearby well, together with a velocity of 9,000 feet/second for the underlying sandstone.

We have drawn a single line through the seven seismic arrivals along the main shot line. This yields a depth of 960 feet (1,100 feet if 10,000 feet/second is used for the sandstone) to Red Clastics with a velocity of about 16,000 feet/second. No basalt arrival is observed, suggesting a minimum depth of several thousand feet.



LINES 42 and 79
TIME (MILLISECONDS)
DISTANCE (FEET)
LINE 42
LINE 79
5,600, fair. Large, long period.
16,300-16,800, good. Small but clear.
15,000-16,000, fair. Small arrival.
.75 + x/16,000
18,900, good. Large arrival. Same V continues to 2530 ms.
11,000, fair. Correlation only; no clear arrival.
14,500, fair. Small arrival.
V = ? Small but clear.
(11,000)
13,000, fair. Small but clear.
5,500, fair. Large long period.
11,000, poor. Possible arrival.
11,000-11,500, fair. Clear arrival. Decreases across spread.
V = ? Tiny arrival.
16,000-17,000, fair. Small; dies out rapidly across spread.
19,000, fair. Correlation: no clear arrival.
17,000-19,000, poor. Small but clear.
5,300, good. Large, long period.
18,500, fair. Clear arrival.
11,300-12,300, good. Small but clear. Same V continues to 1600 ms.
6,000, good. Large, long period.
11,000, poor. Small but clear.
18,000-18,300, fair. Tiny but clear.
Line 42: Dakota Co., Minn.
Line 79: Dakota Co., Minn.
Hastings
Miesville
V_{app}
13000
2600
13900
13200
10900
10800
620'
1425'

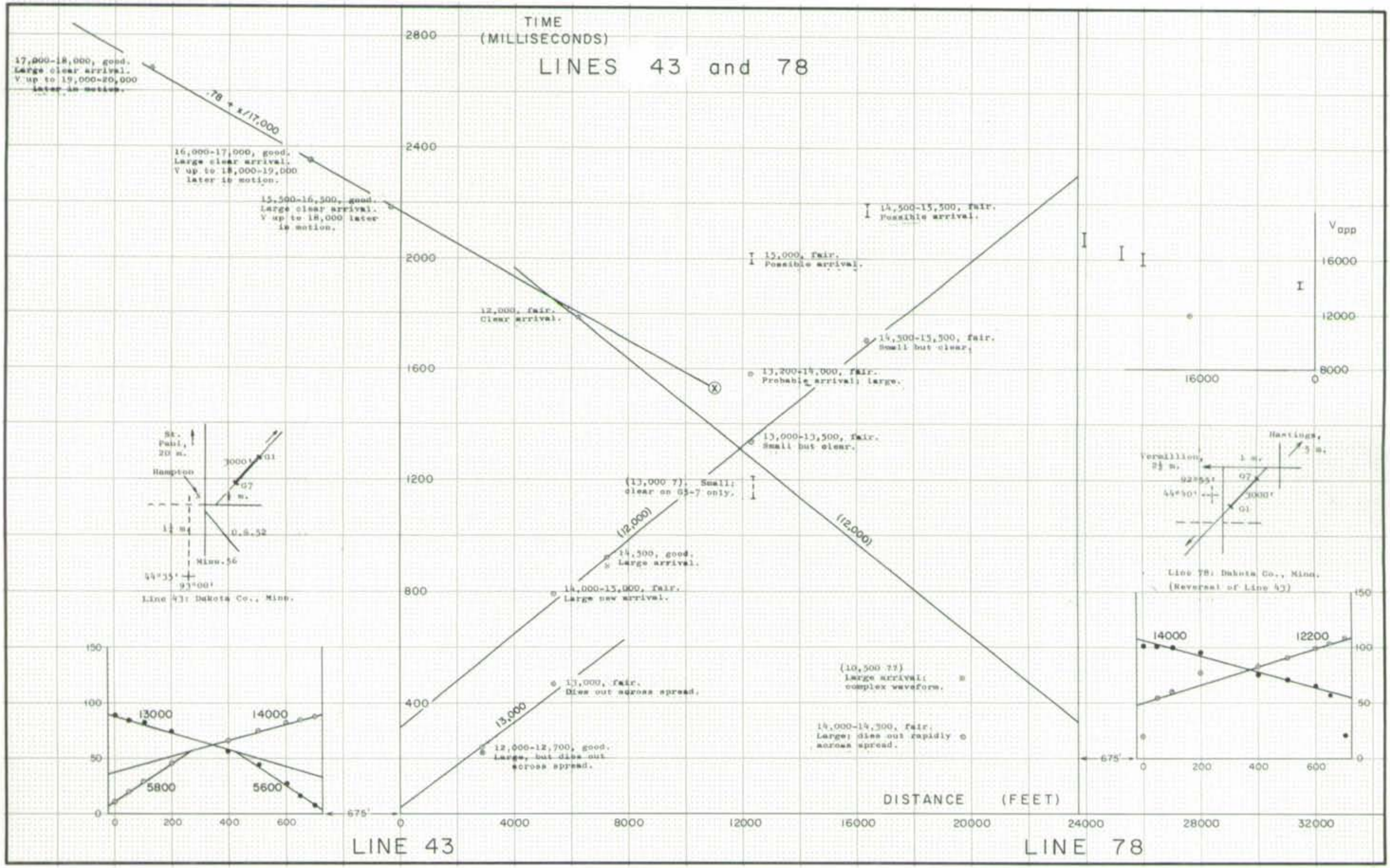


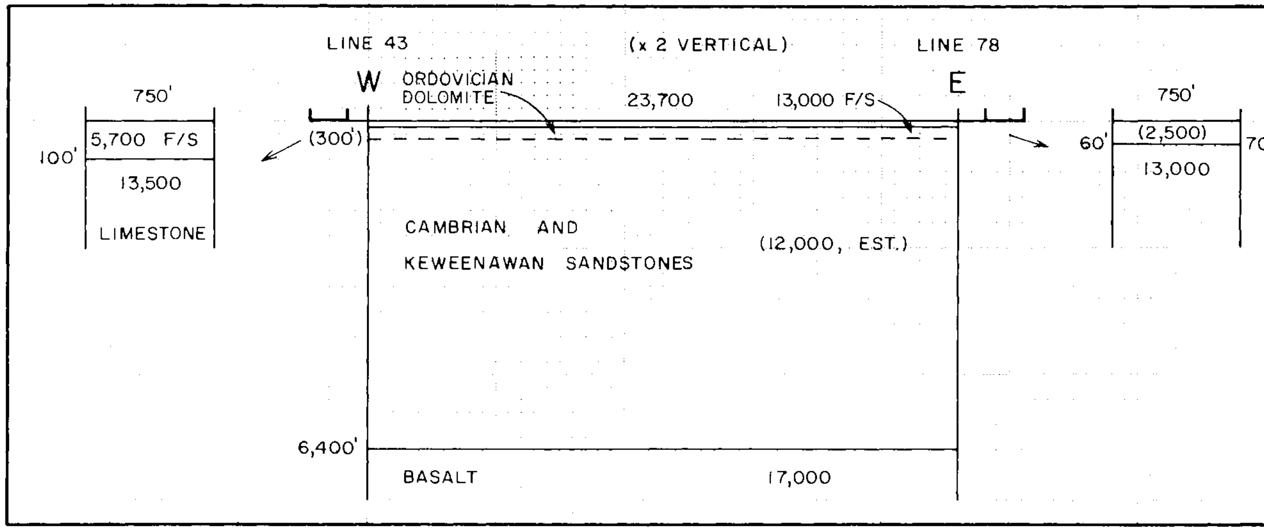
LINES 42 and 79

PURPOSE: Lines 42-79 and 43-78 constitute a pair of reversed profiles located just southeast of the Hastings Fault. They are intended to provide structure within the eastern flanking basin of the St. Croix Horst. Lines 42-79 run east-west and Lines 43-78 run northeast-southwest. Mean surface elevation is 1,000 feet.

RESULTS: In-line data for both Lines 42 and 79 show 13,000-13,500 feet/second dolomite underlying 80 feet of glacial drift. Line 79 appears also to have a thin cap layer of sandstone. The presence of underlying lower-velocity Cambrian sandstones is shown by offset of the travel time graph. Subsequent arrivals suggest 11,000 feet/second as an appropriate velocity for these sandstones, but we have used 12,000 on the basis of adjacent lines.

For Line 42, a sequence of 18,000-19,000 feet/second arrivals fit well to a line, but the line has a slope of 15,600 feet/second. For Line 79, the three most distant shots can be fitted by velocity lines in the range 15,200 to 16,600 feet/second. We have adopted 16,000 feet/second for both; computed depth is 6,400 feet. We tentatively identify the material as basalt, partly on the basis of 17,000 feet/second basalt on adjacent Lines 43 and 78, but we cannot exclude the possibility that it may be sedimentary rock.


TIME
(MILLISECONDS)
LINES 43 and 78
17,000-18,000, good.
Large clear arrival.
V up to 19,000-20,000
later in motion.
.78 + x/17,000
16,000-17,000, good.
Large clear arrival.
V up to 18,000-19,000
later in motion.
15,500-16,500, good.
Large clear arrival.
V up to 18,000 later
in motion.
14,500-15,500, fair.
Possible arrival.
15,000, fair.
Possible arrival.
12,000, fair.
Clear arrival.
14,500-15,500, fair.
Small but clear.
13,200-14,000, fair.
Probable arrival; large.
13,000-13,500, fair.
Small but clear.
(13,000 ?). Small;
clear on G3-7 only.
(12,000)
(12,000)
14,500, good.
Large arrival.
14,000-15,000, fair.
Large new arrival.
13,000, fair.
Dies out across spread.
13,000
12,000-12,700, good.
Large, but dies out
across spread.
(10,500 ??)
Large arrival;
complex waveform.
14,000-14,500, fair.
Large; dies out rapidly
across spread.
St.
Paul,
20 m.
Hampton
3000'
G1
G7
1½ m.
0.S.52
Minn.56
44°35'
93°00'
Line 43: Dakota Co., Minn.
13000
14000
5800
5600
675'
Vapp
16000
12000
8000
16000
0
Hastings,
3 m.
Vermillion,
2½ m.
1 m.
92°55'
44°30'
G7
3000'
G1
Line 78: Dakota Co., Minn.
(Reversal of Line 43)
14000
12200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
150
100
50
0
200
400
600
DISTANCE (FEET)
LINE 43
LINE 78



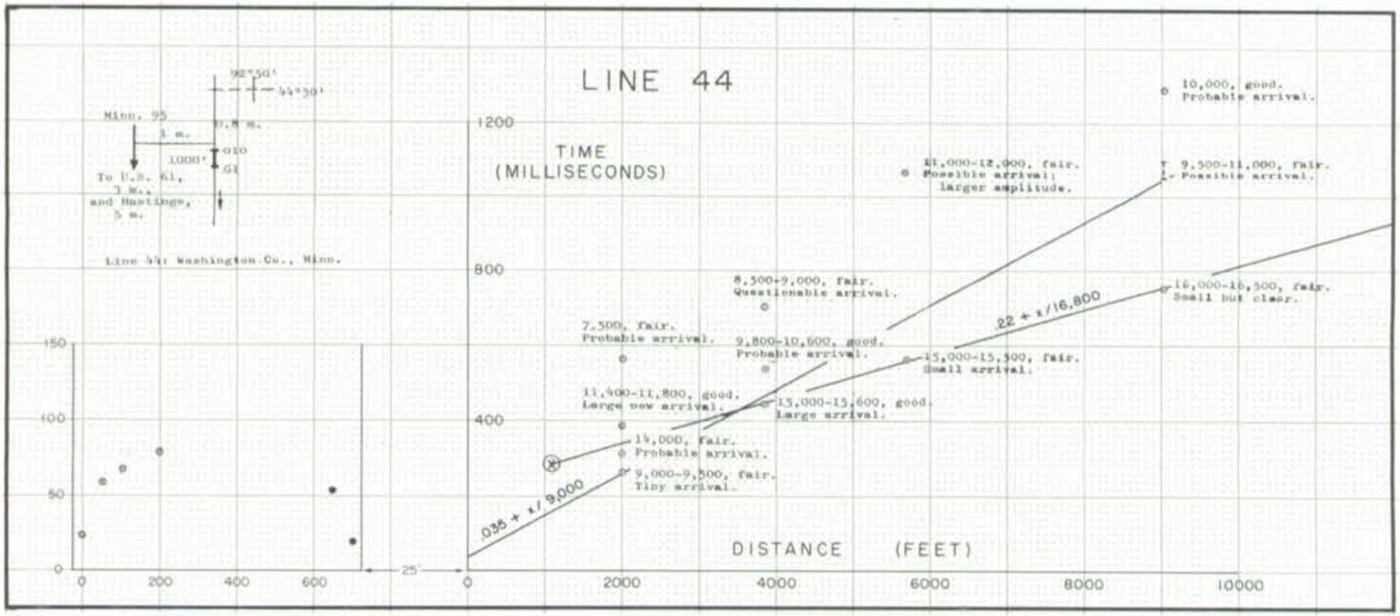
LINES 43 and 78

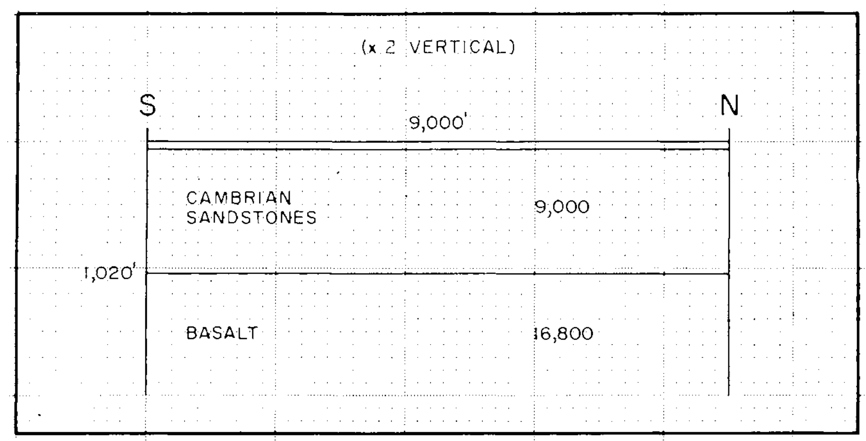
PURPOSE: See Line 42. Mean surface elevation is 1,000 feet.

RESULTS: Confirming similar results from Lines 42 and 79, the in-line data show Shakopee Dolomite with velocity 13,000-13,500 feet/second underlying 60-100 feet of glacial drift. The velocity inversion produced by the Cambrian sandstones is clearly shown by offset of the seismic travel times.

The next sequence of arrivals shows spread velocities up to 14,000-15,000 feet/second, but the data fit 12,000 feet/second seismic lines. We have therefore taken this velocity for the Cambrian and Upper Keweenawan sandstones.

On Line 78, three good arrivals fit well to a 17,000 feet/second line segment. From the well-defined velocity value, we identify the material as basalt at a depth of 6,400 feet.


LINE 44
TIME
(MILLISECONDS)
DISTANCE (FEET)
Line 44: Washington Co., Minn.
Minn. 95
To U.S. 61,
3 m.,
and Hastings,
5 m.
1000'
10,000, good.
Probable arrival.
11,000-12,000, fair.
Possible arrival;
larger amplitude.
9,500-11,000, fair.
Possible arrival.
8,500-9,000, fair.
Questionable arrival.
16,000-16,500, fair.
Small but clear.
22 + x/16,800
7,500, fair.
Probable arrival.
9,800-10,600, good.
Probable arrival.
15,000-15,500, fair.
Small arrival.
11,400-11,800, good.
Large new arrival.
13,000-13,600, good.
Large arrival.
14,000, fair.
Probable arrival.
9,000-9,500, fair.
Tiny arrival.
.035 + x/9,000
25'
1200
800
400
150
100
50
0
200
400
600
2000
4000
6000
8000
10000

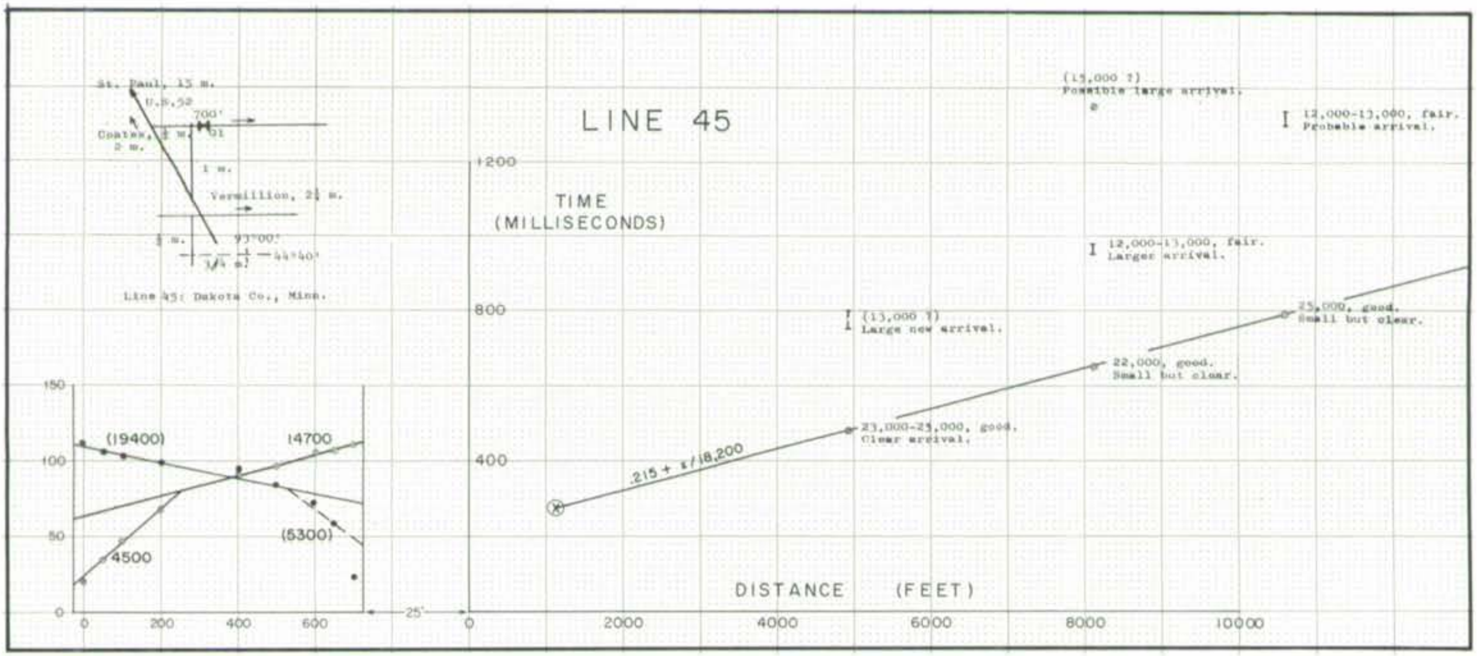


LINE 44

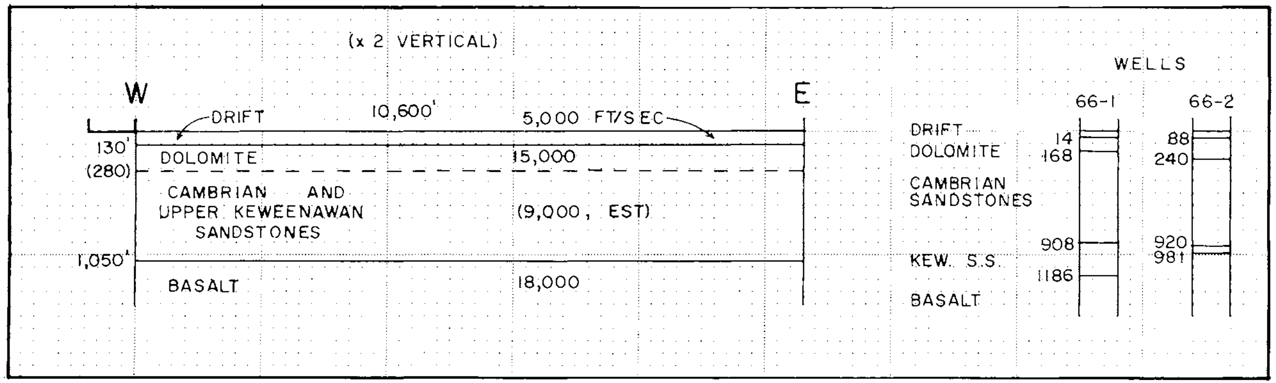
PURPOSE: Lines 44 and 45 are taken over the St. Croix Horst near the southeast margin. Line 44 is 10 miles northeast of Line 45, along the strike of the structure as evidenced by magnetic lineations. For drill hole information, see Line 45. No drill hole data are available near Line 44, but magnetic data suggest shallow basalt at both locations. Mean surface elevation is 960 feet.

RESULTS: The basalt arrival is well-defined, with velocity 16,800 feet/second and depth of about 1,000 feet. Spread velocities are slightly lower, suggesting a localized dip at the geophone spread.

A velocity of 9,000 feet/second for the overlying Cambrian sandstones is taken on the basis of one first arrival.



LINE 45
TIME
(MILLISECONDS)
DISTANCE (FEET)
1200
800
400
0
2000
4000
6000
8000
10000
.215 + x/18,200
(15,000 ?)
Possible large arrival.
12,000-13,000, fair.
Probable arrival.
12,000-13,000, fair.
Larger arrival.
(13,000 ?)
Large new arrival.
25,000, good.
Small but clear.
22,000, good.
Small but clear.
23,000-25,000, good.
Clear arrival.
St. Paul, 15 m.
U.S.52
700'
Coates, 2 m.
1 m.
Vermillion, 2½ m.
93°00'
44°40'
3/4 m.
Line 45: Dakota Co., Minn.
150
100
50
0
200
400
600
-25'
(19400)
14700
4500
(5300)

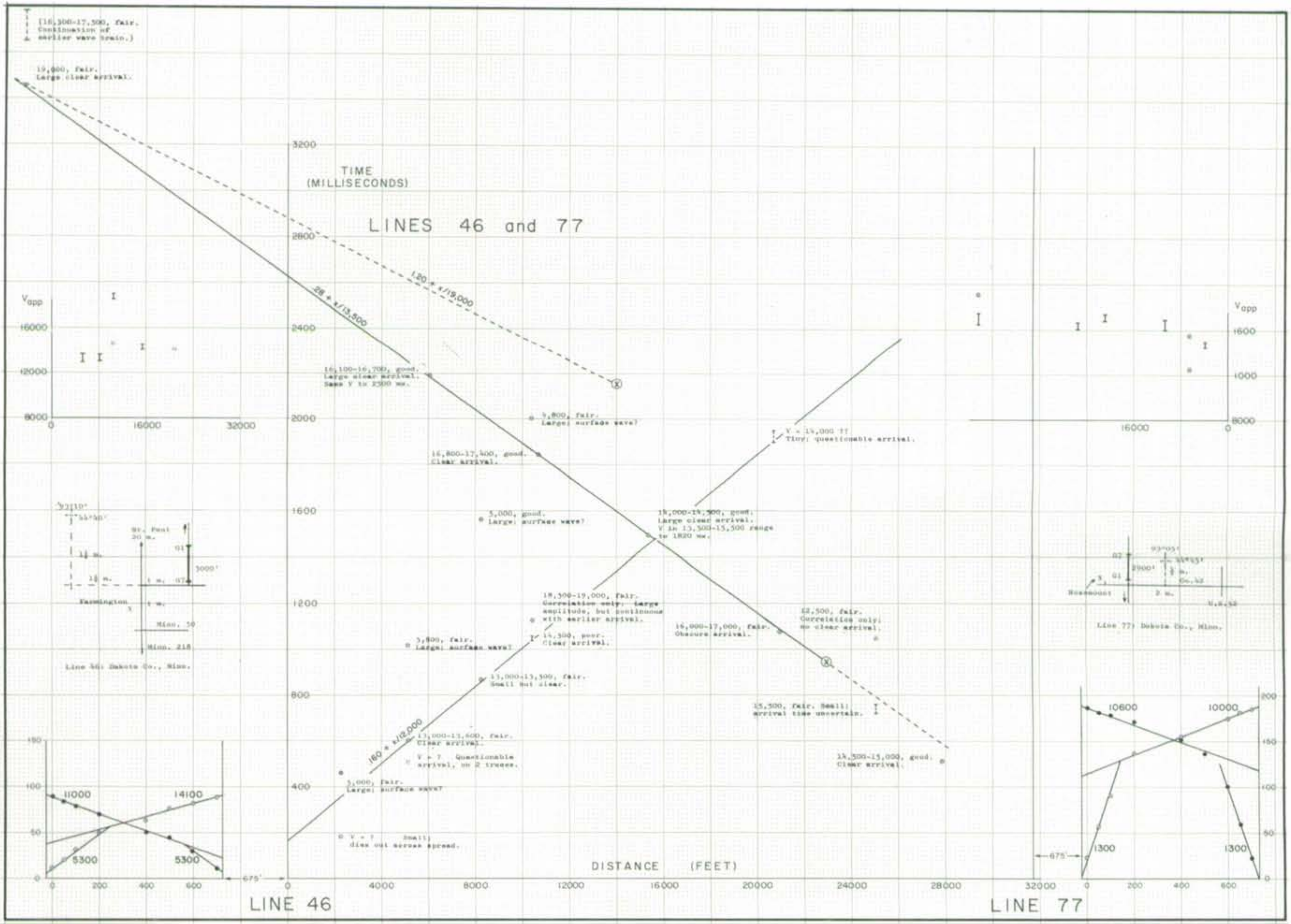


LINE 45

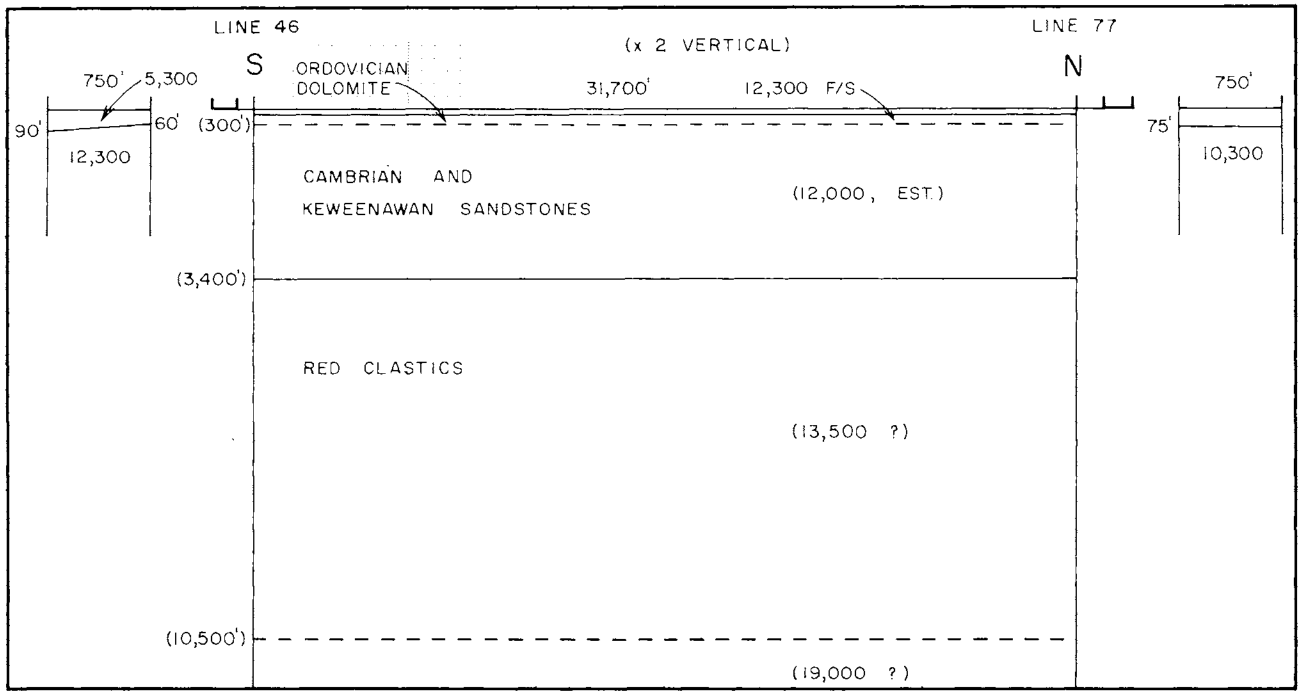
PURPOSE: See Line 44. Two drill holes are available for control, as shown on the section. Well 66-1 is located 1 mile south of shot 1, and well 66-2 is ½ mile west of the geophone spread. Mean surface elevation is 960 feet.

RESULTS: The in-line data show about 100 feet of glacial drift overlying 15,000 feet/second dolomite. We have assumed 150 feet thickness for the dolomite on the basis of the well logs. A velocity of 9,000 feet/second for the Cambrian sandstones is taken from Line 44.

The seismic arrival from the igneous basement at a depth of 1,050 feet is defined by excellent data. This depth agrees satisfactorily with the drill data. Velocity is taken at 18,000 feet/second on the basis of the along-line data. The spread velocities are 22,000 feet/second and higher; we interpret this as local dip downward to the east beneath the geophone spread because (a) the in-line data show the same dip, and (b) such high velocity values would be incompatible with basalt velocities found on other lines nearby.



LINES 46 and 77
TIME (MILLISECONDS)
DISTANCE (FEET)
LINE 46
LINE 77
(16,300-17,300, fair. Continuation of earlier wave train.)
19,000, fair. Large clear arrival.
120 + x/19,000
28 + x/13,500
160 + x/12,000
16,100-16,700, good. Large clear arrival. Same V to 2300 ms.
3,800, fair. Large; surface wave?
16,800-17,400, good. Clear arrival.
V = 14,000 ?? Tiny; questionable arrival.
5,000, good. Large; surface wave?
14,000-14,500, good. Large clear arrival. V in 13,500-15,500 range to 1820 ms.
18,500-19,000, fair. Correlation only; large amplitude, but continuous with earlier arrival.
3,800, fair. Large; surface wave?
14,500, poor. Clear arrival.
16,000-17,000, fair. Obscure arrival.
12,500, fair. Correlation only; no clear arrival.
13,000-13,500, fair. Small but clear.
15,500, fair. Small; arrival time uncertain.
13,000-13,600, fair. Clear arrival.
V = ? Questionable arrival, on 2 traces.
14,500-15,000, good. Clear arrival.
5,000, fair. Large; surface wave?
V = ? Small; dies out across spread.
Vapp
Line 46: Dakota Co., Minn.
Line 77: Dakota Co., Minn.
11000
14100
5300
5300
10600
10000
1300
1300
675'



LINES 46 and 77

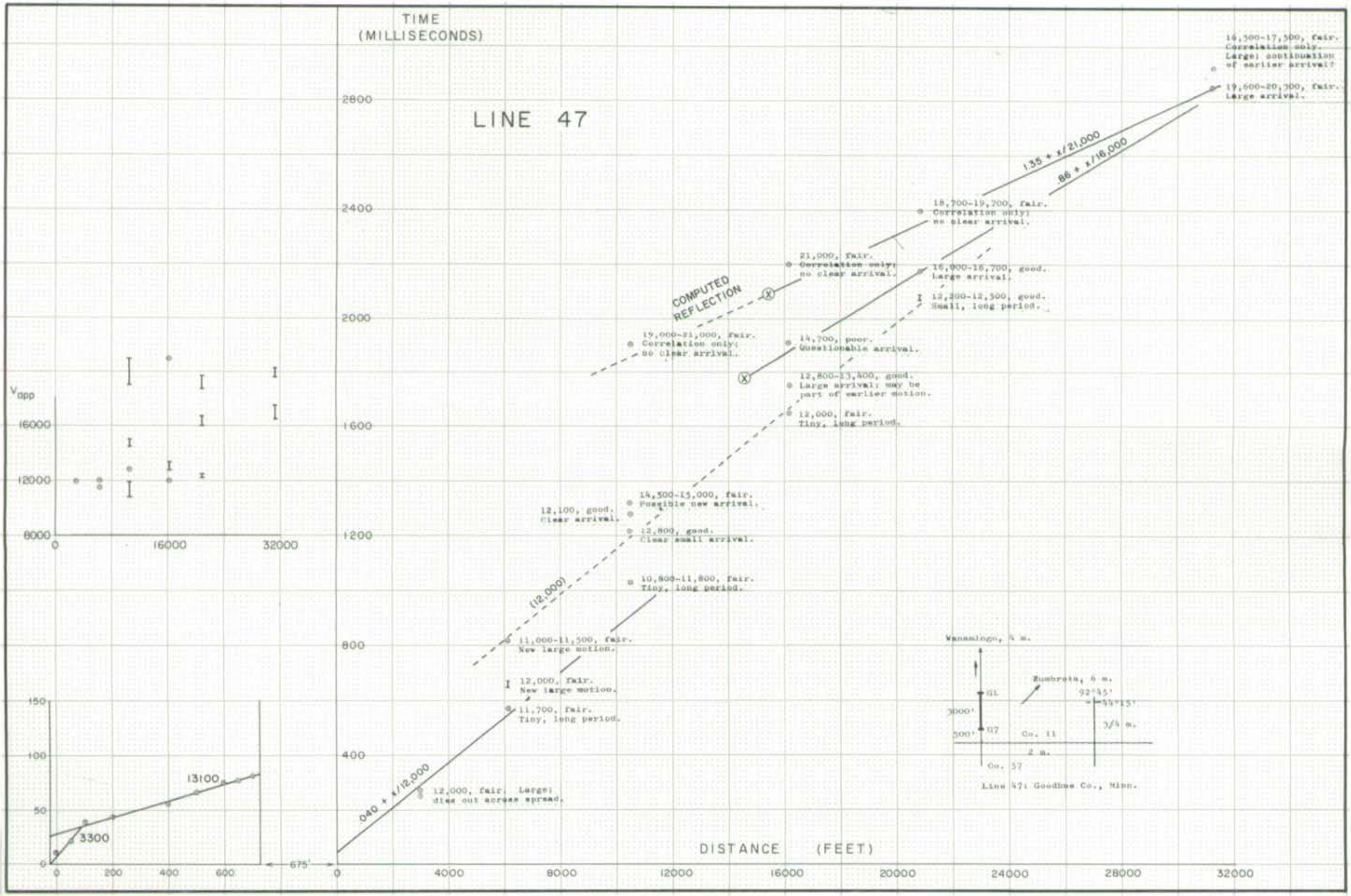
PURPOSE: These lines extend from Farmington to Rosemount, Minnesota, within the St. Croix Horst and just southwest of the down-faulted termination of the shallow basalt.

Magnetic data show that the basalt, if present at all, must be several thousand feet deep. Northeast of the fault, Lines 44 and 45 plus several drill holes show basalt to be present at 800-1,000 feet depth. Mean surface elevation is 920 feet.

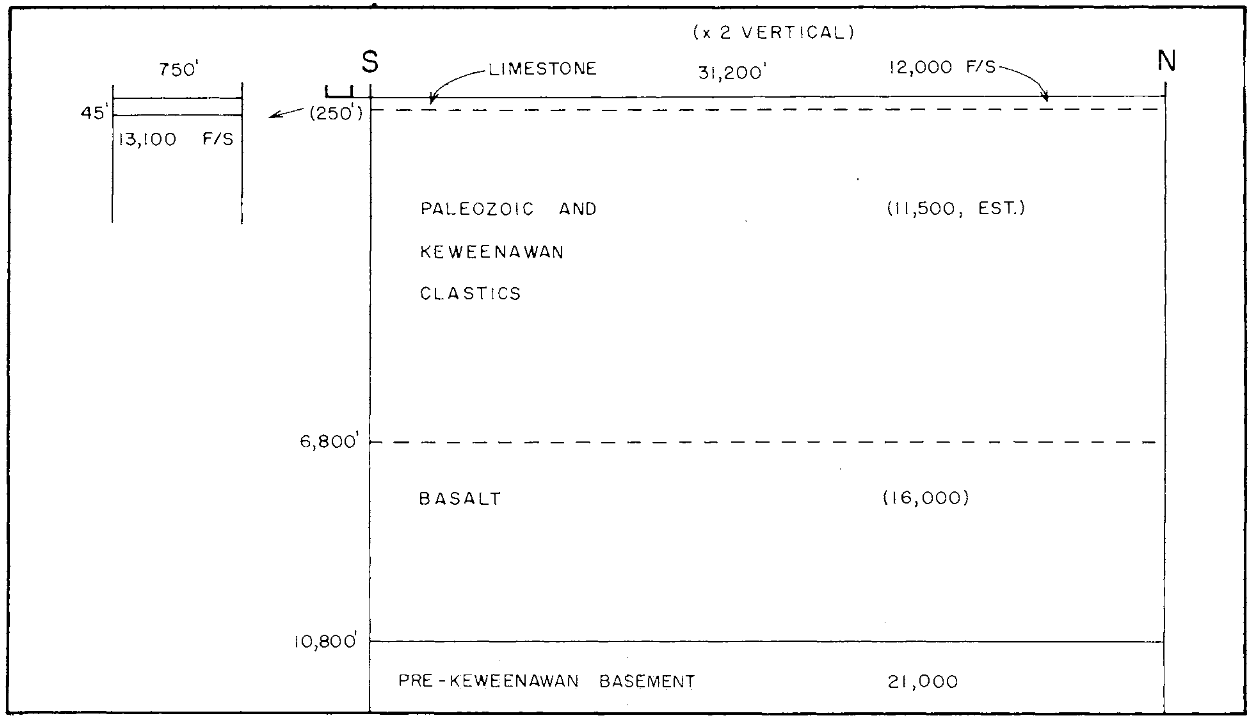
RESULTS: In-line data show 75-100 feet of glacial drift. The subdrift material at Line 46 shows velocity of 12,300 feet/second which is presumably Ordovician dolomite. Subdrift material at Line 77 has lower velocity and may be a cap layer of St. Peter Sandstone.

We are unable to arrive at a satisfactory interpretation for the remaining data. On Line 46, five 13,000-14,000 feet/second arrivals fit well to a 12,000 feet/second line. On Line 77, three 16,000-17,000 feet/second arrivals fit well to a 13,500 feet/second line. Thus the spread velocities do not agree with the line velocities; furthermore, the two lines fail by 200 ms to satisfy reciprocity requirements. A single arrival on Line 77 shows 19,000 feet/second spread velocity; this would be characteristic of intrusive igneous basement, but the point falls on the 13,500 feet/second line hence may not represent a new arrival.

The above structure section is based upon Line 77 data, but it must be regarded as tentative.



LINE 47
TIME
(MILLISECONDS)
DISTANCE (FEET)
16,500-17,500, fair. Correlation only. Large; continuation of earlier arrival?
19,600-20,300, fair. Large arrival.
1.35 + x/21,000
.86 + x/16,000
18,700-19,700, fair. Correlation only; no clear arrival.
21,000, fair. Correlation only; no clear arrival.
16,000-16,700, good. Large arrival.
12,200-12,500, good. Small, long period.
COMPUTED REFLECTION
19,000-21,000, fair. Correlation only; no clear arrival.
14,700, poor. Questionable arrival.
12,800-13,400, good. Large arrival; may be part of earlier motion.
12,000, fair. Tiny, long period.
14,500-15,000, fair. Possible new arrival.
12,100, good. Clear arrival.
12,800, good. Clear small arrival.
10,800-11,800, fair. Tiny, long period.
(12,000)
11,000-11,500, fair. New large motion.
12,000, fair. New large motion.
11,700, fair. Tiny, long period.
.040 + x/12,000
12,000, fair. Large; dies out across spread.
Vapp
13100
3300
675'
Wanamingo, 4 m.
Zumbrota, 6 m.
92°45'
44°15'
3000'
500'
GL
U7
Co. 11
2 m.
3/4 m.
Co. 57
Line 47: Goodhue Co., Minn.



LINE 47

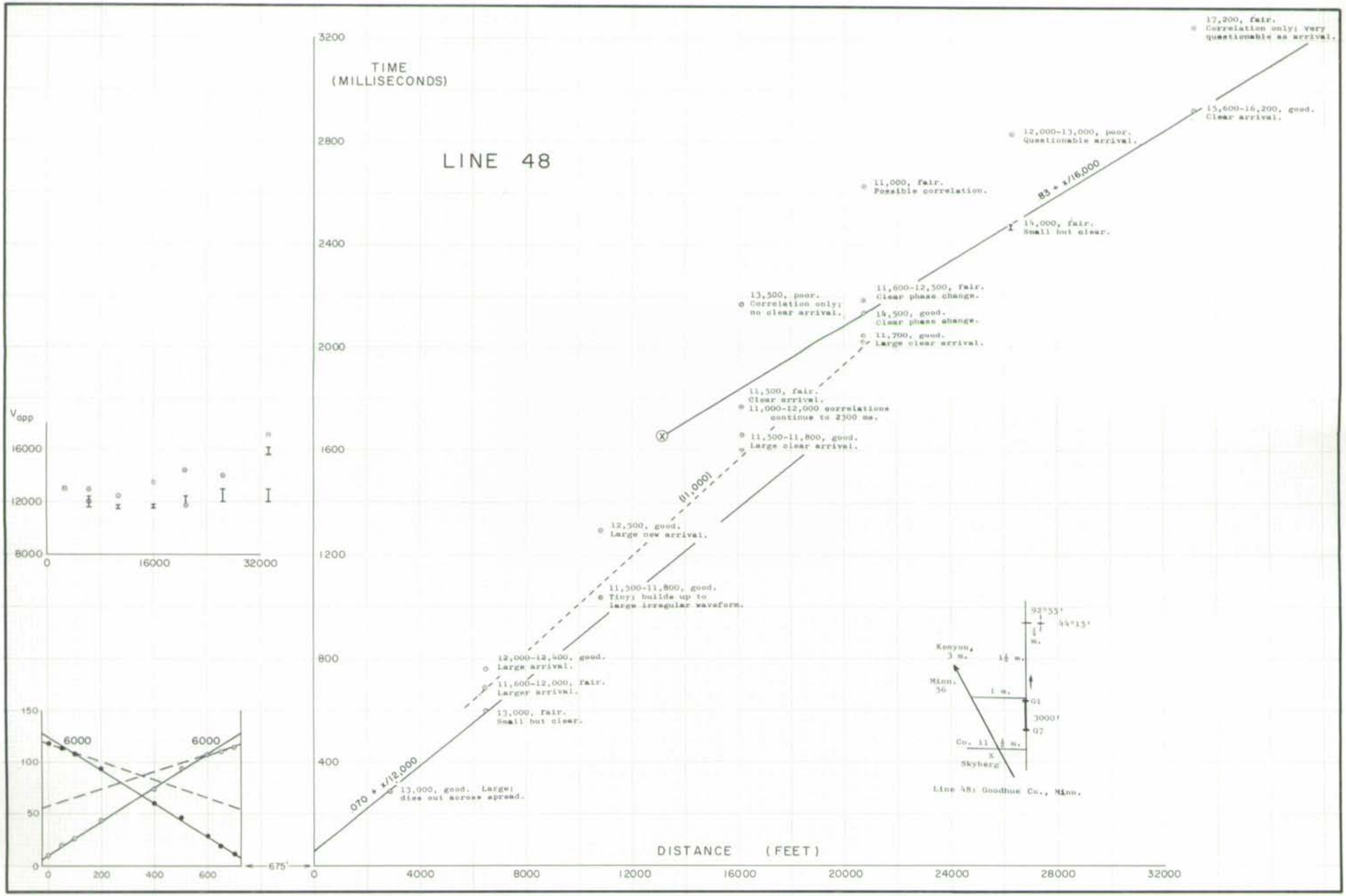
PURPOSE: Lines 47-54 and 74 are intended to supply an east-west structure section across the Midcontinent Gravity High at latitude 44°15′ north. Mean surface elevation is 1,200 feet.

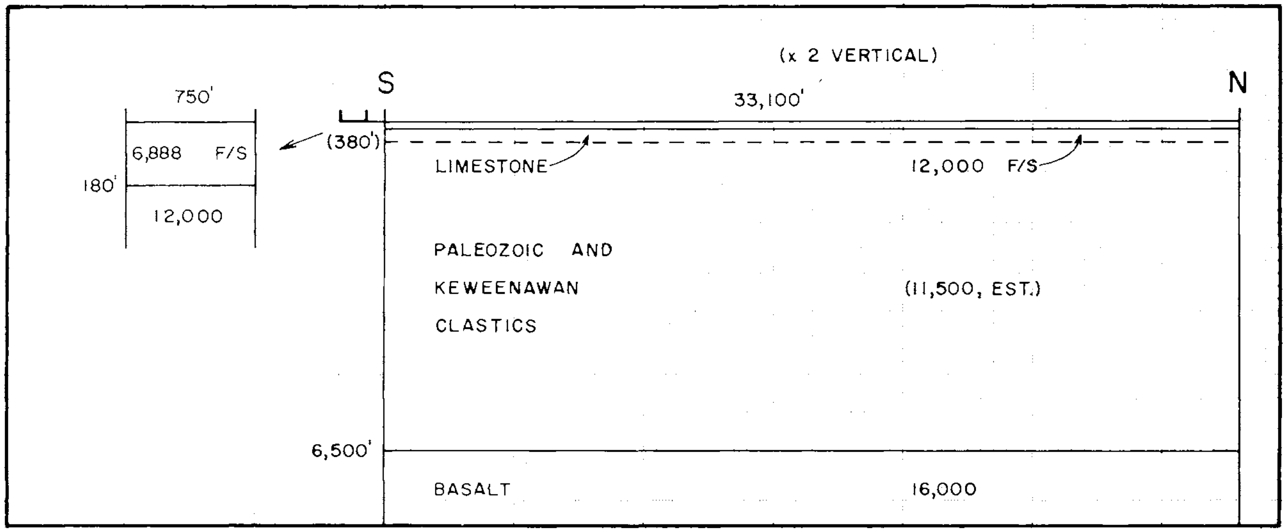
RESULTS: Forty-five feet of drift overlie 12,000-13,000 feet/second material, presumably Ordovician limestone with a known thickness at Kenyon (9 miles west) of 140 feet.

A velocity inversion is shown by offset of the travel time graph. Arrivals at shots 2-5 fit an 11,500 feet/second line, so we have used this value for the lower velocity material. Thickness of the overlying layer is taken as 200 feet for computation purposes.

A 16,000 feet/second line has been drawn on the basis of a joint interpretation of Lines 47 and 48. The data of Line 47 alone would be inadequate to support such a line.

Four seismic arrivals define intrusive igneous basement at a depth of about 11,000 feet. One of these arrivals is interpreted as a reflection.


LINE 48
TIME
(MILLISECONDS)
3200
2800
2400
2000
1600
1200
800
400
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
32000
070 + x/12,000
83 + x/16,000
(11,000)
17,200, fair.
Correlation only; very
questionable as arrival.
15,600-16,200, good.
Clear arrival.
12,000-13,000, poor.
Questionable arrival.
11,000, fair.
Possible correlation.
14,000, fair.
Small but clear.
13,500, poor.
Correlation only;
no clear arrival.
11,600-12,500, fair.
Clear phase change.
14,500, good.
Clear phase change.
11,700, good.
Large clear arrival.
11,500, fair.
Clear arrival.
11,000-12,000 correlations
continue to 2300 ms.
11,500-11,800, good.
Large clear arrival.
12,500, good.
Large new arrival.
11,500-11,800, good.
Tiny; builds up to
large irregular waveform.
12,000-12,400, good.
Large arrival.
11,600-12,000, fair.
Larger arrival.
13,000, fair.
Small but clear.
13,000, good. Large;
dies out across spread.
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
0
200
400
600
6000
6000
675'
Kenyon,
3 m.
Minn.
56
1 m.
1½ m.
¼ m.
92°55'
44°15'
G1
3000'
G7
Co. 11
½ m.
X
Skyberg
Line 48: Goodhue Co., Minn.



LINE 48

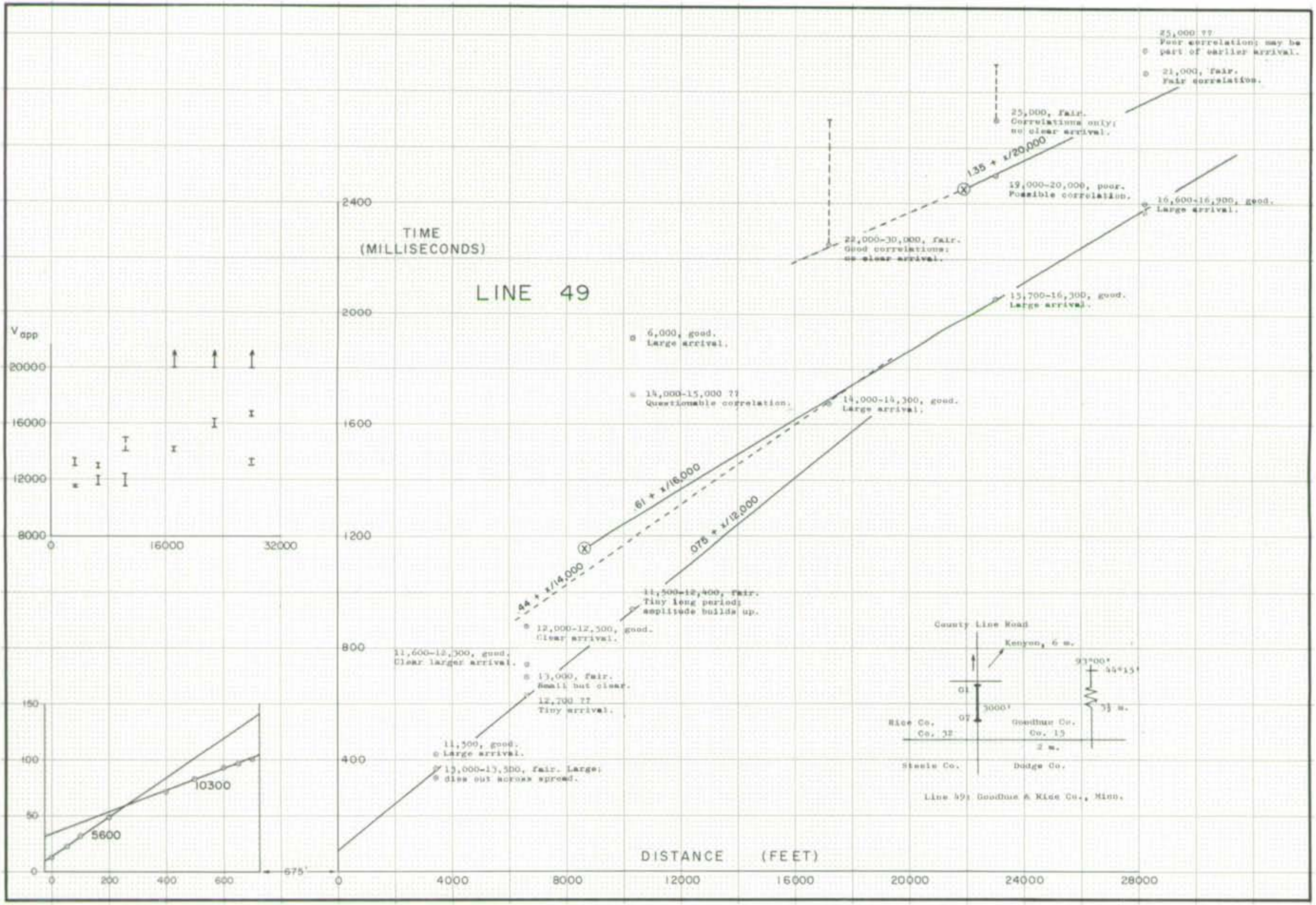
PURPOSE: See Line 47. Mean surface elevation is 1,250 feet.

RESULTS: 180 feet of drift overlie 12,000 feet/second material, presumably Ordovician limestone with a known thickness at Kenyon (3 miles west) of 140 feet.

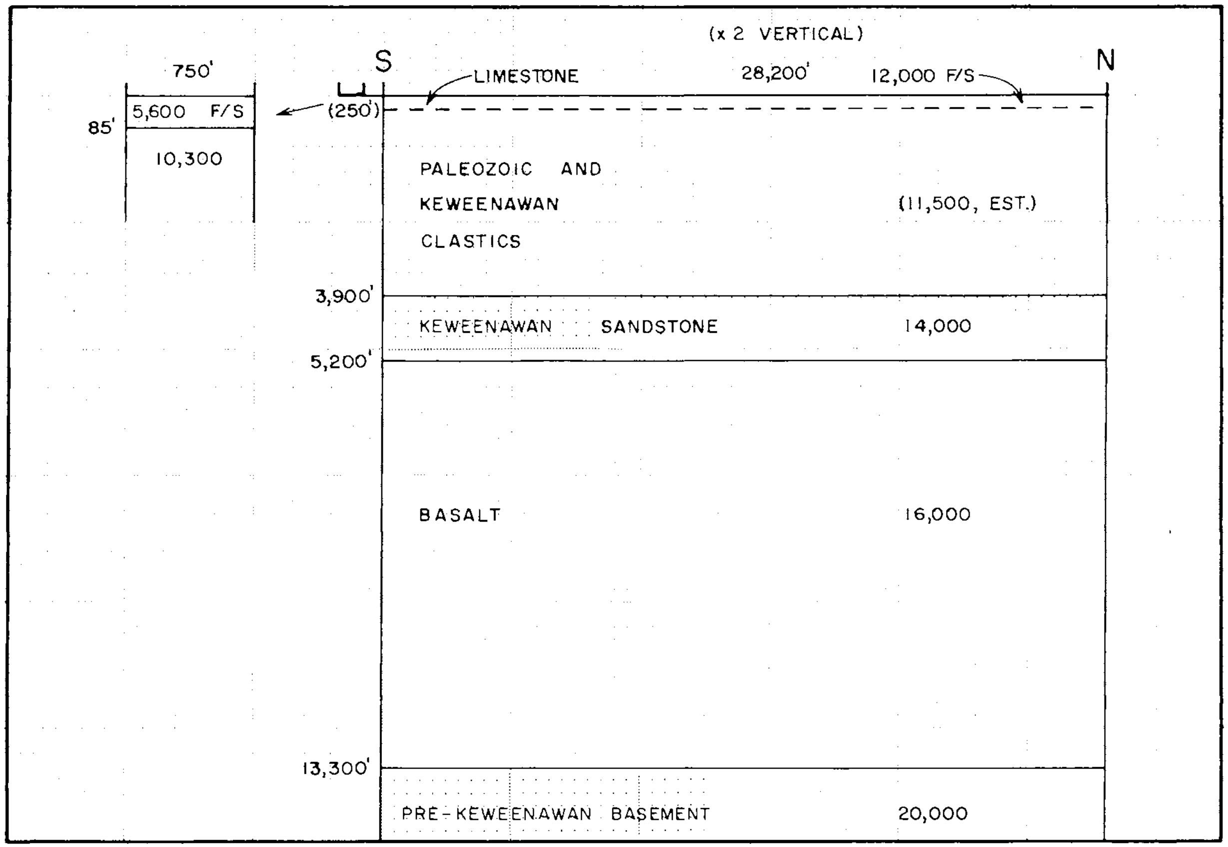
Data showing a velocity inversion are similar to adjacent Lines 47 and 49. We have assumed 200 feet of 12,000 feet/second material overlying 11,500 feet/second material.

A 16,000 feet/second line has been drawn on the basis of a single good arrival at Shot 7, two supporting arrivals with lower spread velocity at Shots 5 and 6, and excellent 16,000 feet/second data on Line 49. We tentatively identify the material as basalt, although velocities of 17,000-18,000 feet/second would be more diagnostic of basalt.

We searched the seismograms for 20,000 feet/second arrivals such as found on adjacent Lines 47 and 49, but failed to find them. Presumably this indicates considerably greater depth to the pre-Keweenawan basement, or else an irregular surface.



LINE 49
TIME (MILLISECONDS)
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
400
800
1200
1600
2000
2400
V_{app}
8000
12000
16000
20000
0
16000
32000
0
50
100
150
0
200
400
600
675'
5600
10300
.44 + x/14,000
.61 + x/16,000
.075 + x/12,000
1.35 + x/20,000
25,000 ??
Poor correlation; may be part of earlier arrival.
21,000, fair.
Fair correlation.
25,000, fair.
Correlations only; no clear arrival.
19,000-20,000, poor.
Possible correlation.
16,600-16,900, good.
Large arrival.
22,000-30,000, fair.
Good correlations; no clear arrival.
15,700-16,300, good.
Large arrival.
6,000, good.
Large arrival.
14,000-15,000 ??
Questionable correlation.
14,000-14,300, good.
Large arrival.
11,500-12,400, fair.
Tiny long period; amplitude builds up.
12,000-12,300, good.
Clear arrival.
11,600-12,300, good.
Clear larger arrival.
13,000, fair.
Small but clear.
12,700 ??
Tiny arrival.
11,500, good.
Large arrival.
13,000-13,300, fair. Large; dies out across spread.
County Line Road
Kenyon, 6 m.
93°00'
44°15'
01
07
3000'
3½ m.
Rice Co.
Co. 32
Goodhue Co.
Co. 15
2 m.
Steele Co.
Dodge Co.
Line 49: Goodhue & Rice Co., Minn.



LINE 49

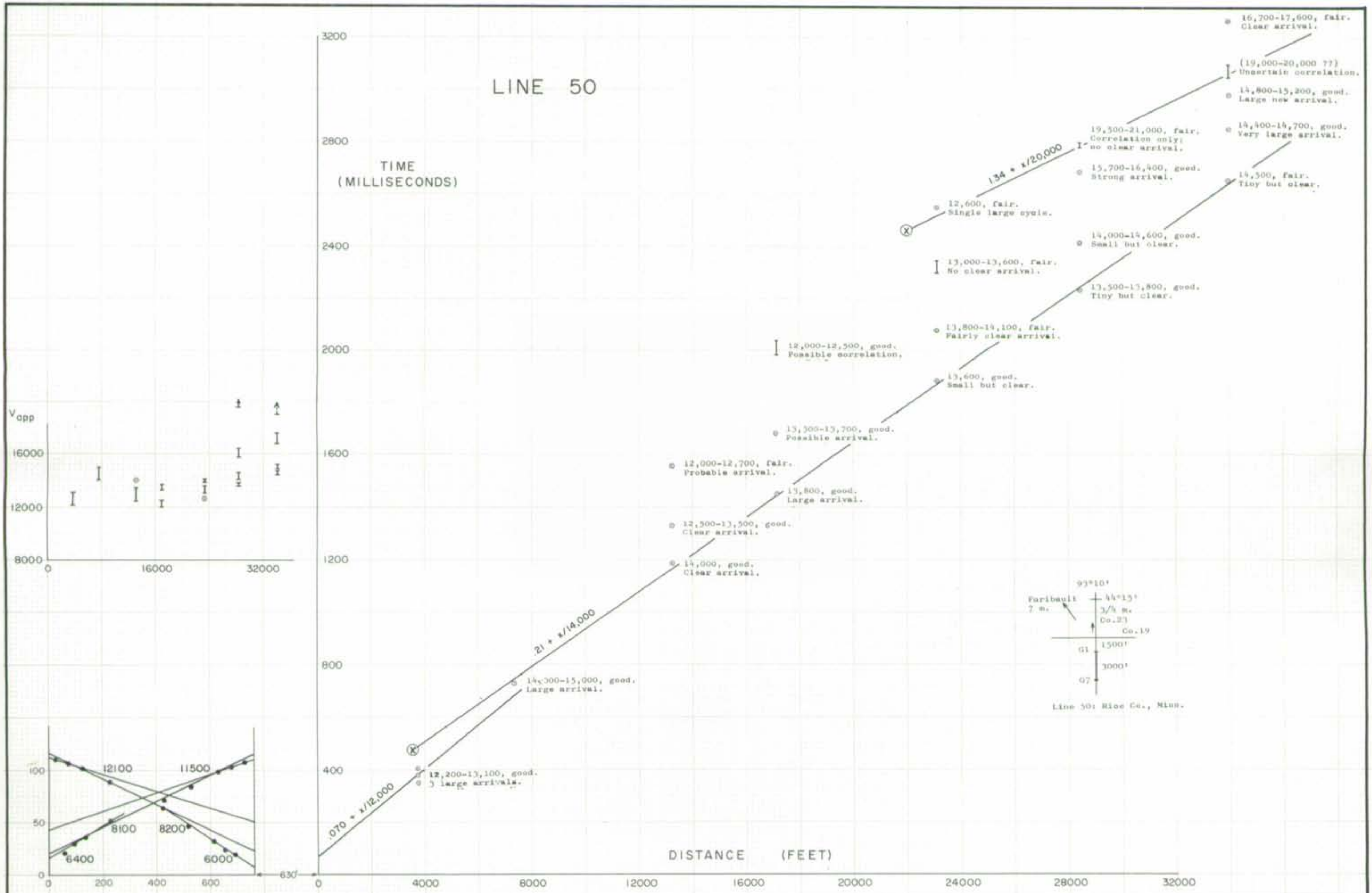
PURPOSE: See Line 47. Mean surface elevation is 1,200 feet.

RESULTS: The in-line data suggest a thin layer of 10,300 feet/second material, presumably Ordovician shale or sandstone, beneath 85 feet of glacial drift. The next deeper layer is well-defined at 12,000-13,000 feet/second. From the well at Kenyon (3 miles east), this would be Galena-Platteville limestone. Since the seismic data show a velocity inversion, we have taken 200 feet as thickness for this member.

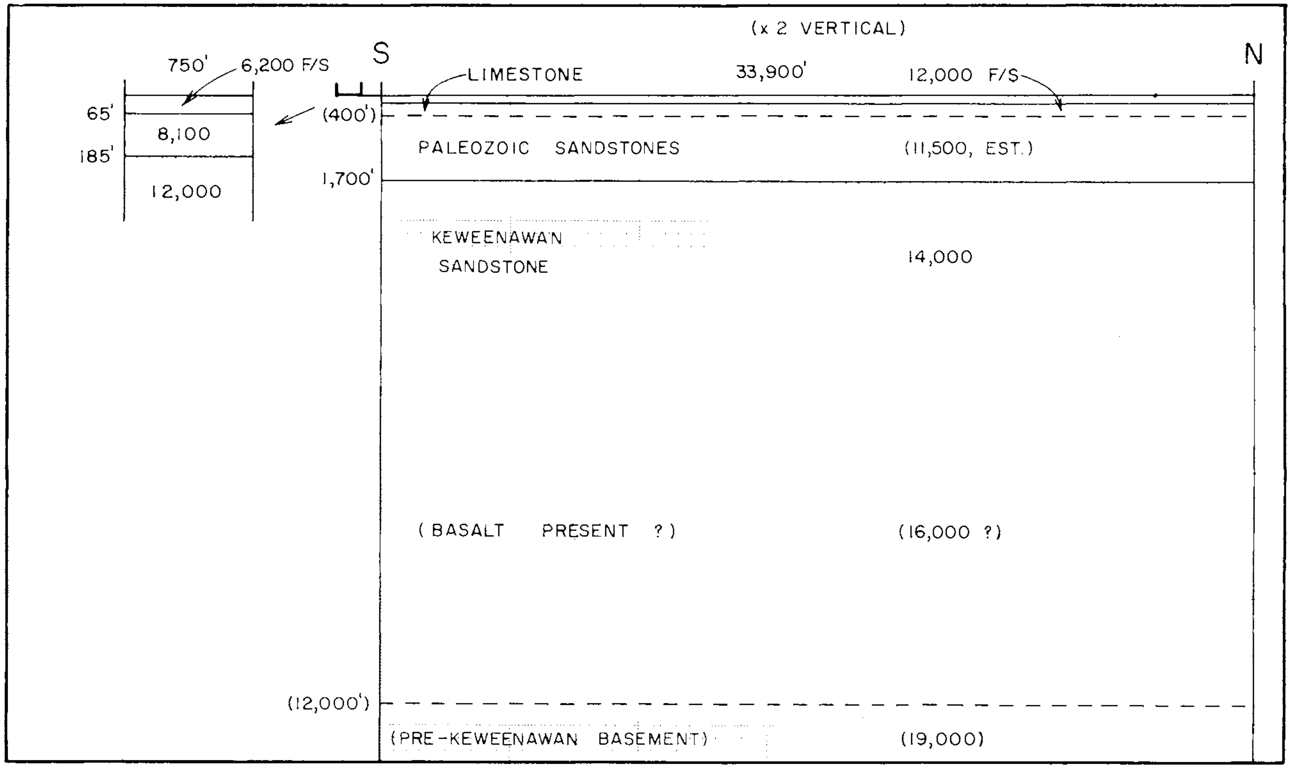
A single 14,000 feet/second arrival, together with excellent 14,000 feet/second data from adjacent Line 50, has been taken as evidence for Keweenawan sandstone at a depth of 3,900 feet.

The presence of 16,000 feet/second material at a depth of 5,200 feet is shown by two good first arrivals. As on Lines 47 and 48, we identify this as basalt although the velocity value is rather low.

Pre-Keweenawan basement is represented by three secondary arrivals which fit roughly to a 20,000 feet/second line. Depth is computed as 13,300 feet.



LINE 50
TIME (MILLISECONDS)
DISTANCE (FEET)
3200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
.070 + x/12,000
21 + x/14,000
134 + x/20,000
12,200-13,100, good. 3 large arrivals.
14,300-15,000, good. Large arrival.
14,000, good. Clear arrival.
12,500-13,500, good. Clear arrival.
12,000-12,700, fair. Probable arrival.
13,800, good. Large arrival.
13,300-13,700, good. Possible arrival.
12,000-12,500, good. Possible correlation.
13,600, good. Small but clear.
13,800-14,100, fair. Fairly clear arrival.
13,000-13,600, fair. No clear arrival.
12,600, fair. Single large cycle.
13,500-13,800, good. Tiny but clear.
14,000-14,600, good. Small but clear.
15,700-16,400, good. Strong arrival.
19,300-21,000, fair. Correlation only; no clear arrival.
14,300, fair. Tiny but clear.
14,400-14,700, good. Very large arrival.
14,800-15,200, good. Large new arrival.
(19,000-20,000 ??) Uncertain correlation.
16,700-17,600, fair. Clear arrival.
93°10'
44°15'
Faribault 7 m.
3/4 m.
Co.23
Co.19
1500'
3000'
G1
G7
Line 50: Rice Co., Minn.
V_{app}
16000
12000
8000
0
16000
32000
100
50
0
200
400
600
630
12100
11500
8100
8200
6400
6000



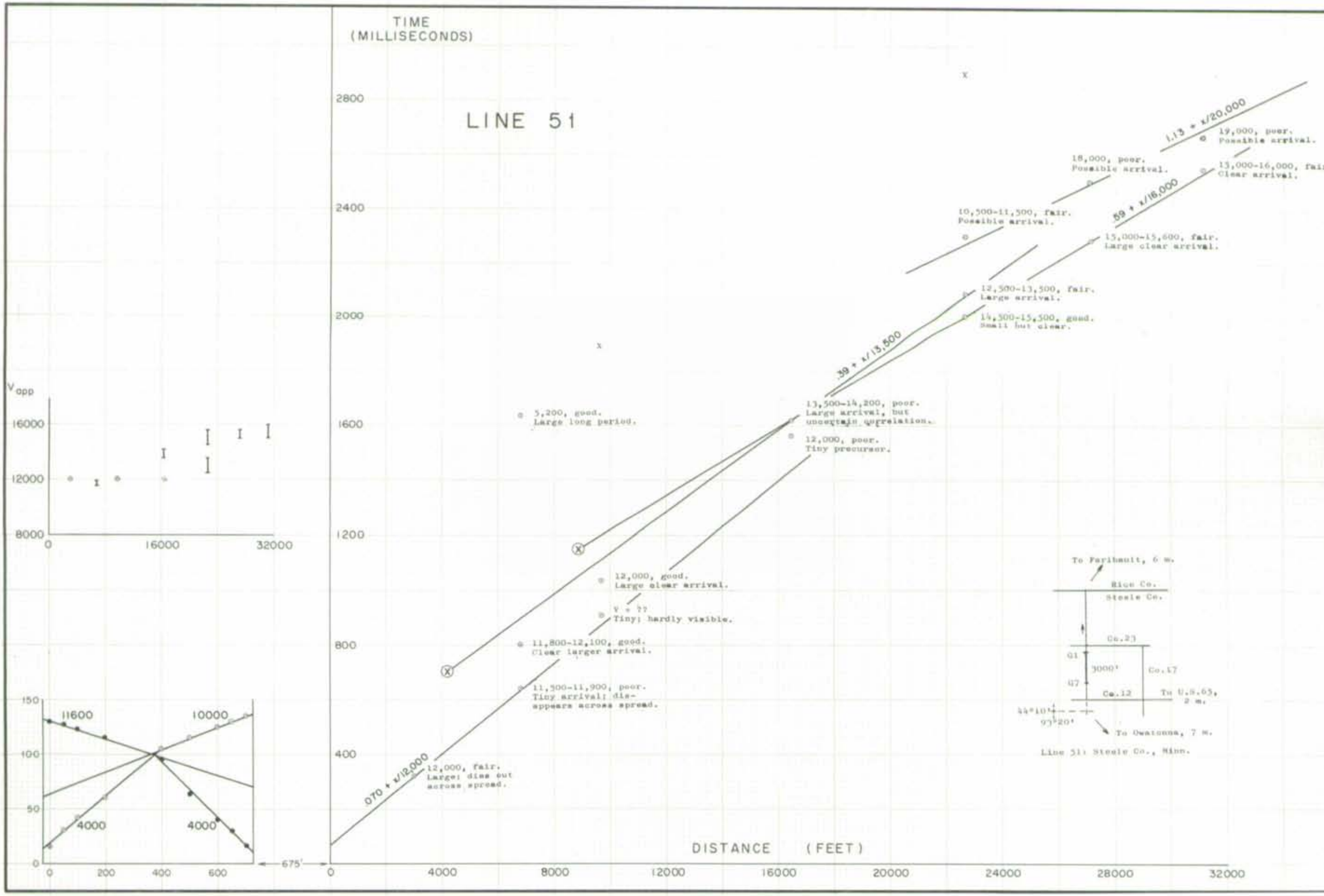
LINE 50

PURPOSE: See Line 47. Mean surface elevation is 1,200 feet.

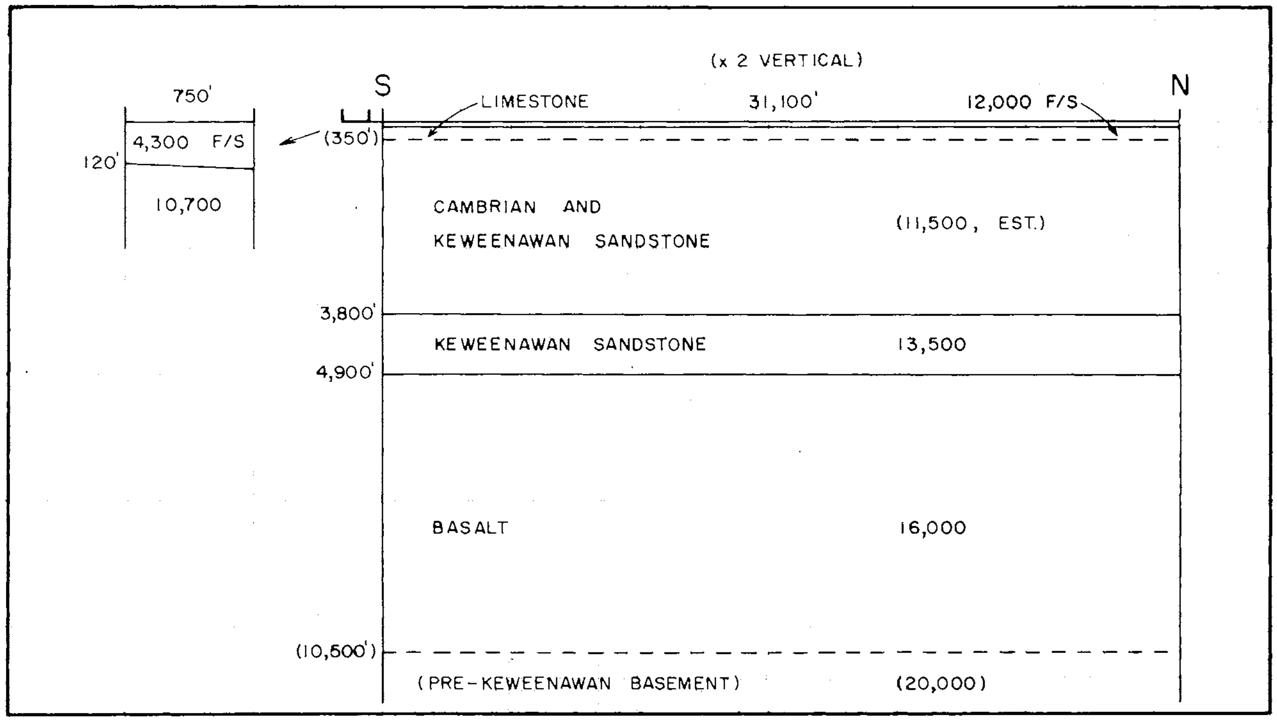
RESULTS: The in-line data show 50 feet of glacial drift underlain by 130 feet of 8,100 feet/second material. This may be part of the glacial drift or a weathered remnant of St. Peter Sandstone. Beneath it lies Ordovician limestone with a velocity of 12,000 feet/second and an estimated thickness of 200 feet. We have included a velocity inversion also, although the seismic data could be accommodated without it. Omission of this low velocity layer would increase depth to the next layer by 150 feet.

Excellent seismic data show a considerable thickness of material with velocity 14,000 feet/second. Depth to top is 1,700 feet. We identify this as a dense sandstone member of the Keweenawan sequence. Neither of the adjacent Lines 49 and 51 show anything like this clear sequence of 14,000 feet/second seismic arrivals.

The evidence for a 19,000-20,000 feet/second arrival is based on only a single arrival hence is very weak. Scattered arrivals hint at 16,000 feet/second material, but they do not fit an interpretable pattern.



TIME
(MILLISECONDS)
LINE 51
1.13 + x/20,000
19,000, poor.
Possible arrival.
18,000, poor.
Possible arrival.
13,000-16,000, fair.
Clear arrival.
.59 + x/16,000
10,500-11,500, fair.
Possible arrival.
15,000-15,600, fair.
Large clear arrival.
12,500-13,500, fair.
Large arrival.
14,500-15,500, good.
Small but clear.
.39 + x/13,500
13,500-14,200, poor.
Large arrival, but
uncertain correlation.
12,000, poor.
Tiny precursor.
5,200, good.
Large long period.
12,000, good.
Large clear arrival.
V = ??
Tiny; hardly visible.
11,800-12,100, good.
Clear larger arrival.
11,500-11,900, poor.
Tiny arrival; dis-
appears across spread.
.070 + x/12,000
12,000, fair.
Large; dies out
across spread.
DISTANCE (FEET)
V_{app}
11600
10000
4000
4000
675'
To Faribault, 6 m.
Rice Co.
Steele Co.
Co.23
G1
3000'
G7
Co.17
Co.12
To U.S.65,
2 m.
44°10'
93°20'
To Owatonna, 7 m.
Line 51: Steele Co., Minn.



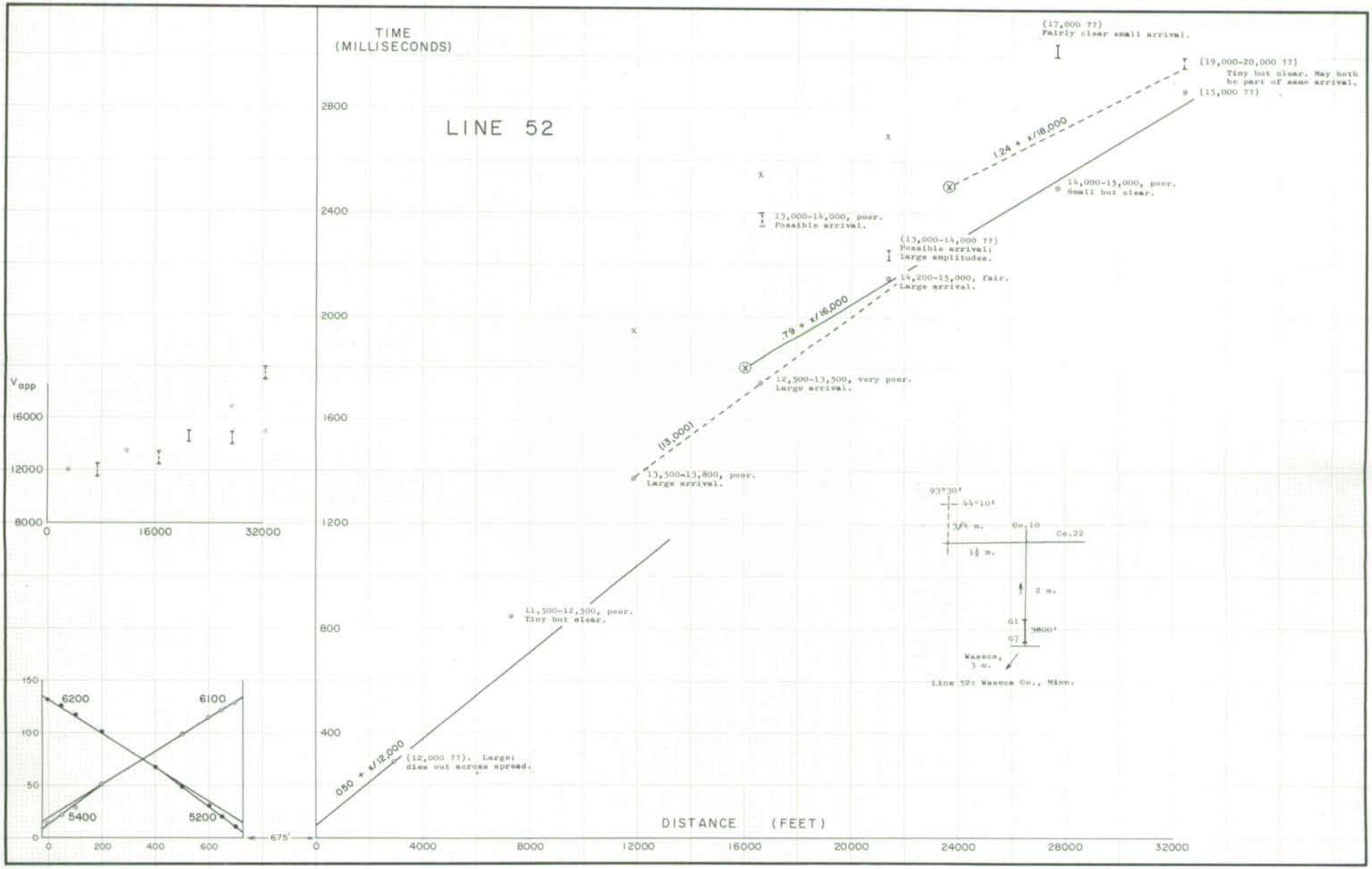
LINE 51

PURPOSE: See Line 47. Mean surface elevation is 1,100 feet.

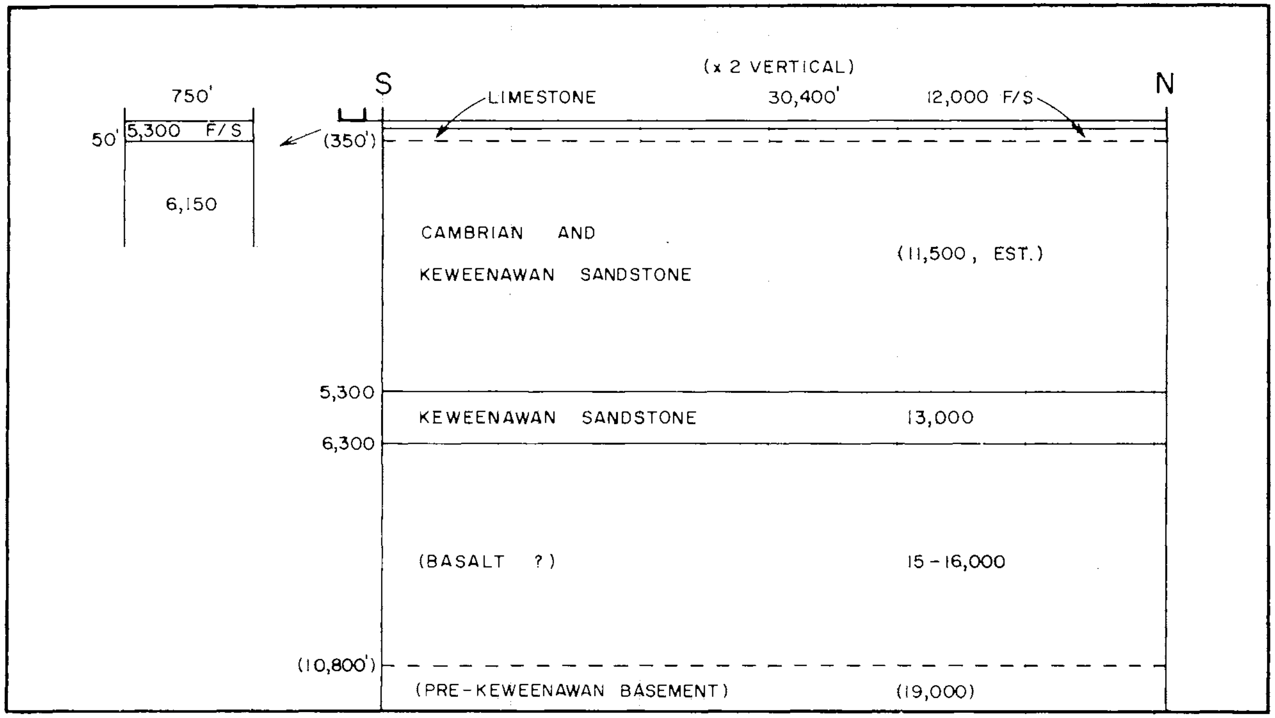
RESULTS: 12,000 feet/second material, presumably Ordovician limestone, underlies 120 feet of glacial drift. In-line velocity for this material is slightly lower than 12,000 but, because intercept times are the same, we attribute this to a weathered layer on the limestone surface. Offset of the travel time graph shows the presence of a velocity inversion.

Three good seismic arrivals fit a 16,000 feet/second line which we identify as basalt at a depth of 4,900 feet. We have also included a 13,500 feet/second line segment based upon two arrivals plus an analogous sequence on Line 52. If this segment had been omitted, depth to basalt would have been reduced by 400 feet.

Two poor arrivals provide weak evidence for pre-Keweenawan basement at an estimated depth of 10,500 feet.



TIME
(MILLISECONDS)
LINE 52
(17,000 ??)
Fairly clear small arrival.
(19,000-20,000 ??)
Tiny but clear. May both be part of same arrival.
(15,000 ??)
1.24 + x/18,000
14,000-15,000, poor.
Small but clear.
13,000-14,000, poor.
Possible arrival.
(13,000-14,000 ??)
Possible arrival;
large amplitudes.
14,200-15,000, fair.
Large arrival.
.79 + x/16,000
12,500-13,500, very poor.
Large arrival.
(13,000)
13,500-13,800, poor.
Large arrival.
11,500-12,500, poor.
Tiny but clear.
(12,000 ??). Large;
dies out across spread.
.050 + x/12,000
93°30'
44°10'
3/4 m.
Co.10
Co.22
1½ m.
2 m.
61
3800'
67
Waseca,
3 m.
Line 52: Waseca Co., Minn.
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
32000
400
800
1200
1600
2000
2400
2800
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
6200
6100
5400
5200
675'

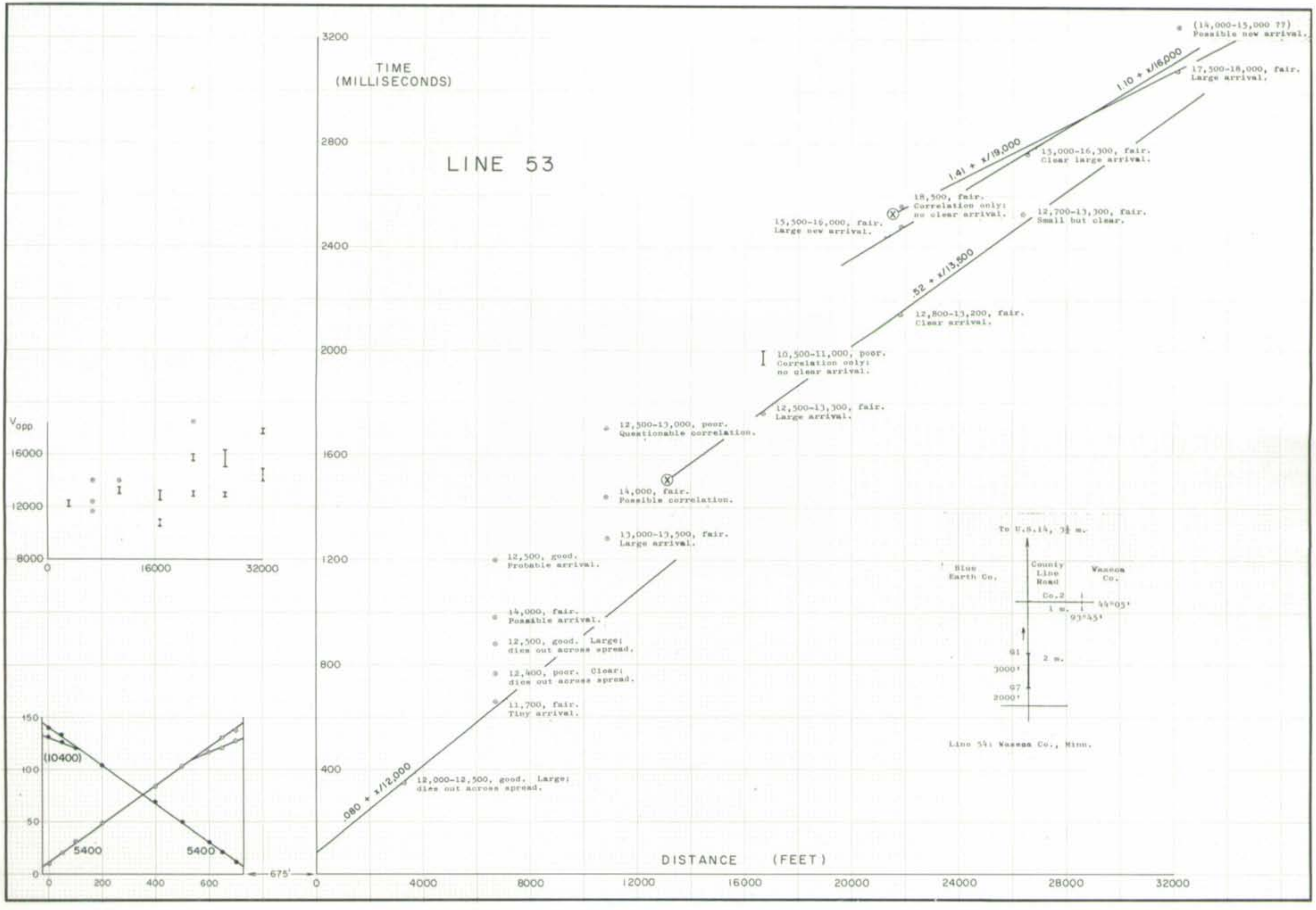


LINE 52

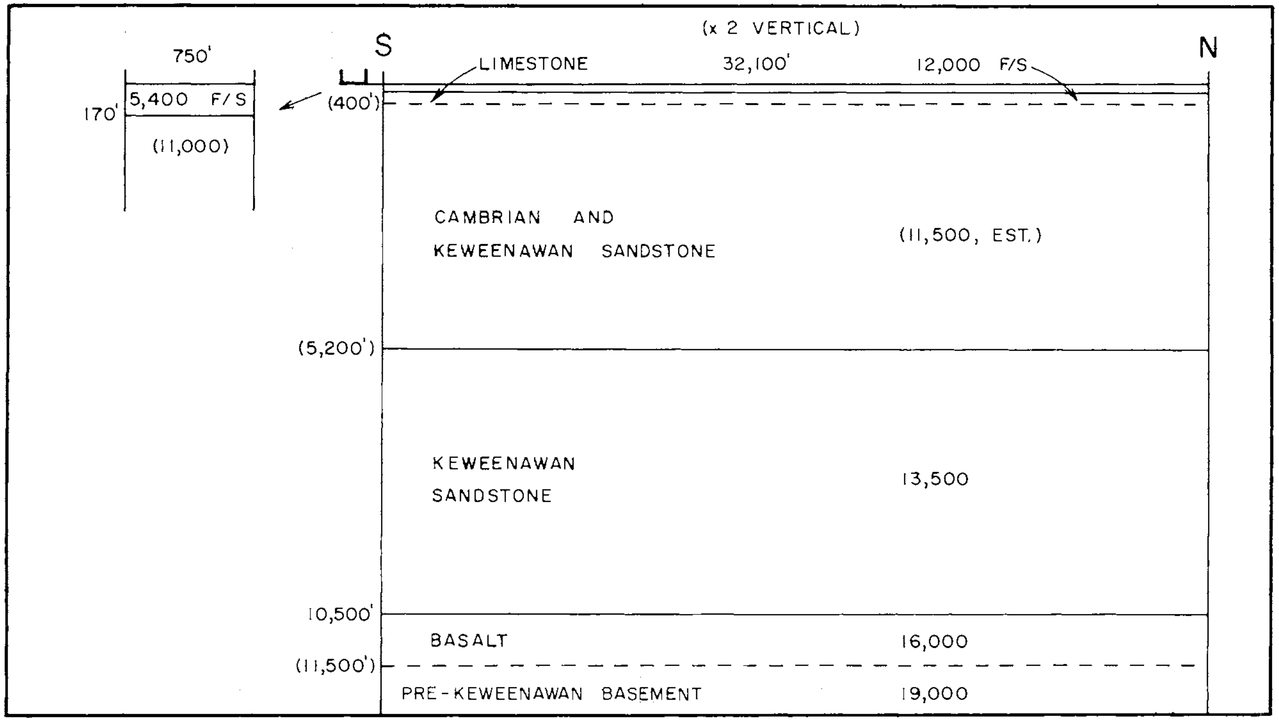
PURPOSE: See Line 47. Mean surface elevation is 1,150 feet.

RESULTS: 160 feet of glacial drift with velocity of about 6,000 feet/second overlies Ordovician limestone. Offset of the travel time graph shows the presence of lower velocity Cambrian sandstone beneath the limestone.

Two first arrivals suggest a 13,000-13,500 feet/second line segment. Three first arrivals fit poorly to a 15,000 or 16,000 feet/second segment. A single secondary gives a 19,000 feet/second arrival. None of these three segments is convincing by itself, but each is supported by similar velocities on adjacent lines. One reasonably clear conclusion is greater depth (6,300 vs 4,900 feet) to the 16,000 feet/second material on Line 52 than on Line 51.



LINE 53
TIME
(MILLISECONDS)
DISTANCE (FEET)
3200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
.080 + x/12,000
.52 + x/13,500
1.41 + x/19,000
1.10 + x/16,000
12,000-12,500, good. Large; dies out across spread.
11,700, fair. Tiny arrival.
12,400, poor. Clear; dies out across spread.
12,500, good. Large; dies out across spread.
14,000, fair. Possible arrival.
12,500, good. Probable arrival.
13,000-13,500, fair. Large arrival.
14,000, fair. Possible correlation.
12,500-13,000, poor. Questionable correlation.
12,500-13,300, fair. Large arrival.
10,500-11,000, poor. Correlation only; no clear arrival.
12,800-13,200, fair. Clear arrival.
15,500-16,000, fair. Large new arrival.
18,500, fair. Correlation only; no clear arrival.
12,700-13,300, fair. Small but clear.
13,000-16,300, fair. Clear large arrival.
17,500-18,000, fair. Large arrival.
(14,000-15,000 ??) Possible new arrival.
V_{opp}
16000
12000
8000
0
16000
32000
150
100
50
0
(10400)
5400
5400
0
200
400
600
675'
To U.S.14, 3½ m.
Blue Earth Co.
County Line Road
Wasecа Co.
Co.2
1 m.
44°05'
93°45'
G1
3000'
2 m.
G7
2000'
Line 54: Waseca Co., Minn.



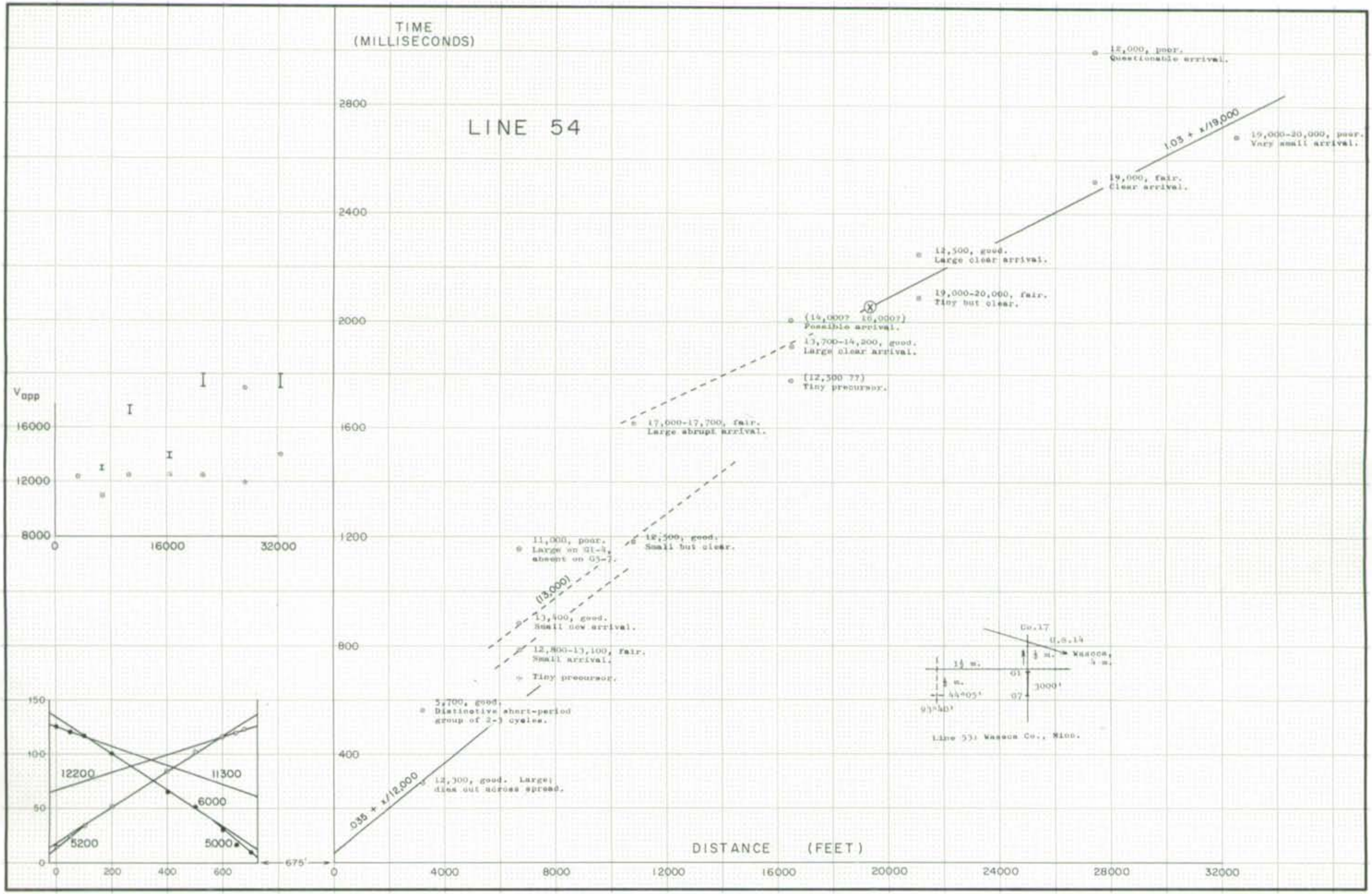
LINE 53

PURPOSE: See Line 47. Mean surface elevation is 1,130 feet.

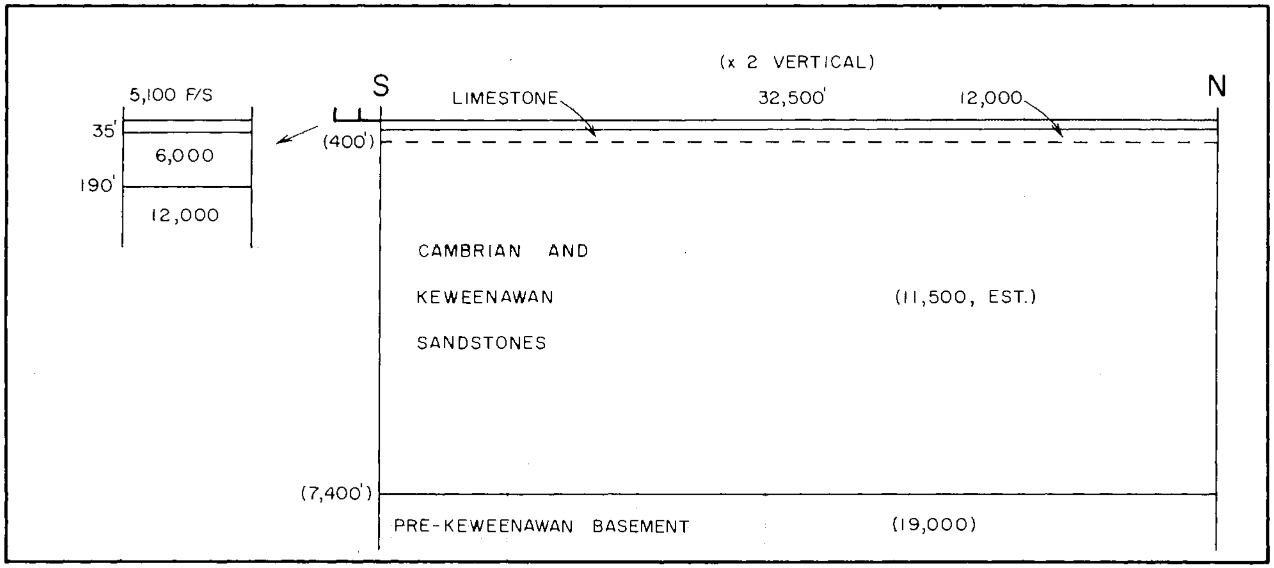
RESULTS: 170 feet of glacial drift overlies Ordovician limestone. Lower-velocity Cambrian sandstones beneath the limestone produce an offset of the seismic travel time graph.

Four good arrivals fit adequately to a 13,500 feet/second line. Compared with Line 74, this line segment is delayed by 180 milliseconds, representing a depth which is greater by 1,600 feet.

A 16,000 feet/second line is defined by two good secondary arrivals. A single good arrival, plus supporting evidence from adjacent lines, indicates 19,000 feet/second pre-Keweenawan basement at a depth of about 11,500 feet.



TIME
(MILLISECONDS)
LINE 54
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
DISTANCE (FEET)
.035 + x/12,000
1.03 + x/19,000
(13,000)
12,000, poor.
Questionable arrival.
19,000-20,000, poor.
Vary small arrival.
19,000, fair.
Clear arrival.
12,500, good.
Large clear arrival.
19,000-20,000, fair.
Tiny but clear.
(14,000? 16,000?)
Possible arrival.
13,700-14,200, good.
Large clear arrival.
(12,500 ??)
Tiny precursor.
17,000-17,700, fair.
Large abrupt arrival.
11,000, poor.
Large on G1-4,
absent on G5-7.
12,500, good.
Small but clear.
13,400, good.
Small new arrival.
12,800-13,100, fair.
Small arrival.
Tiny precursor.
5,700, good.
Distinctive short-period
group of 2-3 cycles.
12,300, good. Large;
dies out across spread.
Co.17
U.S.14
Waseca,
1½ m.
3000'
44°05'
93°40'
Line 53: Waseca Co., Minn.
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
12200
11300
6000
5200
5000
675'



LINE 54

PURPOSE: See Line 47. Line 54 is the westernmost line in the sequence 47-54. Mean surface elevation is 1,100 feet.

RESULTS: 190 feet of glacial drift overlies 12,000 feet/second Ordovician limestone. Along line, the first arrivals from this formation are not entirely consistent; however, good secondary arrivals with nearly the same velocity may be P-to-S conversions.

Interpretation is less clear for the remainder of the line. Four arrivals yield velocities in the 18,000-20,000 feet/second range, but the fit to a 19,000 feet/second line segment is less than adequate. The arrival at Shot 6 in particular is delayed by 100 ms, suggesting extra depth to the basement. We tried including a 14,000 feet/second line segment to fit secondary arrivals on Shots 4 and 5, but no acceptable solution emerged.

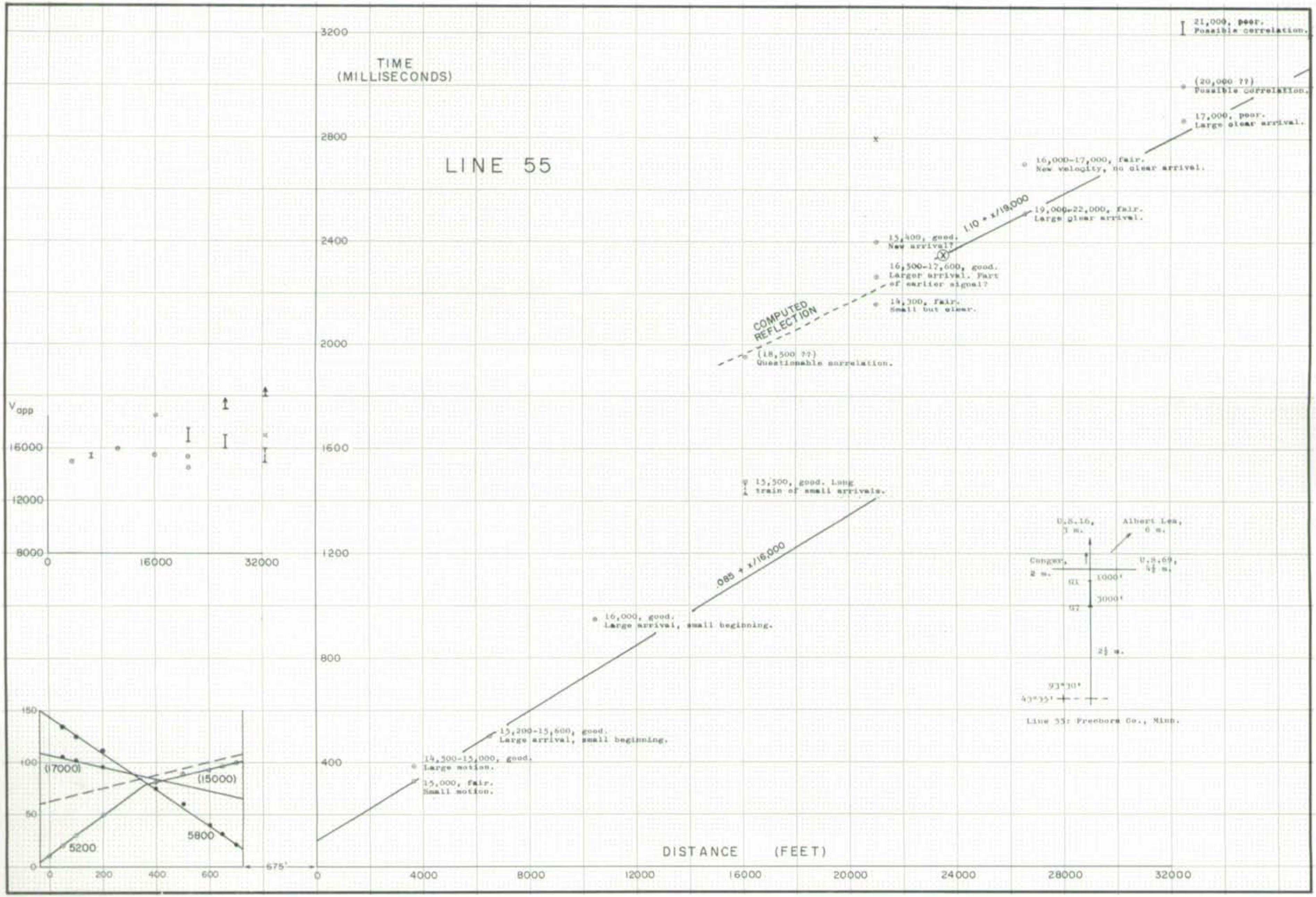
LINES 55-64, General Discussion

Lines 55-64 provide an east-west structure section across the Midcontinent Gravity High at approximately the latitude (43° 30′) of the Minnesota-Iowa border. Lines 55 and 64 are offset slightly to the north of the other lines in order to provide coverage of two distinctive magnetic features.

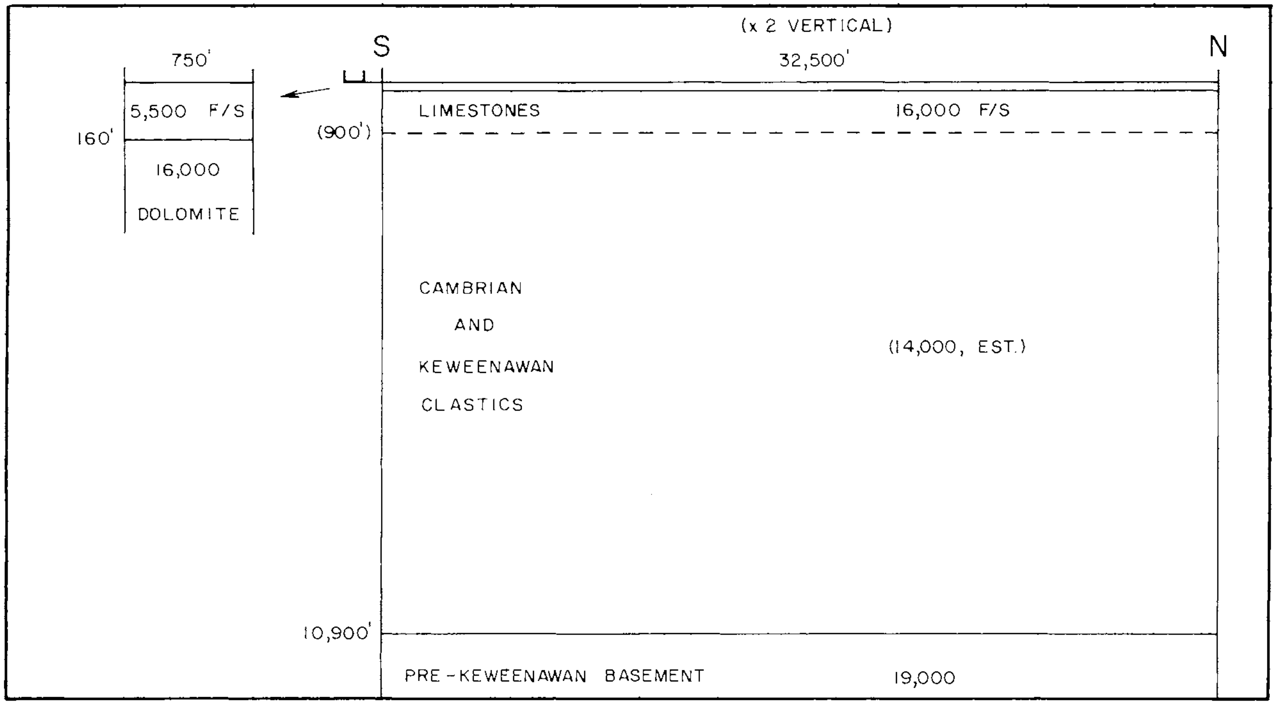
Geological structure to a depth of 1,000 feet is known from drill holes. The two deepest holes are at Albert Lea and Austin. These and other holes confirm the essentially flat-lying nature of the Paleozoic formations throughout the area under consideration.

The material which underlies the glacial drift is dolomite of the Cedar Valley Formation of Devonian age, with thickness of 100-200 feet. The remainder of the section to a depth of 800 feet is principally massive Ordovician limestones and dolomites, except for 100 feet of St. Peter Sandstone at 600 feet depth. The deeper formations are Cambrian sandstones. Detailed well logs are available in Bulletin 31 and other publications of the Minnesota Geological Survey.

The seismic data for Lines 55-64 show a high-velocity (15,000-16,000 feet/second) formation underlying 100-200 feet of glacial drift. This material is presumably the Cedar Valley Formation. The seismic arrivals die out at shot distances of roughly 10,000 feet, leaving a time gap of several hundred milliseconds until later seismic arrivals appear. We interpret this phenomenon as a velocity inversion produced by the lower-velocity sandstones underlying higher-velocity limestones. On the basis of both geological and seismic evidence, we estimate 800 feet thickness for the limestones, and assign an average velocity of 14,000 feet/second to the underlying material. The seismic interpretation requires assumed values for these two quantities, but depths to igneous basement are insensitive to minor variations All of the following interpretations include these two assumptions.



LINE 55
TIME
(MILLISECONDS)
DISTANCE (FEET)
3200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
21,000, poor.
Possible correlation.
(20,000 ??)
Possible correlation.
17,000, poor.
Large clear arrival.
16,000-17,000, fair.
New velocity, no clear arrival.
1.10 + x/19,000
19,000-22,000, fair.
Large clear arrival.
15,400, good.
New arrival?
16,500-17,600, good.
Larger arrival. Part
of earlier signal?
14,300, fair.
Small but clear.
COMPUTED
REFLECTION
(18,500 ??)
Questionable correlation.
15,500, good. Long
train of small arrivals.
.085 + x/16,000
16,000, good.
Large arrival, small beginning.
15,200-15,600, good.
Large arrival, small beginning.
14,500-15,000, good.
Large motion.
15,000, fair.
Small motion.
U.S.16,
3 m.
Albert Lea,
6 m.
Conger,
2 m.
U.S.69,
4½ m.
1000'
3000'
2½ m.
93°30'
43°35'
Line 55: Freeborn Co., Minn.
Vapp
16000
12000
8000
0
16000
32000
150
100
50
(17000)
(15000)
5200
5800
200
400
600
675'



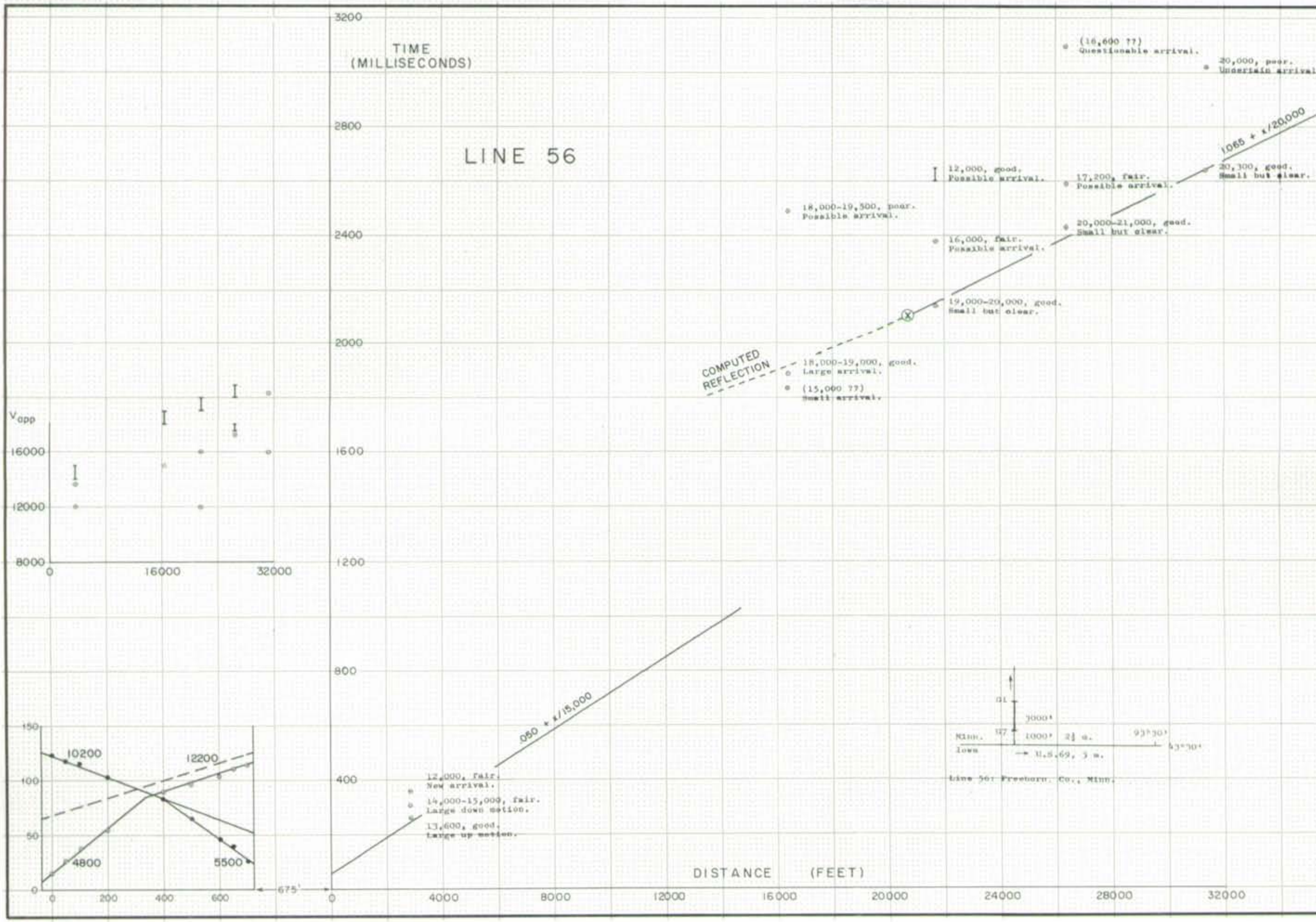
LINE 55

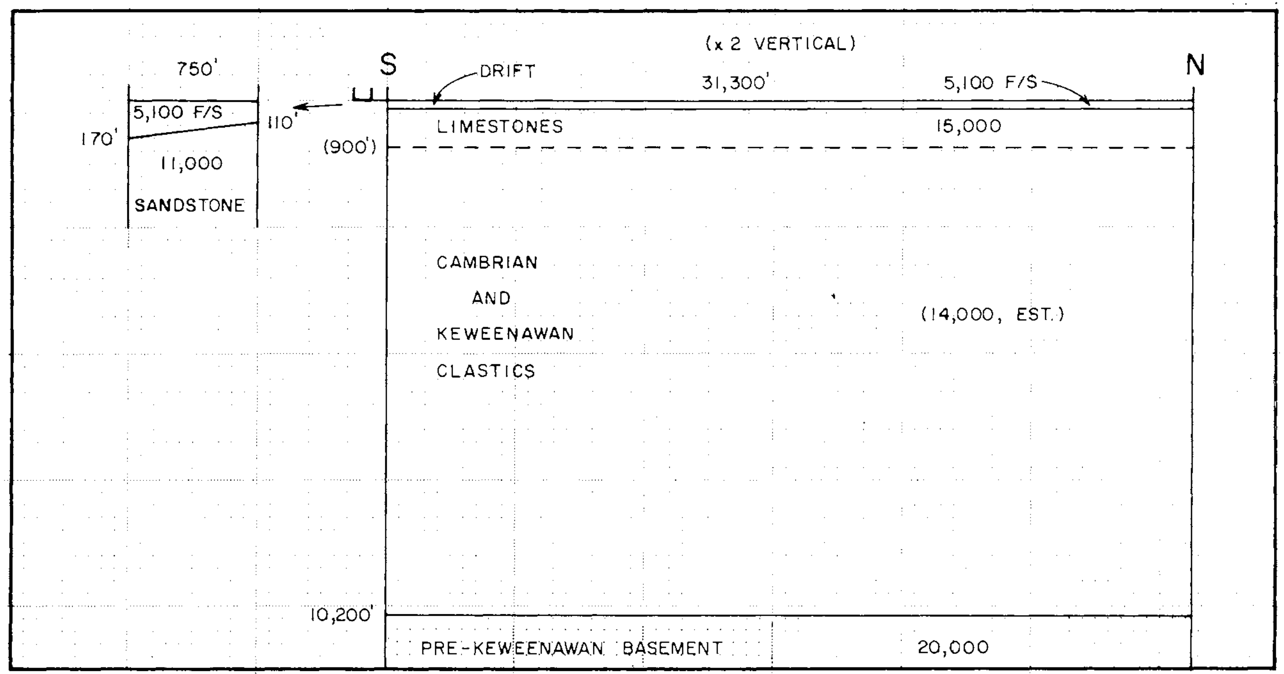
PURPOSE: Line 55 was offset 7 miles northward from the main sequence of profiles, in order to yield information on a broad magnetic high centered 7 miles west of Albert Lea. Mean surface elevation is 1,300 feet.

RESULTS: Cedar Valley Formation with well-defined velocity of 16,000 feet/second lies immediately beneath about 160 feet of glacial drift. The velocity inversion associated with the deeper underlying Ordovician and Cambrian sandstones is clearly shown by offset of the seismic travel time graph.

The presence of one or two deeper refractors is clearly visible in the seismic data, but the exact interpretation is uncertain. We consider the 19,000-20,000 feet/second arrivals to be reasonably secure, partly on the basis of adjacent lines. We tried including a 16,000 feet/second layer overlying the igneous basement, but no acceptable structure could be found.

The seismic data fail to account for the observed magnetic high in terms of either major uplift of the basement or segregations of mafic materials within the basement.


LINE 56
TIME (MILLISECONDS)
DISTANCE (FEET)
1.065 + x/20,000
.050 + x/15,000
COMPUTED REFLECTION
(16,600 ??) Questionable arrival.
20,000, poor. Uncertain arrival.
12,000, good. Possible arrival.
17,200, fair. Possible arrival.
20,300, good. Small but clear.
18,000-19,500, poor. Possible arrival.
20,000-21,000, good. Small but clear.
16,000, fair. Possible arrival.
19,000-20,000, good. Small but clear.
18,000-19,000, good. Large arrival.
(15,000 ??) Small arrival.
12,000, fair. New arrival.
14,000-15,000, fair. Large down motion.
13,600, good. Large up motion.
Line 56: Freeborn Co., Minn.
U.S. 69, 3 m.
V_{app}
10200
12200
4800
5500
675'



LINE 56

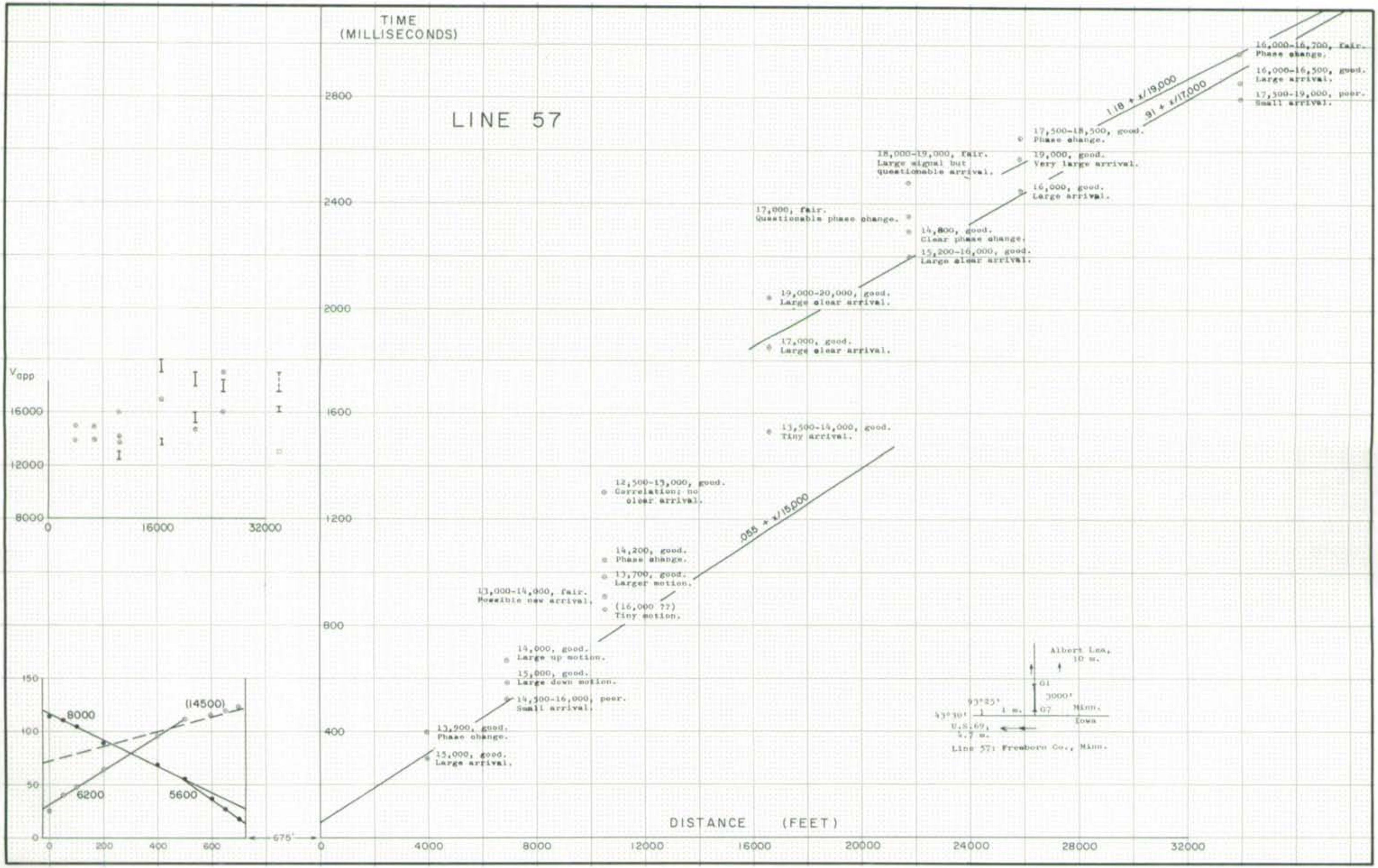
PURPOSE: Line 56 is the westernmost profile in the sequence. Mean surface elevation is 1,250 feet.

RESULTS: The glacial drift is about 150 feet thick. In-line seismic data suggest a thin layer of 11,000 feet/second material, possibly Cretaceous sandstone, on top of the well-defined Cedar Valley Formation.

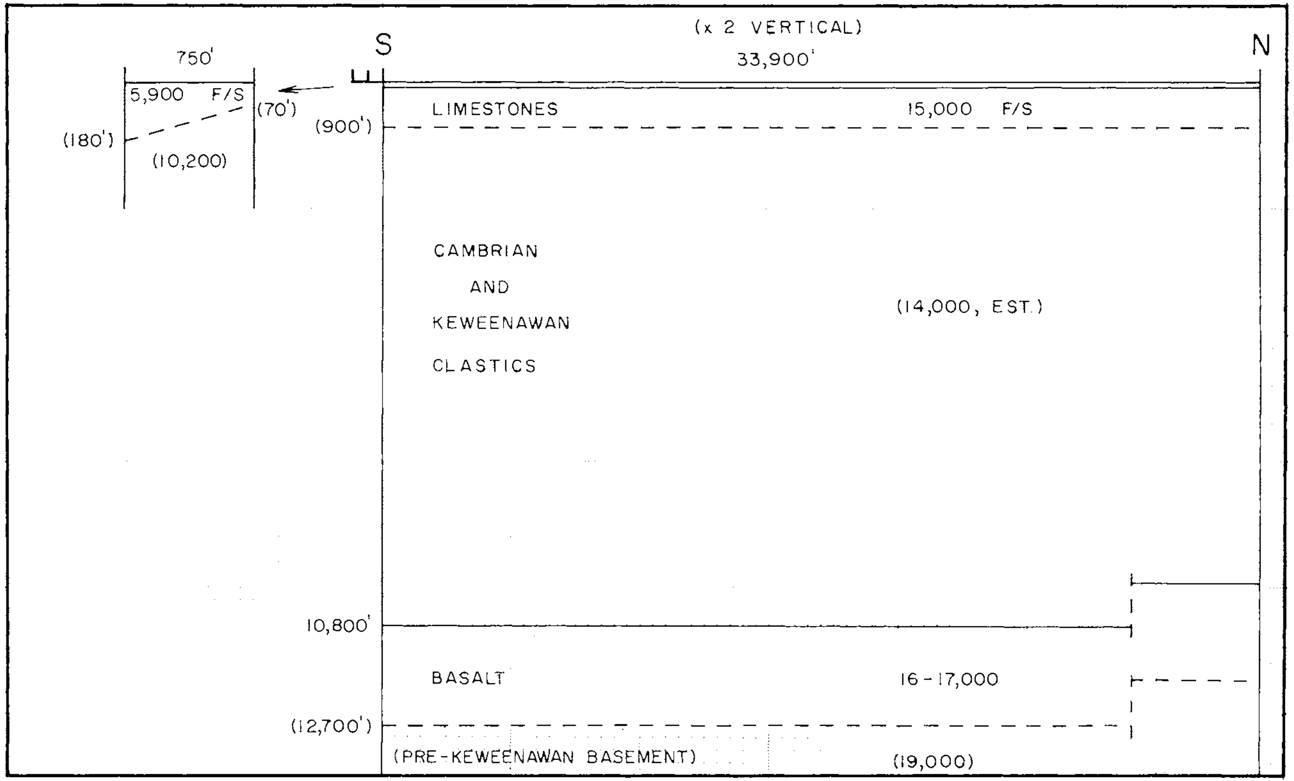
Two of the seismic shots failed, leaving the intermediate-depth structure poorly defined. A velocity inversion produced by the Cambrian sandstones is clearly shown by offset of the seismic travel time graph.

Line 56 provides excellent data by which to define velocity in the crystalline basement, 20,000 feet/second. This is confirmed by both across-spread and along-line velocity values. Basement depth is about 10,000 feet. We identify the material as felsic or intermediate intrusive igneous rock; velocity values for basalt would lie in the 17,000-19,000 feet/second range.

We attempted to compute a structure which includes a 16,000 feet/second layer overlying the igneous basement, but the seismic data do not permit this.



TIME
(MILLISECONDS)
LINE 57
2800
2400
2000
1600
1200
800
400
16,000-16,700, fair.
Phase change.
16,000-16,500, good.
Large arrival.
17,500-19,000, poor.
Small arrival.
1.18 + x/19,000
.91 + x/17,000
17,500-18,500, good.
Phase change.
18,000-19,000, fair.
Large signal but
questionable arrival.
19,000, good.
Very large arrival.
16,000, good.
Large arrival.
17,000, fair.
Questionable phase change.
14,800, good.
Clear phase change.
15,200-16,000, good.
Large clear arrival.
19,000-20,000, good.
Large clear arrival.
17,000, good.
Large clear arrival.
13,500-14,000, good.
Tiny arrival.
12,500-13,000, good.
Correlation; no
clear arrival.
.055 + x/15,000
14,200, good.
Phase change.
13,700, good.
Larger motion.
13,000-14,000, fair.
Possible new arrival.
(16,000 ??)
Tiny motion.
14,000, good.
Large up motion.
15,000, good.
Large down motion.
14,500-16,000, poor.
Small arrival.
13,900, good.
Phase change.
15,000, good.
Large arrival.
Albert Lea,
10 m.
G1
3000'
93°25'
43°30'
1 m.
G7
Minn.
Iowa
U.S.69,
4.7 m.
Line 57: Freeborn Co., Minn.
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
32000
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
8000
(14500)
6200
5600
0
200
400
600
675'



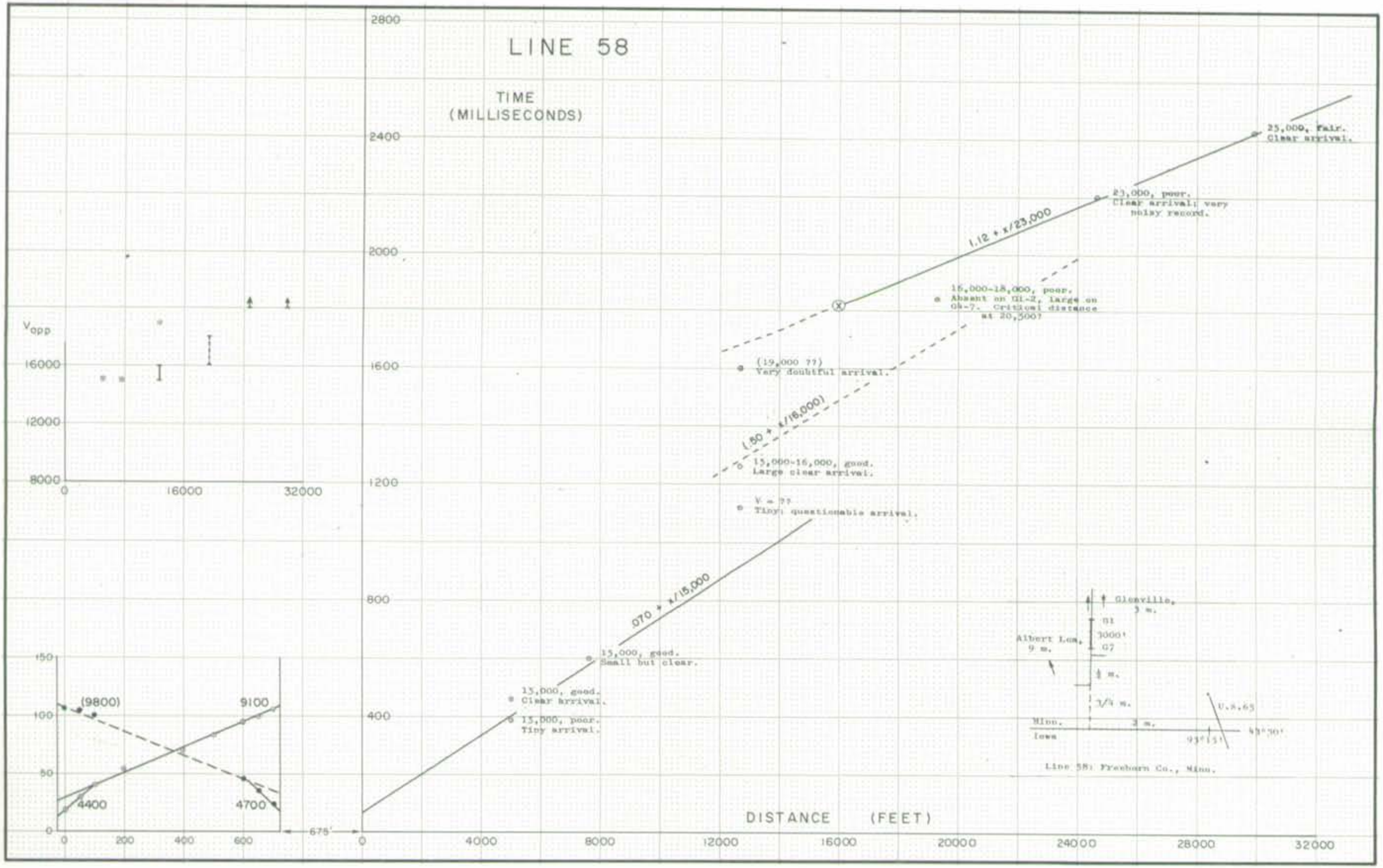
LINE 57

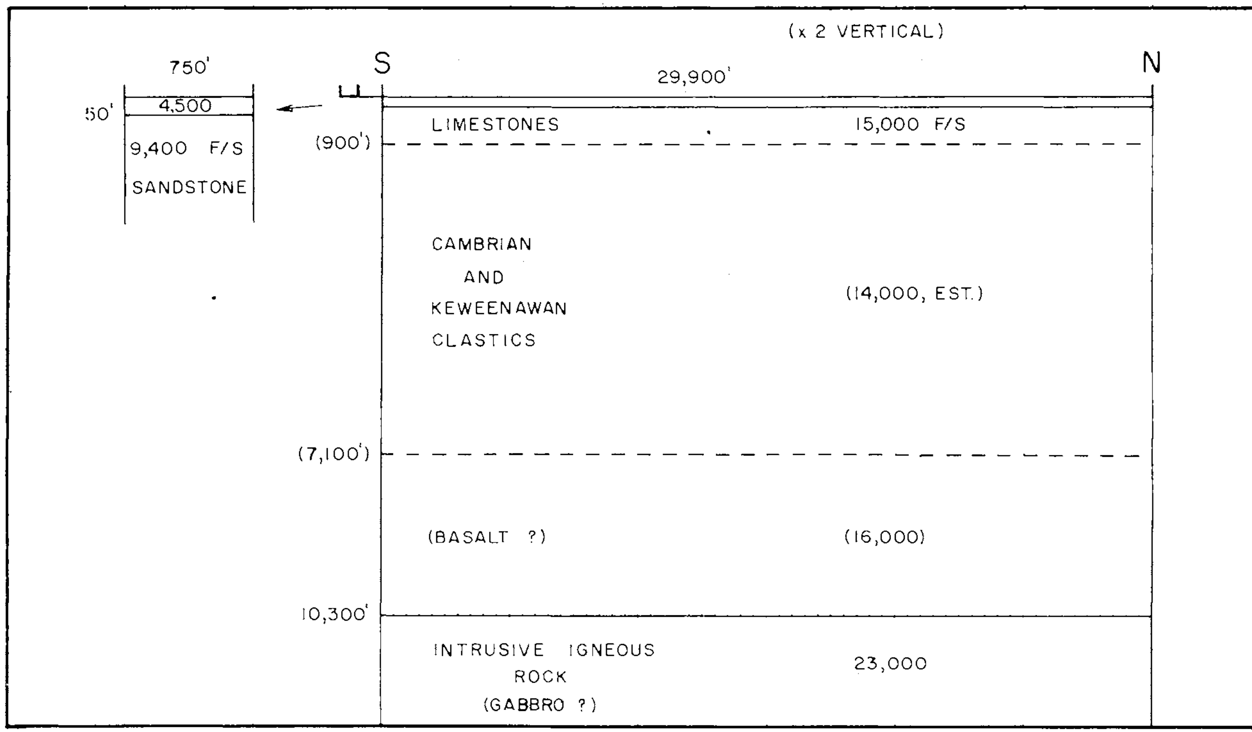
PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,250 feet.

RESULTS: From the in-line seismic data, glacial drift of 100-150 feet thickness overlies a thin layer with velocity 10,000-11,000 feet/second. This may be Cretaceous sandstone. The limestone sequence with Cedar Valley Formation on top yields well-defined 15,000-16,000 feet/second arrivals. Evidence is clear for a velocity inversion.

Four good seismic arrivals provide evidence for a refractor at a depth of about 11,000 feet. We have assigned a velocity of 17,000 feet/second; the data could equally well be satisfied with 16,000 feet/second, in which case depth to the refractor would be 500 feet greater.

A deeper refractor with velocity 19,000 feet/second is shown by two good secondary arrivals, although the evidence is weakened by failure to observe the expected arrivals on shots 5 and 7. The material is presumably crystalline basement. Shot 7 arrivals are too early by 100-150 ms with respect to the other shots; we have tentatively interpreted this as shallowing due to a fault.


LINE 58
TIME
(MILLISECONDS)
DISTANCE (FEET)
1.12 + x/23,000
.070 + x/15,000
(.80 + x/16,000)
25,000, Fair. Clear arrival.
23,000, poor. Clear arrival; very noisy record.
16,000-18,000, poor. Absent on Gl-2, large on G4-7. Critical distance at 20,500'
(19,000 ??) Very doubtful arrival.
15,000-16,000, good. Large clear arrival.
V = ?? Tiny; questionable arrival.
15,000, good. Small but clear.
13,000, good. Clear arrival.
13,000, poor. Tiny arrival.
Glenville, 3 m.
Albert Lea, 9 m.
3000'
1/2 m.
3/4 m.
2 m.
Minn.
Iowa
U.S.65
43°30'
93°15'
Line 58: Freeborn Co., Minn.
Vapp
(9800)
9100
4400
4700
675'



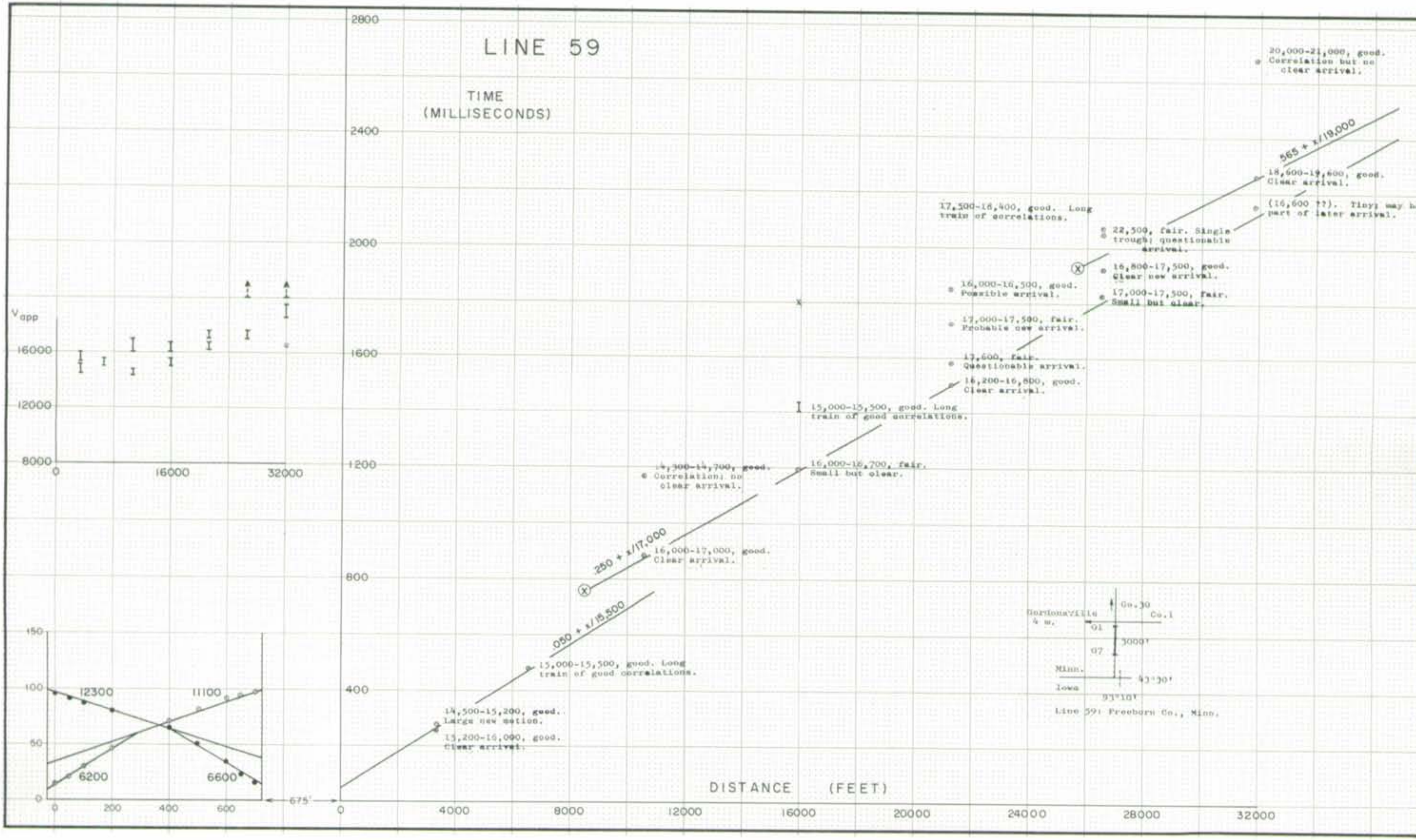
LINE 58

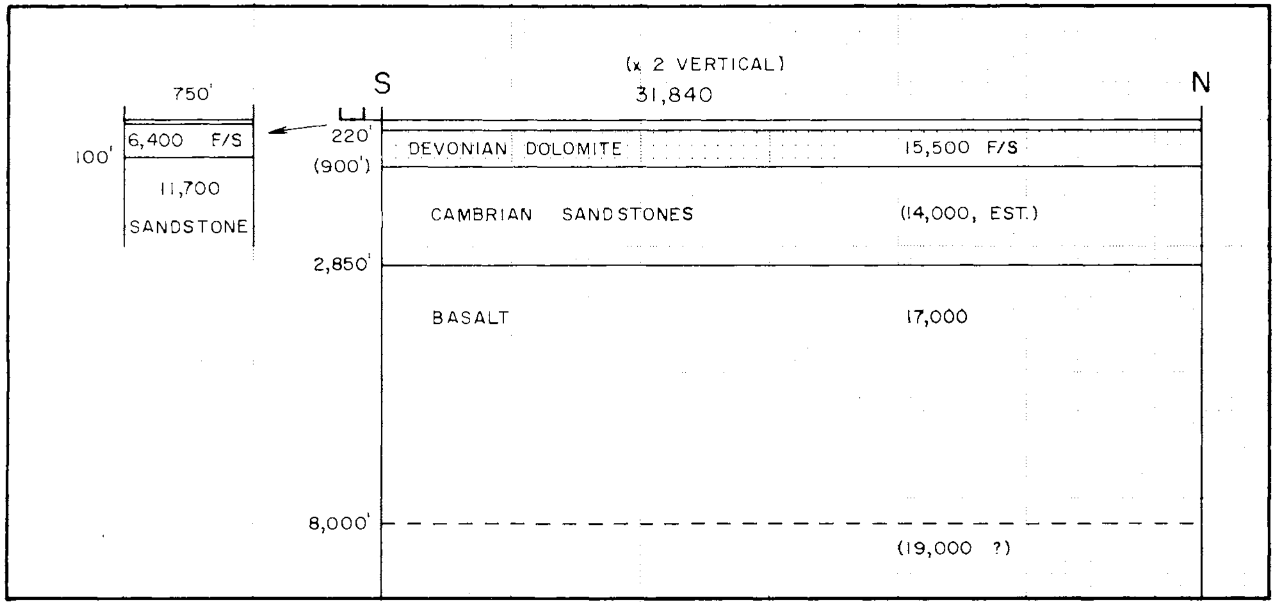
PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,250 feet.

RESULTS: The in-line data show 50 feet of drift underlain by roughly 100 feet of 9,400 feet/second material. From geological evidence, this is probably Cretaceous sandstone. Beneath this lies Cedar Valley Formation with velocity 15,000 feet/second.

The deeper structure is poorly defined by the seismic data. We have included a 16,000 feet/second layer on the basis of a single good arrival at shot 3, but other shots fail to verify it. Omission of this layer would have decreased depth to basement by 600 feet.

Shots 5 and 6 give unexpectedly high spread velocities of 23,000 feet/second; these are confirmed by the fact that the two arrivals lie on a 23,000 feet/second line. Although no definitive conclusion can be justified from only two points, we suggest that the basement at this location may be a mafic rock such as gabbro.


LINE 59
TIME
(MILLISECONDS)
DISTANCE (FEET)
565 + x/19,000
250 + x/17,000
.050 + x/15,500
20,000-21,000, good. Correlation but no clear arrival.
18,600-19,400, good. Clear arrival.
(16,600 ??). Tiny; may be part of later arrival.
17,500-18,400, good. Long train of correlations.
22,500, fair. Single trough; questionable arrival.
16,800-17,500, good. Clear new arrival.
16,000-16,500, good. Possible arrival.
17,000-17,500, fair. Small but clear.
17,000-17,500, fair. Probable new arrival.
17,600, fair. Questionable arrival.
16,200-16,800, good. Clear arrival.
15,000-15,500, good. Long train of good correlations.
16,000-16,700, fair. Small but clear.
14,300-14,700, good. Correlation; no clear arrival.
16,000-17,000, good. Clear arrival.
15,000-15,500, good. Long train of good correlations.
14,500-15,200, good. Large new motion.
15,200-16,000, good. Clear arrival.
Gordonsville 4 m.
Co.30
Co.1
91
07
3000'
Minn.
Iowa
43°30'
93°10'
Line 59: Freeborn Co., Minn.
V app
12300
11100
6200
6600
675'



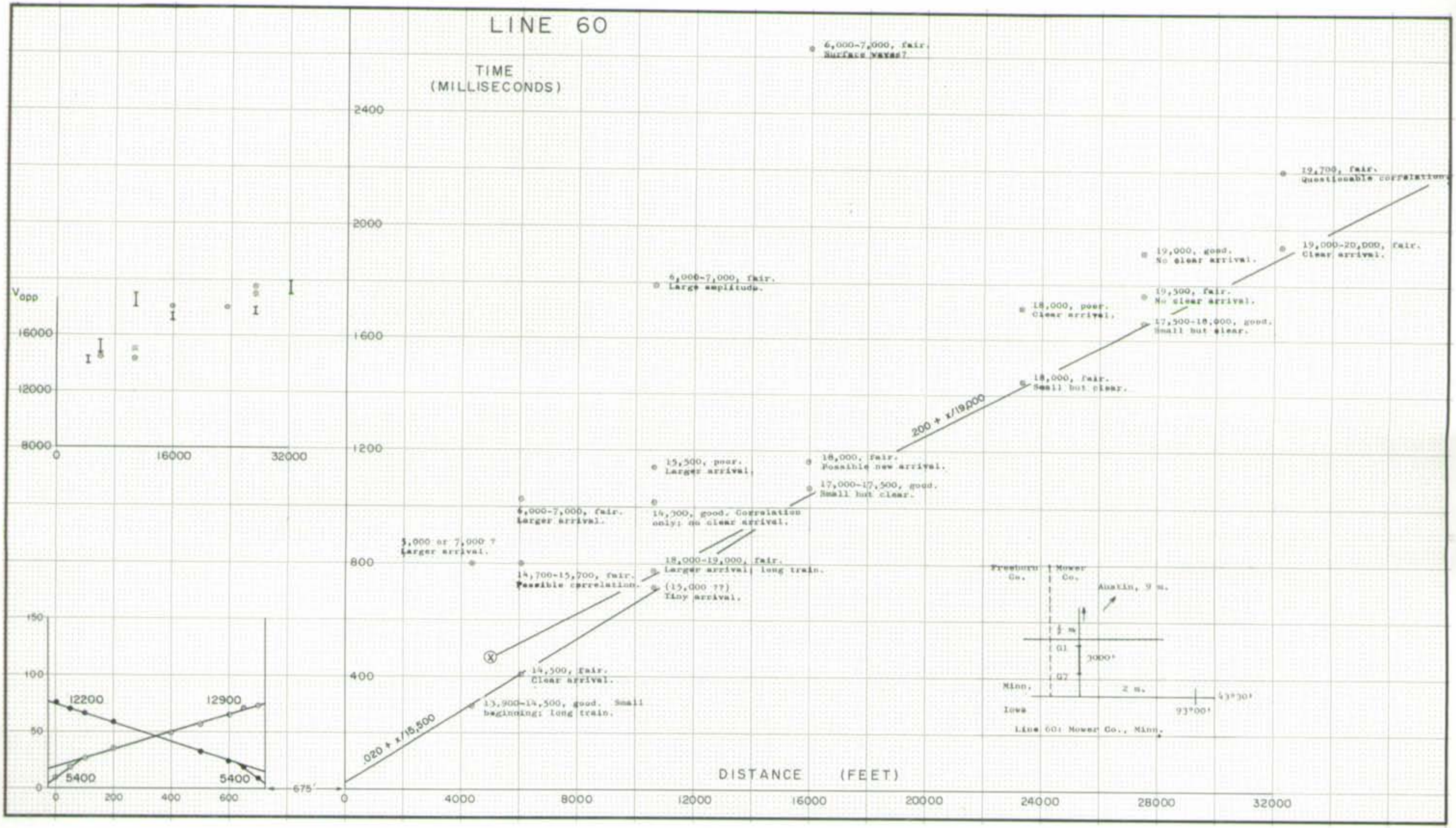
LINE 59

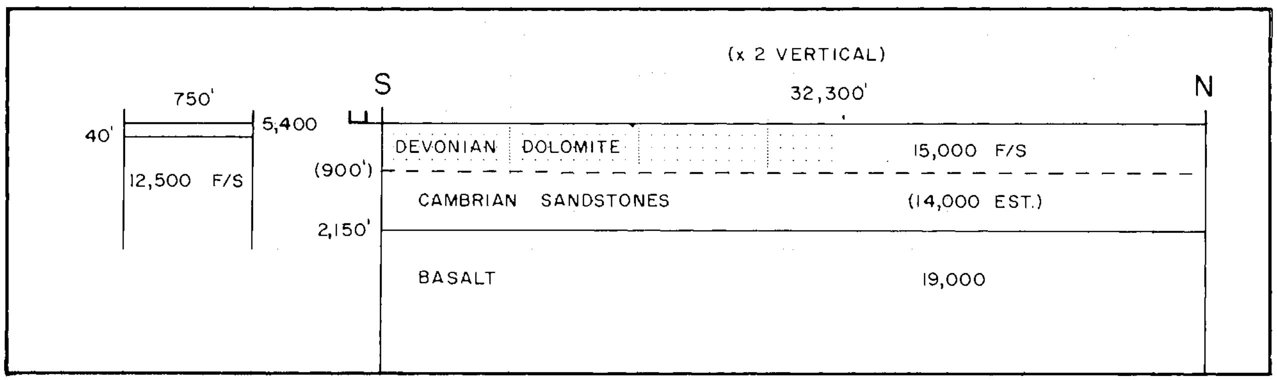
PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,275 feet.

RESULTS: 100 feet of drift overlies Cedar Valley Formation with well-defined velocity of 15,500 feet/second. In-line data suggest a possible thin layer of 11,700 feet/second material on top of the dolomite.

Excellent seismic data define a refractor with velocity 17,000 feet/second at a depth of about 2,800 feet. The most probable material for this velocity value would be basalt; it could not be intrusive igneous rock, and it is unlikely to be an indurated clastic.

The most distant shot gives a good arrival with spread velocity 19,000 feet/second. Earlier shots confirm this only poorly if at all. Computed depth is about 8,000 feet, but the reality of the refractor is open to question.


LINE 60
TIME (MILLISECONDS)
DISTANCE (FEET)
6,000-7,000, fair. Surface waves?
19,700, fair. Questionable correlation.
19,000-20,000, fair. Clear arrival.
19,000, good. No clear arrival.
19,500, fair. No clear arrival.
17,500-18,000, good. Small but clear.
18,000, poor. Clear arrival.
18,000, fair. Small but clear.
6,000-7,000, fair. Large amplitude.
200 + x/19,000
18,000, fair. Possible new arrival.
17,000-17,500, good. Small but clear.
15,500, poor. Larger arrival.
14,300, good. Correlation only; no clear arrival.
6,000-7,000, fair. Larger arrival.
5,000 or 7,000 ? Larger arrival.
18,000-19,000, fair. Larger arrival; long train.
14,700-15,700, fair. Possible correlation.
(15,000 ??) Tiny arrival.
14,500, fair. Clear arrival.
13,900-14,500, good. Small beginning; long train.
.020 + x/15,500
Freeborn Co.
Mower Co.
Austin, 9 m.
3000'
Minn.
Iowa
2 m.
43°30'
93°00'
Line 60: Mower Co., Minn.
Vapp
12200
12900
5400
5400
675'



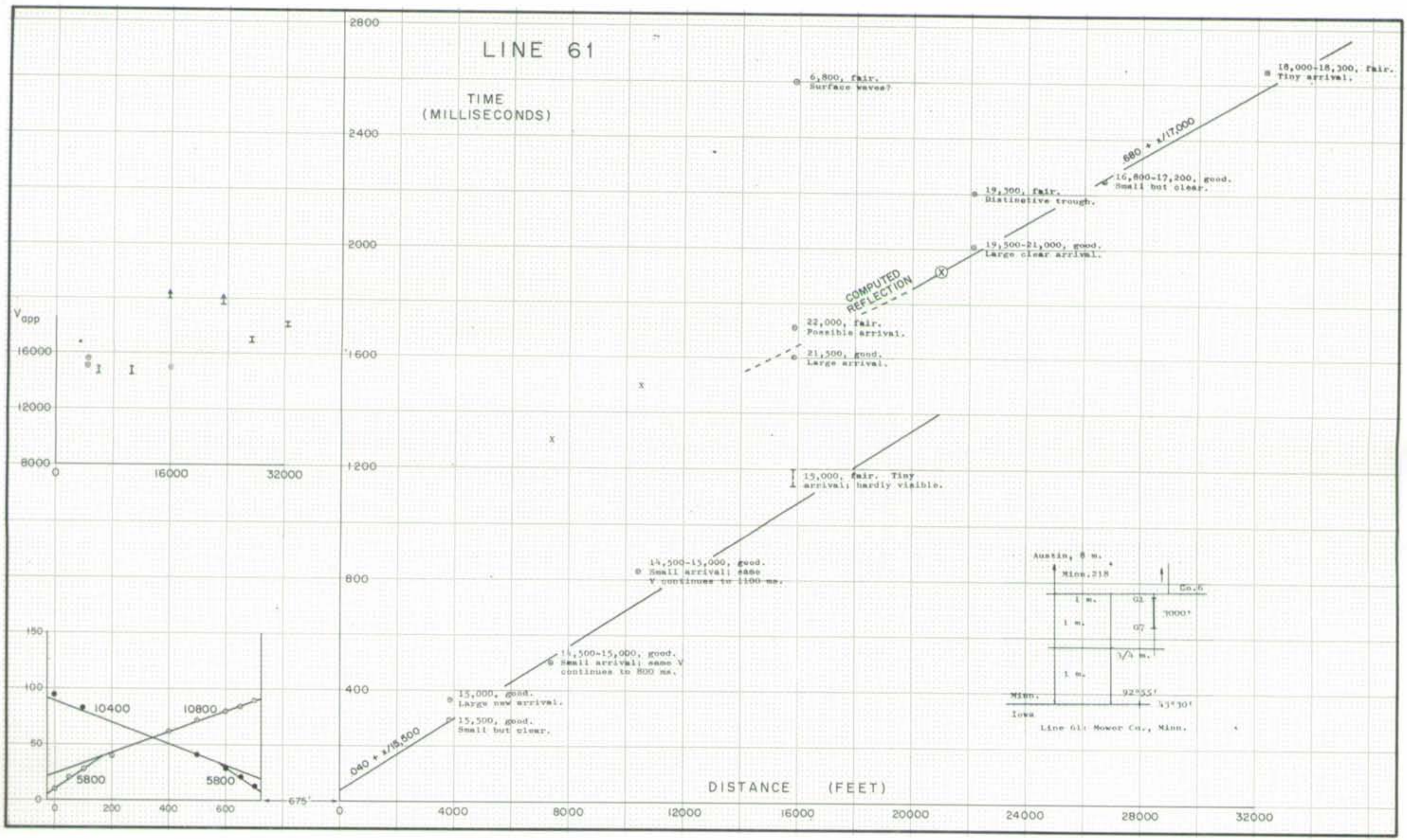
LINE 60

PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,200 feet.

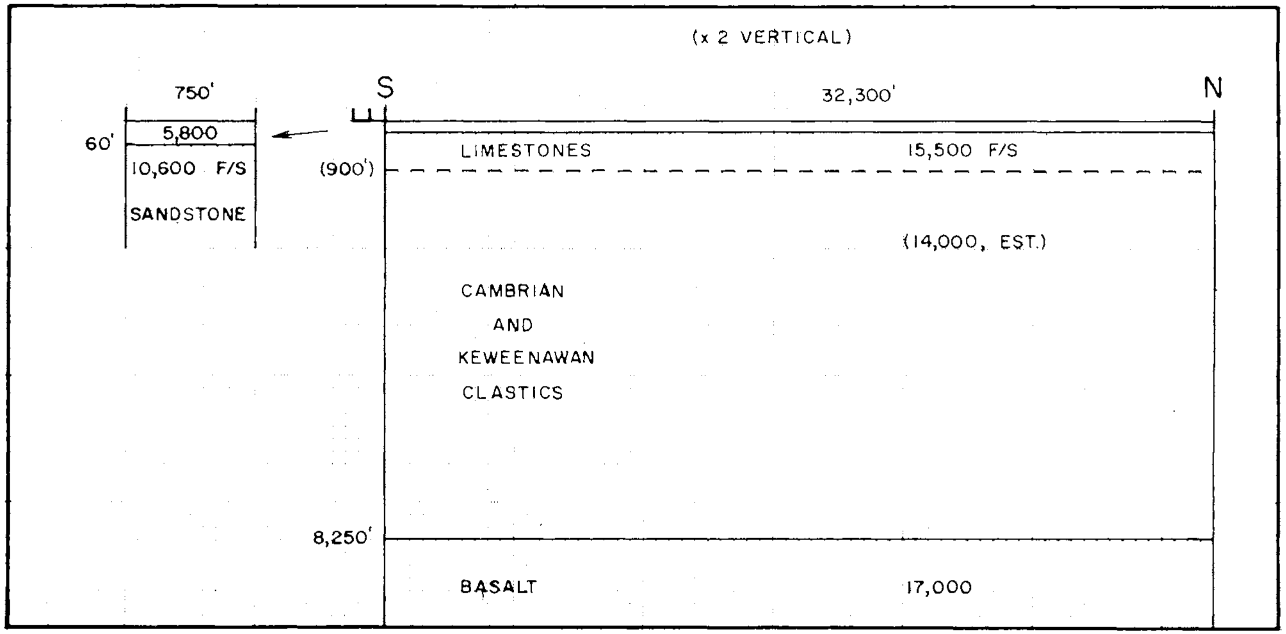
RESULTS: 50 feet of drift overlies Cedar Valley Formation with a velocity of about 15,000 feet/second. The in-line data suggest a thin layer of 12,500 feet/ second material, possibly Cretaceous sandstone, overlying the dolomite.

The seismic data do not show the characteristic offset which implies a velocity inversion, but we have assumed one to be present on the basis of adjoining lines. Omission of the inversion would have increased depth to basement by 300 feet.

Igneous basement at 2,150 feet depth is well determined by five first arrivals which fit a 19,000 feet/second line. No line with lower velocity will fit the data. Spread velocities range from 17,300 to 20,000 feet/second. We feel that the best velocity value to assign to this material is 19,000 feet/second, and that it differs significantly from 17,000 feet/second found at nearly the same depth on Line 59. On geological grounds, however, we are identifying both materials as basalt.



LINE 61
TIME (MILLISECONDS)
DISTANCE (FEET)
040 + x/15,500
680 + x/17,000
COMPUTED REFLECTION
6,800, fair. Surface waves?
18,000-18,300, fair. Tiny arrival.
16,800-17,200, good. Small but clear.
19,300, fair. Distinctive trough.
19,500-21,000, good. Large clear arrival.
22,000, fair. Possible arrival.
21,500, good. Large arrival.
15,000, fair. Tiny arrival; hardly visible.
14,500-15,000, good. Small arrival; same V continues to 1100 ms.
14,500-15,000, good. Small arrival; same V continues to 800 ms.
15,000, good. Large new arrival.
15,500, good. Small but clear.
V_{app}
10400
10800
5800
5800
675'
Austin, 8 m.
Minn. 218
Co. 6
1 m.
1 m.
1 m.
3/4 m.
3000'
92°55'
43°30'
Minn.
Iowa
Line 61: Mower Co., Minn.

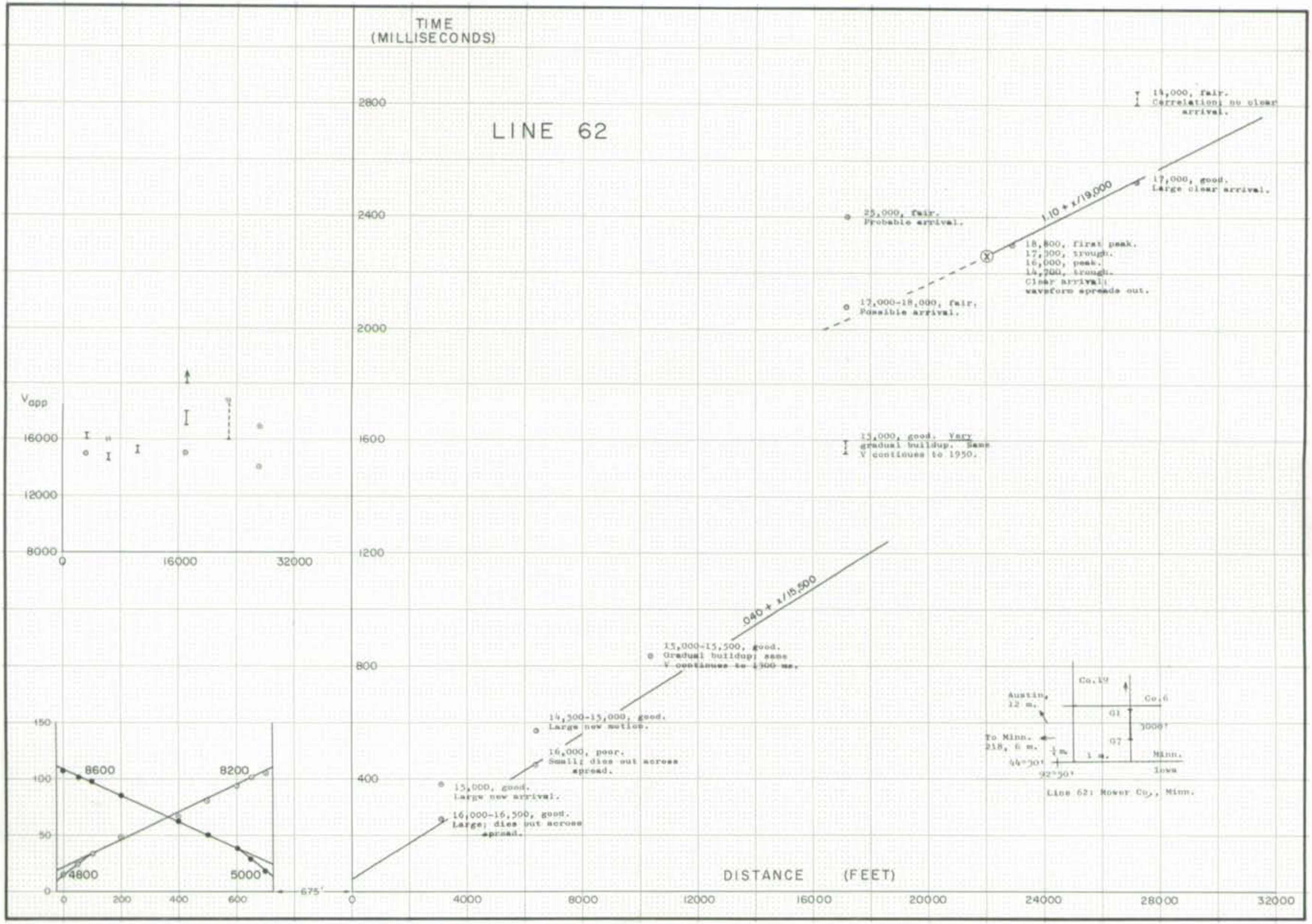


LINE 61

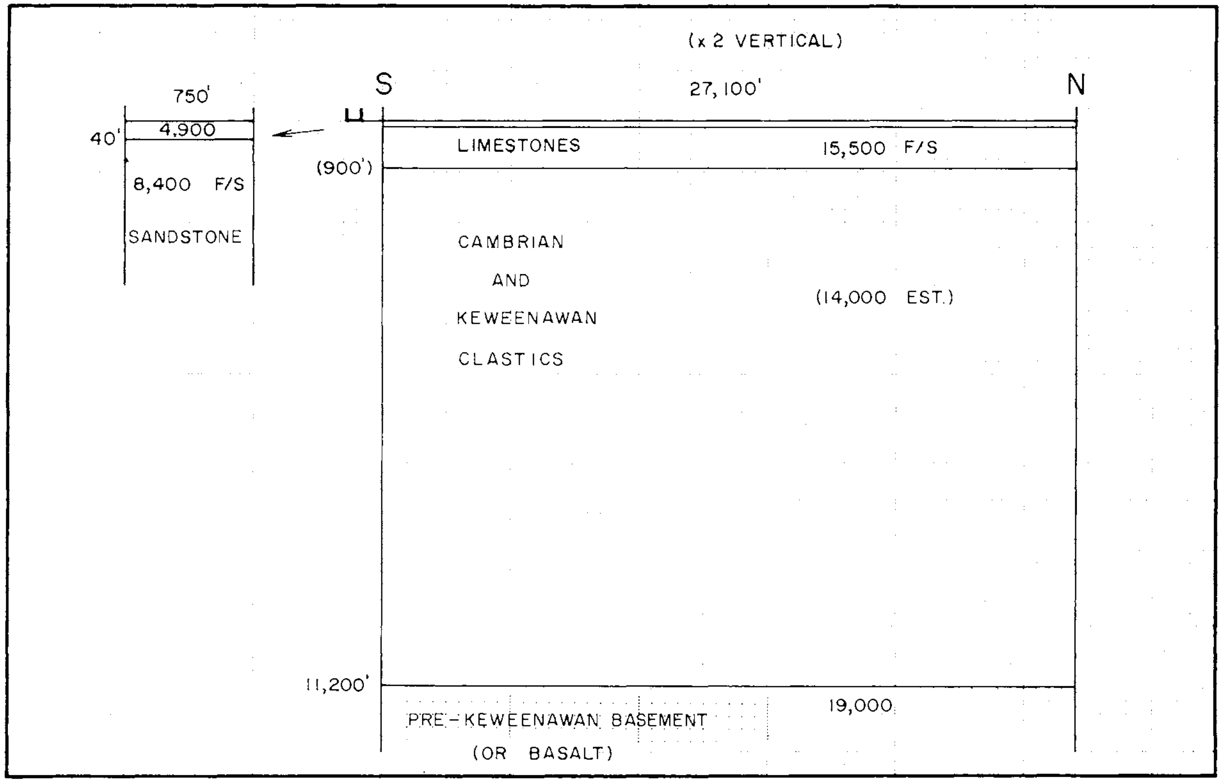
PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,225 feet.

RESULTS: Sixty feet of glacial drift overlies about 100 feet of 10,600 feet/second material, possibly Cretaceous sandstones. Beneath this lies Cedar Valley Formation with well-determined velocity of 15,000-15,500 feet/second. Secondary arrivals along a parallel velocity line may be P-to-S converted waves. A velocity inversion beneath the dolomite is indicated by offset of the travel time graph.

A high-velocity refractor is clearly shown by several good first arrivals, but the velocity to be assigned to it is less clear. We have chosen a 17,000 feet/second line to represent the data, but a 16,000 line would be possible. Spread velocities range from 17,000 to 21,000 feet/second so interpretation as a dipping horizon does not seem justified. A velocity of 17,000 feet/second would be identified as basalt.



LINE 62
TIME
(MILLISECONDS)
2800
2400
2000
1600
1200
800
400
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
32000
675'
14,000, fair.
Correlation; no clear
arrival.
17,000, good.
Large clear arrival.
1.10 + x/19,000
25,000, fair.
Probable arrival.
18,800, first peak.
17,300, trough.
16,000, peak.
14,700, trough.
Clear arrival;
waveform spreads out.
17,000-18,000, fair.
Possible arrival.
15,000, good. Very
gradual buildup. Same
V continues to 1950.
.040 + x/15,500
15,000-15,500, good.
Gradual buildup; same
V continues to 1300 ms.
14,500-15,000, good.
Large new motion.
16,000, poor.
Small; dies out across
spread.
15,000, good.
Large new arrival.
16,000-16,500, good.
Large; dies out across
spread.
Vapp
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
8600
8200
4800
5000
Co.19
Austin,
12 m.
Co.6
01
3000'
To Minn.
218, 6 m.
07
¼ m.
1 m.
Minn.
44°30'
92°30'
Iowa
Line 62: Mower Co., Minn.

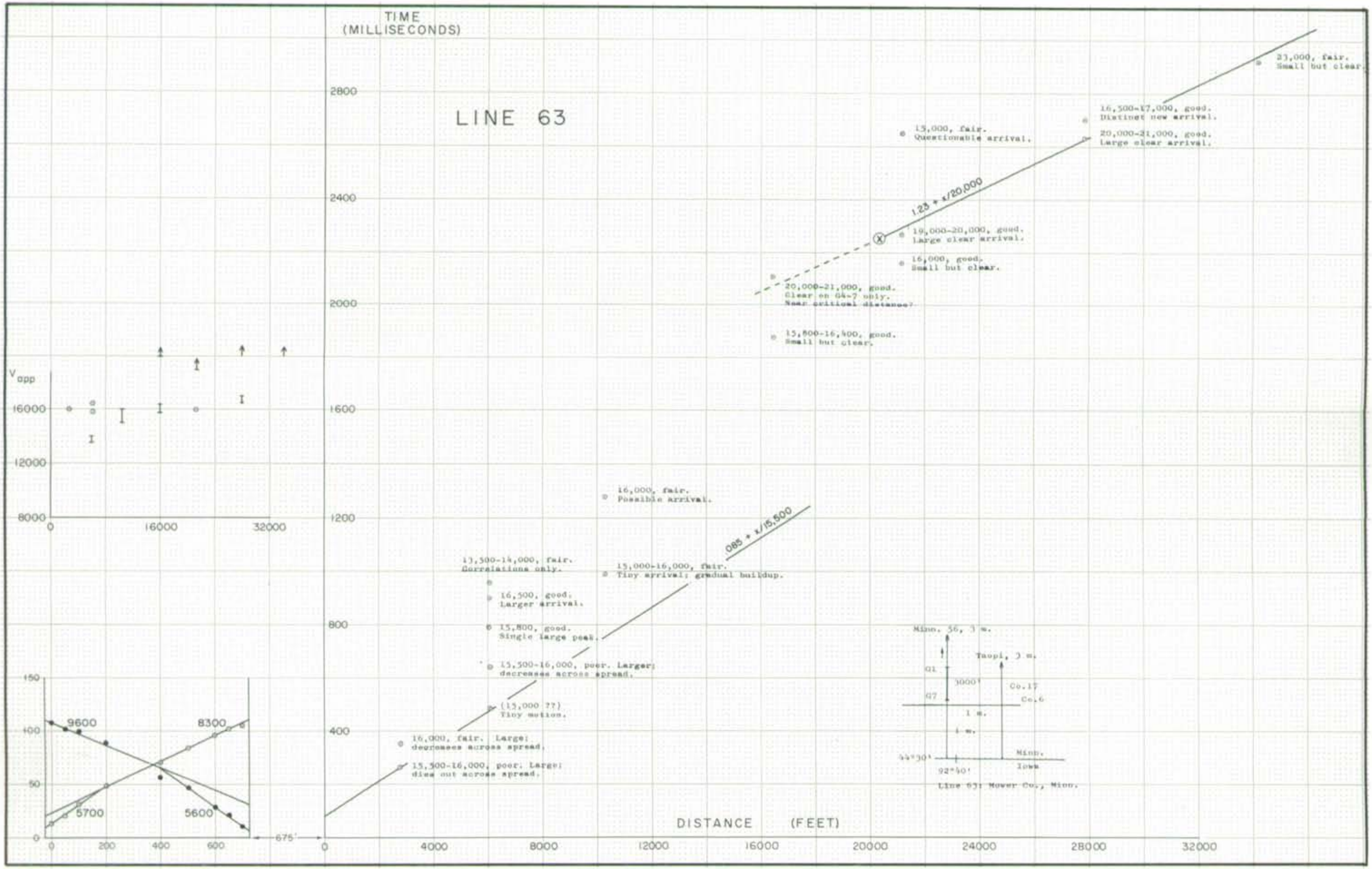


LINE 62

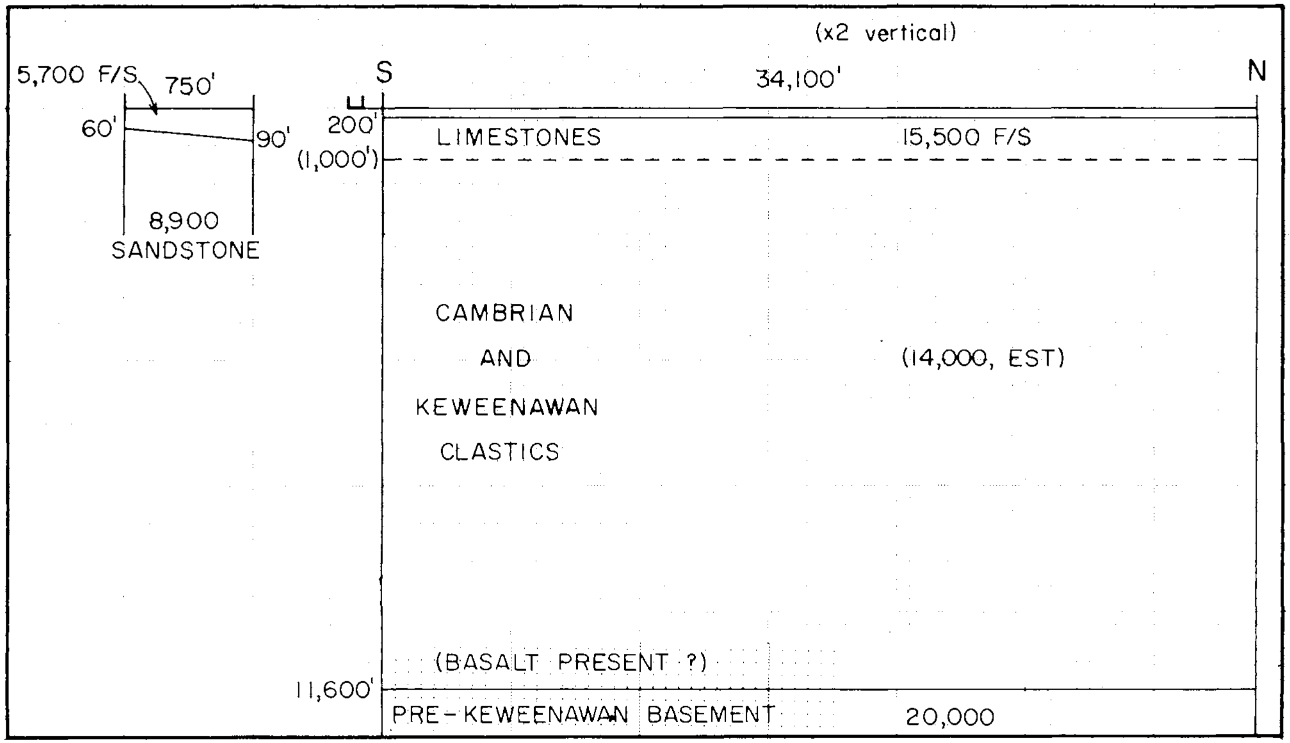
PURPOSE: See General Discussion, Lines 55-64. Mean surface elevation is 1,225 feet.

RESULTS: 40 feet of glacial drift overlies a few tens of feet of 8,400 feet/second material, possibly Cretaceous sandstone. Beneath this lies Cedar Valley Formation with velocity 15,500-16,000 feet/second. A velocity inversion is clearly shown.

The igneous basement appears as two good first arrivals and a secondary arrival. These fit adequately to a 19,000 feet/second line segment. A slightly lower velocity value is suggested by the apparent velocities across the spread, but a higher value rather than lower would be required to improve the fit of the line segment. A velocity of 19,000 feet/second is slightly high for basalt and slightly low for basement rock; we prefer the latter interpretation from correlation with Line 63, but basalt is also a possible identification.



TIME
(MILLISECONDS)
LINE 63
23,000, fair.
Small but clear.
16,500-17,000, good.
Distinct new arrival.
15,000, fair.
Questionable arrival.
20,000-21,000, good.
Large clear arrival.
1.23 + x/20,000
19,000-20,000, good.
Large clear arrival.
16,000, good.
Small but clear.
20,000-21,000, good.
Clear on 64-7 only.
Near critical distance?
15,800-16,400, good.
Small but clear.
16,000, fair.
Possible arrival.
.085 + x/15,500
13,500-14,000, fair.
Correlations only.
15,000-16,000, fair.
Tiny arrival; gradual buildup.
16,500, good.
Larger arrival.
15,800, good.
Single large peak.
15,500-16,000, poor. Larger;
decreases across spread.
(15,000 ??)
Tiny motion.
16,000, fair. Large;
decreases across spread.
15,500-16,000, poor. Large;
dies out across spread.
Minn. 56, 3 m.
Taopi, 3 m.
G1
3000'
G7
Co.17
Co.6
1 m.
Minn.
Iowa
92°40'
Line 63: Mower Co., Minn.
DISTANCE (FEET)
V_{app}
9600
8300
5700
5600
675



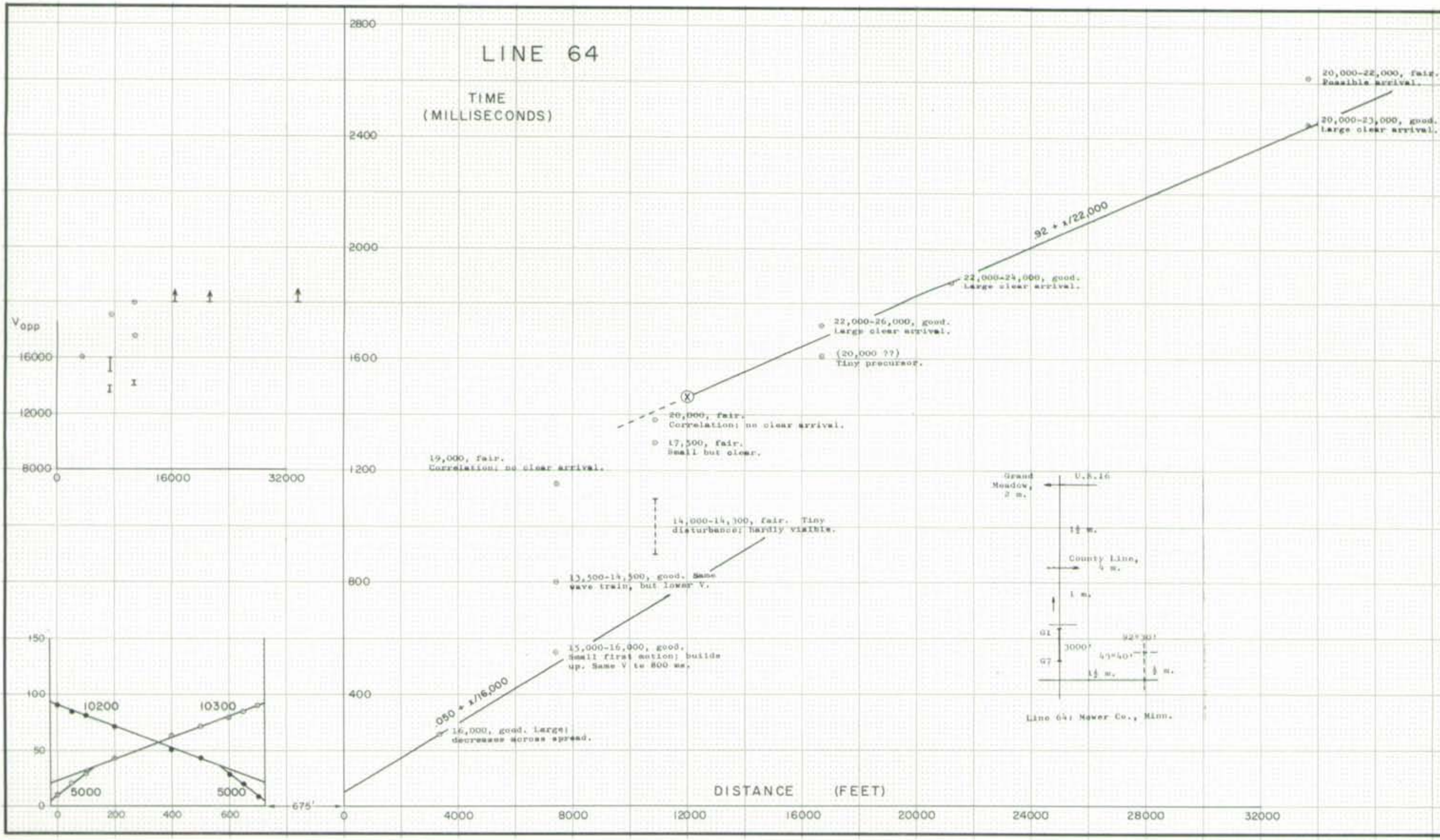
LINE 63

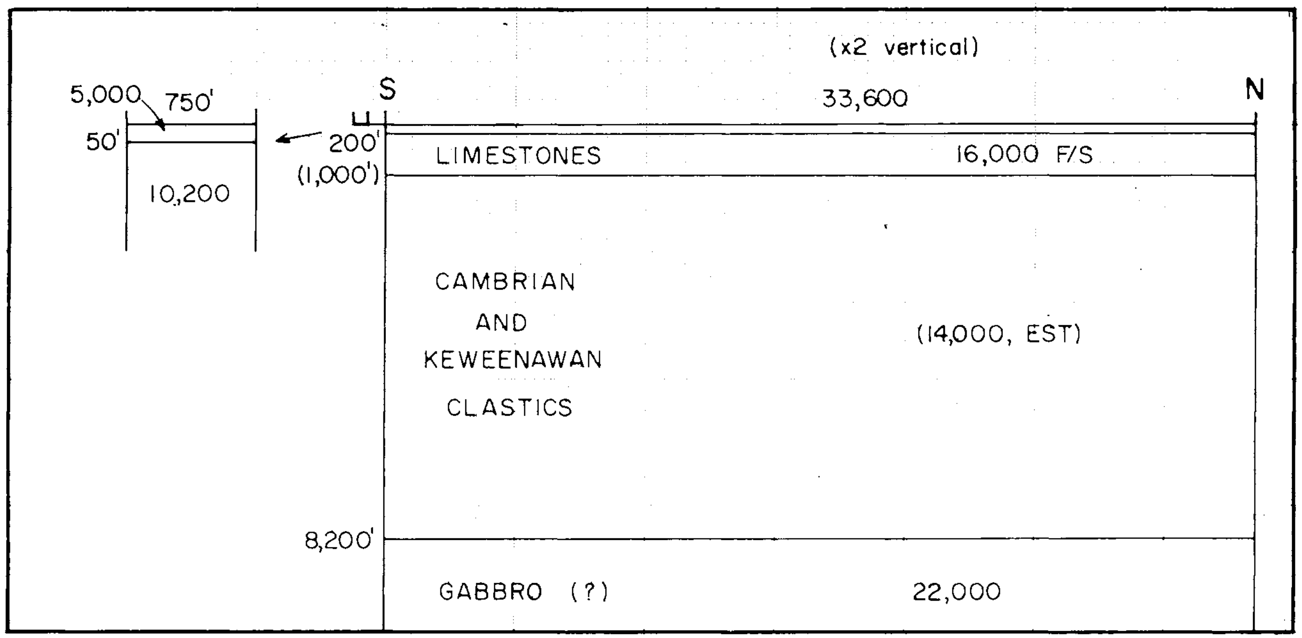
PURPOSE: Line 63 is the easternmost profile in the sequence 56-63. Mean surface elevation is 1,320 feet.

RESULTS: Drift thickness is about 75 feet. A layer of 9,000 feet/second material, perhaps as much as 200 feet thick, underlies the drift; this may be Cretaceous sandstone. The Cedar Valley Formation with velocity 15,500 feet/second is well defined, as is the velocity inversion associated with the underlying Cambrian sandstones.

Pre-Keweenawan basement is well represented by four first arrivals lying on a 20,000-21,000 feet/second line. This velocity value is too high for basalt. Computed depth is 11,600 feet.

The intermediate-depth section appears to contain 16,000 feet/second material, but we have been unable to fit it into the seismic interpretation. The four points fit best to a 13,000 feet/second line, but this would imply very large dips which are contradicted by the 20,000 feet/second arrivals. An attempt to include a 16,000 feet/second line leads to negative layer thicknesses. These arrivals could possibly represent some basalt on top of crystalline basement, but we are unable to define such a structure.


LINE 64
TIME
(MILLISECONDS)
DISTANCE (FEET)
.92 + x/22,000
.050 + x/16,000
20,000-22,000, fair. Possible arrival.
20,000-23,000, good. Large clear arrival.
22,000-24,000, good. Large clear arrival.
22,000-26,000, good. Large clear arrival.
(20,000 ??) Tiny precursor.
20,000, fair. Correlation: no clear arrival.
17,500, fair. Small but clear.
19,000, fair. Correlation: no clear arrival.
14,000-14,300, fair. Tiny disturbance; hardly visible.
13,500-14,500, good. Same wave train, but lower V.
15,000-16,000, good. Small first motion; builds up. Same V to 800 ms.
16,000, good. Large; decreases across spread.
Grand Meadow, 2 m.
U.S.16
County Line, ¼ m.
1 m.
3000'
Line 64: Mower Co., Minn.
V_{opp}
10200
10300
5000
5000
675'

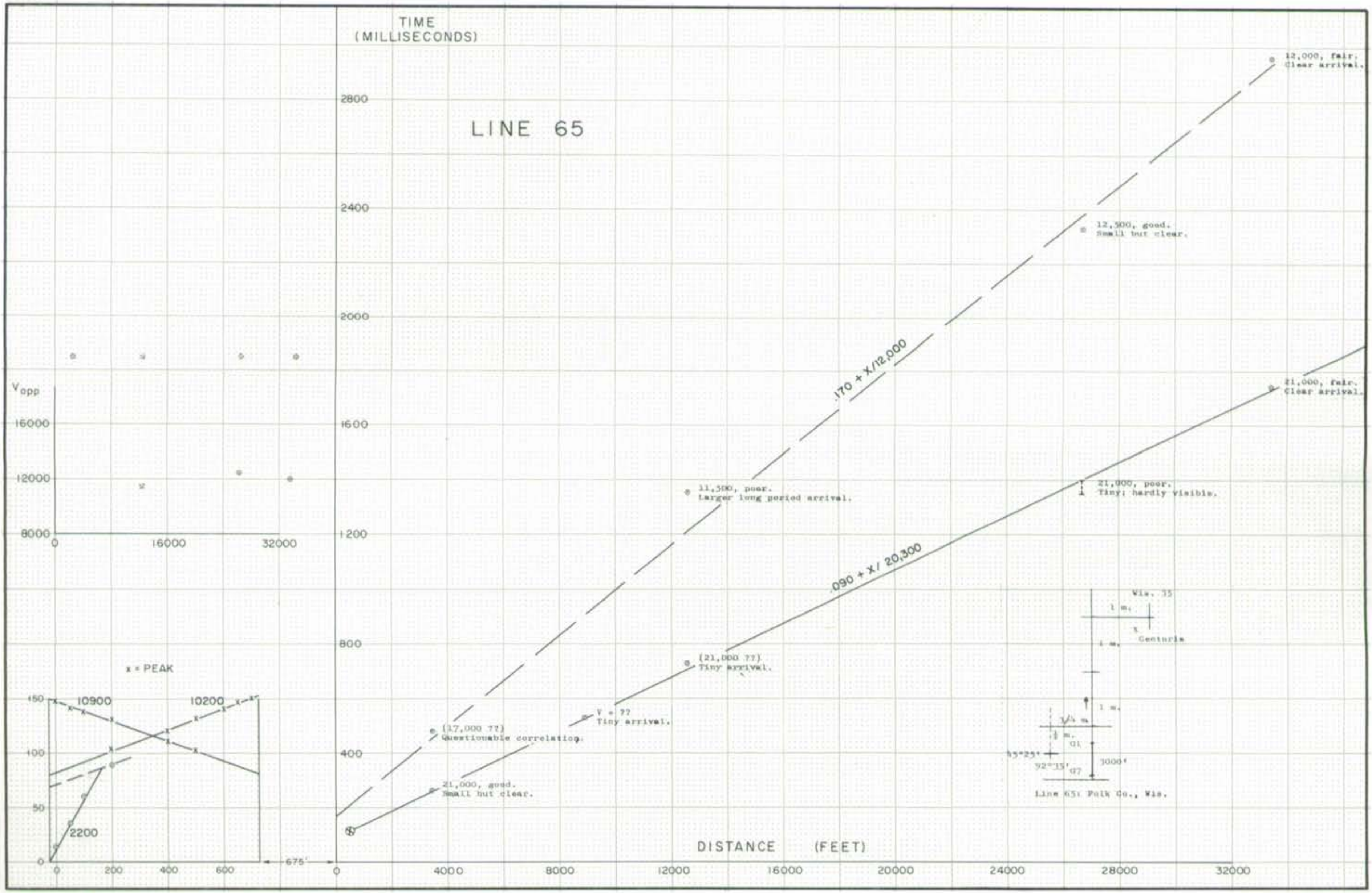


LINE 64

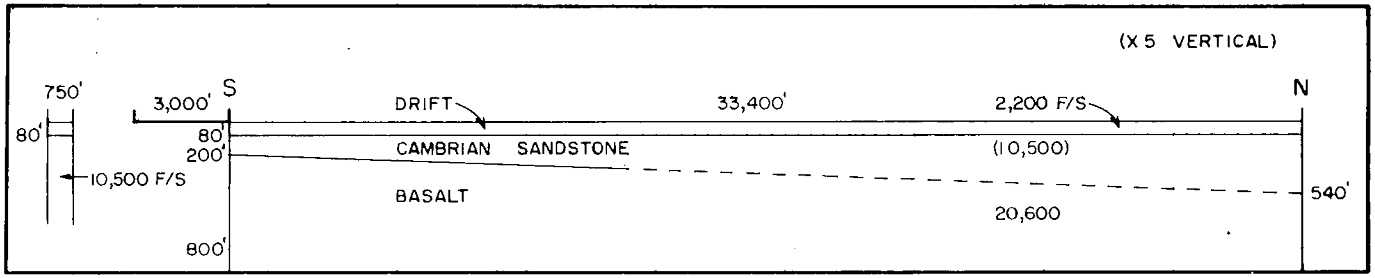
PURPOSE: Line 64 is located on a prominent positive magnetic anomaly. The purpose is to obtain information concerning the geologic cause of the anomaly. Line 64 lies 9 miles northward of the main sequence of profiles. Mean surface elevation is 1,350 feet.

RESULTS: The near-surface data show 50 feet of glacial drift and 100-150 feet of 10,200 feet/second material overlying the Cedar Valley Formation. A major offset of the travel time graph reveals a velocity inversion produced by the Cambrian sandstones.

Crystalline basement at a depth of 8,200 feet is defined by excellent data with velocity 22,000 feet/second. The high velocity value implies a mafic igneous intrusive such as gabbro; it is certainly not basalt and probably not a felsic intrusive. This interpretation, together with the much shallower depth compared with Line 63, suffices to explain the observed magnetic anomaly. Gabbro was encountered at a depth of 724 feet in a well near Peterson, 30 miles east of Line 64.



LINE 65
TIME (MILLISECONDS)
DISTANCE (FEET)
.170 + X/12,000
.090 + X/ 20,300
12,000, fair. Clear arrival.
12,500, good. Small but clear.
21,000, fair. Clear arrival.
21,000, poor. Tiny; hardly visible.
11,500, poor. Larger long period arrival.
(21,000 ??) Tiny arrival.
V = ?? Tiny arrival.
(17,000 ??) Questionable correlation.
21,000, good. Small but clear.
V app
x = PEAK
10900
10200
2200
675'
Wis. 35
Centuria
3000'
Line 65: Polk Co., Wis.



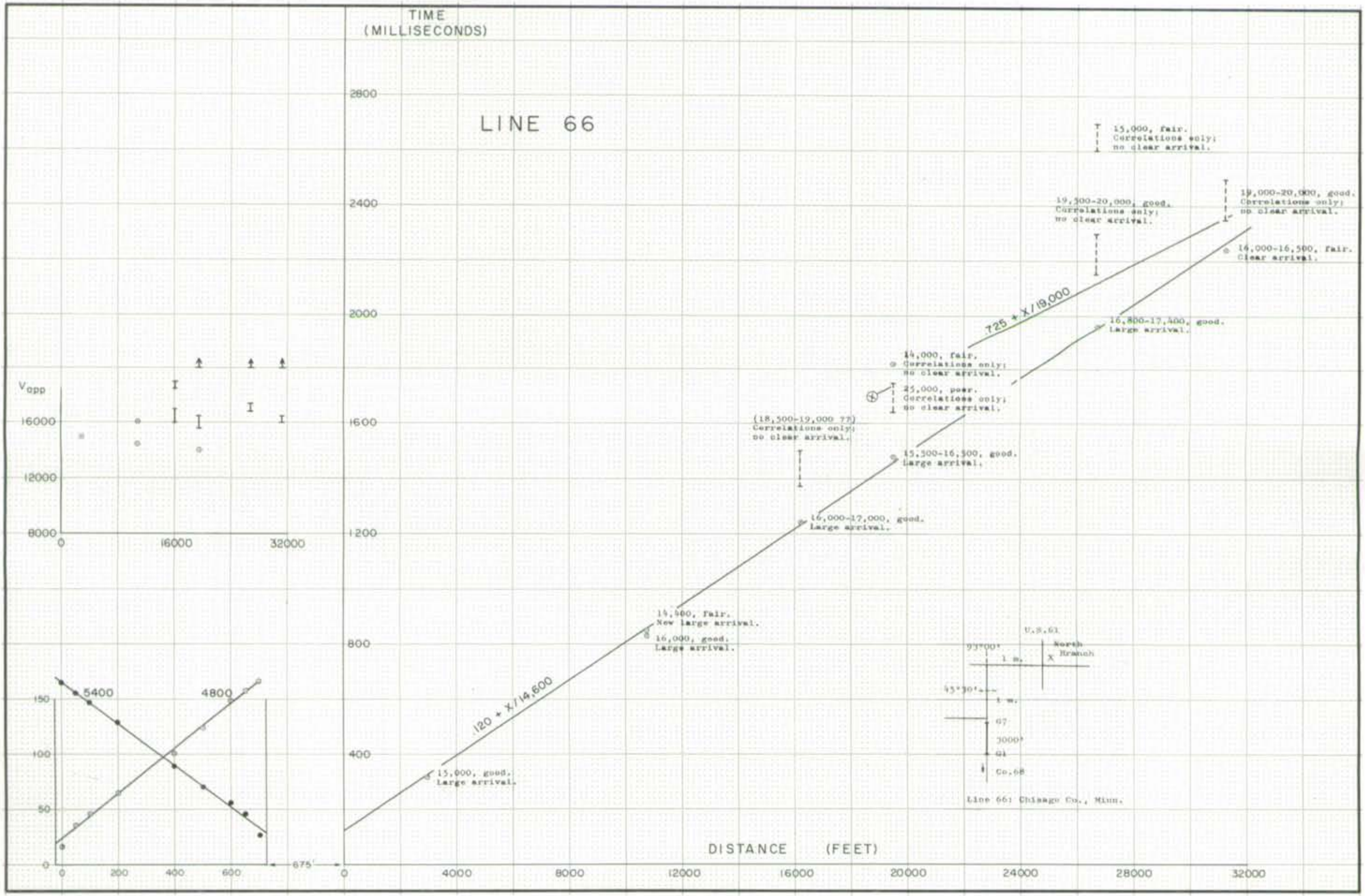
LINE 65

PURPOSE: This line was shot along the crest of the St. Croix Horst in an attempt to detect higher velocity refractors within the basalt or a higher velocity granitic basement beneath the basalt. Mean surface elevation is 1,250 feet.

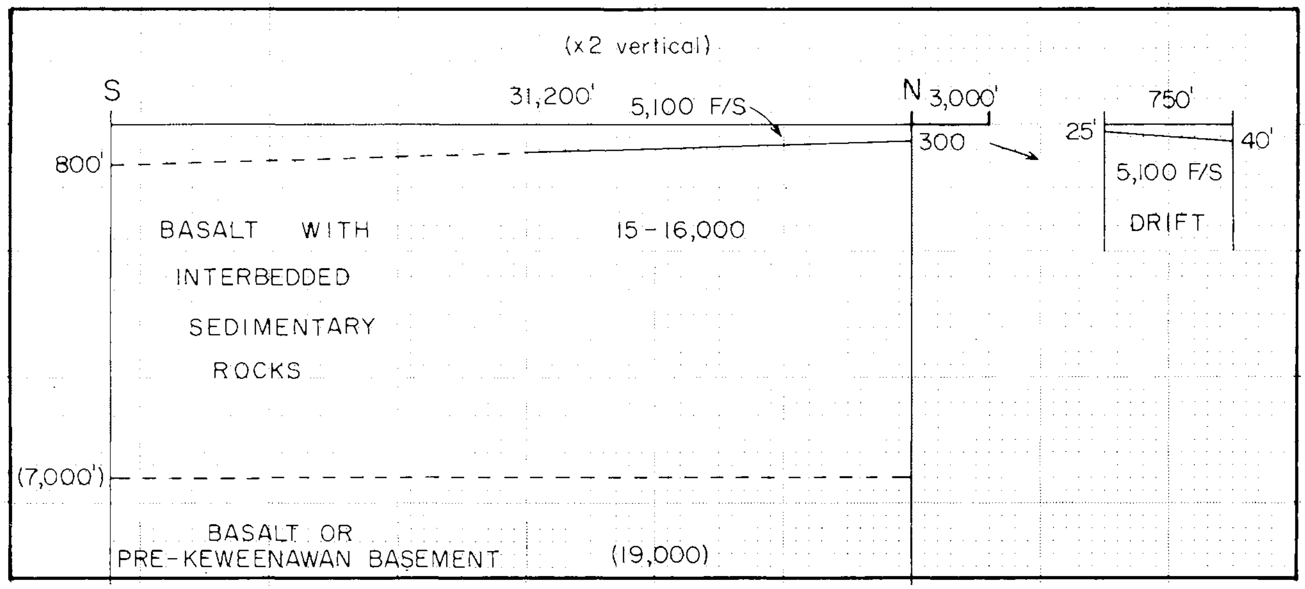
RESULTS: The data show a single high-velocity refractor, at the shallow depth expected for basalt in this area. The velocity value of 20,600 feet/second is unexpectedly high, however. This raises a question as to whether the material differs in some wav from that encountered on Lines 21-24 nearby which show velocities of 18,000-19,000 feet/second. The most likely explanation would be a slightly denser or more compact basalt or an intrusive within the basalt; the observed velocity would be compatible with a gabbro or a granite.

The data suggest the presence of a lower velocity material (in the 10,000 to 12,000 feet/second range) overlying the basalt. From nearby well data, this is identified as Cambrian sandstone.

A depth of about 200 feet to basalt at the south end is well established. The inferred depth of about 500 feet at the north end is less certain.



TIME
(MILLISECONDS)
LINE 66
15,000, fair.
Correlations only;
no clear arrival.
19,000-20,000, good.
Correlations only;
no clear arrival.
19,500-20,000, good.
Correlations only;
no clear arrival.
16,000-16,500, fair.
Clear arrival.
725 + X/19,000
16,800-17,400, good.
Large arrival.
14,000, fair.
Correlations only;
no clear arrival.
25,000, poor.
Correlations only;
no clear arrival.
(18,500-19,000 ??)
Correlations only;
no clear arrival.
15,500-16,500, good.
Large arrival.
16,000-17,000, good.
Large arrival.
14,400, fair.
New large arrival.
16,000, good.
Large arrival.
120 + X/14,600
15,000, good.
Large arrival.
U.S.61
93°00'
1 m.
North Branch
45°30'
1 m.
67
3000'
61
Co.68
Line 66: Chisago Co., Minn.
V_{app}
5400
4800
675'
DISTANCE (FEET)



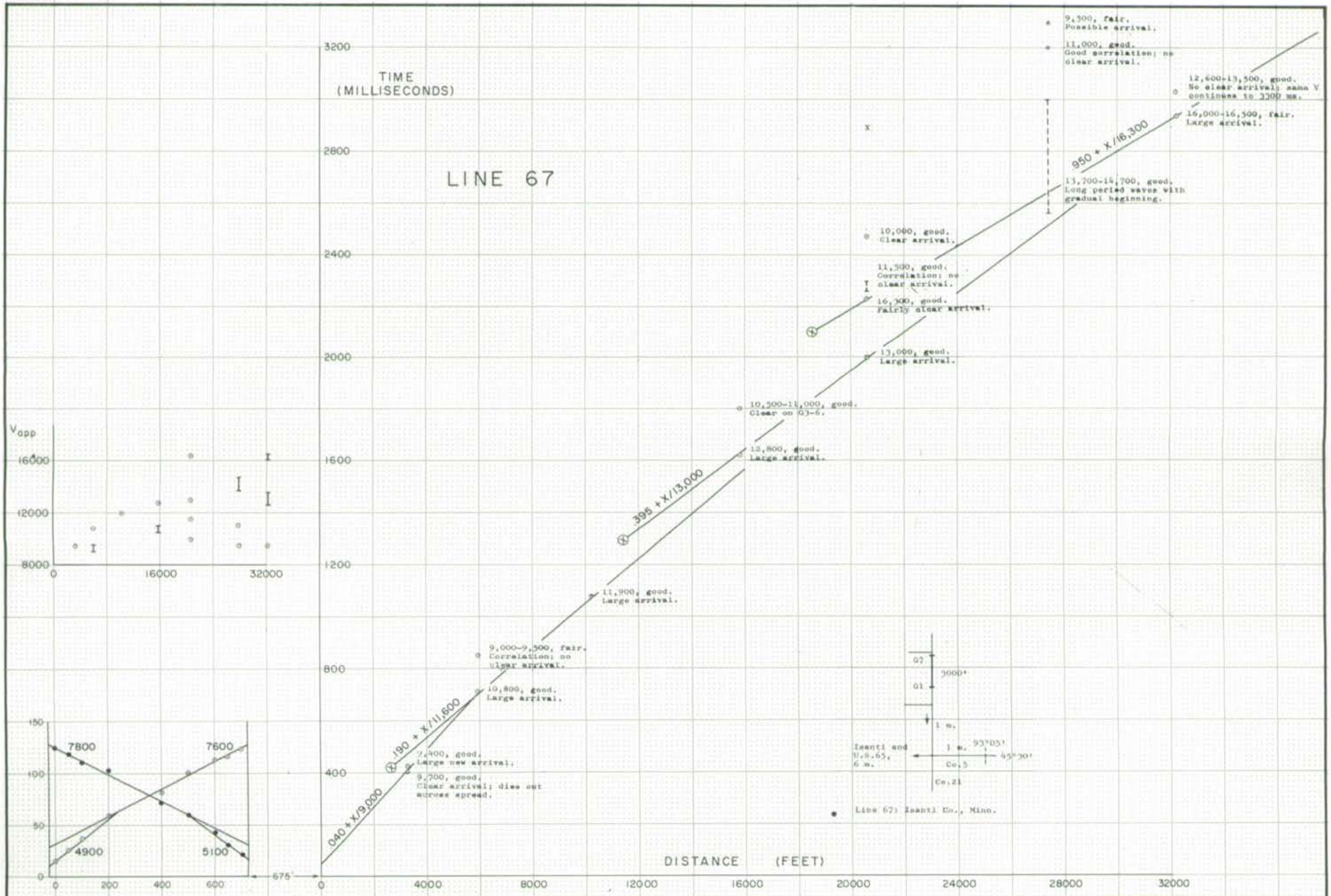
LINE 66

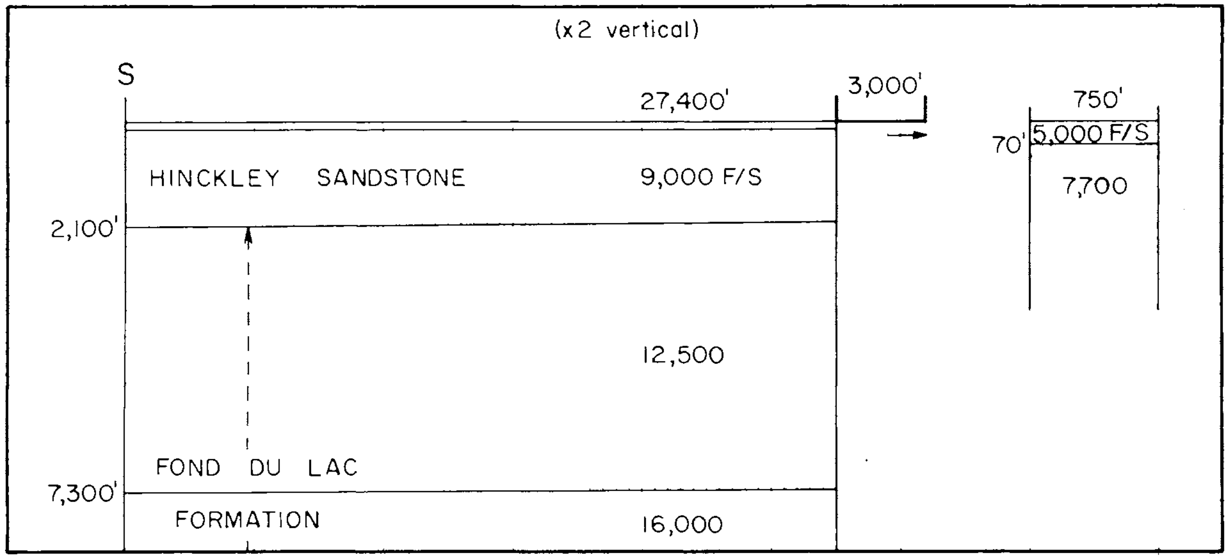
PURPOSE: See Line 19. From the magnetic data, this line appears to lie about 1 mile east of the Douglas Fault and about 1 mile west of the west margin of the supposed sedimentary basin within the St. Croix Horst. Steep magnetic gradients indicate basalt at shallow depth. Mean surface elevation is 950 feet.

RESULTS: Excellent data show the presence of a great thickness of approximately 15,000 feet/second material. The surface appears to dip slightly to the south, with about 300 feet of drift cover at the north end. A thin sandstone cover is probably present but undetected beneath the drift.

Identification of the material is a puzzle. Along-line velocity is very well defined at 14,600 feet/second; spread velocity is 16-17,000 with a resulting mean velocity of 15,300 feet/second. We would identify this as Keweenawan clastic sedimentary rocks, except that the magnetic gradients strongly suggest shallow basalt. We have therefore interpreted this material as basalt with interbedded sedimentary rocks.

A group of secondary seismic arrivals suggest 19-20,000 feet/second material at a depth of roughly 7,000 feet.


LINE 67
TIME
(MILLISECONDS)
DISTANCE (FEET)
040 + X/9,000
.190 + X/11,600
395 + X/13,000
950 + X/16,300
9,300, fair.
Possible arrival.
11,000, good.
Good correlation; no
clear arrival.
12,600-13,500, good.
No clear arrival; same V
continues to 3300 ms.
16,000-16,500, fair.
Large arrival.
13,700-14,700, good.
Long period waves with
gradual beginning.
10,000, good.
Clear arrival.
11,500, good.
Correlation; no
clear arrival.
16,300, good.
Fairly clear arrival.
13,000, good.
Large arrival.
10,500-11,000, good.
Clear on G3-6.
12,800, good.
Large arrival.
11,900, good.
Large arrival.
9,000-9,500, fair.
Correlation; no
clear arrival.
10,800, good.
Large arrival.
7,400, good.
Large new arrival.
9,700, good.
Clear arrival; dies out
across spread.
Isanti and
U.S.65,
6 m.
Line 67: Isanti Co., Minn.
V_{app}
7800
7600
4900
5100
675'

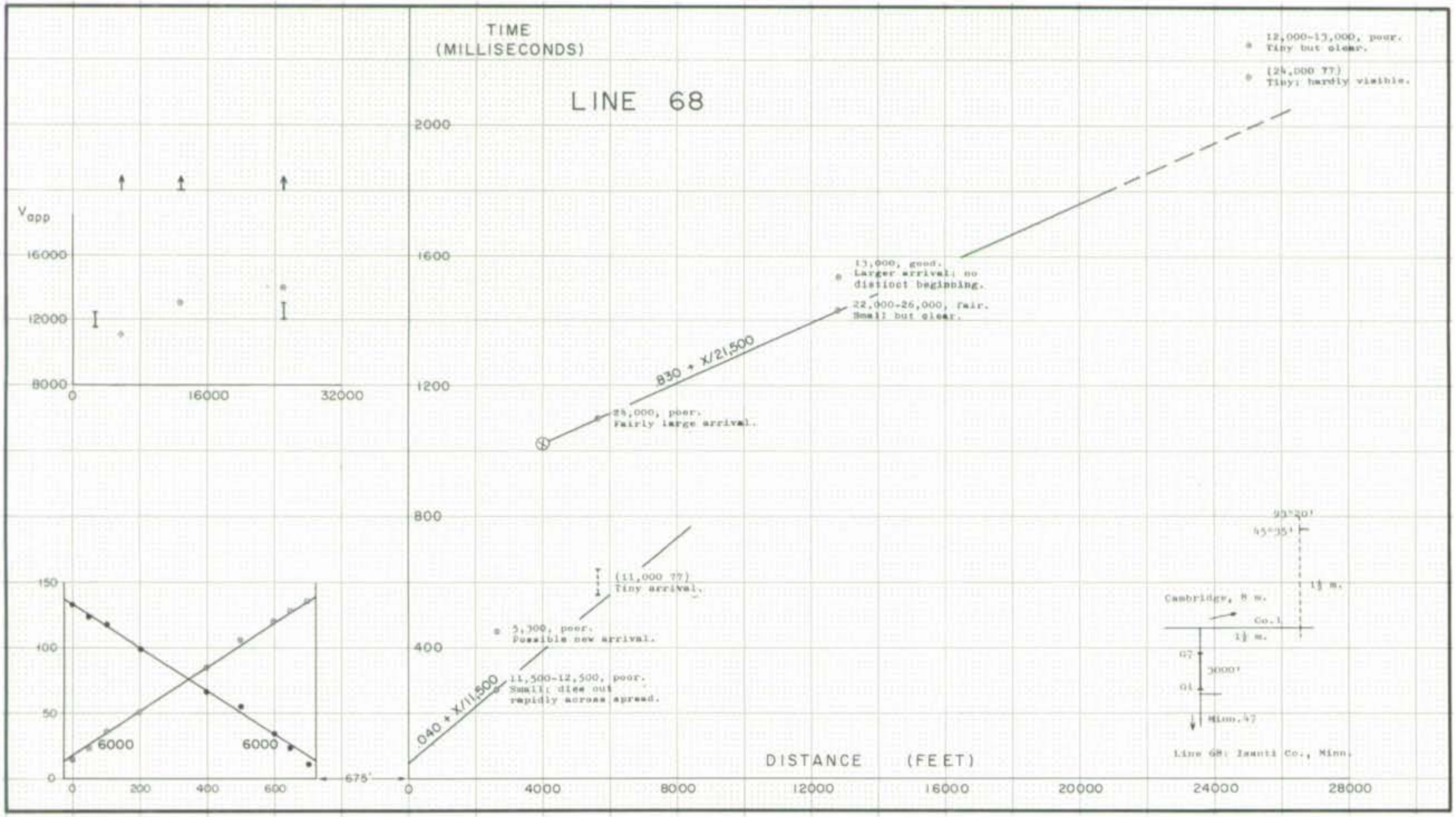


LINE 67

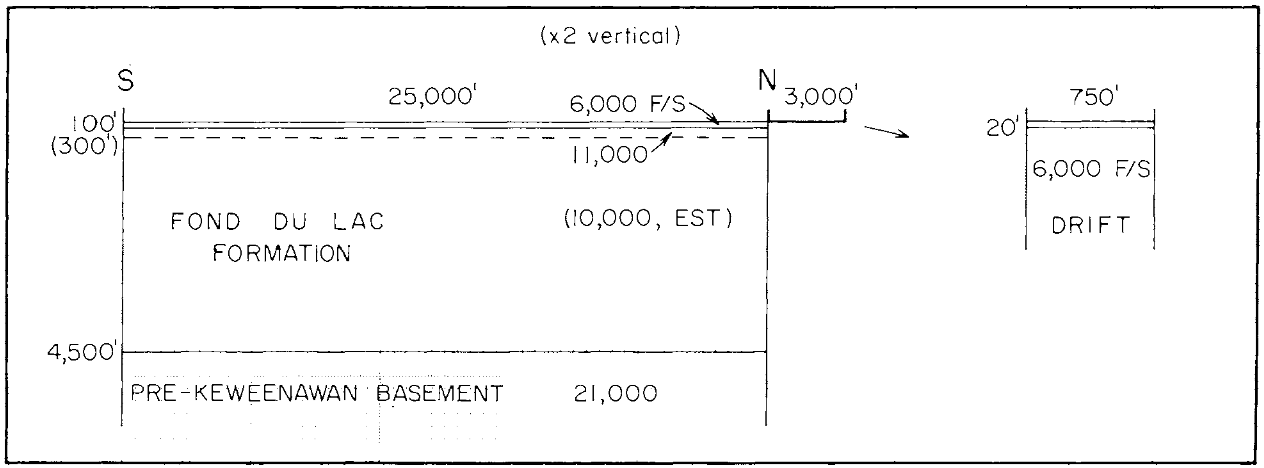
PURPOSE: See Line 19. Mean surface elevation is 975 feet.

RESULTS: Seismic travel times are similar to those for Line 19, except for the absence on Line 67 of velocities higher than 16,000 feet/second. This presumably results from the lesser length of Line 67, although 18,000 and 21,000 feet/second velocities if present should have appeared as second arrivals.

Hinckley Sandstone with a velocity of 9,000 feet/second lies immediately beneath 70 feet of drift. Great thickness of the upper part of the Fond du Lac Formation is indicated by numerous good arrivals. These may be fitted by two separate line segments with slightly different velocities, but we have computed the section using a single 12,500 feet/second layer. Two good 16,000 feet/second arrivals, confirmed by a third on Line 19, show the lower part of the Fond du Lac Formation at a depth of about 7,300 feet.



TIME
(MILLISECONDS)
LINE 68
12,000-13,000, poor.
Tiny but clear.
(24,000 ??)
Tiny; hardly visible.
13,000, good.
Larger arrival; no
distinct beginning.
22,000-26,000, fair.
Small but clear.
830 + X/21,500
25,000, poor.
Fairly large arrival.
(11,000 ??)
Tiny arrival.
5,300, poor.
Possible new arrival.
11,500-12,500, poor.
Small; dies out
rapidly across spread.
040 + X/11,500
DISTANCE (FEET)
V_{app}
6000
6000
675'
Cambridge, 8 m.
Co. 1
1½ m.
1½ m.
93°20'
45°35'
G7
3000'
G1
Minn. 47
Line 68: Isanti Co., Minn.

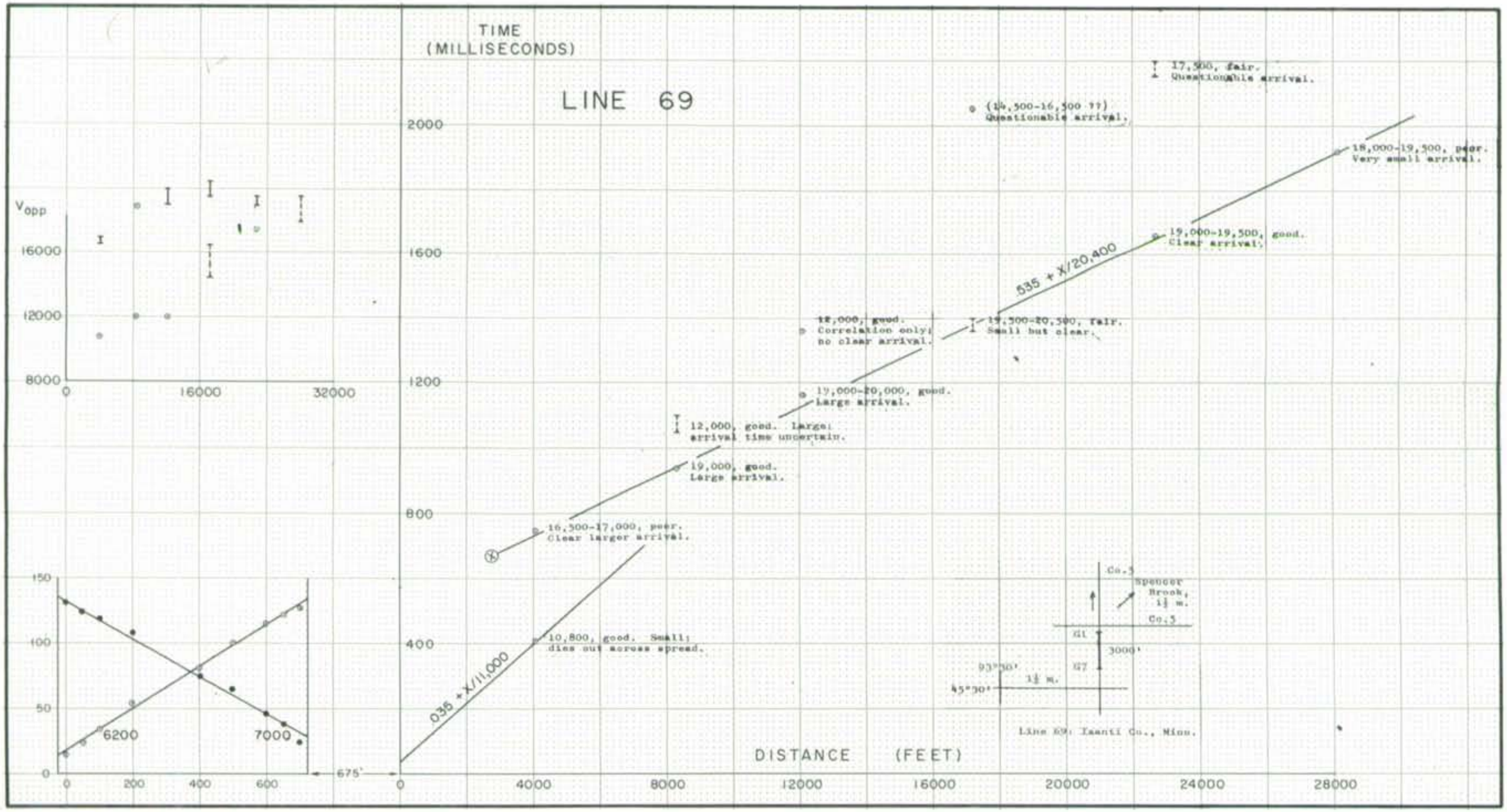


LINE 68

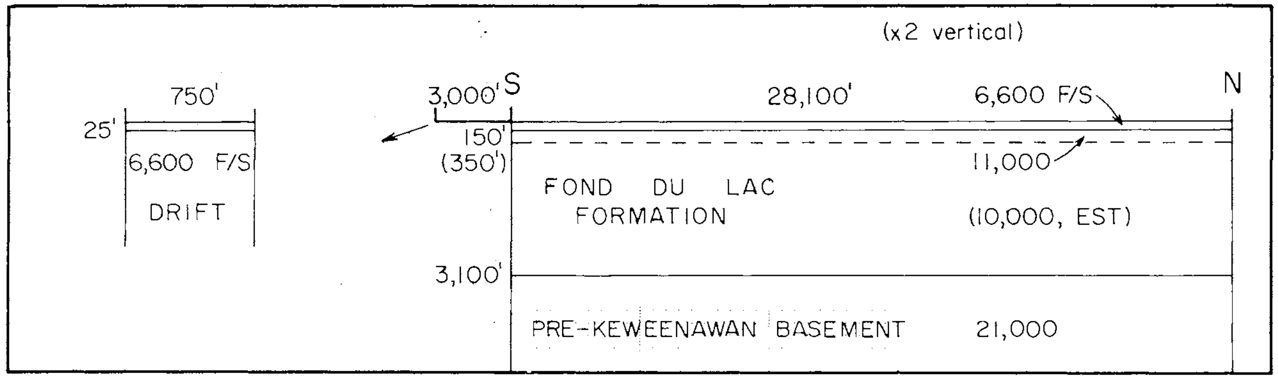
PURPOSE: See Line 19. Mean surface elevation is 950 feet.

RESULTS: A velocity inversion within the sedimentary section is indicated by (a) an 11,000-11,500 feet/second arrival which attenuates rapidly, and (b) a large time delay from this arrival to the high-velocity refractor arrival. Depth to the igneous basement is computed as 4,500 feet using a low-velocity layer value of 10,000 feet/second. A value of 9,000 feet/second would have decreased basement depth by 500 feet.

Arrivals from the most distant shot are delayed with respect to the earlier shots. This may be due to a lateral variation in the section. The arrivals are barely visible on the record, however, so earlier arrivals may have been undetected.



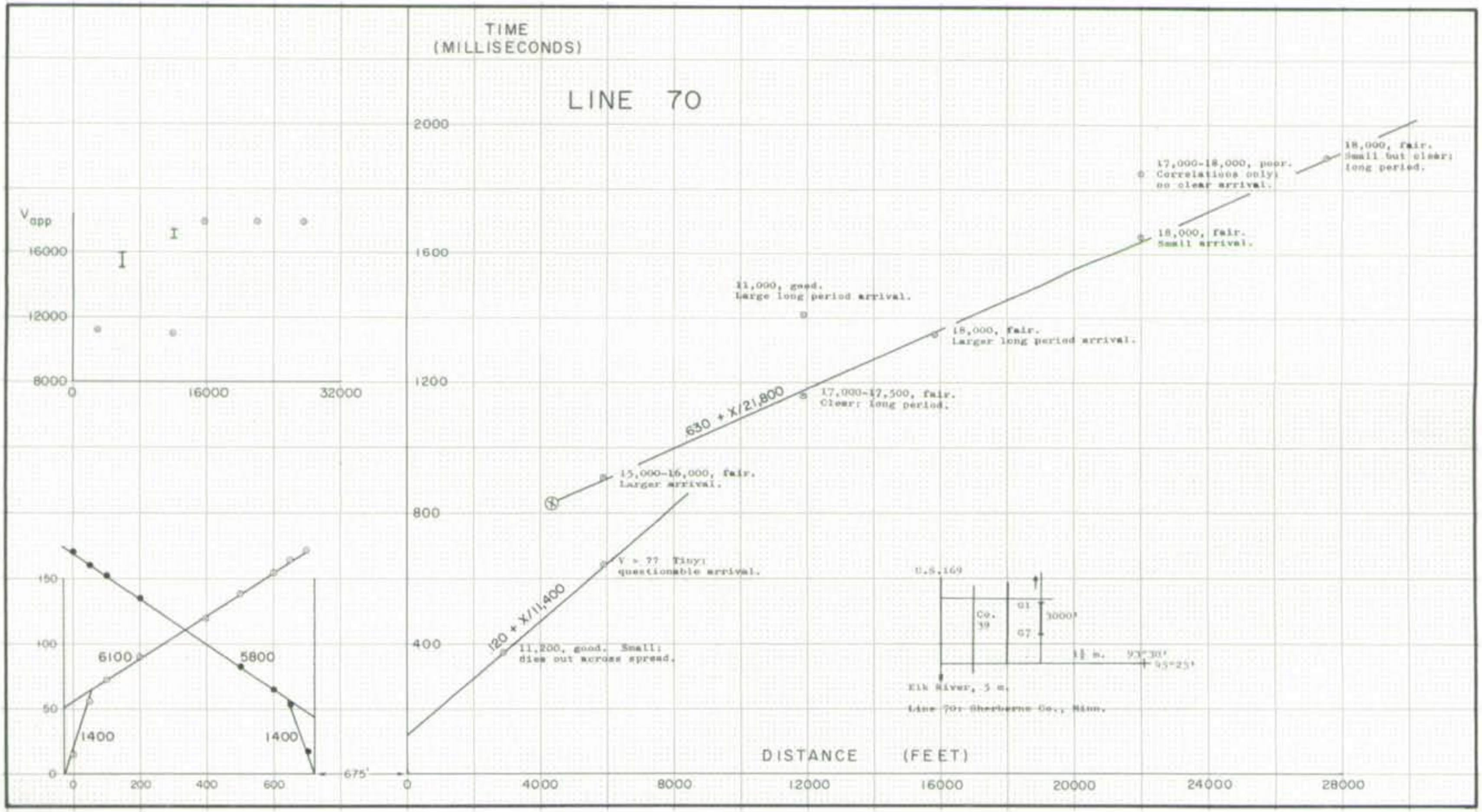
TIME
(MILLISECONDS)
LINE 69
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
DISTANCE (FEET)
.035 + X/11,000
.535 + X/20,400
17,500, fair. Questionable arrival.
(14,500-16,500 ??) Questionable arrival.
18,000-19,500, poor. Very small arrival.
19,000-19,500, good. Clear arrival.
12,000, good. Correlation only; no clear arrival.
19,500-20,500, fair. Small but clear.
19,000-20,000, good. Large arrival.
12,000, good. Large; arrival time uncertain.
19,000, good. Large arrival.
16,500-17,000, poor. Clear larger arrival.
10,800, good. Small; dies out across spread.
Co.5
Spencer Brook, 1½ m.
Co.5
3000'
93°30'
1½ m.
45°30'
Line 69: Isanti Co., Minn.
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
6200
7000
675'



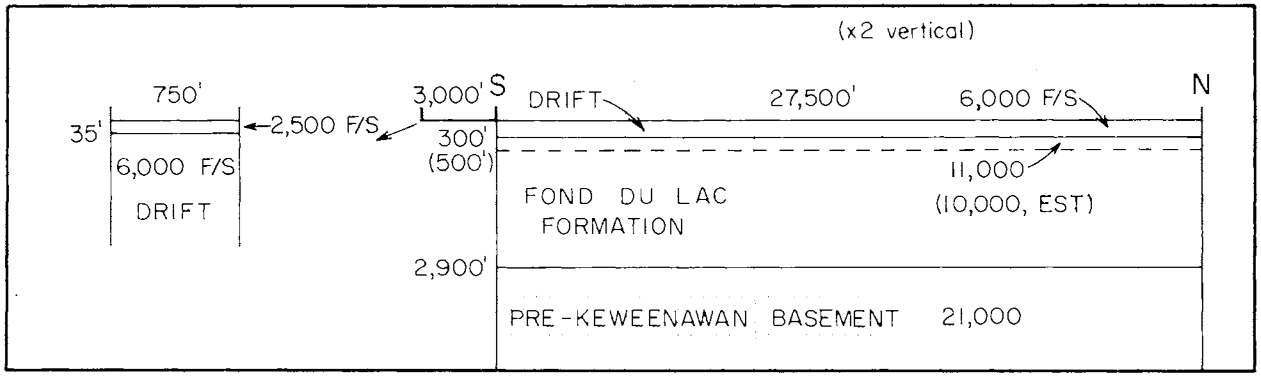
LINE 69

PURPOSE: See Line 19. Mean surface elevation is 975 feet.

RESULTS: Except for depth values, the comments on Line 70 apply here almost without change. Basement depth is computed as 2,800 feet using a 10,000 feet/second low-velocity layer. The basement surface on this line is essentially horizontal. Drift velocity is well defined at 6,600 feet/second.



TIME
(MILLISECONDS)
LINE 70
2000
1600
1200
800
400
DISTANCE (FEET)
0
4000
8000
12000
16000
20000
24000
28000
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
6100
5800
1400
1400
675'
120 + X/11,400
630 + X/21,800
11,200, good. Small;
dies out across spread.
V = 77 Tiny;
questionable arrival.
15,000-16,000, fair.
Larger arrival.
17,000-17,500, fair.
Clear; long period.
11,000, good.
Large long period arrival.
18,000, fair.
Larger long period arrival.
18,000, fair.
Small arrival.
17,000-18,000, poor.
Correlations only;
no clear arrival.
18,000, fair.
Small but clear;
long period.
U.S.169
Co. 39
G1
G7
3000'
Elk River, 5 m.
Line 70: Sherburne Co., Minn.

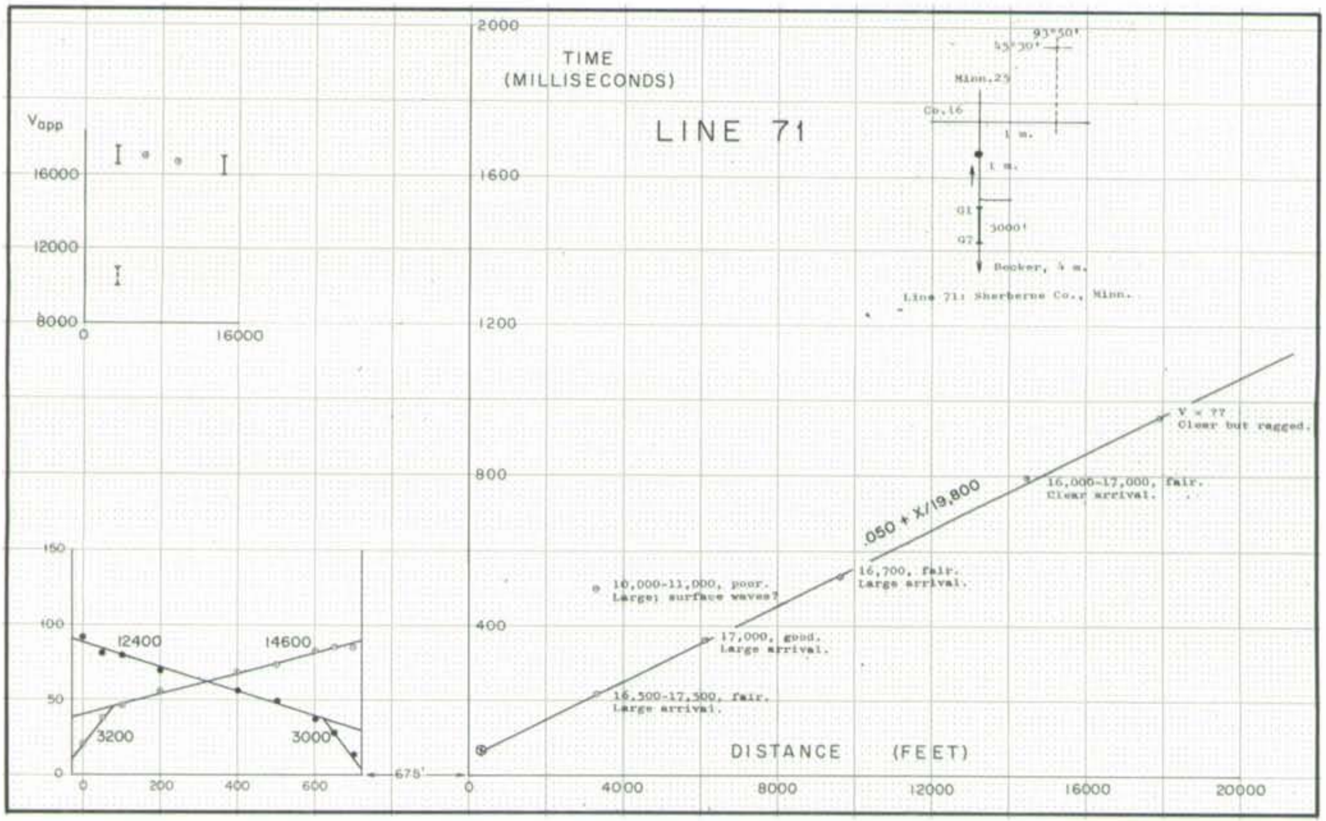


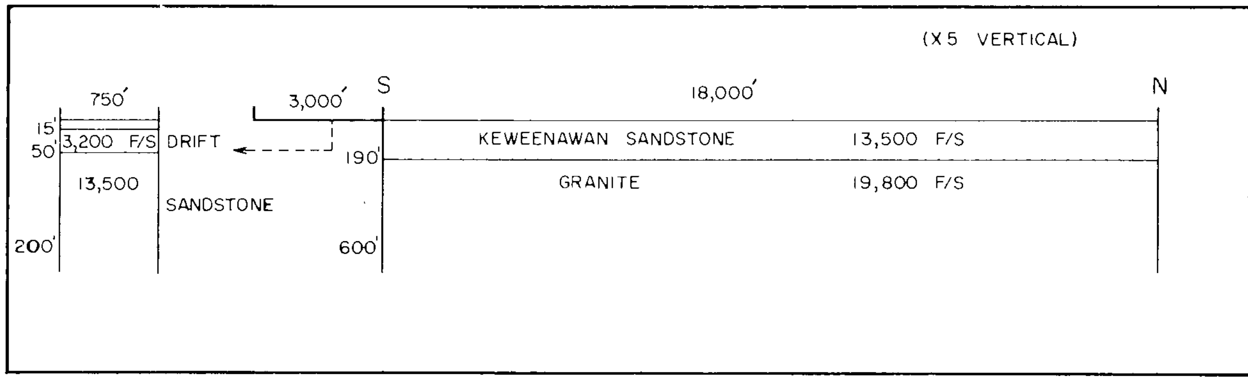
LINE 70

PURPOSE: See Line 19. A well 5 miles southwest found Fond du Lac Formation beneath 145 feet of glacial drift. Mean surface elevation is 1,075 feet.

RESULTS: A sub-drift refractor produces a seismic arrival with velocity 11,000 feet/second which attenuates rapidly with distance. This suggests the presence of a velocity inversion. Assuming 200 foot thickness and 10,000 feet/second velocity in the underlying material, depth to basement is computed as 2,900 feet. The sedimentary section is presumably Fond du Lac Formation.

The seismic arrival from the basement rocks is well defined. The basement surface appears to be reasonably flat with slight upward dip toward the north. The velocity value indicates crystalline rocks rather than basalt.


LINE 71
TIME
(MILLISECONDS)
DISTANCE (FEET)
.050 + X/19,800
16,500-17,500, fair.
Large arrival.
17,000, good.
Large arrival.
10,000-11,000, poor.
Large; surface waves?
16,700, fair.
Large arrival.
16,000-17,000, fair.
Clear arrival.
V = ??
Clear but ragged.
93°50'
45°30'
Minn.25
Co.16
1 m.
1 m.
G1
3000'
G7
Becker, 4 m.
Line 71: Sherburne Co., Minn.
Vapp
16000
12000
8000
0
16000
12400
14600
3200
3000
675'
150
100
50
0
200
400
600
0
4000
8000
12000
16000
20000
2000
1600
1200
800
400

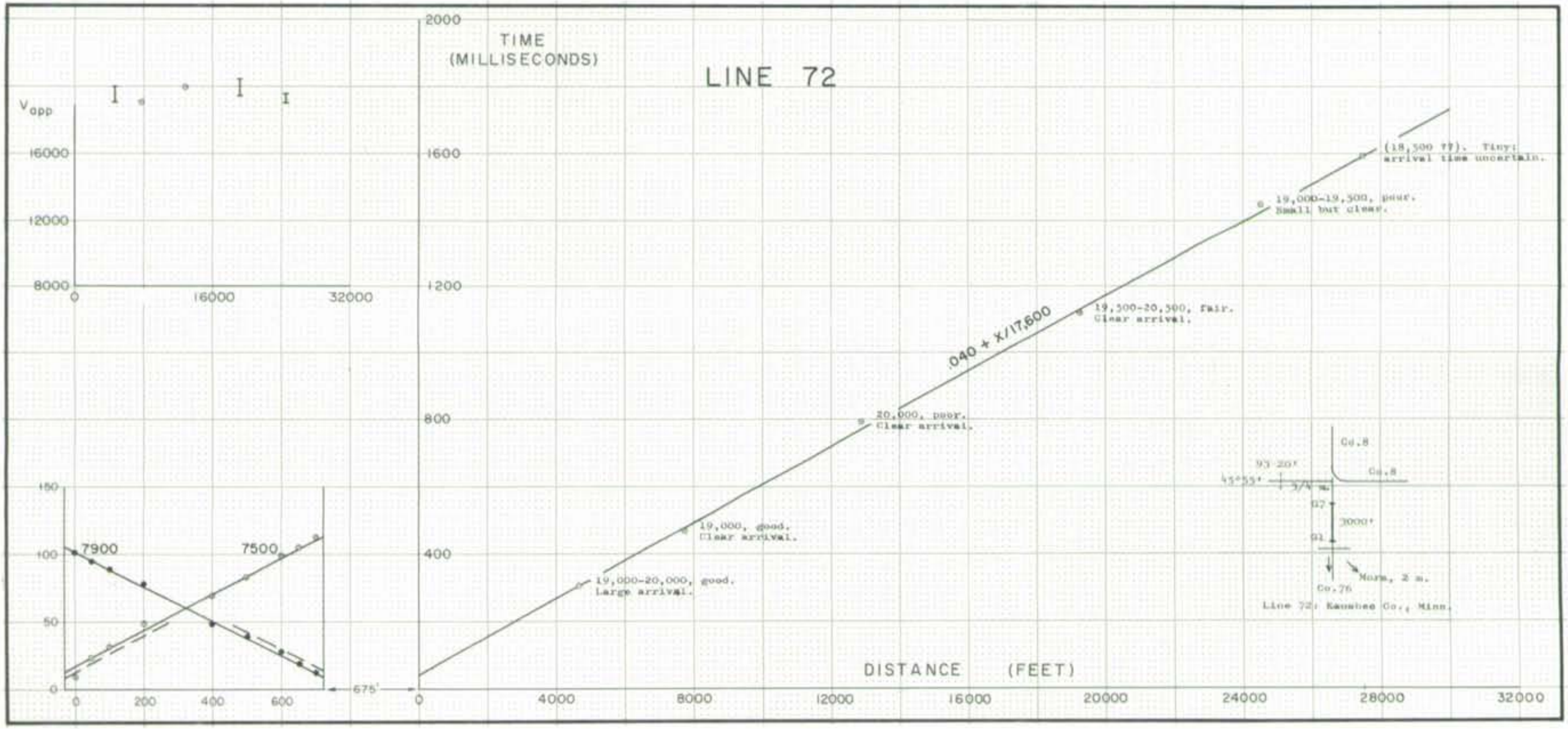


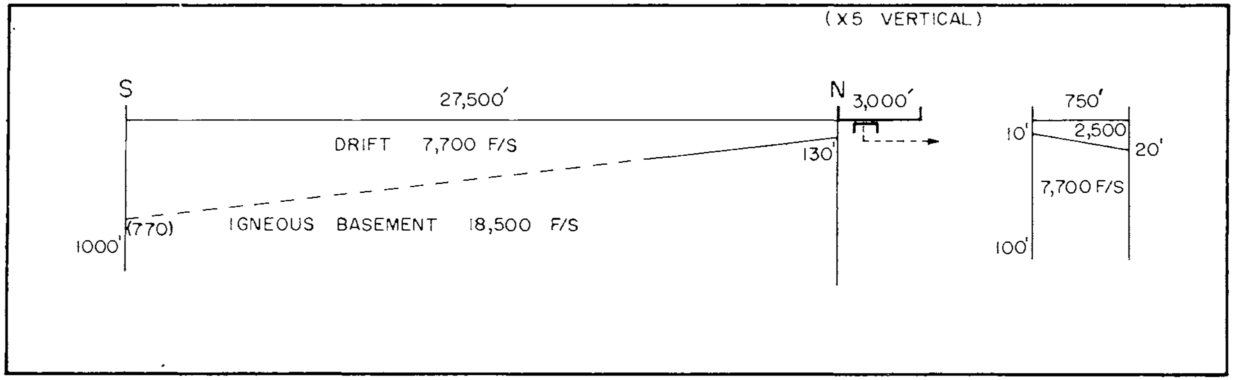
LINE 71

PURPOSE: Line 71 is the westernmost line along latitude 45°30′. Based upon a well 5 miles SW, basement rock is assumed to be St. Cloud gray granite. Mean surface elevation is 1,000 feet.

RESULTS: Excellent seismic data indicate a nearly plane and nearly horizontal basement surface with velocity estimated at 19,800 feet/second. Lower values (16,500-17,000) for the apparent velocity across the spread are interpreted as due to slight local dip because (a) reciprocity requirements establish a lower limit of 18,700 feet/second for the south-to-north velocity along the shot line, and (b) arrivals are consistently 20-25 ms early on geophones 6 and 7 compared with geophones 1-5. Spread velocities are based upon the latter; if all seven had been used, spread velocities would be in the 19,000-20,000 range.

A thin (150 feet) layer of sedimentary rock, presumably Fond du Lac Formation, overlies the basement.


LINE 72
TIME
(MILLISECONDS)
DISTANCE (FEET)
.040 + X/17,600
19,000-20,000, good.
Large arrival.
19,000, good.
Clear arrival.
20,000, poor.
Clear arrival.
19,500-20,500, fair.
Clear arrival.
19,000-19,500, poor.
Small but clear.
(18,500 ??). Tiny;
arrival time uncertain.
V_{app}
7900
7500
675'
93°20'
45°55'
3/4 m.
G2
3000'
G1
Morm., 2 m.
Co.76
Co.8
Line 72; Kanabec Co., Minn.

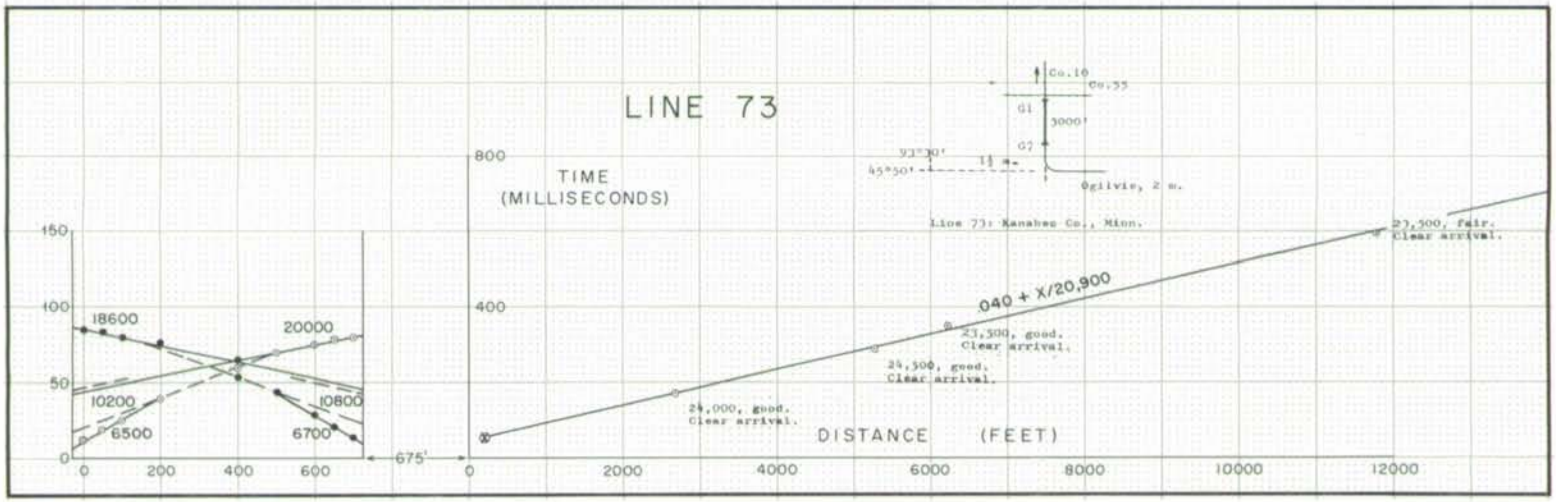


LINE 72

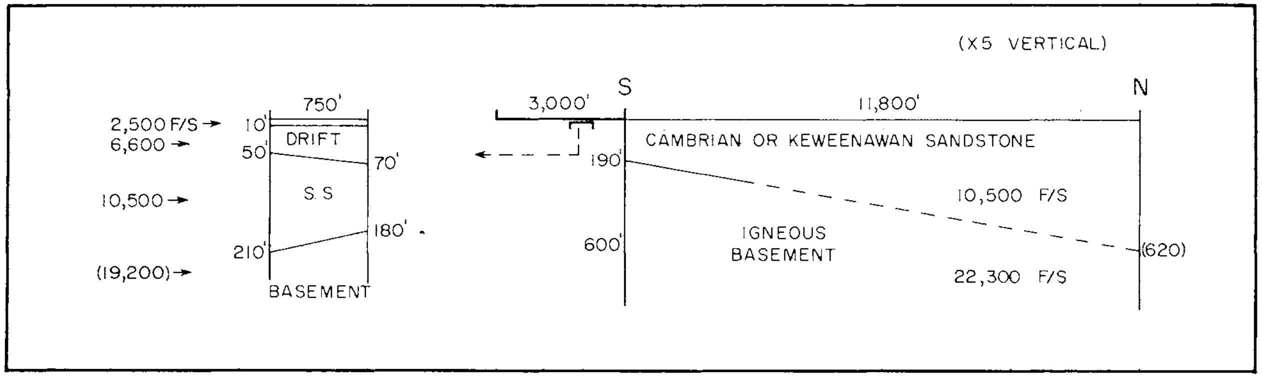
PURPOSE: Lines 72 and 73 are intended to yield control velocities on the igneous complex which presumably underlies much of the western basin. Line 72 is tentatively correlated with the Warman quartz monzonite which crops out 2 miles to the west. The line lies on the SE flank of a 7x3 mile magnetic anomaly with positive relief of 700-1000 gammas. Mean surface elevation is 1,060 feet.

RESULTS: Basement velocity appears to lie in the range 18,000-19,000 feet/second, with 18,500 a preferred value. The basement surface dips downward to the south at about 1½°. Depth at the north end is about 130 feet; the computed depth of 770 feet at the south end is extrapolated and much less certain.

Near-surface velocity of 7,700 feet/second is interpreted as indurated glacial drift, but it could also be a weathered sandstone.



LINE 73
TIME (MILLISECONDS)
800
400
150
100
50
0
18600
20000
10200
10800
6500
6700
675'
200
400
600
2000
4000
6000
8000
10000
12000
Co.10
Co.55
G1
3000'
G7
93°30'
1½ m.
45°50'
Ogilvie, 2 m.
Line 73: Kanabec Co., Minn.
23,500, fair.
Clear arrival.
.040 + X/20,900
23,500, good.
Clear arrival.
24,500, good.
Clear arrival.
24,000, good.
Clear arrival.
DISTANCE (FEET)

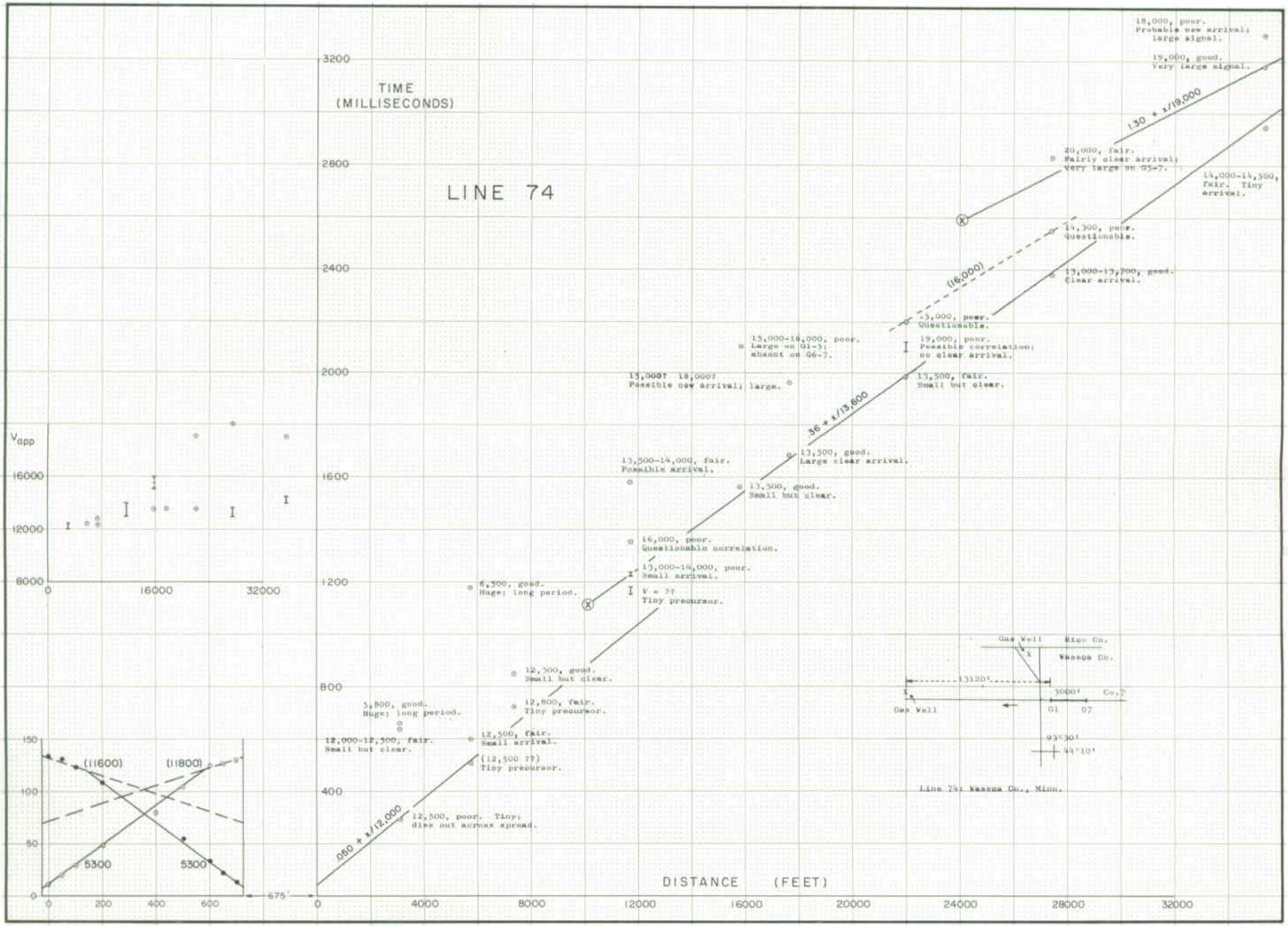


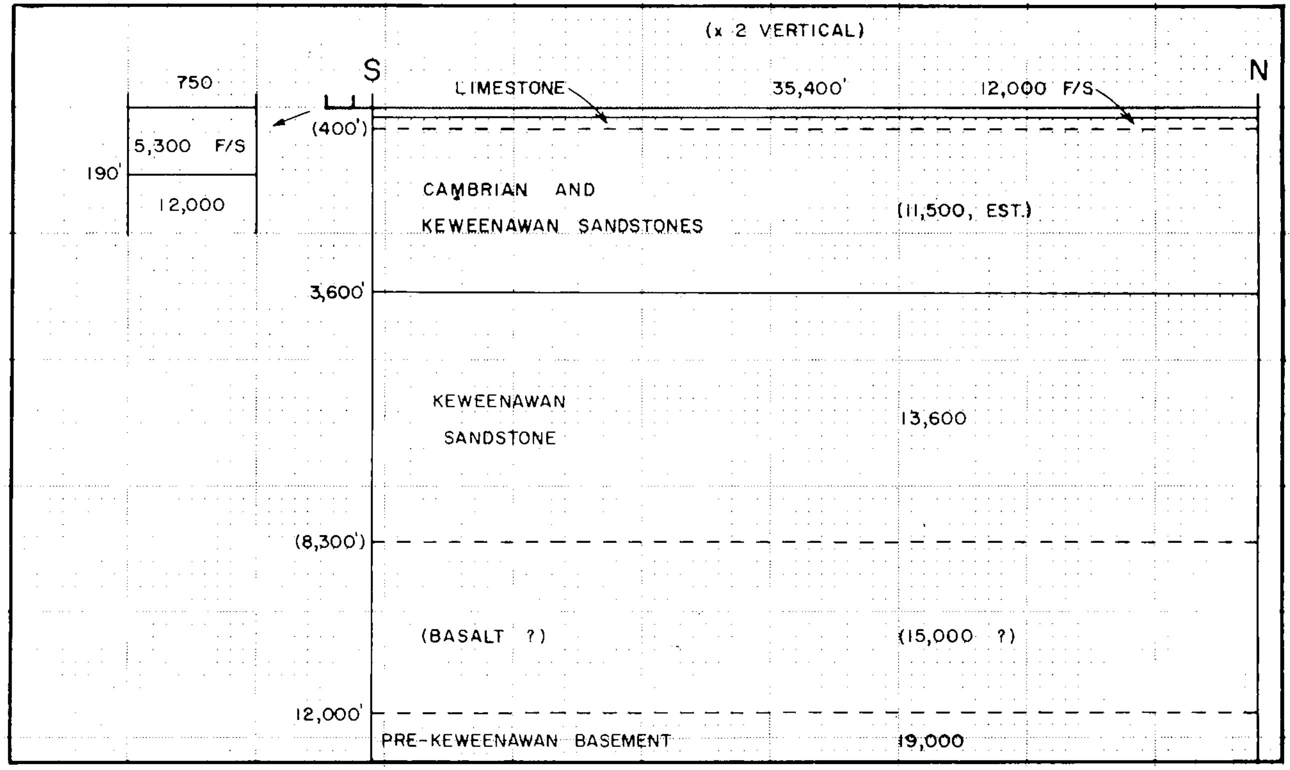
LINE 73

PURPOSE: See Line 72. No nearby outcrops are available to identify the basement rock type, but the line lies close to the mapped contact between the Warman Quartz Monzonite and the Stearns Magma Series. Mean surface elevation is 1,070 feet.

RESULTS: On the basis of velocities, basement rock at Line 73 is distinctly different from that at Line 72, 9 miles to the east. Basement velocity on Line 73 is well defined, with average value 22,300 feet/second. A lower limit of 21,500 is imposed by reciprocity provided the surface is nearly plane, as suggested by lineup of the observed points. The surface appears to dip downward to the north at about 2°. Depth of 200 feet at the south end is well defined; depth of 600 feet at the north end is extrapolated and much less certain.

Drift velocity of 6,600 feet/second is clear. A thin layer of sedimentary rock with velocity of 10,500 feet/second appears to overlie the basement.


LINE 74
TIME
(MILLISECONDS)
DISTANCE (FEET)
3200
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
.050 + x/12,000
.36 + x/13,600
1.30 + x/19,000
(16,000)
18,000, poor.
Probable new arrival;
large signal.
19,000, good.
Very large signal.
20,000, fair.
Fairly clear arrival;
Very large on G5-7.
14,000-14,500,
fair. Tiny
arrival.
14,300, poor.
Questionable.
13,000-13,700, good.
Clear arrival.
15,000, poor.
Questionable.
19,000, poor.
Possible correlation;
no clear arrival.
13,500, fair.
Small but clear.
13,000-16,000, poor.
Large on G1-3;
absent on G6-7.
13,000? 18,000?
Possible new arrival; large.
13,500, good.
Large clear arrival.
13,500-14,000, fair.
Possible arrival.
13,500, good.
Small but clear.
16,000, poor.
Questionable correlation.
13,000-14,000, poor.
Small arrival.
V = ??
Tiny precursor.
6,500, good.
Huge; long period.
12,500, good.
Small but clear.
12,800, fair.
Tiny precursor.
5,800, good.
Huge; long period.
12,000-12,500, fair.
Small but clear.
12,500, fair.
Small arrival.
(12,500 ??)
Tiny precursor.
12,500, poor. Tiny;
dies out across spread.
Gas Well
Rice Co.
Waseca Co.
13120'
3000'
Co.7
Gas Well
G1
G7
93°30'
44°10'
Line 74: Waseca Co., Minn.
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
(11600)
(11800)
5300
5300
675'



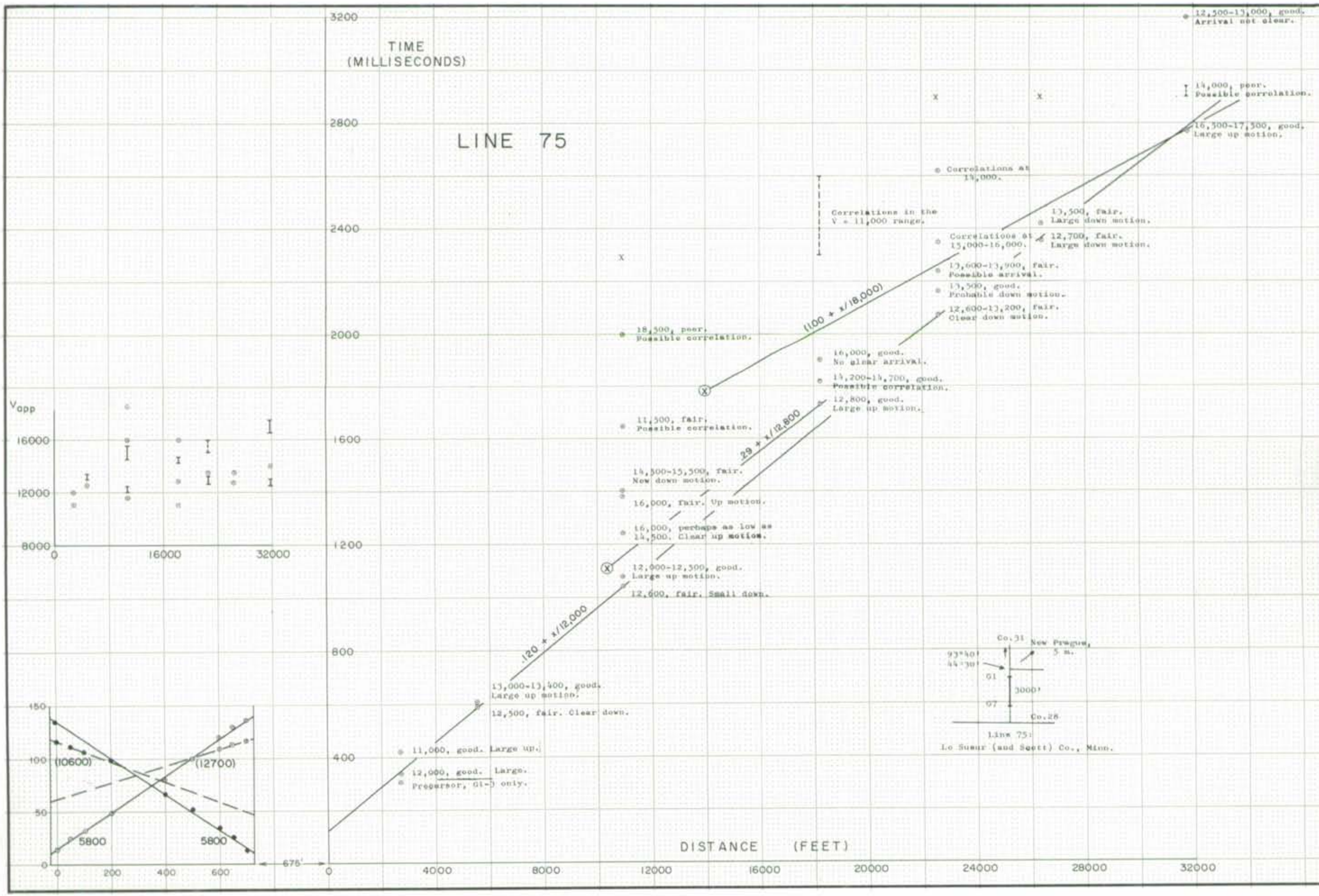
LINE 74

PURPOSE: Line 74 was shot for control purposes 1 mile north of Schuette No. 1 well near Waseca, Minnesota. The well bottomed at 2,371 feet. The records show top of the Shakopee Dolomite at 171 feet, a sequence of Cambrian sandstone formations to 1,117 feet, and Keweenawan sandstones beneath this. Porosity data suggest that little if any velocity contrast should be anticipated between the Cambrian and Keweenawan sandstones. Mean surface elevation is 1,150 feet.

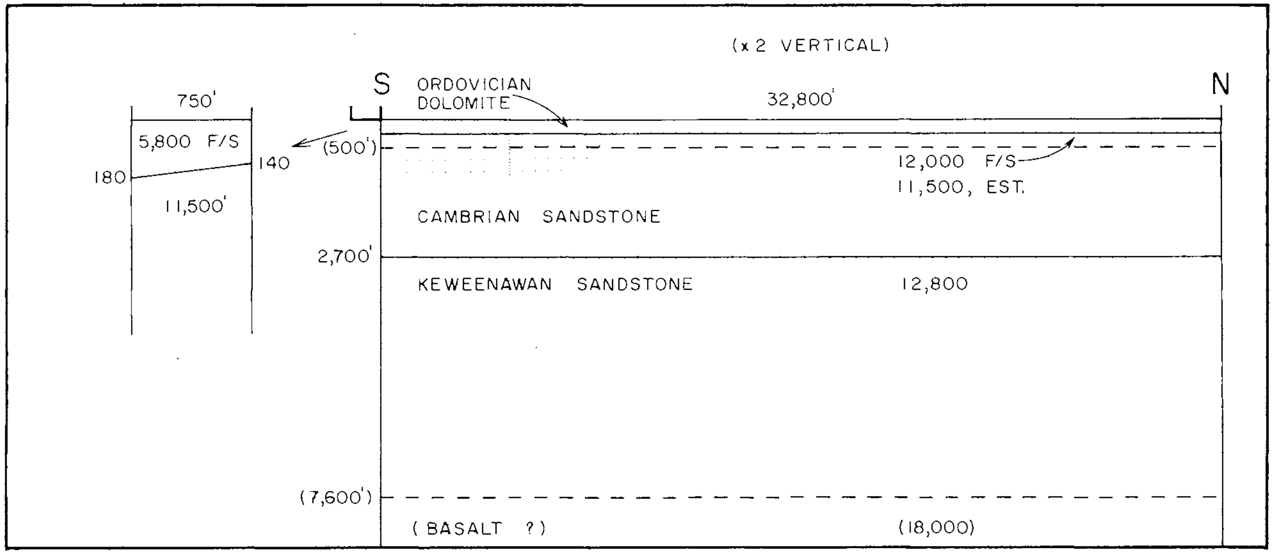
RESULTS: The in-line data show 195 feet of 5,300 feet/second glacial drift overlying limestone. Both well logs and seismic data show a velocity inversion, with 200 feet of limestone overlying lower velocity (assumed 11,500 feet/second) Cambrian sandstone.

Excellent seismic data show 13,600 feet/second material at a depth of 3,600 feet. We identify this with a dense sandstone member in the Keweenawan section. Depth to the same layer on Lines 52 and 53 is estimated at 5,200 feet; since east-west Line 74 lies between them but 3-5 miles north, we infer a slight downward dip to the south.

The deeper section is less clear. Two secondary arrivals provide questionable evidence for a 15,000 feet/second segment. The evidence for a 19,000 feet/second intrusive basement arrival is somewhat better.



LINE 75
TIME (MILLISECONDS)
DISTANCE (FEET)
12,500-13,000, good. Arrival not clear.
14,000, poor. Possible correlation.
16,500-17,300, good. Large up motion.
Correlations at 13,000.
Correlations in the V = 11,000 range.
13,500, fair. Large down motion.
Correlations at 13,000-16,000.
12,700, fair. Large down motion.
13,600-13,900, fair. Possible arrival.
13,500, good. Probable down motion.
12,600-13,200, fair. Clear down motion.
(100 + x/18,000)
18,500, poor. Possible correlation.
16,000, good. No clear arrival.
13,200-13,700, good. Possible correlation.
12,800, good. Large up motion.
11,500, fair. Possible correlation.
29 + x/12,800
14,500-15,500, fair. New down motion.
16,000, fair. Up motion.
16,000, perhaps as low as 14,500. Clear up motion.
12,000-12,500, good. Large up motion.
12,600, fair. Small down.
.120 + x/12,000
13,000-13,400, good. Large up motion.
12,500, fair. Clear down.
11,000, good. Large up.
12,000, good. Large.
Precursor, G1-3 only.
Co.31
New Prague, 5 m.
93°40'
44°30'
G1
G7
3000'
Co.28
Line 75:
Le Sueur (and Scott) Co., Minn.
V_{app}
(10600)
(12700)
5800
5800
675'



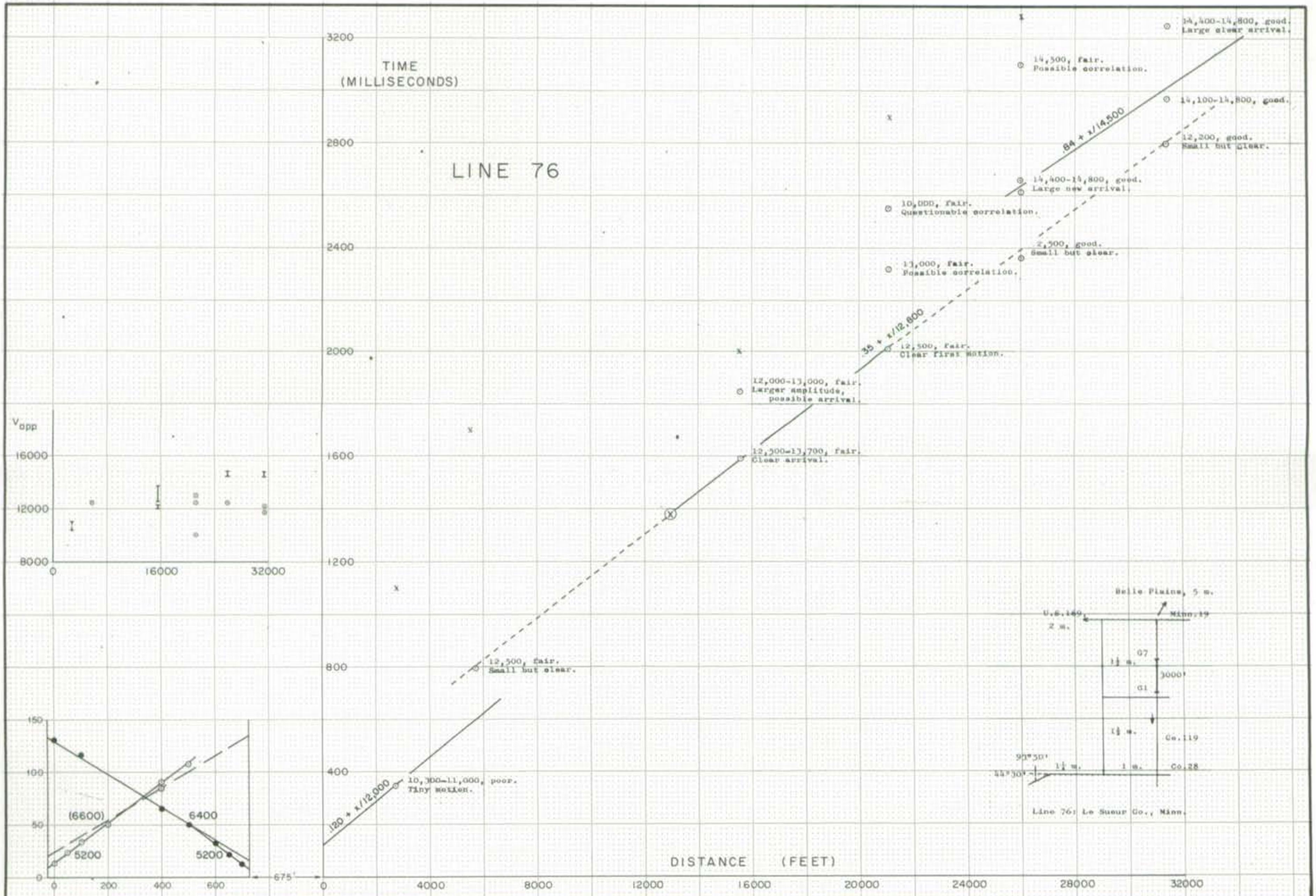
LINE 75

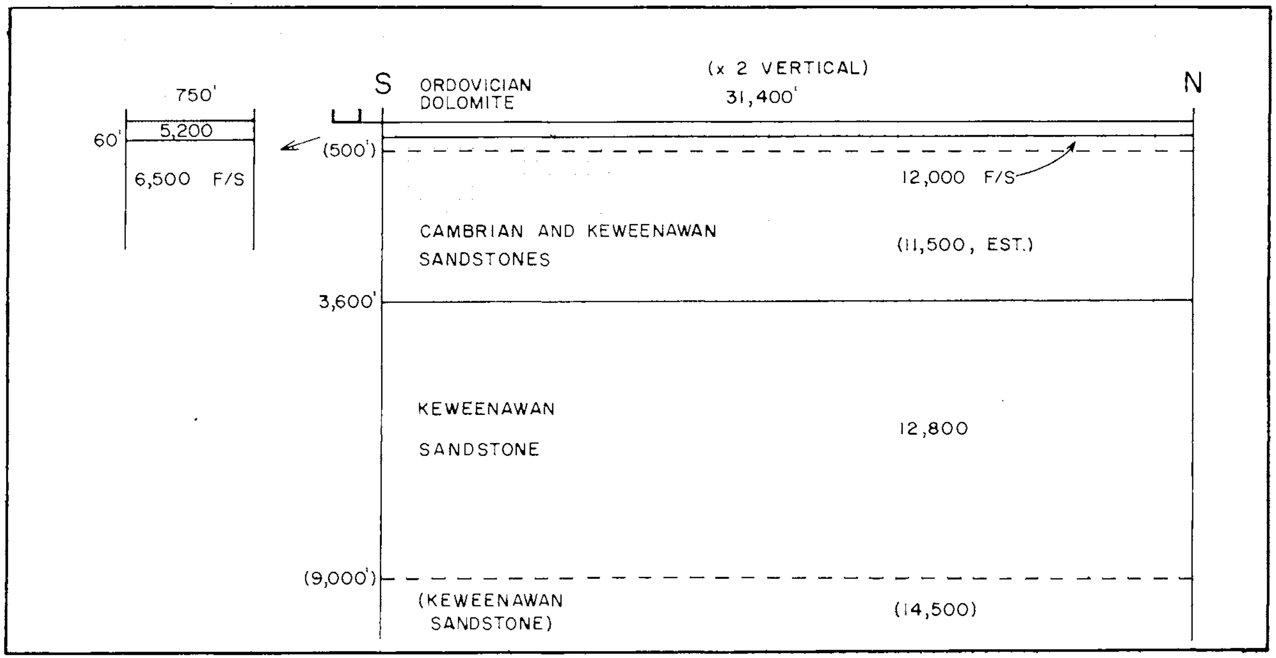
PURPOSE: See Line 76. Mean surface elevation is 1,000 feet.

RESULTS: Major faulting of large throw is obviously present between the gas wells and Lines 75-76. In retrospect this could have been inferred from the magnetic map shown in Figure 8. Thus the wells fail to provide control for the seismic profiles.

In-line data for Line 75 show 160 feet of glacial drift, but an average depth closer to 300 feet is indicated along line by an intercept of 0.120 seconds for the 12,000 feet/second segment. Offset of the travel time graph reveals lower-velocity (assumed 11,500 feet/second) Cambrian sandstones beneath an estimated thickness of 200 feet of Ordovician dolomites.

Excellent seismic data show Keweenawan sandstone with velocity 12,800 feet/second at a depth of 2,700 feet. Two seismic arrivals at shot 7 suggest the presence of 17,000-18,000 feet/second material, presumably basalt. Depth is estimated at 7,600 feet using a velocity of 18,000 feet/second, but the results are based upon limited data hence must be considered tentative.


LINE 76
TIME (MILLISECONDS)
DISTANCE (FEET)
.84 + x/14,500
.35 + x/12,800
.120 + x/12,000
14,400-14,800, good. Large clear arrival.
14,500, fair. Possible correlation.
14,100-14,800, good.
12,200, good. Small but clear.
14,400-14,800, good. Large new arrival.
10,000, fair. Questionable correlation.
2,500, good. Small but clear.
13,000, fair. Possible correlation.
12,500, fair. Clear first motion.
12,000-13,000, fair. Larger amplitude, possible arrival.
12,300-13,700, fair. Clear arrival.
12,500, fair. Small but clear.
10,300-11,000, poor. Tiny motion.
Vapp
(6600)
6400
5200
5200
675'
Belle Plaine, 5 m.
Minn.19
U.S.169
2 m.
3000'
Co.119
Co.28
93°30'
44°30'
Line 76: Le Sueur Co., Minn.



LINE 76

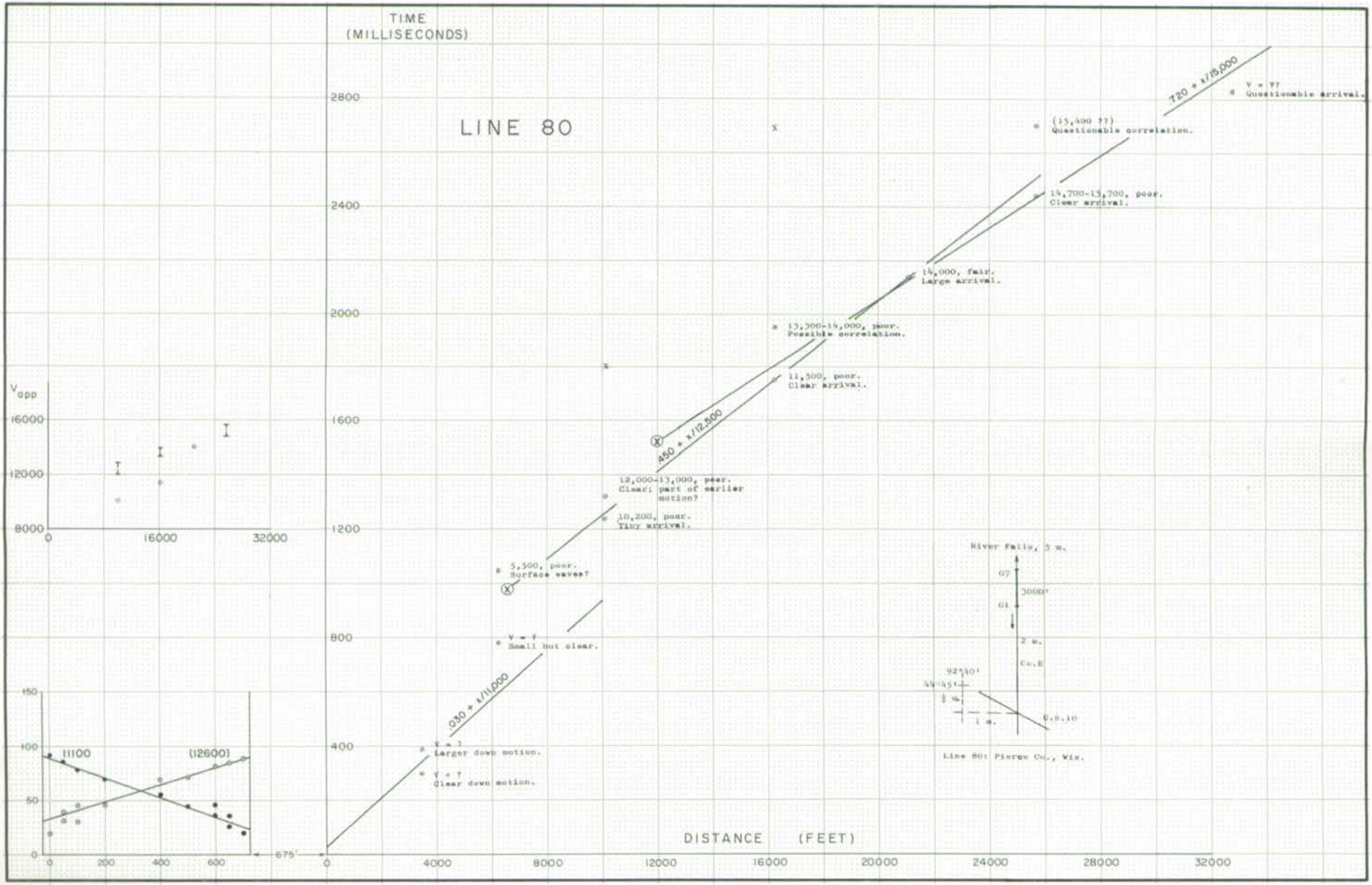
PURPOSE: Lines 75 and 76 were shot for control purposes near several shallow gas wells. The closest wells, NNG No. 1 and NNG No. 2, are 5 and 11 miles east of Lines 75 and 76. Drill logs showed 210 and 270 feet of drift, 193 and 214 feet of Ordovician dolomite; and 337 and 362 feet of Cambrian sandstone overlying basalt at depths of 740 and 846 feet. Mean surface elevation is 1,000 feet.

RESULTS: 325 feet of glacial drift overlies an estimated 200 feet of Ordovician dolomite with velocity 12,000 feet/second. Cambrian and Keweenawan sandstone with assumed velocity 11,500 feet/second underlies this.

Excellent seismic data define Keweenawan sandstone with velocity 12,800 feet/second at a depth of 3,600 feet. Depth to this material is about 900 feet greater here than under Line 75 which is 6 miles to the east.

Two good seismic arrivals have been used to draw a line with velocity 14,500 feet/second. Computed depth is 9,000 feet. The identification is tentative, however, hence the existence of this boundary is open to question.

No arrivals were found with velocities characteristic of basalt or igneous intrusives. Such material if present must be at depths greater than 10,000 feet, considerably deeper than on Line 75.

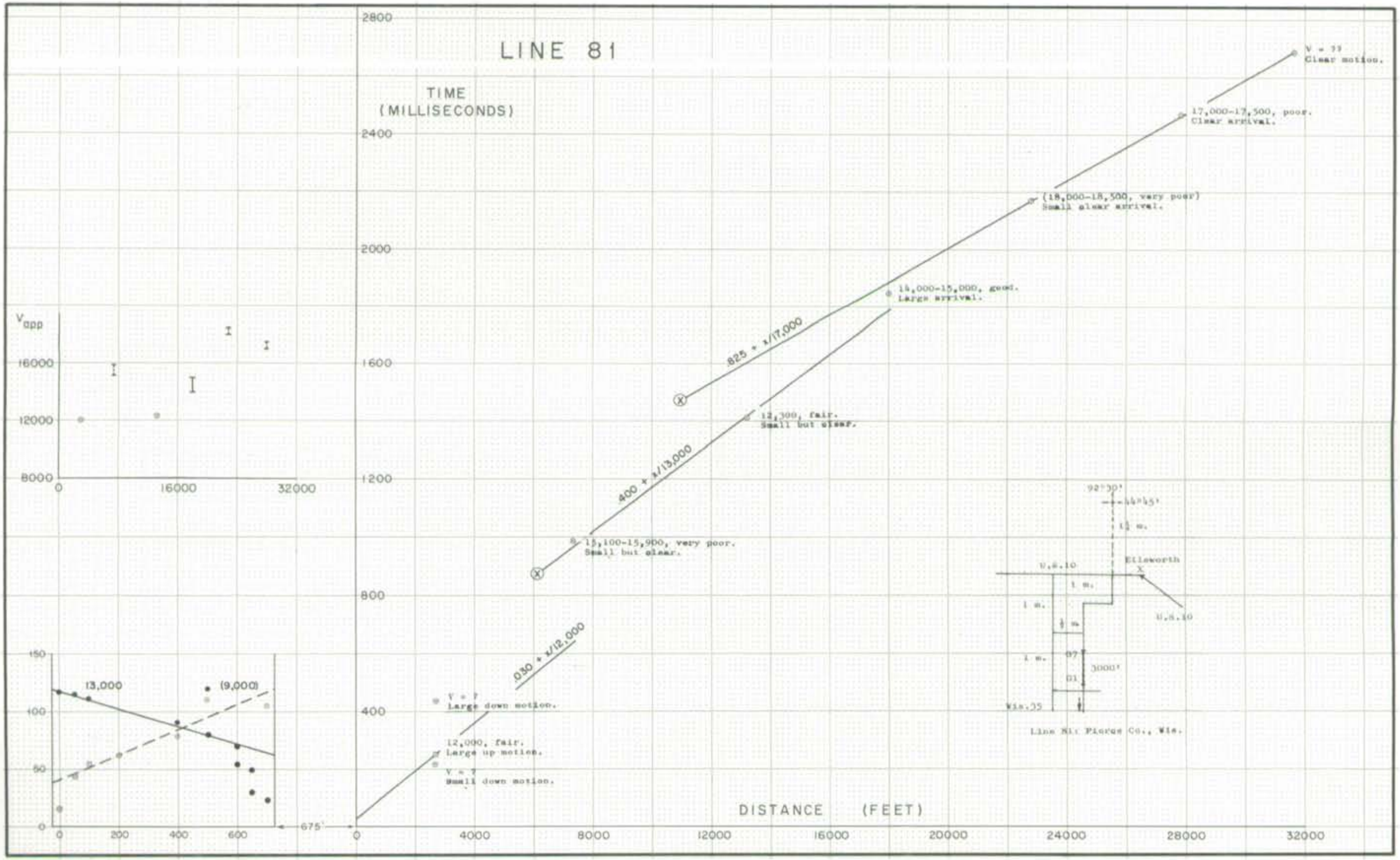


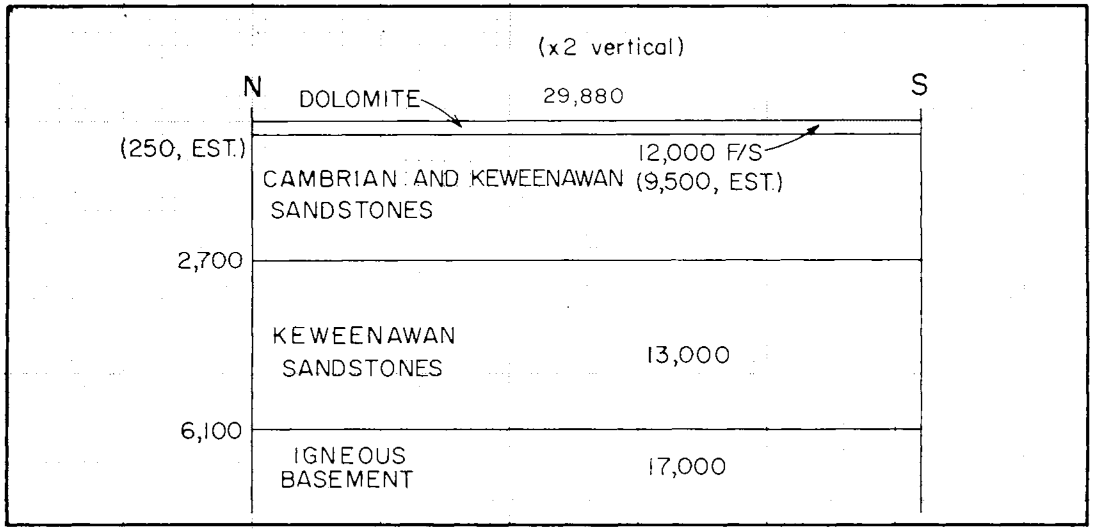
TIME
(MILLISECONDS)
LINE 80
DISTANCE (FEET)
.720 + x/15,000
.450 + x/12,500
.030 + x/11,000
V = ??
Questionable arrival.
(15,400 ??)
Questionable correlation.
14,700-15,700, poor.
Clear arrival.
14,000, fair.
Large arrival.
13,300-14,000, poor.
Possible correlation.
11,500, poor.
Clear arrival.
12,000-13,000, poor.
Clear; part of earlier motion?
10,200, poor.
Tiny arrival.
5,500, poor.
Surface waves?
V = ?
Small but clear.
V = ?
Larger down motion.
V = ?
Clear down motion.
675'
V_{app}
11100
(12600)
River Falls, 5 m.
G7
3000'
G1
2 m.
Co. E
92°40'
44°45'
½ m.
1 m.
U.S. 10
Line 80: Pierce Co., Wis.

LINE 80

PURPOSE: Line 80 was a preliminary profile in western Wisconsin. It lies 1½ miles west of Line 89. Mean surface elevation is 1,000 feet.

RESULTS: See Line 89.


LINE 81
TIME (MILLISECONDS)
DISTANCE (FEET)
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
V = ??
Clear motion.
17,000-17,500, poor.
Clear arrival.
(18,000-18,500, very poor)
Small clear arrival.
14,000-15,000, good.
Large arrival.
825 + x/17,000
12,300, fair.
Small but clear.
400 + x/13,000
15,100-15,900, very poor.
Small but clear.
030 + x/12,000
V = ?
Large down motion.
12,000, fair.
Large up motion.
V = ?
Small down motion.
675'
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
200
400
600
13,000
(9,000)
92°30'
44°45'
1½ m.
Ellsworth
U.S.10
1 m.
½ m.
07
3000'
01
Wis.35
Line 81: Pierce Co., Wis.

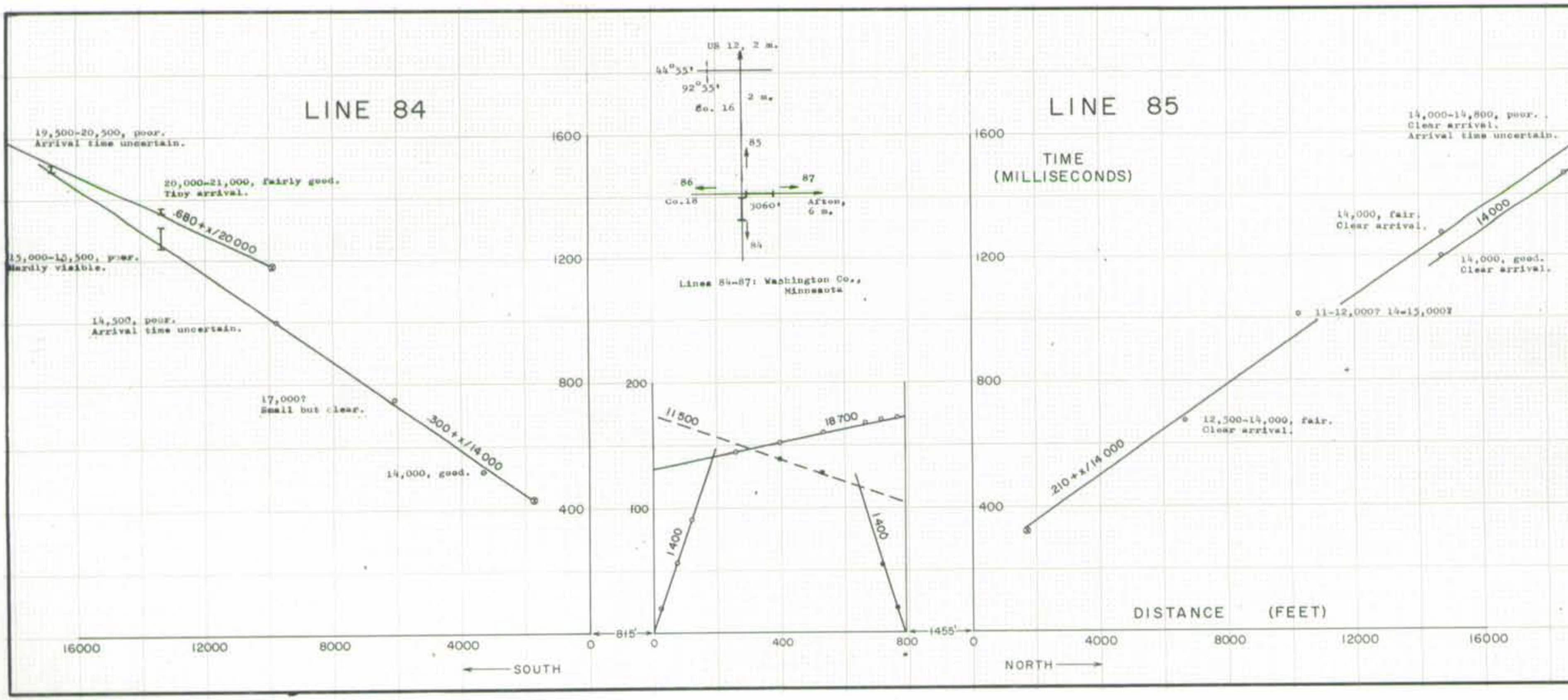


LINE 81

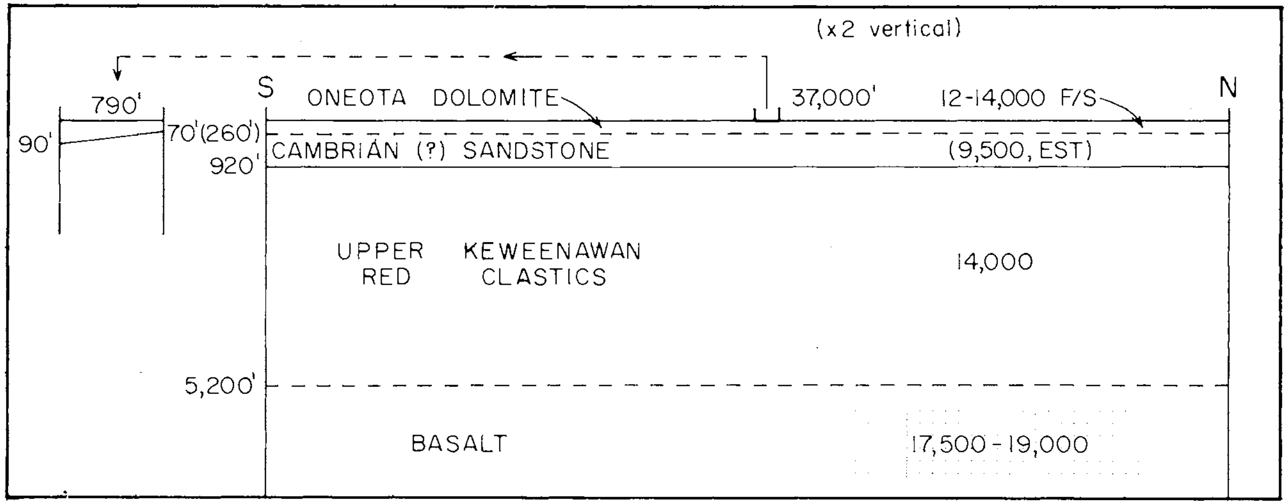
PURPOSE: Line 81 was a preliminary profile in western Wisconsin. It lies co-linear with Line 90 and 8 miles south. Mean surface elevation is 1,030 feet.

RESULTS: The deep refractor at about 6,000 feet with velocity 17,000 feet/second is defined by only two arrivals, but it agrees well with a 16,000-16,500 feet/second arrival on Line 90 at a depth of about 5,400 feet. Uncertainties in interpretation for the overlying section are sufficient to account for the difference without invoking dip on the refractor.

Offset of the travel time segments on Line 81 shows a near-surface velocity inversion. A velocity of 13,000 feet/second has been assigned to the underlying layer, partly on the basis of evidence from Line 90.



LINE 84
LINE 85
19,500-20,500, poor. Arrival time uncertain.
20,000-21,000, fairly good. Tiny arrival.
680+x/20000
15,000-15,500, poor. Hardly visible.
14,500, poor. Arrival time uncertain.
17,000? Small but clear.
300+x/14000
14,000, good.
US 12, 2 m.
44°55'
92°55'
Co. 16
2 m.
85
86
87
Co.18
3060'
Afton, 6 m.
84
Lines 84-87: Washington Co., Minnesota
11500
18700
1400
1400
TIME (MILLISECONDS)
14,000-14,800, poor. Clear arrival. Arrival time uncertain.
14,000, fair. Clear arrival.
14000
14,000, good. Clear arrival.
11-12,000? 14-15,000?
12,300-14,000, fair. Clear arrival.
210+x/14000
DISTANCE (FEET)
1600
1200
800
400
200
100
16000
12000
8000
4000
0
815'
1455'
SOUTH
NORTH



LINES 84-87

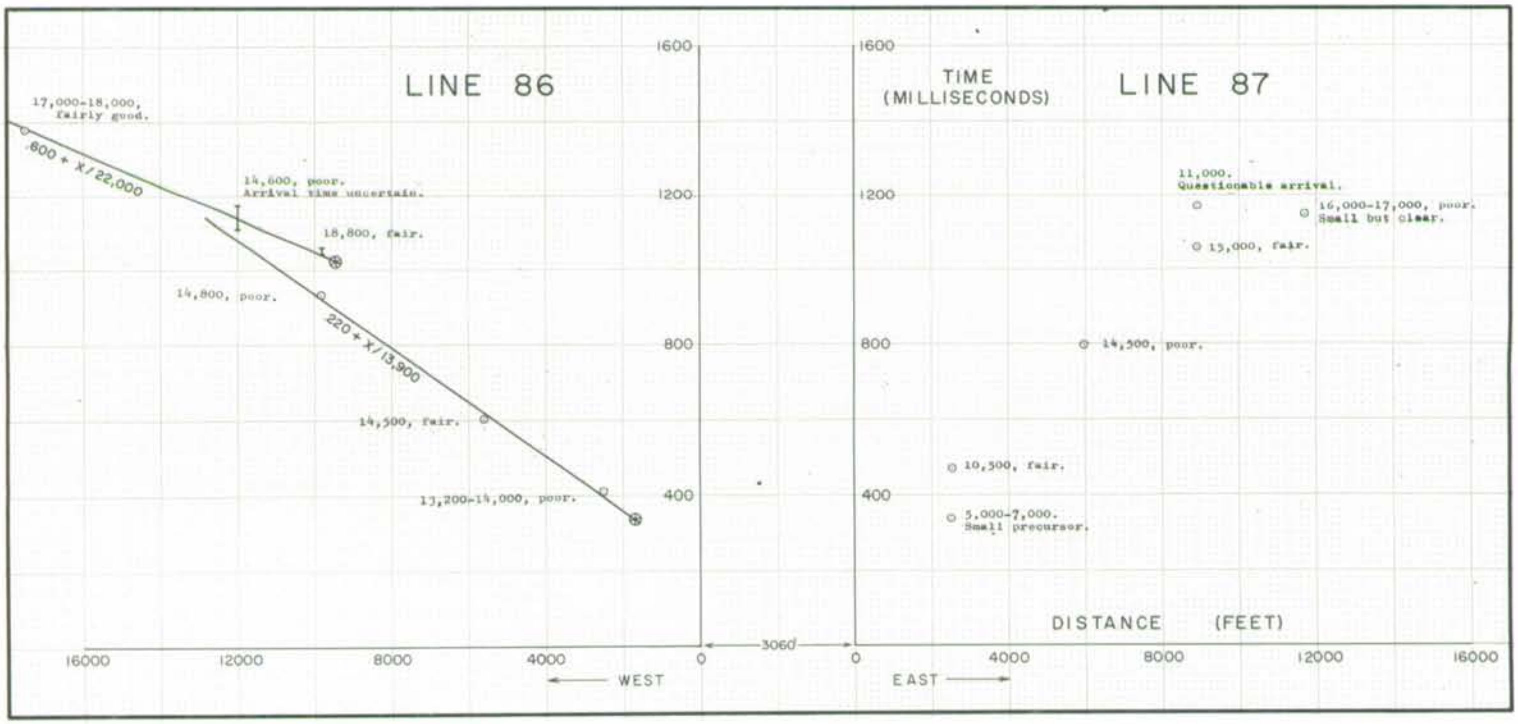
PURPOSE: Lines 84-87 lie on the St. Croix Horst near the southeastern boundary. They are designed to determine the sedimentary section and depth to basement on the upthrown side of the Hastings Fault. Mean surface elevation is 950 feet.

RESULTS: The in-line shots show a high velocity horizon at a depth of about 85 feet. From geologic evidence, we have identified this as Oneota Dolomite with velocity of 12,000 feet/second, although a preferred seismic interpretation would give 14,000 feet/second material dipping strongly to the south.

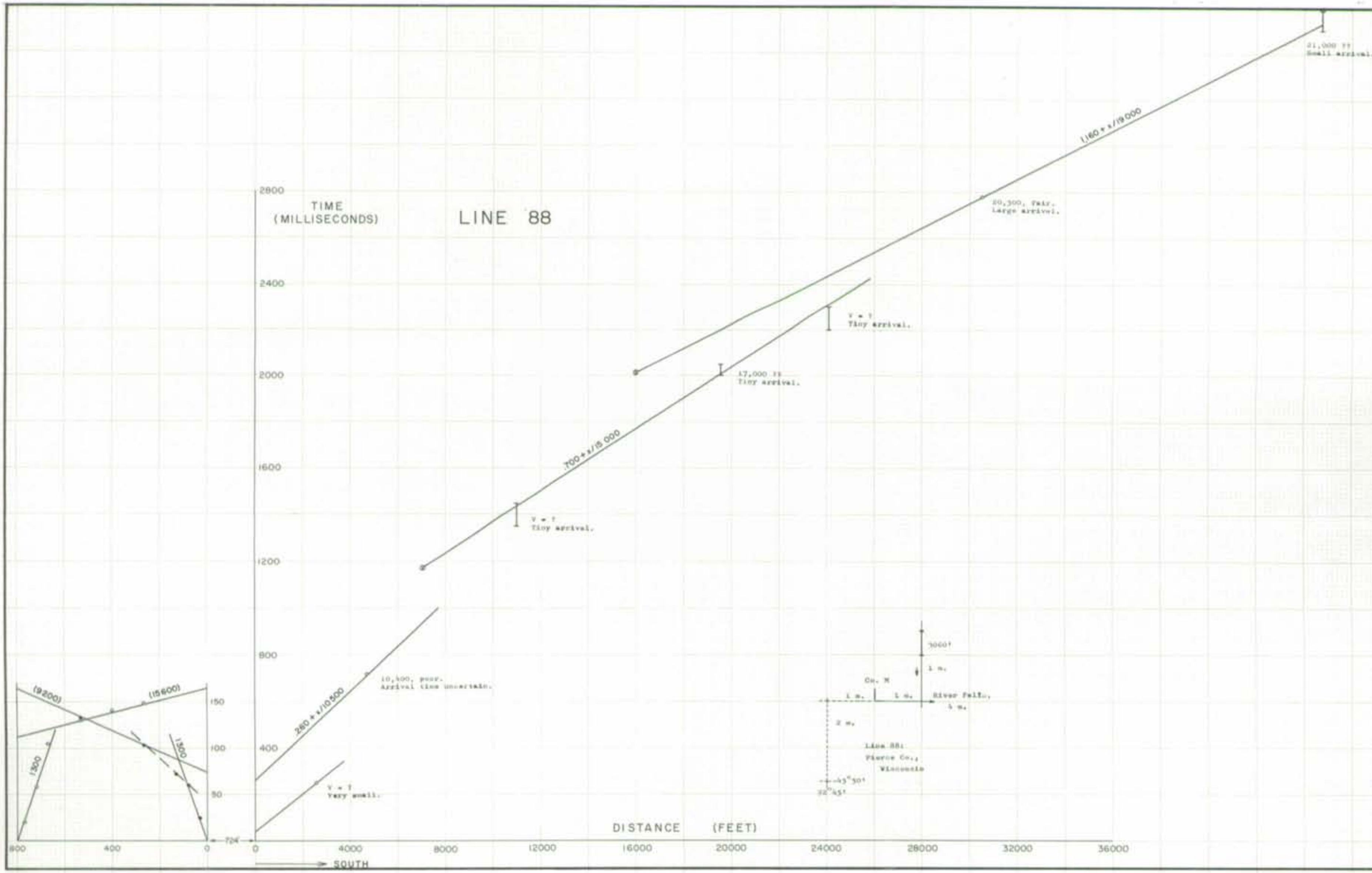
The seismic data show a time offset, indicating a velocity inversion. Nearby well records suggest an average thickness of 175 feet for the Oneota Dolomite. We have assumed this value together with a velocity of 9,500 feet/second for the underlying sandstones.

The most incontrovertible conclusion from Lines 84-86 (line 87 data could not be interpreted) appears to be the presence of a considerable thickness of Upper Keweenawan Red Clastics with velocity of 14,000-14,500 feet/second. A computed depth of 920 feet to the top is consistent with a depth of 900 feet in a well at South St. Paul, 6 miles west.

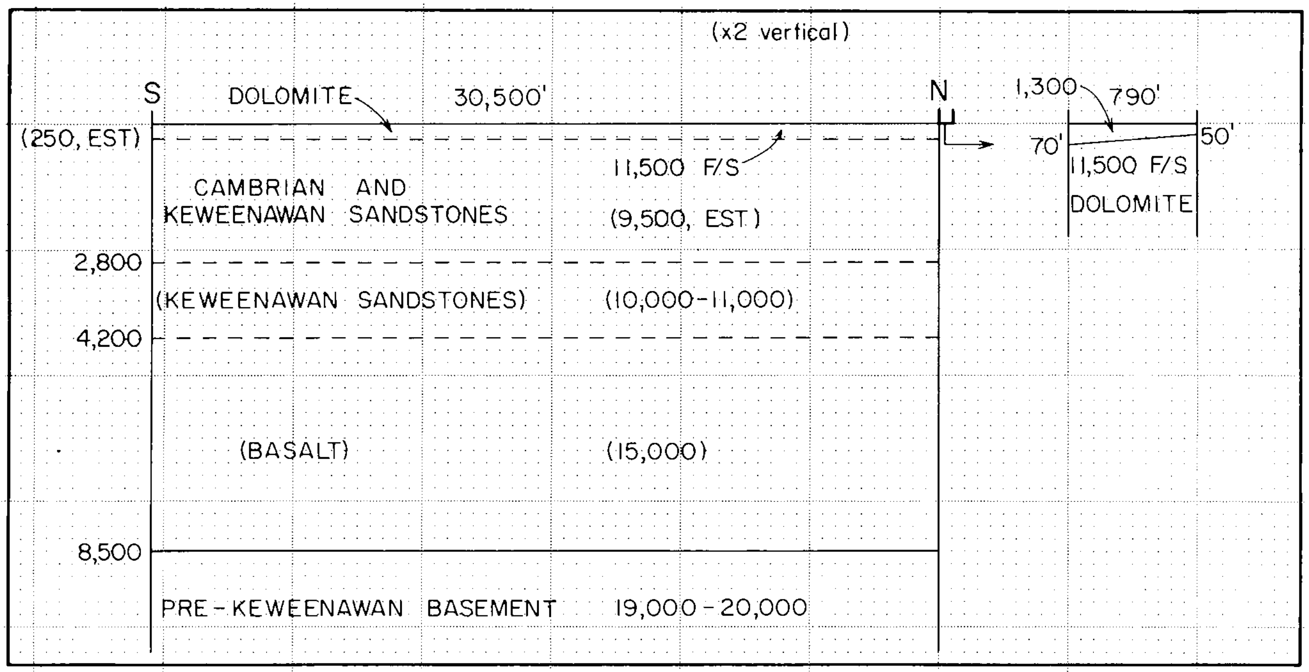
The high velocity refractor, presumably basalt, yields clear arrivals on Lines 84 and 86. A depth of 5,200 feet is computed from averaged data for the two lines, but the data are poor and this figure should be regarded only as an estimate. A well at Stillwater 10 miles to the north encountered basalt at 2,980 feet, which would imply a shallowing of the basin northward.



LINE 86
LINE 87
TIME
(MILLISECONDS)
DISTANCE (FEET)
WEST
EAST
3060
1600
1200
800
400
16000
12000
8000
4000
0
17,000-18,000, fairly good.
600 + X/22,000
14,600, poor. Arrival time uncertain.
18,800, fair.
14,800, poor.
220 + X/13,900
14,500, fair.
13,200-14,000, poor.
11,000. Questionable arrival.
16,000-17,000, poor. Small but clear.
13,000, fair.
14,500, poor.
10,500, fair.
5,000-7,000. Small precursor.



LINE 88
TIME (MILLISECONDS)
DISTANCE (FEET)
SOUTH
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
21,000 ??
Small arrival.
1,160 + x/19,000
20,300, fair.
Large arrival.
V = ?
Tiny arrival.
17,000 ??
Tiny arrival.
700 + x/15,000
V = ?
Tiny arrival.
10,400, poor.
Arrival time uncertain.
260 + x/10,500
V = ?
Very small.
3060'
1 m.
Co. M
1 m.
1 m.
River Falls,
4 m.
2 m.
Line 88:
Pierce Co.,
Wisconsin
43°30'
92°45'
(9200)
(15600)
1300
1300
150
100
50
800
400
0
72ft

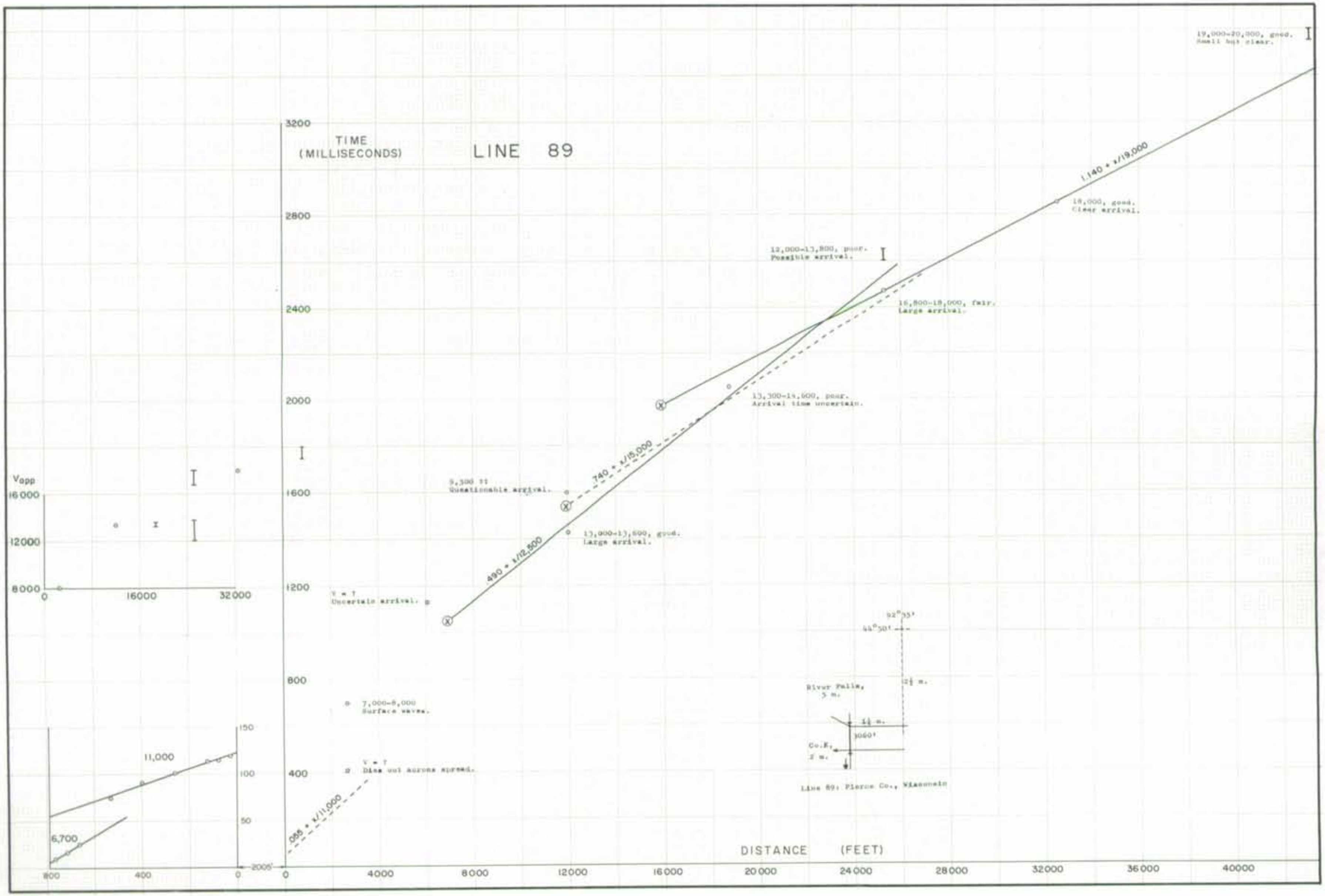


LINE 88

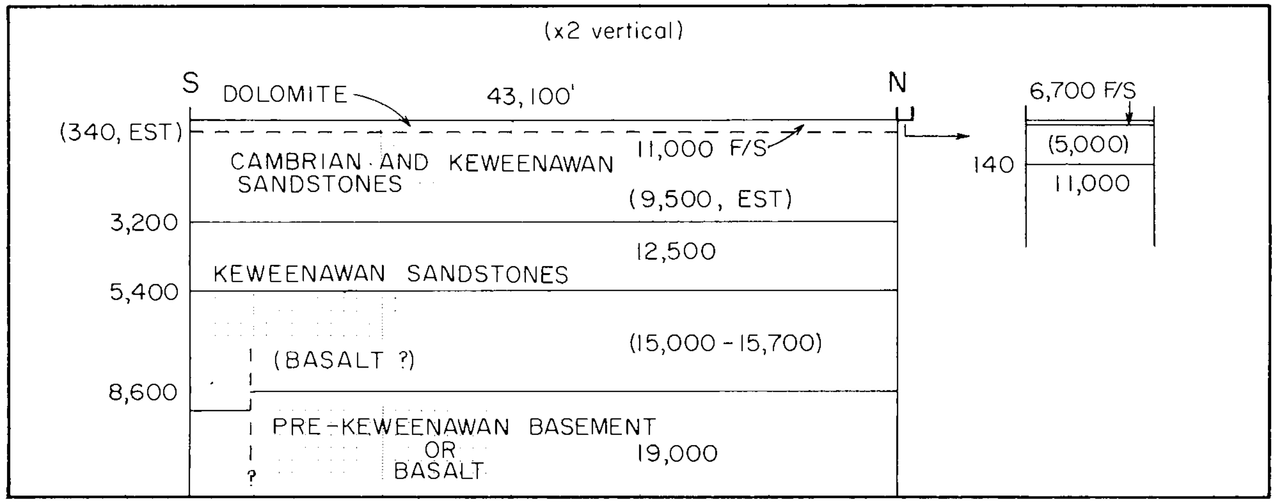
PURPOSE: Lines 88-93 provide a sequence of profiles across the Eastern Basin in west-central Wisconsin. They are oriented north-south and spaced about 6 miles apart except for a 12 mile gap from Line 92 to 93. The goal is to construct a structure section across the Eastern Basin. Mean surface elevation is 950 feet.

RESULTS: On this line as on many of those following, a velocity inversion in the shallow sub-drift section is shown by an offset of the travel-time graph. Using nearby well data, we estimate a thickness of 200 feet for the 11,500 feet/second dolomite, and assume a velocity of 9,500 feet/second for the underlying sandstones.

Results for the deeper section are somewhat ambiguous. High velocity (19,000-20,000 feet/second) arrivals at shots 6 and 7 can be associated with basement at a depth of about 8,500 feet. The velocity value suggests intrusive igneous rock, although the data are not precise enough to exclude basalt as a possibility. The intervening section has been interpreted to indicate 10,000-11,000 and 15,000 feet/second materials, but the data are quite poor and the conclusion insecure.



LINE 89
TIME (MILLISECONDS)
DISTANCE (FEET)
Vapp
1,140 + x/19,000
740 + x/15,000
490 + x/12,500
19,000-20,000, good. Small but clear.
18,000, good. Clear arrival.
12,000-13,800, poor. Possible arrival.
16,800-18,000, fair. Large arrival.
13,300-14,600, poor. Arrival time uncertain.
9,500 ??
Questionable arrival.
13,000-13,600, good. Large arrival.
V = ?
Uncertain arrival.
7,000-8,000
Surface waves.
V = ?
Dies out across spread.
River Falls, 3 m.
Co.E, 2 m.
3060'
Line 89: Pierce Co., Wisconsin
11,000
6,700



LINE 89

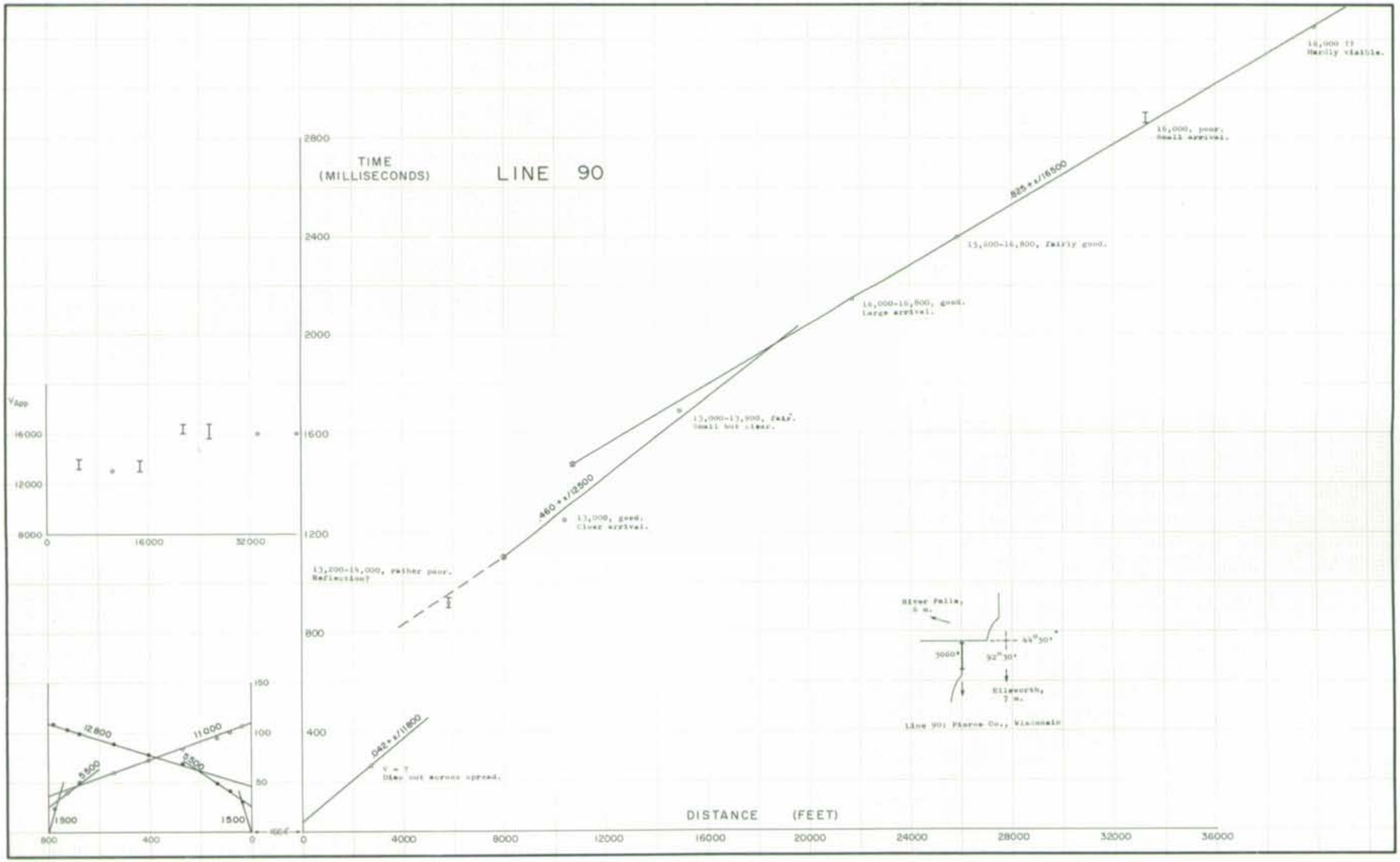
PURPOSE: See Line 88. Mean surface elevation is 1,100 feet.

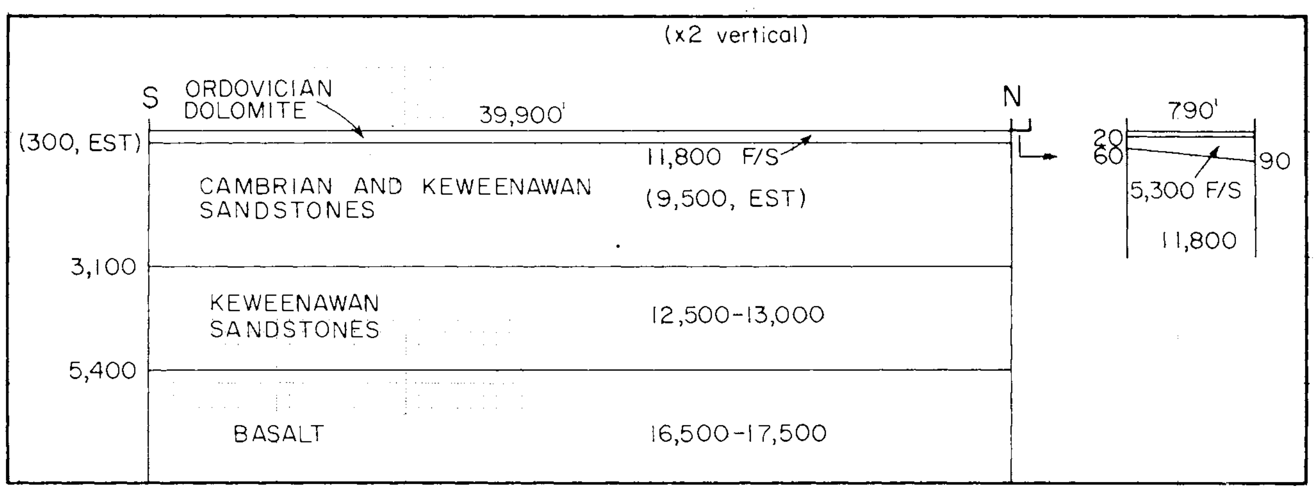
RESULTS: Line 89 was interpreted jointly with Line 80, 2 miles west. Results for the intermediate-depth layers were generally unsatisfactory. One possible explanation may lie in a gradational character for the transition from one formation to the next.

The in-line data for Line 89 show about 140 feet of glacial drift overlying Ordovician dolomite with velocity 11,000-11,500 feet/second. Offset of the along-line seismic arrivals indicates a velocity inversion as on adjoining lines. We have assumed 200 feet thickness for the 11,000 feet/second layer with 9,500 feet/second material beneath it.

The pre-Keweenawan basement appears on Line 89 as two good arrivals which fit on a 19,000 feet/second segment. The most distant shot yields a good but delayed arrival with the same across-spread velocity which we tentatively associate with a slight increase in basement depth.

The intermediate section is poorly defined. A 12,500 feet/second arrival is poor on Line 89, questionable on Line 80. A 15,000 feet/second arrival is fair-to-poor on Line 80, questionable on Line 89. Because the velocity value is so poorly defined, we have associated this with Middle Keweenawan basalts by extension from adjacent Line 90, although by itself it would be more suggestive of lower unit of the Keweenawan sandstones.


LINE 90
TIME (MILLISECONDS)
DISTANCE (FEET)
2800
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
.825 + x/16500
.460 + x/12500
.042 + x/11800
16,000 ?? Hardly visible.
16,000, poor. Small arrival.
15,600-16,800, fairly good.
16,000-16,800, good. Large arrival.
13,000-13,900, fair. Small but clear.
13,000, good. Clear arrival.
13,200-14,000, rather poor. Reflection?
V = ? Dies out across spread.
River Falls, 6 m.
3060'
44°30'
92°30'
Ellsworth, 7 m.
Line 90: Pierce Co., Wisconsin
V_{app}
16000
12000
8000
0
16000
32000
150
100
50
0
800
400
0
12800
11000
5500
5500
1500
1500

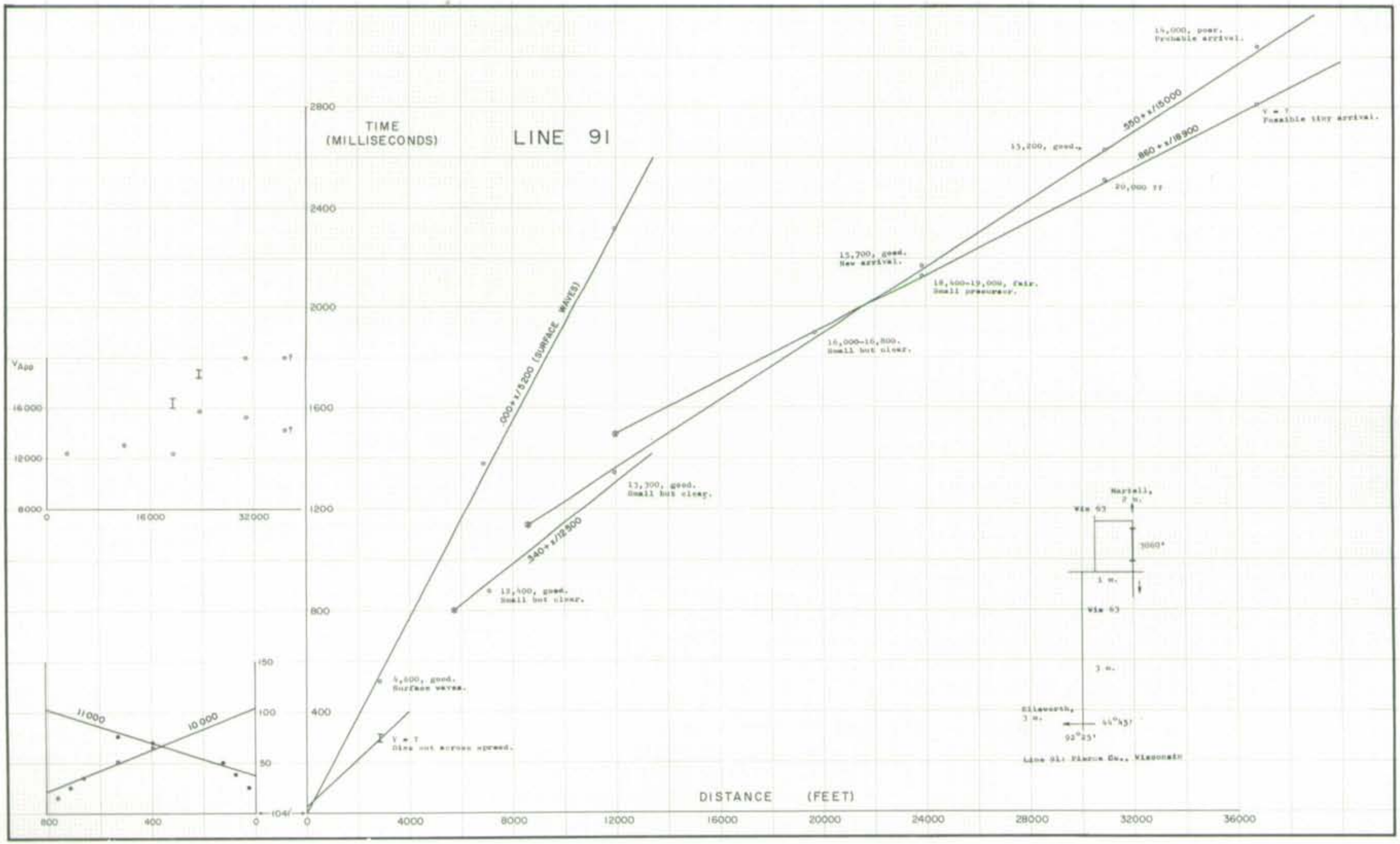


LINE 90

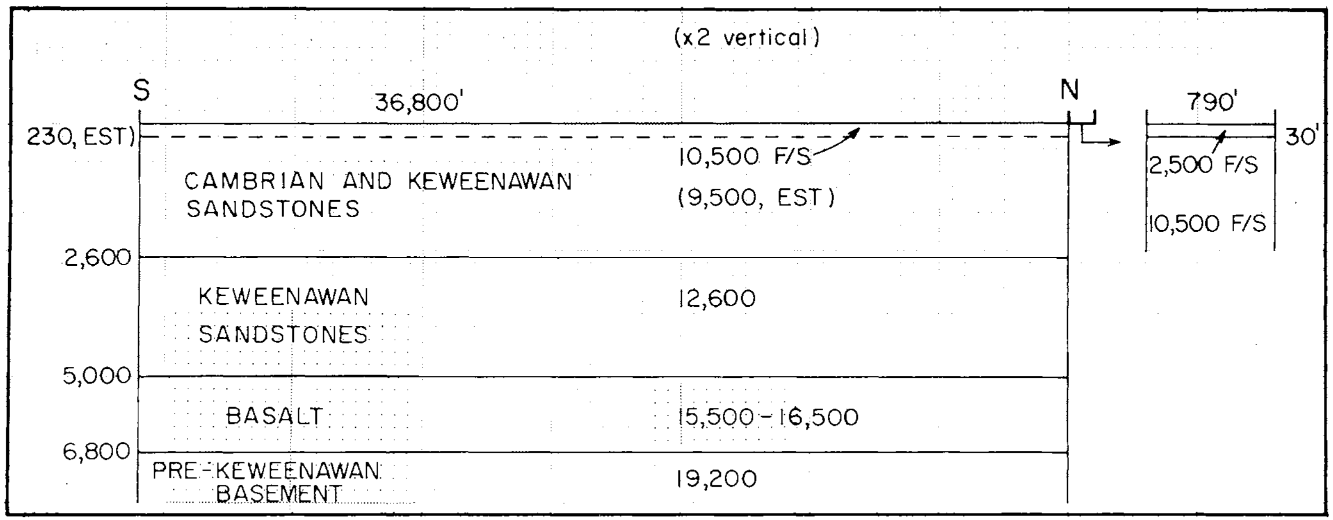
PURPOSE: See Line 88. Mean surface elevation is 1,000 feet.

RESULTS: Line 90 was interpreted jointly with Line 81, parallel to 90 and 8 miles south along strike. The shallow section appears to include a thin (assumed 200 feet) Ordovician dolomite with velocity 11,800-12,000 feet/second overlying lower velocity sandstones (9,500 feet/second assumed). The velocity inversion is evidenced by 350 ms offset of the travel-time graph. Beneath this lies material with velocity 12,500-13,000 feet/second. The seismic arrivals are good but the data fit poorly to a travel-time line segment; one possible explanation is that the velocity change is gradational.

The deepest refractor at a depth of 5,400 feet is well defined on both Lines 81 and 90; depth at Line 81 is 6,000 feet. The velocity value is taken as 16,500 feet/second at Line 90 and 17,000-17,500 feet/second at Line 81. This identifies the material as Middle Keweenawan basalts. Surprisingly, the crystalline basement arrival which appears on lines to both east and west cannot be identified on either Lines 81 or 90. One possible explanation would be substantially greater depth.



LINE 91
TIME (MILLISECONDS)
DISTANCE (FEET)
.000+x/5200 (SURFACE WAVES)
340+x/12500
550+x/15000
860+x/18900
4,600, good. Surface waves.
V = ? Dies out across spread.
13,400, good. Small but clear.
13,300, good. Small but clear.
16,000-16,800. Small but clear.
15,700, good. New arrival.
18,400-19,000, fair. Small precursor.
13,200, good.
20,000 ??
14,000, poor. Probable arrival.
V = ? Possible tiny arrival.
Martell, 2 m.
Wis 63
3060'
1 m.
Wis 63
3 m.
Ellsworth, 3 m.
44°43'
92°25'
Line 91: Pierce Co., Wisconsin



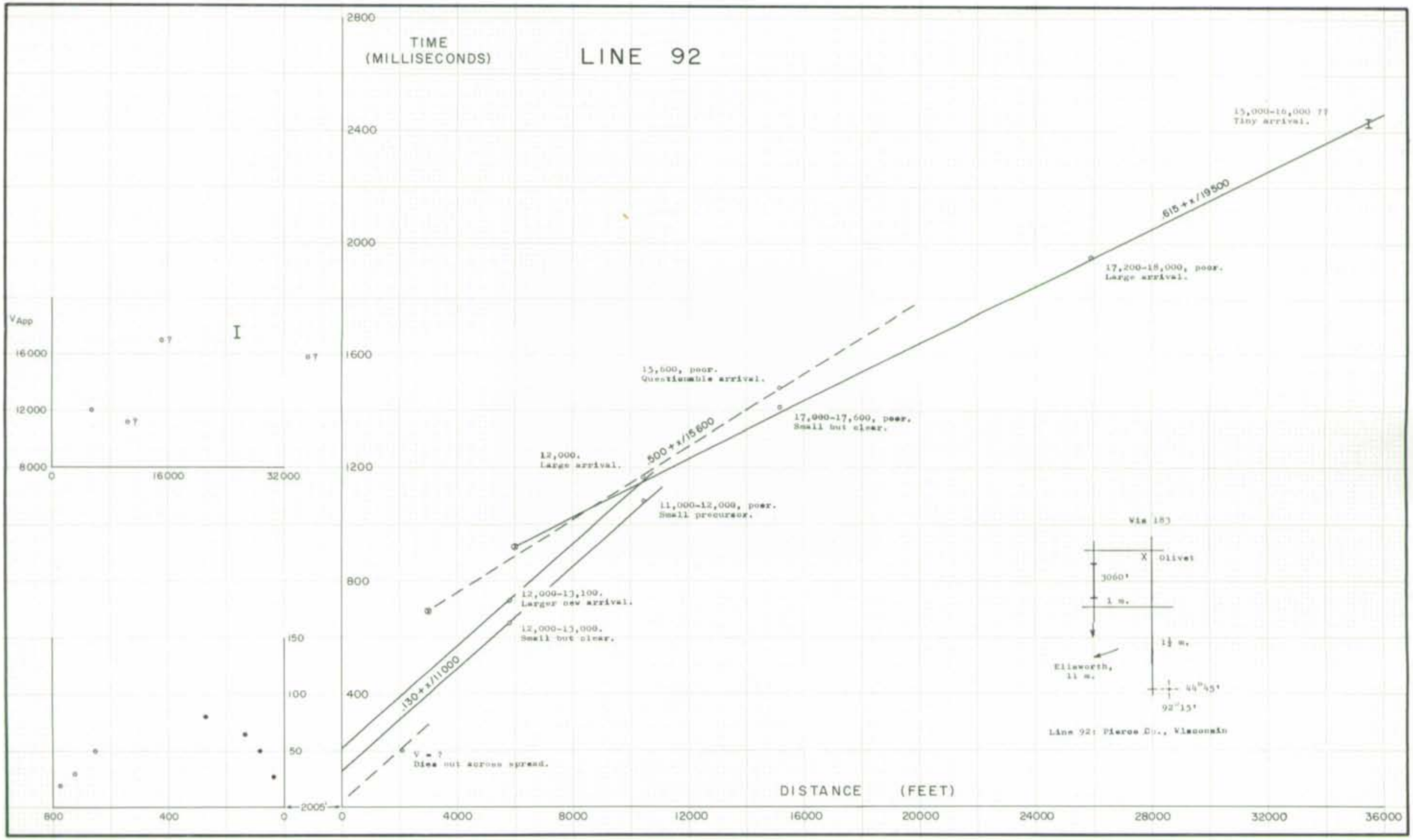
LINE 91

PURPOSE: See Line 88. Mean surface elevation is 1,050 feet.

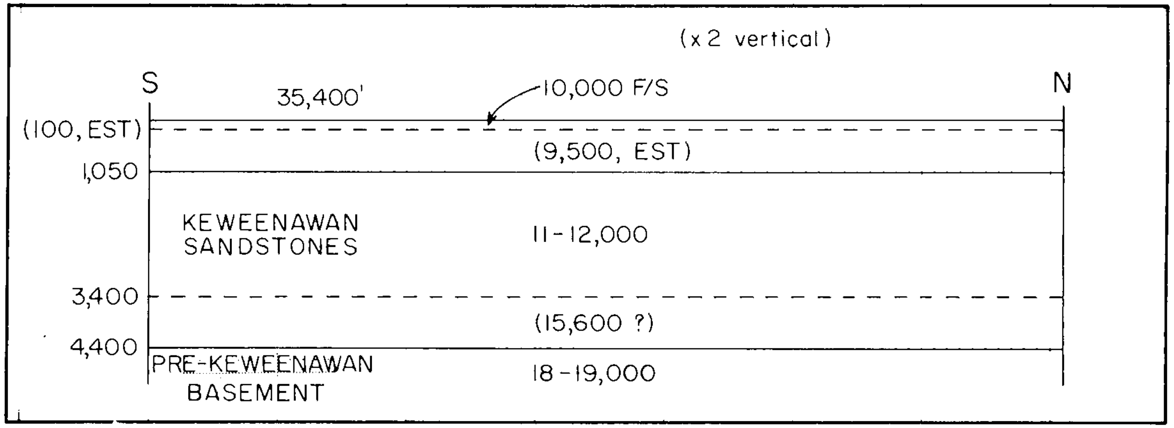
RESULTS: A velocity inversion within the near-surface section is shown by offset of the travel time graph between shots 1 and 2. The structure is based upon an assumed thickness of 200 feet for the 10,500 feet/second material, with 9,500 feet/second material underneath. Underlying material is assigned a velocity of 12,500 feet/second from across-spread velocities and adjacent profiles, although the two arrivals do not fit the line well.

The next deeper horizon is defined by four points, three of them second arrivals. A velocity line of 15,000 feet/second has been drawn through them, but on the basis of across-spread velocities we assign a value 15,500-16,500 feet/second to the material. This is presumably Middle Keweenawan basalt, although a higher velocity would have been expected.

The deepest horizon corresponding to the pre-Keweenawan basement is defined by three seismic arrivals which fit well to a 18,900 feet/second velocity line.



LINE 92
TIME (MILLISECONDS)
DISTANCE (FEET)
615 + x/19500
500 + x/15600
130 + x/11000
15,000-16,000 ??
Tiny arrival.
17,200-18,000, poor.
Large arrival.
15,600, poor.
Questionable arrival.
17,000-17,600, poor.
Small but clear.
12,000.
Large arrival.
11,000-12,000, poor.
Small precursor.
12,000-13,100.
Larger new arrival.
12,000-13,000.
Small but clear.
V = ?
Dies out across spread.
Via 183
Olivet
3060'
1 m.
1½ m.
Ellsworth,
11 m.
44°45'
92°15'
Line 92: Pierce Co., Wisconsin
VApp
2005'

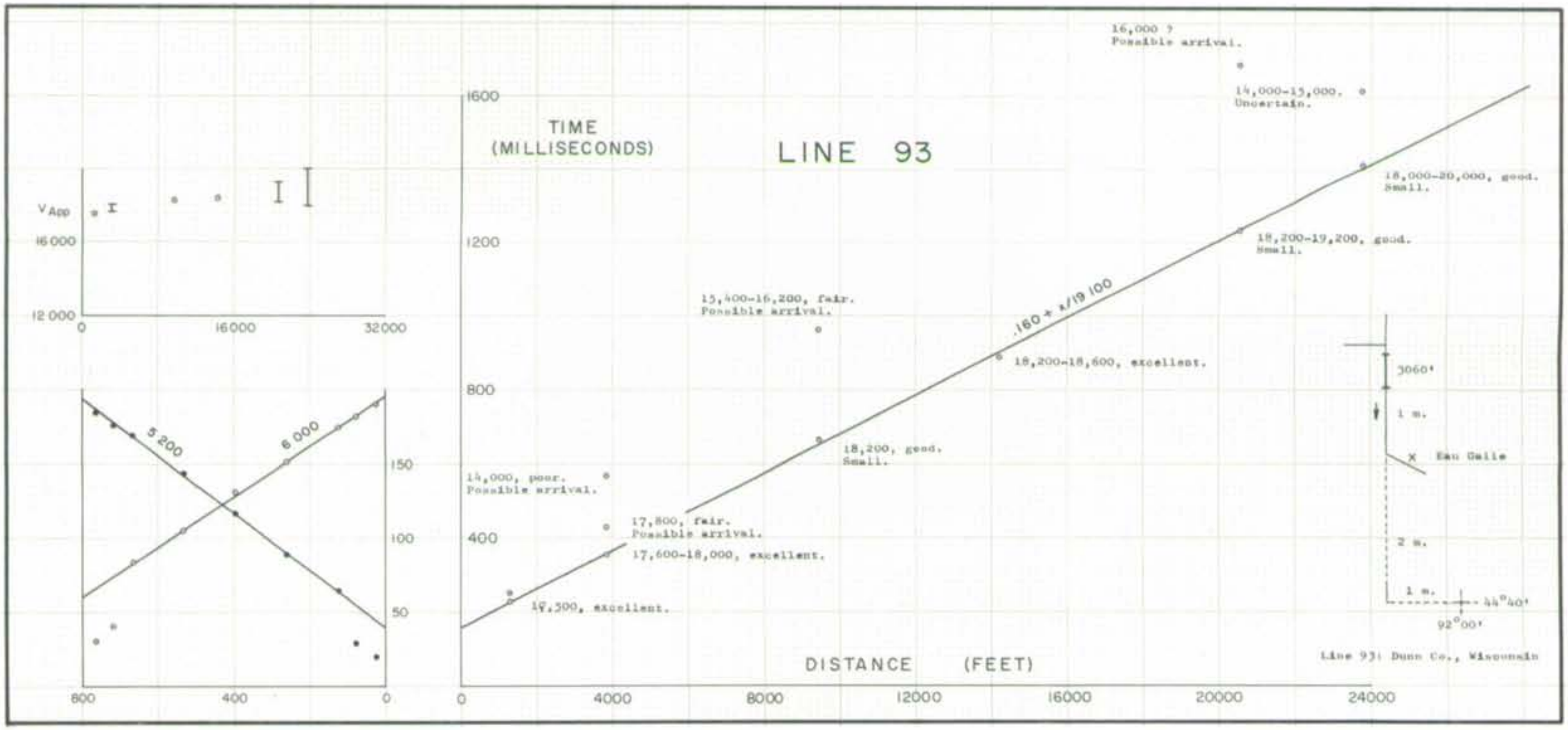


LINE 92

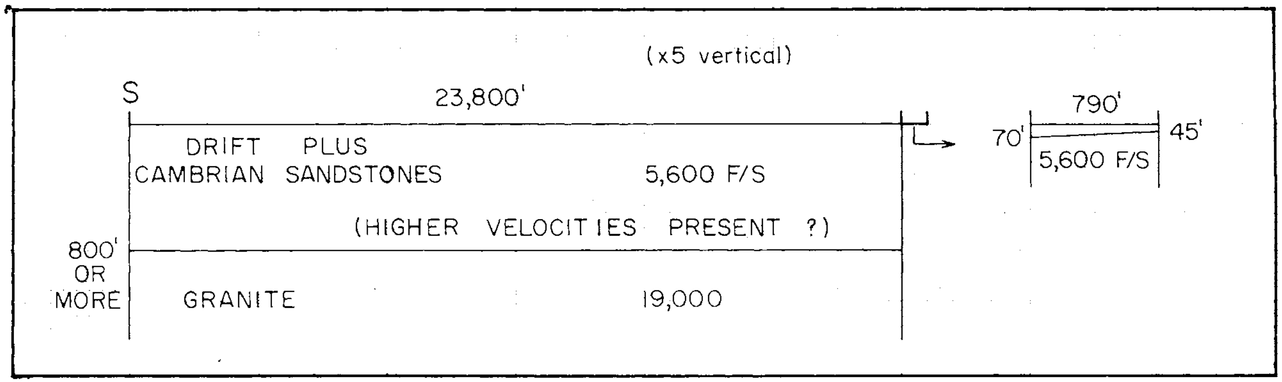
PURPOSE: See Line 88. A nearby well, Spring Valley No. 3, showed 75 feet of drift, then Cambrian sandstone to bottom at 377 feet. Mean surface elevation is 1,100 feet.

RESULTS: The near-surface section shows a thin 10,000-11,000 feet/second layer underlain by lower-velocity material, assumed 9,500 feet/second. Beneath this lies 11,000-12,000 feet/second material; it is defined by first arrivals from two shot points plus secondary arrivals (converted waves?) with the same apparent velocity.

The basement refractor with velocity 18,000-19,000 feet/second is defined by three points. A 15,600 feet/second layer overlying the basement has been included on the basis of a single questionable secondary arrival plus similar velocities from adjacent lines. This yields depth to basement of 4,400 feet; omission of this layer would reduce basement depth to 3,900 feet.



LINE 93
TIME
(MILLISECONDS)
DISTANCE (FEET)
V_{App}
16 000
12 000
0
16000
32000
5 200
6 000
800
400
0
150
100
50
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
16,000 ?
Possible arrival.
14,000-15,000.
Uncertain.
18,000-20,000, good.
Small.
18,200-19,200, good.
Small.
.160 + x/19 100
15,400-16,200, fair.
Possible arrival.
18,200-18,600, excellent.
18,200, good.
Small.
14,000, poor.
Possible arrival.
17,800, fair.
Possible arrival.
17,600-18,000, excellent.
17,300, excellent.
3060'
1 m.
Eau Galle
2 m.
1 m.
44°40'
92°00'
Line 93: Dunn Co., Wisconsin



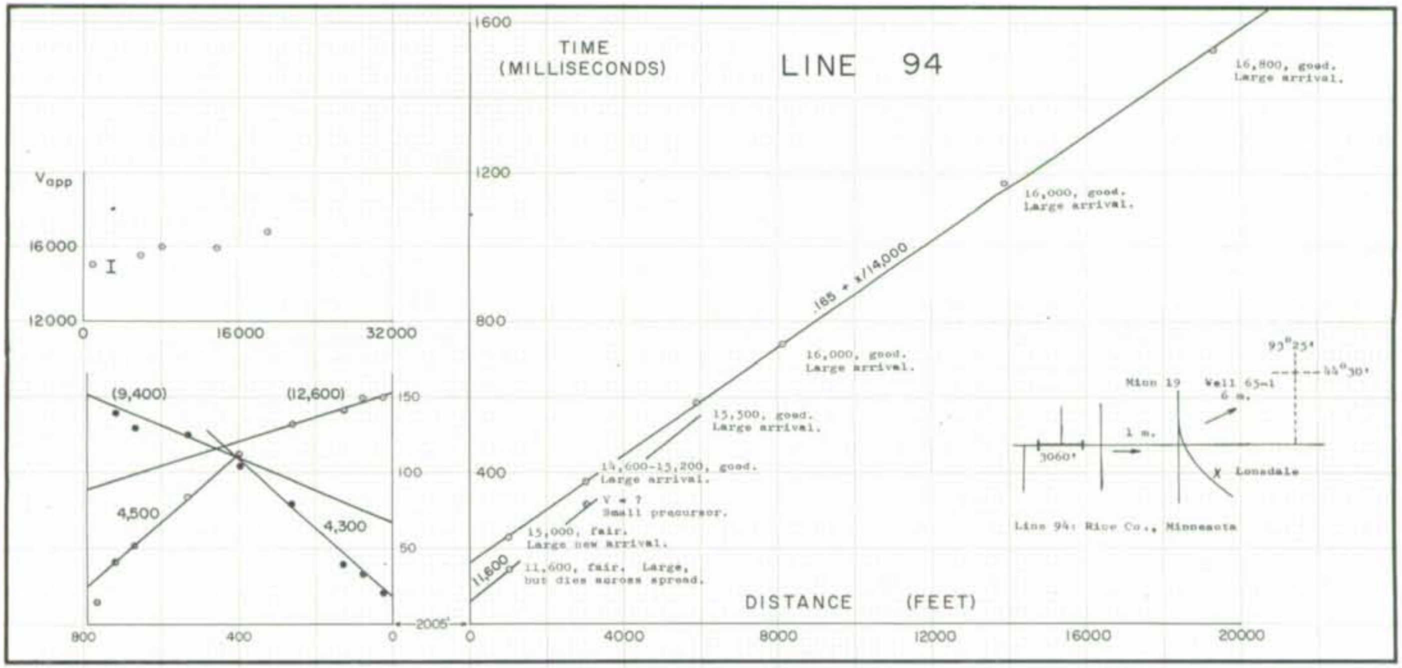
LINE 93

PURPOSE: Line 93 is the easternmost line on the sequence of profiles across the eastern basin in Wisconsin. Mean surface elevation is 800 feet.

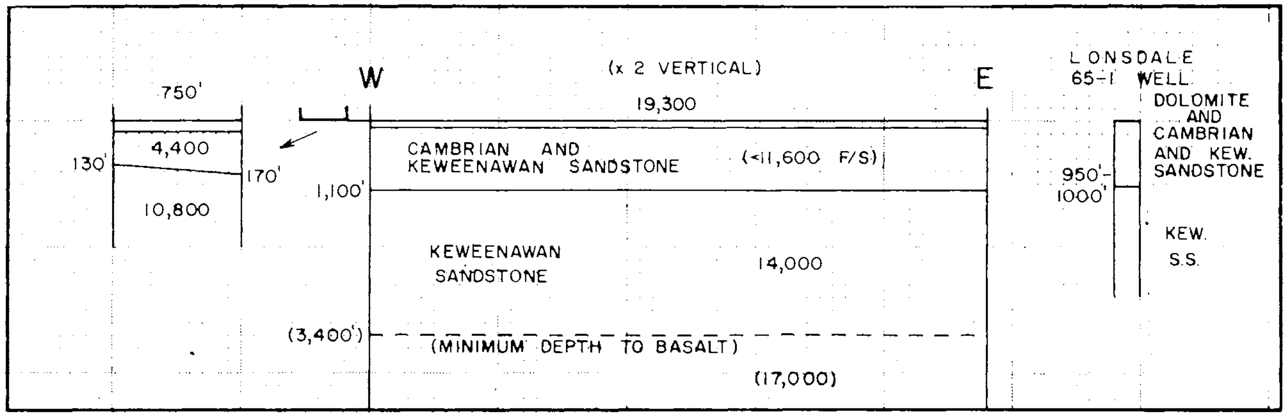
RESULTS: The significant conclusion from this line is a well-defined velocity of 19,000 feet/second for basement. This is a pink granite reported at 417 feet in a well near Durand, 2 miles to the east. The well records show 30 feet of drift, 115 feet of Eau Claire Sandstone, and 272 feet of Mt. Simon sandstone.

The in-line seismic data show a substantial thickness of 5,600 feet/second material beneath about 60 feet of surficial material. Presumably the former represents the Eau Claire member, although the velocity value is more suggestive of glacial drift.

The shot spacings preclude observation of intermediate velocity layers, if present. A depth to granite of 800 feet is computed using an overlying velocity of 5,600 feet/second. The presence of undetected 10,000 feet/second material would increase depth to granite by several hundred feet.



TIME
(MILLISECONDS)
LINE 94
1600
1200
800
400
Vapp
16000
12000
0
16000
32000
(9,400)
(12,600)
4,500
4,300
150
100
50
800
400
0
2005'
.165 + x/14,000
11,600
16,800, good.
Large arrival.
16,000, good.
Large arrival.
16,000, good.
Large arrival.
15,500, good.
Large arrival.
14,600-15,200, good.
Large arrival.
V = ?
Small precursor.
15,000, fair.
Large new arrival.
11,600, fair. Large,
but dies across spread.
DISTANCE (FEET)
4000
8000
12000
16000
20000
93°25'
44°30'
Mion 19
Well 65-1
6 m.
1 m.
3060'
Lonsdale
Line 94: Rice Co., Minnesota



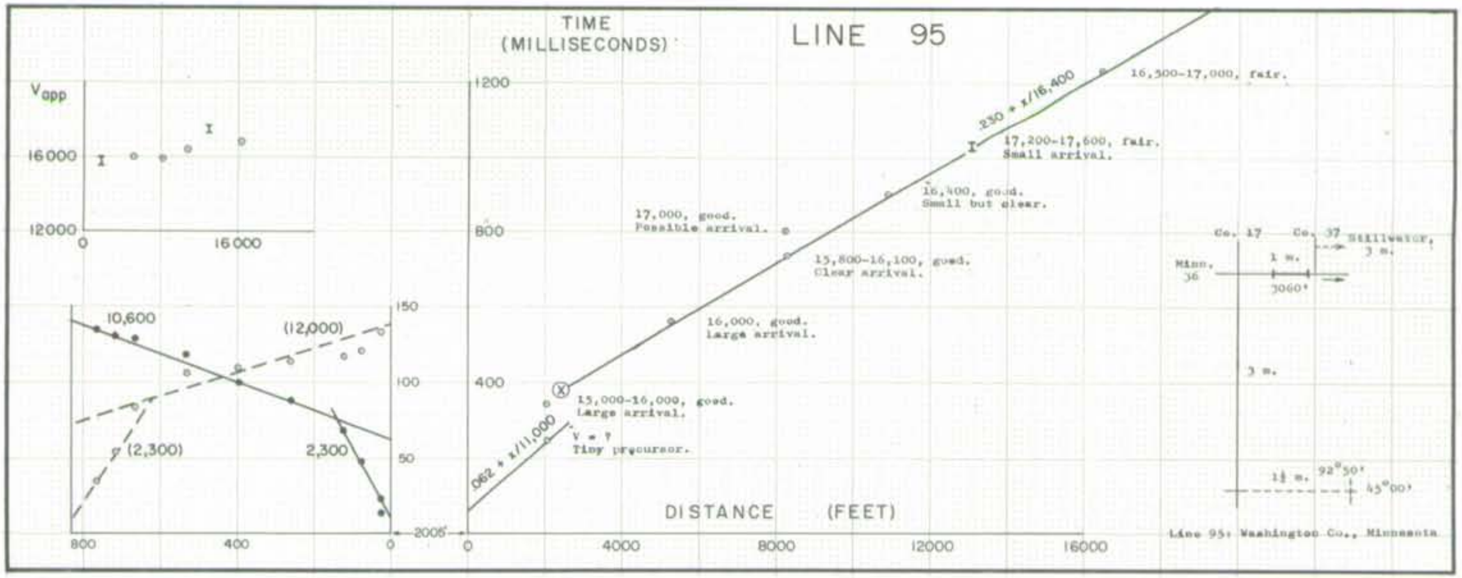
LINE 94

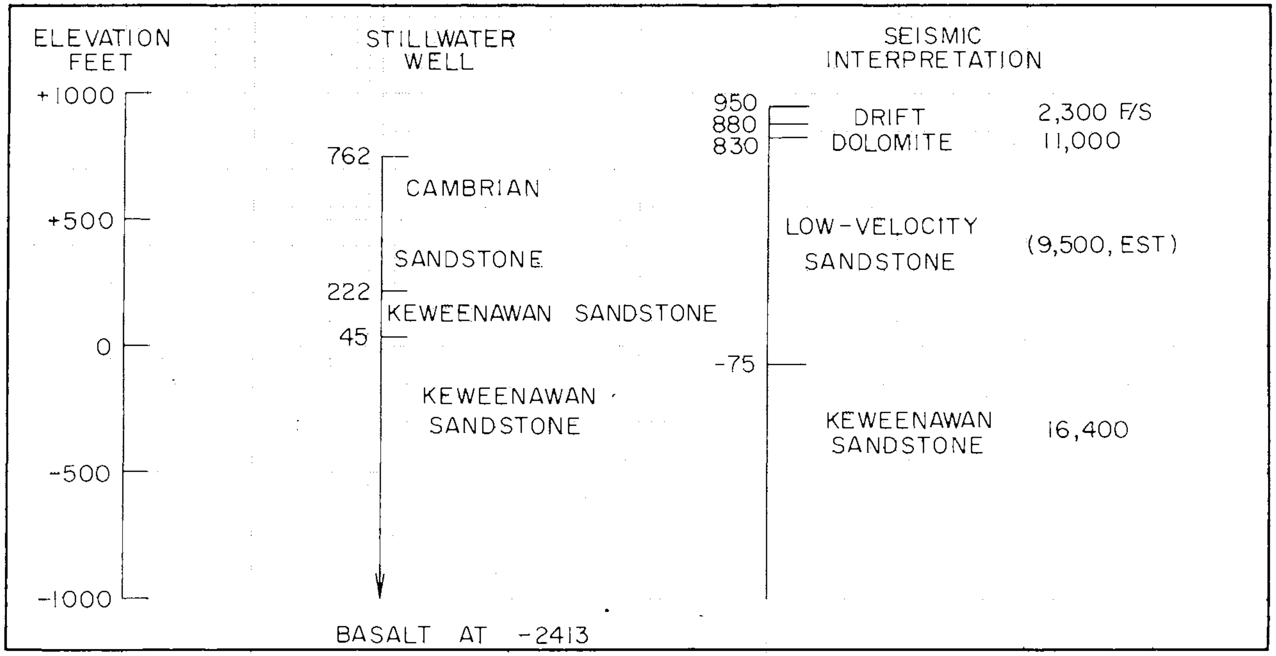
PURPOSE: Line 94 is a calibration line shot close to Lonsdale 65-1 well. The well encountered glacial drift to 70 feet, Ordovician (Prairie du Chien) dolomite to 268 feet, Cambrian sandstone (plus a few tens of feet of younger Upper Keweenawan sandstone) to 945 feet, and older Upper Keweenawan sandstone to the bottom at 2,850 feet. The uppermost 150 feet of the latter member consists of a gradational sequence of shales and siltstone, probably representing an Upper Keweenawan regolith. Below 1,100 feet, the sandstone member contains volcanic fragments and yields an unusually high density of 2.70-2.75 g/cc. The density log is presented as Figure 9. Mean surface elevation is 1,100 feet.

RESULTS: The in-line data show 150 feet of glacial drift overlying Ordovician Prairie du Chien dolomite with velocity of about 11,600 feet/second. A slight offset of the travel time graph suggests the presence of low velocity material beneath the dolomite, corresponding to Cambrian sandstones.

The older Upper Keweenawan sandstone is defined by clear arrivals from every shot point. The arrivals fit a 14,000 feet/second line, yielding a depth of 1,100 feet in good agreement with the well data. Spread velocities are somewhat higher than 14,000, possibly reflecting local irregularities beneath the geophone spread. Spread velocities increase with distance, suggesting a velocity increase with depth.

We have drawn a tentative 17,000 feet/second line through the 16,800 feet/second arrival at shot 6, yielding a depth of 3,400 feet. Since the arrival does fit on the 14,000 feet/second line, however, we prefer to interpret this depth as a minimum limiting value to basalt rather than as an actual geologic horizon.


LINE 95
TIME
(MILLISECONDS)
DISTANCE (FEET)
Vapp
16000
12000
0
16000
1200
800
400
0
4000
8000
12000
16000
800
400
0
150
100
50
2005
10,600
(12,000)
(2,300)
2,300
062 + x/11,000
230 + x/16,400
16,300-17,000, fair.
17,200-17,600, fair.
Small arrival.
16,400, good.
Small but clear.
17,000, good.
Possible arrival.
15,800-16,100, good.
Clear arrival.
16,000, good.
Large arrival.
15,000-16,000, good.
Large arrival.
V = ?
Tiny precursor.
Co. 17
Co. 37
Stillwater,
3 m.
Minn.
36
1 m.
3060'
3 m.
1½ m.
92°30'
45°00'
Line 95: Washington Co., Minnesota



LINE 95

PURPOSE: The line was run for velocity control 2 miles south of a deep well at Stillwater. Both well and seismic line lie on the upthrown side of the St. Croix Horst. Mean surface elevation is 950 feet.

RESULTS: The in-line data show 11,000 feet/second dolomite underlying about 70 feet of glacial drift. The presence of lower-velocity sandstone beneath the dolomite is evidenced by offset of the travel-time graph and by the rapid attenuation with distance of the dolomite arrival as expected for a thin layer. We have assumed a velocity of 9,500 feet/second for the Cambrian and the younger member of the Keweenawan sandstones, based upon Cambrian and Hinckley Sandstone velocity data in the Western Basin.

Excellent seismic data fit a 16,400 feet/second travel-time line, with confirming velocities from across-spread results. Depth to this material is 1,025 feet. This velocity value is nearly high enough to suggest identification as basalt, but correlation with the Stillwater well shows it to be the dense older member of the Keweenawan sandstones.