Final Scientific Report

1966 LAKE SUPERIOR SEISMIC EXPERIMENT — ONTARIO-QUEBEC REFRACTION PROFILES

By: JOSEPH D. EISLER WARREN H. WESTPHAL

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
WASHINGTON, D.C.

ARPA Order No. 292-66, Amend. No. 37
Project Code No. 6 10
Date of Contract 1 April 1966
Amount of Contract $66,399

Contract No. AF49(638)-1740
Contract Termination Date 31 March 1967
Project Scientist – Warren H. Westphal
Phone number 415-326-6200 Ext. 2959

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

April 1967

Final Scientific Report

1966 LAKE SUPERIOR SEISMIC EXPERIMENT — ONTARIO-QUEBEC RFRACTION PROFILES

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
WASHINGTON, D.C.

ARPA Order No. 292-66, Amend. No. 37
Project Code No. 6F10
Date of Contract 1 April 1966
Amount of Contract $66,399

Contract No. AF49(638)-1740
Contract Termination Date 31 March 1967
Project Scientist – Warren H. Westphal
Phone number 415-326-6200 Ext. 2959

By: JOSEPH D. EISLER   WARREN H. WESTPHAL

SRI Project PHU 6032

Approved: E. C. WOOD, MANAGER
GEOPHYSICS DEPARTMENT

Distribution of this document is unlimited.

Copy No. 25

ABSTRACT

As a part of EARLY RISE, a project designed to investigate the crustal structure of the central portion of the North American continent, Stanford Research Institute and Geotech Division of Teledyne Industries recorded the first arrival times and signal amplitudes of refracted compressional waves from 38 chemical explosions detonated in July of 1966 on the floor of Lake Superior. Refraction seismic data were obtained along traverses from Chapleau, Ontario, to Schefferville, Quebec, (SRI traverse), and from Chapleau, Ontario, to Chibougamau, Quebec, to Glace Bay, Nova Scotia (Geotech traverses). From these measurements, the following tentative conclusions are reached: The upper mantle velocity determined from a least squares fit to the overall SRI and Geotech first arrival data is 8.50 ± 0.01 km/sec. This velocity is considerably higher than that observed in other northern regions, notably upper Michigan, central Minnesota and north-central Wisconsin. Close agreement in the magnitude of the slopes of the time-distance curves for the three traverses as well as the low standard deviation (less than 1%) in the slope indicates a high degree of constancy of the upper mantle velocity over that portion of the Precambrian Shield of eastern Canada. The constancy of the upper mantle velocity suggests that the regional dip of the upper mantle—crust boundary is near zero and that the thickness of the crust is uniform. Employing the value of the crustal velocity based on the 1963 Lake Superior experiment data, it was estimated that crust in this region is quite thick, the upper mantle-crust boundary lying at a depth of approximately 60 km.

PREFACE

This report presents the refraction data obtained from Chapleau, Ontario, to Schefferville, Quebec, by Stanford Research Institute and the Geotech Division of Teledyne Industries as a part of Project EARLY RISE, performed during July 1966. The results of the survey and a few tentative interpretations of the crustal structure of a portion of the Precambrian Shield of eastern Canada are presented here. A more detailed interpretation is beyond the scope of the contract under which this research was performed. However, the results reported here are a part of a more comprehensive interpretation presently being undertaken by the authors for subsequent publication in a scientific journal.

Stanford Research Institute participants in the project were as follows: The field data were collected by R. E. Aumiller and L. C. Harlen under the immediate direction of A. L. Lange, Geophysicist. Data processing, interpretation, and report preparation was the responsibility of J. E. Eisler, Senior Geophysicist, who was Project Leader. Dr. Frank Chilton provided help in some of the theoretical aspects of the analysis. Project supervisor was Warren H. Westphal, Leader, Earth Science Group.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The objective of the 1966 Lake Superior Seismic Experiment (Project EARLY RISE) was to investigate the crustal structure of the central portion of the North American continent from eastern Nova Scotia to western Montana, by measuring the seismic velocities and signal amplitudes from chemical explosions in Lake Superior. Project EARLY RISE was an extension of a similar experiment performed in 1963[1]*. From the standpoint of the number of participating organizations** and data collected, it was one of the largest undertakings of its kind.

In this project, Stanford Research Institute (SRI) was responsible for measurements made in the region from Chapleau, Ontario, to Schefferville, Quebec (Figure 1). Also reported here are the seismic data obtained during this experiment by the Geotech Division of Teledyne Industries which operated two seismographs from Chapleau to Chibougamau, Quebec, and on to Glace Bay, Nova Scotia (Figure 1).

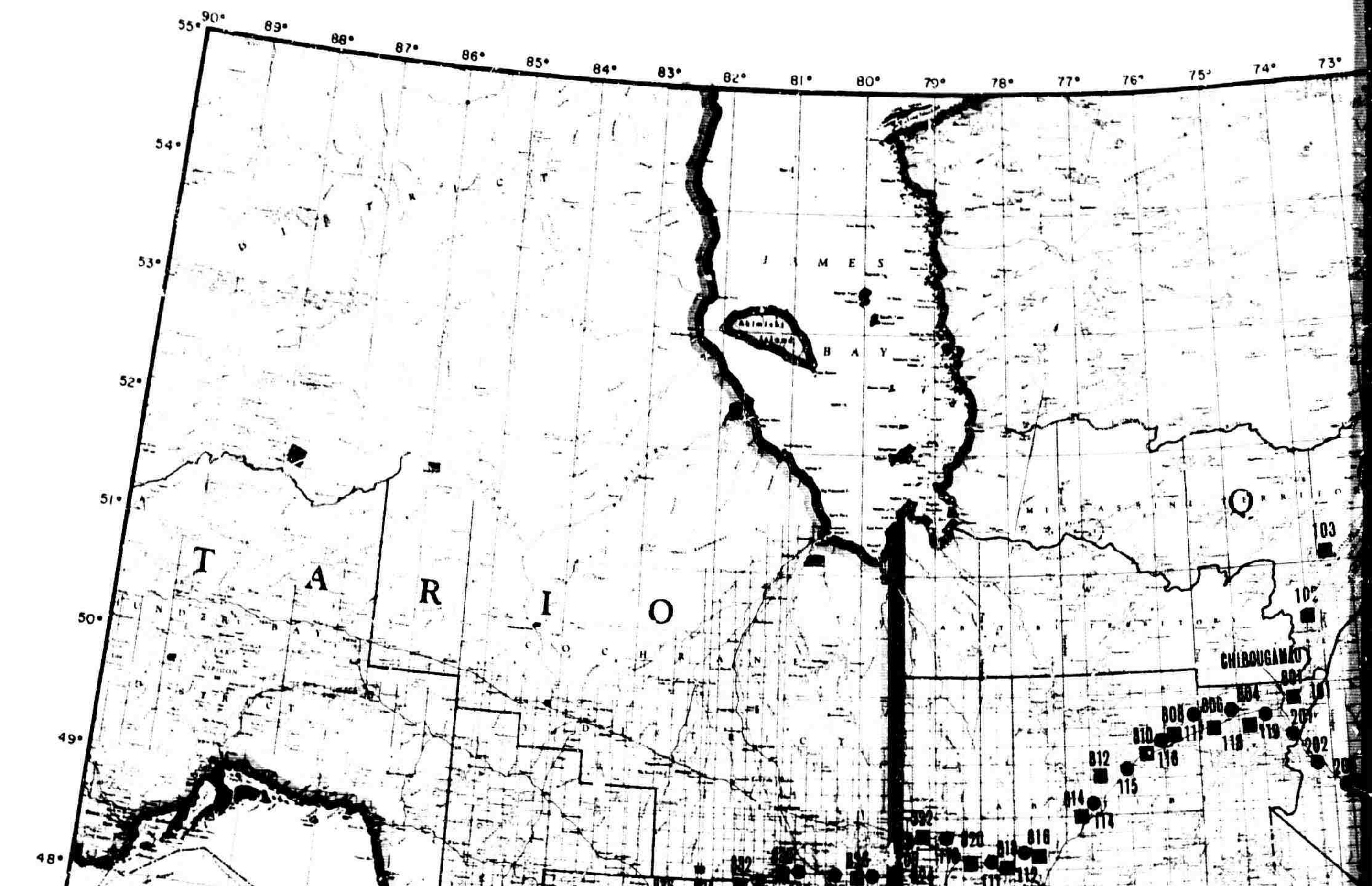
EXPERIMENT PLAN

Thirty-nine charges, each composed of 10,680 lbs of Dupont Nitramon WW(EL), were detonated during a twenty-one day period in July 1966. The shot location was approximately 47°33'N and 88°57' on the floor of Lake Superior, south of Isle Royale (Figure 1). The exact locations and shot times determined by the U.S. Geological Survey are listed in Appendix B. The depth of water at the shot point was about 200 meters.

Seismic data reported here were obtained by two portable stations operated by Stanford Research Institute (SRI), and two portable Air Force Technical Applications Center stations (AFTAC) operated by the Geotech Division of Teledyne Industries. The refraction lines occupied by these

*[1]Superscript numerals refer to references collected at the end of this report.

**The nine participating organizations and assigned profiles are listed in Appendix A.



■ SRI STATIONS
● GEOTECH. STATIONS

A

B

FIG. 1 LOCATION MAP

stations formed roughly a Y-shaped pattern over the Precambrian Shield, as shown on Figure 1. The traverse on one of the legs of the Y running almost due east for a distance of about 650 kilometers from Chapleau, Ontario, and to Chibougamau, Quebec, was occupied by SRI and AFTAC instruments with roughly 20 kilometers between stations. The stations operated by each organization were about 40 kilometers apart. Geotech and SRI station positions were alternated for logistics reasons. The traverse on the second leg of the Y ran approximately due northeast for about 700 kilometers from Chibougamau to Schefferville, Quebec. This traverse was occupied by SRI-operated stations with a nominal station separation of about 40 kilometers. The third leg of the Y ran southeast from Chibougamau, Quebec, to Glace Bay, Nova Scotia—a total distance of about 1100 kilometers. This traverse was occupied by AFTAC equipment operated by Geotech. The coordinates of the stations are listed in Tables 1, 2, and 3 for the three traverses. Although in the Chibougamau-Glace Bay traverse a total of 36 stations were occupied by AFTAC equipment, reliable data were obtained at only 16 sites. The first arrival data at the remaining stations, particularly at those which were farthest from the shot point, were completely submerged in background seismic noise. Consequently only those stations at which useful and reliable data were obtained are listed in these tables. Coordinates of the stations were obtained from three map sources: 1-50-,000, 1-250,000, and 1-500,000 scale Canadian Department of Mines and Technical Survey maps, Department of Lands and Forests maps, and Ontario Department of Highways maps.

INSTRUMENTATION

The seismometers used in obtaining the SRI data were Geospace model HS-10-1 vertical-component, moving coil instruments with a natural frequency at 1 Hz damped to 56% critical. At each station either three or six of these seismometers were connected in parallel and their combined output fed two parallel-connected Electrotech model SPA-1 amplifiers. The amplifiers contained low pass filters having cutoff frequencies of 5,7, and 10 Hz. The selection of a particular frequency of cutoff was dictated by the level and the frequency of the background seismic noise encountered along the traverse. The amplifier outputs were FM recorded on a Precision Instrument model PI-5100

Table 1
Recording Station Coordinates
Chapleau, Ontario, to Chibougamau, Quebec, Traverse
Project EARLY RISE

Station No.	Organization	Latitude (N)	Longitude (W)
101	AFTAC	47°55.8'	83°08.2'
838	SRI	47°59.0'	82°52.0'
102	AFTAC	48°06.1'	82°36.2'
836	SRI	48°15.4'	82°26.4'
103	AFTAC	48°13.6'	82°10.2'
834	SRI	48°14.6'	81°56.3'
104	AFTAC	48°20.3'	81°45.2'
832	SRI	48°24.5'	81°30.7'
105	AFTAC	48°29.3'	81°16.2'
830	SRI	48°33.4'	81°00.5'
106	AFTAC	48°32.3'	80°46.1'
107	AFTAC	48°32.3'	80°16.7'
826	SRI	48°31.3'	80°02.5'
108	AFTAC	48°32.0'	79°51.8'
824	SRI	48°31.3'	79°31.4'
109	AFTAC	48°47.8'	79°21.4'
822	SRI	48°51.8'	79°08.8'
110	AFTAC	48°51.8'	78°51.8'
820	SRI	48°38.8'	78°35.4'
111	AFTAC	48°37.3'	78°18.6'
818	SRI	48°37.8'	78°06.8'
112	AFTAC	48°41.8'	77°54.2'
816	SRI	48°42.5'	77°39.8'
814	SRI	48°57.0'	77°09.0'
114	AFTAC	49°07.2'	77°00.4'
812	SRI	49°21.3'	76°49.6'
115	AFTAC	49°22.9'	76°32.3'
810	SRI	49°28.5'	76°14.5'
116	AFTAC	49°35.5'	76°01.6'
808	SRI	49°45.6'	76°52.5'
117	AFTAC	49°49.4'	75°36.0'
806	SRI	49°48.1'	75°21.3'
118	AFTAC	49°49.2'	75°07.7'
804	SRI	49°46.1'	74°49.0'
119	AFTAC	49°47.4'	74°38.3'
801	SRI	49°55.5'	74°15.5'

Table 2
Recording Station Coordinates (SRI Stations)
Chibougamau, Ontario, to Schefferville, Ontario, Traverse
Project EARLY RISE

Station No.	Latitude (N)	Longitude (W)
101	49°55.5'	74°15.5'
102	50°33.8'	74°01.5'
103	51°05.0'	73°40.2'
105	51°49.2'	72°42.4'
207	52°15.5'	71°38.6'
109	52°49.1'	70°59.6'
110	53°22.6'	70°38.0'
113	53°57.3'	69°15.1'
117	54°45.8'	67°26.4'

Table 3
Recording Station Coordinates (AFTAC Stations)
Chapleau, Ontario, to Glace Bay, Nova Scotia, Traverse
Project EARLY RISE

Station No.	Latitude (N)	Longitude (W)
201	49°35.7'	74°16.6'
202	49°21.2'	74°02.3'
203	49°11.1'	73°40.3'
204	49°02.4'	73°21.8'
205	48°52.5'	72°56.0'
208	48°24.6'	71°58.6'
209	48°29.1'	71°36.2'
211	48°16.5'	70°47.9'
213	48°00.9'	70°04.4'
221	46°54.7'	67°21.9'
223	46°48.8'	66°36.8'
224	46°35.5'	66°13.9'
226	46°20.2'	65°35.7'
227	46°11.8'	65°09.7'
229	46°00.9'	64°31.3'
231	45°52.0'	63°49.2'

magnetic tape recorder.

Timing was provided by both a time code generator and radio time signals from WWV. The modified IRIG-C time code used was generated by SRI Mark I equipment. The time code generator was manually synchronized with the WWV time signals. Errors in synchronization were determined in the laboratory by a direct comparison between the time code and WWV time signals, both recorded on the magnetic tape and an appropriate time correction applied to the seismograms.

The recording portion of the seismograph system was calibrated at each station site by applying a 5 Hz signal of known amplitude to the amplifier inputs and recording the amplifier output on magnetic tape. In the laboratory this calibrated signal was played back and the amplitude of the trace deflection on the seismogram per unit input voltage was determined. The frequency responses of the filters was compensated for by determining the relative gains of the system at the dominant frequency of the recorded signal and at the 5 Hz calibration frequency (see Figure 2). The ground displacement A in millimicrons ($m\mu$) was obtained by introducing the response characteristic of HS-10-1 seismometers to a constant amplitude displacement of the case (see Figure 3). The period T in seconds was obtained from the seismic records by estimating the dominant period of the initial P wave group.

FIELD OPERATIONS

The traverse from Chapleau to Chibougamau, (ranging from 437 to 1110 kilometers from the shot point) was conducted along roads with the seismograph mounted in a truck. Field operations on this traverse were conducted by one man. The traverse from Chibougamau to Schefferville, (ranging from 1110 to 1695 kilometers) was an airlift operation using a float-equipped Beaver aircraft chartered from A. Fecteau Transport Aérien Ltée, Senneterre, Quebec. Two men, in addition to the pilot, were used on this traverse because of logistic and safety considerations.

One location at Chibougamau was occupied by two SRI stations (101 and 801). Signals from shots 2 and 3 of 8 July were recorded on both SRI

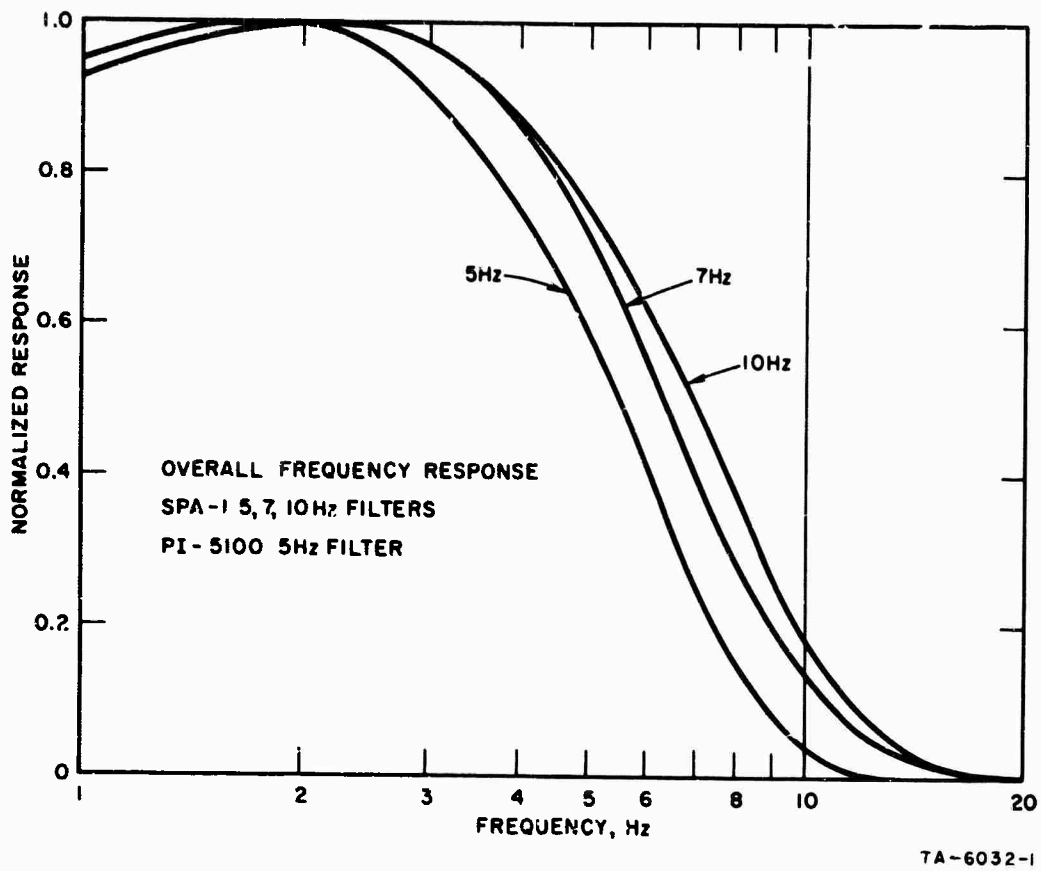


FIG. 2 FREQUENCY RESPONSES OF SRI RECORDING SYSTEM EXCLUSIVE OF SEISMOMETER

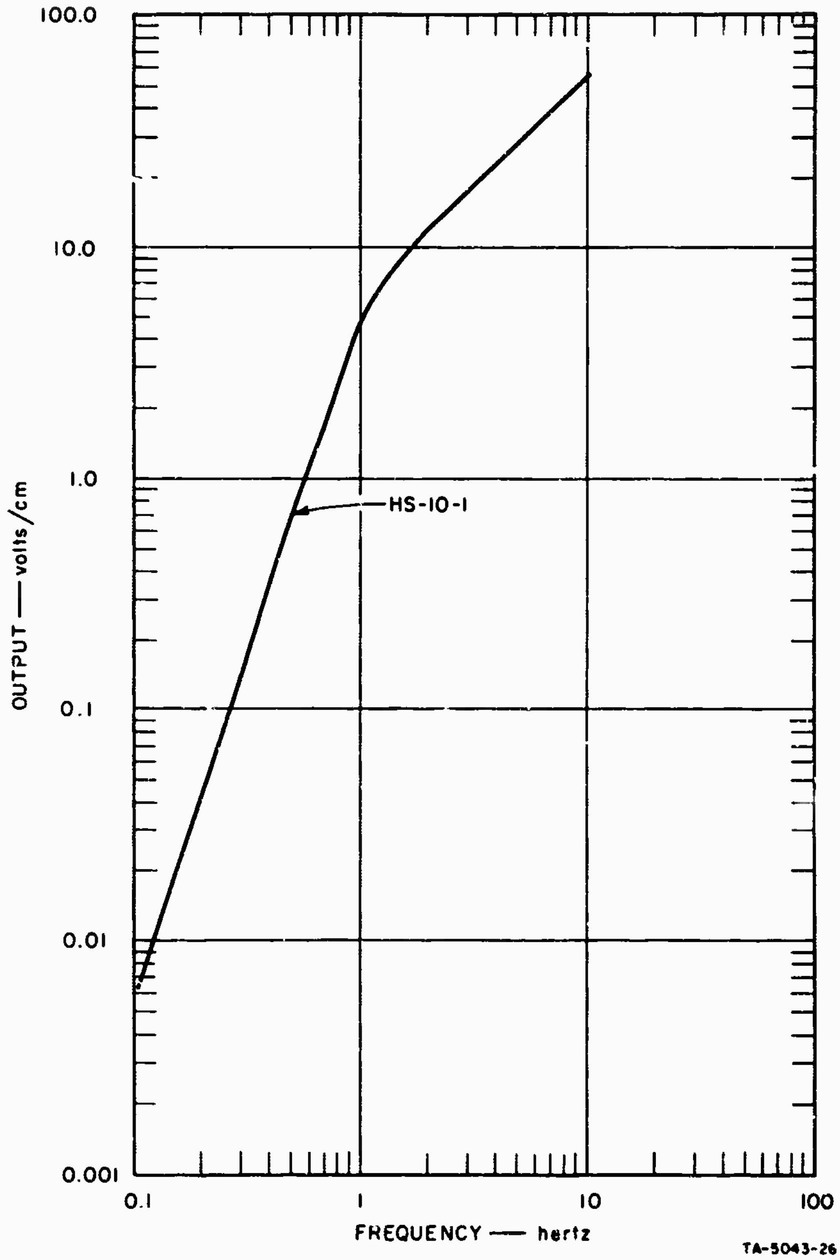


FIG. 3 SEISMOMETER RESPONSE FOR CONSTANT AMPLITUDE OF DISPLACEMENT OF CASE

seismographs at this location for comparison purposes. These data indicated that the response of the seismographs was essentially the same.

Of the total of 38* shots in the series, 33 shots were reliably recorded at 18 stations on the Chapleau-Chibougamau traverse and 15 shots at 9 stations on the Chibougamau-Schefferville traverse. The loss of reliable data for five shots on the Chapleau-Chibougamau traverse is attributed to low signal-to-noise levels encountered when only thick alluvial cover was available for seismometer sites. This same situation, compounded by unfavorable aircraft operating conditions, accounted for the higher loss of data on the Chapleau-Schefferville traverse. At times, unfavorable flying weather and lack of safe landing sites at suitable recording locations forced the use of less satisfactory recording locations. In spite of these difficulties, readable and reliable signals were received up to a distance of 1695 kilometers from the source.

The original intention in using multiple seismometers (3 or 6), connected in parallel, was to improve the signal-to-noise ratio by separating the individual units along a line normal to the line between the station and the shot. It was quickly discovered, however, that the improvement over placing the seismometers in a tight cluster was not significant enough to warrant the increased operational difficulties of deploying the seismometers on a line in heavy bush with a paucity of outcrops.

RESULTS

The source-station geocentric distances, travel times, periods, and amplitudes of the observed signals on the Chapleau-Chibougamau and the Chibougamau-Schefferville traverses are listed in Tables 4 and 5, respectively. Table 4 also includes the Geotech data on the same profile since they are pertinent to the discussion in the following section of this report. Similarly, data obtained by Geotech on the Chibougamau-Glace Bay traverse are included on Table 6.

*One of the 39 originally-scheduled shots misfired.

Table 4
Recording Station Seismic Data
Chapleau, Ontario to Chibougamau, Quebec Traverse
Project EARLY RISE

Station	Shot No.	Distance deg	Distance km	Travel Time sec	Period sec	Amplitude mμ
101 AFTAC	39	3.932	436.9	61.98	0.6	15.2
	38	3.932	436.9	61.99	0.6	18.2
838 SRI	39	4.116	457.3	65.11	0.6	29.0
	38	4.116	457.4	65.17	0.6	29.6
102 AFTAC	37	4.307	478.6	66.68	0.6	32.6
	36	4.310	478.9	66.58	0.6	31.3
836 SRI	37	4.432	492.5	70.25	0.5	13.2
	36	4.434	492.7	69.99	0.5	13.7
103 AFTAC	35	4.604	511.6	72.38	0.6	8.7
834 SRI	35	4.760	528.9	73.80	0.5	11.3
104 AFTAC	33	4.889	543.2	75.58	0.5	24.7
	32	4.895	543.9	75.58	0.4	22.7
832 SRI	33	5.058	562.0	77.90(?)	0.7	11.1
	32	5.064	562.6	77.38	0.6	11.4
105 AFTAC	31	5.233	581.5	79.68	0.5	13.7
	30	5.234	581.6	69.47	0.5	14.0
830 SRI	31	5.414	601.6	82.47	0.5	33.6
106 AFTAC	29	5.567	618.6	84.06	0.6	15.9
	28	5.568	618.7	83.97	0.6	13.7
107 AFTAC	26	5.890	654.5	88.77	0.5	15.3
826 SRI	26	6.044	671.6	90.65	0.5	29.6
108 AFTAC	25	6.163	684.8	92.56	0.6	31.1
	24	6.165	685.1	92.46	0.5	28.8
824 SRI	25	6.387	709.7	94.64	0.4	12.1
	24	6.389	709.9	94.73	0.4	12.1
109 AFTAC	23	6.525	725.1	96.57	0.6	15.5
	22	6.526	725.1	96.56	0.6	15.5
822 SRI	23	6.672	741.3	98.21	0.5	19.1
	22	6.672	741.4	98.21	0.5	19.1
110 AFTAC	20	6.866	762.9	101.09	0.5	23.1
	21	6.867	763.0	101.06	0.6	23.6
820 SRI	20	7.023	780.3	103.22	0.5	25.7
	21	7.023	780.4	103.24	0.5	23.7

Table 4 Contd.

Station	Shot No.	Distance		Travel Time	Period	Amplitude
		deg	km	sec	sec	mμ
111 AFTAC	18	7.199	799.9	105.87	0.6	15.5
	19	7.201	800.2	106.10	0.6	15.5
818 SRI	18	7.330	814.4	107.57	0.6	21.7
	19	7.333	814.8	107.60	0.6	27.2
112 AFTAC	17	7.473	830.3	107.65	0.6	25.0
	16	7.476	830.7	107.86	0.6	25.0
816 SRI	17	7.632	848.1	111.38	0.5	19.7
	16	7.636	848.4	111.41	0.5	10.9
814 SRI	14	7.996	888.4	115.74	0.6	10.7
	15	7.997	888.6	115.74	0.6	9.5
114 AFTAC	13	8.111	901.2	117.16	0.5	26.6
	12	8.112	901.3	117.36	0.6	12.8
812 SRI	13	8.258	917.6	119.90(?)	0.7	51.5
	12	8.259	917.7	119.98(?)	0.7	58.0
115 AFTAC	10	8.445	938.3	121.66	0.5	36.7
	11	8.445	938.4	121.66	0.5	41.1
810 SRI	10	8.649	961.0	124.15	0.5	39.8
	11	8.650	961.1	124.13	0.5	47.2
116 AFTAC	8	8.801	977.9	126.56	0.7	18.8
	9	8.801	977.9	126.56	0.7	19.5
808 SRI	8	8.925	991.7	128.25	0.5	41.9
	9	8.925	991.7	128.51	0.5	47.3
117 AFTAC	7	9.114	1012.7	130.79	0.6	90.7
	6	9.115	1012.7	130.78	0.6	95.8
806 SRI	7	9.267	1029.7	133.22	0.5	27.7
	6	9.268	1029.8	133.23	0.5	28.2
118 AFTAC	4	9.415	[illegible]	134.26	0.5	35.1
	5	9.415	[illegible]	134.35	0.5	36.4
804 SRI	4	9.607	1067.5	137.34	0.5	34.1
	5	9.609	1067.6	137.35	0.5	48.1
119 AFTAC	2	9.730	1081.2	138.38	0.5	46.2
	3	9.727	1080.8	138.59	0.6	41.3
801 SRI	3	9.990	1109.9	142.00	0.5	15.1
	2	9.993	1110.3	142.00	0.5	14.8

Table 5
Recording Station Seismic Data (SRI Stations)
Chibougamau, Quebec, to Schefferville, Quebec,
Project EARLY RISE

Station	Shot No.	Distance		Travel Time	Period	Amplitude
		deg	km	sec	sec	$m\mu$
101	2	9.993	1110.3	141.98	0.5	15.8.
102	5	10.244	1138.2	144.91	0.5	10.5.
103	7	10.576	1175.0	149.34	0.8	7.9.
103	6	10.576	1175.1	149.29	0.8	6.8.
105	13	11.352	1261.3	160.38	0.5	6.3.
207	20	12.102	1344.6	169.60	0.6	0.9.
207	21	12.104	1344.8	169.60	0.6	0.3.
109	23	12.637	1404.0	176.51	0.6	4.5.
109	22	12.638	1404.1	176.52	0.6	2.8.
110	25	13.019	1446.4	181.94	0.6	2.1.
110	24	13.021	1446.7	181.91	0.6	2.5.
113	31	13.991	1554.4	194.35	0.6	3.3.
113	30	13.993	1554.6	194.31	0.6	3.4.
117	37	15.261	1695.4	211.34	0.5	4.1.

Table 6
Recording Station Seismic Data (AFTAC Stations)
Chibougamau, Quebec, to Glace Bay, Nova Scotia,
Project EARLY RISE

Station	Shot No.	Distance deg.	Distance km.	Travel Time sec.	Period sec.	Amplitude mμ
201	1	9.909	1101.0	141.35	0.7	13.1
202	1	10.040	1115.6	143.15	0.6	15.1
203	3	10.295	1143.9	146.59(?)	0.5	3.5
	2	10.298	1144.3	146.28	0.6	3.6
204	3	10.490	1165.6	149.19	0.6	5.4
	2	10.493	1166.0	148.38	0.6	5.4
205	4	10.766	1196.3	151.36	0.6	3.9
	5	10.767	1196.4	151.25	0.6	5.6
208	7	11.406	1267.4	157.29	0.6	5.7
209	9	11.648	1294.3	162.66	0.5	5.1
211	10	12.198	1355.4	171.16	0.5	7.0
	11	12.198	1355.4	170.96	0.5	8.3
213	13	12.704	1411.6	177.06	0.4	9.5
221	20	14.675	1630.7	203.19	0.7	6.9
	21	14.675	1630.7	203.16	0.3	6.6
223	22	15.191	1688.0	210.36(?)	0.6	5.8
	23	15.191	1688.1	210.07	0.6	6.9
224	23	15.491	1721.4	214.97	0.6	34.6
	22	15.492	1721.5	214.96	0.6	33.3
226	24	15.980	1775.7	220.76	0.6	6.9
	25	15.982	1775.9	220.66	0.6	9.7
227	26	16.304	1811.7	224.67	0.5	5.4
	27	16.305	1811.8	224.57	0.5	5.4
229	29	16.779	1864.6	231.06	0.6	7.3
	28	16.780	1864.7	231.27	0.5	5.8
231	31	17.295	1921.9	236.18	0.7	5.0
	30	17.296	1922.0	236.28	0.8	12.0

The results reported in these tables are based on seismograms reproduced from the magnetic tapes by both SRI and Geotech of their respective sets of field recording.

Copies of the seismograms are not included in this report but they will be included in a compilation of seismic record sections to be issued by the U.S. Geological Survey. The geocentric distances quoted are those calculated by United Geophysical Company under a contract to the U.S. Geological Survey.

DISCUSSION

Determination of Mantle Velocity

Figures 4, 5, and 6 present the P wave time of arrival versus geocentric distances for the Chapleau to Schefferville traverse (SRI data), and the Chapleau to Chibougamau and Chibougamau to Glace Bay traverses (Geotech data). The time of arrival data in these figures are the reduced times of the first recognizable trace motion representing compressional arrivals. The reduced arrival time t_a was calculated using the relation

$$t_a = T - \frac{X}{8.0} \qquad (1)$$

where

t_a is the reduced arrival time in sec
T is the observed arrival time in sec
X is the geocentric distance in km.

Just as in Tables 1 through 3 these figures show only the reliable and useful data.

To determine the refractor, or upper mantle, velocity along the three sections of the traverse, i.e., Chapleau to Chibougamau, Chibougamau to Schefferville, and Chibougamau to Glace Bay, a least squares fit to a straight line was made. The equation of the straight line is

$$t = A + B\Delta = A' + B'X \qquad (2)$$

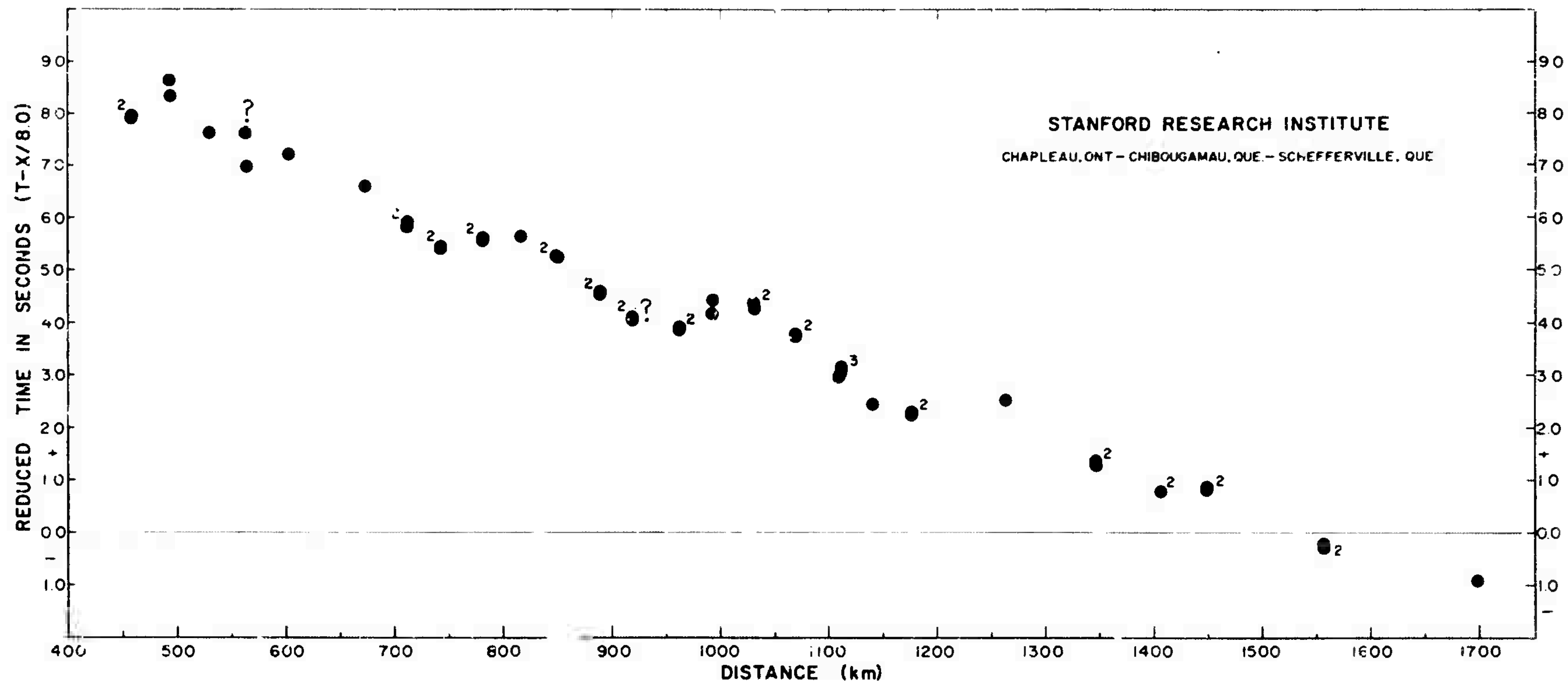


FIG. 4 REDUCED TRAVEL TIME, CHAPLEAU TO SCHEFFERVILLE — SRI DATA

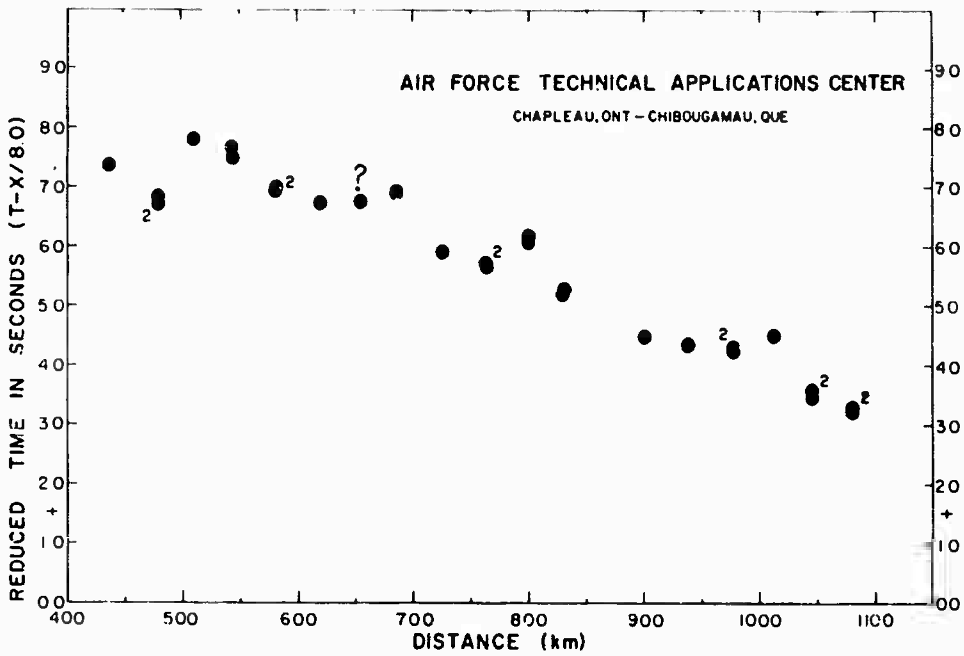


FIG. 5 REDUCED TRAVEL TIME, CHAPLEAU TO CHIBOUGAMAU-GEOTECH DATA

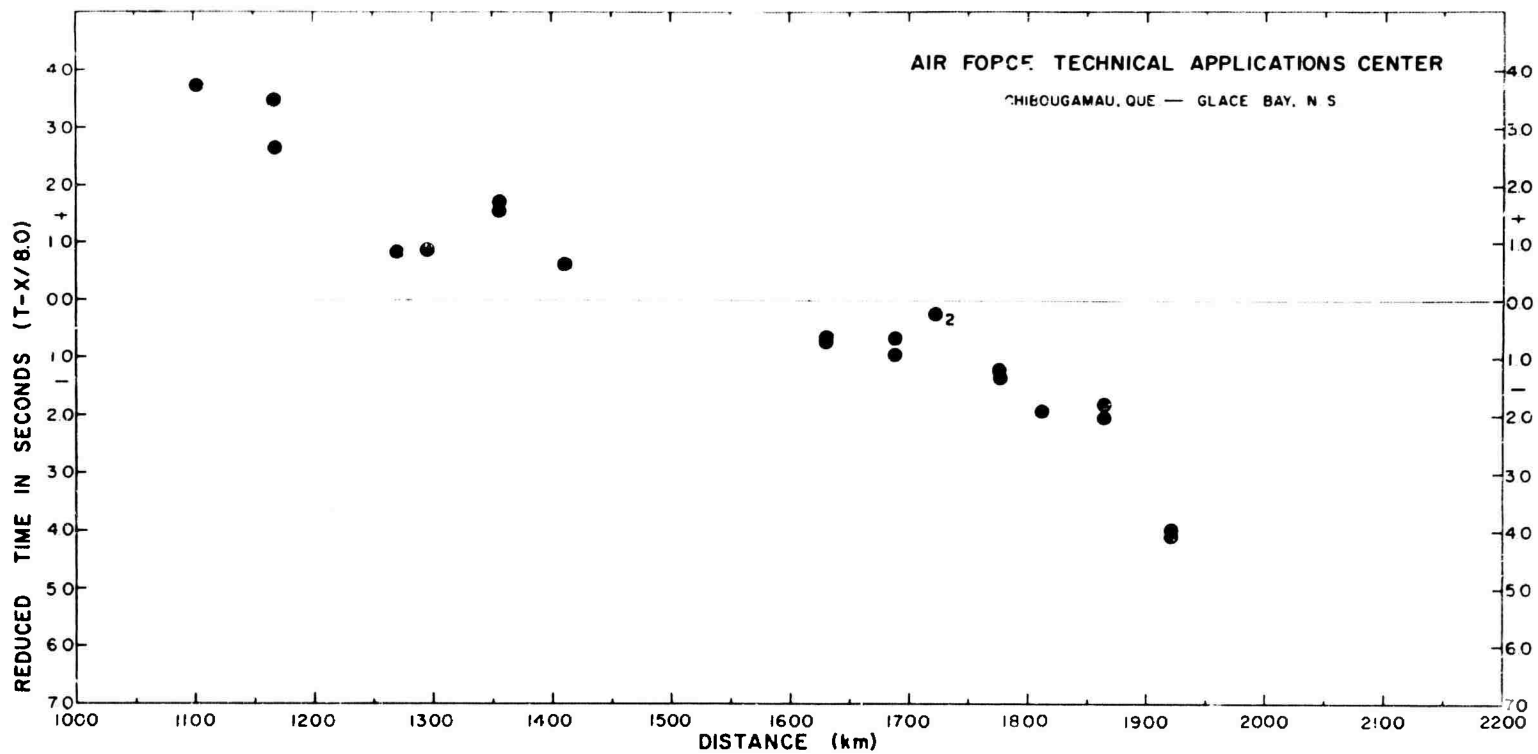


FIG. 6 REDUCED TRAVEL TIME, CHIBOUGAMAU TO GLACE BAY-GEOTECH DATA

where

t = time of arrival in sec

A, A' = intercept time in sec

B = slope of the line in sec/deg

Δ = geocentric distance in deg

B' = slope of the line in sec/km

X = geocentric distance in km

$$P_n = \frac{1}{B'} \qquad (3)$$

and

$$dP_n = -\frac{dB'}{(B')^2} \qquad (4)$$

where

P_n = compressional upper mantle velocity in km/sec

$\frac{dB'}{(B')^2}$ = corresponding standard deviation in compressional velocity, km/sec

The results of the least squares fitting for the three sections of the traverse are presented below

Chapleau to Chibougamau traverse (combined SRI and Geotech data)

$A = 11.18 \pm 0.12$ sec

$B = 13.11 \pm 0.06$ sec/deg

$A' = 11.17 \pm 0.12$ sec

$B' = 0.1180 \pm 0.0006$ sec/km

$P_n = 8.47 \pm 0.04$ km/sec

Chibougamau to Schefferville traverse (SRI data)

$A = 10.28 \pm 0.14$ sec

$B = 13.17 \pm 0.09$ sec/deg

$A' = 10.25 \pm 0.14$ sec

$B' = 0.1185 \pm 0.0008$ sec/km

$P_n = 8.44 \pm 0.06$ km/sec

Chibougamau to Glace Bay traverse (Geotech data)

$$A = 11.08 \pm 0.28 \text{ sec}$$
$$B = 13.09 \pm 0.11 \text{ sec/deg}$$
$$A' = 11.03 \pm 0.28 \text{ sec}$$
$$B' = 0.1179 \pm 0.0010 \text{ sec/km}$$
$$P_n = 8.48 \pm 0.07 \text{ km/sec}$$

Least squares fit for the combined data for the three sections of the traverse from Chapleau eastward.

$$A = 11.33 \pm 0.10 \text{ sec}$$
$$B = 13.08 \pm 0.03 \text{ sec/deg}$$
$$A' = 11.33 \pm 0.10 \text{ sec}$$
$$B' = 0.1177 \pm 0.0002 \text{ sec/km}$$
$$P_r = 8.50 \pm 0.01 \text{ km/sec}$$

Se· ral comments can be made regarding the values of the intercepts and the slopes of the least squares straight line fit to the data. One, in all cases the standard deviation (95% confidence limit) is quite small, ranging between a minimum of about ± 1% for A and ± 0.2% for B to a maximum of about ± 2.5% for A and ± 0.9% for B. Two, the values of intercept and particularly that of the slope are nearly equal for each of the three sections of the traverse and to the traverse as a whole. An exception is the low value of intercept for the Chibougamau-Schefferville line. That line, however, was based on only 15 points versus 33 and 25 data points for the other two lines. Three, a notably high upper mantle velocity (8.50 km/sec) was obtained, a value considerably larger than that observed in other northern regions. The mantle velocities in these regions are 8.03 km/sec for north-central Wisconsin, [2] 8.08 km/sec for upper Michigan[2], 8.01 for Central Minnesota[3], and 8.17 km/sec for upper Michigan (Palmer)[4], Southwest Wisconsin[4], and Ontario (Sudbury)[5]. Smith, et al,[6] estimate the upper mantle velocity as 8.07 km/sec beneath Lake Superior.

From the time of arrival-distance data obtained by the University of Toronto during Project EARLY RISE west of Chapleau a least squares straight line fit to the data beyond the break in the velocity-distance curve provided the following values of the intercept and slope.

$$A = 10.14 \pm 0.16 \text{ sec}$$

$$B = 13.08 \pm 0.15 \text{ sec/deg}$$

$$A' = 10.14 \pm 0.16 \text{ sec}$$

$$B' = 0.1176 \pm 0.0014 \text{ sec/km}$$

$$P_n = 8.50 \pm 0.10 \text{ km/sec}$$

Although the upper mantle velocity corresponds closely to that obtained from the SRI-Geotech combined data east of Chapleau, the values of intercept (A and A') are smaller by approximately 1 second. On the other hand, the intercepts of the time-distance curves obtained separately for the SRI and Geotech data agree quite well, despite the fact that these data were obtained and interpreted independently of each other. The discrepancy between the University of Toronto data and SRI-Geotech combined data has not been resolved at this time. There is a possibility, however, that the noted lack of agreement is due to the wide areal distribution of the University of Toronto recording stations causing the data to reflect the structural complications in the crust in the region east of Lake Superior. A review of data does not indicate any difficulties either in timing or picking of the first arrivals. The reasons for the discrepancy remain unanswered, particularly at geocentric distances where the University of Toronto data overlap those obtained by SRI and Geotech.

Determination of Crustal Velocity

The determination of crustal thickness requires data on both the mantle and crustal velocities. Since the SRI and Geotech traverses start about 440 km from the shot point, it is not possible to determine directly the crustal velocities from these data. To arrive at a value of the crustal velocity, recourse was made to the eastern portion of Lake Superior data on the assumption that the crustal velocities and structures determined by those data are invariant along the entire length of the SRI traverse. Although some question may be raised regarding this assumption, in the absence of any other data, it provides means for making an estimate of the crustal thickness across the Precambrian Shield in Ontario and Quebec.

Several investigators have used the 1963 seismic data using the time-term methods to establish the crustal parameters in the Lake Superior region.[6,7] Smith, et al,[6] estimated a crustal structure in this region composed of an upper layer about 10 km thick with a 5.6 km/sec velocity underlain by a layer with a velocity of 6.8 km/sec. Berry and West[7] obtained a crustal velocity ranging between 6.596 and 6.629 km/sec.

A somewhat different approach from the time-term method used by Smith, et al, and Berry and West was used in the research project reported here in an attempt to tie the 1963 data to the 1966 results. This approach was based on the premise that the shots and recording stations could be interchanged without affecting the travel times. Since all the 1966 shots in EARLY RISE were fired at the location of shot 51 of the 1963 program, the difference in the arrival times between shot 51 and other shots east of shot 51 on the Main and Wawa lines as recorded at Otter Cove were plotted versus the distance between the shots.

Figure 7 is a reduced travel time plot $(T - \frac{X}{7.0})$ of the crustal velocity data. Included in this figure is the travel time from shot 51 to the 1963 station at Dubreuil Road and the 1966 travel times to the University of Toronto stations at distances out to approximately 320 km from the shot point.* Although considerable scatter is noted in this figure, a least squares fit to the data points gives:

$$A = -\ 0.1052 \pm 0.1018 \text{ sec}$$
$$B = 16.80 \pm 0.11 \text{ sec/deg}$$
$$A' = -\ 0.1134 \pm 0.1005 \text{ sec}$$
$$B' = 0.1512 \pm 0.0010 \text{ sec/km}$$
$$P_1 = 6.61 \pm 0.04 \text{ km/sec}$$

where the symbols are the same as those given in the preceding section except that P_1 is the crustal velocity. Note that the intercepts A and A' are essentially zero indicating the arrival of direct waves and that the standard deviation in P_1 is small. This value of 6.61 km/sec for the crustal velocity closely corresponds to that reported by Berry and West (6.596 - 6.629 km/sec).

*This is the distance at which there is a break in the time-distance curve.

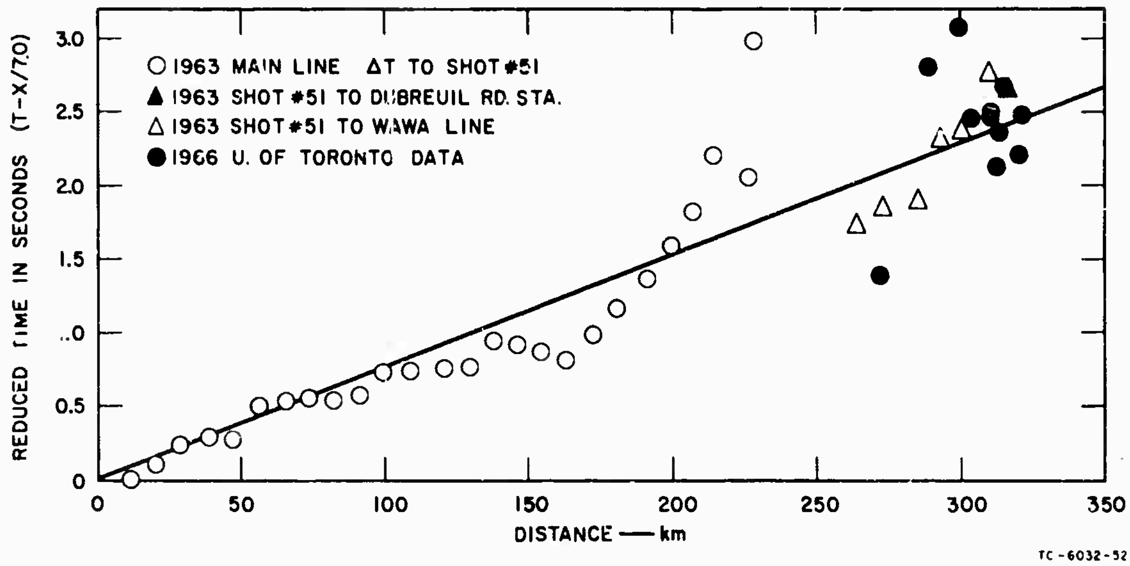


FIG. 7 REDUCED TRAVEL TIME FOR CRUST, 1963 AND 1966 DATA

Dip of Crust—Mantle Boundary

The attitude of the crust-mantle boundary is normally determined by running a reverse refraction profile. No reverse profile, with the source placed on the eastern termination of the traverses, is available on Project EARLY RISE for this purpose. However, it is possible to use the different azimuthal directions of the three sections of the Chapleau-Schefferville-Glace Bay profile to infer the regional dip of this boundary.

The slope of the time-distance curve is related to the critical angle of refraction and to the regional dip of the crust-mantle boundary in the following manner:

$$B = \frac{\cos\theta}{V_2} + \frac{\sin\theta\,(V_2^2 - V_1^2)^{\frac{1}{2}}}{V_1 V_2} \qquad (5)$$

From which

$$B = \frac{\sin(i_c + \theta)}{V_1} \qquad (6)$$

where

B = slope of the time-distance curve

θ = apparent dip angle

i_c = critical angle of refraction

V_1 = P wave velocity in the upper layer

V_2 = P wave velocity in the lower layer

and

$$\sin i_c = \frac{V_1}{V_2} \qquad (7)$$

From Figure 8, where φ is the azimuth or the angle between the direction of the apparent dip θ and the direction of the true dip ξ:

$$c = a \cos\varphi \qquad (8)$$

$$h' = c \sin\xi \qquad (9)$$

$$h' = a \sin\theta \qquad (10)$$

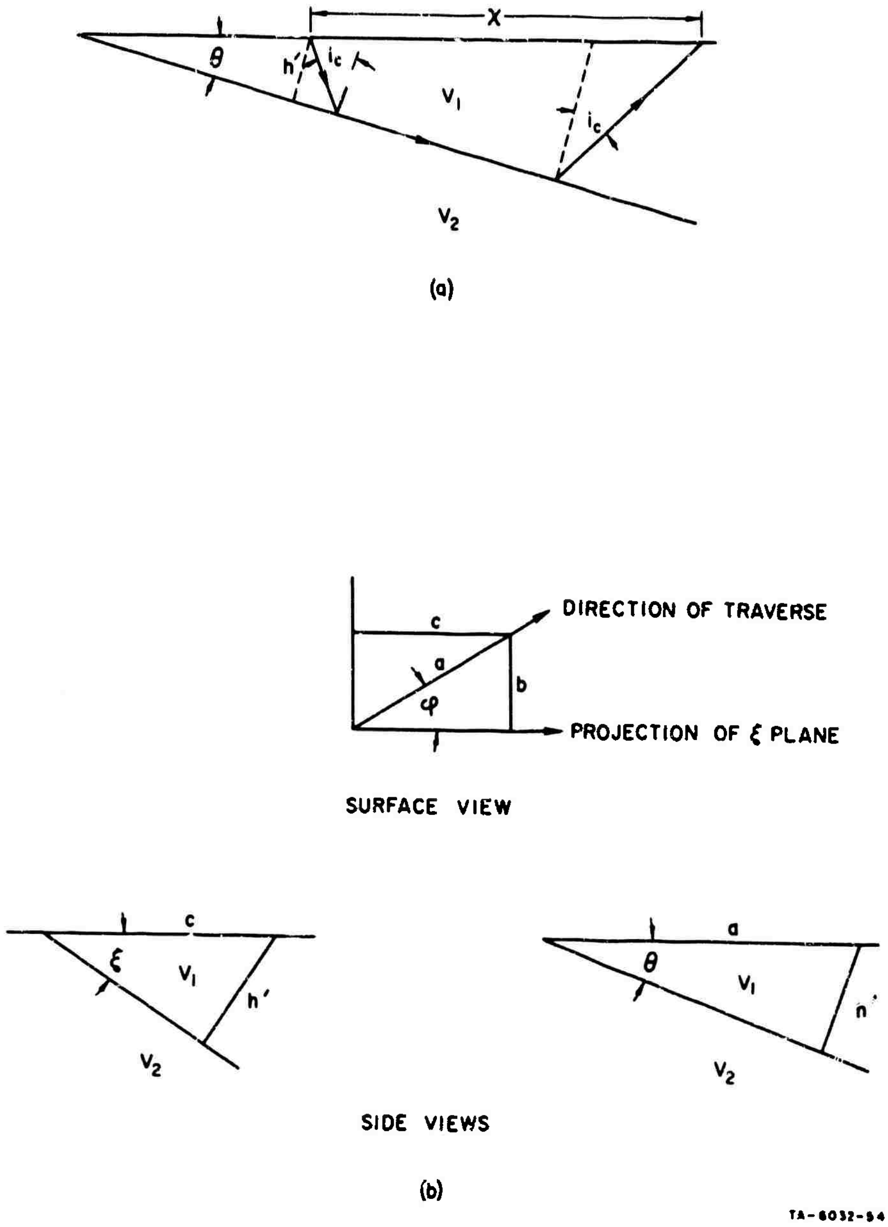


FIG. 8 GEOMETRY OF RAY PATHS FOR TILTED INTERFACE

where h' is the depth normal to the lower layer.

Therefore

$$h' = a \cos \varphi \sin \xi \qquad (11)$$

and

$$\sin \theta = \cos \varphi \sin \xi \qquad (12)$$

$$\cos \theta = (1-\cos^2 \varphi \sin^2 \xi)^{\frac{1}{2}} \qquad (13)$$

Substituting (12) and (13) into (6)

$$B = \frac{(1-\cos^2 \varphi \sin^2 \xi)^{\frac{1}{2}}}{V_2} + \frac{\sin \xi \cos \varphi \cos i_c}{V_1} \qquad (14)$$

If B—the slope of the time-distance curve—is found to be independent of φ, then $\sin \xi = 0$, $\xi = 0$, and the boundary between the two layers must be parallel to the earth's surface. Since the values of B are in close agreement on the three portions of the eastern traverses over the Precambrian Shield it is concluded that the thickness of crust in the region is substantially uniform.

Estimate of the Crustal Thickness

In view of the conclusion reached in the preceding section that the crustal thickness remains substantially constant over the portion of the Precambrian Shield over which the 1966 refraction traverses were run, it becomes feasible to determine the crustal thickness employing a well-known simple relation for a two-layer structure

$$t_0 = \frac{2h}{V_1} \left(1- \frac{V_1^2}{V_2^2}\right)^{\frac{1}{2}} \qquad (15)$$

where

t_0 = intercept of the time-distance curve in sec

h = depth of the upper layer in km

V_1 = P wave velocity in the upper layer in km/sec

V_2 = P wave velocity in the lower layer in km/sec

Using the least squares fit to the entire data

$$t_0 = 11.33 \text{ sec}$$

$$V_1 = 6.61 \text{ km/sec}$$

$$V_2 = 8.50 \text{ km/sec}$$

Substituting these values into (15)

$$h = 59.7 \text{ km}$$

This crustal thickness although large is in accord with that obtained by Smith, et al,[6] under Lake Superior proper although they show an upward trend of the base of the crust toward the east. Contrary to this upward trend, Berry and West[7] using the time-term analysis of the 1963 Lake Superior experiment data suggest that the crust reached "a maximum depth of of 60 km in the region just west of the Keweenan Peninsula. Eastward the time-term values fluctuate but do not increase or decrease systematically."

Employing a crustal structure on the eastern part of Lake Superior[6] which comprises an upper layer 10 km thick having a compressional velocity of 5.6 km/sec and a lower layer having a compressional velocity of 6.8 km/sec, the depth of the crust over the same portion of the Precambrian Shield was recalculated. The crustal depth using this model was found to be 59.1 km, which is in good agreement with the previous value.

CONCLUSIONS

From the analysis of the seismic refraction data obtained by SRI and Geotech over the eastern portion of the Precambrian Shield, the following conclusions are reached.

1. The upper mantle velocity determined from the least squares fit to the overall SRI and Geotech first arrival data is 8.50 ± 0.01 km/sec.
2. The upper mantle velocity obtained by least squares fit to the data for the three individual legs of the traverse agrees well with that obtained for the entire traverse.

3. Close agreement in the magnitude of the slopes of the time-distance curves for the three traverses as well as the low standard deviation (ranging between ±0.2% and ±0.9%) in the slope indicated a high degree of constancy of the upper mantle velocity over the portion of the Precambrian Shield of eastern Canada.

4. The constancy of the upper mantle velocity suggests that the regional dip of the upper mantle-crust boundary is near zero and that the thickness of the crust is constant.

5. Using the results of the 1963 Lake Superior experiment for the crustal velocity, the thickness of the crust in the region traversed is estimated to be approximately 60 km.

REFERENCES

1. Steinhart, John S., Lake Superior Seismic Experiment. Shots and Travel Times, Jour. Geophys. Res., 69, 24 (Dec. 15, 1964)

2. Steinhart, John S., and R. P. Meyer, Explosion Studies of Continental Structure, Carnegie Inst. Wash. Publication 622, 1961

3. Tatel, H. E. and M. A. Tuve, Seismic Waves From Explosions, Carnegie Inst. Wash. Year Book 51, 1962

4. Slichter, L. B., Crustal Structure in the Wisconsin area, Office Naval Res. Report N9 onr 86200, 1961

5. Hodgson, J. H., A Seismic Survey in the Canadian Shield, 2, Publ. Dominion Obs., Ottawa, 16, 6, (1953)

6. Smith, T. T., J. S. Steinhart, and L. T. Aldrich, Lake Superior Crustal Structure, Jour. Geophys. Res. 71, 4, (1966)

7. Berry, M. T. and G. F. West, An Interpretation of the First Arrival Data of the Lake Superior Experiment by the Time-Term Method, Bull. Seismol. Soc. Am., 56, 1, (1966)

APPENDIX A

ORGANIZATIONS PARTICIPATING IN PROJECT EARLY RISE

1. Air Force Technical Applications Center - Wawa, Ontario, to Chibougamau to eastern Nova Scotia. Chicago area to Cumberland Plateau Observatory.

2. University of Alberta - Near Saskatoon, through Edmonton, to Clairmont in western Alberta.

3. U.S. Geological Survey - Duluth to Denver to Las Vegas. Grand Marais, Minnesota, to Miles City, Montana. Flin Flon to Yellowknife.

4. Graduate Research Center of the Southwest - Southern shore of Lake Superior to St. Louis. From near Wichita to Abilene.

5. University of Manitoba - Time-term study in southeastern Manitoba and southwestern Ontario.

6. University of Michigan - Lake Superior to the Washington, D.C., area.

7. Stanford Research Institute - Wawa, Ontario, to Chibougamau to Schefferville.

8. University of Toronto and University of Western Ontario - Lake Nipigon to Churchill and possibly to Bake Lake.

9. University of Wisconsin - Miles City, Montana, toward the west.

APPENDIX B
SHOT COORDINATES AND TIMES
Project EARLY RISE

Shot No.	Date 1966 July	Shot Coordinates Longitude W	Shot Coordinates Latitude N	Shot Times (EST) hr min sec
1	7	88°53.85'	47°32.56'	05:00:00.05
2	8	88°56.57'	47°3[illegible].67'	03:30:00.02
3	8	88°56.35'	47°32.67'	04:30:00.01
4	9	88°56.30'	47°32.95'	03:30:00.04
5	9	88°56.35'	47°32.98'	04:30:00.05
6	10	88°56.35'	47°33.09'	03:30:00.02
7	10	88°56.34'	47°32.03'	04:30:00.01
8	11	88°56.06'	47°33.08'	03:30:00.04
9	11	88°56.05'	47°33.08'	04:30:00.04
10	12	88°56.40'	47°33.19'	03:30:00.04
11	12	88°56.27'	47°32.95'	04:00:00.04
12	13	88°56.54'	47°32.37'	03:30:00.04
13	13	88°56.42'	47°32.32'	04:30:00.04
14	14	88°56.48'	47°33.20'	03:30:00.03
15	14	88°56.54'	47°32.77'	04:30:00.04
16	15	88°56.43'	47°33.14'	03:30:00.04
17	15	88°56.28'	47°32.97'	04:30:00.05
18	18	88°56.16'	47°32.96'	04:00:00.03
19	18	88°56.31'	47°33.02'	05:00:00.00
20	19	88°56.80'	47°33.08'	03:30:00.01
21	19	88°56.79'	47°32.88'	04:30:00.04
22	20	88°56.00'	47°32.94'	03:30:00.04
23	20	88°55.93'	47°32.92'	04:30:00.03
24	21	88°56.49'	47°33.20'	03:30:00.04
25	21	88°56.33'	47°33.28'	04:30:00.04
26	22	88°56.29'	47°33.29'	03:30:00.03
27	22	88°56.33'	47°33.28'	04:30:00.03
28	23	88°56.21'	47°33.07'	03:30:00.03
29	23	88°56.13'	47°33.05'	04:30:00.04
30	24	88°56.66'	47°33.13'	03:30:00.03
31	24	88°56.59'	47°33.19'	04:30:00.02
32	25	88°56.60'	47°33.23'	03:30:00.02
33	25	88°56.02'	47°33.16'	04:30:00.02
35	26	88°56.27'	47°32.88'	04:30:00.02
36	27	88°57.06'	47°33.25'	03:30:00.02
37	27	88°56.73'	47°33.16'	04:30:00.02
38	28	88°56.14'	47°32.91'	03:30:00.01
39	28	88°56.08'	47°32.77'	04:30:00.02

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Stanford Research Institute	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP NA

3 REPORT TITLE

1966 Lake Superior Seismic Experiment—Ontario-Quebec Refraction Profiles

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

SCIENTIFIC FINAL

5 AUTHOR(S) (Last name, first name, initial)

Eisler, J. D.
Westphal, W. H.

6. REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
April 1967	41	9

8a CONTRACT OR GRANT NO AF 49 (638) - 1740	9a ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 8652	
c. 6250601R	9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFOSR 67-1064
d	

10 AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Office of Scientific Research (SRPG) 1400 Wilson Blvd. Arlington, Virginia 22209

13 ABSTRACT As a part of EARLY RISE, a project designed to investigate the crustal structure of the central portion of the North American continent, Stanford Research Institute and Geotech Division of Teledyne Industries recorded the first arrival times and signal amplitudes of refracted compressional waves from 38 chemical explosions detonated in July of 1966 on the floor of Lake Superior. Refraction seismic data were obtained along traverses from Chapleau, Ontario, to Schefferville, Quebec, (SRI traverse), and from Chapleau, Ontario, to Chibougamau, Quebec, to Glace Bay, Nova Scotia (Geotech traverses). From these measurements, the following tentative conclusions are reached: The upper mantle velocity determined from a least squares fit to the overall SRI and Geotech first arrival data is 8.50 ± 0.01 km/sec. This velocity is considerably higher than that observed in other northern regions, notably upper Michigan, central Minnesota and north-central Wisconsin. Close agreement in the magnitude of the slopes of the time-distance curves for the three traverses as well as the low standard deviation (less than 1%) in the slope indicates a high degree of constancy of the upper mantle velocity over that portion of the Precambrian Shield of eastern Canada. The constancy of the upper mantle velocity suggests that the regional dip of the upper mantle—crust boundary is near zero and that the thickness of the crust is uniform. Employing the value of the crustal velocity based on the 1963 Lake Superior experiment data, it was estimated that crust in this region is quite thick, the upper mantle-crust boundary lying at a depth of approximately 60 km.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Geophysics						
Refraction profile						
Seismograms						
Seismographs, Mobile						
Precambrian Shield						
Crustal velocity						
Crustal thickness						
Upper mantle velocity						
Upper mangle thickness						
Project EARLY RISE						
Lake Superior Seismic Experiment						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
__________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
__________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
__________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.