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A SEISMIC SURVEY IN THE CANADIAN SHIELD
II: Refraction Studies Based on Timed Blasts

BY

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ABSTRACT

During the rockburst studies, described in Part I* of this series, blasts timed at their source were recorded at one or more of the stations of the profile.

One group of blasts, at La Cave and at Rolphton, were timed automatically by the stations maintained at those points. These blasts frequently recorded at the other station of the pair, and sometimes at Ottawa. Timing and location were not as precise as in other sections of this work, but it was possible to determine mean velocities for P_1 and S_1 of $6 \cdot 29 \pm 0 \cdot 04$ km/sec. and $3 \cdot 44 \pm 0 \cdot 03$ km/sec. respectively. The uncertainties listed are Probable Errors of the means.

A second group of blasts, occurring at La Cave and at Temiskaming, were precisely located and were timed with the greatest possible accuracy. They were recorded at stations lying northwestward toward Kirkland Lake, and the series thus provided a reverse profile. P_1 and S_1 velocities obtained, with probable errors, were $6 \cdot 19 \pm 0 \cdot 07$ km/sec. and $3 \cdot 54 \pm 0 \cdot 07$ km/sec. A very strong phase, both in the P and S group, suggested the existence of a second layer, but this interpretation proved to be inconsistent with the evidence of other secondary arrivals.

The final group of blasts provided data on the variation of velocity with rock type. The source was near Sudbury and as the blasts were recorded at eight different stations of the rockburst profile a variation of 47° of azimuth was obtained. This provided many different sections across the Huronian basin. Mean velocities, and their Probable Errors, for P_1 and S_1 were $6 \cdot 189 \pm 0 \cdot 023$ and $3 \cdot 551 \pm 0 \cdot 007$ km/sec.

The mean for all determinations, including that made with the aid of rockbursts, together with the Probable Error of the mean, proved to be: for P_1 $6 \cdot 234 \pm 0 \cdot 012$ km/sec., and for S_1 $3 \cdot 544 \pm 0 \cdot 011$ km/sec. Secondary arrivals, in general, satisfied the single-layer travel time curves developed for the rockburst profile, although in this case also there were variations from the curves such as might have been due to variations in rock type and variations in crustal thickness.

INTRODUCTION

Throughout the course of the rockburst travel-time studies described in the first paper of this series* it was occasionally possible to time large blasts at their source and to record them at one or more of the regular stations of the profile. It is the purpose of this, the second paper of the series, to present and analyse the data so obtained.

The blasts to be considered fall into two categories—those which were located in the line of the rockburst profile and those displaced from that line at some distance. Blasts of the former class provide additional information on velocities within the profile; in particular they allow the measurements of travel-times in the reverse direction. Blasts of the latter class permit an investigation of travel-time variations for paths lying wholly outside the rockburst profile.

In the present paper all notations introduced in the first paper of the series will be adhered to. In particular the station numbers of Table II and the quality indexes of Table III will be used throughout, while events will be numbered consecutively with those given in Table IV.

* Hodgson, J. H., "A Seismic Survey in the Canadian Shield, I: Refraction Studies Based on Rockbursts at Kirkland Lake, Ont.", *Publications of the Dominion Observatory*, Vol. XVI, No. 5, 1953.

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FIELD TECHNIQUES

Station-Timed Blasts at Rolphton and La Cave

Stations of the regular profile were maintained at Rolphton and La Cave (See Figure 9, Part I) for the purpose of recording rockbursts. This hope was never realized, but the stations did fulfil a useful purpose. Both locations were the sites of large hydro-electric power developments and blasts in connection with the work were automatically timed by the seismic stations. Frequently these were large enough to record at the other station of the pair and several records became available for analysis in this way. In a few instances the larger blasts were also recorded at Ottawa.

These blasts were recorded in the course of the routine operation of the stations when technical personnel were not available, so that no attempt was made to operate the recording drums at increased speed, nor to determine the precise location of the shot with respect the station. Distances are thus uncertain by about $\pm$ 1 km. and origin times by $\pm$ 0·2 sec. There was one exception to this. On February 12, 1950, a coffer dam at La Cave was blown by a large charge. Care was taken to time and locate this blast as precisely as possible.

Precisely Timed Blasts at La Cave, Temiskaming and Sudbury

Location of Blasts

During the final summer of the field work, when Willmore-Sharpe seismometers were being used and two field stations were in operation, it became apparent that blasts were being recorded from various sources. After preliminary location by means of the seismic records three sources of these blasts were determined.

The first source was at La Cave, where large charges were being fired in connection with the power development. A second source, just south of Temiskaming, was also connected with this development for it was necessary to relocate a railroad which ran from La Cave to Temiskaming and this involved large rock cuts. Arrangements were made to time these blasts by a technique to be described later. The location of the shots was determined with relation to the development survey, and since this was tied in to a Geological Survey marker, precise location was possible. It is unfortunate that the heavy blasting was just about completed by the time machinery had been set up to time it, so that limited use was made of this source.

The remaining blast source proved to be the open-pit mines of the International Nickel Company near Sudbury (for location see Fig. 9, Part I). The officers of the Company very kindly permitted us to time the blasts and provided us with locations relative to a Geodetic Survey monument. The Sudbury blasts proved much more valuable to us than the La Cave series, producing quite usable records to distances of 173 km. despite the fact that the charges were in general, smaller. This is probably due to the fact that whereas at La Cave the blasts were close to the surface and in numerous holes fairly widely dispersed, the Sudbury blasts were designed to break up a limited section of a vertical face at considerable depth.

The geodetic coordinates of the Temiskaming, La Cave and Sudbury blasts were computed by officers of the Geodetic Service of Canada.

Timing Technique

The basic part of the equipment used in timing the blasts was a 6-channel, portable seismic recorder lent by the Ontario Department of Mines. This recorded the output of a geophone placed as close as possible to the blast, and, on a separate trace, the output of a chronometer which indicated every second second. The chronometer indicated the minute by omitting to mark the 60th second, and in practice the blast was set off as close as possible to the exact minute, so that the seconds on the record could be identified. Since the seismic recorder placed lines on the record at intervals of 0·01 sec. it was possible to time the first movement of the geophone relative to the second marks with an accuracy approaching 0·001 sec.

FIGURE 1—The blast timing equipment. It consisted of a six-channel seismic prospecting camera with storage batteries to supply power, a geophone and reel of cable of suitable length, a chronometer to indicate seconds and a control panel to adjust time mark amplitude.

In order to determine the error of the chronometer, time signals were recorded at half-hourly intervals for several hours before and after the blast, the signals being recorded on one galvanometer trace, the chronometer time on another. The chronometer could thus be precisely rated and its correction at the instant of the blast determined to within a few thousandths of a second.

When a blast was to be timed, the equipment was set up at the nearest source of power and radio signals recorded as described above. At the last possible moment the party would go to the site of the blast and set up the equipment at the point occupied by the shooter.

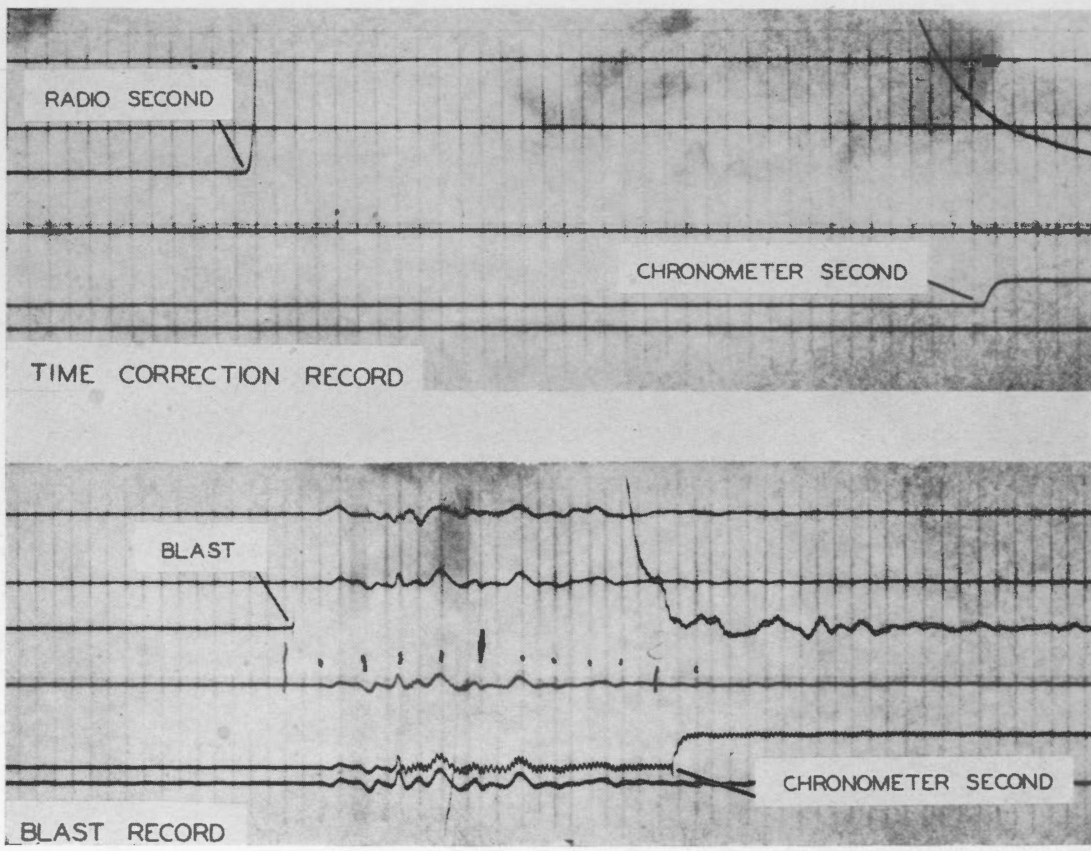

FIGURE 2—Time correction and blast records reproduced full scale. The time lines are at intervals of 0·01 sec.

In order that the identified second appear on the record the shooter would fire as nearly as possibly on the chronometer minute. Immediately after the blast the party would return to its base and continue to record time signals.

The radio signal was of sufficient amplitude that it could be recorded directly, without need of a relay. In Part I of this series it was argued that since relays were employed at the field station and at Kirkland Lake, only the difference in their reaction time contributed to the error of the observation. In timing the blasts this is no longer true, and an arbitrary time of 0·02 sec. has had to be allowed for the closing of the field station relays in computing the appropriate time correction.

PRESENTATION AND ANALYSIS OF DATA

Station-Timed Blasts at Rolphton and La Cave

Presentation of Data

The precision of timing and location of this series of blasts was much inferior to that employed in other sections of this work. Moreover the record amplitude produced at distant stations was small and, in all cases, recording was at a conventional paper speed of 60 mm/min. It seems unnecessary to assign event numbers to each of the blasts; instead the recordings will be summarized in a single table. It will be noted that weights have been assigned to the blasts. These weights were based on record appearance—a weight of two being given to blasts which were particularly well recorded.

Discussion

The blasts recorded at mean epicentral distance of 83 km. (i.e. Rolphton to La Cave and La Cave to Rolphton) do not represent a serious interpretative problem. The first arrivals in the P and S groups must be P_1 and S_1 respectively. Mean travel-times obtained for these phases are $13 \cdot 2 \pm 0 \cdot 1$ sec. and $24 \cdot 1 \pm 0 \cdot 2$ sec. respectively, the uncertainties being Probable Errors of the means. Corresponding velocities are, for P_1 $6 \cdot 29 \pm 0 \cdot 04$ km/sec., and for S_1 $3 \cdot 44 \pm 0 \cdot 03$ km/sec., the uncertainties being those arising from the Probable Errors in the time measurements.

For the smaller blasts only the two phases were recorded, but in the case of the three blasts to which weight 2 has been assigned additional phases were present and there is some suggestion that these phases repeat themselves and so have physical validity. On the basis of the travel-time curves derived in Part I of this series one set has been assigned to S_n; in addition the P phase with travel-time of $19 \cdot 7$ sec. could be $P_1 P_1$ and the S phase with mean travel-time of $24 \cdot 7$ could be $P_1 S_1$. Such assignment is of course very arbitrary. The remaining phases are unaccounted for by the travel-time curves. However they follow S_1 so closely that they may well represent S_1 phases travelling by longer paths provided by lateral variations in rock type.

While the Rolphton blasts produced at Ottawa records of great simplicity, it is difficult to identify the phases with certainty. This is because the distance of 177 km. is close to critical for both P and S phases. The records begin with a single P phase of small amplitude (the arrival times are listed as P_n in Table I). If this is interpreted as P_1 it shows a P_1 velocity of $6 \cdot 25 \pm 0 \cdot 05$ km/sec., a very reasonable value. However, on the basis of the rockburst work we would expect P_1 to be small at this distance and P_n fairly large. Since there is only one phase present it has been assigned to P_n, but it should be pointed out that it arrives about 1 second early. The interpretation is certainly open to question.

In the S group we are faced with a similar problem. Here there are two phases, a small initial phase followed after an interval of about $0 \cdot 7$ seconds by a larger phase. The rockburst travel-time curves suggest that these are S_1, S_n respectively but the large phase

TABLE I.—*Summary of Station-Timed Blasts*

Date	H time E.S.T.	Wt.	Travel-Times (seconds)										
			P_n	P_1			S_n	S_1	Rg				
Mean Epicentral Distance 83 km.													
	Rolphton Blasts recorded at La Cave												
11–23–49	18:15:23·7	1		13·3				23·6					
11–24–49	06:16:10·3	1		14·0				25·6					
11–24–49	12:10:27·6	2		13·4			30·3	24·3			26·3		29·1
11–28–49	12:38:00·7	1		12·5				23·1					
1–26–50	18:09:13·7	1		12·8				24·3					
3–22–50	06:18:50·6	2		12·9			31·1	24·3		24·6	25·8	28·0	28·3
	La Cave Blast recorded at Rolphton												
2–12–50	10:01:36·5	2		13·5	19·7		29·7	23·6		24·8	26·5	27·6	28·7
Mean for Δ = 83				13·2 ± 0·1	19·7		30·4	24·1 ± 0·2		24·7	26·2	27·8	28·7
Mean Epicentral Distance 177 km.													
	Rolphton Blasts recorded at Ottawa												
11–24–49	12:10:27·6	1	28·9				51·1	51·8					
11–28–49	12:38:00·7	1	27·7			30·1	50·6	51·2					
12– 5–49	12:24:05·4	1	27·4				49·7	50·3					
12– 8–49	18:01:23·9	1	27·9				50·4	51·0					
12– 8–49	18:24:36·8	1	27·7				49·9	50·6					
12–14–49	18:11:28·8	1	28·7				50·9	51·7	59·4				
12–14–49	18:13:16·5	1						52·0					
1–14–50	12:33:18·5	1	28·9					51·9					
1–14–50	17:26:43·6	1					50·7	51·3					
1–26–50	18:09:13·7	1	28·9					51·4	58·9				
Mean for Δ = 177			28·3 ± 0·2			30·1	50·5 ± 0·1	51·3 ± 0·1	59·2				
Epicentral Distance = 258 km.													
	La Cave Blast recorded at Ottawa												
2–12–50	10:01:36·5		40·0				68·3	73·3					

looks so much like the prominent S phase in the distant-station rockburst records that this designation has been reversed in the table. Again this interpretation is arbitrary. Those entries given under S_n would, if treated as S_1 give a velocity of $3 \cdot 50 \pm 0 \cdot 01$ km/sec., while the phases listed under S_1, give the velocity of $3 \cdot 45 \pm 0 \cdot 01$ km/sec. At least one can conclude that no second layer is necessary to account for the number of phases observed.

A well-defined surface wave, presumably of the Rayleigh type since is recorded on the vertical component, is apparent on some of the records.

The record produced at Ottawa by the La Cave blast was of extremely small amplitude, and shows only three phases designated P_n, S_n, and S_1. In this case S_1 is a distinct phase but of small amplitude.

The only conclusion which may safely be drawn from the station-timed blasts is that the records do not demand a more complicated crustal structure than that already postulated, and that the indicated velocities lie within the range of those already determined, when the uncertainties of timing and location are considered.

Precisely Timed Blasts at La Cave, Temiskaming and Sudbury

Table II lists the pertinent information for the two series of blasts to be discussed in this section. The station numbers used are those given in Table II of Part 1 of this series,

Table II.—*Data on Precisely Timed Blasts*

Event No.	Location of Blast	Date	Time E.S.T.	Azimuth, Blast to Station	Recorded at Station No.	Quality of Observation	Paper Speed	Δ km.	Elevation of Blast, feet
60	Temiskaming	6:22:50	13:18:01·27	N 24° 17′ W	9	a a a	150	107·01	+ 670
61				N 24° 40′ W	8	a a a	150	118·00	+ 670
62	La Cave	6:13:50	17:15:01·33	N 27° 49′ W	9	a a a	112	143·63	+ 480
63				N 27° 35′ W	8	a a a	112	154·60	+ 480
64	La Cave	6:27:50	17:12:00·38	N 30° 07′ W	6	a a c	150	178·57	+ 480
65				N 29° 09′ W	4	a a c	150	197·10	+ 480
66	Sudbury	8:1:50	15:54:01·05	N 73° 52′ E	14	a a a	150	139·18	+ 725
67				N 68° 06′ E	13	a a a	150	140·80	+ 725
68	Sudbury	8:2:50	Untimed	N 73° 31′ E	14	a d a	150	140·97	+ 680
69				N 67° 50′ F	13	a d a	150	142·67	+ 680
70	Sudbury	7:13:50	11:15:02·77	N 60° 14′ E	12	a a a	150	145·47	+ 680
71				N 52° 24′ E	10	a d a	150	149·29	+ 680
72	Sudbury	7:14:50	15:56:01·20	N 52° 18′ E	10	a a a	150	149·90	+ 796
73	Sudbury	6:20:50	11:16:02·83	N 43° 54′ E	9	a a a	150	152·93	+ 916
74				N 40° 08′ E	8	a a a	150	157·18	+ 916
75	Sudbury	6:28:50	11:19:02·74	N 31° 10′ E	6	a a a	150	160·96	+ 680
76				N 26° 14′ E	4	a a a	150	173·28	+ 680
77	Sudbury	6:29:50	11:08:01·38	N 26° 02′ E	4	a a a	150	171·46	+ 706
78				N 31° 00′ E	6	a a a	150	159·07	+ 706

and the quality of the observations have been evaluated according to the code outlined in Table III of that paper. Event numbers have been continued consecutively from those in the earlier Table IV.

The data will be discussed in two sections, the first consisting of blasts at La Cave and Temiskaming which constitute a reverse profile, the second of the blasts from Sudbury.

Reverse Profile Blasts

Presentation of Data.—Travel times of phases to be discussed in this section have been given in Table III.

TABLE III.—*Reversed Profile Travel-Times*

Event No.	Δ km.	Travel-Times and Residuals (seconds)								
		P_1		P_2		S_1		S_2		
		Travel Time	Residuals Eqn. 1	Travel Time	Residuals Eqn. 3	Travel Time	Residuals Eqn. 2	Travel Time	Residuals Eqn. 4	Residuals Eqn. 5
60	107·01	17·10	− ·20	19·34	− ·01	29·79	− ·50	33·50	+ ·24	− ·53
61	118·00	19·11	+ ·03	20·78	− ·12	33·53	+ ·13	35·97	− ·09	− ·60
62	143·63	—	—	24·59	+ ·08	40·85	+ ·20	42·37	− ·23	− ·25
63	154·60	25·17	+ ·18	26·12	+ ·06	43·82	+ ·06	45·25	− ·14	+ ·04
64	178·57	28·81	− ·06	29·58	+ ·14	—	—	51·73	+ ·23	+ ·86
65	197·10	—	—	31·88	− ·17	—	—	—	—	—

The travel-times have been reduced to a sea-level datum and have been corrected for the delay in the relay closing as mentioned in an earlier section.

It will be noted that entries have been made for phases designated P_2 and S_2. These were very prominent phases, P_2 lying between P_1 and P_n, and S_2 between S_1 and S_n. Because of their prominence they raised once again the possibility of the existence of a second layer. These phases were particularly prominent in the records of the Temiskaming blast but could be observed at all the distances given in Table III. Except at the shorter distances these prominent phases obscured the section of the record in which P_n and S_n might be expected, so that no independent reading of those latter phases has been possible.

The Direct Phases, P_1 and S_1.—As the table suggests, neither of these phases was prominent. In the case of P_1 this corroborates the observation made in the rockburst profile that P_1 is seriously attenuated with distance. The reduced magnitude of S_1 is perhaps to be expected in view of the fact that blasts provided the energy source.

Data listed under P_1 and S_1 were fitted to straight lines by method of least squares. The resulting equations were:

for P_1
$$t = 0{\cdot}29 \pm 0{\cdot}25 + \frac{\Delta}{6{\cdot}12 \pm 0{\cdot}07},$$

and for S_1
$$t = -1{\cdot}29 \pm 0{\cdot}55 + \frac{\Delta}{3{\cdot}416 \pm 0{\cdot}049}.$$

As in previous dealings with these surface phases the constant term was dropped and the line required to go through the origin. In this case the equations became

for P_1
$$t = \frac{\Delta}{6{\cdot}19 \pm 0{\cdot}07}, \qquad (1)$$

and for S_1
$$t = \frac{\Delta}{3{\cdot}535 \pm 0{\cdot}072}. \qquad (2)$$

Residuals from these two equations are listed in Table III. The probable errors in the velocities are considerably larger than those obtained in the rockburst profile. This may arise from a tendency to read the phases late, for in most cases the amplitude is small, but in addition the relatively small number of observations must lead to an increased probable error.

The Phases P_2, S_2.—As was mentioned earlier, these phases were so prominent as to force a reconsideration of the possible existence of a second layer. The best straight line fit to the two sets of data are the following:

for P $$t = 4 \cdot 26 \pm 0 \cdot 16 + \frac{\Delta}{7 \cdot 093 \pm 0 \cdot 052}, \quad (3)$$

and for S $$t = 5 \cdot 98 \pm 0 \cdot 15 + \frac{\Delta}{3 \cdot 923 \pm 0 \cdot 017}. \quad (4)$$

Combining the first of these equations with those for P_1 and P_n in the rockburst profile one can solve for the dimensions of the corresponding two-layer crust. The thickness of the first layer works out to be 28·1 km., that of the second 12·1 km., a total thickness of 40·2 km. Using the S travel time curves the equivalent thicknesses prove to be 24·6 and 24·6 km. for a total of 49·2 km.

This discrepancy might have been interpreted immediately as a failure of the hypothesis, but, considering the large probable error in the equation for S_n and the consequent errors in crustal dimensions, a further investigation seemed desirable. The crustal dimensions determined from the P waves were adopted as standard and travel-time curves for all secondary phases to be expected in a two-layer crust were computed. In order that the S and P values should be consistent it was necessary to adjust the equations of S_2 and S_n to give the same crustal dimensions as the P waves. This was done by successive trial and error computations, the constant term being selected and the best least-square determination of the slope determined. The equation finally adopted for S_2 was the following:

$$t = 8 \cdot 68 + \frac{\Delta}{4 \cdot 234}, \quad (5)$$

which differs considerably from that originally determined. Residuals from this equation are shown in Table III.

When the travel-time curves for the hypothetical two-layer crust had been plotted, observed arrivals were compared with the curves. Except for the phases listed in Table III there was no confirmation of the curves whatever; moreover the numbers of phases observed did not appear to justify the hypothesis, which was therefore discarded.

A second hypothesis was next considered. Could the phases under consideration be P_n and S_n, their travel-time curves displaced due to dip? Combining equation (3) with equation (3) of Part I for P_n it is possible to determine dip and true velocity. The results of this computation were as follows:

Angle of dip	=	4°48′
True P_n velocity	=	7·453 km/sec.
Thickness of crust under Kirkland Lake	=	39·5 km.
Thickness of crust under La Cave	=	24·4 km.

Using the S waves we obtain:

Angle of dip	=	8°50′
True S_n velocity	=	4·29 km/sec.
Thickness of crust under Kirkland Lake	=	51·9 km/sec.
Thickness of crust under La Cave	=	19·1 km/sec.

The inconsistencies between the P and S determinations are not sufficient to allow one to discard the hypothesis, for in the S determination a value of S_n has been used based entirely on the distant stations. The most telling argument against the hypothesis is the low velocities it yields for P_n and S_n. In addition the conclusion that the crust is more shallow under La Cave than under Kirkland Lake is in contradiction to the observation of gravity[1] for these measurements suggest a thickened crust under La Cave.

Thus neither of the hypotheses so far considered are adequate to account for the phases. One final possibility should be raised. Is it possible that the phase interpreted as P_n in Part I of this series is in fact a phase P_2, constrained by the fortuitous arrangement of dip to give a travel-time equation very similar to the expected equation of P_n? It seems most improbable, but without filling up the blank in the rockburst profile between Temiskaming and Ottawa, no argument based on first arrivals can be advanced. It should be mentioned, however, that such uniformity of dip as is implied by the small residuals in the rockburst P_n equation and the reverse profile P_2 equation seems unlikely to be obtained in a Precambrian area. It should also be realized that the travel-time curves for secondary phases in the presence of such a dipping bed would be much modified. While the fit obtained in the rockburst records was not very close, at least the curves based on a uniform crust did account quantitatively for the observations.

At this stage then it is necessary to conclude that the phases called P_2 and S_2 cannot be interpreted in terms of a second layer. As in Part I of this series, we must assign these arrivals to phases which have travelled a minimum path other than the direct one, provided by lateral variations in rock type.

Sudbury Blasts

Examination of Table II will show that the Sudbury blasts were not recorded over a sufficient range of distance to allow the construction of a satisfactory refraction profile. Their principal interest lies, on the contrary, in the variation of azimuth through which they were recorded. The several traverses involve widely differing sections of the Huronian basin. This large basin consists principally of metamorphosed sedimentary rocks of various types. Its thickness at its southern boundary has been estimated[2] at about 23,000 feet, say 7 km. roughly, and it presumably thins towards the north although no estimate of the rate of thinning appears to have been made. When the opportunity arose to time the Sudbury blasts it seemed to offer a desirable chance to study the variations to to be expected in P_1 and S_1 velocities.

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[1] Garland, G. D. "Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario", *Publications of the Dominion Observatory*, Vol. XVI No. 1, 1950.

[2] Quirke, T. T., and Collins, W. H. "The Disappearance of the Huronian", Geological Survey of Canada, Memoir 160.

Travel-Times for P_1 and S_1.—Travel-times for P_1 and S_1 are given in Table IV. The readings have been corrected for the delay in relay closing. P_1 exhibits the amplitude characteristics which we have observed earlier, being of very small amplitude throughout. S_1 is not a well defined phase and some recourse has had to be had to the expected arrival times in identifying it. In this sense the S_1 observations are not as unbiased as might be desired.

TABLE IV.—*Sudbury Blasts, Travel-Times and Velocities*

Event No.	Δ km	Travel-Times (seconds)		Velocities and Residuals (km. per second)			
				P_1		S_1	
		P_1	S_1	Velocity	Residual	Velocity	Residual
66	139·18	23·00	39·70	6·051	−0·138	3·506	−0·045
67	140·80	22·95	—	6·135	−0·054	—	—
70	145·47	23·77	—	6·120	−0·069	—	—
72	149·90	24·47	42·44	6·126	−0·063	3·532	−0·019
73	152·93	25·22	43·19	6·064	−0·125	3·541	−0·010
74	157·18	25·39	44·55	6·191	+0·002	3·528	−0·023
75	160·96	25·73	45·19	6·256	+0·067	3·562	+0·011
78	159·07	25·47	44·65	6·245	+0·056	3·563	+0·012
76	173·28	27·26	48·06	6·357	+0·168	3·605	+0·054
77	171·46	27·01	48·01	6·348	+0·159	3·571	+0·020

Considering the variations in azimuth, and the poor distance distribution of stations, it seems undesirable to fit the observations to straight line curves. Instead the velocities have been computed in each separate observation simply by dividing epicentral distance by observed time. The mean velocity obtained for P_1 is $6 \cdot 189 \pm 0 \cdot 023$ km/sec. the uncertainty being the Probable Error of the mean. The equivalent S_1 value is $3 \cdot 551 \pm 0 \cdot 007$. The low Probable Error of this latter mean suggests that the selection of S_1 has not been completely objective, although every effort was made to make it so.

If the P_1 data given in Table IV are treated as defining a refraction profile and fitted to a straight line equation it works out to be

$$t = 5 \cdot 42 \pm 0 \cdot 57 + \frac{\Delta}{7 \cdot 906 \pm 0 \cdot 023} .$$

Since the velocity indicated is a P_n velocity it was tempting to speculate on the possibility that the crust under Sudbury was much thinner than that under the principal rockburst profile. However, as we shall see in a later section, P_n and S_n, as well as P and S phases reflected from the base of the crust seem to have been well recorded at all distances approximately as forecast by the rockburst travel-time curves. Apparently the P_n velocity obtained by routine least-square analysis of the first arrivals is a matter of accident, resulting principally from the grouping of stations over a short distance range, the group being at considerable distance from the blast source. It might be mentioned that several other interesting possible interpretations of the Sudbury blast data have been discarded on the grounds that the traverse is not appropriate for such analysis.

Secondary Arrivals:—Secondary arrivals on the Sudbury blast records have in general given a very satisfactory fit to the single-layer travel-time curves obtained in the rockburst profile. As in the rockburst profile the fit has not been exact, and sometimes a burst of energy occurs instead of a single sharp phase, but in a general way the curves do appear to account for the principal phases observed. P_n, S_n, P_1P_1, and S_1S_1 are apparently observed over the range of the observations and a phase fitting the curve for S_1P_1 has been observed at some stations.

Recalling the fact that the reverse-profile blasts suggested the existence of a phase P_2, it should be mentioned that a number of strong phases lying intermediate between P_1 and P_n may be fitted to the following equation:

$$t = 3\cdot81 \pm 0\cdot86 + \frac{\Delta}{7\cdot03 \pm 0\cdot27}\cdot$$

Again it should be stressed that the analysis of the data by profile technique is of questionable merit. At first it was thought that this phase might be one refracted beneath the Huronian basin. However, the thickness of the basin so determined works out to be 22 km., a most unreasonable figure, so that the hypothesis has had to be discarded. Again we must assume that the phases in question are due to propagation over other minimum paths than the direct one.

Under the circumstances we shall be content to note that the Sudbury blasts appear in general to confirm the single layer hypothesis and provide us with some idea of the variations to be expected in surface velocities.

DISCUSSION

Data obtained from the various blasts have been summarized in Table V which provides also a comparison with the results obtained in the rockburst profile. Weighted means of the P_1 and S_1 velocity determinations are included in the table, the several

TABLE V.—*Summary of Velocity Determinations*

Source	Velocities and Probable Errors (km. per second)					
	P_1	P_2	P_n	S_1	S_2	S_n
Rockburst Profile	6·246 ± 0·015		8·176 ± 0·013	3·544 ± 0·023		4·85 ± 0·10
Reverse Profile Blasts	6·19 ± 0·07	7·093 ± 0·052		3·54 ± 0·07	3·923 ± 0·017	
Sudbury Blasts	6·189 ± 0·023	7·03 ± 0·27		3·551 ± 0·007		
Station Timed Blasts	6·29 ± 0·04			3·44 ± 0·03		
Weighted Means	6·234 ± 0·012			3·544 ± 0·011		

measurements having been weighted inversely as the squares of their probable errors. It is unfortunate that more observations cannot be included on P_n and S_n, but in the case of the station timed blasts and the Sudbury blasts, in each of which P_n and S_n were observed, the traverse was not adequate for profile analysis, while in the case of the reverse profile blasts P_n and S_n were obscured by the phases P_2 and S_2.

Velocities for the phases P_2 and S_2 have been included in the table, in order that their existence shall not be forgotten, but it should be recalled that the existence of a two-layer crust could not be established.

The results from the blast records are interesting in several ways. First of all they establish that results from blasts provide satisfactory data on both P and S waves. It was the realization of this fact that led to the decision not to continue observations on the rockburst profile until it had been completed in the final details. Instead the program is being reinstrumented and will be carried on primarily with blasts.

What lessons can we learn from the present work as a guide to the future? First of all, because of the doubt that must still exist in connection with the extra phases (P_2, S_2) observed on the reverse profile blasts, we must still be alert for evidence of a second layer. Secondly, since reflections seem to have been well-recorded close to the critical angle, and since the thickness of the crust is variable, we should endeavour to make more efficient use of these reflections. An enlarged program based on blasts should allow for the correlation of reflections from point to point, and techniques of ordinary reflection seismology should be adopted as much as possible. Thirdly we should endeavour to work in as many different areas as possible, since the area here investigated has been a relatively small one. Finally it seems probable that seismic methods might be used with advantage in problems involving finer structure—such for example as the structure of the Huronian basin—and this suggests that more open time-scales should be employed than have been utilized in the present work.

CONCLUSIONS

The conclusions of the present paper are largely provided in Table V. In addition it should be noted that, while the single-layer is not quite as well established as it appeared to be from the rockburst work, still there are no serious objections to accepting it as a working hypothesis. As in Part I, if we accept the hypothesis that the crust is heterogenous because of various rock-types involved, and of the variable thickness suggested by gravity observations, it seems possible to account in general for the phases observed.

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