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CRUSTAL STRUCTURE IN THE WISCONSIN AREA

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Summary:

Seismic results from six large blasts in the Wisconsin area are reported. The observations were made with a group of 12 three-component instruments, of period 1 second, located on selected bed-rock sites. Time signals at 1 second intervals were transmitted by radio. On the scale of the present experiments, which involved an area about 600 km. long by 150 km. wide, the major structure revealed was a relatively homogeneous layer about 40 km. thick. The time-distance segment corresponding to this layer is always nearly linear; and, at the four areas investigated implies compressional wave velocities of 6.16, 6.26, 6.22 and 6.16 km./sec. respectively. Although the assumption of a homogeneous layer of uniform wave velocity leads to satisfactorily small residuals (see Table I--the mean absolute value for 8 residuals for the Davenport blast is, for example, .09 seconds), an improved fit with the observed time-distance data results throughout the area if the wave velocity in the major layer is assumed to increase linearly with depth, in accordance with the relations:

$$v = 6.034(1 + .0038z) \text{ (Northern Area)}$$

$$v = 5.94(1 + .0045z) \text{ (Southern Area)}$$

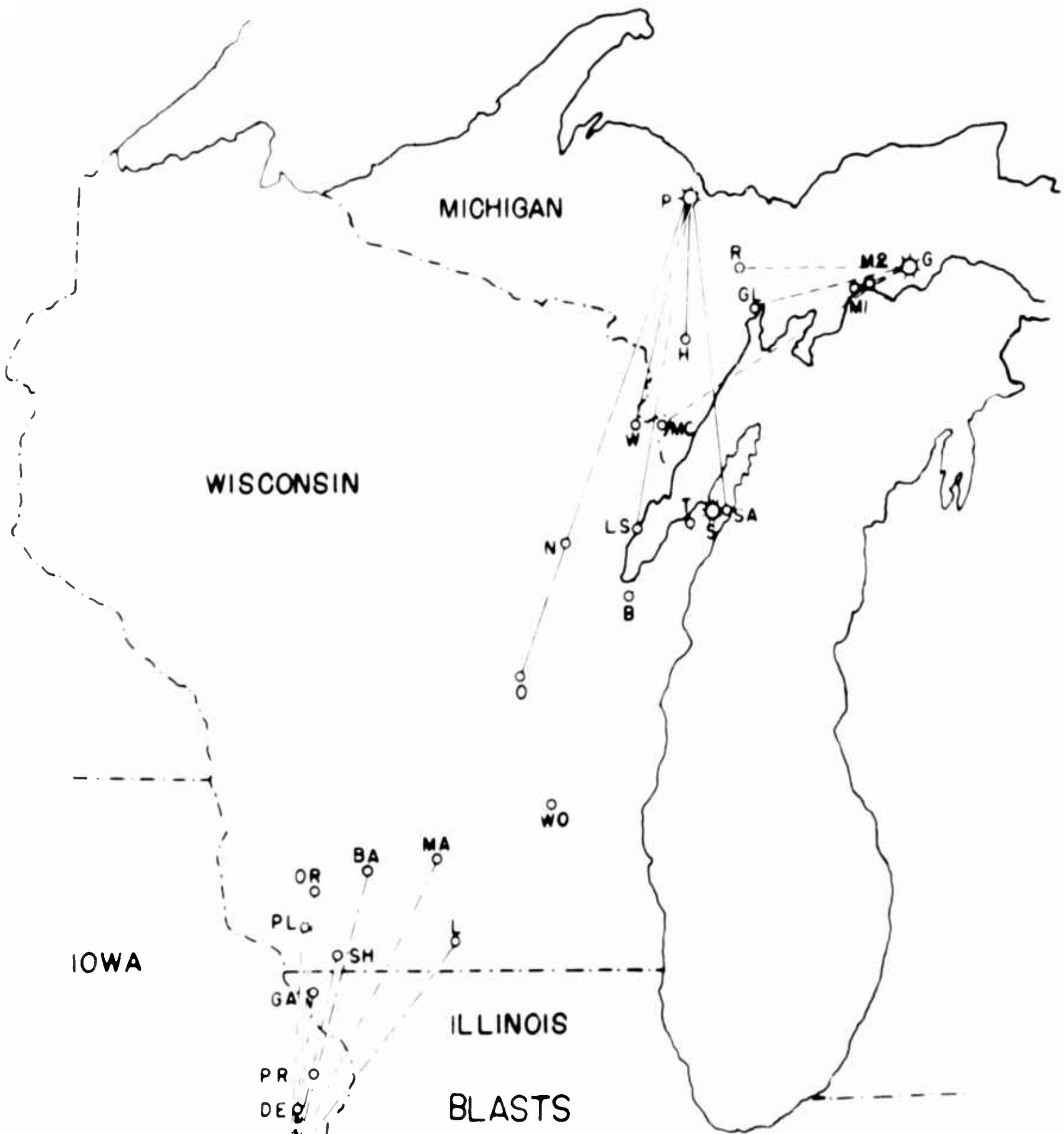
where z = depth below top of layer in km.

In Table III is shown a summary of the seismic interpretations corresponding to several postulated crustal models. The preferred models, "Palmer III" and "Davenport II" incorporate, respectively, the two velocity functions above. A significant effect of the assumption of the increase in velocity with depth is the increase in thickness deduced for the major layer, and the decrease assignable to the thin overlying layer. The increase (see Table III) is about 15 %, but the decrease in the thickness of the superficial layer may vary from 25 % to several hundred percent. The residuals associated with the several crustal models specified in Table III are listed in Table I. Table I also lists complete Time-Distance data for compressional phases for the several blast locations. The non-homogeneous layer in model "Palmer III" avoids the ad-hoc split into two homogeneous layers involved in the two comparison equations T_2 and T_2' . The corresponding Davenport model "Davenport II" removes a small² systematic trend in the residuals for "Davenport I", and also reduces their mean absolute magnitude by about 1/2. Note, however, that the first arrival at $\Delta = 204.2$ km. is definitely early on either basis. (See Figure 3, for reproduction of this seismogram.) This early arrival is attributed to the fast wave below the Mohorovičić discontinuity. Plans in 1940 to observe this phase at greater distances with subsequent Davenport blasts were necessarily abandoned due to the impact of the war. In deducing the depth to the Moho discontinuity at Davenport, it has been assumed that the wave-velocity, v_3 , is 8.17 km./sec., as observed in the northern part of the area; and the early arrival at $\Delta = 204.2$ is attributed to the v_3 phase. More extensive observational data throughout the area, is greatly to be desired in amplification of the present observations.

The scale of the present field work is obviously much too coarse for mapping the details of the thin superficial layer. The observed velocities in this layer vary from 4.16 to 4.58, and the thickness from .63 km. in the south to 2.8 km. in the north (basis of preferred interpretations). That the layer can not be subject to extremely large local fluctuations in thickness or wave velocity is evidenced by the generally small and regular residuals of the time-distance data with respect to smooth comparison functions. These residuals are generally less than .1 or .2 seconds, indicating that the local fluctuations in the layer thickness are generally less than .4 to 1.2 km. The travel-time data are indeed insensitive in the present case to variations in the thickness of the superficial layer.

Map 1 shows the distribution of the blast points and observing stations. Figures 1 to 4 reproduce 16 of the seismograms. In particular, Figure 1, Figure 2, Figure 3, ($\triangle = 143.3$) and Figure 4 (e) and (f) show significant second arrivals. Figure 4 shows 6 pairs of "duplicate" records and the useful degree of similarity of such pairs. The Palmer records were duplicated pair-wise with an east-west separation of 2.8 km. between shot points in neighboring mines. Figures 4 (e) and 4 (f) exhibit comparisons of Palmer records at large epicentral distances. In Table II, the time-distance data are consolidated by reduction to a common origin time at $\triangle = 112.2$ km. (i.e. the midpoint of the 6.16-6.26 km./sec. segments). This choice of origin relegates differences due to local conditions near the blast points to the initial, less significant part of the travel-time curve. The preferred interpretations lead to depths to the Moho of 40 to 44 km., with a thin superficial layer .6 to 2.8 km. thick, of wave velocity about 4.2 to 4.5 km./sec. In the major layer the velocity increases gradually from about 6.0 km./sec. at the top, to 7.0 km./sec. at the bottom. Below this layer, the compressional wave velocity is about 8.17 km./sec.

Map 1. Location of Elast and Observing Stations.



D ★ Palmer, Mich.
 Manistique, Mich.
 Sturgeon Bay, Wis.
 Davenport, Iowa

Scale in Kilometers
 0 50 100 150

Figure 1. Seismogram for Manistique, $\Delta = 34.13$ km.,
Showing Second P Phase.

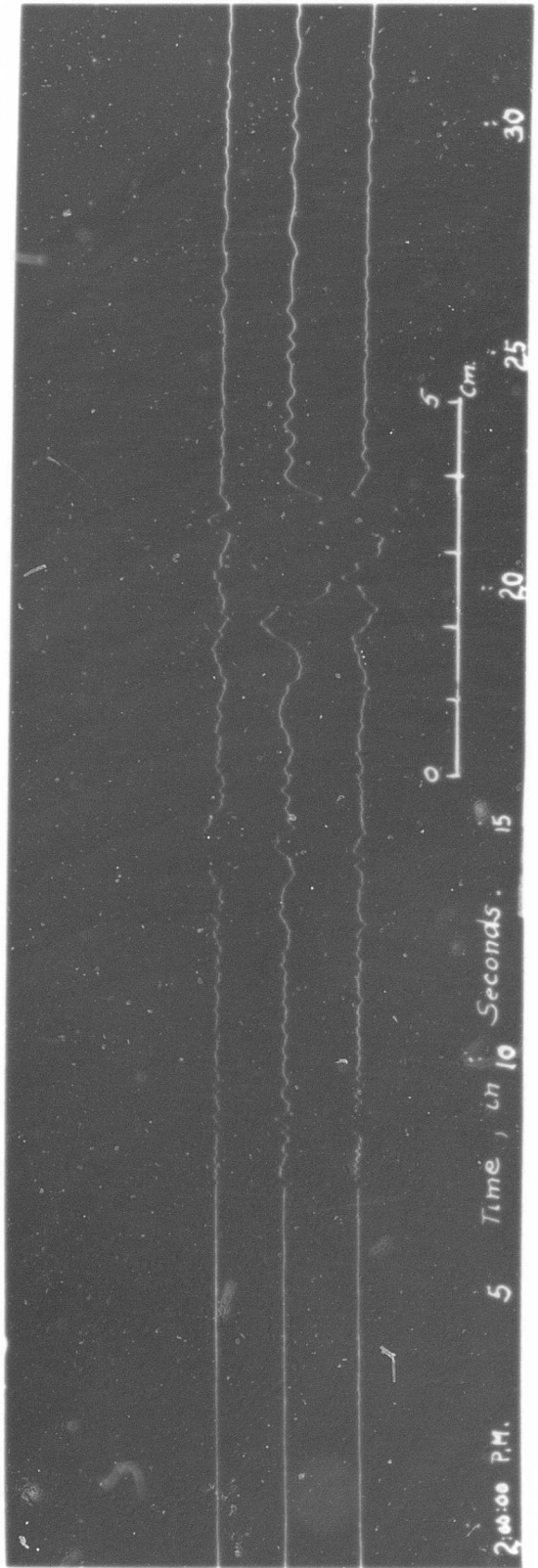


Figure 2. Seismogram for Palmer, $\Delta = 128.0$ km.,
Showing second P Phase.

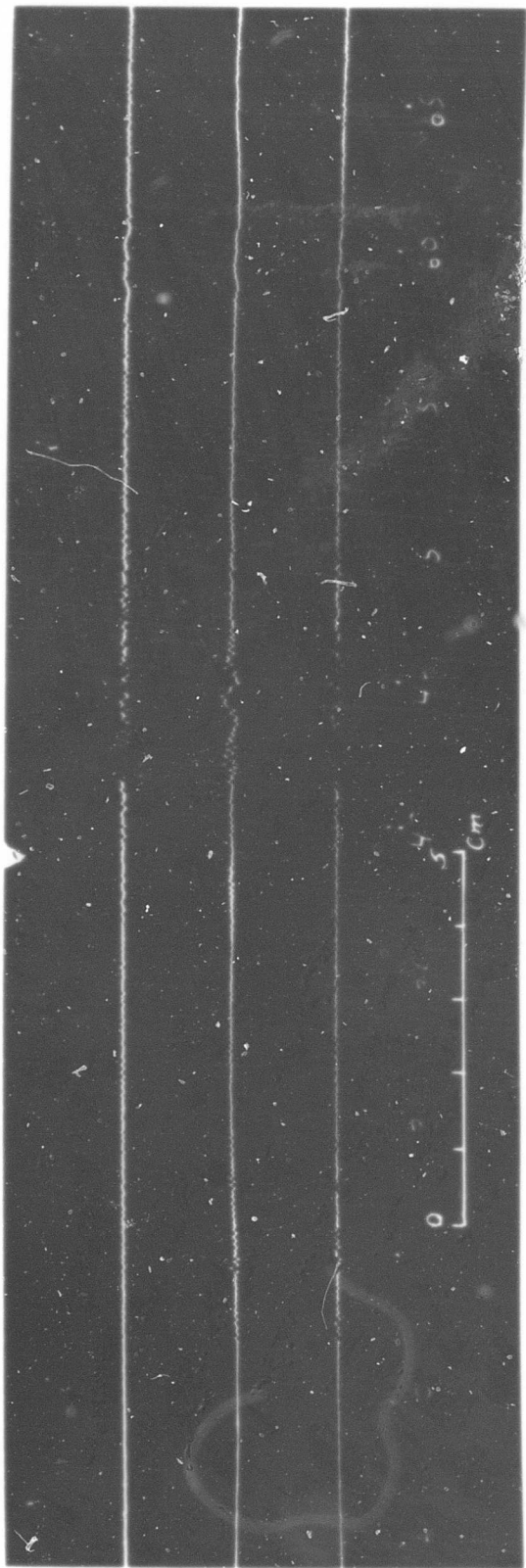


Figure 3. Seismograms for Sturgeon Bay, and Seismogram for Daven. \triangle ,
 $\triangle = 204.2$

$\Delta = 66.57 \text{ km}$

$\Delta = 143.36 \text{ km}$

STURGEON BAY

$\Delta = 109.38 \text{ km}$

STURGEON BAY

$\Delta = 204.2 \text{ km}$

DAVENPORT

$\Delta = 0.407 \text{ km}$

$\Delta = 2.062 \text{ km}$

$\Delta = 8.56 \text{ km}$

$\Delta = 15.51 \text{ km}$

STURGEON BAY

Figure 4. Record Pairs for Repeated Blasts. Epicentral range 8.39 km. to 277.5 km.

COMPARISON OF REPEAT SEISMOGRAMS

A, A' Transverse Component
 B, B' Vertical Component
 C, C' Longitudinal Component

BLAST	DATE	POUNDS DYNAMITE	TRACE MARKS	EPICENTRAL	DISTANCE
Manistique	June 22, 1940	47,000	A, B, C	Fig. (a) 8.51	Fig. (b) 21.16
"	Aug. 7, 1940	58,000	A', B', C'	8.39	21.46
Hudson	June 15, 1939	30,000	A, B, C	Fig. (c) 32.20	Fig. (d) 204.5
"	Nov. 11, 1939	56,000	A', B', C'	32.70	204.5
Palmer	July 20, 1940 a.m.	20,000	B, C	Fig. (e) 216.1	Fig. (f) 277.5
"	July 20, 1940 p.m.	13,000	B', C'	216.1	277.5

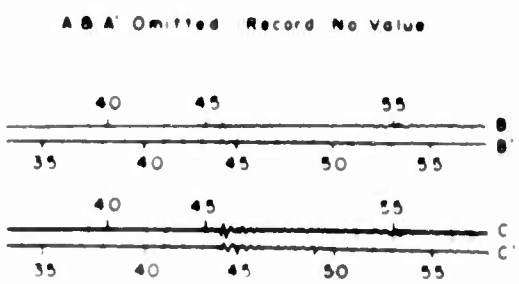
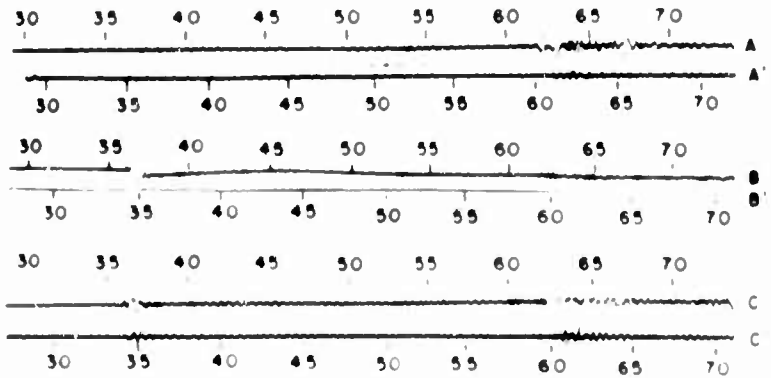
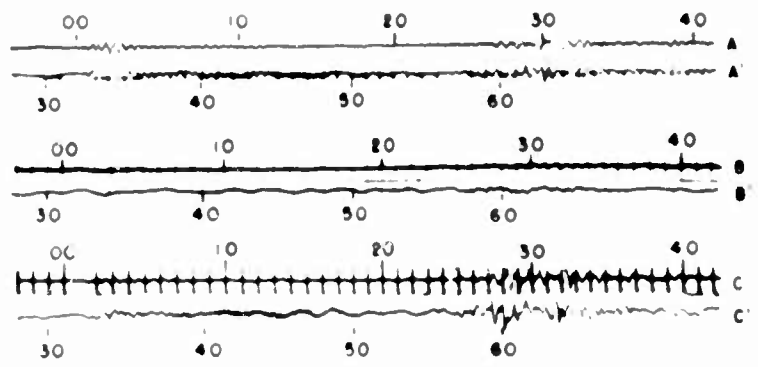
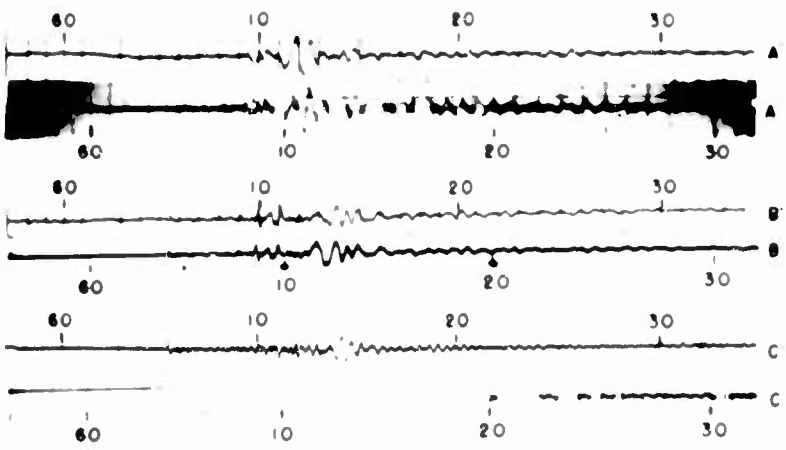
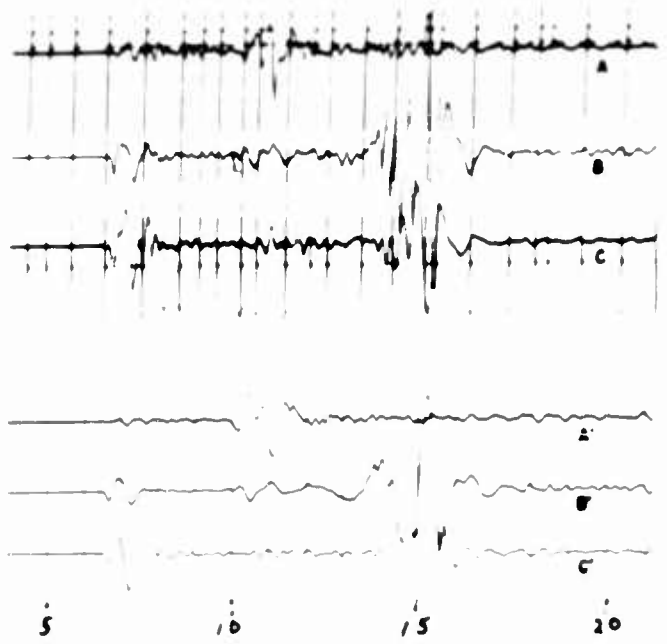
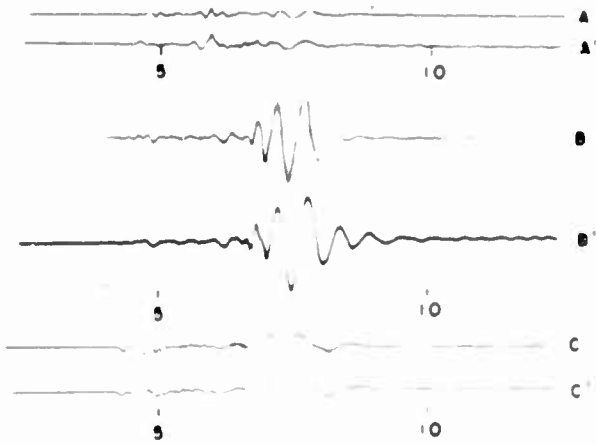


TABLE I

TRAVEL TIME DATA FOR COMPRESSIONAL PHASES
 P A R T I. Palmer Mich. (20,000 lbs.) July 20, 1940 (t_0 = origin time = 0 for Palmer Blast)

Station	Sym bol	Δ , km	$t-t_0$ sec.	Comparison Equation I	T_1	Residuals $t-t_0$			Remarks
						I $\Delta = 0$	II $\Delta = .00307$	III $\Delta = .0038$	
Volunteer Mine, Mich.	V1	0	0	$T_1 = \Delta/4.16$	0.00	0.00			
" "	V2	.57	.15	" "	.138	.002			
Palmer, Mich.	P	10.41	2.51	" "	2.51	0.00			
Hertmansville, Mich.	H	84.83	14.95	$T_2 = \Delta/6.16 + 1.20$	14.97	-.02	-.002	-.032	
Mausaukee, Wis.	M	128.0	22.01	" "	21.98	+.03	+.007	+.006	
Sawyer, Wis.	SA	179.4	30.30	" "	30.32	-.02	-.007	+.009	
Sawyer, Wis.	SA	179.4	30.30	$T_2' = \Delta/6.58 + 3.03$	30.30	0.00	-.007	+.009	
NAVERTINO, Wis.	N	216.1	35.80*	" "	35.87	-.07	-.34	-.113	Strong; Note (1)
Onton, Wis.	O	277.5	44.25 ± .1	" "	45.20	0.00	-.485	+.050	" "
Mausaukee, Wis.	M	128.0	24.13*	$T_3 = \Delta/8.17 + 8.34$	24.01	+.12			Strong
Sawyer, Wis.	SA	179.4	30.30	" "	30.30	-.01			High frequency
Little Stramico, Wis.	LS	188.5	31.35	" "	31.41	-.07			
NAVERTINO, Wis.	N	216.1	34.82	" "	34.79	+.02			
Onton, Wis.	O	277.5	42.32	" "	42.31	0.00			
Sawyer, Wis.	SA	179.4	31.30*	Reflection	31.14			+.16	
Little Stramico, Wis.	LS	188.5	32.67*	" "	32.42			+.25	High frequency
Mausaukee, Wis.	M	128.0	24.13**	" "	24.12			+.01	Alternative Inter-pretation

Note (1) On basis of $T_2 = \Delta/6.16 + 1.20$ these residuals would be $-.48$ and -1.05 respectively.
 P A R T II. Manitistique, Mich. #1 (47,000 lbs) June 22, 1940; #2 (58,400 lbs) Aug. 8, 1940.
 ($t_0 = .70$ for Manitistique #1; $t_0 = 1.95$ for Manitistique #2)

Station	Sym bol	Δ , km	$t-t_0$ sec.	Comparison Equation I	T_1	I $\Delta = 0$	II $\Delta = .00307$	III $\Delta = .0038$	Remarks
Gulliver (1) Mich.	G1	100	.00	$T_1 = \Delta/4.53$	0	0			Blast No. #1, #2
Gulliver (2) Mich.	G2	.33	.07	" "	.073	-.003			#1
Gulliver (3) Mich.	G3	.68	.15	" "	.15	0			#2
Gulliver (4) Mich	G4	8.39	2.20	" "	1.85	+.35			#2
Manitistique (2) Mich.	M2	21.46	4.61	" "	4.74	-.13			#2

Table I Travel-Time Data for Compressional Phases, and Residuals
Corresponding to Several Crustal Models.

P A R T IV Deavenport, Iowa. (34,000 lbs) May 29, 1940

Station	Sym bol	Δ , km	t_0 sec	Correc- tion Equation T_1	Residual $t_0 - T_1$		Remarks
					I $\lambda = 0$	II $\lambda = .00449$	
Quarry, Dewey Portland Cement Co.	D1	.00	$t_0 = .90$.00	$T = \Delta/4.5$ "	.00	.00	
	D2	.45	.10	"	.10	.00	
Dewitt, Iowa Preston, Iowa Galena, Ill. Sholisburg, Wis Platteville, Wis. Linden, Wis. Orfordsvillle, Wis. Barneveld, Wis. Madison, Wis. Madison, Wis.	DE	35.60	6.25	$T_2 = \Delta/6.16 + .55$	6.33	-.08	+.086
	PR	72.19	12.24	"	12.27	-.03	-.039
	GA	108.0	18.24	"	18.08	+.16	+.064
	SH	128.0	21.45	"	21.33	+.12	+.017
	PL	144.6	24.10	"	24.03	+.07	-.010
	L	165.0	27.25	"	27.34	-.09	-.099
	OR	177.2	29.23	"	29.32	-.09	-.038
	BA	185.6	30.60	"	30.68	-.08	+.023
	MA	204.2	33.20	"	33.70	-.50	-.246
	MA	204.2	33.20	$T_3 = \Delta/8.17 + 8.206$	33.20	0	

See text

* Second Arrival
** Third Arrival

Table II Consolidated Travel-Time Data Reduced to Common Origin at
 $\Delta = 112.2$ km.

TABLE II

Composite Travel-Time Data, Adjusted to
Common Point. $\Delta = 112.2$, $t = 19.41$

Sym- bol	Blast	Δ km.	t_A , sec	Comparison equation	T_1	Residual $t_A - T_1$	Remarks
V1	P	.00	.00	$T_1 = \Delta / 4.2$.00	.00	
G1	M1, M2	.00	.56		.00	.51	
S1	S	.00	.11		.00	.11	
D1	D	.00	.65		.00	.65	
G2	M 1	.33	.63		.078	.55	
S2	S	.41	.48		.097	.38	
D2	D	.45	.75		.107	.64	
V2	P	.57	.15		.136	.01	
G3	M 2	.68	.71		.162	.55	
S3	S	2.06	.56		.49	.05	
SA	S	8.56	1.98		2.04	-.06	
P	P	10.41	2.51		2.48	.03	
M2	M 2	21.46	5.17		5.11	.06	
M1	M 1	34.13	8.10*		8.10	.00	
SA	S	8.56	1.98	$T_2 = 5.74 + .49$	1.98	.00	
T	S	15.51	3.13		3.19	-.06	
B	S	66.57	12.08		12.08	.00	
G4	M2	8.39	2.76	$T_2 = \Delta / 6.18 + 1.26$	2.62	.14	
M1	M1	34.13	7.02		6.78	.24	
DE	D	35.6	6.90		7.02	-.12	
B	S	66.6	12.08		12.04	.04	
PR	D	72.2	12.89		12.94	-.05	
H	P	84.8	14.95		14.98	-.03	
R	M2	101.1	17.51		17.62	-.11	
GL	M2	102.0	17.62		17.77	-.15	
GA	D	108.0	18.89		18.74	.15	
SA	D	128.0	22.10		21.97	.13	
W	P	128.0	22.01		21.97	.04	
O	S	143.3	24.42		24.45	-.03	
PL	D	144.6	24.75		24.66	.09	
L	D	165.0	27.90		27.96	-.06	
MC	M 1	168.1	28.41		28.46	-.05	
OR	D	177.2	29.88		29.93	-.05	
SA	P	179.4	30.30	30.29	.01		
BA	D	185.6	31.25	31.29	-.04		
LS	P	188.5	31.35	31.76	-.41		
MA	D	204.2	33.85	34.30	-.45		
SA	P	179.4	30.30	$T_2 = 46.58 + 3.03$	30.30	0	
N	P	216.1	35.80*		35.87	-.07	
O	P	277.5	45.20*		45.20	.00	

TABLE II (Continued)

W	P	128.0	24.13*	$T_3 = \Delta/8.17 + 8.24$	24.01	.12	
O	S	143.3	25.32*		25.87	-.35	
MC	M1	168.1	29.81*		28.92	.39	
SA	P	179.4	30.30		30.30	.00	
L3	P	188.5	31.35		31.41	-.06	
WO	S	189.9	31.66		31.57	.09	
N	P	216.1	34.82		34.79	.03	
O	P	277.5	42.32	42.32	.00		
MA	D	204.2	33.85	$T_3 = \Delta/8.17 + 8.86$	33.85	.00	see text
MC	M1	168.1	29.81	Reflection	29.76	.05	see text

* Second Event

Note: The following time adjustments were added to the listed values of $t - t_0$ in Table I to bring the travel times into accord at $\Delta = 112.2$: Palmer blast, 0; Manistique blasts, .56 sec.; Sturgeon Bay, .11 sec; Davenport, .65 sec.

Table III Summary of Interpretations.

TABLE II
Summary of Interpretations

Model I	PALMER		WINSTON		ST. GEORGE BAY		DAVENPORT	
	Model II	Model III	Model I	Model I	Model II	Model I	Model II	
$\alpha = 0$	$\lambda = .00307$	$\lambda = .0038$	$\lambda = 0$	$\alpha = 0$	$\alpha = 0$	$\lambda = 0$	$\alpha = .00449$	
$v_1 = 4.16$	$v_1 = 4.16$	$v_1 = 4.16$	$v_1 = 4.53$	$v_1 = 4.58$	$v_1 = 4.58$	$v_1 = 4.5$	$v_1 = 4.5$	
$v_2 = 6.16$	$v_2 = 6.034(1 + .00307z)$	$v_2 = 6.034(1 + .0038z)$	$v_2 = 6.26$	$v_2 = 6.22$	$v_2 = 5.74$ $v_2 = 6.22$	$v_2 = 6.16$	$v_2 = 5.94(1 + .00449z)$	
$v_3 = 8.17$	$v_3 = 8.17$	$v_3 = 8.17$	Not Determined	$v_3 = 8.17$	$v_3 = 8.17$	$v_3 = (8.17)$	$v_3 = (8.17)$	
$t_1 = \Delta/4.16$	$t_1 = \Delta/4.16$	$t_1 = \Delta/4.16$	$t_1 = \Delta/4.53$	$t_1 = \Delta/4.58$	$t_1 = \Delta/4.58$	$t_1 = \Delta/4.5$	$t_1 = \Delta/4.5$	
$t_2 = \Delta/6.16 + 1.2$			$t_2 = \Delta/6.26 + 1.2$	$t_2 = \Delta/6.22 + 1.27$	$t_2 = \Delta/5.74 + .38$	$t_2 = \Delta/6.16 + .55$		
$t_3 = \Delta/8.17 + 8.34$	$t_3 = \Delta/8.17 + 8.34$	$t_3 = \Delta/8.17 + 8.34$		$t_3 = \Delta/8.17 + 8.30$	$t_3 = \Delta/6.22 + 1.27$	$t_3 = \Delta/8.17 + 8.21$	$t_3 = \Delta/8.17 + 8.21$	
	$v(h_2) = 6.717 \text{ km./sec}$	$v(h_2) = 6.904 \text{ km./sec}$					$v(h_2) = 7.09 \text{ km./sec.}$	
$h_1 = 3.4 \text{ km.}$	2.7 km.	2.80	$h_1 = 2.94$	$h_1 = 4.3$	$h_1 = 1.44$ $h_1 = 6.05$	$h_1 = 1.8$	$h_1 = .63$	
$h_2 = 32.7$	36.9 km.	37.95		$h_2 = 32.1$	$h_2 = 30.0$	$h_2 = 35.3$	$h_2 = 42.95$	
Depth to Moho = 36.1	39.6 km.	40.75		36.4	37.49	37.1	43.58	