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# SEISMIC DATA OBTAINED FROM THE ATOMIC WEAPONS TEST AT MARALINGA, SOUTH AUSTRALIA, 1956

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## ABSTRACT

A study of seismic waves generated by explosions in the south-eastern region of South Australia suggested the following ideas concerning the earth's crust.

The P-wave velocity is 5.8 ± 0.1 km/sec at the surface and 6.3 ± 0.1 km/sec below a depth of approximately 1 or 2 km. Whether the increase is sharp or gradual could not be ascertained. The apparent velocity of the S wave is 3.6 ± 0.05 km/sec in the major portion of the granitic layer.

The depth of the Mohorovicic discontinuity was calculated to be 39 to 43 km from refracted wave data and 36 to 38 km from reflected wave data.

## 1. INTRODUCTION

During September and October 1956, the United Kingdom Ministry of Supply conducted atomic weapons tests at Maralinga, South Australia. During these tests seismic measurements were made by the Australian National University and the Commonwealth Bureau of Mineral Resources, Geology and Geophysics. Seismic waves were also recorded near Adelaide by the Adelaide University seismic station. Full co-operation was given by the British Atomic Weapons Research Establishment in these in carrying out measurements. The objects of the seismic work were to determine time versus distance curves for seismic phases and to investigate the earth's crustal structure. The area in which operations were carried out is fairly flat and elevations range from 0 to 900 feet (275 m) above sea level. Sedimentary layers up to 1,800 feet (550m) thick overlie Pre-Cambrian granitic and metamorphic rocks.

This report is a summary and interpretation of the results obtained by the Bureau party, members of which were K.R.Vale, I.B.Everingham and J.P.Pigott. Results of other measurements have been published by Bolt, Doyle and Sutton (1958).

## 2. EQUIPMENT AND RESULTS

Two types of seismograph were used for the project, namely:-

(a) Two Willmore portable station-type seismographs having one-second horizontal and vertical component seismometers, 0.25-second galvanometers, amplification of approximately 30,000 at 0.1 c.p.s. and a paper speed of 50 mm/minute.

(b) A T.I.C. 24-channel prospecting type seismograph (model 621) covering a frequency range of 5 to 350 c.p.s. for 70 per cent response. High and low-cut filters, pre-suppression controls and A.V.C. were available. Paper speed was 18 mm/second. Six-cycle vertical component seismometers were used and in addition one-cycle horizontal Willmore seismometers were used in attempts to obtain transverse wave velocities.

The distance of each station from the explosion point and travel times of the various seismic waves are shown in Table 1. Also, the geophone velocity is given for the two stations (B and D) at which the T.I.C. prospecting type seismograph was used.

A "correction for sediments" for each station was either estimated or determined by refraction surveying with the T.I.C. seismograph. Details of the local refraction surveys are given in Table 2. The "correction for sediments" was applied to the travel times in order to eliminate the effects of sedimentary sections on the travel times of the seismic waves. The maximum recorded thickness of sediments was 1800 feet, (550m) and at most stations the thickness is between 0 and 500 feet (150m). The thickness of the sediments at the explosion position was known and allowed for in this correction. Pre-Cambrian granitic rocks underlie the sediments.

In Fig.1, the times of arrival of the various phases are plotted with respect to distance and the resulting time/distance curves for the P and S phases are shown. Figures 2 and 3 show the graphs of the P and S phases in another form to give increased accuracy. In these graphs the value of travel time -

distance is given as a residual time and plotted against distance.
velocity

## 3. INTERPRETATION OF RESULTS

### (a) The granitic layer

From refraction surveys at points nearly 200 miles apart the velocity of the P phase at the surface of the granitic layer was found to range from 5.70 to 5.88 km/sec (Table 2). As this range of values is of the order of accuracy of the method employed it could not be determined whether the variation is real. The variation is surprisingly small, however, and the mean value of 5.8 km/sec would give a fairly accurate value for the velocity of the P waves in the surface region of the granitic layer.

The corresponding velocity of S waves could not be determined as it was not possible to excite measurable S waves in the granitic rocks, except at station D.

From consideration of Figs. 1 and 2, two interpretations of the P-wave velocities of greater depth appear possible:-

(a) The P-wave velocity is 6.25 km/sec from very near the surface to the M-layer (Mohorovicic discontinuity).

(b) The P-wave velocity is 5.8 km/sec at the surface and increases to 6.3 km/sec at a depth of the order of 2 km, thereafter remaining constant down to the M-layer.

Case (b) is considered to be more likely, as the residual times (Fig.2) were smaller than for case (a), and a low velocity was actually measured at the surface.

It is quite likely that the velocity increases gradually with depth (Gutenberg, 1955) and Fig.4 shows curves determined by laboratory experiments in the U.S.A. which indicate that the velocity gradually increases from 5.8 km/sec near the surface to 6.3 km/sec at a depth of 4 km.

The intercept time of 0.1 seconds (Fig.2) cannot be regarded as accurate; an accurate time could be determined only by very precise measurements. However, using this intercept time and assuming a linear increase of velocity with depth, it can be shown that the depth to the higher velocity section would be of the order of only about 1 or 2 km.

Values for intercept time and velocity for the S waves were also determined (Fig.3). The velocity of the S phase in the granitic layer is considered to be 3.60 km/sec.

The geophone velocities obtained for the first event at stations B and D were 6.5 and 6.2 km/sec respectively. The mean is near the value of 6.3 km/sec chosen by plotting travel times. This may be a coincidence. However, bearing in mind the accuracy of the measurements of this first incoming phase (particularly at Station A), it is obvious that there is some layering or regional non-homogeneity in the granitic layer. It is difficult to assess how close to the surface or over what area these anomalies occur. It seems very likely that the 2-km layer with velocity 5.8 km/sec is the cause of the range of geophone velocities. It is notable that at station B, where a high geophone velocity of 6.5 km/sec was recorded, a higher velocity in the near-surface granitic rocks was found in the local refraction survey.

(b) The M-layer

Following practice overseas, the term M-layer is used to denote the Mohorovicic discontinuity.

For an estimate of the depth to the M-layer it is necessary to know the velocity of P or S waves below the M-layer and also the Pn intercept time (see Fig.1). The depth to the M-layer can also be determined by timing reflections from this layer. Reflections were recognised at stations B and D. The record obtained at station S12 during the 1953 tests showed a very strong reflection (Doyle 1953). The travel times and geophone velocities for station S12 were revised on the basis of a Pg velocity of 6.30 km/sec and an intercept time of 0.1 seconds (the actual travel times were not observed owing to a chronometer breakdown).

Table 3 shows the details of the reflected phases and subsequent estimates of depth to the reflecting horizon, assuming the P velocity is 6.3 km/sec from the surface to the M-layer.

TABLE 3.

DEPTH TO M-LAYER ESTIMATED FROM REFLECTION DATA

| Station | Corrected travel time (secs.) | Observed geophone velocity (km/sec) | Theoretical geophone velocity (km/sec) | Depth to M-layer (km) |
|---|---|---|---|---|
| B | 15.65 | 9.2 ± 0.5 | 9.3 | 36.2 |
| S12 | 19.0 | 9.2 ± 0.5 | 8.0 | 37.2 |
| D | 22.2 | 7.3 ± 0.3 | 7.5 | 38.4 |
| | | | MEAN | 37.3 |

For the estimation of depth to the M-layer using the time distance curves, no value of Pn velocity was obtained. Only station G was far enough away from the explosion point for the Pn waves to arrive first. The Pn phase, being very weak, was not discernible on records of stations nearer the explosion. However, the range of Pn velocities found throughout the world is relatively small - about 8.0 to 8.3 km/sec. A value of 8.1 km/sec. was used to illustrate the Pn phase in Fig.1. The Pn velocity selected does not greatly alter the determined depth to the M-layer. Table 4 lists the depth to the M-layer calculated from the time/distance curve.

TABLE 4.

DEPTH TO M-LAYER FOR DIFFERENT Pn VELOCITIES

| Pn Velocity (km/sec) | Pg Velocity (km/sec) | Depth to M-layer (km) |
|---|---|---|
| 8.0 | 6.3 | 39.4 |
| 8.1 | 6.3 | 40.5 |
| 8.2 | 6.3 | 41.8 |
| 8.3 | 6.3 | 43.3 |
| 8.15 | 6.2 | 39.7 |

To calculate the depth of the M-layer, use was made of the following expression:-

$$\text{Depth to M-layer} = \frac{k}{2C}$$

where k = intercept time of Pn phase

$$C^2 = \frac{1}{(V_1)^2} - \frac{1}{(V_2)^2}$$

$V_1$ = Pg velocity

$V_2$ = Pn velocity

It should be remembered that this estimate of M-layer depth is dependant on the record of station G. A record from a station set up during the 1953 tests at an epicentral distance of about 300 km was re-examined. The P waves were only just visible and the P times listed (Doyle, 1953), were considered to be unreliable. Hence the record could not be used to supplement the information of station G on the Pn phase.

The S-phase times were used in a similar manner to calculate the depth of the M-layer. An Sn velocity of 4.75 km/sec was chosen. This is the mean of many values determined overseas (Gutenberg, 1953). The values of the depth to the M-layer for slightly different values of Sn velocity are given in Table 5.

TABLE 5.

DEPTH TO M-LAYER FOR DIFFERENT Sn VELOCITIES

| Sn Velocity (km/sec) | Sg Velocity (km/sec) | Depth to M layer |
|---|---|---|
| 4.7 | 3.6 | 40.5 |
| 4.75 | 3.6 | 41.7 |
| 4.8 | 3.6 | 42.8 |
| 4.75 | 3.5 | 39.1 |

In all estimates of the depth to the M-layer no allowance has been made for the low-velocity zone at the surface, as the effect of this zone is small.

It can be seen from Tables 4 and 5 that for the range of Pn, Sn, Pg and Sg velocities likely to be encountered, the calculated depth to the M-layer does not alter materially.

## 4. RECOMMENDATIONS

The following programme, in order of priority, is recommended for future tests:-

(a) At least two Willmore stations should be set up at a greater epicentral distance than Station G and in the general direction of G. This could furnish a Pn velocity.

(b) Willmore seismographs should be used along a traverse to the north of Maralinga to investigate Pn velocity and dip (in conjunction with data from this project).

(c) Prospecting-type seismographs should be set up between 5 and 20 km epicentral distance from explosions to investigate upper granitic-layer conditions. A few hundred pounds of gelignite could possibly be used (if tamped) for the shorter distances.

(d) Prospecting-type seismograph recordings should be made at an epicentral distance of 226 km between stations F and G. If it exists, the phase P* may be recorded as a first arrival at this distance. An easier alternative to this would be a recording at station G, which is an ideal site for the prospecting seismograph.

(e) A prospecting-type seismograph record should be made about 160 km north of the explosion to pick up reflections from the M-layer; this would supplement (b) above.

## 5. REFERENCES


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TABLE I (Contd.)

STATION "C" Epicentral distance 88.3 ± 1.0 km

Instrument - Willmore Seismograph

| Phase | Travel time (Δ t) Vertical Component (secs) | Travel time (Δ t) Transverse horizontal component (secs) | Correction for Sediments (secs) | Corrected Δ t (secs) | Remarks |
|---|---|---|---|---|---|
| iPg | 13.8 | 13.8 | -0.1 | 13.7 | |
| i | 14.3 | | -0.1 | 14.2 | |
| i | 21.2 | | -0.1 | 21.1 | |
| iSg | | 25.3 | -0.2 | 25.1 | |
| i | 27.2 | 27.4 | -0.2 | 27.2 | |
| Air-wave | 257.9 | | | | Δ t ± 0.3 sec. |

STATION "D" Epicentral distance 116.9 ± 1.0 km

Instrument - T.I.C. Seismograph

| Phase | Travel time (Δ t) vertical component (secs) | Correction for sediments (secs) | Corrected Δ t (secs) | Geophone velocity (km/sec) | Remarks |
|---|---|---|---|---|---|
| ePg | 18.80 | -0.15 | 18.65 | 6.2 ± 0.1 | |
| e | 19.70 | -0.15 | 19.55 | 5.9 ± 0.5 | |
| ePP | 22.35 | -0.15 | 22.20 | 7.3 ± 0.3 | |
| e | 24.60 | -0.15 | 24.45 | 9.3 ± 1.0 | |
| e | 24.65 | -0.15 | 24.50 | 11.2 ± 1.0 | |
| eSg | 32.55 | -0.2 | 32.35 | 3.9 ± 0.5 | Δ t ± 0.2 sec. |
| e | 32.95 | -0.2 | 32.75 | 4.6 ± 0.5 | Relative times |
| e | 41.35 | -0.2 | 41.15 | 5.4 ± 0.5 | ± 0.05 sec. |

TABLE I (Contd.)

STATION "E"    Epicentral distance 144.3 ± 1.0 km

Instrument  -  Willmore Seismograph

| Phase | Travel time (Δ t) | | Correction for sediments | Corrected Δ t | Remarks |
|---|---|---|---|---|---|
| | Vertical component (secs) | Transverse horizontal component (secs) | (secs) | (secs) | |
| iPg | 23.1 | | -0.1 | 23.0 | |
| i | | 23.4 | -0.1 | 23.3 | |
| i | 23.6 | | -0.1 | 23.5 | |
| i | 25.0 | 25.1 | -0.1 | 24.9 | |
| iSg | 40.7 | | -0.2 | 40.5 | |
| e | | 41.2 | -0.2 | 41.0 | |
| i | 42.4 | | -0.2 | 42.2 | |
| e | | 43.8 | -0.2 | 43.6 | |
| i | | 47.7 | -0.2 | 47.5 | |
| eAir-wave | 432.1 | | | | |
| i " | 434.3 | | | | Δ t ± 0.2 sec. |

STATION "F"    Epicentral distance 187.7 ± 1.0 km

Instrument  -  Willmore Seismograph

| Phase | Travel time (Δ t) | | Correction for sediments | Corrected Δ t | Remarks |
|---|---|---|---|---|---|
| | Vertical component (secs) | Transverse horizontal component (secs) | (secs) | (secs) | |
| iPg | 30.3 | 30.4 | -0.2 | 30.1 | |
| i | 30.7 | | -0.2 | 30.5 | |
| i | | 31.0 | -0.2 | 30.8 | |
| e | 36.0 | | -0.2 | 35.8 | |
| iSg | | 53.1 | -0.3 | 52.8 | |
| iSn | 54.8 | | -0.3 | 54.5 | |
| e | 57.0 | 57.0 | -0.3 | 56.7 | Δ t ± 0.2 sec. |

TABLE I (Contd.)

STATION "G" Epicentral distance 268.3 ± 1.0 km

Instrument - Willmore Seismograph

| Phase | Travel time (Δ t) Vertical component (secs) | Travel time (Δ t) Transverse horizontal component (secs) | Correction for sediments (secs) | Corrected Δ t (secs) | Remarks |
|---|---|---|---|---|---|
| iPn | 41.4 | | -0.2 | 41.2 | Small amplitude |
| i(P*) | 41.9 | 42.0 | -0.2 | 41.7 | |
| iPg | 42.4 | 42.6 | -0.2 | 42.2 | Large amplitude |
| eSn | 71.9 | | -0.3 | 71.6 | |
| iSg | 74.8 | 74.8 | -0.3 | 74.5 | |
| i Air-Wave | 897.3 | | | | Δt ± 0.2 sec. |

1953 STATION - S12 Epicentral distance 93.8 km

Instrument - Century prospecting-type seismograph.
Paper speed 18 cm/sec.
Geophone period 0.1 sec.

| Phase | *Travel time (corrected for sediments), vertical component (secs) | **Observed geophone velocity (km/sec) | Possible corrected geophone velocity (km/sec) | Relative magnitude |
|---|---|---|---|---|
| A Pg | 15.0 | 5.18 | 6.3 | 6 |
| B | 15.3 | 4.94 | 6.0 | 2 |
| C | 16.0 | 5.31 | 6.4 | 1 |
| D | 16.3 | (4.70) | 5.7 | small |
| E | 17.1 | 6.46 | 7.9 | " |
| F | 17.6 | 8.50 | 10.8 | " |
| G | 18.5 | 6.58 | 8.1 | " |
| H PP | 19.0 | 9.24 | 11.9 | 4 |
| I | 19.3 | 8.32 | 10.6 | 1 |
| J | 19.7 | 8.44 | 10.6 | 1 |
| K | 20.1 | (5.6) | 6.8 | 1 |

* Travel time of A was not known, hence a value was calculated such that $\Delta t = \frac{93.8}{6.3} + 0.1$ seconds.

** Uncorrected for sedimentary layers.

## TABLE 1.

## SEISMIC PHASES AND TRAVEL TIMES

STATION "A" Epicentral distance 31.2 ± 0.2 km.

Instrument - Willmore Seismograph

| Phase | Travel time (Δt) | | | Correction for sediments (secs) | Corrected Δ t (secs) | Remarks |
|---|---|---|---|---|---|---|
| | Vertical component (secs) | Transverse horizontal component (secs) | Longitudinal horizontal component (secs) | | | |
| iPg | 5.1 | 5.2 | 5.2 | -0.25 | 4.9 | |
| i | | | 5.5 | -0.25 | 5.2 | |
| eSg | | 8.8 | 8.9 | -0.4 | 8.4 | |
| e | | | 12.7 | -0.4 | 12.3 | Δt ± 0.2 sec. |

STATION "B" Epicentral distance 66.8 ± 0.2 km

Instrument - T.I.C. Seismograph

| Phase | Travel time (Δ t), vertical component (secs) | Correction for sediments (secs) | Corrected Δ t (secs) | Geophone velocity (km/sec) | Remarks |
|---|---|---|---|---|---|
| iPg | 11.10 | -0.25 | 10.85 | 6.5 ± .05 | |
| e | 11.70 | -0.25 | 11.45 | 7.0 ± .5 | |
| e | 11.90 | -0.25 | 11.65 | 7.0 ± .5 | |
| e | 12.15 | -0.25 | 11.90 | 7.3 ± .5 | |
| e | 12.50 | -0.25 | 12.25 | 7.0 ± .5 | |
| e | 13.10 | -0.25 | 12.85 | 6.1 ± .5 | |
| ePP | 15.90 | -0.25 | 15.65 | 9.2 ± .5 | Δ t ± 0.2 sec. Relative times ± 0.05 sec. |

Note:- All geophone velocities corrected for dips of sedimentary layers and of basement surface.

TABLE 2. RESULTS OF LOCAL REFRACTION SURVEYS

| Site | Layer | P wave velocity<br>ø S " " (km/sec) | Depth to upper surface (meters) | Description |
|---|---|---|---|---|
| Explosion Site | A | 1.7 -2.6 | | Travertine Limestone |
| | B | .67- .82 | (thin) | Sand |
| | C | 1.3 | 6 | Sand and clay |
| | D | 3.35-3.65<br>ø 2.5 -2.6 | 60 | Sandstone and/or shale |
| | E | 5.79 | 400 | Granitic or metamorphic basement |
| Results of survey over wide area (Wiebenga and Hawkins, 1956) | | | | |
| Station B | A | .45 | | Alluvium |
| | B | .75 | 1.5 | Dense limestone |
| | C | 1.7 | 38 | Sand and clay |
| | D | 3.2<br>ø 2.4 approx. | 90 | Sandstone and/or shales |
| | E | 5.88 | 550 | Granitic or metamorphic basement |
| Result of a 1-mile traverse and a ½-mile traverse at right angles | | | | |
| Station C | A | - | | Sand, alluvium, weathered granite |
| | B | 5.70<br>ø 3.4 approx. | 0-30 approx. (Surface undulations) | Granitic basement (outcropping) |
| Results of a 1-mile traverse | | | | |
| Between Stations D and E | A | 0.9 approx. | | Sand and alluvium |
| | B | 2.45 " | 15 approx. | - |
| | C | - | 150 " | Granitic or metamorphic basement |
| Insufficient data | | | | |
| Station G | A | - | | Alluvium |
| | B | 2.45 | 5 approx. | Limestone |
| | C | 5.85 | 30-90 (Surface undulations) | Granitic or metamorphic basement |

ø Results of a 1-mile traverse