# SEISMIC RECORDINGS OF LARGE EXPLOSIONS IN SOUTH-EASTERN AUSTRALIA

By H. A. Doyle,* I. B. Everingham,† and T. K. Hogan‡

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*Summary*

Three very large quarry explosions of between 50 and 100 tons of high explosive in the Snowy Mountains area were recorded by seismographs at distances up to 375 km. $P$ and $S$ wave velocities within the Earth's crust for this part of south-eastern Australia were formally determined to be 6·04 (±0·04) and 3·62 (±0·03) km/sec, respectively. The $P_n$ velocity was found to be 8·03 km/sec, with an estimated error of 0·2 km/sec. Assuming a uniform layer above the Mohorovičić discontinuity with these velocities, the discontinuity was formally estimated to be at a depth of 37 km.

## I. Introduction

During 1956 and 1957 three very large explosions of between 50 and 100 tons were detonated at Eaglehawk quarry in the Snowy Mountains area of New South Wales to provide rock-fill for the Adaminaby dam. The positions and times of these explosions (Table 1) were determined accurately and the ground waves produced were recorded at 13 different stations (Fig. 1) by the Scientific Services Division of the Snowy Mountains Hydro-Electric Authority (S.M.H.E.A.), the Geophysics Department of the Australian National University, and the Geophysical Section of the Bureau of Mineral Resources.

The aim of this programme was to obtain accurate seismic velocities for the study of the Earth's "crust" in this region, and to assist in the location of naturally occurring earth tremors. The S.M.H.E.A. has recently set up seismic stations at Wambrook, Jindabyne, Cabramurra, and Geehi (Jaeger and Browne 1958) for engineering purposes, while the National University has established stations at Canberra and Inveralochy (Fig. 1). The Bureau of Mineral Resources has a station at Melbourne, and until recently ran a temporary one at Warragamba in conjunction with the Sydney Water Board. A Century prospecting seismograph was used at Mt. Stromlo, as its distance (96 km) was near the best distance for critical reflection from the Mohorovičić discontinuity. In addition temporary recording sites were used at Cooma, Indi, Berrima, and Marulan (N.S.W.) by the S.M.H.E.A. and the University, and at Whitfield (Vic.) by the Bureau of Mineral Resources. Radio warnings of the expected times of the explosions were broadcast from the S.M.H.E.A. station VL2PA Wambrook, and from the Cooma commercial station 2XL. The times of the explosions were determined with an error of less than 10 msec by transmitting a pulse by radio from the detonation apparatus to the Cooma laboratories of the Scientific Services Division

* Department of Geophysics, Australian National University, Canberra.
† Bureau of Mineral Resources, Geology and Geophysics, Melbourne.
‡ Scientific Services Division, Snowy Mountains Hydro-Electric Authority, Cooma, N.S.W.

where it was recorded by a Minirack recorder. Second impulses (with the 59th second omitted) were produced by a crystal clock at the Cooma laboratories and broadcast over the radios and also recorded on the Minirack. The crystal clock was rated from WWVH to an accuracy of $\pm 5$ msec. The detonations had delays of less than 10 msec. The geographic positions of the explosions were obtained from survey marks related to the S.M.H.E.A. grid with an error less than $0 \cdot 01$ km (Table 1).

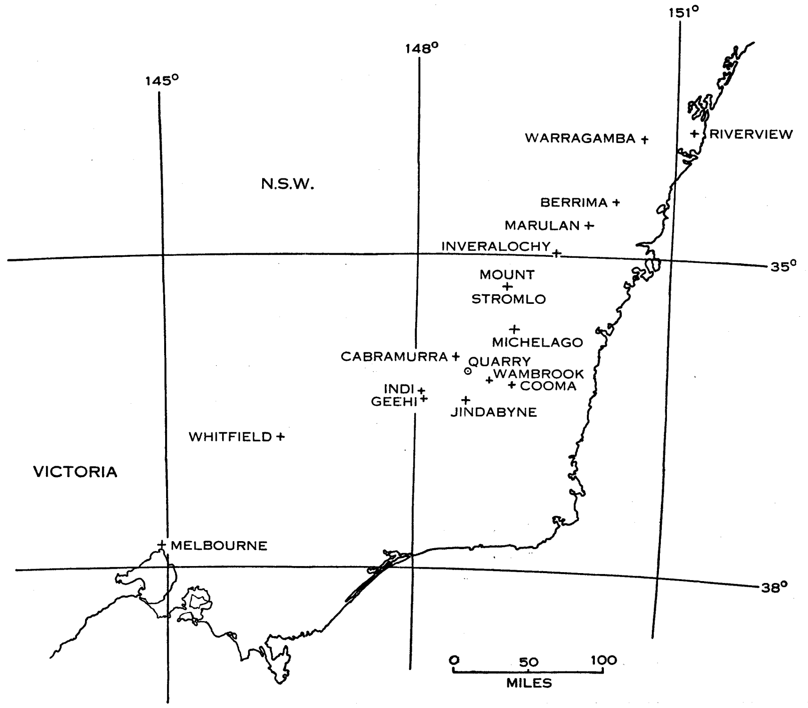


Fig. 1.—Recording sites.

The distances to each recording station were calculated with an error no greater than $\frac{1}{2}$ km (Table 3). The maximum height difference between sites was about 1 km and so no height correction was made. The travel-times were usually measured to about $\pm 0 \cdot 2$ sec, but some instruments gave much better accuracy (e.g. at Cooma).

Table 1

DETAILS OF EXPLOSIONS

| Explosion | Date | Time (G.M.T.) | Geographic Coordinates $\varphi$ | $\lambda$ | Size (tons) |
|---|---|---|---|---|---|
| A | 23. xii.56 | 02 19 49·6 | 36° 08′·2 | 148° 37′·7 | 60 |
| B | 10. ii.57 | 03 00 54·5 | 36° 07′·6 | 148° 36′·8 | 50 |
| C | 7.viii.57 | 00 23 41·1 | 36° 08′·2 | 148° 37′·7 | 100 |

The instruments used were generally of short period and high magnification (Table 2). They ranged from permanent observatory-type instruments (Benioff and Wood-Anderson), portable observatory-type (Willmore), to refraction survey seismographs (Century) and composite units put together temporarily for the work (e.g. Willmore geophone plus Minirack amplifier and recorder, as used at Cooma).

Table 2

STATION INSTRUMENTATION

| Station | Explosion | Instruments | Components | Paper Speed (mm/sec) |
|---|---|---|---|---|
| Wambrook | A | Willmore | 1Z, 1H | 1 |
| | C | Wood-Anderson | 2H | 1 |
| Cabramurra | B | Willmore | 1Z | 1 |
| | C | Willmore | 1Z | 1 |
| Indi | B | S.M.A. recorder with Willmore geophone | 1Z | 50 |
| Jindabyne | C | S.M.A. recorder with Willmore geophone | 1Z | 50 |
| Cooma | B | Minirack recorder and Willmore geophone | 2Z, 2H | 95 |
| | C | Minirack recorder and Willmore geophone | | 25 |
| Geehi | C | Century | 4Z | 15 |
| Mt. Stromlo | B | Century | 12Z | 95 |
| Inveralochy | C | B.P.I. recorder* | 2Z | 4 |
| Marulan | C | B.P.I. recorder | 2Z | 4 |
| Whitfield | B | Willmore | 1Z | 1 |
| Berrima | C | Willmore | 1Z | 1 |
| Warragamba | B, C | Willmore | 1Z | 1 |
| Melbourne | A, B, C | Benioff | 1Z, 2H | 1 |

* Kindly loaned by the Bernard Price Institute, Johannesburg.

It was considered most important to measure accurately the first $P$ arrival ($P_1$) at the near stations, as this velocity is required for the locations of near earthquakes by the $P$ difference method. For this reason there was not so much concern at this stage with the recording of later arrivals such as $P_n$.

## II. Physiography and Geology

The recording sites formed two long traverse lines, one to the north-east towards Sydney, and one to the south-west towards Melbourne, with a total span of approximately 600 km (Fig. 1).

The traverse lines crossed the south-east portion of the " Great Divide ", otherwise called the South-eastern Highlands. These Highlands consist of elevated tableland country, generally 2000–3000 ft above sea-level, with higher areas culminating in the Kosciusko horst, which reaches 7000 ft above sea-level.

Rock types are mainly Palaeozoic shales and slates, occurring in ill-defined meridional belts and separated by granitic intrusions, which are sometimes in the form of large batholiths (David 1950). At the northern end of the traverse line two stations (Warragamba and Riverview) were situated on the Sydney basin. This is a shale and sandstone basin of considerable thickness. Recent seismic reflection surveys have shown at least 14,000 ft of sediments (C. S. Robertson, Bureau of Mineral Resources, unpublished data 1957).

## III. Discussion of Results

Only reasonably clear " phases " are listed in Table 3 and graphed in Figure 2. The Benioff and Willmore records in particular contained other possible arrivals. In the case of some stations (e.g. Mt. Stromlo and Inveralochy) the large amplitude of the first arrival and the lack of automatic volume control made the reading of arrivals other than the first very difficult, and so no $P_n$, reflected waves, or $S$ waves were observed at these stations. This was unfortunate, particularly in the case of the expected reflected wave at Mt. Stromlo. Riverview Observatory reported only very small amplitudes from explosion C, while Brisbane reported no observable motion, so that these stations could not be included.

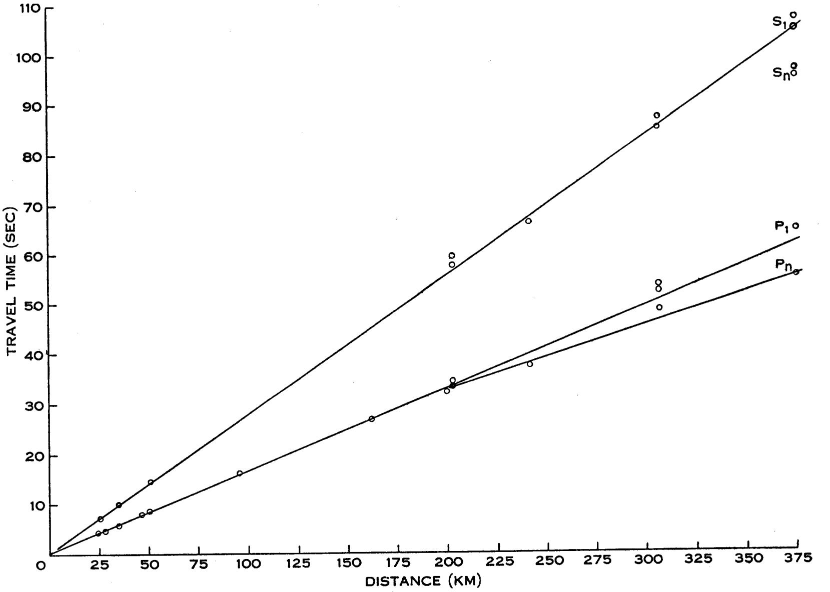


Fig. 2.—Travel-time curves.

It can be seen from Figure 2 that the arrivals are divisible into three groups. For the closer stations out as far as Inveralochy (160 km), the plot of travel-times of the first arrivals against distance gave a consistent velocity close to 6 km/sec. This phase, denoted $P_1$, was also recorded at some of the distant stations as a second arrival, but with less certainty. It was interpreted as the longitudinal wave in the Earth's " crust ". The curve of first arrivals changes at about 180 km to a velocity near 8 km/sec. This was interpreted as the arrival of longitudinal waves ($P_n$) from below the Mohorovičić discontinuity. The third group of arrivals was taken as the transverse wave $S_1$. It was a wave of larger amplitude, usually of longer period, with a velocity of about $3\frac{1}{2}$ km/sec.

### (a) *The* $P_1$ *Phase*

The travel-time equation for $P_1$ was calculated using the method of least squares. Only first arrivals were used in the final calculation because of the lack of ambiguity and the greater accuracy obtained by using first arrivals only. The omission of the distant stations from the calculation was also justified by their larger residuals. The Melbourne residuals were about $+1\cdot8$ sec compared with the standard deviation of $0\cdot12$ sec for the closer stations.

$P_1$ recordings from two explosions were used at Wambrook, Cabramurra, and Cooma (Table 3). The Cooma times were used in the calculation separately as they were much more accurate, so giving Cooma double weight. However, for the other two stations the average travel-time was used. Thus in effect nine results were used to determine the formal $P_1$ travel-time equation

$$t=0\cdot335\ (\pm0\cdot073)+0\cdot1655\ (\pm0\cdot0010)\Delta \text{ sec},$$

where $\Delta$ is the distance in kilometres.

This corresponds to a $P_1$ velocity of $6\cdot04$ ($\pm0\cdot04$) km/sec. The standard errors of course measure the internal consistency of the observations but do not reveal systematic errors. The largest residuals amongst the close stations were only $0\cdot18$ sec for Cooma and Jindabyne. At Cooma there appears to be a slight delay compared to the other stations. This delay may be related to a wide belt of Ordovician sediments lying between Wambrook and Cooma.

It is noteworthy that if only $P_1$ phases are used that are second arrivals at distant stations, a lower apparent velocity of between $5\cdot8$ and $5\cdot9$ km/sec is obtained. This is probably due to the first part of the phase being missed, and, as is well known, probably explains the low velocities obtained in early near earthquake studies when the amplitudes were small.

### (b) *The* $P_n$ *Phase*

The $P_n$ equation was not very well determined. In preliminary calculations it was found that the indefinite first arrival at Warragamba had a large residual (2–3 sec) from both the $P_n$ and $P_1$ curves and so it was not used in the later calculations for either. This left only four stations that could be used for $P_n$, Marulan and Berrima to the north-east, and Whitfield and Melbourne to the south-west. All three explosions were recorded at Melbourne and these three values were averaged.

The two groups of stations, to the north-east and to the south-west, were treated separately to avoid the effect of the different time delays in the two directions. The velocity and time intercept obtained using the two Victorian stations, Whitfield and Melbourne, were $7\cdot96$ km/sec and $7\cdot8$ sec, while those for the northern stations Marulan and Berrima were both appreciably higher, $8\cdot3$ km/sec and $8\cdot2$ sec respectively. The values gave a weighted mean $P_n$ velocity of $8\cdot03$ km/sec and a mean time intercept of $8\cdot0$ sec. Errors for these last two figures were estimated by assuming errors of $\pm0\cdot2$ sec in the travel-times to each station and calculating the mean velocity and time intercept in the extreme cases. These estimated errors were $\pm0\cdot2$ km/sec and $\pm1\cdot0$ sec respectively.

The formal $P_n$ travel-time equation is then

$$t=8\cdot0(\pm1\cdot0)+0\cdot124(\pm0\cdot003)\Delta \text{ sec.}$$

More recordings of $P_n$ from timed explosions are required in this area to check this equation.

### (c) *The* $S_1$ *Phase*

The two Warragamba $S_1$ times were averaged. One of the three Melbourne recordings was treated separately and the other two averaged, so giving Melbourne extra weight. The eight results then gave the following travel-time equation :

$$t=0\cdot48(\pm0\cdot49)+0\cdot276(\pm0\cdot002)\Delta \text{ sec.}$$

This is equivalent to an $S_1$ velocity of $3\cdot62(\pm0\cdot03)$ km/sec.

Whitfield and Berrima had much higher residuals (1·1 and 1·2 sec) than the other stations. It was found that by omitting these two stations the large standard error in the time intercept was greatly reduced, showing the intercept to be significantly above zero. The standard deviation was reduced from 0·62 to 0·18 sec, but little difference was made to the velocity $3\cdot613(\pm0\cdot007)$. The equation is then

$$t=0\cdot44(\pm0\cdot13)+0\cdot2768(\pm0\cdot0005)\Delta \text{ sec.}$$

As is usual in explosion work, the $S$ amplitudes were not much greater than the $P$ amplitudes ; for example, at Melbourne the $S$ amplitudes were 1·5 times those of $P$.

### (d) *Other Phases*

The only $S_n$ phases worth listing were recorded at Melbourne. On the Cooma records $P_1$ was followed a second later by a sharp arrival ($P_s$) of twice the amplitude. This is shown clearly in Figure 3. It could not be correlated by ordinary ray theory with phases at other stations. However, less definite waves following $P_1$ and $S_1$ were noticed at Melbourne. It is suggested that this

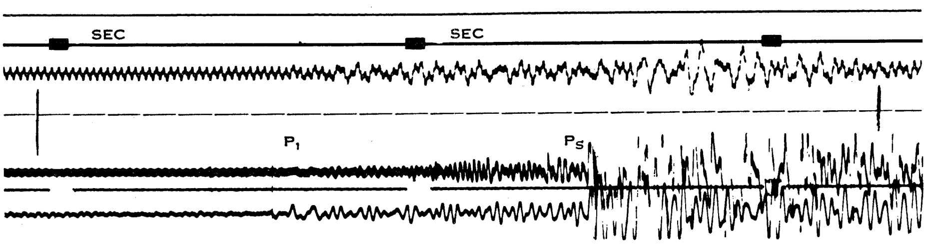


Fig. 3.—$P_1$ and $P_s$ at Cooma.

arrival is either a $P$ wave guided by slower material near the surface, particularly in the sediments west of Cooma, or a surface wave produced by conversion from the $P$ wave at inhomogeneities as described by Tatel and Tuve (1955).

Hodgson (1953) noted large phases closely following $P_1$ at epicentral distances between 66 and 120 km. Katz (1955) described small $P_1$ first arrivals each " followed within one second by a much larger arrival that could not be correlated

TABLE 3

PHASES AND TRAVEL-TIMES

| Station | Explosion | Distance (km) | Travel-time (sec) | Phase | Residual (sec) |
|---|---|---|---|---|---|
| Wambrook | A | 23·7 | 4·3 | $P_1$ | +0·02 (mean) |
| | B | 25·2 | 4·5 | $P_1$ | |
| | | | (7·2) | $S_1$ | —0·25 |
| Cabramurra | B | 27·2 | 4·6 | $P_1$ | —0·14 (mean) |
| | C | 29·05 | 5·1 | $P_1$ | |
| Jindabyne | C | 34·62 | 5·89 | $P_1$ | —0·18 |
| | | | 9·97 | $S_1$ | —0·08 |
| | | | 12·62 | $L$ | |
| Cooma | B | 47·0 | 8·29 | $P_1$ | +0·18 |
| | | | 9·17 | $P_s$? | |
| | C | 45·23 | 7·98 | $P_1$ | +0·16 |
| Indi | B | 46·8 | 8·06 | $P_1$ | —0·02 |
| Geehi | C | 50·57 | 8·73 | $P_1$ | +0·02 |
| | | | 14·73 | $S_1$ | +0·27 |
| Mt. Stromlo | B | 95·9 | 16·20 | $P_1$ | —0·01 |
| Inveralochy | C | 160·7 | 26·9 | $P_1$ | —0·03 |
| Marulan | C | 200·0 | 32·2 | $P_n$ | —0·7 |
| Whitfield | B | 202·8 | 33·3 | $P_n$ | —0·1 |
| | | | 34·4* | $P_1$ | (+0·5) |
| | | | 57·6 | $S_1$ | +1·06 |
| | | | (59·4) | | |
| Berrima | C | 241·7 | 37·2 | $P_n$ | —0·9 |
| | | | 66·1 | $S_1$ | —1·20 |
| Warragamba | B | 307·2 | 48·3* | ($eP$) | (+2·1) |
| | | | 52·0* | $P_1$ | (+0·8) |
| | | | 85·0 | $S_1$ | +0·10 (using mean of B & C) |
| | | | (87·1) | | |
| | C | 307·2 | 48·4 | ($eP$) | (+2·2) |
| | | | 52·4* | $P_1$ | (+1·2) |
| | | | (53·3) | | |
| | | | 86·0 | $S_1$ | +0·10 (mean B & C) |
| | | | (87·0) | | |
| Melbourne | A | 375·5 | 55·1 | $P_n$ | +0·4 |
| | | | 64·2* | $P_1$ | (+1·8) |
| | | | 95·0 | $S_n$ | |
| | | | 104·5 | $S_1$ | —0·04 (mean A & C) |
| | B | 375·0 | 54·7 | $P_n$ | 0·0 |
| | | | 64·4* | $P_1$ | (+2·0) |
| | | | 104·3 | $S_1$ | +0·15 |
| | C | 375·5 | 55·0 | $P_n$ | +0·3 |
| | | | 63·6* | $P_1$ | (+1·2) |
| | | | 96·5 | $S_n$ | |
| | | | (104·0) | $S_1$ | —0·04 (mean A & C) |
| | | | (106·8) | | |

* Not used in final calculation.

with any arrivals on other seismograms ". Gane *et al.* (1956) reported similar phases, describing them as follows: "These data suggest that these second phases follow at a roughly constant time after the first arrivals." All these above cases are difficult to explain by simple refraction in a second crustal layer and may have been caused by local trapping of energy near the surface.

Another possible explanation is a reflection from a Conrad discontinuity at 10–15 km depth, but no consistent evidence was seen for further layering above the Mohorovičić discontinuity. However, later arrivals would be difficult to see on most records owing to the high " noise-level " caused by the early arrivals.

The very small amplitude of the Riverview recording was mainly because of the longer period instruments. Also the high noise level at short periods at that site makes the recording of quarry explosions and near earthquakes difficult.

If the first arrival at Warragamba is a $P_n$ phase, its large positive residual (2·1–2·2 sec) from the $P_n$ curve is possibly caused by the thickness of the sediments of the Sydney basin.

## IV. Crustal Structure

Assuming a uniform " crust " above the Mohorovičić discontinuity with a $P_1$ velocity of 6·04 km/sec, a $P_n$ velocity of 8·03 km/sec, and time intercept 8·0 sec, the depth to the discontinuity was formally calculated as 37 km. Although this figure is approximate only, it is to be noted that it is close to the value normally obtained in continental regions such as the shield areas of Western Australia (Doyle 1957; Bolt, Doyle, and Sutton 1958), Canada (Hodgson 1953), and South Africa (Gane *et al.* 1956).

In earlier published explosion recordings in Western Australia (Doyle 1957; Bolt, Doyle, and Sutton 1958) a good determination was made of the $P_n$ velocity (8·2 km/sec), and a less accurate one of $P_1$ velocity (6·0–6·1 km/sec), the reverse of the case in this work. At about the same time, the Bureau of Mineral Resources made seismic recordings at the eastern end of the Nullarbor Plain in South Australia. The velocities found were 6·3 km/sec for $P_1$ and 3·6 km/sec for $S_1$. The depth to the Mohorovičić discontinuity was found to be 35–42 km by reflection and refraction measurements (I. B. Everingham, unpublished data 1958).

From the evidence obtained so far, the Nullarbor and Eastern Highlands regions do not appear very different seismically, though the former is a flat shield area reaching only 1000 ft in height, while the latter extends to 7000 ft in height. In both areas the sediments are thin (about 0·3 and 1–2 km respectively) compared with crustal dimensions, and the underlying basements have similar velocities. It is uncertain whether there is any significant difference between the depths to the Mohorovičić discontinuity in the two areas because of the uncertainties in the depth determinations (3–5 km). Future reflection recordings in south-eastern Australia will be useful to elucidate this.

Marshall and Narain (1954) found gravity Bouguer values which decreased from positive values at the coast to about −50 mgal in the South-eastern Highlands region. On the basis of the seismic results it appears most likely that the negative gravity values are not caused by a depression of the Mohorovičić discontinuity below the normal continental depth (35 km), but by emplaced granite masses having a relatively low density. In Western Australia, Gunsen and Van der Linden (Bureau of Mineral Resources, unpublished data 1956) recorded a large negative anomaly which has been similarly interpreted, and Innes (1957) has recently discussed a Canadian example.

## V. Acknowledgments

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