A SEISMIC EXPERIMENT USING QUARRY BLASTS NEAR SYDNEY

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Summary

The seismic waves generated by quarry blasts from 2 to 6 tons in weight, over an interval of 7 months, at Prospect, about 30 km west of Sydney, are examined. Shot times at the quarry were measured from radio time signals. The waves were recorded by seismographs at 10 seismological stations ranging in distance from 20 km (Riverview) to 380 km (Geehi in the Snowy Mountains). Analysis of the seismograms indicated two main bodily-wave phases, called P_1 and S_1. The S_1 waves, which possess considerable energy relative to the compressional first-arrivals P_1, appear to be shear waves generated in part by the unsymmetrical nature of the source.

The observations at the nearest four stations yield a P_1 velocity of $5 \cdot 88 \pm 0 \cdot 14$ km/sec and an S_1 velocity of $3 \cdot 51 \pm 0 \cdot 02$ km/sec. It is suggested that these waves travelled in basement rock beneath the sediments of the Sydney basin.

I. Introduction

Over a number of years seismologists at Riverview College Observatory, near Sydney, noticed that similar seismic disturbances were recorded on week-day afternoons at about monthly intervals. They inferred from the records that the sources were probably quarry blasts situated within 30 km of the Observatory. Inquiries made by the author, after being shown some of these records, revealed that the blasts occurred at the Prospect quarries of the N.S.W. Associated Blue Metal Quarries Pty. Ltd.

Inquiries also disclosed that a Willmore seismograph installed at the Warragamba Dam, near Werombi (cf. Fig. 1), for periods from 1954 to 1958, had recorded numerous local blasts. Careful correlation by Gray (1958) between these data and detonation times at various quarries had shown that a number of records were from blasts at the Prospect quarries, about 30 km away.

The N.S.W. Associated Blue Metal Quarries Pty. Ltd. was approached through its secretary, Mr. R. A. Parrott, and the company generously agreed to permit the author to time future explosions at Prospect. The main aim of the experiment was to investigate the transmission of seismic waves through the continental crustal layers of eastern New South Wales. The gathered travel-time data, which are tabulated in the present paper, may also prove useful to future investigators.

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II. The Quarry Blasts

The Prospect blue-metal quarries are in a hill (coordinates 34° 00′ S. (geographic), 150° 55′ E.), which stands about 400 ft above sea-level, approximately 15 miles west of Sydney. This hill is a differentiated basaltic mass intruded into the surrounding Triassic Wianamatta Shale (Jevons *et al.* 1911).

Details of the timed explosions are given in Table 1.

Table 1

EXPLOSION DATA

Explosion	Date 1959	Time (G.M.T.)	Weight (lb)
I	May 15	0600	4800
II	June 24	0600	8000
III	July 17	0600	5000
IV	August 14	0600	13800
V	September 30	0600	7500
VI	October 23	0600	5580
VII	November 20	0600	4500

The explosive (ammonium nitrate and quarry gelatin) was placed in vertical bore holes 80–120 ft deep, drilled in a line parallel to the quarry face, and electrically detonated. Explosion IV was detonated in two sections and the connections between holes in explosion VII contained 0·015 sec delays. In these cases the spread in detonation time was of the order of 0·25 sec; in the remaining cases the spread was no more than a few milliseconds.

Table 2

RECORDING STATIONS

Station	Δ (km)	Instrument	Components
Riverview	21·74	Sprengnether	Z
Hall's Lagoon	34·4	Benioff	Z
Werombi	35·1	Benioff	Z, N.-S., E.-W.
Avon	67·2	Benioff	Z
Jenolan	83·1	Benioff	Z
Canberra	242·2	Benioff	Z, N.-S., E.-W.
Wambrook	320·2	Benioff	Z, N.-S., E.-W.
Cabramurra	324·6	Benioff	Z
Jindabyne	358·0	Benioff	Z
Geehi	379·2	Benioff	Z

Detonation times were fixed by aural synchronization with the six time signals transmitted on the hour by the Australian Broadcasting Commission. It is estimated that consequent timing errors do not exceed $\frac{1}{10}$ sec, so that the error in the mean origin time, when observations from a number of blasts are combined, is well within the general observational uncertainties.

The shot-point positions are known to the nearest 50 yards ($<0 \cdot 05$ km) from a survey kindly made by Mr. P. B. Jones of the Department of Civil Engineering, the University of Sydney.

III. Recording Stations and Seismic Profiles

Timed Prospect blasts were recorded at Riverview, on seismographs installed by the Sydney Water Board, at the Australian National University seismic station (Spring Valley, Canberra), and on seismographs of the Snowy Mountains Hydro-Electric Authority (cf. Table 2).

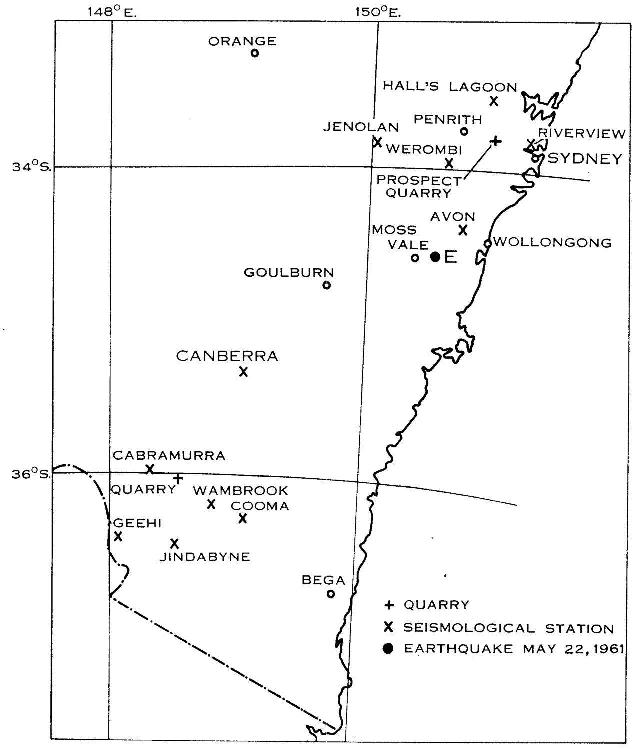


Fig. 1.—Map of south-eastern New South Wales showing the positions of the Prospect quarry, seismological stations recording the Prospect blasts, the estimated epicentre of the earthquake of 1961, May 22, and a quarry in the Snowy Mountains referred to by Doyle, Everingham, and Hogan (1959).

At Riverview, the Sprengnether short-period instrument provided the most detailed records but the blasts were sometimes also recorded on the Mainka and Galitzin seismographs. The recording speeds of instruments at all stations were sufficiently high to give a confidence interval of less than $0 \cdot 5$ sec for the reading of an *impetus* onset.

The position of Prospect in relation to the recording stations is shown in Figure 1 and the relevant distances are tabulated in Table 2.

IV. Recorded Data

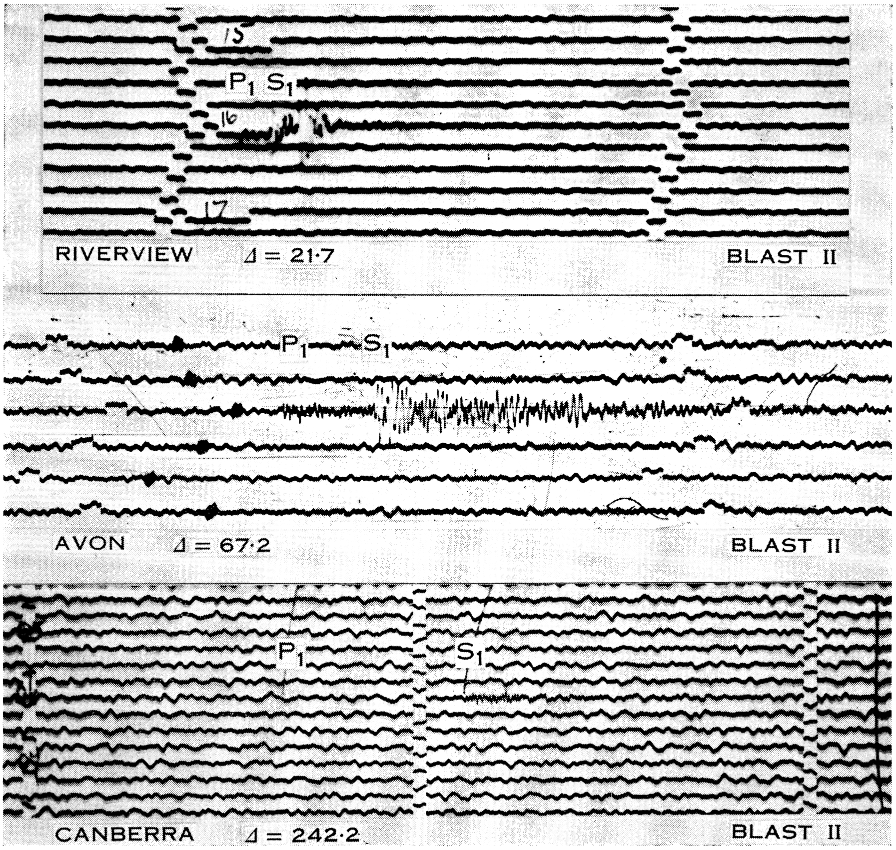
The weight of explosive in blasts I to VII varied between 4800 and 13,800 lb. On the basis of 4×10^{16} ergs per ton (Wright *et al.* 1958), the energy released by the 13,800 lb explosion (blast IV) was of order 24×10^{16} ergs. If the assumption is made that the seismic efficiency of the explosion was near the frequently stated value of $0 \cdot 3\%$, the seismic energy from this blast was about 7×10^{14} ergs. This energy is the same order as that released by an earthquake of magnitude 2.

Table 3

Travel-time data

Station	Explosion	Arrival Times of Phases (after 0600 hr G.M.T.)	Comments
Riverview ..	I	$04 \cdot 5$s(iP_1), $08 \cdot 3$s(iS_1), $11 \cdot 7$s(i)	
	II	$04 \cdot 4$s(P_1), $07 \cdot 9$s(e), $08 \cdot 1$s(iS_1), $11 \cdot 2$s(i)	
	III	$08 \cdot 9$s(i)	Not well recorded
	IV	$04 \cdot 5$s(P_1), $08 \cdot 5$s(iS_1), $10 \cdot 2$s(i), $11 \cdot 8$s(i)	
	VII	$04 \cdot 7$s(P_1), $08 \cdot 6$s(iS_1)	
Hall's Lagoon	V	$07 \cdot 0$s(eP_1), $12 \cdot 3$s(iS_1), $18 \cdot 0$s(i)	Clear record
	VI	$07 \cdot 3$s(P_1), $11 \cdot 6$s(S_1)	S_1 partly obscured by time mark
Werombi ..	I	$07 \cdot 0$s(iP_1), $11 \cdot 9$s(iS_1)	
	II	$07 \cdot 1$s(iP_1)	Remaining phases obscured by rapid motion
	IV	$07 \cdot 2$s(P_1), $12 \cdot 0$s(S_1)	
	V	$07 \cdot 3$s(P_1), $12 \cdot 0$s(S_1)	Clock correction uncertain
	VI	S_1—P_1=$05 \cdot 1$s	Clock correction unavailable
Avon ..	I	$12 \cdot 3$s(P_1), $21 \cdot 3$s(iS_1)	
	II	$12 \cdot 6$s(iP_1), $21 \cdot 1$s(iS_1), $26 \cdot 0$s(i), $29 \cdot 6$s(i), $32 \cdot 7$s(i)	Clear record
	III	$12 \cdot 7$s(iP_1), $21 \cdot 8$s(iS_1), $25 \cdot 9$s(i), $40 \cdot 1$s(e)	
	IV	$12 \cdot 4$s(P_1), $21 \cdot 4$s(S_1)	
	V	$12 \cdot 2$s(iP_1), $20 \cdot 4$s(S_1 ?)	
	VI	$11 \cdot 6$s(eP_1), $20 \cdot 9$s(iS_1)	
Jenolan ..	I	$21 \cdot 9$s(iP_1), $23 \cdot 5$s(i), $32 \cdot 2$s(iS_1), $34 \cdot 6$s(i)	Clear record
	VI	$21 \cdot 6$s(P_1), $30 \cdot 4$s(i), $32 \cdot 6$s(iS_1)	
Canberra ..	I	1m $08 \cdot 5$s(iS_1)	
	II	$41 \cdot 0$s(iP_1), 1m $08 \cdot 0$s(iS_1)	
	III	1m $08 \cdot 5$s(eS_1)	
	IV	1m $08 \cdot 0$s(iS_1)	Preliminary Bulletin — corrected by 1m
	V	1m $03 \cdot 5$s(i), 1m $08 \cdot 0$s(iS_1)	
Wambrook ..	II	$52 \cdot 5$s(eP_1), 1m $28 \cdot 8$s(eS_1), 1m $32 \cdot 5$s	Times from vertical instrument
Cabramurra ..	II	1m $27 \cdot 4$s(e), 1m $30 \cdot 2$s(iS_1)	
Jindabyne ..	II		Traces only
Geehi.. ..	II	1m $06 \cdot 7$s(e), 1m $47 \cdot 0$s(e)	

SEISMIC EXPERIMENT USING QUARRY BLASTS



Portions of seismograms from vertical-component instruments at Riverview, Avon, and Canberra showing the wave trains generated by a blast at Prospect quarry. The distance between time breaks is 1 min in each case.

Phases at times attributable to blast II were recorded at the Snowy Mountains stations (cf. Table 3) over 300 km away. These distant observations suggest that with suitable portable equipment the relatively small explosions at the Prospect quarries could be used to investigate crustal structure over a considerable area of N.S.W., including Orange to the west, Canberra to the south, and Newcastle to the north.

Travel-time data for Riverview and Canberra were taken from the Station Bulletins ; the remaining data were read by the author from copies of the original seismograms. Arrival times for only the most prominent onsets are listed in Table 3. An aspect of the experiment which needs stressing is that the accumulated series of observations at a number of the stations allow a check on onset times ; repeated observation of a phase establishes confidence that it is genuine.

The seismographs at Riverview, Hall's Lagoon, Werombi, and Avon show clearly two main high-frequency onsets, called in this work P_1 and S_1 phases. Examples of records showing the P_1 and S_1 phases are presented in Plate 1. (As examples of the consistency of the measured transmission times of these phases, the mean travel times to Avon, with their standard errors, are $12 \cdot 30 \pm 0 \cdot 12$ sec from six P_1 observations, and $21 \cdot 30 \pm 0 \cdot 18$ sec from six S_1 observations.)

For $\Delta > 20$ km, the compressional wave P_1 is a clear first arrival, if recorded. The S_1 travel-time curve is always above that of P_1 so the S_1 phase is taken to be a shear wave with similar paths to P_1 ; it carries considerable energy, trace amplitudes being three to four times those of P_1 on the vertical instruments at the four nearest stations and on the horizontal components at Werombi. This transverse motion is presumably partly generated as SV waves by P reflection at interfaces but some shear motion may arise from the horizontally unsymmetrical nature of the quarry explosions.

No waves corresponding to P_n and S_n phases were recorded at the distant stations. Some other clear onsets given in Table 3 are interpreted in Section V.

V. Interpretation

A plot of mean travel times of the observed P_1 and S_1 phases indicated that most points fall near two linear time–distance curves. Such linear curves are consistent with the hypothesis of a system of plane crustal layers extending under all stations with insignificant variation of velocity with azimuth. Least-squares solutions, using linear forms to fit the mean travel times, are

$$P_1: \quad t = (1 \cdot 39 \pm 0 \cdot 44) \text{ sec} + \Delta/(6 \cdot 16 \pm 0 \cdot 10) \tag{1}$$

$$S_1: \quad t = (2 \cdot 45 \pm 0 \cdot 21) \text{ sec} + \Delta/(3 \cdot 67 \pm 0 \cdot 02). \tag{2}$$

Weights were allotted as in Table 4 where the resulting residuals are also listed. The weights were chosen mainly from a consideration of the clarity of the records and the number of observations at each station. The main contributions to the standard errors in solutions (1) and (2) come from the observations from the distant stations, particularly Geehi, which may have been read late due to the weakness of onsets. (The observations from the three Snowy Mountains Authority stations are unchecked, coming only from explosion II.)

TABLE 4

STATION WEIGHTS AND TRAVEL TIME RESIDUALS

Station	Weights: P_1 Solution (1)	Residual (sec)	Weights: P_1 Solution (3)	Residual (sec)	Weights: S_1 Solution (2)	Residual (sec)	Weights: S_1 Solution (4)	Residual (sec)
Riverview	2	—0·4	2	—0·2	2	—0·1	2	0·0
Hall's Lagoon	1	+0·1	1	+0·3	1	+0·2	1	+0·1
Werombi	2	0·0	2	0·0	2	0·0	2	—0·1
Avon ..	2	0·0	2	—0·1	2	—0·5	2	+0·1
Jenolan	0	[+5·8]	0	[+6·6]	0	[+7·3]	0	[+6·6]
Canberra	1	+0·3	0	[—1·2]	2	—0·2	0	[—3·0]
Wambrook	1	—0·9	0	[—2·9]	1	—0·9	0	[—4·6]
Cabramurra	0		0		0·5	—0·7	0	[—4·5]
Geehi ..	0·5	+3·7	0	[+1·2]	0·5	+1·3	0	[—3·2]

The region covered here overlaps that investigated by Doyle, Everingham, and Hogan (1959) from seismic records of three blasts at a quarry (shown in Fig. 1 near Wambrook). They report three distinct phases; P_n with a velocity near 8·03 km/sec, and P_1 and S_1 phases with travel times (for P_1 based mainly on data from the Snowy Mountains Authority stations) given by

$$P_1: \quad t=(0\cdot 335\pm 0\cdot 073)\ \text{sec}+\Delta/(6\cdot 04\pm 0\cdot 04),$$
$$S_1: \quad t=(0\cdot 48\pm 0\cdot 49)\ \text{sec}+\Delta/(3\cdot 62\pm 0\cdot 03).$$

Although the velocities are close to those computed from the present data, the differences between the constant terms in corresponding equations are significant and suggest that crustal properties below the Sydney basin (Triassic) may be different from those in the south-eastern highlands (Palaeozoic). Trial numerical analyses, which combined the data of Doyle, Everingham, and Hogan (1959) with the present data, partly confirmed this possibility.

More meaningful solutions for P_1 and S_1 were therefore made from the present data using only mean travel times to Riverview, Hall's Lagoon, Werombi, and Avon. The yielded equations, applicable to the Sydney basin, are

$$P_1: \quad t=(0\cdot 97\pm 0\cdot 18)\ \text{sec}+\Delta/(5\cdot 88\pm 0\cdot 14), \tag{3}$$
$$S_1: \quad t=(2\cdot 07\pm 0\cdot 08)\ \text{sec}+\Delta/(3\cdot 51\pm 0\cdot 02). \tag{4}$$

The value of Poisson's ratio, using the velocities in solutions (3) and (4), is $0\cdot 225\pm 0\cdot 017$.

Travel-time data, provided by the New South Wales earthquake of 1961, May 22, has led (Cooney 1962) to the following relation for the P_1 phase:

$$t=(0\cdot 72\pm 1\cdot 6)\ \text{sec}+\Delta/(6\cdot 06\pm 0\cdot 17). \tag{5}$$

The adopted epicentre (shown as **E** in Fig. 1) was 34° 35′ S. (geographic), 150° 24′ E.; data were from the Avon, Werombi, Jenolan, Riverview, and Hall's Lagoon stations. Agreement between (3) and (5) is within the calculated formal uncertainties.

In equations (3) and (4) the constant terms are significantly greater than the formal standard errors and the constant from the S_1 observations is about twice that from the P_1 data. There is thus a presumption that the recorded P_1 and S_1 waves travel in a layer at some depth below the surface of the Sydney basin. In this event recorded onsets from compressional and shear waves, propagated in overlying sedimentary layers (mainly sandstone, shale, tuff, and coal measures) with slower velocities than P_1 and S_1, might be expected.

No records show definite arrivals of phases between the *impetus* P_1 and S_1 onsets (cf. Plate 1) and on most records it is hazardous to read phases following S_1 owing to rapid motion of the light trace. At Avon (blasts II and III) onsets at 26·0 and 25·9 sec, where the amplitude suddenly increases to a maximum, are consistent with the arrival of a compressional wave with surface velocity about 2·6 km/sec. This phase would arrive at Riverview, Hall's Lagoon, and Werombi within a few seconds *after* the large S_1 onsets and would partly explain the large amplitudes recorded in that time interval (cf. Plate 1).

Compressional and shear velocities of 5·88 and 3·51 km/sec are typical of P and S velocities measured in granites and similar basement material (cf. Gutenberg 1959, Table 3.4). At Gulgong, north-west of Sydney, Edge and Laby (1931) determined P velocities of 2·4 and 5·6 km/sec in sandstone conglomerate and exposed granite, respectively.

On adoption of 5·88 and 2·60 km/sec as mean P velocities in a crust consisting of a basement overlain with a horizontal layer of sediments, the constant term in (3) indicates a thickness of sediments near 5000 ft. Adoption of a mean velocity in the sediments as high as 3·50 km/sec yields a thickness of about 8000 ft. This estimated range is compatible with published geological maps for the Sydney basin which are partly based on information from deep bores.

Particularly interesting among the later onsets is one repeated on three occasions at Riverview with travel times near $11\frac{1}{2}$ sec. These onsets are characterized by relatively large amplitudes for several cycles of about $1–1\frac{1}{2}$ sec period. The arrival times correspond to a surface velocity of approximately 1·9 km/sec. It is possible that the observations refer to an Airy phase of Rayleigh waves travelling through surface sedimentary layers.

The Jenolan mean arrival times for P_1 and S_1 are about 7 sec late (Table 4). However, the S_1 minus P_1 interval agrees closely with the interval calculated from (3) and (4). Radio time signals were recorded weakly at Jenolan and there is a chance that the adopted clock corrections are in error. This station lies on the Blue Mountains to the west of the Lapstone monocline so that the wave-path may differ in physical properties somewhat from paths to stations in the Sydney basin. Further observations are required to clarify this point.

Available gravity data (Hancock 1958) for the region are in accord with the small variation between residuals at Riverview, Hall's Lagoon, Werombi, and

Avon, which are all situated on the Sydney basin. The major feature of the Bouguer gravity anomaly is a regional trench parallel to the coast. A small systematic decrease inland of the anomalies from +50 mgal at the coast to −50 mgal near Jenolan is consistent with a possible thickening of the crustal layers towards the Great Dividing Range. The profile of zero anomaly lies almost along the Lapstone monocline, close to Werombi.

VI. Acknowledgments

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