A STUDY OF P TRAVEL-TIMES FROM SOME AUSTRALIAN EARTHQUAKES

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[*Manuscript received October* 1, 1965]

Summary

The epicentres of 11 Australian earthquakes have been determined using two different sets of travel-times, namely, the Jeffreys–Bullen times and the linear travel-time relation obtained by Bolt, Doyle, and Sutton from the 1956 nuclear explosions at Maralinga. The latter gave the better fit for earthquakes on the mainland. The residuals from the revised epicentres have been used to draw up a tentative average P travel-time curve. This is linear to $18\frac{1}{2}°$, beyond which the slope decreases sharply from 13·54 sec/deg to 10·5 sec/deg. The intersection and the change in slope probably vary from the north-west to the south-east of Australia. Beyond 25° the Jeffreys–Bullen times apply. At distances less than 5°, slopes between 13·7 and 13·8 sec/deg have been found for P_n. There are indications that the P_n velocity decreases considerably towards the edge of the continental shelf. A model for the upper mantle is suggested.

I. Introduction

Knowledge of seismic travel-times in Australia has been hampered by a lack both of earthquakes and of seismograph stations. During the past few years the number of stations has increased greatly, and the installation of more sensitive seismographs has resulted in better and more accurate recordings of Australian earthquakes. The largest of these earthquakes (of magnitude 5 approximately) have been recorded at several stations, giving P onsets that can usually be determined to 0·2 sec. The azimuthal distribution of stations for Australian earthquakes, however, is often not uniform. This means that the epicentres obtained for these earthquakes can be critically dependent on the travel-times used. The Jeffreys–Bullen (JB) tables (Jeffreys and Bullen 1948) have been used in earlier studies of Australian earthquakes (e.g. Bullen and Bolt 1956) and are used by the United States Coast and Geodetic Survey (USCGS) in its program for determining epicentres. These times are known to be a few seconds late, especially at shorter distances, in other continental regions. Australian studies so far have led to similar results. Cleary and Doyle (1962) deduced from their study of the Robertson earthquake (21.v.61, see Table 2) a surface velocity for P_n of 8·16 km/sec. There appeared to be no departure from a linear travel-time curve out to 15°. In a number of instances, explosions have been used to make direct determinations of seismic velocities. The data from these explosions are summarized in Table 1, and the velocities stated are surface velocities. Only two P and two S phases have been reported definitely, and their velocities differ significantly from the JB velocities.

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The linear travel-time relation of Bolt, Doyle, and Sutton (1958) (hereafter referred to as the BDS relation) has been used in the present paper to determine the epicentres of some Australian earthquakes, and the results are compared with solutions using the JB tables. This comparison was made following a suggestion by Bolt (1958) that, although determined for a region west of Maralinga, the BDS relation may apply in other regions of Australia. The suggestion is supported by the P_n data given by Doyle, Everingham, and Hogan (1959) for south-eastern Australia, which can be fitted by BDS travel-times to approximately the same standard error by subtracting a constant term. Also, when the residuals from the revised JB solutions for several of these earthquakes were plotted against distance, they were found to lie on a curve roughly equivalent to times from the BDS relation. The two sets of times intersect at 19·6°, which is the same as the intersection for the *Pd* and *Pr* branches of the JB curve. The linear travel-times of BDS have been found to give consistent results almost out to this distance.

TABLE 1

SEISMIC VELOCITIES DETERMINED FROM EXPLOSIONS

Author	$v(P_1)$ (km/sec)	$v(P_n)$ (km/sec)	$v(S_1)$ (km/sec)	$v(S_n)$ (km/sec)	Depth of M (km)
Bolt, Doyle, and Sutton (1958)	6·03	8·21	3·55	4·75	32
Doyle, Everingham, and Hogan (1959)	6·04	8·0	3·62	—	37
Bolt (1962)	5·88	—	3·51	—	—
Doyle and Everingham (1964)	6·30	8·05	3·59	4·61	39

II. Earthquakes Studied

Table 2 lists the earthquakes that have been studied. From Figure 1 it can be seen that they are concentrated mainly in the south-eastern corner of the continent. This is partly due to the concentration of stations in this area, since earthquakes were chosen that were well recorded at a reasonable number of stations.

III. Method of Revision of Epicentres

The provisional epicentres and origin times used were generally those given by the USCGS and were revised using the method of least squares (Bullen 1963, p. 159).

Original records were studied from all the Australian stations that recorded the shocks at Robertson, at Kangaroo Island, and in Bass Strait (1.vi.61). For the remaining earthquakes the readings were taken from station bulletins. Comparison for the earthquakes named above showed that the authors' readings agreed with those from station bulletins to within 0·5 sec or less for clear *P* onsets. Other phases did not show such good agreement. Readings for the Robertson earthquake were also in good agreement, often to 0·1 sec, with the readings published by Cleary and Doyle (1962) and by Cooney (1962). Jeffreys (1936), in a comparison of routine *P* observations with those from special studies, also found good agreement.

An IBM 1620 computer was used to calculate the distances and azimuths of the recording stations from the provisional epicentre and also the slope $dt/d\Delta$ of the JB P_n travel-time curve, together with all relevant P travel-times from JB tables and from BDS. The times were corrected for focal depth, station elevation, and ellipticity (Bullen 1937). The program has been well checked and gives the JB times to 0·2 sec up to 30°.

Residuals $(O-C)$ were then calculated and plotted against azimuth, giving a rough estimate of the corrections to be applied to the epicentre and indicating any

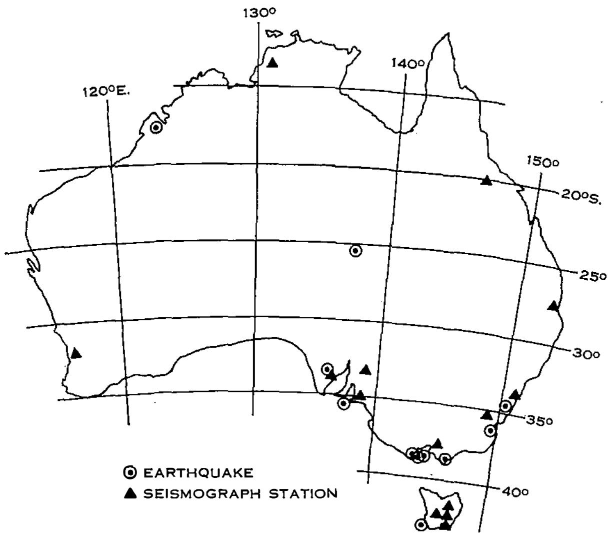

Fig. 1.—Locations of earthquakes and seismograph stations.

inconsistent residuals. These residuals were then fitted by a further computer program, using the method of least squares, to the relation

$$(O-C) = \tau - \frac{dt}{d\Delta}(x \cos Az + y \sin Az).$$

This gives corrections x°N., $(y/\cos\phi)$°E. to the epicentre and an increase of τ sec to the origin time. Standard errors and the revised residuals were also printed out. This program has been well checked by hand calculations and with published solutions (e.g. Bullen and Bolt 1956).

If P_n is the only phase recorded at all stations, then the focal depth and origin time cannot be obtained independently. When P_1 readings were available, the focal depth was chosen that produced the best agreement between the P_1 and P_n readings. In general, the assumption of a different focal depth had little effect on the position of an epicentre or its accuracy.

Any residual that disagreed by more than 2 sec with other residuals of the same phase from similar azimuths was not used in the final calculations. Late eP readings were not used, but some eP readings given to 0·1 sec have been used. Any doubtful eliminations were tested by running various solutions containing the

TABLE 2

COORDINATES OF REVISED EPICENTRES

Event		JB Solution						BDS Solution					
		Geographic Coordinates Lat. (S.) (deg)	Geographic Coordinates Long. (E.) (deg)	Origin Time h m s	Depth (km)	S.E. of Residual (sec)	No. of Readings Used	Geographic Coordinates Lat. (S.) (deg)	Geographic Coordinates Long. (E.) (deg)	Origin Time h m s	Depth (km)	S.E. of Residual (sec)	No. of Readings Used
18. v.59	Berridale	35·94 (±0·12)	148·31 (±0·13)	06 13 01·3 (±1·1)	17	1·37	6	36·12 (±0·05)	148·58 (±0·06)	06 13 00·2 (±0·5)	0	0·63	5
2. xi.59	Eyre Peninsula	33·36 (±0·16)	135·98 (±0·13)	01 17 57·2 (±1·3)	0	2·40	7	33·38 (±0·04)	135·99 (±0·03)	01 18 00·9 (±0·4)	0	0·66	5
24.xii.60	Victorian coast	38·89 (±0·04)	143·64 (±0·05)	16 42 11·6 (±0·5)	33	0·99	8	38·88 (±0·06)	143·59 (±0·08)	16 42 10·4 (±0·8)	0	1·33	6
21. v.61	Robertson	34·53 (±0·07)	150·47 (±0·10)	21 40 03·7 (±0·7)	27	1·69	10	34·52 (±0·04)	150·49 ±(0·06)	21 40 03·9 (±0·5)	0	0·94	7
1. vi.61	Victorian coast	38·68 (±0·01)	144·12 (±0·03)	09 35 32·7 (±0·2)	0	0·46	6	38·67 (±0·02)	144·21 (±0·03)	09 35 35·7 (±0·3)	0	0·55	5
1. vi.61	Aftershock	38·67 (±0·03)	144·22 (±0·04)	13 19 50·2 (±0·4)	29	0·5	4	38·70 (±0·05)	144·26 (±0·05)	13 19 50·1 (±0·5)	0	1·0	4
16. v.62	Kangaroo Island	35·51 (±0·15)	137·66 (±0·18)	21 41 35·5 (±1·7)	25	2·47	7	35·49 (±0·06)	137·56 (±0·06)	21 41 37·7 (±0·6)	25	0·89	6
14. iii.63	Northern Territory	25·65 (±0·01)	137·48 (±0·02)	01 57 30·1 (±0·2)	33	0·33	6	25·65 (±0·01)	137·41 (±0·01)	01 57 35·0 (±0·1)	33	0·14	5
14. vi.63	Victorian coast	38·59 (±0·04)	146·37 (±0·08)	19 23 50·5 (±0·5)	33	0·91	6	38·58 (±0·03)	146·49 (±0·07)	19 23 49·8 (±0·4)	0	0·77	6
3. xi.63	Tasmania	43·45 (±0·07)	145·66 (±0·03)	12 00 39·6 (±0·8)	33	0·43	5	43·32 (±0·20)	146·03 (±0·09)	12 00 44·3 (±2·2)	33	1·11	5
23. iii.64	Dampier Land	17·51 (±0·18)	122·44 (±0·24)	22 41 08·1 (±1·7)	33	1·82	9	17·81* (±0·11)	122·79 (±0·15)	22 41 14·5 (±1·0)	33	1·13	6

* Not strictly BDS times (see §(6), Section III).

doubtful reading. In fact, most readings fitted well, and the residuals that were eliminated using BDS times show a definite pattern (see Section V). A system of weighting was incorporated in the program, but it was found to have little effect; consequently, it was not used, especially as it leads to complications with regard to the number of degrees of freedom to be used in significance tests.

The coordinates of the revised epicentres are listed in Table 2, together with their standard errors, the standard error of a residual, and the number of readings used. The following notes indicate some special features.

(1) The earthquakes on Kangaroo Island and Eyre Peninsula are both fitted much better by the times from BDS than by the JB times. A one-tailed F-test gives significance at the 10% level. Neither earthquake has a reading from the southern quadrant. The S_1 and S_n residuals show no variation with azimuth.

(2) The Robertson and Berridale shocks also are better fitted by the BDS times. The fit could be further improved in both cases by assuming that the crust is 6 km thicker under the Great Dividing Range. Both solutions for the Robertson shock agree well with that obtained by Cleary and Doyle using the network of stations in the Snowy Mountains region. However, the epicentre for the Berridale shock obtained by use of the BDS relation agrees far better than the JB solution with the epicentre given by Cleary, Doyle, and Moye (1964) using this network.

(3) The standard errors computed for earthquakes near the Victorian coast, using the two sets of travel-times, are not significantly different. Inspection of the revised BDS residuals (see Section IV) indicates a lower P_n velocity. The shocks on June 1, 1961, have few readings but are self-consistent. The Tarraleah reading for the shock on December 14, 1960, was 3 sec early compared with the Fort Nelson arrival. The reading has been confirmed by Miss Read of the University of Tasmania and is the one used in the solutions. No justification could be found for the focal depth of 77 km stated by the USCGS.

(4) The Tasmanian earthquake is near the edge of the continental shelf, and the JB times fit much better in this case. This is possibly due to the fact that the path to Adelaide is partly oceanic and that velocities under Tasmania differ somewhat from those measured on the Australian continent (Green 1965). The azimuthal distribution of stations is poor.

(5) The Melbourne and Brisbane iP readings for the Northern Territory earthquake are over 2 sec early compared with other readings for both sets of travel-times. Most of the readings occur in the range 9°–13° where BDS and JB travel-time curves are almost parallel, so that there is no significant difference in the errors. The records have been inspected and there is no doubt about these early arrivals; both are followed a few seconds later by larger P arrivals. This earthquake is discussed in Section V.

(6) The Dampier Land earthquake was recorded at only two stations (Darwin and Perth) at less than 18°. It has been included because it was well recorded beyond this distance. The "BDS" solution was obtained using BDS times for the range 0°–18·6° and by constructing a tentative travel-time curve for the range 18·6°–23·3°, of slope 10·54 sec/deg, based on three readings from previous earthquakes. The solution

gives P arrivals in the range 28°–32·5° that fit the JB times extremely well, the mean residual being $-0{\cdot}3 \pm 0{\cdot}6$ sec. It is preferred to the JB solution, since the latter will give travel-times to Darwin and Perth that are too large.

IV. Inspection of the Revised P Residuals

The revised JB residuals when plotted against distance Δ show a much wider scatter than do the revised BDS residuals. Some correlation with distance can be seen, confirming a more linear relation well beyond 10°.

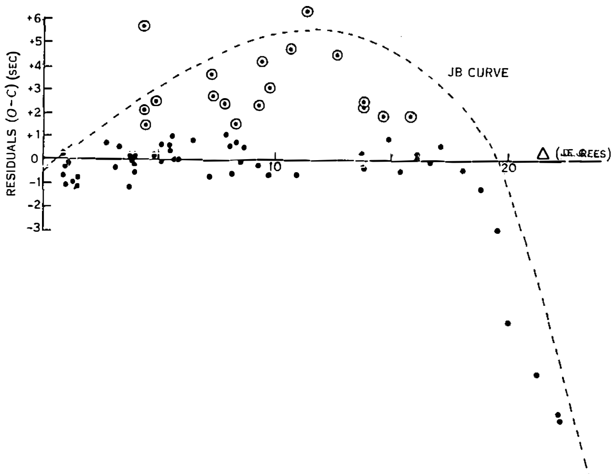

Fig. 2.—P residuals (●) obtained by use of the BDS relation, plotted against distance Δ. ○ late arrivals.

The revised residuals obtained by use of the travel-times from BDS are plotted against distance in Figure 2. These residuals show several interesting features.

(1) With one exception, all the corrected residuals obtained from readings used in the epicentre determinations fall within ± 1 sec out to 18·5°. These residuals represent 80% of all reported P phases.

(2) There is a group of negative P_1 residuals near 1°. The mean P_1 residual is $-0{\cdot}7$ sec. This can be explained by either a higher P_1 velocity or larger P_n times. The P_n times for the Robertson and Berridale shocks could be increased by a thicker crust for south-eastern Australia. This would also account for the negative residuals at Adelaide for these earthquakes.

(3) For the earthquakes near the Victorian coast, the residuals to the Tasmanian stations and those to Canberra, Melbourne, and Riverview show a marked increase with distance. Regressions of these residuals against Δ gave:

(i) for Tasmania, $-0{\cdot}79(\pm 0{\cdot}39)+0{\cdot}16(\pm 0{\cdot}07)\Delta$ sec;

(ii) for Canberra, Melbourne, and Riverview,

$$-0{\cdot}72(\pm 0{\cdot}65)+0{\cdot}22(\pm 0{\cdot}12)\,\Delta \text{ sec.}$$

Eight P_n readings were used in regression (i), which is significant at the 10% level, and five P_n readings in regression (ii), which is significant at the 20% level. The corresponding surface velocities are 8·12 and 8·08 km/sec respectively. The constant term corresponds to the mean P_1 residual.

(4) Beyond 18° there is a sharp increase in $dt/d\Delta$. The data are not sufficient to give much quantitative information, and the shape of the travel-time curve near this discontinuity is likely to vary from region to region. The Adelaide and Charters Towers readings for the Dampier Land earthquake (both near 22°) fitted the tentative slope of 10·54 sec/deg. On the other hand, the Cleve and Hallett readings, at 20·03° and 21·25° respectively, indicate a slope of approximately 11·5 sec/deg. This leads to an intersection near 16·5°. The slope (but not the intersection) is almost independent of the position of the true epicentre for this earthquake. Cleary and Doyle have commented that the Robertson earthquake gave times at 25° and 28° that fitted the JB tables. The "BDS" epicentre for the Dampier Land earthquake would confirm this fit in the range 28°–32·5°.

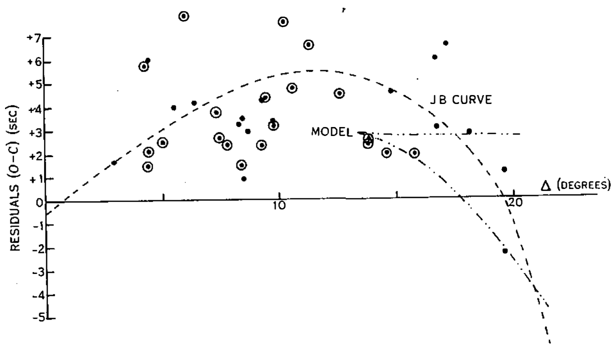

Fig. 3.—Residuals of late (○) and second *P* (●) arrivals, plotted against distance Δ.

V. Late *P* Readings

The late *P* arrivals not used in the determinations of epicentres are included in Figure 3. They tend to be grouped just earlier than the JB curve. It is also noticeable that all these late arrivals come from either Brisbane, Riverview, or the Tasmanian stations. A large number of second arrivals shortly after *P* were recorded and are also shown in Figure 3. When plotted as residuals against distance, these show more scatter but tend to be grouped with the late *P* readings. It is suggested that the late arrivals and these second arrivals are related.

Cleary and Doyle noted that this prominent second arrival was present on many records of the Robertson earthquake. It was interpreted as *pP*. Inspection of the records for the Kangaroo Island shock shows that this second arrival is present on all records that recorded the initial *P* pulse with the exception of Brisbane, whose record is much disturbed by microseisms, and Adelaide, which was very close to the shock. Its amplitude is usually larger than the first pulse. The arrival times for the Northern Territory earthquake can be explained by assuming that only Brisbane and

Melbourne picked up the early arrival and all other stations the late one. The Melbourne record shows a prominent second arrival at just the right time; the Brisbane record is not clear, although there is a definite increase in amplitude a few seconds after the first arrival. Since the earthquake was well recorded at azimuths on either side of Melbourne and Brisbane, and at roughly the same epicentral distances, it is not likely that these early arrivals are due to any major irregularity in structure.

Instead of interpreting these late arrivals as pP, an alternative explanation can possibly be made in terms of a low velocity layer at shallow depth below the Mohorovičić discontinuity. The following "flat-earth" model gives late arrivals from 13° onwards as well as the BDS travel-time curve, with an intersection near 18°. The velocities are surface velocities, and the velocities below 62 km are those given by Bullen (1963, p. 223) based on the JB tables.

Crust	32 km	$v(P_1) = 6\cdot03$ km/sec
M		
	30 km	$v(P_n) = 8\cdot21$ km/sec

$v(P) = 7\cdot95$ km/sec, increasing at the rate of $0\cdot0045$ (km/sec)/km

The late arrivals corresponding to this model would fall on the curve plotted in Figure 3. An increase in velocity gradient at a depth of approximately 350 km would give a travel-time curve close to the JB curve beyond 20°. Since the slope $dt/d\Delta$ of the JB travel-time curve is greater than the BDS value of $13\cdot54$ sec/deg up to $11\cdot5°$, rays refracted into the low velocity layer in any model of the type given above can return to the surface only at distances greater than $11\cdot5°$. Thus the model cannot explain the late arrivals from 5° onwards. However, the model assumes perfectly plane interfaces; any irregularities in these interfaces would give rise to rays with parameters that would allow a return to the surface within $11\cdot5°$. The late arrivals at Brisbane, Riverview, and the Tasmanian stations can be explained by the disappearance of the $8\cdot21$ km/sec layer near the edge of the continental shelf. The stations named are those closest to the edge of the shelf. This could also explain the better fit obtained using the JB times for the earthquake (3.xi.63) near the Tasmanian coast.

The linearity of the travel-time curve could also be an indication of a low velocity layer at shallow depth. Alternatively, P_n may travel as a headwave out to 18°.

Late arrivals similar to those found in the present study were found by Romney (1957), who also obtained a very similar residual–distance plot from the recordings of Gnome (Romney *et al.* 1962). This was explained by different velocities to the east and to the west of the test site. A systematic contour map of the residuals was plotted and was found to be correlated with the depth of the Mohorovičić discontinuity. Possibly the increase in the depth of the discontinuity under the mountains to the west causes the disappearance of the higher velocity sub-Mohorovičić layer in this region. Lehmann (1964) found many belated *P* phases at distances greater than 700 km in a study of *P* times from nuclear explosions. This was explained by a low velocity layer which was confined to the western mountain regions.

VI. Conclusions

The times of BDS from the 1956 Maralinga explosions were found to fit the two South Australian earthquakes very well. A third South Australian earthquake, discussed in the Appendix, supports this result. The times also give a good fit for earthquakes in some other regions of Australia. This good fit indicates that the continent of Australia does not have as wide regional variations in upper mantle and crustal structure as, for example, North America. There are indications that the P_n velocity decreases near the edge of the continent, and this may be connected with a shallow low velocity layer in some areas of the continent. The travel-time curve for *P* is linear at least to 16·5°, and probably to 18·5° in some regions. Its shape near 20° may vary considerably from region to region. From 25° to 32·5° the JB times appear to give a good fit.

VII. Acknowledgments

The authors wish to thank the Director of Riverview College Observatory; the Directors of the seismological stations of the Universities of Queensland and Tasmania; Professor J. C. Jaeger, Department of Geophysics, Australian National University; and the Director, Bureau of Mineral Resources (Geology and Geophysics), for their help in sending seismograms and copies of seismograms.

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Appendix

An earthquake occurred near Hawker in South Australia on January 25, 1965, which was well recorded throughout Australia. This earthquake confirmed that the times of BDS provide a good fit for South Australian earthquakes. It gave the following solutions (N = number of readings used):

(i) BDS times

$$31\cdot 91(\pm 0\cdot 02)^\circ\text{S.}, \ 138\cdot 42(\pm 0\cdot 02)^\circ\text{E.}; \ 10^{\text{h}}\ 22^{\text{m}}\ 53^{\text{s}}\cdot 7(\pm 0\cdot 2); \ h = 0 \text{ km};$$

$$N = 7; \ \text{std error of residual} = 0\cdot 53 \text{ sec};$$

(ii) JB times

$$31\cdot 81(\pm 0\cdot 08)^\circ\text{S.}, \ 138\cdot 51(\pm 0\cdot 09)^\circ\text{E.}; \ 20^{\text{h}}\ 22^{\text{m}}\ 50^{\text{s}}\cdot 2(\pm 0\cdot 8); \ h = 0 \text{ km};$$

$$N = 9; \ \text{std error of residual} = 2\cdot 03 \text{ sec}.$$

The Brisbane and Darwin readings were not used in solution (i). The Brisbane reading (eP) gave a residual of $+3\cdot 0$ sec; the Darwin reading at $\varDelta = 20\cdot 66^\circ$ gave a residual of $+0\cdot 5$ sec when fitted to the tentative slope of $10\cdot 54$ sec/deg beyond $18\cdot 6^\circ$. The Mundaring reading at $18\cdot 86^\circ$ fits the times of BDS to $0\cdot 1$ sec. Kalgoorlie at approximately the same azimuth and $\varDelta = 14\cdot 55^\circ$ gave a residual of $-0\cdot 4$ sec.

The epicentre (i) fits the readings at the three South Australian stations ($\varDelta < 3\cdot 1^\circ$) well. It may be interesting to mention that the times given by Doyle and Everingham (1964) for South Australia have been found to give a better fit for local earthquakes within the range $0^\circ < \varDelta < 3^\circ$ than the times of BDS. The latter times appear to fit better beyond 3°. Thus, there is evidence that in South Australia, as well as in Bass Strait and in south-eastern Australia, the P_n velocity is less than $8\cdot 2$ km/sec for small distances.