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A long-range, controlled source seismic profile in northern Australia

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Summary. A two-ship refraction profile was fired on the Australian continental shelf during the Banda Sea geophysical programme carried out by the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography and the Geological Survey of Indonesia. Some of the 55-kg shots fired during this profile were observed at an array of stations in northern Australia to a distance of 1150 km.

The first arrival *P* travel times at the land stations had apparent velocities of 6.52, 8.24 and 8.48 km/s. The observed travel times correspond closely with those for other stable continental platform or shield regions. The travel times in these regions are of the order of 6 s less than those given in the Jeffreys–Bullen tables at distances of 700 to 1150 km.

The observations are interpreted as implying an upper-mantle velocity of 8.4 km/s at a depth of about 75 km.

Introduction

During 1976 September and October, the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography, in cooperation with the Geological Survey of Indonesia, carried out a programme of geophysical studies at sea in the Banda Sea region (Bowin *et al.* 1977). A two-ship seismic refraction profile on the continental shelf to the north of Australia was included in the programme. The position of the profile is marked on Fig. 1. The two-ship refraction results have been reported by Jacobson *et al.* (1978, in preparation). The shots fired on this profile were recorded by four ocean bottom seismometers at the sites shown on Fig. 1. The analysis of the OBS observations is reported in a separate paper (Rynn & Reid 1978, in preparation). In addition, the shots were recorded at a sub-array of stations of the ANU Central Australia Project. The positions of the stations used during this project are shown on Fig. 1. This paper is concerned with the analysis of the *P* observations from the land stations.

Portable magnetic tape recorders, as described by Hales *et al.* (1975), were used for this sub-array. The analogue recordings were played back and digitized. All readings analysed in the present paper were made from filtered station or event record sections. The signal frequency was close to 3 Hz whereas much of the noise, especially that at the stations close to the

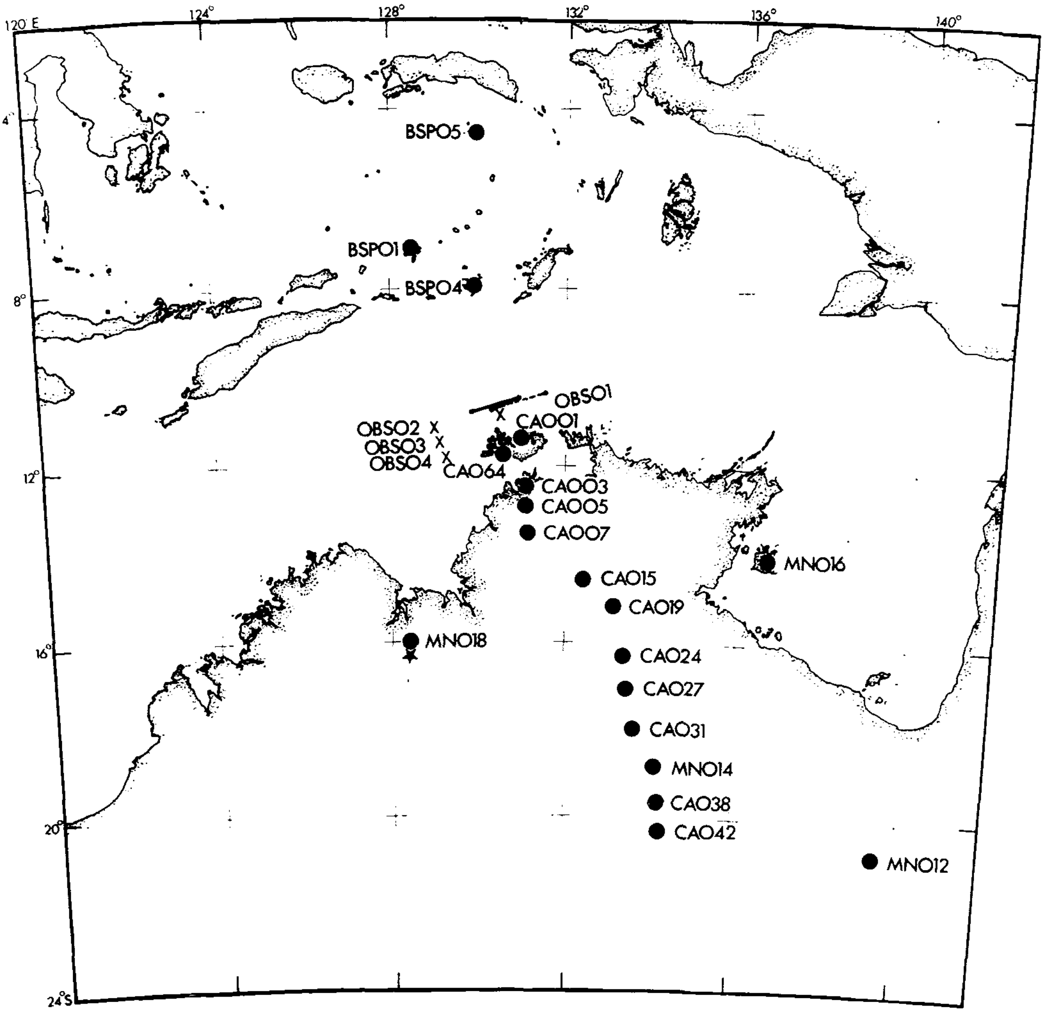

Figure 1. Map showing the profiles along which the shots were fired and the positions of the observing stations. The solid line shows the SIO shots of 31 kg upwards, the dashed line the WHOI shots of 27 kg upwards. OBS01, OBSO02, OBS03, OBS04 show the positions of the OBS units. BSP01, BSP04 and BSP05 *show the positions of the recorders on islands installed after the profile had been shot.*

coast, had a frequency of 0.5 to 1 Hz. A differentiation filter, $Y''_n = (Y_{n+2} - 2Y_n + Y_{n-2})/4$ was applied to the digitized records before the record sections were made. With the exception of those for station CA024 all the records reproduced in this paper are filtered.

The shots fired on the refraction profile ranged in size from 0.5 to 121 kg in water depths ranging from 30 to 90 m. A number of 55-kg shots were recorded at a distance of about 1150 km and some of the 14-kg shots at about 250 km.

Crustal refractions

The distance of the closest shots from the northernmost land station was 94 km. Thus the land station records did not provide information on the sedimentary section or the uppermost layer of the crust. However, the two-ship refraction and OBS observations provide this information for the shelf and the geological information available on land shows that

Table 1. Arafura sea models.

Rynn and Reid (1978)		Jacobson et al (1978) mean	
Velocity km/s	Depth km	Velocity km/s	Depth km
2.00	0.00	1.53	0.00
2.00	0.70	1.53	0.08
2.39	0.70	2.17	0.08
2.39	1.30	2.17	1.78
2.73	1.30	5.88	1.78
2.73	1.80	5.88	7.96
4.32	1.80	6.32	7.96
4.32	2.10	6.32	32.77
5.97	2.10	7.91	32.77
5.97	11.00		
6.52	11.00		
6.52	17.00		
7.00	17.00		
7.33	30.00		
7.33	34.00		
8.00	34.00		

there the correction for delays in the sediments would be insignificant. The layer thicknesses and velocities given by Jacobson *et al.* (1978, in preparation) and Rynn & Reid (1978, in preparation) are summarized in Table 1.

The travel-time equations found by least squares for the arrivals at stations CA001 and CA064 are:

CA001

$t = (2.71 \pm 0.22) + d/(6.65 \pm 0.09)$, 38 observations, $94 < d < 151$. (1)

CA064

$t = (2.33 \pm 0.18) + d/(6.53 \pm 0.05)$, 28 observations, $128 < d < 190$. (2)

CA001 + CA064

$t = (2.56 \pm 0.10) + d/(6.59 \pm 0.04)$, 66 observations, $94 < d < 190$. (3)

It is possible that some of the observations included in the least-squares analysis were not the first arrival phases. If these observations are excluded from the least-squares analysis the travel-time equations are:

CA001

$t = (2.38 \pm 0.16) + d/(6.56 \pm 0.06)$, 28 observations, $94 < d < 151$. (4)

CA064

$t = (2.17 \pm 0.12) + d/(6.49 \pm 0.03)$, 26 observations, $128 < d < 190$. (5)

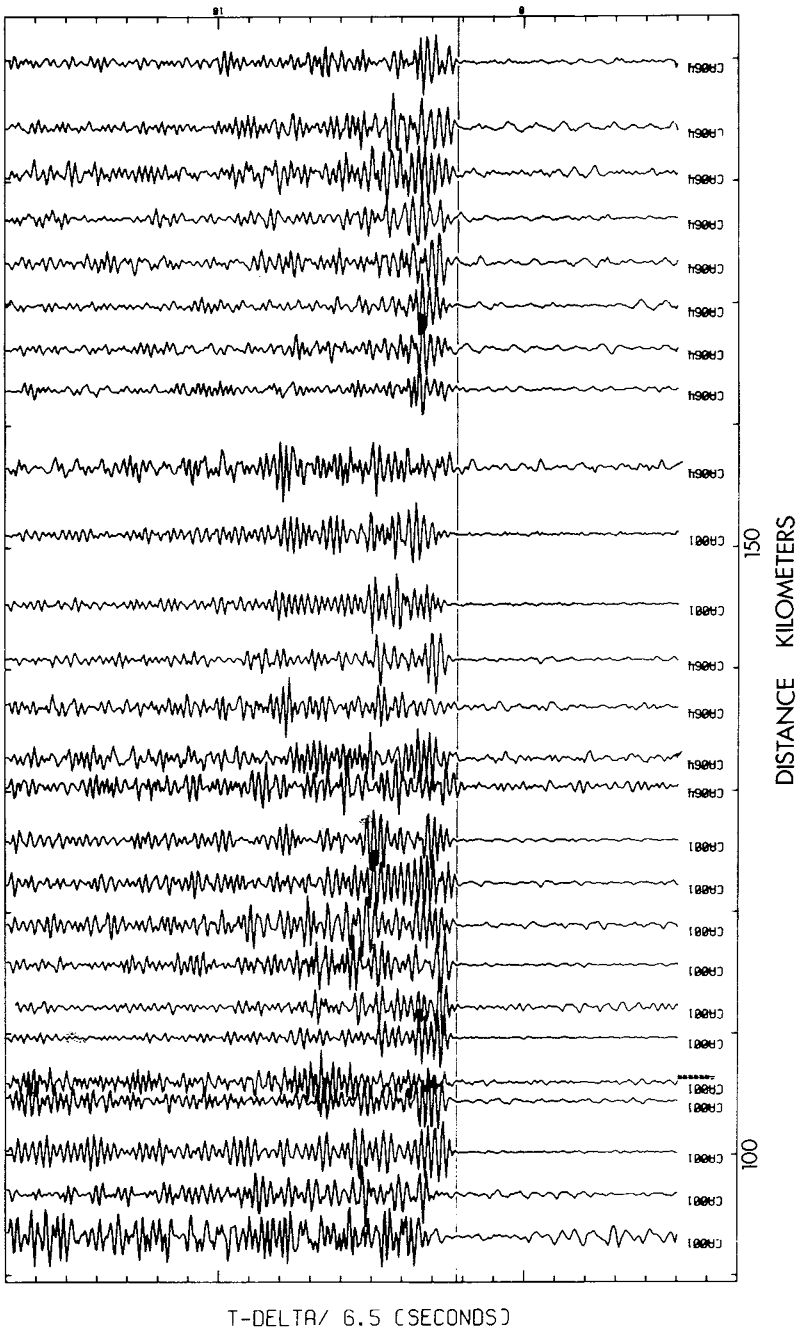

Figure 2. Record section of shots recorded at stations CA001 and CA064. The equation of the line marked on the section is $t = 2.28 + d/6.52$.

CA001 + CA064

$$t = (2.28 \pm 0.07) + d/(6.52 \pm 0.02), \text{ 54 observations}, 94 < d < 190. \quad (6)$$

This analysis confirms the finding from the two-ship refraction and OBS observations that a layer with a velocity significantly greater than 6.0 km/s occurs at a relatively shallow depth.

The apparent velocities determined from the individual analyses of stations CA001 and CA064 as given in equations (4) and (5), namely 6.56 and 6.49 km/s, refer to conditions at the shot end of the paths. Apparent velocities were determined from the differences in time of arrival at stations CA001 and CA064. These velocities, which refer to the station end of the path, were 6.59 ± 0.04 km/s (27 observations) and, excluding the late arrivals, 6.53 ± 0.04 km/s (20 observations). Thus it is improbable that the estimates of the layer velocity were much affected by the dip of the upper boundary of the layer. A record section showing some of the records at stations CA001 and CA064 is given as Fig. 2. The records reproduced were selected for uniform coverage of the distance range and are reasonably representative of the quality of the data.

Mantle refractions

The Woods Hole shots of 27 and 55 kg were fired between 1106 and 0252 local time. The Scripps shots of 31 kg and more were fired between 0755 and 1332 local time. The noise level by day when the Scripps shots were fired was higher than at night. Cultural activity, heavy road traffic and wind contributed to the increased noise level. In consequence, the series of observations was not as complete at all stations beyond 200 km as it was at CA001 and CA064. Relatively few of the day-time shots were recorded well enough for accurate determination of the first arrival times at stations CA003, CA019, CA024, CA027, CA031, MN014, CA038 and CA042.

Mean reduced times of all arrivals at the stations beyond 200 km are given in Table 2 and plotted in Fig. 3. The reduction velocity was 8.25 km/s. The travel-time equations found by least squares are:

from 200 to 600 km

$$t = (8.61 \pm 0.29) + d/(8.23 \pm 0.05) \quad (7)$$

and from 600 to 1150 km

$$t = (10.70 \pm 0.32) + d/(8.48 \pm 0.02). \quad (8)$$

These lines are plotted on Fig. 3. It is clear from the figure and from the residuals given in Table 2 that arrivals at CA005 are significantly late and at CA007 significantly early with respect to the times found from equation (7). It is possible that these deviations arose because of the inclusion of arrivals from the Scripps shots at stations CA005 and CA007. Therefore the mean reduced travel times for stations CA003, CA005, CA007, CA015 and CA019 were determined using only those shots for which first arrivals could be read at all stations. These are given in Table 2. The travel-times equation found from this set of mean reduced travel times is

$$t = (8.60 \pm 0.46) + d/(8.24 \pm 0.08). \quad (9)$$

The apparent velocity and intercept do not differ significantly from those found using all the readings. However, the solution in equation (9) is preferred. The mean of the reduced travel times at CA005 is 0.29 s late and at CA007 0.34 s early, with respect to equation (9). This deviation is probably due to variations in crustal and/or mantle structure in the neighbourhood of the stations.

Table 2. Mean reduced travel times.

STATION	ALL READINGS				READINGS FOR ONLY THOSE SHOTS OBSERVED AT ALL STATIONS CA003-CA019			
	Mean Distance (km)	Mean Reduced Travel Time (sec)	Standard Error	Residuals from Equations (6,7,8)[1]	Mean Distance (km)	Mean Reduced Travel Time (sec)	Standard Error	Residuals from Equation (9)
CA001	111.19	6.02	0.07	+0.16				
CA064	166.78	7.46	0.13	-0.18				
CA003	220.08	8.62	0.03	-0.06	222.88	8.66	0.03	+0.03
CA005	266.26	8.88	0.04	+0.20	269.56	8.93	0.08	+0.29
CA007	335.87	8.47	0.10	-0.24	339.56	8.31	0.08	-0.34
CA015	478.07	8.72	0.04	-0.03	474.61	8.69	0.03	+0.02
CA019	566.84	8.79	0.04	+0.01	564.69	8.82	0.04	+0.14
CA024	695.41	8.29	0.07	-0.12				
CA027	773.57	8.20	0.07	+0.04				
CA031	879.02	7.98	0.04	+0.17				
MN014	990.47	7.49	0.05	+0.05				
CA038	1070.47	7.16	0.04	-0.04				
CA042	1149.27	6.85	0.04	-0.07				

(1) For CA001, CA064 equation (6); for CA003–CA019 equation (7); for CA024–CA042 equation (8).

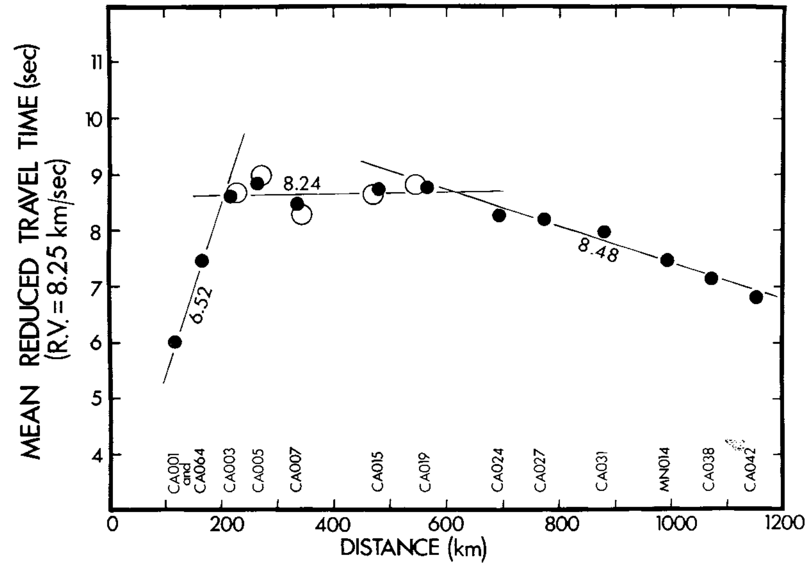

Figure 3. Mean reduced travel times at the stations beyond 200 km. The open circles show the means for all readings, the full circles the means for those events for which all stations of the group CA003, CA005, CA007, CA015 and CA019 were read. The least-squares lines from equations (6), (8) and (9) are marked on the figure.

Interpretation

Models of the structure at the source end of the path have been derived by Rynn & Reid (1978, in preparation) and Jacobson *et al.* (1978, in preparation). A simplification of the Rynn & Reid model was used in setting up the flat-earth model AF for the shelf and northern Australia given in Table 3. This model was then modified using a spherical earth ray-tracing programme. The spherical-earth model is also given in Table 3 as model AS.

The structure described above represents the simplest solution based on the observations at the land stations for the phases with apparent velocities of 6.5 km/s and more. However, it should be noted that the sea observations of Rynn & Reid (1978, in preparation) and Jacobson *et al.* (1978, in preparation) indicate a crustal thickness of about 33 km on the shelf and a velocity of about 8.0 km/s below the Mohorovičić discontinuity. It should be noted also that the apparent velocity found from the shots observed at stations CA003 and CA005 is 7.88 km/s. There are two possibilities. It could be assumed that a layer with apparent velocity close to 8 km/s intervenes between the crust and the layer with apparent velocity 8.24 km/s, and that some of the first arrivals at CA005 are missed because they are very weak. Alternatively, it is possible that the *Pn* velocity is 8.0 km/s and that the velocity decreases with depth, i.e. that there is a low-velocity layer above the layer with apparent velocity of 8.25 km/s.

The second set of models, BF and BS, given in Table 3 corresponds to the first of these possibilities. It has been assumed, following Rynn & Reid, that the travel-time equation for *Pn* for the shelf observations is

$$t = 7.25 + d/8.0.$$

It is assumed further that the 8.0 km/s arrival at station CA003 is not earlier than that giv in Table 2. On this assumption the travel time for *Pn* for the land stations would be:

$$t = 7.82 + d/8.0.$$

Table 3. Models.

MODEL								MODEL B							
FLAT EARTH (AF)				SPHERICAL EARTH (AS)				FLAT EARTH (BF)				SPHERICAL EARTH (BS)			
SHELF		LAND		SHELF		LAND		SHELF		LAND		SHELF		LAND	
Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km	Vel. km/s	Depth km
2.39	1.76			2.39	1.76			2.39	1.76			2.39	1.76		
2.73	2.05			2.73	2.05			2.73	2.05			2.73	2.05		
5.97	11.48	5.97	12.85	5.97	11.48	5.97	12.85	5.97	11.48	5.97	12.85	5.97	11.48	5.97	12.85
6.52	40.01	6.52	40.01	6.51	40.70	6.51	40.70	6.52	31.41	6.52	43.93	6.51	31.41	6.51	43.93
8.24	71.06	8.24	71.06	8.19	76.00	8.19	76.00	8.00	45.00	8.00	45.00	7.95	45.00	7.95	45.00
8.48	↓	8.48	↓	8.405	↓	8.405	↓	8.24	73.48	8.24	73.48	8.18	76.00	8.18	76.00
								8.48	↓	8.48	↓	8.38	↓	8.38	↓

Notes: All layers constant velocity. All depths to base of layer.

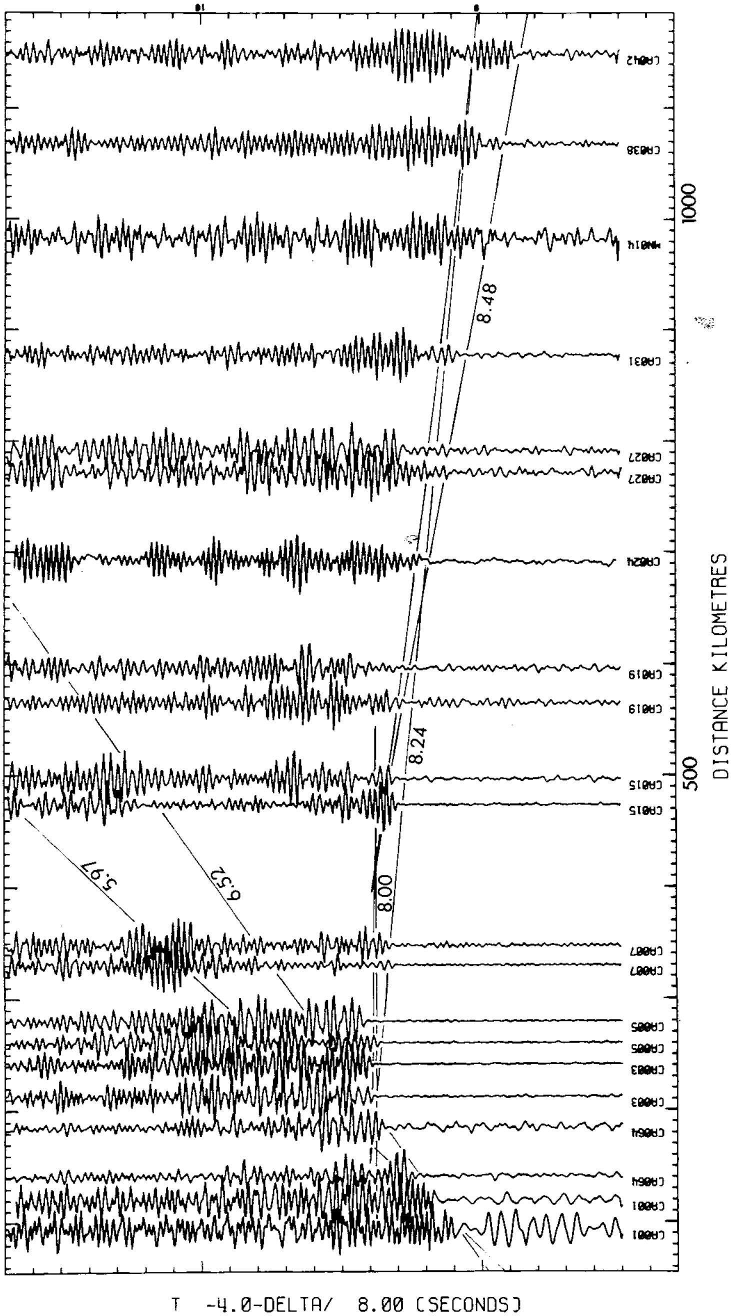

Figure 4. Record section reduced on 8.0 km/s. The calculated times for the spherical earth model BS are also shown.

Finally, it has been assumed that the layers corresponding to the apparent velocities of 8.24 and 8.48 km/s are at the same depths below the shelf and below the land stations.

Travel times calculated from model BS are compared with the observations in the composite record section of Fig. 4. There are, of course, some model parameters which are not well controlled. In the first place there is no direct evidence for the 8 km/s layer under the land stations. Secondly, replacement of the sharp discontinuities of the models by rapid changes of velocity over limited depth intervals would not conflict with the travel-time observations. Amplitudes of the refracted branch, calculated for models with constant velocity regions separated by step discontinuities, are smaller, relative to the calculated amplitudes of the reflected branch, than is observed. Thus, the kind of leading and trailing edges to the discontinuities which would be expected in the case of phase transformations are probably necessary.

The travel times of this paper are similar to those found in the Early Rise experiment and the models presented here are similar to those derived from Early Rise data by Green & Hales (1968) for the central United States, and Mereu & Hunter (1969) for Ontario. It is probable that the upper-mantle velocity structure beneath most stable continental platform or shield regions conforms to the general pattern of these models.

This similarity places constraints upon the possible contribution of the temperature distribution to the observed high apparent velocities. If, as is not unlikely, isothermal surfaces dip downwards towards the middle of the continent, then surfaces of equal velocity will dip downwards towards the continental margin. The data available are not adequate for determination of a pseudo-dip of this kind. It is clear, however, that the pseudo-dip effect is small, for the Early Rise shots were fired in the middle of the continent, the shots discussed in this paper at the margin, and yet the travel times and apparent velocities are very similar. Alternatively the pseudo-dip is only significant close to the continental margin.

Comparison with the Jeffreys–Bullen travel times

It was pointed out by Hales, Muirhead & Rynn 1978, that the travel times in continental shield or platform areas differed significantly from the Jeffreys–Bullen times. The deviations of the travel times of this paper from the Jeffreys–Bullen travel times are compared with those from the Ord River explosion (Denham *et al.* 1972), the Early Rise, Texas and Carolina profiles (Iyer *et al.* 1969) and a profile in France (Hirn *et al.* 1973) in Fig. 5. Deviations of the calculated times of model 8 (Hales *et al.* 1978) and model BS from the Jeffreys–Bullen travel times are also plotted in Fig. 5.

The travel times of this paper are consistent with those for the somewhat different path for the Ord River explosion data. Both sets are grossly similar to those found in the United States and Europe. The travel times found by Choudhury & Rothé (1965), for paths in

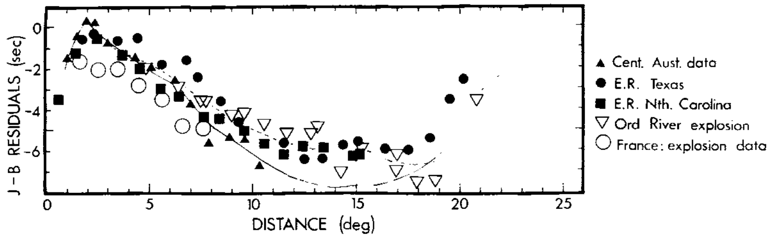

Figure 5. Deviations of observated travel times from the Jeffreys–Bullen times. The deviations of the calculated times of Model 8 (Hales *et al.* 1978) (dashed) and Model BS (solid) from the Jeffreys–Bullen times are also shown.

North Africa and Europe are also similar. Thus there is no doubt that travel times in continental platform or shield areas differ significantly from the Jeffreys–Bullen times. The deviations from the Jeffreys–Bullen times between 5 and 20° far exceed the differences between the times for different regions and also exceed the scatter in the observations discussed earlier in this paper.

It should also be emphasized that the modelling uncertainties discussed in the section on Interpretation correspond to variations in the travel times of less than 1 s, whereas the deviations of the travel times from the Jeffreys–Bullen times are of the order of 6 s. Thus the modelling uncertainties do not affect the conclusion that travel times in all continental shield or platform regions where adequate data exist are systematically and significantly early with respect to the Jeffreys–Bullen times. This requires that upper-mantle velocities at depths of about 70 to 120 km should be greater than in the Jeffreys model. These conclusions do not apply to tectonically active areas such as the western United States in which there is evidence for a low-velocity layer at a depth of less than 100 km.

It is improbable that the deviations from the Jeffreys–Bullen times are due to anisotropy, for the Australian observations are in the direction of spreading, whereas the Early Rise Texas, Arkansas and Ontario profiles were more or less normal to the spreading direction.

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