Crust and upper mantle shear velocities from controlled sources

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Summary. A two ship refraction profile was undertaken on the Australian continental shelf during the Banda Sea geophysical program, carried out by the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography and the Geological Survey of Indonesia. S waves originating close to the sea bottom were observed to distances of up to 1150 km at an array of stations in northern Australia.

These observations are interpreted as implying S mantle velocities of 4.60 km s⁻¹ from a depth of 45 km to a depth of 76 km and 4.72 km s⁻¹ below a depth of 76 km.

Ratios of the P and S travel times (V_P/V_S) have been determined to be 1.74 in the crust rising to a value of greater than 1.79 below a velocity discontinuity at a depth of 200 km. It is inferred that this high value arises because the effect of temperature is greater for S than for P.

Using the data from this and other studies in the shield region of Northern Australia it has been found that the S travel times are significantly less than predicted by the Jeffreys–Bullen tables.

Introduction

Hales & Rynn (1978) (hereafter referred to as Paper I) reported observations of P waves from shots fired on the continental shelf to the north of Australia at land stations in northern Australia. The shots were fired during the cooperative Indonesian Geological Survey—Woods Hole Oceanographic Institution—Scripps Institution of Oceanography geophysical program in the Banda Sea region. The same shots were also recorded at four ocean bottom seismometers and these OBS data have been analysed by Rynn & Reid (1980). The locations of the shot profiles and the positions of the stations, as given by Hales & Rynn (1978) are reproduced in Fig. 1.

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The present paper discusses the travel times of the $S$ waves from the shots. A major reason for this study was to determine the uppermost upper mantle shear velocities as a preliminary step to the modelling of the upper mantle $S$ velocity distribution based on the travel times of $S$ phases from Banda Sea earthquakes.

The precise onset times of $S$ phases are more difficult to determine than those of the $P$ phases because the $S$ phases arrive while there is still significant energy in the $P$ wave coda. Reinforcement and interference between the $P$ and $S$ energy undoubtedly contribute to the scatter in the $S$ arrivals. The general character of the records is illustrated in the record section of Fig. 2. Most of the records in this section are from a single shot, but records for which there was local noise at the time of the shots have been replaced by records of other shots at the same station. The records reproduced are from the vertical seismometers. The horizontal seismometers were oriented 15° west of north and 15° north of east so as to be approximately radial and transverse to the profile of the land stations. The $P$ coda was generally of larger amplitude on the radial than on the vertical and transverse seismometers. Nevertheless, all seismometer components generally show increases in amplitude and changes in character at the same time or within two or three seconds of each other. Efforts were made to identify the $S$ arrival onsets by forming the product $Z \times R$ which should be of opposite sign for $P$ and $S$ phases. This procedure was only partially successful in one or two cases, probably because of the significant contribution of the $P$ coda to the amplitude of the $S$ phases, particularly on the radial traces.

Crustal refractions

Crustal refraction phases were recorded by the two Melville Island stations CA001 and CA064. A record section containing a selection of these traces is shown in Fig. 3. For some events the first arrival is too small to be seen. In these cases it is comparatively easy to identify a relatively strong later arrival. Analysis of these crustal phases was accomplished.
Figure 2. Record section showing the general character of the records of a 55 kg shot.

Figure 3. Composite record section of events recorded at stations CA001 and CA064. The records at 94, 128 and 135 km were from 27 kg shots, the others from 55 kg shots. The lines marked on the section have equation $T = 1.50 + d/3.58$ and $T = 3.78 + d/3.70$. 
by measuring the arrival time of each of the two onsets for all explosions and then fitting them with straight line segments using least squares analysis techniques. The travel time equations determined for these lines, which have been marked on Fig. 3, are

\[ T = 1.50 + d/3.58, \]  
\[ T = 3.70 + d/3.70, \]

(1)

(2)

\( T \) is in s and \( d \) in km.

It is presumed that these phases are the \( S \) equivalents of the \( P \) phases with velocities 5.97 and 6.52 km s\(^{-1}\) reported in Paper I.

**Mantle refractions**

For stations CA003 to CA042 the records were read from unfiltered replays of all three components. For each station the mean reduced travel time was obtained as a function of the mean distance and these values are given in Table 1. In many of the records the first arrivals are weak but are followed by strong second arrivals. Times of some of these second arrivals are also given in Table 1 and are plotted in Fig. 4. The equations of lines fitted by least squares to the first arrivals are:

From 200 to 600 km

\[ T = (15.33 \pm 0.64) + d/(4.68 \pm 0.04), \]  

(3)

and from 600 to 1150 km

\[ T = (16.66 \pm 1.03) + d/(4.73 \pm 0.02). \]  

(4)

**Figure 4.** Mean reduced travel times for the \( S \) phases. The solid circles show first arrival phases, the open circles later arrivals. The calculated times for the composite model given in Table 2 are also shown.
Table 1. Mean reduced travel times.

| Station | Mean distance (km) | Mean reduced travel time (s) | Standard error (s) | Number of observations | Mean distance (km) | Mean reduced travel time (s) | Standard error (s) | Number of observations |
|---------|--------------------|----------------------------|-------------------|------------------------|--------------------|----------------------------|-------------------|------------------------|
| CA003   | 218.69             | 14.77                      | 0.09              | 31                     | –                  | –                          | –                 | –                      |
| CA005   | 267.84             | 15.46                      | 0.11              | 23                     | 265.06             | 0.88                       | 0.20              | 14                     |
| CA007   | 335.80             | 14.84                      | 0.13              | 26                     | 332.65             | 0.54                       | 0.22              | 24                     |
| CA015   | 475.75             | 14.40                      | 0.21              | 16                     | 477.07             | 1.25                       | 0.30              | 14                     |
| CA019   | 565.89             | 14.80                      | 0.20              | 15                     | –                  | –                          | –                 | –                      |
| CA024   | 693.33             | 14.39                      | 0.23              | 11                     | –                  | –                          | –                 | –                      |
| CA027   | 773.70             | 13.48                      | 0.17              | 10                     | 772.59             | 15.62                      | 0.18              | 10                     |
| CA031   | 881.32             | 12.90                      | 0.20              | 1                      | 880.94             | 15.15                      | 0.13              | 9                      |
| CA038   | 1068.35            | 12.64                      | 0.20              | 10                     | 1068.43            | 15.29                      | 0.15              | 10                     |
| CA042   | 1149.36            | 12.39                      | 0.40              | 10                     | –                  | –                          | –                 | –                      |
An alternative interpretation is that all the first arrival S phases from 200 to 1150 km could be combined into a single straight line with intercept 15.99 s and apparent velocity 4.72 km s\(^{-1}\). However, the corresponding P phases of Paper I are distinct, which suggests that the S phases should be treated similarly. Also the second arrivals beyond 600 km lie close to the continuation of the line of the first arrivals between 200 and 600 km. This is consistent with the hypothesis that the first arrivals from 200 to 1150 km should be regarded as lying on two lines rather than one. If the second arrivals beyond 600 km are combined with the first arrivals from 200 to 600 km in a single least-squares solution the intercept is 14.74 s and the apparent velocity 4.64 km s\(^{-1}\).

**Interpretation**

Explosions in water do not generate S energy, but S energy originates as a result of conversion from P energy, probably at the largest velocity jumps; that is, at the sea bottom or, alternatively, at the base of the sediments about 2 km below the sea bottom (Rynn & Reid 1980). In the initial inversions it was assumed that the energy propagated as P waves to the base of the sediments where the conversion took place. Using the layer thicknesses of Paper I and the S velocities of equations (1)–(4) the calculated intercepts were consistently less than those observed. The most probable explanation for this discrepancy is that the conversion from P to S occurred close to the sea bottom. Less likely explanations are that S has been read systematically late throughout or that the intercepts given by equations (1)–(4) are too great and the apparent velocities slightly too high.

Assuming that the conversion to S energy occurred close to the sea bottom and that the S velocities in the sediments are 1/√3 of the corresponding P velocities, a spherical model of velocities in the crust and upper mantle was derived from the mean reduced travel times given in Table 1. This model is tabulated in Table 2 and its calculated travel times are shown superimposed on the time/distance plot in Fig. 4 and the composite record sections in Fig. 5.

Fig. 5 shows some arrivals which are early with respect to the calculated times at the greater distances. This may be explained by reference to the OBS records between 120 and

| Table 2. Models. |
|------------------|------------------|
| **Shelf**        | **Land**         |
| Velocity (km s\(^{-1}\)) | Depth (km) | Velocity (km s\(^{-1}\)) | Depth (km) |
| 1.38             | 0.00            | 3.58             | 0.00            |
| 1.38             | 1.76            | 3.58             | 12.85           |
| 1.58             | 1.76            | 3.70             | 12.85           |
| 1.58             | 2.05            | 3.70             | 43.93           |
| 3.58             | 2.05            | 4.48             | 43.93           |
| 3.58             | 11.48           |                 |                 |
| 3.70             | 11.48           |                 |                 |
| 3.70             | 31.41           |                 |                 |
| 4.48             | 31.41           |                 |                 |
| 4.48             | 45.00           | 4.48             | 45.00           |
| 4.60             | 45.00           | 4.60             | 45.00           |
| 4.60             | 76.00           | 4.60             | 76.00           |
| 4.72             | 76.00           | 4.72             | 76.00           |
| 4.72             | 200.00          | 4.72             | 200.00          |
140 km (Fig. 6) which have a clear arrival with a reduced travel time of about 14 s. The corresponding times calculated from the shelf model in Table 2 for the reflection from the 31.41 km discontinuity are 13.34 s at 120 km and 13.98 s at 140 km. The fit to the record section suggests that both the $S_n$ velocity and the depth to this discontinuity under the shelf should be slightly greater than in the model. There is also some evidence in the vertical record section of a phase with an apparent velocity of 4.55 km s$^{-1}$ (shown by the dashed line in Fig. 5a). This is assumed to be a phase refracted from above the discontinuity at 45 km.

The ratio $T_s/T_p$

The ratio $T_s/T_p$ is a useful parameter in determining the time of origin in preliminary examination of seismic records. Similarly, the separation velocity for $P$ and $S$ phases is a convenient parameter for estimation of the distance and initial location of local earthquakes.

Ratios of $T_s/T_p$ are given in Table 3. In calculating these ratios some adjustments have been made to allow for the differences between the mean distances of the $P$ observations of Paper I and the $S$ observations given in Table 1.

In so far as the crustal phases are concerned: Fig. 2 shows clear second arrival $P_l$ (or $P_g$) phases (or the corresponding reflected phases) out to about 500 km. Ratios have been calculated for those events for which both $P_1$ and $S_1$ were readable at station CA015 and was found to be $1.741 \pm 0.015$.

In Fig. 7 these ratios and the corresponding separation velocities are compared with those for a Banda Sea earthquake at a depth of 167 km (PDE location, depth of focus and time of origin). The ratios for the Banda Sea earthquake are less than those for the explosions. The bars from the solid squares to the corresponding open squares show the effect of changing the origin time of the Banda Sea earthquake so that it is one second later than the time given by the PDE cards. This is not at all improbable. When the observation data set is dominated by teleseismic data (distances greater than 30°), there is a trade-off between depth of focus and time of origin such that, on the average, if the depth of focus is increased by about 10 km, the time of the origin is later by one second. This trade-off occurs frequently for Banda Sea events and in one case, discussed by Hales, Muirhead & Rynn (1980) (hereafter referred to as Paper II) the time of origin is later by as much as 7 s.

In fact, for the earthquake for which the PDE depth was 167 km (event 256 of Paper II) the time of origin given in the recently published ISC Bulletin for 1975 October, 0.9 s later and the depth of focus 9 km deeper than the corresponding figures from the PDE lists. This is within the limits of $\pm 12$ km suggested in Paper II. The open squares therefore correspond very nearly with those which would have been obtained using the ISC times of origin.

Similarly the bars on the explosion data of Fig. 7 show the effect of increasing the $S$ onset times by 1 s. Clearly if the $S$ readings for the mantle phases were 1 s late there would be no significant inconsistency. This is more probable than that the $S$ phases were read early.

It has been suggested that there is lateral inhomogeneity of the $P_n$ travel times (Hess 1964; Raitt 1969). If there is, ultrasonic velocity determinations on single crystals imply that the velocities in directions inclined to the horizontal will also vary with azimuth and with the inclination of the path to the vertical. Table 4, compiled from Kumuzawa & Anderson (1969) and Kumuzawa (1969) shows the ratios $V_p/V_s$ for different directions of propagation in single crystals of olivine, forsterite and pyroxene. It is clear that if there is horizontal orientation of olivine or pyroxene crystals in the mantle, the ratio $V_p/V_s$ for paths in the vertical direction or inclined to the vertical direction could be low. The evidence in Fig. 7 is not sufficiently strong for this possibility to be considered here, but further study
is clearly necessary. For the present the increase in $T_S/T_P$ with increasing distance is interpreted as implying an increase in $V_p/V_s$ with depth.

In the case of another event studied in Paper II (event 256 at a depth of 156 km), the phases from 1000 to 1700 km bottom below a discontinuity at a depth of about 200 km. Using the ISC time of origin, the ratios of $T_S/T_P$ for these phases range from 1.741 to 1.792. Because significant portions of the paths lie in the upper mantle and, as the portion below...
200 km increases as the distance increases, it follows that the ratio of $V_p/V_s$ must exceed 1.79 below 200 km. It is inferred that this high value of $V_p/V_s$ arises because the effect of temperature is greater for the $S$ velocity than for $P$. Studies in progress for other regions indicate that this effect is general.

Figure 6. OBS records of three shots. The line shows the calculated times for the reflection from the discontinuity at 31.40 km.
Table 3. $T_s/T_p$ as a function of distance.

| Distance (km) | $T_s/T_p$ | Distance (km) | $T_p/T_s$ | ISC  |
|---------------|------------|---------------|------------|------|
| 111.19        | 1.684      | 1.735         | 1.744      |
| 166.78        | 1.726      | 1.735         | 1.730      |
| 220.08        | 1.759      | 1.735         | 1.741      |
| 266.26        | 1.767      | 1.746         | 1.751      |
| 335.87        | 1.770      | 1.763         | 1.767      |
| 478.07        | 1.758      | 1.769         | 1.773      |
| 566.84        | 1.764      | 1.783         | 1.779      |
| 695.41        | 1.771      | 1.788         | 1.792      |
| 773.57        | 1.764      | 1.793         | 1.796      |
| 879.02        | 1.763      | 1.786         | 1.789      |
| 1070.47       | 1.774      |               |            |
| 1149.27       | 1.776      |               |            |

Banda Sea event 256

| Distance (km) | $T_s/T_p$ | Distance (km) | $T_p/T_s$ |
|---------------|------------|---------------|-----------|
| 513.7         | 1.735      | 1.744         |
| 680.6         | 1.723      | 1.730         |
| 811.9         | 1.735      | 1.741         |
| 993.5         | 1.746      | 1.751         |
| 1303.4        | 1.763      | 1.767         |
| 1408.9        | 1.769      | 1.773         |
| 1493.5        | 1.783      | 1.779         |
| 1572.1        | 1.793      | 1.796         |
| 1661.0        | 1.771      | 1.789         |
| 1893.6        | 1.786      | 1.789         |

Figure 7. Ratios $T_s/T_p$ for the explosion data and for a 156 km depth Banda Sea earthquake. The bars from the solid symbols to the corresponding open ones show the effect of increasing the $S$ travel times by 1 s in the case of the explosion data and making the time of origin 1 s later for the Banda Sea earthquake. Two readings are given for the Banda Sea earthquake at a distance of 511 km. It is uncertain which is the true $S$ arrival.

Table 4. $V_p/V_s$ ratios for single crystals.

| Modes          | Direction of plane wave propagation | Olivine $V_p/V_s$ | Orthopyroxene $V_p/V_s$ | Forsterite $V_p/V_s$ |
|----------------|-------------------------------------|-------------------|-------------------------|----------------------|
| Pure modes     | a                                   | 2.029             | 2.023                    | 1.737                | 1.713                | 2.011                | 2.015                |
|                | b                                   | 1.749             | 1.581                    | 1.411                | 1.450                | 1.741                | 1.571                |
|                | c                                   | 1.908             | 1.729                    | 1.574                | 1.639                | 1.891                | 1.702                |
| Coupled modes  | 45 to b and c                       | 1.636             | 1.745                    | 1.621                | 1.716                | 1.620                | 1.719                |
|                | 45 to c and a                       | 1.893             | 1.596                    | 1.630                | 1.636                | 1.873                | 1.595                |
|                | 45 to a and b                       | 1.864             | 1.664                    | 1.633                | 1.871                | 1.855                | 1.648                |

There are two possible ratios for any direction of propagation depending on the direction of particle motion in the $S$ phase. Data from Kumazawa & Anderson (1969) and Kumazawa (1969).
Crust and upper mantle shear velocities

This paper
Ord River (Denham et al. 1972)
Land Model, Table 2

Figure 8. Deviations of the observed $S$ times for the explosion data of this paper and the Ord River explosion data of Denham et al. (1972) from the Jeffreys–Bullen times. The curve shows the deviations of the calculated travel times of the land model of Table 2 from the Jeffreys–Bullen times.

Discussion

Shear waves were observed from the Ord River explosion by Denham et al. (1972). The shear velocity estimated for the arrivals between 400 and 900 km was $4.75 \pm 0.07$ km s$^{-1}$. Molnar & Oliver (1969) estimate the $S_n$ velocity as $4.66 \pm 0.02$ km s$^{-1}$ for North American and South American observations of earthquakes in the West Indies.

Fig. 8 shows a plot of deviations of the mean travel times from those of the Jeffreys–Bullen tables, together with the $S$ observations of Denham et al. (1972). The deviations of the $S$ travel times from the Jeffreys–Bullen travel times follow a similar pattern to those of the $P$ phases described in Papers I and II. They are, however, much larger. The deviations of the $S$ travel times calculated from the land model for this paper (Table 2) are also plotted in Fig. 8. The deviations from the Jeffreys–Bullen times are many times larger than the scatter in the observations or the uncertainties in the interpretation. In the case of the $S$ phases, the data of Fig. 8 apply only to the Australian platform or shield. However, the fact that the deviations of the $P$ observations of Papers I and II are similar to those of other continental shield regions for which data are available, suggests that $S$ will behave in the same way in these shield regions.

An $S$ model phase at an arc distance of 18 deg bottoms at a depth of about 150 km. Therefore the absence of any abrupt increase in the residuals of Fig. 8 implies that there is no significant low velocity zone above this depth in northern Australia. Furthermore, the direct arrivals for event 256 at a depth of 176 km (ISC) imply an average mantle velocity of 4.7 km s$^{-1}$ above 176 km. Given this velocity of 4.7 km s$^{-1}$ there is little possibility of a marked low velocity zone above 200 km. However, this does not preclude temperature leading to a small decrease in $V$ though possibly not in $V/r$.

In the light of the $P$ velocity distribution given in Paper II it appears that if there is a zone of decreasing $V$ or $V/r$ above 200 km the decrease is very limited. It may be therefore, that the lithosphere is at least 240 km thick below continental shield regions. This conclusion
raises a question of the mechanisms of movement of plates having both continental and oceanic segments.

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