# THE NEW SOUTH WALES EARTHQUAKE OF MAY 22, 1961

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[*Manuscript received January* 8, 1962]

*Summary*

The earthquake of May 21, 1961 is investigated. The finally revised epicentre is 34° 36′ S. (geographic), 150° 24′ E., and the adopted origin time $21^{h}\ 40^{m}\ 01^{s}$ (G.M.T.). The five near stations with $\Delta \leqslant 1°\cdot 5$ give a $P_1$ velocity of $6\cdot 06 \pm 0\cdot 17$ km/s, and the eight stations with $2° \leqslant \Delta \leqslant 9°$ give a $P_n$ velocity of $8\cdot 00 \pm 0\cdot 08$ km/s. The distribution of the residuals contains no evidence of appreciable focal depth. Using the $P_1$ and $P_n$ phases, a crustal thickness (on the assumption of a uniform crust) of $40 \pm 5$ km is formally indicated.

Three Rayleigh wave trains, to Port Moresby, Mundaring, and Brisbane, are analysed. The results from these records are not extensive enough to show any regional differences over the Australian continent.

## I. Introduction

On 1961 May $22^{d}\ 7^{h}\ 40^{m}$ local time, New South Wales was visited by an earthquake which, according to press reports, was felt over a region of some 50,000 square miles, extending from the Snowy Mountains to Newcastle and inland to Dubbo and Narrandera (see Fig. 1). The earthquake caused significant damage to buildings in the Moss Vale-Robertson-Bowral area, blockage of the Macquarie Pass road through rockfalls, and some power failures; it was noted for the sharpness with which it was felt in Sydney, where minor damage was done and considerable alarm caused.

The amplitude of the seismogram trace at Riverview (distant about 100 km from the epicentre) led to a magnitude estimate of $5\frac{1}{2}$ (Richter scale, 1935). According to Burke-Gaffney (1951), only three other N.S.W. earthquakes (in 1930, 1934, and 1938) had reached a magnitude of this order prior to 1951. Their epicentres are indicated as A, B, C respectively in Figure 1.

The purpose of the present paper is to investigate the epicentre, origin time, and focal depth of the 1961 shock, to extract possible information bearing on travel times, and to examine surface-wave dispersion.

## II. First Estimation of Epicentre and Origin Time

Endeavours were made to receive data and records from all stations of the world which had recorded the shock. Seismograms from all Australian stations and from a number of overseas stations were personally examined.

Table 1 shows the arrival times after $t_0$, where

$$t_0 = 1961 \text{ May } 21^{d}\ 21^{h}\ 40^{m} \text{ (G.M.T.)}, \tag{1}$$

of all available first arrivals, with station identifications.

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A provisional origin time of $t_0$ and an epicentre ($E_0$) of 34° 18′ S. (geocentric), 150° 31′ E., based on macroseismic data, were assumed. For $\Delta \geqslant 2°$, the corresponding geocentric angular distances ($\Delta$) and azimuths ($\psi$) are shown in Table 2, together with the residuals, $\mu$ say, of the first-arrival times against the Jeffreys-Bullen (1948) *P* and *PKP* travel times (*T*) for a surface focus, corrected for ellipticity (Bullen 1937) where necessary.

The residuals suggest an epicentral displacement to the south-west and a positive increase to $t_0$. (The origin-time correction is indicated from a comparison between the *P* and *PKP* residuals, the latter being less affected than the former by small epicentral changes.)

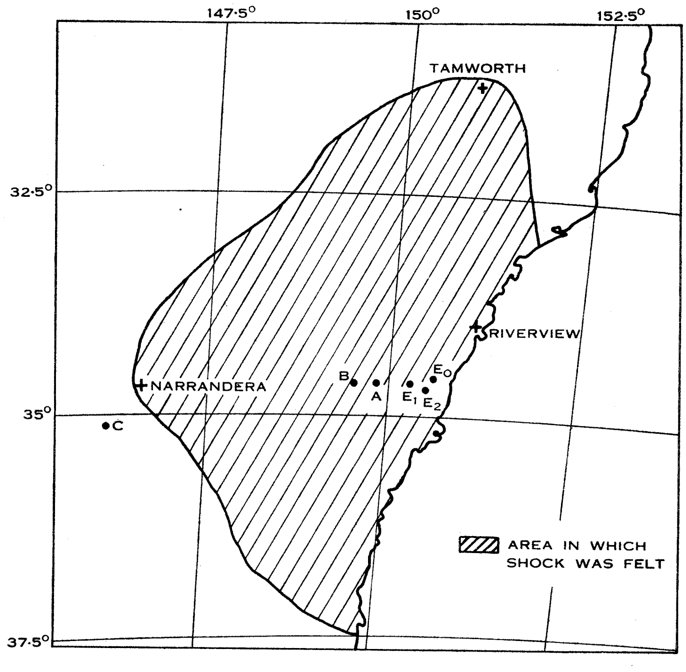


Fig. 1.—The area affected by the shock of May 22, 1961.

The distribution of values of $\mu$ makes it evident that there was no appreciable depth of focus. Accordingly it was decided to continue to use the travel-time tables for a surface focus.

Corrections to $E_0$ and $t_0$ were determined by least squares. In this determination, the readings at Chateau and Apia were omitted since the provisional residuals exceeded 5 s and were seriously incompatible with the indications from other stations. Readings for the range $143° \cdot 5 \leqslant \Delta \leqslant 145°$ were also omitted because of uncertainty as to the branch of the time curve involved.

Let the required corrections be $Y$ s, $x°$ N., and $y°$ E. The subscript $i$ will relate to a particular small group of stations (sometimes a single station) with approximately the same $\Delta$ and $\psi$; $\Delta_i$, $\psi_i$, and $\mu_i$ will denote means for the group, and $\varepsilon_i$ the mean error in the measured arrival time. Let $n$ be the number of

TABLE 1

SUMMARY OF ARRIVAL TIMES AFTER $t_0$ ($22^h$ $40^m$ G.M.T.) OF ALL AVAILABLE FIRST ARRIVALS, WITH STATION IDENTIFICATIONS

| | m s | | m s |
|---|---|---|---|
| Avon | 0 8·0 ($iP_1$) | Riverview | 0 19·0 ($iP_1$) |
| Werombi | 0 14·5 ($iP_1$) | Hall's Lagoon | 0 22·4 ($iP_1$) |
| Jenolan | 0 18·0 ($iP_1$) | Canberra | 0 30·0 ($iP_1$) |
| Wambrook | 0 39·7 ($iP$) | Chateau | 4 48·5 ($eP$) |
| Jindabyne | 0 44·0 ($iP$) | Port Moresby | 5 31·4 ($eP$) |
| Geehi | 0 48·0 ($iP$) | Darwin | 5 58·1 ($eP$) |
| Melbourne | 1 27·0 ($eP$) | Mundaring | 6 0·0 ($iP$) |
| Brisbane | 1 53·8 ($eP$) | Apia | 7 45·0 ($iP$) |
| Moorlands | 2 04·5 ($eP$) | Djakarta | 8 45·0 ($eP$) |
| Tarraleah | 2 06·5 ($eP$) | South Pole | 9 40·0 ($iP$) |
| Fort Nelson | 2 10·0 ($eP$) | Byrd | 9 45·0 ($iP$) |
| Adelaide | 2 22·5 ($iP$) | Mawson | 9 55·0 ($iP$) |
| Charters Towers | 3 33·7 ($eP$) | | |
| Eureka | 18 42·0 ($ePKP$) | San Juan | 19 35·0 ($iPKP$) |
| Wichita | 19 03·0 ($ePKP$) | Pruhonice | 19 39·0 ($iPKP$) |
| Fayetteville | 19 10·0 ($iPKP$) | Palisades | 19 38·0 ($ePKP$) |
| Kiruna | 19 26·0 ($iPKP$) | Montreal | 19 39·0 ($iPKP$) |
| Ottawa | 19 35·0 ($ePKP$) | Stuttgart | 19 49·0 ($iPKP$) |

TABLE 2

SUMMARY OF RESIDUALS CORRESPONDING TO ($E_0$, $t_0$)

| Station | Δ (deg) | ψ (deg) | μ (s) | Station | Δ (deg) | ψ (deg) | μ (s) |
|---|---|---|---|---|---|---|---|
| Wambrook | 2·367 | 215 | —0·9 | Djakarta | 48·12 | 300 | 1·3 |
| Jindabyne | 2·633 | 218 | 0·5 | South Pole | 55·70 | 180 | 0·2 |
| Geehi | 2·705 | 225 | 2·4 | Byrd | 56·22 | 168 | 1·4 |
| Melbourne | 5·60 | 232 | 0·4 | Mawson | 57·75 | 207 | 0·6 |
| Brisbane | 7·33 | 19 | 2·8 | Eureka | 113·47 | 57 | 2·2 |
| Moorlands | 8·37 | 197 | —0·6 | Wichita | 123·97 | 68 | 3·2 |
| Tarraleah | 8·43 | 201 | —0·1 | Fayetteville | 128·18 | 69 | 1·9 |
| Fort Nelson | 8·78 | 195 | —0·8 | Kiruna | 136·38 | 335 | 1·5 |
| Adelaide | 9·75 | 263 | —2·1 | Ottawa | 143·50 | 58 | 0·6* |
| Charters Towers | 14·82 | 344 | 2·9 | San Juan | 143·73 | 107 | —1·2* |
| Chateau | 20·55 | 120 | 6·0 | Pruhonice | 144·57 | 300 | 1·2* |
| Port Moresby | 25·15 | 345 | 3·0 | Palisades | 144·58 | 66 | 0·1* |
| Darwin | 28·36 | 316 | 0·7 | Montreal | 144·90 | 58 | 0·3* |
| Mundaring | 28·77 | 266 | —1·4 | Stuttgart | 148·13 | 308 | 3·9 |
| Apia | 39·78 | 60 | 8·4 | | | | |

* Branch BC assumed.

groups taken. The usual $n$ equations of conditions (Jeffreys and Bullen 1935) may then be written in matrix form as

$$\boldsymbol{\epsilon} = \mathbf{A}\mathbf{x} - \boldsymbol{\mu}, \tag{2}$$

where

$$\mathbf{A}_i = [1, \ -(\mathrm{d}T/\mathrm{d}\Delta)_{\Delta_i} \cos \psi_i, \ -(\mathrm{d}T/\mathrm{d}\Delta)_{\Delta_i} \sin \psi_i], \tag{3}$$

$\mathbf{A}$ denotes the matrix of the $A_i$, $\boldsymbol{\epsilon}$ denotes the column matrix of the $\varepsilon_i$, and $\mathbf{x}$ denotes the column matrix $[Y, x, y]$. Asterisks will denote transposed matrices. The $\varepsilon_i$ are taken to be a set of mutually independent variables with zero mean and variance $\sigma^2$.

The least-squares method of solution is to find an estimate of $\mathbf{x}$, $\boldsymbol{\lambda}$ say, such that $\mathbf{e}^*\mathbf{e}$ is a minimum, where

$$\mathbf{e} = \mathbf{A}\boldsymbol{\lambda} - \boldsymbol{\mu}. \tag{4}$$

The solution for $Y, x, y$ is thus given by

$$\boldsymbol{\lambda} = (\mathbf{A}^*\mathbf{A})^{-1}\mathbf{A}^*\boldsymbol{\mu}. \tag{5}$$

The standard errors of $Y, x, y$ are (Whittaker and Robinson 1952) given as the diagonal terms of $\sigma^2$ $(\mathbf{A}^*\mathbf{A})^{-1}$ where (the most probable value of) $\sigma^2$ is given by

$$\sigma^2 = \mathbf{e}^*\mathbf{e}/(n-3), \tag{6}$$

assuming a normal law for $\boldsymbol{\epsilon}$.

The following seven groups of stations were taken :

(i) Brisbane, Charters Towers
(ii) Melbourne
(iii) Adelaide, Mundaring
(iv) Moorlands, Tarraleah, Fort Nelson
(v) South Pole, Mawson, Byrd
(vi) Darwin, Port Moresby, Djakarta
(vii) Eureka, Wichita, Fayetteville.

These gave :

$$\mathbf{A} = \begin{bmatrix} 1 & -13\cdot50 & 0\cdot00 \\ 1 & 8\cdot75 & 11\cdot06 \\ 1 & 1\cdot13 & 11\cdot39 \\ 1 & 13\cdot22 & 4\cdot30 \\ 1 & 7\cdot20 & 0\cdot00 \\ 1 & -8\cdot27 & 3\cdot01 \\ 1 & -1\cdot00 & -1\cdot73 \end{bmatrix}, \qquad \boldsymbol{\mu} = \begin{bmatrix} 2\cdot8 \\ 0\cdot4 \\ -1\cdot8 \\ -0\cdot5 \\ 0\cdot9 \\ 1\cdot6 \\ 2\cdot5 \end{bmatrix}. \tag{7}$$

Trial solutions showed that the effects of weighting the rows of $\mathbf{A}$ (for example, using assigned reliabilities such as those of Jeffreys (1936) or taking weights proportional to the square root of the number of stations in a group) were not significant. In the actual solution, groups were therefore given equal weight.

The solution thus obtained is

$$\boldsymbol{\lambda} = \begin{bmatrix} 1\cdot6 \pm 0\cdot9 \text{ s} \\ -0^\circ\cdot07 \pm 0^\circ\cdot05 \\ -0^\circ\cdot19 \pm 0^\circ\cdot1 \end{bmatrix} \tag{8}$$

with $\sigma = 1\cdot4$ s.

The corresponding epicentre $E_1$ (shown in Fig. 1) and origin time $t_1$ are, respectively,

$$\left.\begin{array}{c}34^\circ\ 22'\ \text{S. (geocentric), } 150^\circ\ 20'\ \text{E.,}\\ \text{and 1961 May } 21^{\text{d}}\ 21^{\text{h}}\ 40^{\text{m}}\ 1\cdot 6^{\text{s}}\ \text{(G.M.T.).}\end{array}\right\}. \tag{9}$$

The calculated standard errors are of the same order of magnitude as the corrections, indicating that the revision may not be very significant. It should be noted also that the sensitivity of the solution suffers from the asymmetrical distribution of the recording stations, the majority of which lie to the west of the epicentre. Only those stations recording *PKP*, for which $dT/d\Delta$ is low, lie in the north-east quadrant, and no readings are available for the south-east quadrant. Thus any change of epicentre is governed largely by readings at western stations.

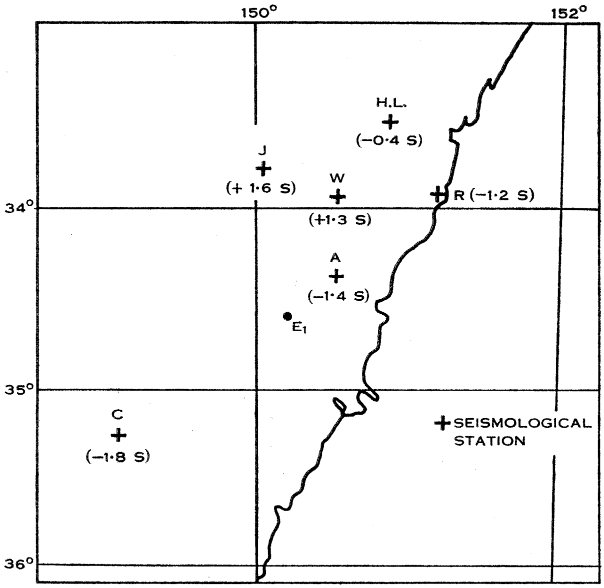


Fig. 2.—The positions of the stations (recording $P_1$) relative to $E_1$.

## III. Consideration of the Near Stations ($\Delta < 2^\circ \cdot 0$)

The distances of the five near stations from $E_1$ were determined, and a linear form fitted to the excess $T$ of the first-arrival times over $t_1$. The result was

$$T = (2\cdot 0 \pm 2) + \Delta/(6\cdot 35 \pm 0\cdot 4)\ \text{s}, \tag{10}$$

with $\sigma = 1\cdot 7$ s, $\Delta$ being here measured in kilometres. The residuals against (10) for the five stations and also Canberra are as indicated in Figure 2, where the stations are denoted by their initial letters.

Since the epicentral distance of Canberra is about 190 km, it is uncertain if the first arrival (which is the only phase recorded on the seismogram) is $P_1$ or $P_n$. It was decided, therefore, not to use this reading in the calculations.

To make the readings from these near stations more self-consistent, several representative epicentres (and corresponding origin-times) were considered. The epicentre $E_2$ and origin time $t_2$, which gave the most self-consistent set of residuals, are:

$$\left.\begin{array}{c} 34^\circ\ 25'\ \text{S. (geocentric)},\ 150^\circ\ 24'\ \text{E.}, \\ \text{and 1961 May } 21^{\text{d}}\ 21^{\text{h}}\ 40^{\text{m}}\ 1^{\text{s}}\ \text{(G.M.T.).} \end{array}\right\} \tag{11}$$

This involved a shift of the epicentre to a position 11 km to the east and 6 km to the south of $E_1$, and a decrease of $0 \cdot 6$ s in the origin time $t_1$. Both of these changes lie within the standard errors of the solution ($E_1$, $t_1$).

TABLE 3

SUMMARY OF THE $P$ RESIDUALS OBTAINED USING ($E_0$, $t_0$), ($E_1$, $t_1$), AND ($E_2$, $t_2$)

| Station | $\Delta_2$ (deg) | Residuals (s) | | |
|---|---|---|---|---|
| | | ($E_0$, $t_0$) | ($E_1$, $t_1$) | ($E_2$, $t_2$) |
| Wambrook . . | 2·23 | —0·9 | —0·6 | 0·0 |
| Jindabyne . . | 2·38 | 0·5 | 1·5 | 2·1 |
| Geehi . . . . | 2·57 | 2·4 | 2·8 | 3·4 |
| Melbourne . . | 5·50 | 0·4 | 0·6 | 0·8 |
| Brisbane . . | 7·47 | 2·8 | 0·0 | 0·0 |
| Moorlands . . | 8·23 | —0·6 | —0·9 | 0·4 |
| Tarraleah . . | 8·28 | —0·1 | 0·1 | 1·2 |
| Fort Nelson . . | 8·67 | —0·8 | —1·4 | —0·6 |
| Adelaide . . | 9·63 | —2·1 | —1·1 | —1·4 |
| Charters Towers | 14·93 | 2·9 | —2·7 | —1·1 |
| Chateau . . | 20·60 | 6·0 | 4·9 | 4·5 |
| Port Moresby . . | 25·25 | 3·0 | 1·4 | 1·1 |
| Darwin . . . . | 28·33 | 0·7 | —0·5 | 0·4 |
| Mundaring . . | 28·67 | —1·4 | —1·5 | —0·6 |
| Apia . . . . | 39·75 | 8·4 | 5·7 | 6·4 |
| Djakarta . . | 48·08 | 1·3 | 0·2 | 0·2 |
| South Pole . . | 55·12 | 0·2 | —1·0 | 0·0 |
| Byrd . . . . | 56·12 | 1·4 | 0·0 | 1·2 |
| Mawson . . | 57·60 | 0·68 | —0·2 | —0·4 |

The evidence favouring this small change ignores possible and local geological influences and assumes that the near readings refer to a common phase, $P_1$ say. It was not possible from the data to make any reasonable estimate of the focal depth, as neither $P_n$ nor any $S$ phase was recorded at the near stations, and $S_n$ was poorly recorded at the remainder of the Australian stations.

Table 3 shows the residuals for all stations which recorded $P$, obtained using ($E_0$, $t_0$), ($E_1$, $t_1$), and ($E_2$, $t_2$) respectively; $\Delta_2$ denotes the station distances from $E_2$. As the $PKP$ residuals are affected mainly by the increase in origin-time and not by the small epicentral displacements, the $PKP$ residuals obtained using ($E_1$, $t_1$) were omitted from Table 3. Those found using ($E_2$, $t_2$) will be treated in Section V.

The Chateau and Apia residuals are improved with the use of $(E_2, t_2)$, but are still incompatible with the indications from the remaining residuals. They are omitted in forming the sum of squares of residuals.

For $(E_0, t_0)$, $\chi^2=44\cdot15$ for 14 degrees of freedom (i.e. $\mu=14$), this being highly significant at the $0\cdot5\%$ level of confidence. The residuals from the five near stations are not included in this determination, but are included when determining the sum of squares of the residuals for $(E_1, t_1)$ and $(E_2, t_2)$, and contribute three degrees of freedom in each case. For $(E_1, t_1)$, $\chi^2=36\cdot30$ $(\mu=17)$, which is significant at the $0\cdot5\%$ level. For $(E_2, t_2)$, $\chi^2=30\cdot08$ $(\mu=17)$, which is just not significant at the $2\cdot5\%$ level.

The use of the $\chi^2$-test gives an index of preference. Thus, on the stated assumptions, the results $(E_2, t_2)$ are to be preferred to $(E_1, t_1)$ and $(E_0, t_0)$.

## IV. Near-earthquake Phases

$P_1$ *Phase.*—A revision of (10) based on $(E_2, t_2)$ gave, for the phase $P_1$,

$$T=(0\cdot72\pm1\cdot6)+\Delta/(6\cdot06\pm0\cdot17)\text{ s}, \tag{12}$$

with $n=5$, $\sigma=1\cdot3$ s.

This may be compared with the result of Doyle, Everingham, and Hogan (1959) who found, in a study of seismic recordings of large explosions in the Snowy Mountains area, a $P_1$ velocity of $6\cdot04\pm0\cdot04$ km/s. The close agreement of the two sets of results gives further support to the estimated $E_2$ and $t_2$.

The constant term is compatible with the absence of a crustal layer of lower velocity above a rather uniform crust.

$P_n$ *Phase.*—For $2°\cdot0\leqslant\Delta\leqslant9°\cdot0$, the first readings were found to fit the form

$$T=(9\cdot3\pm1\cdot0)+\Delta/(8\cdot00\pm0\cdot08)\text{ s}, \tag{13}$$

with $n=8$, $\sigma=1\cdot2$ s.

The indicated $P_n$ surface velocity of $8\cdot00\pm0\cdot08$ km/s is again consistent with the velocity of $8\cdot03$ km/s found by Doyle, Everingham, and Hogan (loc. cit.).

The improvement of the results using $(E_2, t_2)$ over those using $(E_1, t_1)$ is perhaps best seen in the reductions of the standard errors in the above determinations. These errors are not a measure of the total error involved, but do indicate the self-consistency of the results.

Assuming a uniform crust above the Mohorovičić discontinuity, and using the equations (12) and (13), the thickness of the layer was formally calculated to be 40 km, compared with 37 km as found by Doyle, Everingham, and Hogan for the same area, and 35 km found by Bolt, Doyle, and Sutton (1958) for a Western Australian region. When the uncertainties of the calculations, including those in focal depth, are taken into account, the uncertainty in the calculated thickness is indicated to be of the order of 5 km. Hence the findings from this earthquake are compatible with findings from investigations from explosions in this region.

## V. *PKP* Readings

Table 4 gives the *PKP* residuals $\mu$ against the Jeffreys-Bullen times using $(E_2, t_2)$.

For $110° \leqslant \Delta \leqslant 140°$, the mean *PKP* residual against the Jeffreys-Bullen travel times for the DE branch of the *PKP* curve is $+1 \cdot 3$ s. This is in agreement with the mean *PKIKP* residual of $1 \cdot 2$ s for $\Delta < 140°$ in Jeffreys's preferred solution (1942) of the earthquake of June 29, 1934.

Table 4 also shows residuals $\omega$ against Bolt's times (1959).

Table 4

SUMMARY OF THE *PKP* RESIDUALS CORRESPONDING TO $(E_2, t_2)$

| Station | $\Delta$ (deg) | $\mu$ (s) | $\omega$ (s) |
|---|---|---|---|
| Eureka . . . . | 113·45 | 1·3 | —0·5 |
| Wichita . . . . | 123·97 | 1·8 | 0·3 |
| Fayetteville . . | 128·18 | 0·7 | —0·8 |
| Kiruna . . . . | 136·38 | 1·3 | —0·5 |
| Ottawa . . . . | 143·50 | —0·7* | —0·2 |
| San Juan . . . . | 143·77 | —2·4* | —0·9 |
| Pruhonice . . . . | 144·57 | 0·7* | 1·0 |
| Palisades . . . . | 144·70 | —1·3* | —0·4 |
| Montreal . . . . | 145·00 | —1·0* | —0·2 |
| Stuttgart . . . . | 148·13 | 3·0 | |

* Assuming BC branch.

## VI. Surface Waves

Clearly identifiable surface waves were recorded. Details are as follow.

*Port Moresby.*—Love and Rayleigh wave trains (Figs. 3, 4) are both well developed and show clear dispersion on the records.

Starting from the first identifiable onset, every Rayleigh-wave period was measured over a continuous part of the record (from the north-south component of the Spregnether instrument with $T_0 = 15 \cdot 8$ s, $T_g = 15 \cdot 8$ s) and a dispersion curve constructed giving the period against the corresponding arrival time. The curve was smoothed and the arrival times converted into corresponding group velocities.

The great-circle path involved is half oceanic and half continental (see Fig. 5) so that any estimated thickness must relate to some form of " average " structure.

The measured group velocities were compared with the group velocities obtained by Bolt and Butcher (1960) for the fundamental mode for several single-layer model crustal structures, and the associated " average " crustal thickness estimated. Table 5 gives details of the calculation using the model B of Bolt and Butcher. Table 6 summarizes the results obtained using the model B and four others and also gives the seismic parameters of these models. (Other models of Bolt and Butcher are not relevant since the group velocities of their

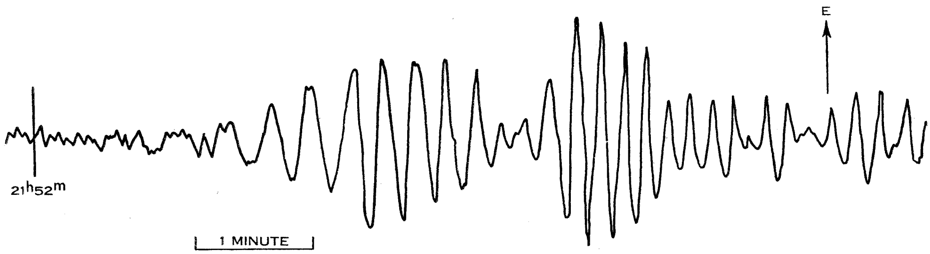


Fig. 3.—Port Moresby Spregnether record showing Love wave train.

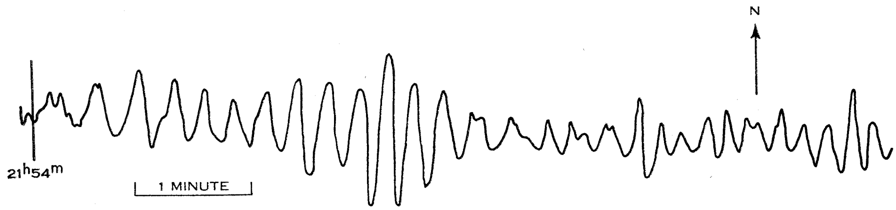


Fig. 4.—Port Moresby Spregnether record showing Rayleigh wave train.

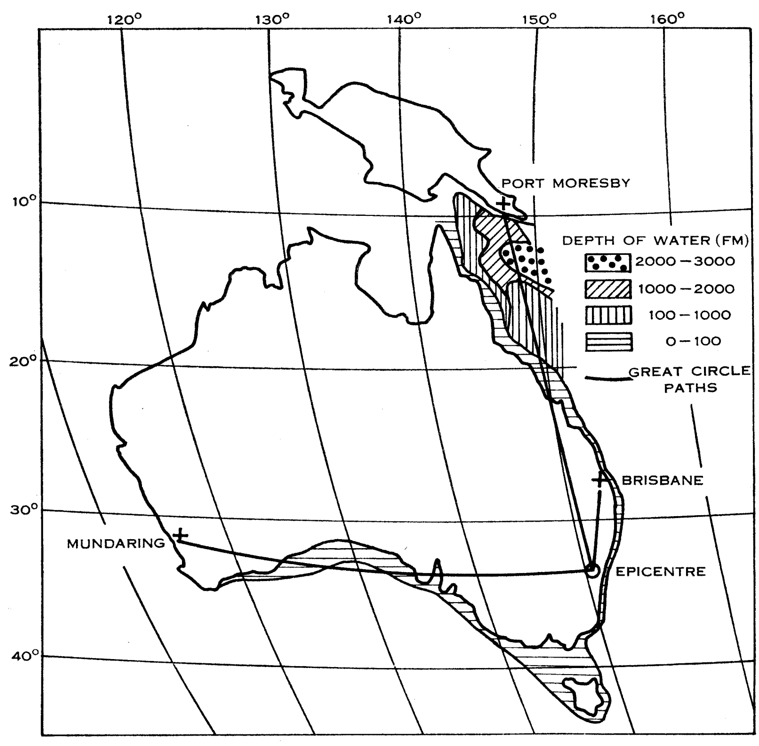


Fig. 5.—Paths of surface wave trains.

Airy phases are greater than the measured value of 2·86 km/s.) In Table 6, $\alpha$ and $\beta$ denote $P$ and $S$ velocities, $\rho$ density, and the subscripts 1, 2 the crustal layer and the region just below.

Since the depth of ocean along the path ranges from 1000 to 3000 fathoms, the formally indicated thicknesses are of the expected order. The results in Table 6 show that the formally computed thickness is fairly precisely determined. At the same time, the particular model (and hence the set of seismic parameters) which best fits the available data is not finely determined.

TABLE 5

ESTIMATION OF CRUSTAL THICKNESS FROM THE SURFACE-WAVE TRAIN AT PORT MORESBY USING BOLT AND BUTCHER'S CRUSTAL-STRUCTURE MODEL B

| Measured Period (s) | Measured Group Velocity (km/s) | Theoretical Phase Velocity (km/s) | Calculated Thickness (km) |
|---|---|---|---|
| 20 | 3·25 | 3·95 | 24 |
| 19 | 3·22 | 3·92 | 23 |
| 18 | 3·18 | 3·90 | 22 |
| 17 | 3·12 | 3·86 | 22 |
| 16 | 3·06 | 3·82 | 22 |
| 15 | 2·98 | 3·78 | 21 |
| 14 | 2·86 | 3·59 | 24 |

*Mundaring.*—Rayleigh waves were recorded at Mundaring on the vertical component of the long-period Benioff instrument ($T_0$=1·0 s, $T_g$=14·4 s). Though an Airy phase is clear (see Fig. 6), dispersion is not well developed. The absence of a long dispersion train does not allow a high degree of precision in the calculations of the dispersion curve.

The wave path is about 70% continental (see Fig. 5) and the mean depth of water for the remaining section is about 300–400 fathoms. A single-surface-

TABLE 6

SUMMARY OF CALCULATED THICKNESSES AND SEISMIC PARAMETERS OF THE SEVERAL CRUSTAL-STRUCTURE MODELS USED TO APPROXIMATE THE ACTUAL CRUSTAL STRUCTURE BETWEEN PORT MORESBY AND THE EPICENTRE

| Model | Calculated Thickness (km) | $\alpha_1$ (km/s) | $\beta_1$ (km/s) | $\alpha_2$ (km/s) | $\beta_2$ (km/s) | $\rho_2/\rho_1$ |
|---|---|---|---|---|---|---|
| B | 23±0·4 | 6·0 | 3·6 | 8·2 | 4·8 | 1·296 |
| D | 24±4·0 | 6·0 | 3·4 | 8·2 | 4·8 | 1·296 |
| F | 23±0·5 | 6·0 | 3·6 | 8·2 | 4·8 | 1·400 |
| I | 23±0·4 | 6·0 | 3·6 | 8·4 | 4·8 | 1·296 |
| K | 22±0·4 | 6·0 | 3·6 | 8·2 | 5·0 | 1·296 |

layer model of continental type may therefore be used to give a rough estimate of the mean crustal thickness along the path.

The velocities of $P_1$, $S_1$, $P_n$, $S_n$, calculated by Bolt, Doyle, and Sutton (1958) for this region are available. With these velocities, the Bolt and Butcher models are restricted to either B or F.

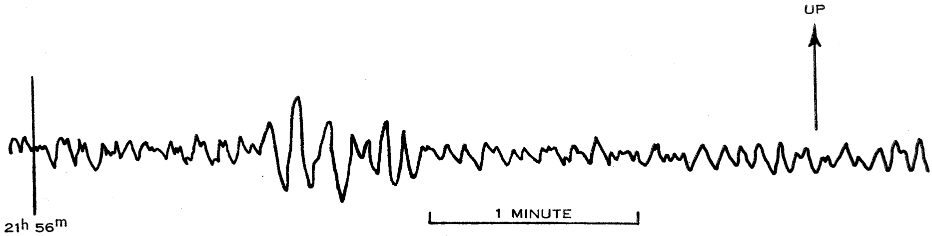


Fig. 6.—Mundaring Benioff record showing Rayleigh wave train.

Comparison of the measured group velocity of the wave with largest amplitude with that obtained for the direct branch of the fundamental mode of model B leads to a calculated thickness of about 11 km. This appears incompatible with the 35 km thickness obtained by Bolt, Doyle, and Sutton (1958) for this region. On the assumption that the measurement refers to the inverse branch of the fundamental mode, Table 7 shows the results using models B and F.

The indicated average crustal thickness is of the order of 21 km. This result is low compared with the result of Bolt, Doyle, and Sutton (1958) from refraction data.

Table 7

Estimation of crustal thickness from the surface-wave train at Mundaring using Bolt and Butcher's crustal-structure models B and F (inverse branch of the fundamental mode)

| Model | Measured Period (s) | Measured Group Velocity (km/s) | Theoretical Phase Velocity (km/s) | Calculated Thickness, $H$ (km) |
|---|---|---|---|---|
| B | 8 | 3·09 | 3·36 | 21·4 |
| F | | 3·09 | 3·34 | 23·4 |

*Brisbane*.—The record from the north-south component of the long-period Benioff instrument ($T_0$=20 s, $T_g$=20 s) shows the presence of a double maximum of the amplitudes of the waves of the Rayleigh surface-wave train (see Fig. 7). The presence of this double maximum makes difficult the accurate determination of the dispersion curve.

Comparison of the measured group velocity of the second maximum with that obtained for the direct branch of the fundamental mode of model B yields a calculated thickness of about 12 km. This seems inconsistent with the average crustal thickness obtained for the great-circle path between the epicentre and Port Moresby.

On the assumption that the second maximum refers to the inverse branch of the fundamental mode, Table 8 shows the results using models B and D.

The indicated average crustal thickness is of the order of 21 km. The first maximum may be the first higher Rayleigh mode or may be a consequence of the presence of a sedimentary layer on the fundamental Rayleigh mode (Oliver,

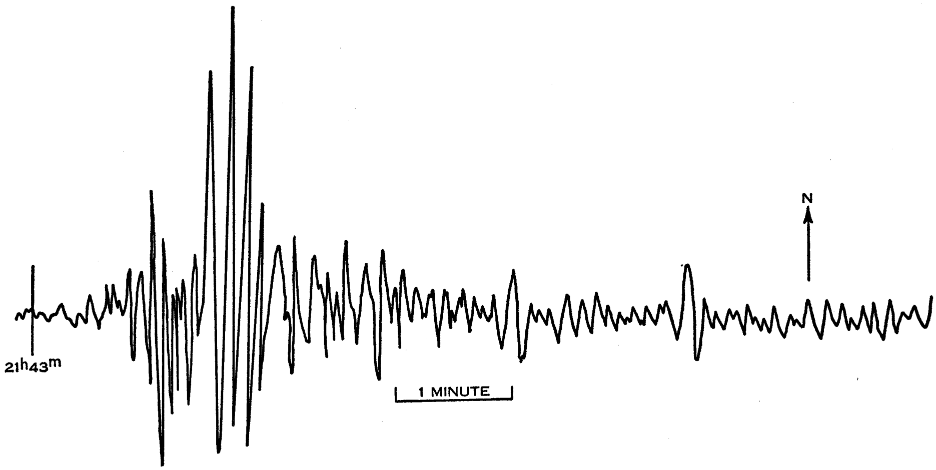


Fig. 7.—Brisbane Benioff record showing Rayleigh wave train.

Dorman, and Sutton 1959). On the assumption that it is the first higher mode, comparison of its measured group velocity with that obtained for the direct branch of the first higher mode of model B yields a calculated thickness of about 25 km.

The results from the surface-wave trains at Port Moresby, Mundaring, and Brisbane indicate that, to achieve a reasonable degree of accuracy, dispersion

TABLE 8

ESTIMATION OF CRUSTAL THICKNESS FROM THE SURFACE-WAVE TRAIN AT BRISBANE USING THE INVERSE BRANCH OF THE FUNDAMENTAL MODE OF BOLT AND BUTCHER'S CRUSTAL-STRUCTURE MODELS B AND D

| Model | Measured Period (s) | Measured Group Velocity (km/s) | Theoretical Phase Velocity (km/s) | Calculated Thickness, *H* (km) |
|---|---|---|---|---|
| B | 9 | 3·02 | 3·39 | 21·4 |
| D | 9 | 3·02 | 3·16 | 27·0 |

should be well observed over a considerable range of wave periods. Where short-period surface waves are in evidence, the possible effects of a sedimentary layer above the crustal layer need some consideration (Oliver, Dorman, and Sutton 1959) since such a layer may produce a systematic error in the calculated thicknesses.

## VII. Acknowledgments

The author is indebted to the Directors of the various seismological stations, both in Australia and overseas, who kindly supplied records and information; to Professor K. E. Bullen for suggesting the investigation; and to Dr. Bolt for his helpful discussions.

## VIII. References

Bolt, B. A. (1959).—*Geophys. J.* **2**: 3.

Bolt, B. A., and Butcher, J. C. (1960).—*Aust. J. Phys.* **13**: 498.

Bolt, B. A., Doyle, H. A., and Sutton, D. J. (1958).—*Geophys. J.* **1**: 135.

Bullen, K. E. (1937).—*Mon. Not. R. Astr. Soc. Geophys. Suppl.* **4**: 143.

Burke-Gaffney, S. J. (1951).—*J. Roy. Soc. N.S.W.* **85**: 47.

Doyle, H. A., Everingham, I. B., and Hogan, T. K. (1959).—*Aust. J. Phys.* **12**: 222.

Jeffreys, H. (1936).—*Mon. Not. R. Astr. Soc. Geophys. Suppl.* **3**: 9.

Jeffreys, H. (1942).—*Mon. Not. R. Astr. Soc. Geophys. Suppl.* **5**: 33.

Jeffreys, H., and Bullen, K. E. (1935).—*Bur. Centr. Seism. Internat.* **A11**: 9.

Jeffreys, H., and Bullen, K. E. (1948).—Brit. Assoc. Adv. Sci., Gray Milne Trust.

Oliver, J., Dorman, J., and Sutton, G. (1959).—*Bull. Seismol. Soc. Amer.* **49**: 379.

Whittaker, E. T., and Robinson, G. (1952).—"The Calculus of Observations." pp. 239–45. (Macmillan: New York.)