

# Coseismic slip in the mantle: evidence from the 1989 Macquarie Ridge earthquake

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## Abstract

The rupture process of the  $M_s$  8.2, 23 May, 1989 Macquarie Ridge earthquake was studied using a surface wave inversion procedure that incorporates detailed source-time functions obtained from shorter-period body waves. The seismic-source model obtained using this method is consistent with observations of both body waves and long-period Rayleigh waves from the earthquake. The Macquarie Ridge earthquake rupture has a centroid time of 28 s and a right-lateral strike-slip fault mechanism with a rake of  $175^\circ$  on a vertical fault plane striking  $N38^\circ E$ . This mechanism is consistent with  $P$ -wave first motions of the event. Allowing for uncertainty in attenuation, the long-period Rayleigh waves (periods from 150 to 300 s) indicate that the Macquarie Ridge earthquake had a seismic moment of between  $1.7$  and  $2.1 \times 10^{21}$  Nm and a corresponding centroid depth of between 15 and 28 km. The centroid depth range, combined with the lack of resolvable directivity of the earthquake rupture, suggests that significant slip occurred beneath the Moho, which has a maximum depth of about 16 km in the epicentral region. We infer that the mantle slip component preferentially radiated long-period seismic energy because the shorter-period body wave observations indicate shallower centroid depths and lower moment values than those determined from the surface wave inversion.

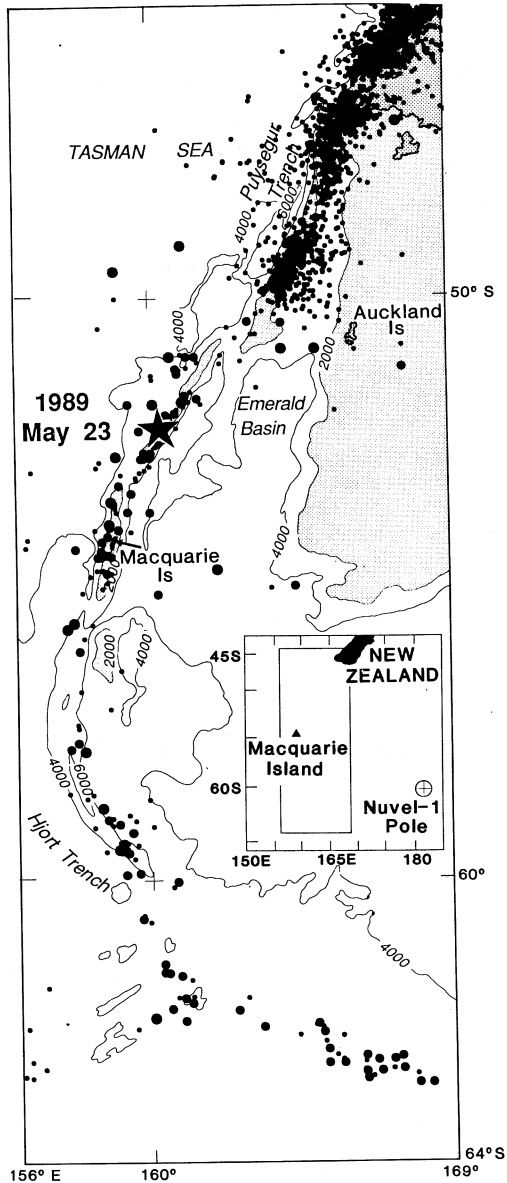
Similar studies of other great earthquakes in oceanic crust (*e.g.*, 1977 Sumba and 1977 Tonga) indicate that these also had moment release concentrated in the upper part of the plate but that significantly deeper moment release was required to explain the surface waves. Thus some great earthquakes appear to rupture a significant thickness of the lithosphere, although the slip distribution is probably modified by the different rheological properties of the plate. Recognition of this phenomenon has important implications for seismic hazard.

## 1. Introduction

The depth distribution of earthquakes shows concentrations in the upper crust and upper mantle (Chen and Molnar, 1983). This is usually correlated with strength profiles and interpreted as two separate regions of the lithosphere that fail independently. Major earthquakes, with large fault areas, might have their slip confined to the upper crust (for instance) but have significantly long faults lengths or large coseismic slip to accommodate the moment release. The earthquakes that rupture the upper and middle crust with significant fault length caused broad surface deformation and seismic wave radiation directivity and they can be recognized with geological

and seismological observations. Alternatively brittle failure associated with large earthquakes may not be confined to the brittle layer of the crust or mantle, and whole lithosphere rupture might occur. We have tested these alternatives by examining the rupture process of the largest earthquake since 1977, the 23 May 1989 Macquarie Ridge earthquake.

The 1989 Macquarie Ridge earthquake occurred in an isolated area about 800 km SSW of New Zealand (fig. 1). The earthquake is significant in its tectonic setting, focal mechanism, large size ( $M_s = 8.2$ ) and rupture process. It was the largest event located along the Pacific-Australian plate boundary south of New Zealand in more than 70 years. The fault slip of the Mac-



**Fig. 1.** Seismicity distribution along the Macquarie Ridge Complex with shaded area indicating bathymetry less than 2000 m. All earthquakes shown are for 1918 to 24 May 1989 from the historical catalogue of the International Seismological Centre. Various symbols indicate epicentral locations of events of the 23 May 1989 (star), magnitude less than 5.0 (small dots), and magnitude 6.0 or larger (large dots).

quarie Ridge earthquake therefore represents a large amount of seismic deformation occurring on this plate boundary, and contributes significantly to the relative motion between the Australian and Pacific plates.

The Macquarie Ridge earthquake has been analyzed using seismic body waves (Braunmiller and Nabelek, 1990; Dziewonski and Zwart, 1989; Ekström and Romanowicz, 1990; Houston, 1990; Satake and Kanamori, 1990; Tichelaar and Ruff, 1990) and long-period surface waves and free oscillations (Dziewonski and Zwart, 1989; Ekström and Romanowicz, 1990; Kedar and Tanimoto, 1990; Park, 1990; Satake and Kanamori, 1990). These studies show that it was a large shallow strike-slip event, with a relatively short source process time compared to other earthquakes of similar size. However, due to the difficulties in modelling seismic body and surface wave excitations for the earthquake, estimates of the source parameters of the Macquarie Ridge earthquake are subject to large uncertainties. Table I lists some important source parameters of this earthquake obtained by various investigators.

The ranges of total process time (sometimes termed duration in other studies) obtained from both body waves and surface waves are large (table I), and there appears to be a systematic increase in the seismic moment and depth with the period of seismic waves used in the inversion. An explanation for the greater depth determined from surface waves, compared to body waves, is not immediately obvious, but the variation in moment and process time can be explained if significant moment release occurs at longer periods than those used in an inversion, in which case the total moment and process time will be underestimated. Similarly, surface wave inversion methods lack resolution at the relatively short periods required to define a detailed moment rate function.

In order to obtain a unified source process model for the Macquarie Ridge earthquake that is compatible with both the body and surface wave data, we used a method described by Anderson and Zhang (1991), which incorporates the detailed moment rate function (pre-determined from body waves) in the surface wave inversion. We compare our results with those from other

methods and discuss the physical significance and tectonic implications of the source process for the Macquarie Ridge earthquake.

## 2. Tectonic setting and crustal structure

The Macquarie Ridge earthquake occurred in a region of complicated tectonics (fig. 1). The Macquarie Ridge Complex is defined by a belt of seismicity, which follows elongate ridges and trenches from the southwest corner of the South Island, New Zealand to the Australian-Antarctic-Pacific triple junction (van de Linden and Hayes, 1972; Summerhayes, 1967a,b) forming several

distinct segments of the plate boundary (Anderson, 1990). Rocks on Macquarie Island have been derived from oceanic crust that was uplifted to the present elevation within the last 10 Ma (Williamson, 1988), suggesting that the elongate ridges along the Macquarie Ridge Complex are probably the result of obduction processes.

While the complexity of bathymetry and the presence of obducted oceanic crust suggest a tectonic regime influenced by compression, seismic slip on the central portion of the Macquarie Ridge Complex is predominantly strike-slip. The *P*-wave first-motion mechanism for the Macquarie Ridge earthquake is essentially vertical strike-slip (fig. 2) with a strike (038°) almost

**Table I.** Source parameters for the 1989 Macquarie Ridge earthquake.

Author(s)	Inversion type	Moment ( $\times 10^{21}$ Nm)	Depth (km)	Source process time (s) <sup>a</sup>	Distinct sub-events	Directivity resolvable?	Mechanism strike/dip/rake
Ekström and Romanowicz (1990)	Rayleigh	2.4	50	(28)	–	–	040/82/181
	160s < <i>T</i> < 320s	1.8	20 <sup>b</sup>	(28)	–	–	040/69/186
	Broadband <i>P</i> + <i>SH</i>	1.8	15	75	–	No	029/90/178
Satake and Kanamori (1990)	Rayleigh and Love	1.8	10 <sup>b</sup>	(30)	–	–	131/65/13
	Broadband <i>P</i> + <i>SH</i>	1.1	10 <sup>b</sup>	30	4	Yes	228/87/18°
Tichelaar and Ruff (1990)	<i>P</i> + <i>SH</i>	1.8	12	20	No	No	212/85/185
Braumiller and Nabelek (1990)	<i>P</i> + <i>SH</i>	1.34	10	52	4	Yes	211/86/180
		0.47 <sup>d</sup>	10 <sup>b</sup>	16	2		210/95/174
		0.55		30			212/82/187
Dziewonski and Zwart (1989)	<i>P</i> (and <i>SH</i> ?)	1.4	10.5	32	2	No	
Kedar and Tanimoto (1990)	Normal mode (962s)	2.8 ± 0.5		–	–	–	used Satake and Kanamori (1990)
This study	Rayleigh	2.11 <sup>e</sup>	28	93 (28)	–	azimuth only	038/86/180
	150s < <i>T</i> < 300s	1.75 <sup>f</sup>	15	92 (28)			037/75/178

<sup>a</sup> No. in brackets indicates centroid time  $\approx$  1/2 process time.

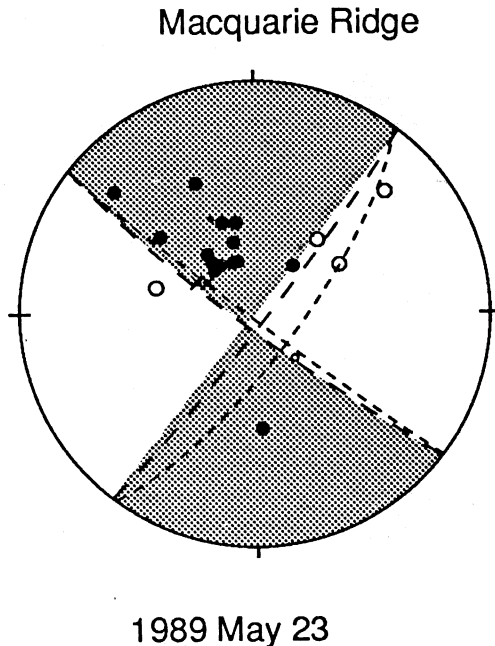
<sup>b</sup> Fixed.

<sup>c</sup> Largest sub-event.

<sup>d</sup> Bilateral rupture model.

<sup>e</sup> Using default Earth model (see text).

<sup>f</sup> Using M+G Q model, young ocean model (Regan and Anderson, 1984).



**Fig. 2.** Focal mechanism (lower hemisphere equal-area projection) determined from  $P$ -wave first-motion polarities on long-period vertical WWSSN records with compressional quadrants shaded. Open circles indicate dilatations and dots indicate compressions. Nodal planes of the best double couple of the moment tensor solution obtained in this study using default earth models (long-dashed lines) and using the Masters and Gilbert (1983)  $Q$  model for attenuation and Regan and Anderson (1984) 20 to 50 Ma ocean model for excitations (short-dashed lines) are also shown.

parallel to the relative plate motion direction for the epicentral area ( $041^\circ$ ) predicted using the DeMets *et al.* (1990) pole position.

Knowledge of the crustal structure in the epicentral area is important for both body and surface wave inversions for earthquake source parameters. Detailed velocity structure for the epicentral area is not known, but gravity and bathymetry data suggest that the Moho depth in the epicentral region is between 12 and 16 km (Williamson, 1988). For body wave analysis, the resolution of source characteristics is limited by the extreme variations in water depth (250 to 5250 m within 50 km of the epicenter), which produce complex  $P$ -wave water multiples

(Weins, 1989). However, for our surface wave analysis, the crustal structure on a broader scale (within several hundred kilometers of the epicenter) affects the estimates of source parameters, in particular the depth.

### 3. Method

We used long-period Rayleigh wave spectra from the Macquarie Ridge earthquake that had been calculated at periods of 150, 175, 200, 225, 256, 275 and 300 s using data from the Global Seismograph Network (GSN) and GEOSCOPE (Romanowicz *et al.*, 1984) networks.

For the surface wave inversion (which is described in detail by Anderson and Zhang, 1991), we used a two-step inversion developed by Zhang and Kanamori (1988a). The first step isolates the source-finiteness effect, and the second step finds the best depth and moment tensor.

Body wave studies for the Macquarie Ridge earthquake indicate that the high-frequency source process consists of several sub-events with most of the moment released in the first subevent spanning about 24 s long (*e.g.*, Braunmiller and Nabelek, 1990; Ekström and Romanowicz, 1990; Tichelaar and Ruff, 1990). The source time function (represented by a series of isosceles triangles) obtained by Braunmiller and Nabelek (1990), using the most complete data set was included in our surface wave inversion and the longer-period component was represented by a half-sine. We used only the first 24 s of the moment rate function determined by Braunmiller and Nabelek because the later pulses probably reflect unmodelled water reverberations in the  $P$  waveforms (Weins, 1989).

In our inversions we used default models for the earth structure to calculate phase velocity, attenuation and excitation functions. In order to test whether any systematic bias in the source parameters is introduced by the choice of this Earth model we repeated all our calculations with several different Earth models.

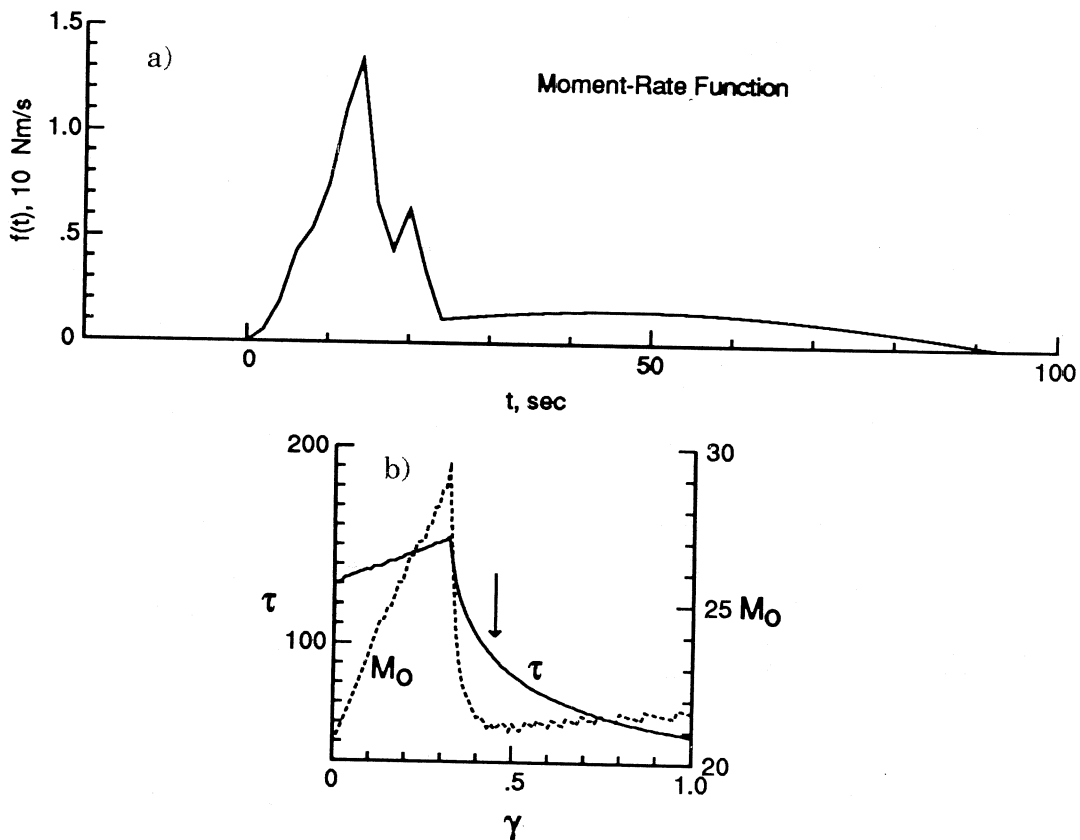
### 4. Results

The surface wave inversion results obtained

using a simple body wave moment rate function are shown in fig. 3. If the shape of the early part of the source time function described by isosceles triangles is fixed, three parameters are required to define our combined moment rate model. The first is the process time,  $\tau$ , of the half-sine; the second is the ratio of the half-sine component to the total moment rate function,  $\gamma$  ( $0 \leq \gamma \leq 1$ ); and the third is the total moment. For  $\gamma = 0$  only the body wave moment rate function, defined by the isosceles triangles, contributes to the total-moment rate function. A  $\gamma$  value of about 0.45 minimizes errors and maximizes the contribution of the body wave moment rate function. In this

case the total moment is about  $2.11 \times 10^{21}$  Nm, with a corresponding optimal process time of 93 s and centroid depth of 28 km.

For the above calculations we used an average ocean excitation model (Regan and Anderson, 1984) and an attenuation model determined by Dziewonski and Steim (1982). We performed calculations with other values of young ocean (Regan and Anderson, 1984) and an attenuation model determined by Masters and Gilbert (1983). This latter combination produces an indistinguishable moment rate function but the values for some of the source parameters differed significantly. The centroid depth determined was 15 km



**Fig. 3.** a) The moment rate functions for the Macquarie Ridge earthquake. The first 24 s of the moment rate function for a point source determined by Braunmiller and Nabelek (1990) using body waves is combined with a half-sine representing the long-period component. b) The process time  $\tau$  (solid line) and total moment (dashed line) plotted against  $\gamma$ . The arrow indicates the chosen value of  $\gamma$  (0.45) that maximizes the contribution of the body waves to the total moment and minimizes the errors (see Anderson and Zhang, 1991 for more details).

and the total moment was  $1.74 \times 10^{21}$  Nm. We are not aware of any a priori reason to prefer either of the attenuation models (which had the most significant effect on the depth and total moment), so source parameter values for both are presented in table I.

## 5. Discussion

### 5.1. Process time

From inversions of the long-period Rayleigh waves, the rupture process of the Macquarie Ridge earthquake had a centroid time of about 28 s and lasted 93 s. This indicates that the greatest moment release of the event occurred in the early part of the rupture. The difference in the moments determined using body waves, surface waves and free oscillations require a delayed centroid time (about 28 s) from the 10 to 15 s body wave centroid time.

The Macquarie Ridge earthquake was unusual in being a relatively simple event for its size. The moment rate functions of most other large earthquakes obtained from body wave observations usually consist of two or more distinct episodes of concentrated moment release each with a process time of 20 s or a few seconds longer (e.g., 1977 Tonga, Zhang and Lay, 1989a,b; 1979 Colombia, Beck and Ruff, 1984, Kanamori, 1986; 1986 Andean Is., Houston and Engdahl, 1989).

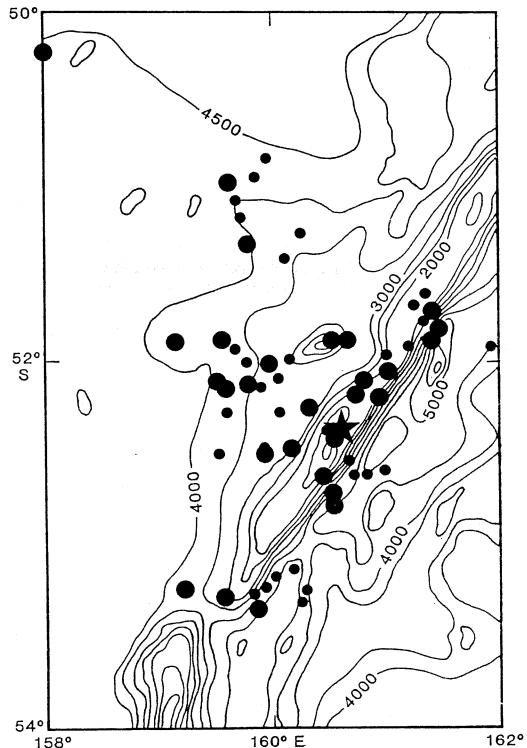
However, most of the large earthquakes available for similar surface wave studies have been thrust or normal faulting events. A detailed study of other large strike-slip earthquakes in a similar tectonic setting would be necessary to establish whether source simplicity is a characteristic of such events.

### 5.2. Focal mechanism

The best double-couple focal mechanism determined from our surface wave inversion using the default earth models is very similar to that determined from first motions (fig. 2). This suggests that the earthquake rupture was simple, and that there were no major sub-events with a

focal mechanism significantly different from the first-motion solution.

The northeast striking nodal plane is roughly parallel to the regional trend of the bathymetry ( $(35 \pm 5)^\circ$ ) and the predicted plane motion direction ( $41^\circ$ , NUVEL-1 pole, DeMets *et al.*, 1990) so it probably represents the fault plane. The aftershock locations determined by the National Earthquake Information Center (NEIC) are spread out over a large area (fig. 4) and have depths fixed at 10 km so they do not clearly define a fault plane. Relocation of the aftershock could refine this pattern slightly, but only 8 events had  $M_S$  greater than 5.0 and none exceeded 6.0, so the number of well-recorded events suitable for relocation is small.



**Fig. 4.** Aftershocks of the 23 May 1989 Macquarie Ridge earthquake located by the International Seismological Centre for the period from 23 May 1989 to 17 September 1990. The largest dots are events greater than 5.0 and no aftershock exceeded  $m_b$  5.9. The main shock location is shown by a star.

### 5.3. Depth extent of faulting

The centroid depth obtained using surface waves ranges from 15 to 28 km, depending on the model used for earth structure. This range includes other values determined from both body waves and surface waves with simple moment rate functions (table I), although the body wave centroid depths tend to be much shallower than our range. This may suggest that surface waves are sensitive to slip at deeper levels than can be resolved using body waves.

The Moho depth beneath the epicentral area varies from about 12 to 16 km (Williamson, 1988). Our range of possible centroid depths indicates that at least some seismic slip occurred in the upper mantle during the Macquarie Ridge earthquake. If uniform slip occurred, then the base of the rupture extent could range from 30 to 56 km, although uniform slip seems unlikely because of the marked change in physical properties at the Moho. The preliminary determination of hypocentral depth (10 km, NEIC) does not indicate that this was an unusually deep event so it probably initiated at a relatively shallow depth, either within the crust or upper mantle, with slip occurring in both.

Significant rheological differences would exist from the top to the bottom of any fault that ruptures through the crust and into the mantle. Hartzell and Heaton (1988) suggest that under these conditions, the lower section of the fault may not radiate as much high-frequency energy as the upper brittle section. The mantle slip component may therefore have preferentially radiated long-period energy thus producing the apparent discrepancies between the body wave and surface wave durations, moments and centroid depths.

The conditions under which the mantle fails brittly is related to several parameters, such as composition, temperature, pressure and strain rate. Experimental studies have shown that the depth at which the transition from brittle to ductile behaviour occurs in the mantle increases with increasing strain rate (Ashby and Verrall, 1977). At the high strain rates experienced during such a large earthquake, the upper mantle is probably able to deform brittly, while at subcrustal depths smaller aftershocks would not occur. The NEIC aftershocks of the Macquarie Ridge earthquake

are spread over a broad region, and this also supports our interpretation of significant subcrustal deformation, since if slip were concentrated in a narrow zone in the crust, post-earthquake strain redistribution as manifest by aftershocks should be similarly concentrated.

It is known that earthquakes may occur in the upper mantle beneath oceanic crust (Chen and Molnar, 1983) but the Macquarie Ridge earthquake is unusual in probably having seismic slip in both the crust and mantle. Other large normal faulting earthquakes are thought to have ruptured significant thicknesses of the lithosphere (1977 Sumba and 1977 Tonga, Lay *et al.*, 1988; 1933 Sanriuku, Kanamori, 1971), and since all of these events have occurred in regions with oceanic crust, it would probably require an even larger earthquake ( $M_w \sim 8.2$ ) to rupture relatively thicker but weaker continental crust. Major faults in the upper mantle have been recognized in deep seismic profiles in continental regions (*e.g.*, Flannan Fault, Matthews and Cheadle, 1986, Flack *et al.*, 1990). These faults dip at a low angle and are thought to have been normal or thrust faults so they are inappropriate for direct comparison with the Macquarie Ridge tectonic setting but, nevertheless, they suggest that brittle failure has occurred in the mantle. Our model for the rupture process of the Macquarie Ridge earthquake indicates seismic slip on a fault that breaks through both the crust and uppermost mantle.

The effects of rupture directivity of the Macquarie Ridge earthquake are small. Although our results show a preferred azimuth similar to the strike of the northeast striking nodal plane, the actual direction of the rupture propagation cannot be resolved. This is an unexpected result for such a large earthquake. Other earthquakes of similar moment often have well-resolved directivity effects (*e.g.*, 1979 Colombia, Zhang and Kanamori, 1988b) but these are shallow events with dominantly horizontal rupture extent in continental areas. The small directivity effects are probably the result of the downward continuation of slip, which is favoured in this case by the steep dip of the fault in an oceanic crust.

The suggestion that some large earthquakes may involve whole lithosphere failure has important implications. Coseismic failure of the mantle requires either high frictional strength of

the uppermost mantle or at least sufficient strain accumulation that high strain rate loading can drive brittle fracture. Whatever the mechanism by which coseismic failure occurs in the mantle, it means that direct scaling of ground motion and other hazard-related parameters to large-scale strike slip earthquakes should be made with extreme caution. The recognized failure of self-similarity for other large earthquakes is also probably related to brittle failure in regions of significantly different rheology (Hartzell and Heaton, 1988).

## 6. Conclusions and implications

Source process parameters determined for the Macquarie Ridge earthquake by various authors show a significant difference in values obtained from body and surface waves (table I). We have presented a modification of a two-step surface wave inversion method that incorporates a detailed body wave moment rate function and so allows us to determine a unified model for the source process.

Using our unified model we determine ranges for various source parameters. The estimates of process and centroid times are about 93 and 28 s, respectively. This indicates that the moment release was concentrated in the early part of the rupture, and long-period moment release continued for at least 93 s. The best double-couple focal mechanism is well resolved and is very similar to that derived from first motions. The ranges of values of moment  $((1.75 \div 2.11) \times 10^{21}$  Nm) and centroid depth (15 to 28 km) derived using different earth models are large.

The depth range and lack of significant directivity suggest that at least some slip occurred in the mantle during this earthquake. The rupture may have initiated in either the crust or upper mantle but slip probably occurred through the entire lithosphere.

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