PAGEOPH, Vol. 136, No. 4 (1991)

0033-4553/91/040459-19$1.50 + 0.20/0

Partial Breaking of a Mature Seismic Gap: The 1987 Earthquakes in New Britain

R. DMOWSKA,[1,2] L. C. LOVISON-GOLOB[1] and J. J. DUREK[2]

Abstract—To better understand the mechanics of subduction and the process of breaking a mature seismic gap, we study seismic activity along the western New Britain subduction segment (147°E–151°E, 4°S–8°S) through earthquakes with $m_b \geq 5.0$ in the outer-rise, the upper area of subducting slab and at intermediate depths to 250 km, from January 1964 to December 1990. The segment last broke fully in large earthquakes of December 28, 1945 ($M_s = 7.9$) and May 6, 1947 ($M_s = 7.7$), and its higher seismic potential has been recognized by MCCANN *et al.* (1979). Recently the segment broke partially in two smaller events of February 8, 1987 ($M_s = 7.4$) and October 16, 1987 ($M_s = 7.4$), leaving still unbroken areas.

We observe from focal mechanisms that the outer-rise along the whole segment was under pronounced compression from the late 60's to at least October 1987 (with exception of the tensional earthquake of December 11, 1985), signifying the mature stage of the earthquake cycle. Simultaneously the slab at intermediate depths below 40 km was under tension before the earthquake of October 16, 1987. That event, with a smooth rupture lasting 32 sec, rupture velocity of 2.0 km/sec, extent of approximately 70 km and moment of 1.2×10^{27} dyne-cm, did not change significantly the compressive state of stress in the outer-rise of that segment. The earthquake did not fill the gap completely and this segment is still capable of rupturing either in an earthquake which would fill the gap between the 1987 and 1971 events, or in a larger magnitude event ($M_s = 7.7$–7.9), comparable to earthquakes observed in that segment in 1906, 1945 and 1947.

Key words: Subduction zone, New Britain earthquakes, mature seismic gap, earthquake prediction.

Introduction

Recent observational and theoretical work on earthquake cycles in subduction zones (CHRISTENSEN and RUFF, 1983, 1988; ASTIZ and KANAMORI, 1986; DMOWSKA *et al.*, 1988; DMOWSKA and LOVISON, 1988; ASTIZ *et al.*, 1988; LAY *et al.*, 1989) has explained certain seismic phenomena in relation to stress accumulation and release associated with great underthrust events. It has been realized that temporal variations of stress, associated with earthquake cycles, occur in the subducting slab and, as well, in the area of the outer-rise, oceanward from the main zones of subduction earthquakes. In the outer-rise, the bending stresses present

---

[1] Division of Applied Sciences, Harvard University, Cambridge, MA 02138, U.S.A.
[2] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, U.S.A.

become overprinted with tensional stresses in the beginning of the cycle, caused by the slip in the main subduction event. By the latter part of the cycle that has changed to a compressional overprint, occurring because the main thrust zone remains locked while converging motion of the remote ocean floor continues. These factors result in typical tensional outer-rise earthquakes following large subduction events, as well as sporadic compressional ones preceding large subduction events, as documented in the works cited above.

At intermediate depths, in the down-going subducting slab, the tensional stresses caused by slab pull receive a superposed compressional component in the beginning of the cycle, caused by the slip in the main thrust subduction event. In the latter part of the cycle the continuing slab pull and the locking of main thrust zone result in higher tensional stresses at intermediate depths.

We have utilized these new insights when analyzing the mechanics of partial breaking of a mature seismic gap along the western New Britain subduction segment (147°E-152°E, 4°S–8°S). In particular, we have used seismic mechanisms to infer the temporal and spatial changes in stress patterns in the outer-rise and in the downgoing slab caused by the recent partial breaking of the segment in the October 16, 1987 ($m_b = 5.9$, $M_s = 7.4$) earthquake. We have complemented our study by the analysis of the source process of that earthquake.

Tectonic Setting and Seismic History of the New Britain Subduction Segment

The New Britain-Solomon Islands area, east of New Guinea (Figure 1), is characterized by complex interactions between several microplates and high seismicity levels both at the plate interfaces and at intermediate and great depths in the subducted slabs.

The Solomon plate subducts towards NNW under the Bismarck plate along the New Britain trench and towards the northeast under the Pacific plate along the Solomon trench, with a contortion around the junction of the Solomon and New Britain trenches.

In the north, backarc spreading operates along the Bismarck Sea seismic zone, with left-lateral strike-slip movements. This seismic lineation arches from around 2°S, 147°E and enters the Solomon Sea tangentially to the Solomon trench at the convergent region of the Solomon and New Britain trenches, creating in that region a triple junction. Seismic activity in the Bismarck Sea seismic zone is high, and earthquakes with magnitudes larger than 7.0 have occurred there during the past 60 years.

In the south another spreading center is operational along the Woodlark ridge, with weak, shallow seismicity (PASCAL, 1979; LAY and KANAMORI, 1980; COOPER and TAYLOR, 1987).

The Wadati-Benioff zone to the west of the junction between the New Britain and Solomon trenches trends southwest and dips to the northwest at about 70°–75°

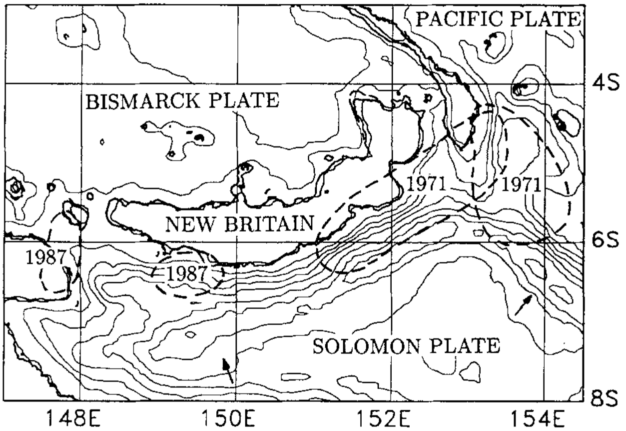


Figure 1
The New Britain subduction segment with aftershock zones of recent large subduction earthquakes (broken line).

(Burbach and Frohlich, 1986). Seismicity extends to about 550 km depth, but a significant gap in activity occurs between about 300 and 500 km. At shallow depth the dip of the slab is around 30° (Jarrard, 1986).

To the west of around 148°E the New Britain trench intersects New Guinea and the seismicity forms two planar zones, one dipping south, and the other dipping north (Burbach and Frohlich, 1986). The northward dipping zone extends to over a 200 km depth and appears to be a continuous extension of the zone east of 148°E. The zone dipping south extends to nearly a 200 km depth. Both the northward and southward dipping seismic zones terminate to the west at around 145°E.

The New Britain subduction segment is moderately coupled, with variations in rupture extent and occasional ruptures reaching 500 km length, with close clustering of large events and doublets (Kanamori, 1981; Christensen and Ruff, 1988).

In eastern New Britain (151°E-153°E) earlier sequences of events (February 2, 1920, $M_s = 7.9$, September 29, 1946, $M_s = 7.7$, April 23, 1953, $M_s = 7.6$, and July 26, 1971, $M_s = 7.7$) have repeatedly ruptured substantial portions of the plate boundary. The recurrence times for this region appear to be very short, only 25 ± 5 y (Lay and Kanamori, 1980). Given that the last event occurred in 1971 (a doublet; the aftershock zones are shown in Figure 1, see also Schwartz *et al.*, 1989), the probability of a large earthquake occurring in that area in the next 10 years is estimated at the 59% level (Nishenko, 1991).

In western New Britain two large earthquakes occurred in 1945 and 1947 (December, 28, 1945, $M_s = 7.9$ and May 6, 1947, $M_s = 7.7$, Table 1, epicenters shown in Figure 2). An event on September 14, 1906 ($M_s = 7.7$, Table 1, Figure 2) is located in this area, but could not be reliably relocated (Nishenko, 1991). If we

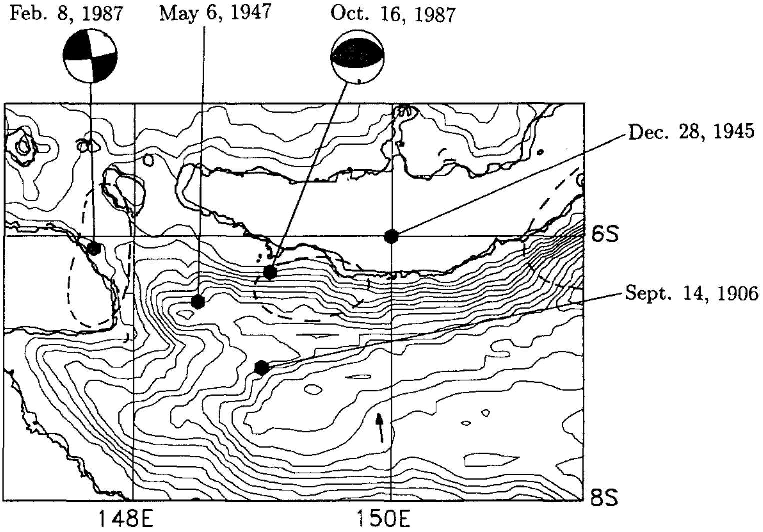


Figure 2
The western New Britain segment with epicenters of large subduction events that occurred in this century. Aftershock zones of recent events shown by broken line. Also shown the CMT solutions for both 1987 earthquakes with $M_s = 7.4$. The direction of plate motion marked by an arrow.

assume that this earlier event was the predecessor to the events in the 1940's, the repeat time is approximately 40 years. The higher seismic potential of western New Britain, based on historic seismicity, has been recognized by McCann *et al.* (1979) in their map of seismic potential of major plate boundaries. Currently Nishenko (1991) estimated the probability of the recurrence of a large earthquake in that area within the next 10 years at the 58% level.

Even if the western New Britain segment did not experience any earthquakes with $M_s \geq 7.5$ since the 1945/1947 events, it ruptured partially in 1987 in two

Table 1

Largest shallow earthquakes in western New Britain in this century

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Sept. 14, 1906	7.00S	149.00E			8.1		GR
Dec. 28, 1945	6.00S	150.00E			7.8		GR
May 6, 1947	6.50S	148.50E	30		7.5		AS87
Feb. 8, 1987	5.94S	147.79E	34	5.8	7.4	S	ISC/HAR
Oct. 16, 1987	6.25S	149.09E	24	5.9	7.4	C	PDE/HAR

AS87—Astiz, 1987; GR—magnitude from Gutenberg and Richter, 1949; HAR—centroid moment tensor solutions by the Harvard group; ISC—Bullet. Intern. Seismol. Center; PDE—Prelim. Deter. of Epic., USGS; C—compr., S—strike-slip focal mechanisms.

earthquakes with $M_s = 7.4$ (February 8, 1987, $m_b = 5.8$ and October 16, 1987, $m_b = 5.9$, Table 1; the 10-day aftershock zones are shown in Figure 1 and focal mechanisms in Figure 2). These earthquakes certainly did not fill the gap recognized by McCANN *et al.* (1979) and NISHENKO (1991). Their size, however, was significant enough for us to decide to look into the subduction of that part of the New Britain segment, with particular attention given to the outer-rise and intermediate depth earthquakes and their mechanisms, with the aim to better understand the mechanics of partial breaking of a mature seismic gap. A preliminary report of our work has been presented earlier (LOVISON *et al.*, 1988).

The 1987 ($M_s = 7.4$) Earthquakes in New Britain

Two earthquakes with $M_s = 7.4$ occurred in western New Britain in 1987.

The first one ruptured the western end of the New Britain subduction segment on February 8, 1987 ($m_b = 5.8$, hypocentral depth 34 km, 10-day aftershock zone and mechanism shown in Figure 2). It was a strike-slip event with a slight reverse component. The length of the ruptured area was approximately 120 km, and the width 45 km.

The other $M_s = 7.4$ earthquake occurred on October 16, 1987 ($m_b = 5.9$, 10-day aftershock zone and mechanism shown in Figure 2) in the middle of the western segment of New Britain, recognized as a seismic gap by McCANN *et al.* (1979) and NISHENKO (1991). It was a shallow, thrust event; the length of the rupture zone was approximately 100 km, and the width 60 km, the duration of rupture process was 32 seconds. The distribution of the few catalogued aftershocks suggested a dominant component of rupture to the east-northeast, but poorly constrained the extent of rupture. We have analyzed the rupture process of that earthquake and the results are presented in the next section.

Analysis of the Source Process of the October 16, 1987 New Britain Earthquake

We have applied recently developed source inversion methods, which resolve spatial and temporal variations in the rupture process. The particular inversion method employed, the very broad-band (VBB) technique developed by EKSTRÖM (1987, 1989), combines the analysis of broad-band P-wave phases with results of the centroid-moment tensor (CMT) inversion of long-period body and mantle wave seismograms (DZIEWONSKI *et al.*, 1981). Because an earthquake source is completely described by the moment-density rate tensor $\dot{m}_{ij}(\mathbf{x}, t)$, its determination is the objective of the inversion process. However, the actual spatial and temporal distribution of the moment rate tensor is difficult to constrain with a finite number of observations, forcing an approximation of $\dot{m}_{ij}(\mathbf{x}, t)$ to be adopted. A parameterization of the moment density rate tensor, which is enlightening while remaining practical to apply, consists of a linearly propagating point source. The seismic source is represented by a focal mechanism, given by the normalized zero-order moment tensor, a source time function describing the rate of moment release, and a point source initially at location $\mathbf{x}_0$, with a directivity vector $\mathbf{v}$:

$$\dot{m}_{ij}(\mathbf{x}, t) = \{M_{ij}/M_0\} \times F(t - t_0) \times \delta(\mathbf{x} - \mathbf{x}_0 - (t - t_0)\mathbf{v}). \tag{1}$$

Such a parameterization approximately characterizes all but the most complex of sources, in which case additional model complexity must be introduced (see EKSTRÖM, 1987).

In contrast to other studies, the VBB technique combines GDSN long-period and triggered short-period records and deconvolves for broad-band ground displacement (flat response from 1 to 100 Hz) to form the set of observations to be inverted. The obvious advantage of using displacement records is that $\dot{m}_{ij}(\mathbf{x}, t)$ is directly related to ground displacement. The arrival times are manually picked to provide proper alignment of the observed and synthetic seismograms, a necessary process which unfortunately removes travel time information about the epicentral location. The focal depth, however, is constrained by the shapes and arrival times of the depth phases *pP* and *sP* given an accurate model for the structure of the source region. During the inversion, the source parameters defined in equation (1), as well as the focal depth, are determined using a standard iterative least-squares technique in which the robust CMT long-period mechanism is employed as a weighted constraint.

The CMT solution for the October 16, 1987 event indicates a shallow thrust mechanism which is consistent with the tectonic regime. The predicted CMT depth of 48 km seems too deep for the region. It has been observed (EKSTRÖM, 1987) that the CMT inversion tends to overestimate the focal depth in certain geographical regions, most likely the result of high-frequency deviations of the source region structure from the weakly heterogeneous earth model used for calculation of the synthetic seismograms in the CMT analysis.

In applying the VBB method, ten deconvolved records were available. The model for the structure of the source region includes a two-layer crust with a 3 km surface water layer (Table 2). The final source solution is presented in Figure 3 and possesses a normalized residual variance of only 0.046. Records from the two stations SNZO and NWAO, which lie near the nodal plane, were not included in the final inversion. The predicted seismograms were calculated for these stations, however, and the general agreement in shape is good, considering the reduced signal-to-noise ratio near the nodal plane. The remaining stations reveal simple pulses indicative of an unusually uniform rupture. The inversion corroborates the smooth rupture process, retrieving a source time function with a dominant low frequency component. The temporal extent of the rupture was 32 seconds, although the source time function was unconstrained up to 40 seconds. The smooth source time

Table 2

Crustal velocity structure used in the VBB calculation of synthetic seismograms

Depth range (km)	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (g/cm^3)
0.0–3.0	1.52	0.00	1.02
3.0–15.0	5.80	3.20	2.60
15.0–24.4	6.80	3.90	2.90
24.4–64.4	8.10	4.50	3.40
64.4		PREM	

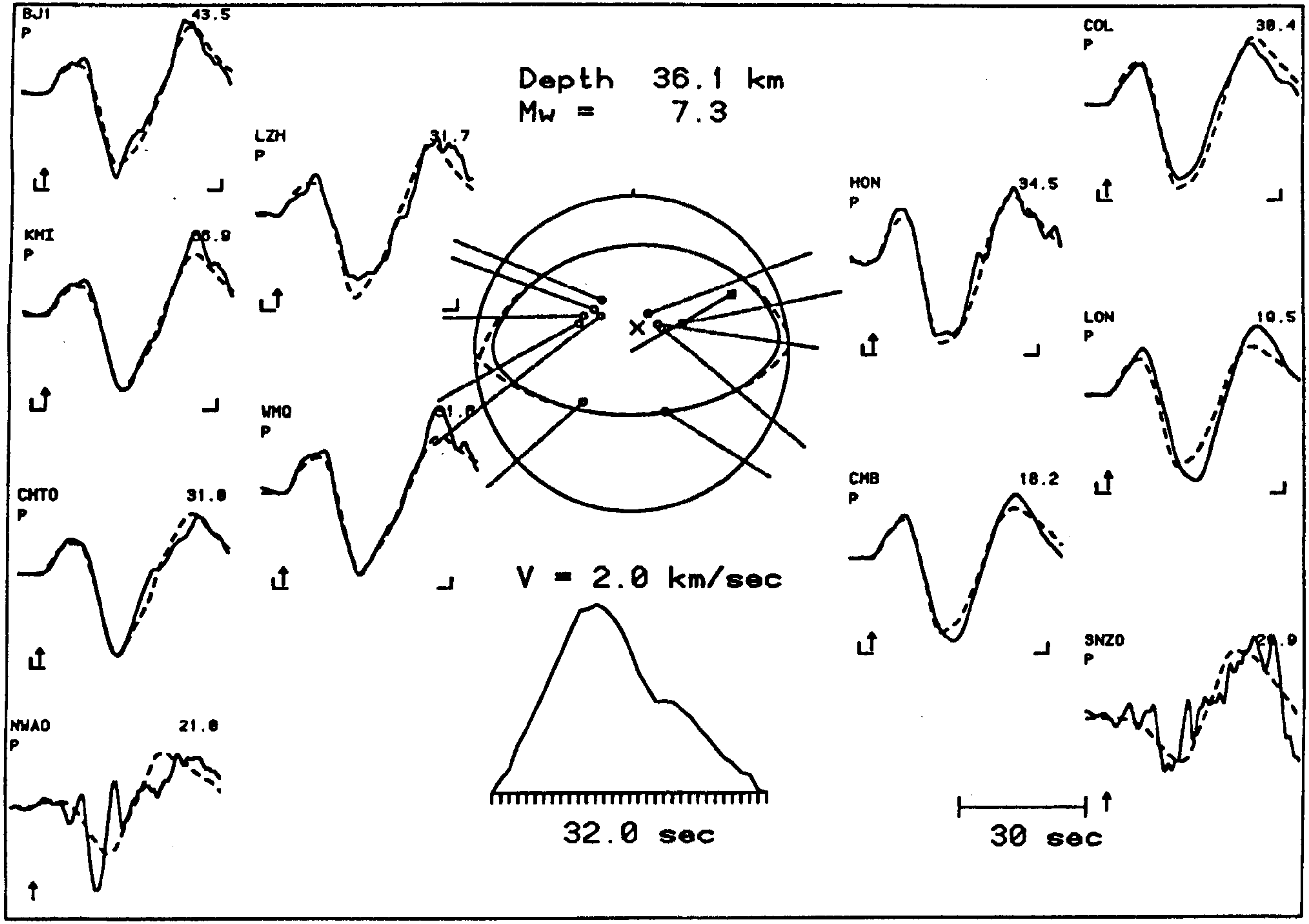
function suggests that the fault rupture was nearly uniform with no significant asperities or barriers to modify the rupture propagation. The fault plane solution does not significantly deviate from the CMT solution of a shallow thrust mechanism (Table 3). The moment of 1.2×10^{27} dyne-cm determined by the VBB inversion is consistent with that determined by the CMT inversion, while the resolved focal depth of 36 km is appreciably shallower than that of the CMT solution and more consistent with the regional tectonics. However, when investigating a large event the wave forms are more dominated by the shape of the source time function and the depth phases inverted to constrain the depth are suppressed by direct arrivals from the source. In such a case the VBB inversion experiences a diminished sensitivity to depth. Further inversions with a depth fixed at 25 km resulted in marginally poorer fits and unacceptable alterations of the selected arrival times, allowing the conclusion that the focal depth was not likely to be less than 30 km.

The directivity vector describing the centroid propagation has a trend of N59°E, a plunge of 26°, and is essentially contained within the fault plane. The rupture velocity of 2.0 km/sec, combined with the source duration of 32 seconds, requires a lower limit of approximately 60 km of breakage. Both the direction and extent of rupture obtained from the VBB analysis are consistent with the limited aftershock distribution.

Table 3

CMT and VBB moment tensor comparisons

Moment Tensor ($\times 10^{27}$ dyne–cm)		
	CMT solution	VBB solution
$M_{\tau\tau}$	1.15	1.13
$M_{\theta\theta}$	−1.11	−1.10
$M_{\phi\phi}$	−0.05	−0.04
$M_{\tau\theta}$	0.54	0.50
$M_{\tau\phi}$	0.04	−0.04
$M_{\phi\phi}$	−0.07	−0.08


BJI
P
43.5
KMI
P
CHTO
P
31.0
NWAO
P
21.0
LZH
P
31.7
WMQ
P
21.0
Depth 36.1 km
Mw = 7.3
V = 2.0 km/sec
32.0 sec
HON
P
34.5
CMB
P
18.2
COL
P
30.4
LON
P
10.5
SNZO
P
20.9
30 sec

Mechanical Behavior of the Outer-Rise

In order to analyze any temporal and/or spatial changes in the state of stress in the outer-rise area of the western New Britain, we show the seismicity in that area in Figures 4 and 5. The CMT solutions are presented when available. All earthquakes are listed in Tables 4 and 6, with mechanisms, if known.

Figure 4 presents the earthquakes with $m_b \geq 5.0$ for the period between January 1, 1964 and October, 16, 1987, that is for as long time as possible before the October 1987 earthquake which partially ruptured that segment. The data for the period January 1, 1964 to July 31, 1987 are taken from the ISC catalogue, and for August 1, 1987 to October 16, 1987 from the USGS PDE catalogue. We are aware of the differences in confidence levels of these catalogues. However, we would like to cover the longest time periods possible.

The compressional state of stress, characteristic of the outer-rise areas adjacent to mature seismic gaps (DMOWSKA *et al.*, 1988; DMOWSKA and LOVISON, 1988; CHRISTENSEN and RUFF, 1988; ASTIZ *et al.*, 1988; LAY *et al.*, 1989) has been

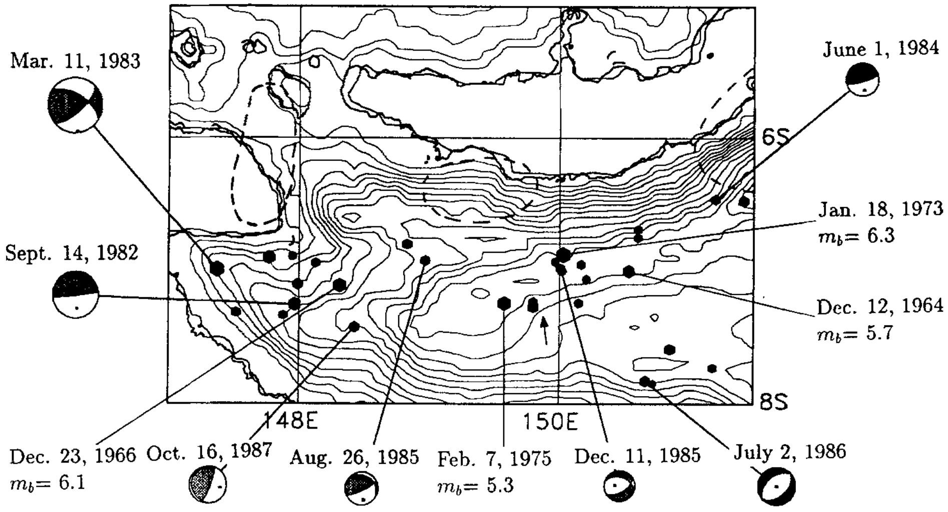


Figure 4
Epicenters of earthquakes with $m_b \geq 5.0$ in the outer-rise area of western New Britain for period January 1, 1964 to October 16, 1987.

Figure 3
Source solution for the New Britain event of October 16, 1987 as obtained by the VBB analysis of EKSTRÖM (1987). The source mechanism is shown in lower hemisphere projection. For each station, the observed record is solid, while the synthetic seismogram is dotted. The arrows indicate the selected P-wave arrival times and brackets the data windows used for inversion. The directivity vector is plotted on the focal sphere with the arrow denoting the direction of centroid propagation.

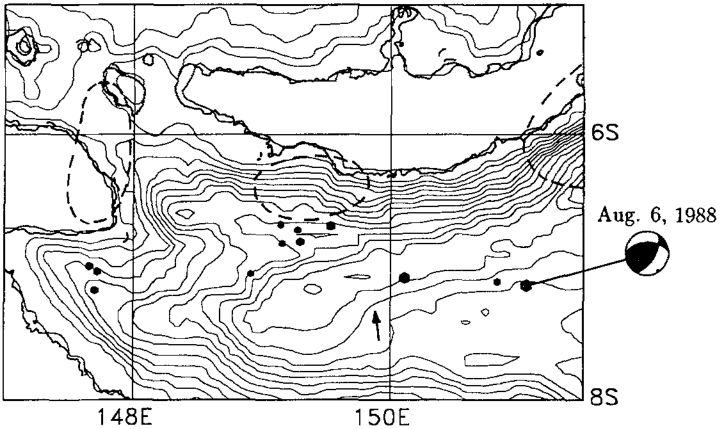


Figure 5
Epicenters of earthquakes with $m_b \geq 4.5$ in the outer-rise area of western New Britain for period October 16, 1987 to December 31, 1990.

recognized in that segment by CHRISTENSEN and RUFF (1988), based on two compressional earthquakes, one in the western end of the trench area, on December 23, 1966 ($m_b = 6.1$), and the other in the middle of the segment, on January 18, 1973 ($m_b = 6.3$). We can add to that list two other compressional events that occurred later, namely the June 1, 1984 event ($m_b = 5.2$), and the August 26, 1985 event ($m_b = 5.2$). Both earthquakes are shown in Figure 4 with their CMT solutions. All these events suggest that before the October 16, 1987 earthquake, that partially ruptured the area, the outer-rise has been indeed in the compression dominated state of stress along the whole western segment of the New Britain, signaling the maturity of that segment.

Because of the tectonic complexity of the western end of the New Britain trench, that is the area around 147°E–148°E, we do not attempt to interpret the mechanisms of earthquakes in that area (Figure 4).

We comment here on an outer-rise earthquake that slightly puzzled CHRISTENSEN and RUFF (1988) during their analysis of the state of stress in the New Britain segment. This is the tensional event of December 11, 1985 (shown with its CMT solution in Figure 4), that occurred near the January 18, 1973 compressional earthquake. CHRISTENSEN and RUFF (1988) suggested that the accumulated compressional stress has been dissipated by some mechanism such as aseismic slip in the subduction zone following the compressional outer-rise event. We have found that a cluster of other tensional earthquakes with $5.0 \leq m_b \leq 5.7$ occurred during a few days in September 1985, that is a few months earlier than the outer-rise event, in or close to the thrust contact zone adjacent to the outer-rise earthquake. The cluster is shown in Figure 6, with CMT solutions when known, and the earthquakes are listed in Table 5.

Table 4

Earthquakes with $m_b \geq 5.0$ in the outer-rise area of western New Britain, January 1, 1964–October 16, 1987

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Dec. 12, 1964	7.00S	150.54E	33	5.7			ISC
Aug. 26, 1966	7.31S	147.52E	60	5.3			ISC
Dec. 23, 1966	7.11S	148.31E	46	6.1		C	ISC/JM
Dec. 30, 1967	6.69S	150.61E	26	5.0			ISC
Feb. 26, 1970	6.95S	150.17E	37	5.0			ISC
Apr. 30, 1971	7.24S	150.15E	27	5.1			ISC
Jan. 18, 1973	6.88S	150.03E	38	6.3		C	ISC/P79
Feb. 23, 1973	6.98S	150.01E	40	5.2			ISC
Dec. 4, 1974	7.33S	147.88E	60	5.0			ISC
Feb. 7, 1975	7.24S	149.58E	9	6.2			ISC
Feb. 7, 1975	7.23S	149.80E	15	5.3			ISC
Feb. 25, 1975	7.27S	149.80E	21	5.5			ISC
Aug. 14, 1975	6.90S	147.77E	53	5.8			ISC
June 9, 1976	6.47S	151.43E	21	5.5			ISC
Aug. 19, 1976	7.06S	150.21E	36	5.0			ISC
May 10, 1977	7.73S	151.19E	13	5.1			ISC
Oct. 14, 1980	6.80S	148.83E	59	5.3			ISC
June 10, 1981	6.94S	148.13E	50	5.2	5.0		ISC
Sept. 14, 1982	7.25S	147.97E	34	5.3	6.3	C	ISC/HAR
Nov. 28, 1982	6.75S	150.61E	33	5.0			ISC
Mar. 11, 1983	6.99S	147.37E	66	5.9		C	ISC/HAR
June 1, 1984	6.46S	151.21E	16	5.2		C	HAR
June 6, 1984	6.89S	147.95E	53	5.0			ISC
June 9, 1984	7.10S	147.99E	57	5.4			ISC
Jan. 9, 1985	6.50S	150.50E	11	5.3	4.5		ISC
Mar. 16, 1985	6.93S	149.97E	51	5.0			ISC
Aug. 26, 1985	6.92S	148.97E	33	5.2	6.1	C-S	ISC/HAR
Dec. 11, 1985	7.00S	150.02E	29	5.3		T	ISC/HAR
May 27, 1986	7.85S	150.73E	33	5.7	4.6		ISC
May. 31, 1986	7.59S	150.86E	10	5.4			ISC
July. 2, 1986	7.83S	150.67E	19	5.5	4.8	T	ISC/HAR
Oct. 16, 1987	7.42S	148.43E	39	5.4	4.5	C-S	PDE/HAR

HAR—centroid moment tensor solutions by the Harvard group; ISC—Bullet. Intern. Seismol. Center; JM—Johnson and Molnar, 1972; P79—Pascal, 1979; PDE—Prel. Determ. of Epic.—USGS; C—compr., T—tens., S—strike-slip focal mechanisms.

Such tensional earthquakes are unusual in or close to the thrust contact zone, as unusual as a tensional outer-rise earthquake in the area adjacent to a mature seismic gap. The cluster and the outer-rise event are in the same subducting strip of the oceanic crust (see Figures 4 and 6). We infer that it is mechanically plausible that an aseismic slip downdip from that area, perhaps along the lower part of the interface between the slab and the Bismarck plate, caused a temporary tensional state of stress in the area of cluster and in the outer-rise as well. We have inferred

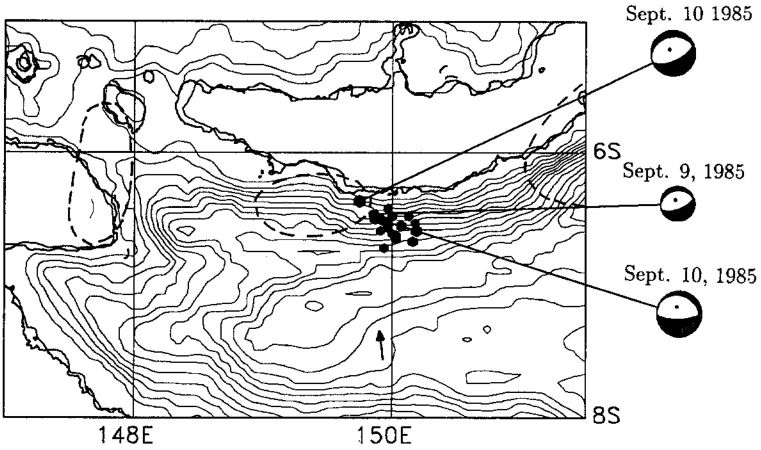


Figure 6
Cluster of tensional earthquakes in or close to the thrust contact zone or in the pretrench area from September 1985.

Table 5

Cluster of earthquakes with $m_b \geq 5.0$ *from September 1985*

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Sept. 9, 1985	6.47S	149.86E	19	5.5	5.3	T	ISC/HAR
Sept. 10, 1985	6.50S	149.87E	37	5.1	4.8	T	ISC/HAR
Sept. 10, 1985	6.37S	149.75E	10	5.7	6.3	T	ISC/HAR
Sept. 10, 1985	6.53S	149.97E	19	5.0			ISC
Sept. 10, 1985	6.73S	149.94E	49	5.1			ISC
Sept. 10, 1985	6.43S	149.97E	46	5.4	5.1		ISC
Sept. 10, 1985	6.58S	149.97E	33	5.1			ISC
Sept. 10, 1985	6.54S	150.18E	41	5.0			ISC
Sept. 10, 1985	6.56S	150.07E	10	5.4			ISC
Sept. 10, 1985	6.64S	150.03E	10	5.4			ISC
Sept. 10, 1985	6.60S	150.19E	33	5.4			ISC
Sept. 10, 1985	6.68S	150.16E	10	5.3			ISC
Sept. 10, 1985	6.66S	150.03E	10	5.3			ISC
Sept. 11, 1985	6.49S	150.13E	33	5.0			ISC
Sept. 11, 1985	6.62S	150.00E	22	5.1			ISC
Sept. 11, 1985	6.60S	149.91E	33	5.0			ISC
Sept. 12, 1985	6.52S	149.93E	33	5.2			ISC
Sept. 14, 1985	6.49S	150.00E	50	5.1			ISC

HAR—centroid moment tensor solutions by the Harvard group; ISC—Bullet. Intern. Seismol. Center; T—tens. focal mechanisms.

similar events along the Mexico convergent plate boundary (though they were smaller, causing only temporary quietening of thrust events), and we modelled such interactions as well (DMOWSKA *et al.*, 1988).

The outer-rise earthquakes in the western segment of New Britain after its partial breaking, that is after October 16, 1987, are shown in Figure 5 with CMT solutions when available, and are listed in Table 6. The data are taken from the USGS PDE catalogue and cover the period until December 31, 1990, for events with $m_b \geq 4.5$.

There is a cluster of small events in the pretrench area adjacent to the aftershock zone of the October 16, 1987 earthquake, the largest with $m_b = 5.1$. We do not have their mechanisms, but we would expect them to be classical tensional earthquakes that follow a subduction event; many of such earthquakes have been observed in the New Britain and Solomon trenches after the 1971 and 1975 interplate doublets (LAY *et al.*, 1989).

The largest event, shown in Figure 5 with its CMT solution, is a compressional earthquake, with a strike-slip component, in front of the unbroken part of the subduction segment.

We infer from Figure 5, that the state of stress in the outer-rise along the western segment of New Britain did not change dramatically as a result of the partial breaking of the segment and that it is still compressional, typical for the outer-rise areas adjacent to mature seismic gaps (see e.g., DMOWSKA *et al.*, 1988; CHRISTENSEN and RUFF, 1988; DMOWSKA and LOVISON, 1988).

Table 6

Earthquakes with $m_b \geq 4.5$ in the outer-rise area of western New Britain, October 16, 1987–December 31, 1990

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Oct. 17, 1987	7.05S	148.91E	33	4.5			PDE
Oct. 20, 1987	6.82S	149.16E	33	4.6			PDE
Nov. 2, 1987	6.81S	149.30E	43	4.8			PDE
Jan. 5, 1988	7.17S	147.70E	63	4.9			PDE
Feb. 11, 1988	6.69S	149.54E	23	5.1			PDE
July 5, 1988	6.72S	149.28E	33	4.6			PDE
Aug. 6, 1988	7.14S	151.06E	25	5.9	5.7	C-S	PDE/HAR
Dec. 6, 1988	6.99S	147.66E	56	4.9			PDE
May 28, 1989	7.03S	147.72E	33	4.7			PDE
July 27, 1989	7.11S	150.83E	33	4.6			PDE
Apr. 25, 1990	7.08S	150.11E	2	5.4			PDE
June 16, 1990	6.68S	149.15E	5	4.6			PDE

HAR—centroid moment tensor solutions by the Harvard group; PDE—Prel. Determ. of Epic.—USGS; C—compr., S—strike-slip focal mechanisms.

Mechanical Behavior of the Slab at Intermediate Depths

The New Britain subduction segment is characterized by abundant seismicity at intermediate depths, with numerous tear faults and oblique mechanisms suggesting the complexity of the intraplate stress regime. The steep dip of the subducting slab presents some difficulty in distinguishing intraplate tensional events from interplate thrusts. Also, there is a general tendency for the catalogue source depths of large interplate events in this region to be greater than in other zones. With all these limitations in mind we will analyze here the mechanical behavior of the slab at intermediate depths before and after the partial rupturing of the segment in the October 16, 1987 earthquake.

Table 7

Earthquakes with $m_b \geq 5.7$ at intermediate depths (40 km to 250 km) in western New Britain, January 1, 1964–October 16, 1987

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Jan. 14, 1964	5.21S	150.83E	169	5.7			ISC
July 31, 1964	6.01S	149.36E	58	5.7			ISC
Nov. 17, 1964	5.75S	150.74E	60	6.3		T	ISC/JM
Dec. 7, 1964	5.39S	151.24E	70	5.7		T	ISC/JM
March 4, 1965	5.46S	147.00E	191	5.7			ISC
Sept. 22, 1965	5.35S	151.49E	62	5.7		S	ISC/C73
Apr. 1, 1966	5.81S	149.19E	97	5.7			ISC
Sept. 16, 1968	6.08S	148.77E	49	5.9			ISC
Mar. 10, 1969	5.60S	147.29E	194	5.7			ISC
Nov. 16, 1970	6.05S	148.55E	80	5.7			ISC
Feb. 27, 1975	6.07S	148.21E	72	5.8			ISC
May 22, 1976	5.60S	148.35E	164	5.9			ISC
Jan. 24, 1978	5.97S	148.87E	95	5.7	5.4	S	ISC/HAR
Oct. 15, 1978	5.61S	148.08E	168	5.7	4.9	C	ISC/HAR
Nov. 1, 1979	5.91S	150.19E	56	5.7	5.5		ISC
Feb. 27, 1980	6.02S	150.12E	52	5.9	6.7	T	ISC/HAR
Feb. 27, 1980	6.04S	150.01E	55	5.8			ISC
Feb. 24, 1981	6.04S	148.77E	79	5.8	6.5	T	ISC/HAR
Aug. 26, 1981	5.34S	151.48E	67	5.9		T	HAR
June 9, 1982	5.66S	150.99E	80	5.8		T	ISC/HAR
Jan. 16, 1983	5.45S	147.05E	228	5.8		S-T	ISC/HAR
Jan. 26, 1983	6.13S	150.05E	47	5.7		S	HAR
May 10, 1983	5.40S	150.94E	116	6.0		S	ISC/HAR
Sept. 30, 1984	6.05S	148.49E	77	5.7		T	ISC/HAR
Dec. 30, 1985	5.53S	150.69E	116	5.8		T	ISC/HAR
Aug. 20, 1986	5.32S	151.33E	92	5.7		S	ISC/HAR
May. 12, 1987	5.30S	151.33E	107	5.7		S-T	ISC/HAR

C73—Curtis, 1973; HAR—centroid moment tensor solutions by the Harvard group; ISC—Bullet. Inter. Seism. Center; JM—Johnson and Molnar, 1972; C—compr., T—tens., S—strike-slip focal mechanisms.

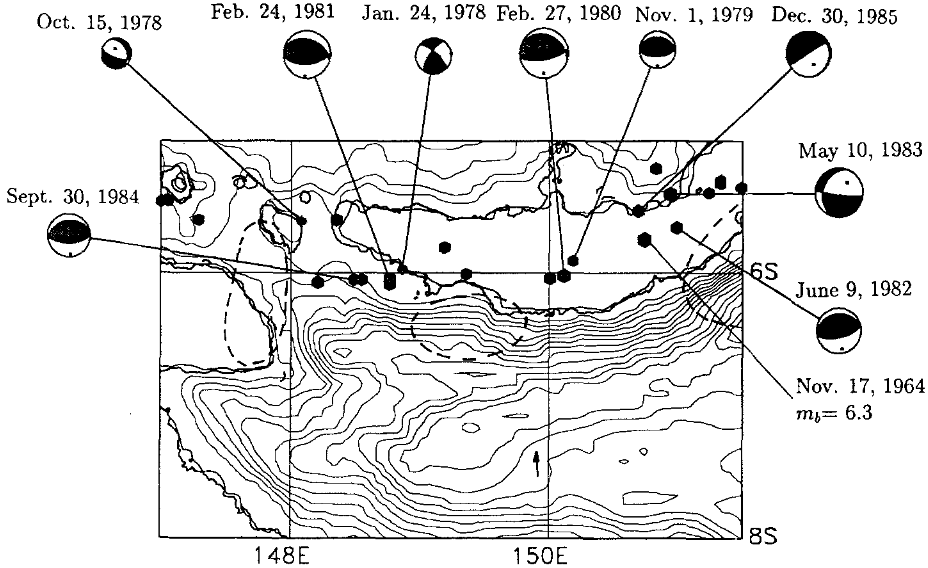


Figure 7
Epicenters of earthquakes with $m_b \geq 5.7$ at intermediate depths (40–250 km) in the area downdip from western New Britain, for the period January 1, 1964 to October 16, 1987.

Because of the abundant seismicity, we are limiting our search to the earthquakes with $m_b \geq 5.7$ only. Epicenters of such events, located at depths 40 km to 250 km downdip from the western segment of New Britain, during the period between January 1, 1964 and October 16, 1987, are shown in Figure 7 and are listed in Table 7. Data are taken from the ISC catalogues for the period between January 1, 1964 and July 31, 1987, and from the USGS PDE catalogue for the period between August 1, 1987 and October 16, 1987. The CMT solutions of earthquakes located downdip from the segment between the February 8, 1987 aftershock zone and the western end of the 1971 aftershock zone are shown in Figure 7, if available.

As mentioned before, the western segment of New Britain ruptured fully in 1945 and 1947 earthquakes, so, with approximately 40 years recurrence time, we are investigating the mechanical behavior of the slab at intermediate depths for approximately the second half of the current, not yet closed, cycle.

In general the slab at intermediate depths is characterized by the tensional state of stress, as inferred from the mechanisms of larger ($m_b \geq 5.7$) earthquakes (Figure 7). At that level of magnitude there is no observable increase in the number of tensional earthquakes downdip from the October 16, 1987 event, that partially ruptured the segment. However in the 1980's there were many more tensional events at intermediate depths (see Table 7) downdip from the unbroken

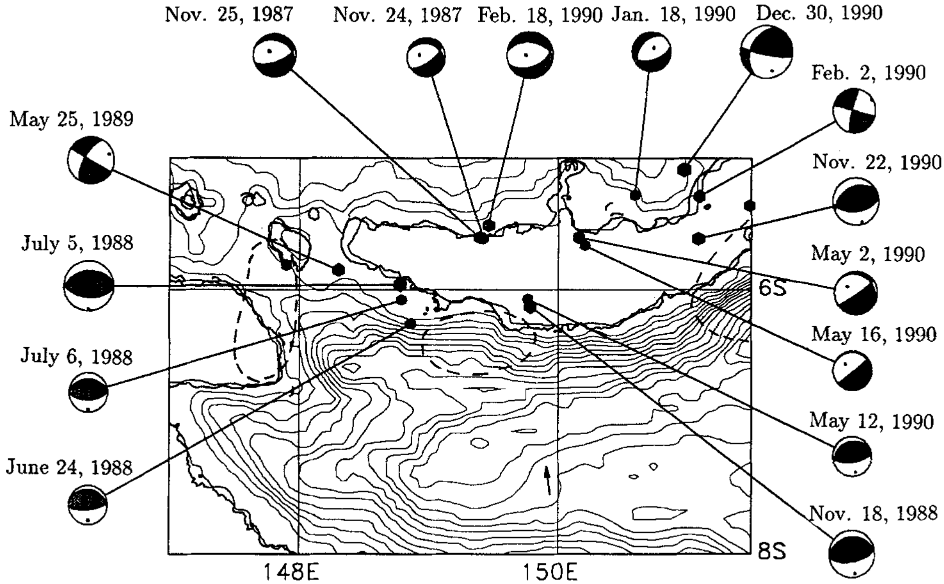


Figure 8
Epicenters of earthquakes with $m_b \geq 5.5$ at intermediate depths (40–250 km) in the area downdip from western New Britain, for the period October 16, 1987 to December 31, 1990.

Table 8

Earthquakes with $m_b \geq 5.5$ *at intermediate depths (40 km to 250 km) in western New Britain, October 16, 1987–December 31, 1990*

Date	Lat. (°)	Lon. (°)	Depth (km)	m_b	M_s	F. M.	Ref.
Nov. 24, 1987	5.61S	149.42E	142	5.5		C	PDE/HAR
Nov. 25, 1987	5.60S	149.39E	141	5.7		C	PDE/HAR
June 24, 1988	6.26S	148.86E	42	5.5	5.3	C	PDE/HAR
July 5, 1988	5.96S	148.78E	53	6.0	6.8	C	PDE/HAR
July 6, 1988	6.08S	148.79E	67	5.5		C	PDE/HAR
Aug. 5, 1988	5.81S	147.90E	141	5.5			PDE
Nov. 18, 1988	6.13S	149.79E	61	5.8	6.4	C	PDE/HAR
May 25, 1989	5.85S	148.30E	112	5.9		S	PDE/HAR
Jan. 18, 1990	5.28S	150.60E	136	5.6		C	PDE/HAR
Feb. 2, 1990	5.29S	151.10E	44	5.7	5.5	S	PDE/HAR
Feb. 18, 1990	5.51S	149.46E	144	5.9		C	PDE/HAR
May 2, 1990	5.60S	150.16E	82	6.2		C	PDE/HAR
May 12, 1990	6.07E	149.77E	74	5.6		C	PDE/HAR
May 16, 1990	5.66S	150.21E	77	5.6		C	PDE/HAR
Nov. 22, 1990	5.61S	151.09E	45	5.9	6.0	C	PDE*/HAR
Dec. 24, 1990	5.36S	151.49E	49	5.7	5.6	C	PDE*/HAR
Dec. 30, 1990	5.09S	150.98E	188	6.7	7.0	S	PDE*/HAR

HAR—centroid moment tensor solutions by the Harvard group; PDE—Prel. Determ. of Epic.; * weekly list—USGS; C—compr., S—strike-slip.

segment between the October 16, 1987 and 1971 earthquakes (it should be noted here that we interpret the mechanisms according to the direction along the dipping slab). This observation suggests that that part of the subducting slab is under increased tension, typical for areas downdip from a mature seismic gap (ASTIZ *et al.*, 1988; LAY *et al.*, 1989).

Figure 8 shows seismicity at the same depth for the period between October 16, 1987 and December 31, 1990, data being taken from the USGS PDE catalogue. All earthquakes are listed in Table 8 with their mechanisms, if known. Because this is a short period of time, we show seismicity at $m_b \geq 5.5$ level, slightly lower than in Figure 7. In spite of this we could not add any significant new observation, and we must conclude that the slab at intermediate depths downdip from the western segment of New Britain is still under tension.

Discussion and Conclusions

We have investigated in detail the seismicity in the outer-rise and downdip areas adjacent to the western segment of New Britain, which broke fully in the 1945 and 1947 earthquakes, and partially in the October 16, 1987 event. The outer-rise is currently in compression, and the slab at intermediate depths under tension, characteristic of outer-rise and downdip areas adjacent to mature seismic gaps. These observations, added to the fact that the segment has an approximate recurrence time of 40 years (NISHENKO, 1991), suggest that it might rupture in the nearest 10 years or so. Unfortunately our observations concerning the state of stress in the outer-rise and at intermediate depths are of only intermediate-term precursors (see also DMOWSKA and LOVISON, 1988), and we are not able to make this prediction more specific. Also, our observations do not allow us to comment on the future mode of rupture of that segment: it might break in an earthquake filling only the gap between the 1971 and 1987 earthquakes (the length of that segment is approximately 150 km), or the whole western segment could rupture in one event with $M_s = 7.7-7.9$, similar to the magnitudes of the 1945 and 1947 events.

It is plausible that the situation in western New Britain is mechanically similar to that of the Michoacan, Mexico, where the earthquake of Playa Azul on October 25, 1981 ($M_s = 7.3$) occurred in the central part of the area identified previously as a seismic gap (Michoacan gap, KELLEHER *et al.*, 1973) along the Cocos-North American convergent plate boundary, rupturing an area of about $40 \times 20\ \mathrm{km}^2$. Subsequently, the whole gap broke on September 19, 1985 in the $M_s = 8.1$ Michoacan earthquake. It is perhaps worth noting that even after the Playa Azul earthquake, the seismic potential of the gap could not have been defined with any precision (HAVSKOV *et al.*, 1983; LEFEVRE and MCNALLY, 1985).

Acknowledgements

We would like to thank many people who discussed with us over the years the issues of subduction mechanics. They include Kei Aki, Susan Beck, Doug Christensen, Hiroo Kanamori, Thorne Lay, Jim Rice, Larry Ruff, Susan Schwartz, Bill Spence, Bill Stuart and Bart Tichelaar. Also, we are grateful to Adam Dziewonski and Göran Ekström for many discussions and for smoothing our data retrieval efforts. Göran Ekström also provided his VBB inversion algorithms.

The research was supported primarily by the USGS, under grants 14-08-0001-G-1367 and 1788, and in part by NSF, under grant EAR-90-04556.

REFERENCES

ASTIZ, L. (1987), I. *Source Analysis of Large Earthquakes in Mexico.* II. *Study of Intermediate-depth Earthquakes and Interplate Seismic Coupling*, Ph.D. Thesis.

ASTIZ, L., and KANAMORI, H. (1986), *Interplate Coupling and Temporal Variation of Mechanisms of Intermediate-depth Earthquakes in Chile*, Bull. Seismol. Soc. Am. *76*, 1614-1622.

ASTIZ, L., LAY, T., and KANAMORI, H. (1988), *Large Intermediate Depth Earthquakes and the Subduction Process*, Phys. Earth Planet. Inter. *53*, 80-166.

BURBACH, G. V., and FROHLICH, C. (1986), *Intermediate and Deep Seismicity and Lateral Structure of Subducted Lithosphere in the Circum-Pacific Region*, Rev. Geophys. *24*, 833-874.

CHRISTENSEN, D. H., and RUFF, L. J. (1983), *Outer-rise Earthquakes and Seismic Coupling*, Geophys. Res. Lett. *10*, 697-700.

CHRISTENSEN, D. H., and RUFF, L. J. (1988), *Seismic Coupling and Outer-rise Earthquakes*, J. Geophys. Res. *93*, 13421-13444.

COOPER, P., and TAYLOR, B. (1987), *Seismotectonics of New Guinea: A Model for Arc Reversal Following Arc-continent Collision*, Tectonics *6*, 53-67.

CURTIS, J. W. (1973), *The Spatial Seismicity of Papua New Guinea and the Solomon Islands*, J. Geol. Soc. Australia *20*, 1-20.

DMOWSKA, R., and LOVISON, L. C. (1988), *Intermediate-term Seismic Precursors for Some Coupled Subduction Zones*, Pure Appl. Geophys. *126*, 643-664.

DMOWSKA, R., RICE, J. R., LOVISON, L. C., and JOSELL, D. (1988), *Stress Transfer and Seismic Phenomena in Coupled Subduction Zones During the Earthquake Cycle*, J. Geophys. Res. *93*, 7869-7884.

DZIEWONSKI, A. M., CHOU, T. A., and WOODHOUSE, J. H. (1981), *Determination of Earthquake Source Parameters from Waveform Data for Studies of Global and Regional Seismicity*, J. Geophys. Res. *86*, 2825-2852.

EKSTRÖM, G. A. (1987), *A Broad Band Method of Earthquake Analysis*, Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

EKSTRÖM, G. A. (1989), *A Very Broad Band Inversion Method for the Recovery of Earthquake Source Parameters*. Tectonophysics. *166*, 73-100.

GUTENBERG, B., and RICHTER, C. F, *Seismicity of the Earth* (1949).

HAVSKOV, J., SINGH, S. K., NAVA, E., DOMINGUEZ, T., and RODRIGUEZ, M. (1983), *Playa Azul, Michoacan, Mexico, Earthquake of 25 October, 1981* ($M_s = 7.3$), Bull. Seismol. Soc. Am. *73*, 449-458.

JARRARD, R. D. (1986), *Relations Among Subduction Parameters*, Rev. Geophys. *24*, 217-284.

JOHNSON, T., and MOLNAR, P. (1972), *Focal Mechanisms and Plate Tectonics of the Southwest Pacific*, J. Geophys. Res. *77*, 5000-5032.

KANAMORI, H., *The nature of seismicity patterns before large earthquakes*, In *Earthquake Prediction* (eds. Simpson D. W., and Richards P. G.) (Am. Geophys. Union 1981) pp. 1-19.

KELLEHER, J., SYKES, L., and OLIVER, J. (1973), *Possible Criteria for Predicting Locations and their Applications to Major Plate Boundaries of the Pacific and the Caribbean*, J. Geophys. Res. *78*, 2547–2583.

LAY, T., ASTIZ, L., KANAMORI, H., and CHRISTENSEN, D. H. (1989), *Temporal Variation of Large Interplate Earthquakes in Coupled Subduction Zones*, Phys. Earth Planet. Inter. *54*, 258–312.

LAY, T., and KANAMORI, H. (1980), *Earthquake Doublets in the Solomon Islands*, Phys. Earth Planet. Inter. *21*, 283–304.

LEFEVRE, L. V., and MCNALLY, K. C. (1985), *Stress Distributions and Subduction of Aseismic Ridges in the Middle America Subduction Zone*, J. Geophys. Res. *96*, 4495–4510.

LOVISON, L. C., DMOWSKA, R., and DUREK, J. (1988), *Mechanics of Subduction as Inferred from Earthquake Cycle Observations: New Britain Area*, Abstract U51–104, AGU Fall Meeting Program, p. 153.

MCCANN, W. R., NISHENKO, S. P., SYKES, L. R., and KRAUSE, J. (1979), *Seismic Gaps and Plate Tectonics: Seismic Potential for Major Boundaries*, Pure Appl. Geophys. *117*, 1082–1147.

NISHENKO, S. P. (1991), *Circum-Pacific Seismic Potential: 1989–1999*, Pure Appl. Geophys. *135*, 169–259.

PASCAL, G. (1979), *Seismotectonics of the Papua New Guinea—Solomon Islands Region*, Tectonophysics *57*, 7–34.

SCHWARTZ, S. Y., LAY, T., and RUFF, L. J. (1989), *Source Process of the Great 1971 Solomon Islands Doublet*, Phys. Earth Planet. Inter. *56*, 294–310.

(Received April 26, 1991, accepted May 20, 1991)