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Historical Seismicity and Seismotectonic Context of the Great 1979 Yapen and 1996 Biak, Irian Jaya Earthquakes

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Abstract—We present relocations of over 220 historical and recent earthquakes in the northwestern part of Irian Jaya, in the context of the large earthquakes of 1979 and 1996. Our results document continuous activity on a 420-km segment of the Sorong Fault, with a possible extension over an additional 330 km to the west. We also show that some level of activity did take place on the New Guinea Trench prior to the 1996 Biak earthquake, and relocate a large ($M_{PAS} = 7.4$) event on 02 April 1947 to the trench, at 138°E. We speculate that the large earthquake of 26 May 1914 may also have taken place on the New Guinea Trench. We study the pattern of activity following the 1979 Yapen earthquake, which triggered stress release in the Pandaidori Islands, also the location of stress transfer following the 1996 Biak earthquake.

Key words: Seismicity, Irian Jaya, New Guinea, stress transfer.

1. *Introduction and Background*

On 17 February 1996, at 05:59 GMT, a major earthquake occurred at 0.89°S; 136.95°E, about 40 km north of the island of Biak, Indonesia. This event was remarkable in many respects. First, at $M_0 = 2.4 \times 10^{28}$ dyn-cm, it remains the largest interplate thrust event in the 23-year Harvard CMT catalogue[2]. The earthquake did significant damage on Biak itself, and generated a tsunami whose run-up heights reached 7 m on Biak, and which wrought destruction on Biak and the neighboring islands of Pandaidori and Yapen (TANIOKA *et al.*, 1996; TANIOKA and OKADA, 1997). But perhaps more interestingly, it took place along a section of the New Guinea Trench (NGT) where no seismicity was documented prior to its occurrence.

New Guinea, in the shape of a flying vulture and the second largest island in the world, is located at the boundary between the Pacific and Australian plates, in an area featuring an extremely complex tectonic regime, described in detail by, among

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[2] As of the day of writing, February 20, 1999.

others, VISSER and HERMES (1962), HAMILTON (1979) and DOW and SUKAMTO (1984). Figure 1 is a sketch of the principal tectonic features relevant to the present study, in the general framework of Hamilton's now classical tectonic map of the area.

The island of Biak is located at the northern end of a large triangular indentation of the coast of Irian Jaya (the Indonesian province of New Guinea) named the Cenderawasih (or Geelvik) Bay. Global plate motion models, such as DEMETS *et al.*'s (1990) indicate that the velocity vector of relative motion of the stable Pacific plate with respect to stable Australia, computed at Biak, is 11 cm/yr at azimuth N248°E, this direction being significantly oblique to the azimuth of the plate boundary (290°) as grossly defined by the New Guinea shoreline. The plate boundary is also strongly delocalized, as evidenced most eloquently by the dramatic active orogeny in New Guinea, where altitudes reach over 5000 m. On the Pacific side, the Caroline plate has been recognized as different in age, and possibly moving independently of the rest of the Pacific plate (WEISSEL and ANDERSON, 1978), even though the lack of island sites in the Caroline plate has prevented the direct investigation of its motion by space geodesy. Inside New Guinea, a GPS program

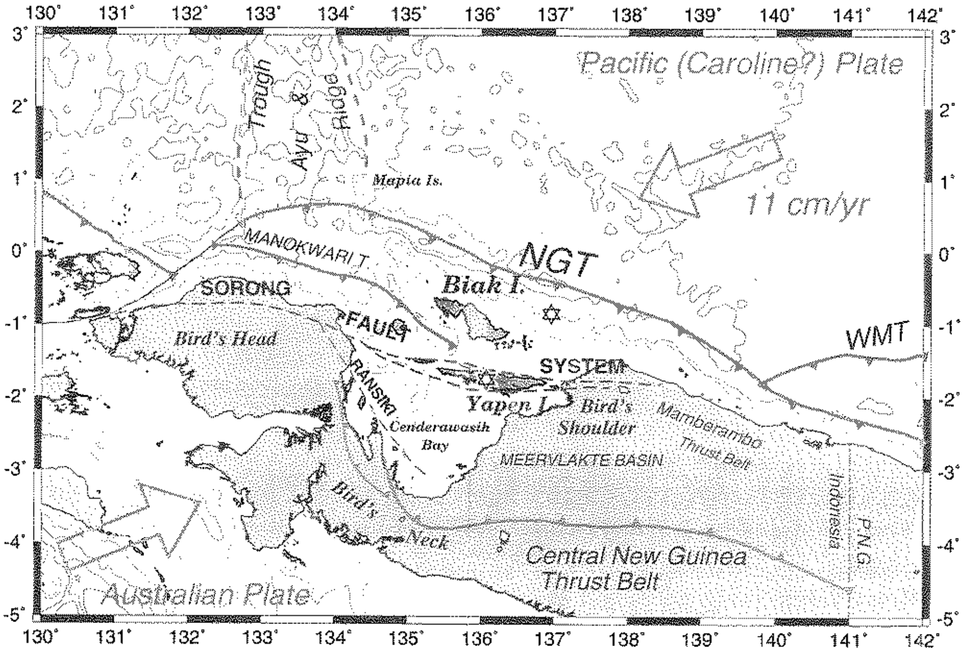

Figure 1

Tectonic sketch of Northwestern New Guinea, after HAMILTON (1979). This map is a reference for the principal tectonic features described in the paper. NGT: New Guinea Trench; WMT: West Melanesian Trench. The stars of David show the location of the great 1979 Yapen and 1996 Biak events.

has confirmed the delocalization of the plate boundary, and the existence of a complex regime involving multiple tectonic blocks (PUNTODEWO *et al.*, 1994).

Figure 1 shows the principal geological features in Western New Guinea. The Central New Guinea thrust belt suture bisects the island approximately 250 km inland from the Caroline sea shore, and curves north along the Bird's Neck into the Wandamen–Ransiki Fault system. Further north, the Sorong Fault system extends approximately east–west from the "Bird's Shoulder" to the Ransiki Fault and the Bird's Head which it bisects before forming the southern boundary of the Halmahera block, eventually reaching into the Molucca Sea. The Sorong system itself is braided into at least two major strands in the vicinity of Yapen Island. HAMILTON (1979) has expressed some doubts as to the surficial expression of the Sorong Fault especially in its overland parts, the Bird's Head to the west of the Bird's Shoulder in the vicinity of 137.5°E to the east. His argument was supported, at least in part, by the fact that the epicenters of most large earthquakes in the region (which date back before 1963) do not immediately correlate with the mapped fault zone. However, the central part of the Sorong system was later the site of a large left-lateral strike-slip earthquake at Yapen Island on 12 September 1979 ($M_0 = 2.7 \times 10^{27}$ dyn-cm); the seismic sequence which followed this earthquake is analyzed in some detail below. Inside the Bird's Head, the Koor Fault has been recognized about 40 km north of the Sorong Fault. Its exact interpretation as either a strand of the braided Sorong system or an accretionary boundary is unclear (HAMILTON, 1979; DOW *et al.*, 1986; PUNTODEWO *et al.*, 1994). DOW and SUKAMTO (1984) have shown that the Sorong Fault may have accumulated 370 km of left-lateral displacement in the Bird's Head. Finally, in the western part of Cenderawasih Bay, PUNTODEWO *et al.* (1994) have suggested that seismicity takes place on a southern offshoot of the Sorong system, which they term the Bird's Neck Fault, where left-lateral strike-slip motion at azimuth N267°E would eventually lead to the decapitation of the Bird.

North of the island, the New Guinea Trench (NGT) is well defined in the bathymetry, reaching depths of 5000 m due north of Biak. However, it stops at $134\frac{1}{2}$°E, where it abuts against the Ayu trough-and-ridge system, in the vicinity of the Mapia (St. David) Islands. West of 134°E, a bathymetric low (reaching only 4000 m) known as the Manokwari Trough is documented approximately 100 km to the south of the NGT. This geometry would suggest a transform connection between the two troughs, in a direction roughly parallel to the Pacific-Australia relative motion (PUNTODEWO *et al.*, 1994). The NGT has a strong signal in the geoid, which exhibits a low of approximately 5.5 m at the longitude of Biak. Both the bathymetric trough and the geoid low are characteristic of an active subduction zone; on the other hand, the absence of seismicity in the NGT west of 138°E has been noticed by many investigators, among others EVERINGHAM (1974), OKAL *et al.* (1983), SENO and KAPLAN (1988), ABERS and MCCAFFREY (1988) and PUNTODEWO *et al.* (1994). This observation led CAZENAVE and OKAL (1985) to speculate that the NGT might be a waning subduction zone, possibly as part of the process of relocating the convergent component of the Pacific-Australia motion north of the Caroline plate and Ontong–Java Plateau (KROENKE and WALKER, 1986; OKAL *et al.*, 1986).

The scenario then suggested would have the strike-slip component of the plate motion taken up along the Sorong Fault (a situation common in zones of oblique subduction (ALLEN, 1965; FITCH, 1972), such as for example Sumatra (KATILI, 1970)), but the convergent component taken up entirely by the ongoing orogeny further south inside the island. Initial results of a GPS campaign in Irian Jaya (PUNTODEWO *et al.*, 1994) indicate that a large amount of deformation is taken up in the thrust belt, where ABERS and MCCAFFREY (1988) have also proposed that significant convergence occurs at depths reaching 45 km.

However, recent seismic tomography (R. VAN DER HILST, pers. comm., 1998) fails to identify a slab system under the Bird's Neck, a result supported by the absence of confirmed earthquakes (CMT solutions with $M_0 \geq 10^{24}$ dyn-cm) deeper than 61 km (in contrast to the situation east of 138°E, where seismicity reaches 117 km below the Mamberambo thrust belt). Furthermore, the occurrence of the 1996 Biak earthquake (with its focal mechanism expressing the exact convergent component of the relative Pacific-Australia motion) clearly indicates the active character of the NGT and the idea of a fossil subduction system should be abandoned.

In this very general framework, the purpose of the present study is to reassess some of the crucial seismicity in the NGT and Sorong systems. We seek answers to the following questions:

- What was the true level of seismicity in the New Guinea Trench (including historical events) prior to the 1996 Biak earthquake? We are motivated by the singular character of the 1996 Biak earthquake, and one of our goals will be to define precisely if any instrumental seismicity could be identified in its epicentral area.
- Where do the largest ($M_{PAS} \geq 7$) historical earthquakes take place in Northwestern New Guinea and can we associate them with specific fault zones?
- What is the pattern of seismicity following the 1979 and 1996 earthquakes, both characterized by the post-seismic activation of clusters of seismicity outside their fault zone?

Data Set and Methodology

Our relocation efforts follow the methodology of WYSESSION *et al.* (1991), based on an interactive nonlinear inversion of P times reported by the ISS/ISC (and occasionally BCIS) databases. In this particular environment featuring complex tectonic provinces, we generally do not use S waves whose travel times could be significantly affected by lateral heterogeneity at the source. The relocations are

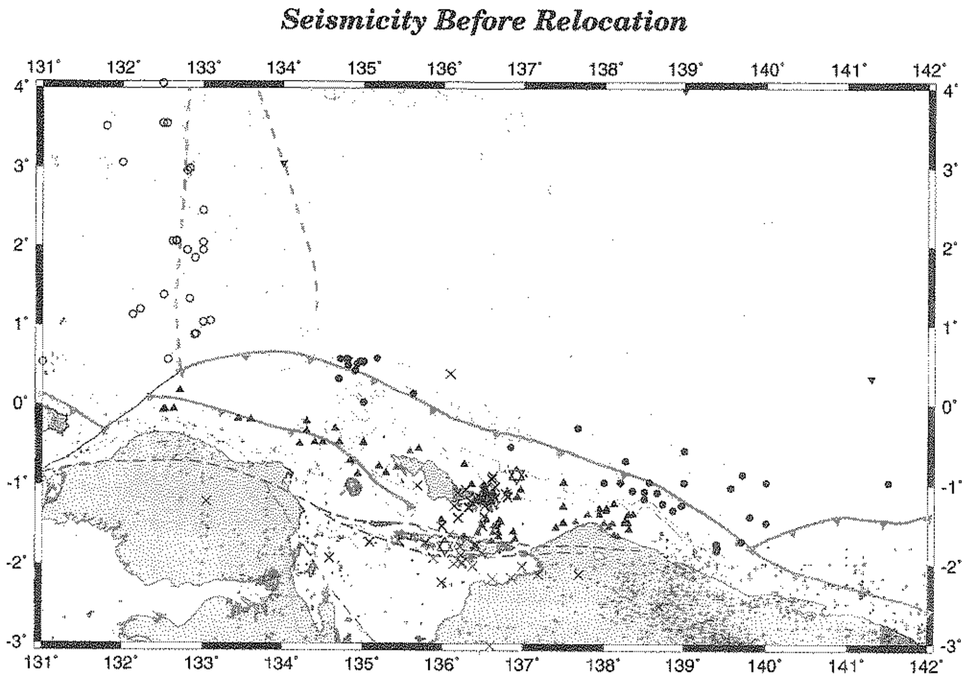

Figure 2
Seismicity of Northwestern New Guinea (before relocation), showing epicenters as reported in the various available bulletins (NEIC, ISS/ISC, BCIS). We use the following symbols: solid circles: events possibly associated with the NGT; open circles: events in the Ayu Trough; upwards triangles: Transition Province; downwards triangles: Intraplate Caroline events, × symbols: 1979 sequence and associated events; small + symbols: background seismicity, not directly associated with the features under study. The stars of David show the 1979 Yapen and 1996 Biak epicenters. See text for details.

complemented by Monte Carlo tests, consisting of injecting the data with Gaussian noise, the standard deviation σ_G of the Gaussian being taken as representative of timing errors, and as such varying from 1 s for post-1963 events to as much as 20 s for events in the 1910s. For post-1956 events whose bulletin solutions were determined by computer inversion, the ISS/ISC solution was examined and it was kept if it passed a quality test based on number of stations and quality of residuals. This was generally the case for the majority of the larger events.

Short of a general relocation of all the historical seismicity of New Guinea, we isolated for study a number of regions identified on Figure 2 (the "before" figure plotting the original instrumental locations), with Figure 3 (the "after" figure) showing the relocated epicenters.

The small + signs on Figure 2 identify background seismicity (1962–June 1996) whose *prima facie* location is inside the New Guinea block, and as such not directly associated with the NGT, the central section of the Sorong Fault outside the Bird's Head, or their margins; these events were not relocated. The solid dots identify those events whose original location would associate them with the New Guinea Trench. Solid upwards-pointing triangles identify an approximately linear trend of seismicity, half-way between the NGT and the Sorong system, which we term the "Transition Province (between those two features)." To the northwest, open circles identify events associated with the Ayu Trough, believed to represent the boundary between the Caroline and Philippine plates. The three solid downwards-pointing triangles are events originally located inside the Caroline plate. The × symbols constitute the 1979 sequence, as described in detail below. In addition to this data set, 13 large ($M \geq 6.9$) earthquakes, some of which associated with features in the background "block" seismicity, were also targeted for study. They are shown as squares on Figure 3. The 1979 Yapen and 1996 Biak earthquakes are shown as stars of David. The same conventions are used in the other figures in the paper.

In the next section of the paper, we give the results of our relocation efforts in the various provinces listed above. We then examine in detail the case of the major historical earthquakes. Finally, we discuss the seismicity of the central Yapen–Biak region, before, during and after the two large earthquakes of 1979 at Yapen and 1996 at Biak. We also use older focal mechanisms published in the literature; our approach in this last respect is comparable to that of PUNTODEWO *et al.* (1994), but we include pre-CMT solutions, and make use of an updated data set.

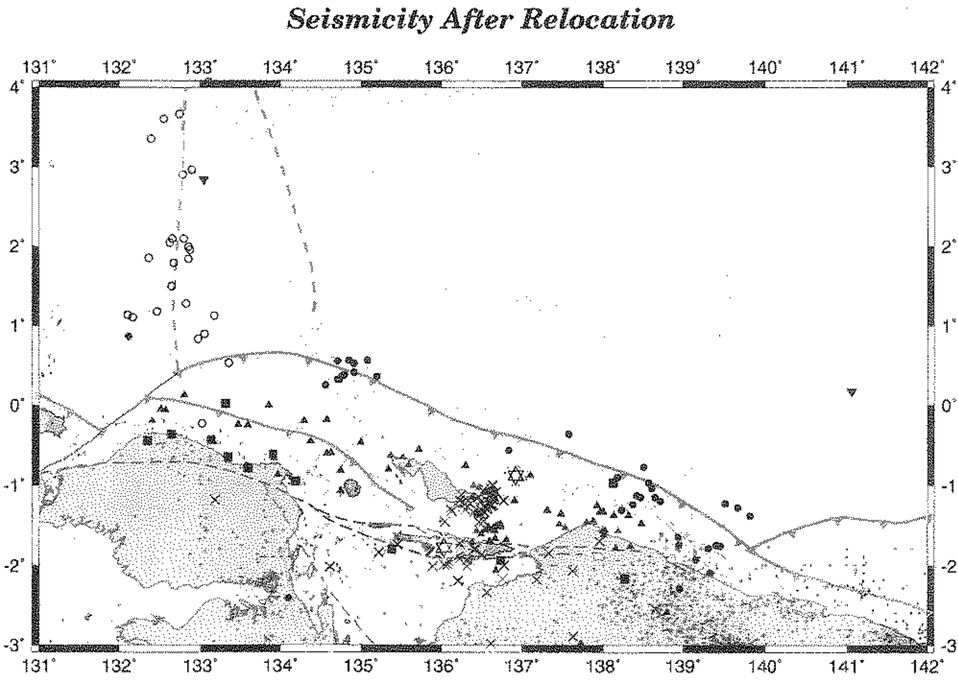
Seismicity After Relocation

Figure 3
Same as Figure 2 for relocated epicenters. In addition, the squares show the large historical events detailed in Section 3.

2. Relocation in Individual Provinces

The New Guinea Trench

This is clearly a puzzling seismic province, since it features a dramatic variation of background seismicity and hence of mode of strain release, while the physiographic expression of the New Guinea Trench, i.e., the trough, is relatively consistent from $134\frac{1}{2}$°E to 139°E.

Bulletin seismicity predating the 1996 Biak earthquake along the New Guinea Trench features three separate provinces (Fig. 2). First, at the western end of the trench (whose bathymetric expression stops abruptly at $134\frac{1}{2}$°E), we find a cluster of 17 earthquakes covering longitudes 134.7°E to 135.2°E, with an additional outlier at 135.6°E. We then note a mainly aseismic zone, with only two earthquakes scattered on either side of the trench from 136.8°E to 138°E. Then, east of 138°E, the trench starts again supporting what appears as continuous seismicity, all the way to the triple junction at 1.8°S; 140°E, where the aseismic West Melanesian Trench (WMT) branches out to the northeast, delimiting the Admiralty platelet in the Bismarck Sea. We discuss in detail below our relocation efforts in the three provinces, with all results listed in Table 1.

● *The Western Cluster*

This group is defined by 12 recent (post-1962) and 5 historical earthquakes. Among the recent earthquakes, several were well recorded events with $m_b \geq 5$, and their ISC location could be kept after examination. The outlier in the initial distribution, a small event ($m_b = 3.1$) on 26 June 1991, could not be reliably relocated. One recent earthquake (29 June 1976; $m_b = 5.0$) featured inconsistent arrivals, notably in Asia; a location in the cluster was kept, but at the cost of several unexplained late arrivals, which could however, be interpreted at *pP* assuming a focal depth of 30 km. Of the five historical earthquakes originally located in the cluster, none could be reliably relocated to the cluster. Details are found in the Appendix.

Our final results (Fig. 4) show five recent events spread along a 55-km segment of trench (the transverse dimension, 20 km, being comparable to the precision of relocations). From this group, a further set of six events branches out to the WSW, exactly in the azimuth of the Pacific-Australia plate motion vector.

Only one CMT solution is available for the western cluster: a strike-slip mechanism for the small event of 11 July 1977 ($M_0 = 2.2 \times 10^{24}$ dyn-cm). We were able to build two additional solutions, shown on Figure 4, based on first motions read on WWSSN seismograms, for the events of 15 and 23 June 1976 ($m_b = 5.9$ and 5.8, respectively). The first of those was also obtained by SENO and KAPLAN (1988). Even though the three epicenters are within 25 km of each other, their focal

Table 1

Relocation of NGT events

Date D M (J) Y	Origin time (GMT)	Bulletin location °N	Bulletin location °E	Bulletin location Depth (km)	Magnitude and agency	Relocation °N	Relocation °E	Relocation Depth (km)	Relocation *NS*	Relocation σ (*s*)
					Western Cluster					
23 NOV (327) 1919	05:57:30.0	0.00	135.00	0.		−5.18	142.73	10. C	5	4.46
01 MAR (060) 1921	06:36:52.0	0.00	135.00	0.		0.83	132.11	10. C	4	1.66
10 OCT (283) 1921	02:06:00.0	0.00	135.00	0.		−3.07	139.43	39. F	7	3.67
15 JAN (015) 1925	16:50:50.0	0.00	135.00	0.						
17 SEP (260) 1927	00:45:15.0	0.00	135.00	0.		−2.42	134.09	30. C	8	2.66
03 OCT (276) 1930	18:09:04.0	0.50	135.00	0.	6.00 PAS					
06 MAR (066) 1968	15:51:39.5	0.40	134.90	46.		0.33	134.75	55. C	15	1.58
15 JUN (167) 1976	06:09:01.8	0.54	134.79	33.	6.50 PAS	0.52	134.70	36. I	202	1.72
16 JUN (168) 1976	14:47:56.2	0.39	134.89	33.	5.0 m_b	0.29	134.70	33. I	23	2.98
23 JUN (175) 1976	13:49:58.0	0.54	134.81	33.	5.8 m_b	0.53	134.84	35. I	215	1.58
29 JUN (181) 1976	11:52:05.3	0.29	134.69	32.	5.0 m_b	0.29	134.72	10. C	13	1.04
20 MAY (140) 1977	18:02:45.5	0.48	134.92	33.	5.6 m_b	0.53	135.07	30. I	36	2.12
11 JUL (192) 1977	22:39:52.2	0.51	134.96	33.	5.6 m_b	0.49	134.90	33. I	81	2.00
29 OCT (302) 1979	02:52:52.8	0.46	134.81	33.		0.35	134.78	40. I	15	1.42
27 JUN (179) 1980	19:10:51.9	0.54	134.71	33.	5.1 m_b	0.38	134.90	24. I	59	4.25
14 JUL (195) 1981	11:39:39.6	0.55	135.17	33.	4.2 m_b	0.22	134.55	20. C	12	1.11
19 DEC (354) 1984	23:21:53.4	0.51	135.01	33.	5.3 m_b	0.33	135.19	3. C	30	3.45
26 JUN (177) 1991	17:35:52.4	0.11	135.63	33.	3.1 m_b					
					Central Segment					
24 OCT (298) 1984	02:26:00.7	−0.32	137.67	33.	4.9 m_b	−0.39	137.57	10. C	9	0.91
18 JAN (018) 1989	17:58:48.4	−0.56	136.84	33.	3.1 m_b	−0.59	136.83	23. I	42	0.98
					Eastern Section					
22 MAR (081) 1925	14:05:24.0	−1.00	140.00	0.		−4.97	141.13	100. F	7	2.80
05 APR (095) 1931	21:30:58.0	−1.00	140.00	0.		−1.80	139.30	40. M		
04 JAN (004) 1937	23:54:43.0	−1.00	139.00	0.		−1.26	138.36	20. C	16	3.69

05 JAN (005) 1937	04:46:19.0	−1.00	139.00	0.		−0.93	138.17	22. C	22	2.68
29 MAY (150) 1940	00:58:06.0	−1.00	141.50	0.		−2.10	139.32	35. F	12	1.65
17 DEC (352) 1940	14:42:05.0	−1.00	138.20	0.	6.50 PAS	−0.80	138.50	20. C	30	1.97
16 MAY (136) 1959	14:23:37.0	−1.50	140.00	0.		−2.31	138.95	72. F	7	1.61
26 FEB (057) 1960	02:08:31.0	−1.00	138.00	0.	5.63 MAT	−1.33	138.22	20. C	45	1.99
08 DEC (342) 1961	09:36:24.9	−1.80	139.40	55.	4.20 QUE	−1.94	139.14	10. C	53	1.34
05 JUL (186) 1962	10:32:28.8	−0.60	139.00	25.		−3.58	135.83	76. F	12	2.05
04 NOV (308) 1963	22:25:02.8	−0.90	139.70	33.		−1.25	139.50	10. M	5	1.16
08 MAY (129) 1972	06:18:57.8	−1.10	138.35	33.	5.7 m_b	−1.15	138.41	33. I	111	1.17
21 FEB (052) 1974	07:41:16.6	−1.84	139.39	33.		−1.77	139.44	35. C	10	1.27
18 NOV (322) 1979	21:50:01.0	−1.73	139.69	201.	4.2 m_b	−4.42	139.73	27. F	8	1.70
20 DEC (355) 1980	14:50:32.4	−0.99	138.56	33.	5.5 m_b	−0.99	138.56	33. U		
26 JUN (177) 1981	12:22:05.5	−1.20	138.50	33.	5.2 m_b	−1.17	138.46	25. I	54	1.30
01 OCT (274) 1983	19:39:01.4	−1.26	138.73	33.	5.1 m_b	−1.22	138.71	14. I	49	1.35
06 MAY (127) 1984	02:04:59.7	−1.12	138.66	33.	5.4 m_b	−1.17	138.64	41. F	37	1.53
29 AUG (242) 1984	12:42:08.6	−1.34	138.86	33.		−1.76	138.94	4. F	9	1.74
08 FEB (039) 1986	02:16:15.4	−1.28	138.97	33.		−1.66	138.93	10. C	8	1.47
23 APR (113) 1986	09:09:48.7	−0.73	138.26	33.		−3.97	138.77	54. F	6	1.31
14 MAR (074) 1988	00:27:57.2	−1.06	139.56	33.	4.1 m_b	−1.30	139.65	10. C	8	2.34
21 JAN (021) 1994	07:37:09.2	−1.42	139.79	33.	4.1 m_b	−1.40	139.80	33. I	5	0.95
10 APR (100) 1994	15:07:40.6	−1.11	138.50	33.	4.2 m_b	−1.06	138.60	47. I	48	1.10
29 MAR (088) 1995	13:55:04.0	−1.76	139.39	33.	4.0 m_b	−1.73	139.35	10. C	9	0.88

NS is the number of stations used and σ the standard deviation achieved in the relocation. Depth codes are: F: Relocation carried with floating depth; C: Relocation carried with constrained depth; I: ISC solution retained; M: Epicenter chosen on active feature reached by Monte Carlo ellipse; U: USGS location retained.

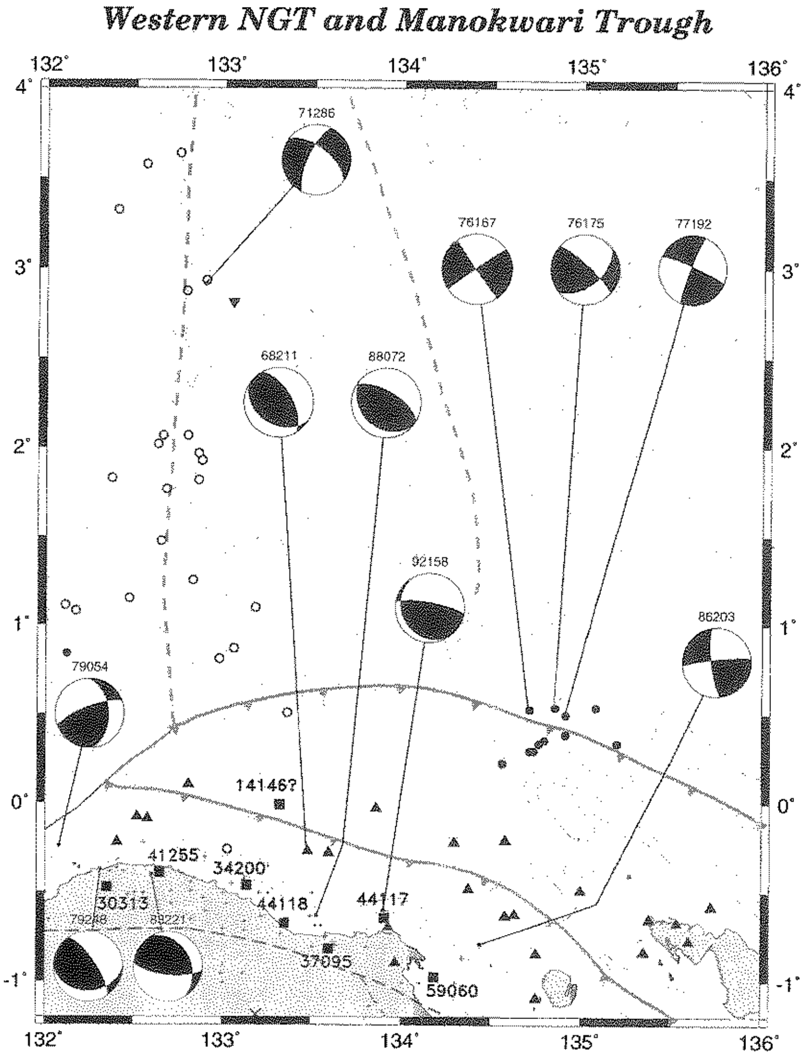

Figure 4

Close-up of the western part of Figure 3, showing relocated epicenters in the Western NGT, the Ayu Trough, the Monakwari Trench and the Bird's Head. Solid squares with Julian dates indicate large historical earthquakes, relocated in Section 3. All available CMT solutions predating the Biak earthquake (as well as other mechanisms; see text for details) are plotted, and coded by Julian dates.

solutions are not consistent. The 1976 mainshock could express the strike-slip motion of the Pacific plate with respect to Australia along the transform connecting the NGT with the Manokwari Trough; its aftershock 8 days later and 15 km to the east, would involve oblique subduction at the NGT accommodating essentially the same plate motion. The interpretation of the 1977 event is less straightforward. Finally, we note that EKSTRÖM and NETTLES (1997) recently obtained a strike-slip

CMT for the event of 15 June 1976, but rotated some 40° away from our (and Seno and Kaplan's) solution. Since our first-motion solution was very well constrained, this suggests source complexity, as also indicated by the CMT's large CLVD component ($\varepsilon = 22\%$).

• *The Central Segment*

Proceeding eastwards, we confirm the location of the two earthquakes scattered across the central "aseismic" segment of the NGT (28 October 1984; $m_b = 4.9$, and 18 January 1989; $m_b = 5.1$). The latter, for which we keep the ISC solution, is only 30 km north of the 1996 Biak epicenter (Fig. 3). It thus appears that the central segment was not totally deprived of seismicity before the large 1996 events.

• *The New Guinea Trench East of 138°E*

East of 138°E, abundant seismicity is reported along the NGT in the form of 10 recent (post-1962) and four historical earthquakes, to which we add six recent and five historical events scattered around the West Melanesia–New Guinea Trench junctions, east of 139°E. Of those 25 earthquakes, we confirm ten clustering around 1°S; 138½°E (Fig. 5) in a pattern becoming continuous with the on-land activity, and possibly linking with the eastern extremity of the Sorong Fault, as discussed below in the section on the Transition Province. This includes a large event on 17 December 1940 ($M_{PAS} = 6\frac{1}{2}$). Further east, the trench features only three small events in the vicinity of the branch point of the West Melanesian Trough, at 1½°S; 140°E. These shocks relocate approximately 30 km NW of the trench, but their Monte Carlo ellipses intersect it. In addition, eight earthquakes relocate into the Mamberambo belt, part of the background block of seismicity. Four earthquakes are grossly mislocated and relocate further south into New Guinea (22 March 1925; 05 July 1962; 18 November 1979 and 23 April 1986; see details in the Appendix).

Only one CMT solution (21 December 1980) is available for the eastern part of the NGT. Figure 5 includes one CMT mechanism for an event classified in the Transition Province, and we also show four solutions in the unrelocated background block north of 2°S, one of which due to JOHNSON and MOLNAR (1972). With the exception of the 1984 earthquake at the eastern end of the Sorong system, which has a significant strike-slip component, all these mechanisms express the convergent component of Pacific-Australia plate motion. All these shocks remain small, with the largest published moment reaching only 5.7×10^{24} dyn-cm. There are many additional CMT solutions farther south in the Mamberambo belt, and for post-Biak events on the western margin of Figure 5, the latter discussed in detail by TAYLOR *et al.* (1998), and shortly described in Section 4. As for the former, the example of the large earthquake on 25 October 1987, shown at the bottom of Figure 5, as well as more comprehensive studies such as PUNTODEWO *et al.*'s (1994), show that the stress field varies rapidly inside that tectonic province.

The Caroline Basin

Figure 2 shows three earthquakes reported intraplate, within the southern portion of the Caroline Basin, defined for the purpose of this study as extending to 4°N and 142°E: two historical earthquakes (20 October 1923 and 05 January 1932) and a recent event on 23 September 1982. As shown on Figure 2, in Table 2 and detailed in the Appendix, we find that the 1923 event could be grossly mislocated, and that the 1932 earthquake is on the Ayu Trough. The 1982 event is tentatively confirmed inside the Caroline plate.

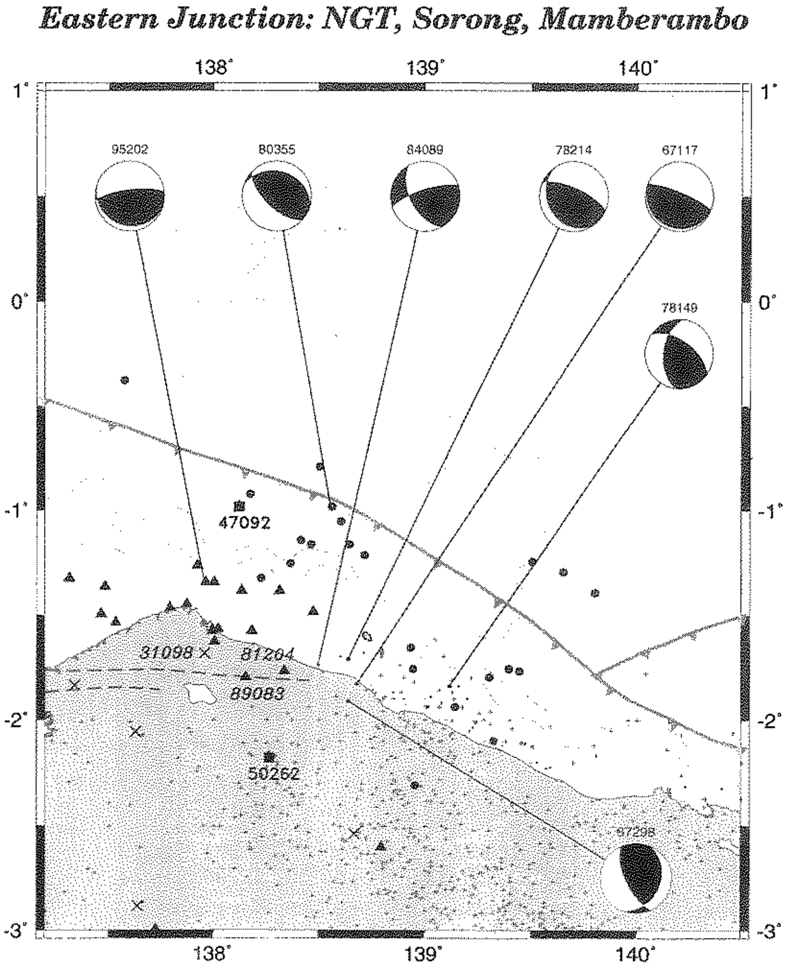

Figure 5
Same as Figure 4 for the Eastern NGT and "Bird's Shoulder" Region. Dates in *italics* refer to the solutions documenting activity at the eastern end of the Sorong Fault system.

Table 2

Relocation of intraplate (Caroline) events

Date D M (J) Y	Origin time (GMT)	Bulletin location			Magnitude and agency	Relocation				
		°N	°E	Depth (km)		°N	°E	Depth (km)	*NS*	σ (*s*)
20 OCT (293) 1923	10:01:40.0	4.00	139.00	0.		15.61	121.57	203. F	4	0.00
05 JAN (005) 1932	00:34:50.0	3.00	134.00	0.		2.79	133.04	10. C	7	2.81
23 SEP (266) 1982	02:37:13.7	0.31	141.29	33.	4.00	0.15	141.05	21. M	10	

The Ayu Trough

We regroup in Table 3 the earthquakes (open circles on Figs. 2–4) originally located between latitudes 0.5°N and 4°N and longitudes 131°E to 134°E. These events are generally interpreted as associated with the Philippine–Caroline plate boundary, expressed in the bathymetry as the Ayu Trough (WEISSEL and ANDERSON, 1978). Of the original 25 earthquakes (7 historical and 18 recent), one (on 02 January 1960) relocates into the Transition Province further south, and one (28 October 1972) at intermediate depth under Halmahera, 300 km to the west. In addition, one event originally located in the NGT, and one intraplate Caroline earthquake relocate to the trough (see above). The relocation makes the seismic zone narrower in the north of the Ayu Trough, but it remains about 100-km wide near its southern extremity.

The seismicity in the Ayu Trough is generally of very low magnitude, the largest recent activity reaching $m_b = 5.5$ (04 April 1975). There are no CMT solutions available on the trough, and the only mechanism published in the literature (13 October 1971) is reported by WEISSEL and ANDERSON (1978) as featuring normal faulting in a predominantly east–west direction, in support of a model of accretion across the Ayu Trough.

The Transition Province (Biak Region Excepted)

We consider here the group of seismic events (shown as upwards triangles on Figs. 2–5) occurring along a band located between the NGT to the north and the Bird's Head to the south, and extending laterally from the very tip of the Philippine plate around $132\frac{1}{2}$°E through Biak and into the Mamberambo belt to the east. The western part of the Transition Province is outlined on HAMILTON's (1979) map as a zone of overthrusting parallel to the NGT. It may be expressed in the bathymetry west of 134°E (the "Manokwari Trough"), which would suggest that the NGT is transformed south upon abutting against the Ayu Trough-and-Ridge system in the vicinity of the Mapia Islands.

We identified 71 events originally located in this province (including five historical ones) before the 1996 Biak mainshock; these are listed in Table 4. Relocation resulted in generally more scattered epicenters to the extent that in the western part, the seismicity appears largely continuous with the Sorong and Ransiki systems to the south (Fig. 4). In the eastern part, the relocated epicenters join those relocated from the NGT to form a continuous seismic province (Fig. 5). The seismicity of the central portion of the Transition Province, between 135°E and 137.2°E, is described separately, in the framework of the two major sequences of 1979 and 1996.

There are few available focal mechanisms in the Transition Province, a general expression of the low level of recent seismicity: in the western segment, there are no

Table 3

Relocation of Ayu Trough events

Date	Origin time	Bulletin location			Magnitude and agency	Relocation				
D M (J) Y	(GMT)	°N	°E	Depth (km)		°N	°E	Depth (km)	*NS*	σ (*s*)
15 NOV (320) 1928	02:32:18.0	2.00	133.00	0.	5.60 PAS	1.81	132.36	20. C	10	2.26
15 NOV (320) 1928	07:37:09.0	2.40	133.00	0.		1.75	132.67	30. C	7	1.11
13 MAY (133) 1938	15:06:37.0	3.50	132.50	0.	5.75 PAS	4.01	133.10	10. C	13	2.45
23 MAY (143) 1951	06:46:23.0	0.50	131.00	0.		1.14	132.46	10. C	13	1.94
25 NOV (329) 1957	20:03:18.0	3.00	132.00	0.		3.30	132.39	10. C	5	0.57
22 JAN (022) 1959	05:36:06.0	4.00	132.50	0.		3.61	132.74	39. F	14	0.90
02 JAN (002) 1960	16:05:51.0	1.00	133.00	0.		−0.26	133.02	30. C	8	1.20
01 NOV (305) 1962	15:33:22.6	1.90	133.00	56.		1.91	132.87	48. F	61	1.53
01 NOV (305) 1962	15:52:42.4	1.80	132.90	54.		1.80	132.85	65. F	7	2.10
01 NOV (305) 1962	17:52:20.2	1.90	132.80	36.		1.95	132.85	17. F	86	1.58
13 OCT (286) 1971	09:31:00.5	2.93	132.83	41.	5.3 m_b	2.91	132.89	47. I	82	1.84
13 OCT (286) 1971	11:50:34.2	2.90	132.80	33.	5.3 m_b	2.85	132.78	33. I	74	1.42
25 OCT (298) 1971	16:52:14.1	2.02	132.67	33.	5.2 m_b	2.00	132.62	24. I	62	1.39
25 OCT (298) 1971	17:20:07.8	2.01	132.62	33.	5.2 m_b	2.05	132.65	15. I	48	1.09
28 OCT (302) 1972	22:02:22.4	3.46	131.80	107.		3.30	128.95	224. F	8	0.67
04 APR (094) 1975	05:52:33.3	1.09	132.13	33.	5.5 m_b	1.07	132.16	7. F	61	1.63
29 NOV (334) 1976	21:17:39.9	1.02	133.09	33.	5.2 m_b	1.09	133.17	10. C	23	2.35
29 NOV (334) 1976	23:26:08.6	0.85	132.91	33.		0.80	132.97	15. C	13	1.63
30 NOV (335) 1976	00:30:04.4	0.84	132.89	33.		0.86	133.05	10. C	9	1.63
18 OCT (291) 1977	06:07:21.8	2.01	132.66	33.	5.1 m_b	2.05	132.79	33. I	79	1.29
24 MAY (144) 1982	19:37:29.8	3.50	132.55	33.	5.0 m_b	3.55	132.55	33. I	71	1.59
17 JAN (017) 1987	03:35:30.7	1.29	132.83	33.	5.0 m_b	1.24	132.82	33. I	26	1.21
12 APR (102) 1989	01:28:14.9	0.53	132.57	33.	4.9 m_b	0.50	133.35	10. C	7	1.93
18 MAR (077) 1994	10:12:04.1	1.16	132.22	33.	4.6 m_b	1.10	132.10	33. I	9	1.39
06 SEP (249) 1994	19:13:31.4	1.34	132.51	33.	5.2 m_b	1.46	132.64	5. F	29	1.08

Table 4

Relocation of events in the Transition Province

Date D M (J) Y	Origin time (GMT)	Bulletin location °N	Bulletin location °E	Bulletin location Depth (km)	Magnitude and agency	Relocation °N	Relocation °E	Relocation Depth (km)	*NS*	σ (*s*)
					Monokwari Trough					
29 MAY (150) 1964	20:09:00.6	−0.50	134.70	33.	5.1 m_b	−0.63	134.57	10. C	34	2.35
01 SEP (244) 1966	08:57:13.7	−0.50	134.40	60.	5.3 m_b	−0.48	134.37	56. F	23	1.39
29 JUL (211) 1968	23:52:15.0	−0.21	133.44	12.	6.1 m_b	−0.27	133.47	25. I	190	1.28
29 NOV (334) 1968	12:46:47.2	−0.09	132.53	33.	5.4 m_b	−0.08	132.51	10. C	20	1.46
30 NOV (335) 1968	07:51:11.3	0.14	132.72	15.	5.3 m_b	0.10	132.80	33. F	19	1.18
25 FEB (056) 1976	16:36:32.6	−0.22	133.60	27.	5.3 m_b	−0.28	133.59	44. F	51	1.47
19 MAY (139) 1977	11:21:41.1	−0.33	134.65	33.	4.9 m_b	−0.62	134.62	30. F	6	0.84
05 JUN (156) 1978	10:45:51.2	−0.89	134.93	33.	5.2 m_b	−1.09	134.74	55. F	32	2.10
25 DEC (359) 1982	04:19:31.2	−0.73	134.84	46.	4.6 m_b	−0.84	134.74	43. I	40	1.64
07 JAN (007) 1987	07:47:48.2	−0.51	135.01	33.	4.4 m_b	−0.49	134.99	10. C	14	0.87
29 JUN (181) 1988	12:29:47.8	−0.10	132.51	33.	4.2 m_b	−0.22	132.40	61. F	13	1.55
01 JUL (183) 1988	13:23:14.7	−0.09	132.64	33.	3.8 m_b	−0.09	132.57	10. C	15	1.65
06 AUG (219) 1988	16:28:41.3	−0.36	134.30	33.	4.8 m_b	−0.21	134.57	10. C	9	2.20
24 MAY (145) 1992	13:58:49.3	−0.24	134.30	33.	4.7 m_b	−0.22	134.29	10. C	4	0.16
21 FEB (052) 1995	14:13:54.4	−0.52	134.21	33.	4.2 m_b	−0.69	133.92	10. C	18	1.34
					Central Segment: Biak Island					
07 APR (097) 1957	10:14:08.0	−1.00	137.50	0.	6.13 PAS	−0.95	136.94	10. C	94	2.74
18 JUN (169) 1961	08:16:55.0	−1.70	136.90	22.		−2.07	136.67	10. C	5	0.53
24 AUG (236) 1965	04:48:13.8	−1.10	136.50	58.	5.8 m_b	−1.05	136.46	42. F	10	0.88
19 JUN (170) 1967	21:39:32.2	−0.80	135.20	66.	4.7 m_b	−0.65	135.37	10. C	15	1.84
20 APR (110) 1969	04:51:34.5	−1.61	136.88	42.	5.5 m_b	−1.69	136.80	10. C	14	1.27
04 DEC (339) 1972	17:51:22.4	−1.52	136.68	33.	6.1 m_b	−1.52	136.67	0. I	185	1.34
05 DEC (340) 1972	02:46:20.7	−1.62	136.62	33.	5.5 m_b	−1.58	136.65	0. I	96	1.50

05 DEC (340) 1972	21:59:54.3	−1.47	136.70	33.	5.5 m_b	−1.53	136.69	20. I	141	1.57
05 DEC (340) 1972	22:08:28.9	−1.72	136.60	33.	5.3 m_b	−1.57	136.53	10. C	35	2.36
05 DEC (340) 1972	22:31:46.1	−1.46	136.54	33.		−1.53	136.73	33. I	69	1.44
05 DEC (340) 1972	22:46:53.5	−1.62	136.69	33.		−1.67	136.66	10. C	24	1.73
06 DEC (341) 1972	02:25:40.2	−1.53	136.48	33.	4.9 m_b	−1.62	136.49	10. C	41	2.30
06 DEC (341) 1972	03:41:27.5	−1.67	136.69	33.		−1.71	136.59	10. C	30	2.36
07 DEC (342) 1972	06:58:46.5	−1.62	136.43	33.	4.8 m_b	−1.58	136.43	10. C	34	1.92
08 DEC (343) 1972	22:02:34.2	−1.49	136.72	33.		−1.56	136.56	10. C	25	1.54
10 DEC (345) 1972	07:44:20.7	−1.66	136.26	33.	4.7 m_b	−1.72	136.37	10. C	13	1.68
11 DEC (346) 1972	00:15:51.5	−1.54	136.63	33.	5.1 m_b	−1.54	136.58	33. I	74	1.49
11 DEC (346) 1972	01:13:25.8	−1.55	136.66	33.	5.1 m_b	−1.54	136.64	36. I	76	1.17
20 JUL (201) 1973	02:19:08.1	−1.02	136.35	33.	5.5 m_b	−1.02	136.39	27. F	18	1.02
25 SEP (268) 1973	22:20:50.2	−1.03	136.51	33.	5.2 m_b	−1.19	136.66	10. I	35	2.72
29 SEP (272) 1973	13:37:02.4	−1.23	136.40	46.	5.5 m_b	−1.38	136.43	10. C	19	1.93
17 JUL (198) 1977	10:41:03.7	−0.81	135.42	33.	5.0 m_b	−0.77	135.59	15. C	11	0.72
29 SEP (272) 1977	22:20:06.7	−1.13	136.63	33.	5.3 m_b	−1.11	136.66	41. F	22	1.45
19 AUG (232) 1980	19:02:40.1	−1.46	135.98	33.	4.4 m_b	−1.32	136.40	10. C	20	1.98
17 NOV (322) 1980	17:02:54.6	−1.11	136.80	33.	3.7 m_b	−1.28	136.49	59. F	14	1.36
13 APR (103) 1981	16:38:59.2	−1.08	136.52	21.	5.4 m_b	−1.11	136.54	34. I	135	1.33
06 MAR (065) 1982	11:35:06.9	−0.77	136.26	46.	5.6 m_b	−0.78	136.29	41. I	155	1.16
13 JUN (164) 1982	06:24:22.6	−1.19	136.43	33.	4.0 m_b	−1.17	136.38	2. F	18	1.33
18 MAY (138) 1983	11:55:24.3	−1.17	136.63	33.	5.1 m_b	−1.11	136.63	22. I	81	1.05
20 JUN (171) 1986	16:26:52.5	−0.88	135.29	33.	4.4 m_b	−0.83	135.34	32. F	9	1.14
04 NOV (308) 1987	01:12:02.4	−1.09	136.97	33.	5.0 m_b	−1.50	136.73	31. F	23	2.03
22 APR (112) 1989	12:31:58.8	−1.18	136.93	33.	5.2 m_b	−1.21	136.90	33. I	27	1.11
07 MAY (127) 1990	10:53:45.1	−0.58	135.70	33.	4.7 m_b	−0.58	135.72	33. I	33	0.82
30 AUG (242) 1993	16:08:44.7	−0.61	135.59	24.	4.7 m_b	−0.67	135.52	25. C	15	1.80
07 DEC (341) 1993	23:55:54.3	−0.84	136.81	33.	4.4 m_b	−0.85	136.82	8. F	6	0.31
05 APR (095) 1995	21:54:07.0	−0.96	137.01	33.	4.0 m_b	−1.00	136.92	10. C	6	0.97
02 OCT (275) 1995	10:34:48.5	−1.15	136.53	33.	4.0 m_b	−1.07	136.62	10. C	7	0.60
27 NOV (331) 1995	03:03:39.3	−0.90	137.01	33.	4.4 m_b	−0.90	137.10	33. I	37	0.81

Table 4 (*Continued*)

Date D M (J) Y	Origin time (GMT)	Bulletin location °N	 °E	 Depth (km)	Magnitude and agency	Relocation °N	 °E	 Depth (km)	 *NS*	 σ (*s*)
					Eastern Junction					
09 FEB (040) 1957	01:53:05.0	−1.50	137.50	0.		−1.33	137.31	10. C	13	1.00
02 OCT (275) 1961	11:52:33.8	−1.50	138.30	41.		−1.58	138.18	40. F	15	1.87
21 DEC (355) 1961	23:56:55.1	−1.50	138.10	33.		−2.99	137.72	10. C	5	0.98
03 FEB (034) 1962	00:37:57.4	−1.30	137.50	33.		−1.37	137.48	10. C	139	2.16
28 FEB (059) 1966	21:03:45.4	−1.40	138.30	33.	5.3 m_b	−1.39	138.31	10. C	8	0.54
20 JUL (201) 1969	20:39:56.2	−1.48	137.65	93.	4.8 m_b	−1.54	137.53	74. F	12	1.70
27 JUL (208) 1971	00:59:57.5	−1.64	138.12	33.	5.3 m_b	−1.63	138.00	40. I	54	1.24
25 DEC (359) 1971	01:32:59.1	−1.35	138.02	33.		−1.45	137.87	47. F	15	1.92
14 JUL (195) 1975	14:41:39.8	−1.55	138.06	33.	5.7 m_b	−1.57	138.02	33. I	172	1.40
23 JUL (204) 1981	15:05:52.2	−1.39	138.36	33.	4.9 m_b	−1.77	138.33	15. F	25	1.64
28 FEB (059) 1984	20:01:39.5	−1.56	137.41	33.	5.0 m_b	−1.50	137.46	10. C	19	1.46
03 NOV (308) 1984	15:43:43.6	−1.47	138.26	33.	4.9 m_b	−1.39	138.13	10. C	28	1.74
19 AUG (231) 1985	07:01:59.6	−1.58	138.31	33.	4.2 m_b	−2.60	138.79	33. C	11	2.09
03 MAY (123) 1986	12:24:00.6	−1.26	138.12	33.	4.6 m_b	−1.27	137.92	10. C	11	1.62
27 AUG (239) 1987	08:36:19.5	−1.39	137.94	33.	4.6 m_b	−1.35	138.00	10. C	7	0.92
08 OCT (282) 1988	07:44:02.8	−1.32	138.03	33.	4.9 m_b	−1.58	137.99	10. C	17	1.83
18 OCT (292) 1988	21:19:43.9	−1.39	137.80	33.	5.1 m_b	−1.47	137.79	10. C	11	1.57
24 MAR (083) 1989	06:34:50.1	−1.66	138.17	10.	3.7 m_b	−1.80	138.15	10. C	8	1.18
17 APR (108) 1992	20:22:53.1	−1.50	138.26	33.	4.9 m_b	−1.49	138.47	10. C	18	1.18
21 JUL (202) 1995	13:27:26.8	−1.32	137.94	33.	5.2 m_b	−1.35	137.96	29. I	107	0.92

CMT solutions, and only one mechanism given by FITCH (1972) for the event of 29 July 1968; this focal solution would express convergence along the direction of plate motion. One thrust CMT solution (21 July 1995) is available at the eastern junction; it is significantly rotated from the direction of convergence of the rigid plates.

3. Individual Large Historical Earthquakes of Northwestern Irian Jaya

In this section, we relocate the large historical earthquakes of northwestern Irian Jaya. We are motivated in this endeavor by the observation that apart from the 1979 Yapen and 1996 Biak events, most large earthquakes ($M \geq 7$) in the region have taken place prior to 1963, when their locations are less precise than in modern times. As a result, several authors (e.g., HAMILTON, 1979) have noted that these large events do not seem to be associated with the principal fault zones identified in the region, based on the epicentral parameters listed in various bulletins. Our purpose is then to relocate these large events, and in particular to obtain error ellipses, thus providing the means of more definite associations with individual faults. In many instances, we were able to obtain moment estimates for these historical earthquakes from the measurement of the mantle magnitude M_m (OKAL and TALANDIER, 1989, 1990; OKAL, 1992) on high-quality single records obtained from various stations. The scarcity of well-calibrated records precluded a formal multi-station inversion of their source mechanism.

Table 5 lists the large ($M_{PAS} \geq 6.9$) historical earthquakes reported in the area of Figure 2 for the years 1900–1962. For events predating 1950, the epicentral estimates are from GUTENBERG and RICHTER (1954; hereafter G-R). We note that the two earliest events have the largest reported magnitudes.

● *26 May 1914*

This earthquake was given a large magnitude ($M_{PAS} = 7.9$) by G-R, who located it at 2°S; 137°E, along the Sorong Fault, in the straits between Yapen and the Bird's Shoulder. The ISS on the other hand had adopted the more easterly location (0.3°S; 138.8°E) given by Pulkovo, slightly north of the active segment of the New Guinea Trench. A tsunami was reported, with significant damage in Pom and Ansus, on the western side of the island of Yapen, and recorded in Honolulu (HECK, 1947; SOLOV'EV and GO, 1984).

We could not relocate the event conclusively. The best solution would be in the Manokwari Trench, at 0.01°S; 133.31°E; the Monte Carlo ellipse computed for $\sigma_G = 20$ s englobes neither of the published epicenters, but could be compatible with a focus in the general area of Biak Island (Fig. 6). As often the case for very old events, the tsunami data may be crucial to a correct interpretation. A strike-slip

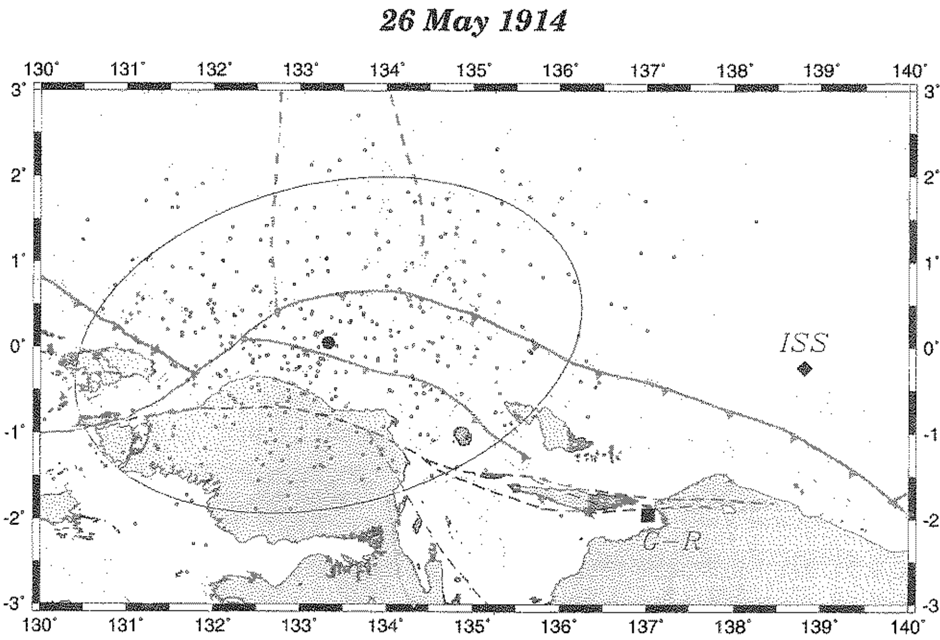

Figure 6
Relocation of the large tsunamigenic event of 1914. The square and diamond give the G-R and ISS epicenters, respectively. The solid dot is the solution best fitting the available ISS data set. The small open dots are individual Monte Carlo epicenters after injection of random noise with $\sigma_G = 20$ s, a value adequate for the 1910s (WYSESSION *et al.*, 1991). The 95%-confidence ellipse includes a significant fragment of the NGT, which we speculate was the true epicentral location.

earthquake occurring along the Yapen Fault (as suggested by G-R) may have caused a deadly local tsunami (and indeed the 1979 tsunami killed about 100 people on Yapen and Biak), which would however be expected to be largely contained to the Cenderawasih Bay, as was the 1979 wave, for which no report is made at any Pacific stations (SOLOV'EV *et al.*, 1986). The record of the 1914 tsunami in Honolulu makes it then most likely that the earthquake occurred in the open Caroline Sea, north of Cenderawasih Bay, presumably along the NGT. The report of combined earthquake and tsunami damage on Yapen would then argue for a relatively close-by focus, quite conceivably in the same general area as the 1996 event. Since the latter's tsunami was not recorded in Honolulu, the 1914 may indeed have been larger than the 1996 earthquake. Direct inspection of the two events on instruments having remained in operation during the intervening 82 years (such as the Uppsala Wiechert) may shed some light on this issue.

● *13 January 1916*

This event has the largest magnitude reported among historical earthquakes in northwestern Irian Jaya ($M_{PAS} = 8.1$). However, no mention is made of any tsunami following this earthquake. There are actually three shocks reported by the ISS on that day, the largest being the second one, at 08:20 GMT. Our relocation of the mainshock (3.04°S; 135.57°E) is surprisingly good for such an old event ($\sigma = 3.91$ s on 14 stations). It reproduces G-R's solution (3°S; $135\frac{1}{2}$°E). Although its Monte Carlo ellipse (computed for $\sigma_G = 20$ s, a figure appropriate for pre-1920 events) would barely intersect the Sorong Fault, it is more likely that the event is related to the Central Thrust Belt inside the Bird's Neck. On the other hand, no large earthquakes are known in that area, with the largest reported magnitude being $M_s = 6.8$ (08 November 1970; (SENO and KAPLAN, 1988)). The foreshock and aftershock could not be reliably relocated.

● *09 November 1930*

Bulletin locations for this shock are 0.5°S; 132°E (G-R) and 0.7°S; 131.8°E (ISS). Its magnitude is $M_{PAS} = 6.9$. The earthquake relocates significantly to the east, at 0.47°S; 132.34°E, in the central part of the Bird's Head, between the Sorong system and the coastline, possibly on the Koor Fault. While the quality of the solution is acceptable ($\sigma = 3.05$ s on 35 stations), 11 readings had to be eliminated, suggesting possible source complexity. The Monte Carlo ellipse ($\sigma_G = 7$ s) intersects a large segment of the Sorong Fault (see Fig. 7).

● *19 July 1934*

The ISS epicenter for this event ($M_{PAS} = 7.0$) is at 0.5°S; 133.5°E, off the northern shore of the Bird's Head. We relocate the earthquake on the shoreline at 0.46°S; 133.13°E (see Fig. 7). The Monte Carlo ellipse ($\sigma_G = 7$ s) reaches the Sorong Fault.

● *05 April 1937*

We relocate this event (with $M_{PAS} = 6.9$) to 0.81°S; 133.59°E, which is essentially the ISS epicenter (0.8°S; 133.5°E), and in good agreement with G-R's (1°S; 133°E); however, we find no evidence for the latter's suggestion of intermediate depth (90 km). This location puts the earthquake on the Sorong Fault inside the Bird's Head, just west of its confluence with the Ransiki Fault (see Fig. 7). The Monte Carlo ellipse (computed for $\sigma_G = 5$ s) does not intersect the Manokwari Trough, and the earthquake can be reasonably asserted to involve the Sorong Fault.

- *12 September 1941*

This earthquake ($M_{PAS} = 7.0$) is located by the ISS on the Sorong Fault inside the Bird's Head; we relocate it on the shoreline, 40 km to the NNW, but the Monte Carlo ellipse ($\sigma_G = 5$ s) would intersect the fault. Our solution (0.39°S; 132.64°E) coincides with the epicenter of a thrust CMT solution on 09 August 1983 (see Figs. 4 and 7).

- *26 and 27 April 1944*

We relocate these two large events at [0.64°S; 133.90°E] and [0.80°S; 133.18°E] respectively, in the immediate vicinity of the 1937 earthquake (see Fig. 7). Their magnitudes were given by G-R as $M_{PAS} = 7.2$ and 7.4, respectively. The quality of the second solution is rather mediocre ($\sigma = 5$ s). Yet, while the two Monte Carlo ellipses intersect, neither of the preferred solutions falls into the other's ellipse. Thus, it is probable that the first event is about 65 km east of the mainshock. Despite their comparable locations, the two events show significantly different wave forms on the few seismograms we were able to gather.

We measured the mantle magnitude (OKAL and TALANDIER, 1989) of the two shocks on the Benioff 1–90 records at Pasadena, obtaining $M_m = 7.5$ for the mainshock, and $M_m = 6.3$ for the foreshock.

- *02 April 1947*

This event is given by the ISS at 1°S; 138°E; we relocate it essentially at the same location (0.99°E; 138.12°E), which corresponds to the western end of the seismically active eastern segment of the NGT (see Figs. 6 and 8). On the other hand, G-R proposed a focus at 1.5°S; 138°E, which falls outside the Monte Carlo ellipse ($\sigma_G = 4$ s). We propose to associate the earthquake with the NGT. There is no record of a tsunami following the earthquake. The mantle magnitude computed at Pasadena is $M_m = 7.1$, corresponding to $M_0 = 1.3 \times 10^{27}$ dyn-cm.

- *27 May 1947*

We relocate the event at 1.81°S; 135.38°E, a solution essentially identical to that of the ISS, at the western end of Yapen Island, and thus part of the Sorong Fault system (see Fig. 8). G-R on the other hand propose an epicenter slightly to the northwest (and outside our Monte Carlo ellipse computed for $\sigma_G = 4$ s), in the vicinity of the islet of Mosnum. At any rate, the event belongs to the braided Sorong system.

Mantle magnitude estimates computed at Honolulu, Tucson and Pasadena range from $M_m = 7.07$ (PAS) to $M_m = 7.83$ (TUC). All three records show a regular and significant increase in moment with period, also clearly apparent in the wave forms. A tentative moment of $M_0 = 3 \times 10^{27}$ dyn-cm is inferred. The earthquake has no reported aftershocks.

● *19 September 1950*

We relocate the event at 2.18°S; 138.26°E, about 20 km southwest of both the ISS and G-R epicenters, which both fall on the edge of the Monte Carlo ellipse. Thus, the earthquake is clearly inside the Mamberambo belt (see Fig. 8). It coincides in location with a thrust earthquake ($M_0 = 1.9 \times 10^{26}$ dyn-cm) on 25 October 1987. Mantle magnitudes computed at Pasadena for the 1950 earthquake show a significant growth of moment with period, suggesting a complex and slow

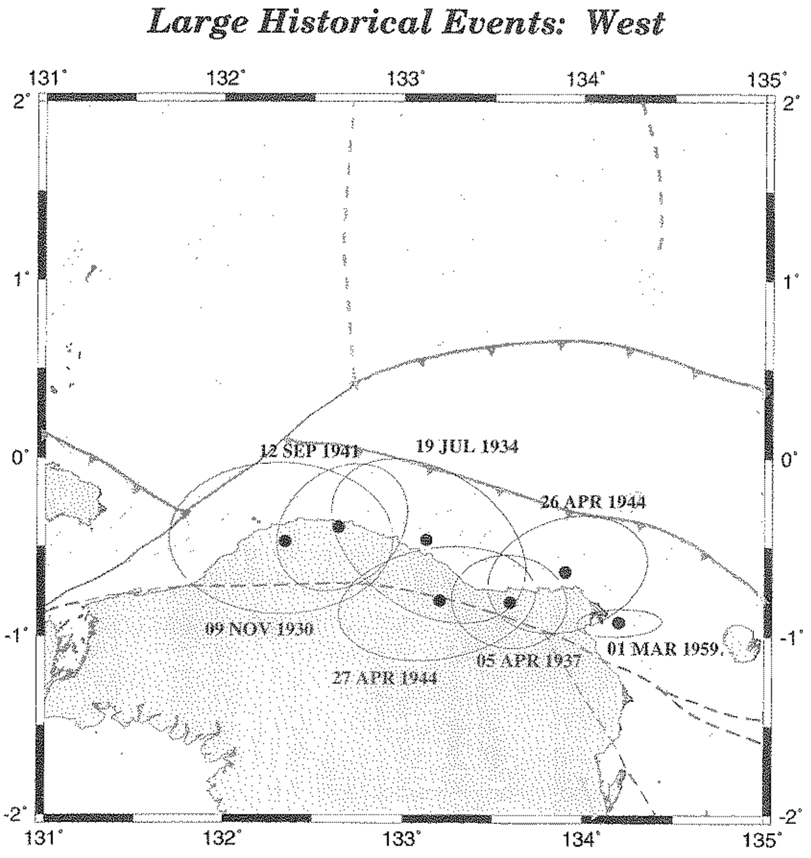

Figure 7
Relocations of large historical earthquakes in and around the Bird's Head. Note that six out of seven 95%-confidence ellipses intersect the Sorong Fault, but that the best solutions are usually displaced 20–30 km to the north.

source. The maximum values are $M_m = 6.6$ at 170 s (Love) and $M_m = 6.9$ at 205 s (Rayleigh). We estimate a moment $M_0 = 8 \times 10^{26}$ dyn-cm. Much larger events are known in the thrust belt, such as the earthquake of 10 January 1971 further east ($M_s = 8.1$; $M_m = 8.2$).

- *22 June 1957*

We relocate this large earthquake ($M_{PAS} = 7\frac{1}{2}$) at 1.88°S; 136.77°E, only a few km away from the ISS epicenter (1.95°S; 136.73°E), on the southern branch of the Sorong Fault, at the eastern tip of Yapen Island, approximately 75 km east of the 1979 event (Fig. 8). The NEIC location (1.5°S; 137°E) falls outside the range of our Monte Carlo ellipse, drawn for $\sigma_G = 2.5$ s. The earthquake was followed by two apparent aftershocks, on 17 July and 09 August (see Appendix), which suggest that the rupture may have extended 65 km across the straits into the Bird's Shoulder.

We obtained moment estimates for this earthquake from Love wave mantle magnitudes (OKAL and TALANDIER, 1990) at De Bilt and Pasadena, ranging from $M_m = 6.50$ to $M_m = 7.02$. There is some indication of an increase of moment at very long periods, but the instruments in use (De Bilt Golitsyn; Pasadena Press–Ewing) cannot resolve it conclusively; we tentatively propose a moment of 6×10^{26} dyn-cm. An optimized focal mechanism is given by WICKENS and HODGSON (1968), based on a solution by RITSEMA and VELDKAMP (1960). The mechanism ($\phi = 139°$; $\delta = 90°$; $\lambda = -7°$) is pure strike-slip, but the azimuth of the fault would be offset by 40° from that in 1979. The strike-slip character of the event is confirmed by a weak *PKIKP* arrival at La Paz.

- *01 March 1959*

The NEIC entry for this event shows a depth of 100 km, listing the source as the ISS. However, the original ISS bulletin gives a similar epicenter (0.97°S; 134.18°E) and origin time (16:49:11), but a zero depth, suggesting that the NEIC entry results from a transcription error. At any rate, all attempts to locate the earthquake at 100 km exhibit a trend of residuals increasing with distance, characteristic of excessive depth. Furthermore, no CMT solution about 10^{24} dyn-cm is known below 50-km depth in the area. The earthquake is obviously surficial. Our preferred epicenter (0.92°S; 134.20°E) is essentially the same as given by the ISS. This location is offshore of the Bird's Head, 15 km north of the Sorong Fault as mapped in HAMILTON (1979), and approached by the Monte Carlo ellipse drawn for $\sigma_G = 2.5$ s (see Fig. 7). Given the braided nature of the Sorong system elsewhere in the Cenderawasih Bay, one could speculate that the 1959 event did indeed take place on the Sorong system.

First motion reports in the ISS would be compatible with left-lateral strike-slip along the Sorong system. Our examination of records from Perth, College and

Djakarta support this mechanism, which is also equivalent to that proposed by HODGSON and WICKENS (1965). The mantle magnitude was computed on Love waves recorded at Pasadena, yielding $M_m = 6.43$, or $M_0 = 2.7 \times 10^{26}$ dyn-cm.

In conclusion of this section, we find that we can possibly associate six major earthquakes (1930, 1937, 27 April 1944, 22 May 1947, 1957 and 1959) with the Sorong system, including in its western part, inside the Bird's Head, thus alleviating at least some of the reservations expressed by HAMILTON (1979), and SENO and KAPLAN (1988) regarding the lack of documented activity along several segments of the system.

4. The Yapen–Biak Sequence: 1979–1996

We focus in this section on the sequence of seismicity accompanying the great Yapen and Biak earthquakes of 12 September 1979 and 17 February 1996. We choose not to use the phrase "aftershocks" because many of these events are displaced from the location of the rupture, and they may not qualify as aftershocks in the traditional sense of "smaller events following the mainshock on the same fault plane." Rather, the Biak sequence was recently described in detail and modeled as an example of co- and post-seismic stress transfer by TAYLOR *et al.* (1998), and we will discuss it only very briefly; these authors also analyzed the four available CMT solutions following the 1979 Yapen event. We present in Table 6 a fully detailed compilation of the aftershock and post-mainshock sequence of the 1979 event, defined as all seismicity reported in the NEIC and ISC catalogues in the range 3°S–1°N, 133–139°E during the years 1979–1980. By the summer of 1980, the activity had trickled down to as little as one event per month. We add to this data set nine background events (seven of which historical) with original locations along the central segment of the Sorong Fault. We also discuss here the earthquakes in the central part of the Transition Province which were not considered in Section 2.

• *Background Seismicity on and North of the Sorong System*

Prior to the 1979 earthquake, the background seismicity of the Sorong system between 134 and 138°E was extremely low. Of the nine earthquakes considered, one (07 July 1919) could not be relocated, and three relocate to the south of the system, as far as the Central Thrust Belt (05 April 1922; 17 July 1925; 01 Sept. 1932). The event of 08 April 1931 relocates further east on the Sorong Fault (Fig. 6), inside the Bird's Shoulder, at 1.67°S, 137.96°E, and the two earthquakes of 17 July and 09 August 1957 discussed above relocate on the Sorong Fault, inside the Bird's Shoulder and at the eastern tip of Yapen, respectively; they appear to be aftershocks of the large earthquake of 22 June 1957. The remaining two small events (07

Table 5

Relocation of large historical events in northwestern New Guinea

Date D M (J) Y	Origin time (GMT)	Bulletin location			Magnitude and agency	Relocation and size estimate						
		°N	°E	Depth (km)		°N	°E	Depth (km)	*NS*	σ (s)	M_m	M_0 (10^{27} dyn-cm)
26 MAY (146) 1914	14:22:42.0	−2.00	137.00	0.	7.90 PAS	−0.01	133.31	10. C	12	8.87		
13 JAN (013) 1916	08:20:48.0	−3.00	135.50	25.	8.10 PAS	−3.04	135.57	10. C	14	3.91		
09 NOV (313) 1930	19:08:38.0	−0.50	132.00	0.	6.90 PAS	−0.47	132.34	10. C	35	3.05		
19 JUL (200) 1934	01:27:26.0	−0.50	133.50	0.	7.00 PAS	−0.46	133.13	10. C	51	2.93		
05 APR (095) 1937	06:56:32.0	−1.00	133.00	90.	6.90 PAS	−0.81	133.59	10. C	99	3.20		
12 SEP (255) 1941	07:02:00.4	−0.70	132.40	0.	7.00 PAS	−0.39	132.64	10. C	28	2.32		
26 APR (117) 1944	01:54:15.0	−1.00	134.00	50.	7.20 PAS	−0.64	133.90	10. C	28	3.34	6.3	0.2
27 APR (118) 1944	14:38:09.0	−0.50	133.50	50.	7.40 PAS	−0.80	133.18	10. C	31	4.78	7.5	3
02 APR (092) 1947	05:39:11.0	−1.50	138.00	0.	7.40 PAS	−0.99	138.12	10. C	55	3.09	7.1	1.3
27 MAY (147) 1947	05:58:54.0	−1.50	135.25	0.	7.25 PAS	−1.81	135.38	10. C	46	2.09	7.07–7.83	3
19 SEP (262) 1950	20:29:48.0	−2.00	138.50	0.	6.90 PAS	−2.18	138.26	10. C	62	2.35	6.6–6.9	0.8
22 JUN (173) 1957	23:50:23.0	−1.50	137.00	0.	7.50 PAS	−1.95	136.73	10. C	165	2.63	6.50–7.02	0.6
01 MAR (060) 1959	16:49:11.0	−0.97	134.18	100.	7.00 PAS	−0.92	134.20	10. C	172	3.20	6.43	0.27

Table 6

The 1979 sequence and associated events

Date D M (J) Y	Origin time (GMT)	Bulletin location °N	Bulletin location °E	Bulletin location Depth (km)	Magnitude and agency	Relocation °N	Relocation °E	Relocation Depth (km)	Relocation *NS*	Relocation σ (s)
					Background Seismicity					
07 JUL (188) 1919	13:55:00.0	−2.00	137.00	0.						
05 APR (095) 1922	09:59:15.0	−2.00	137.00	0.		−3.29	135.95	10. C	10	3.00
17 JUL (198) 1925	21:07:40.0	−2.00	137.00	0.		−2.86	137.64	10. C	9	3.50
08 APR (098) 1931	19:03:25.0	−2.00	137.00	0.	6.00 PAS	−1.67	137.96	10. C	15	2.98
01 SEP (245) 1932	01:53:34.0	−2.00	137.00	0.		−3.31	136.79	10. C	6	3.63
17 JUL (198) 1957	12:26:06.0	−2.00	137.00	0.		−1.82	137.34	10. C	19	1.77
09 AUG (221) 1957	02:29:20.0	−2.00	137.00	0.		−1.97	136.79	10. C	84	2.49
07 JAN (007) 1968	21:09:26.5	−1.90	135.90	33.	4.8 m_b	−1.98	135.90	10. C	8	1.08
17 JAN (017) 1974	09:23:08.0	−1.97	136.24	33.	5.4 m_b	−1.91	136.32	10. C	22	1.73
					The 1979 Sequence					
12 SEP (255) 1979	05:17:51.4	−1.68	136.04	5.	7.90 BRK	−1.71	136.05	5. C	266	2.26
12 SEP (255) 1979	06:04:46.1	−1.72	136.41	33.	5.3 m_b	−1.76	136.43	33. I	66	1.51
12 SEP (255) 1979	06:43:36.9	−1.64	136.22	33.	5.6 m_b	−1.70	136.23	15. I	92	1.42
12 SEP (255) 1979	07:16:56.6	−1.72	135.79	33.	5.5 m_b	−1.79	135.90	28. I	102	2.35
12 SEP (255) 1979	07:52:16.0	−1.60	136.10	33.		−1.43	136.05	5. C	7	0.62
12 SEP (255) 1979	09:57:28.0	−1.70	136.10	33.		−1.62	136.04	10. C	7	1.15
12 SEP (255) 1979	10:42:16.2	−1.77	135.95	33.	5.3 m_b	−1.84	135.96	10. C	19	1.30
12 SEP (255) 1979	11:18:55.5	−2.15	136.63	33.	4.3 m_b	−2.31	136.57	10. C	11	0.74
12 SEP (255) 1979	11:38:32.0	−3.00	136.60	33.		−2.95	136.62	36. F	6	0.62
12 SEP (255) 1979	11:57:36.6	−1.83	136.49	33.	5.2 m_b	−1.84	136.50	33. I	67	1.49
12 SEP (255) 1979	13:42:05.7	−1.86	136.23	33.	3.5 m_b	−1.89	136.23	39. F	9	1.26
12 SEP (255) 1979	18:27:21.5	−1.97	136.15	33.	3.2 m_b	−1.96	136.08	10. C	20	1.99
12 SEP (255) 1979	18:33:21.0	−1.40	136.20	33.		−1.30	136.13	10. C	7	1.11
13 SEP (256) 1979	04:29:23.0	−1.00	135.70	112.		−1.19	136.27	40. C	5	1.19
13 SEP (256) 1979	06:33:02.5	−1.15	136.47	26.	5.90 BRK	−1.18	136.49	28. I	220	1.44
13 SEP (256) 1979	06:41:20.8	−1.03	136.54	33.	5.5 m_b	−0.98	136.64	10. C	69	1.37

Table 6 (*Continued*)

Date D M (J) Y	Origin time (GMT)	Bulletin location °N	Bulletin location °E	Bulletin location Depth (km)	Magnitude and agency	Relocation °N	Relocation °E	Relocation Depth (km)	Relocation *NS*	Relocation σ (*s*)
13 SEP (256) 1979	09:00:12.3	−1.15	136.56	33.	5.1 m_b	−1.16	136.56	18. I	56	1.11
13 SEP (256) 1979	09:14:25.0	−1.50	136.50	33.	4.8 m_b	−1.21	136.29	9. F	6	0.69
13 SEP (256) 1979	09:31:58.9	−1.05	136.52	33.	4.7 m_b	−1.06	136.54	10. C	11	1.03
13 SEP (256) 1979	12:35:26.2	−1.27	136.33	33.	4.8 m_b	−1.28	136.30	16. F	11	1.22
13 SEP (256) 1979	14:30:07.0	0.40	136.10	68.		−1.42	136.53	30. C	6	0.82
13 SEP (256) 1979	20:36:13.1	−1.19	136.35	33.	4.8 m_b	−1.20	136.36	23. F	10	0.82
14 SEP (257) 1979	01:08:45.7	−1.95	136.25	33.	3.4 m_b	−1.92	136.09	4. F	14	1.70
14 SEP (257) 1979	09:18:12.3	−0.91	136.62	33.	4.8 m_b	−1.02	136.54	33. I	33	1.36
14 SEP (257) 1979	10:17:14.9	−1.25	136.15	33.	4.7 m_b	−1.27	136.12	10. C	7	0.85
17 SEP (260) 1979	16:33:43.0	−2.50	138.70	33.		−2.52	138.67	20. C	7	2.12
19 SEP (262) 1979	12:53:18.0	−1.75	136.22	33.	5.5 m_b	−1.86	136.21	33. I	40	2.10
23 SEP (266) 1979	17:55:51.5	−1.68	135.47	33.		−1.71	135.47	18. F	12	1.10
23 SEP (266) 1979	18:55:51.5	−1.20	133.06	33.		−1.16	133.19	10. C	8	1.05
23 SEP (266) 1979	22:22:48.6	−2.14	136.87	34.		−2.14	136.77	53. F	12	1.96
26 SEP (269) 1979	21:53:19.0	−1.05	136.29	33.	4.8 m_b	−1.10	136.25	10. C	11	0.99
27 SEP (270) 1979	14:24:24.5	−1.09	136.19	33.	4.9 m_b	−1.17	136.23	25. F	11	0.69
28 SEP (271) 1979	23:57:37.8	−1.75	136.41	33.	5.4 m_b	−1.77	136.41	33. I	88	1.45
16 OCT (289) 1979	10:04:27.8	−1.15	136.42	33.	5.5 m_b	−1.12	136.46	22. I	115	2.05
16 OCT (289) 1979	19:55:40.0	−1.16	136.51	33.	4.9 m_b	−1.25	136.54	10. C	24	1.47
17 OCT (290) 1979	23:29:26.4	−1.16	136.60	33.	5.9 m_b	−1.18	136.59	24. I	170	1.31
18 OCT (291) 1979	00:07:11.3	−1.25	136.53	33.	5.2 m_b	−1.43	136.47	10. C	15	1.34
18 OCT (291) 1979	00:48:03.7	−0.88	136.63	33.	5.2 m_b	−1.13	136.46	10. C	14	1.29
18 OCT (291) 1979	00:57:21.8	−1.18	136.52	33.	5.3 m_b	−1.11	136.60	10. C	51	1.63
18 OCT (291) 1979	01:29:14.5	−1.12	136.57	33.	4.9 m_b	−1.33	136.49	10. C	15	1.39
18 OCT (291) 1979	13:30:58.5	−1.10	136.60	33.	5.0 m_b	−1.06	136.68	10. C	15	1.63
18 OCT (291) 1979	14:19:54.9	−1.15	136.66	33.	5.4 m_b	−1.22	136.60	10. C	36	1.75
19 OCT (292) 1979	15:40:59.4	−1.01	136.66	33.	5.4 m_b	−1.07	136.63	3. I	93	1.73
19 OCT (292) 1979	01:40:58.0	−1.22	136.63	33.	4.9 m_b	−1.23	136.62	20. C	9	0.90
31 OCT (304) 1979	09:58:49.8	−1.20	136.61	33.	5.3 m_b	−1.16	136.65	7. I	74	1.17

01 NOV (305) 1979	00:56:16.9	−1.84	136.11	33.	4.3 m_b	−1.96	136.04	11. F	15	1.55
01 NOV (305) 1979	04:12:54.8	−1.13	136.57	26.	5.6 m_b	−1.20	136.61	25. I	152	1.32
02 NOV (306) 1979	19:20:48.5	−1.14	136.82	33.	4.9 m_b	−1.17	136.78	10. C	26	1.86
08 NOV (312) 1979	21:25:21.6	−1.90	134.60	33.	5.1 m_b	−1.99	134.62	10. C	22	1.44
20 NOV (324) 1979	18:58:21.1	−2.00	136.38	33.		−1.98	136.32	10. C	11	1.48
07 DEC (341) 1979	08:57:42.0	−1.38	136.52	33.	5.2 m_b	−1.31	136.54	10. C	19	1.12
27 DEC (361) 1979	15:49:00.5	−1.82	135.93	33.	5.2 m_b	−1.80	135.88	38. O	60	2.21
11 JAN (011) 1980	23:10:21.8	−2.10	137.70	33.	4.9 m_b	−2.04	137.63	0. I	89	2.61
21 FEB (052) 1980	22:26:53.8	−2.10	137.20	33.	4.9 m_b	−2.15	137.19	16. I	45	2.22
25 APR (116) 1980	14:52:51.4	−2.20	136.00	33.	5.1 m_b	−2.16	136.21	10. C	12	1.05
17 JUN (169) 1980	06:01:12.2	−1.70	135.10	33.	5.2 m_b	−1.81	135.23	26. F	13	1.40
19 AUG (232) 1980	19:02:40.1	−1.50	136.00	33.	5.1 m_b	−1.32	136.40	10. C	19	1.50
30 SEP (274) 1980	23:53:16.9	−1.70	135.80	33.	5.1 m_b	−1.79	135.87	38. I	30	1.84
17 NOV (322) 1980	17:02:54.6	−1.10	136.80	33.	5.1 m_b	−1.28	136.49	59. F	14	1.36

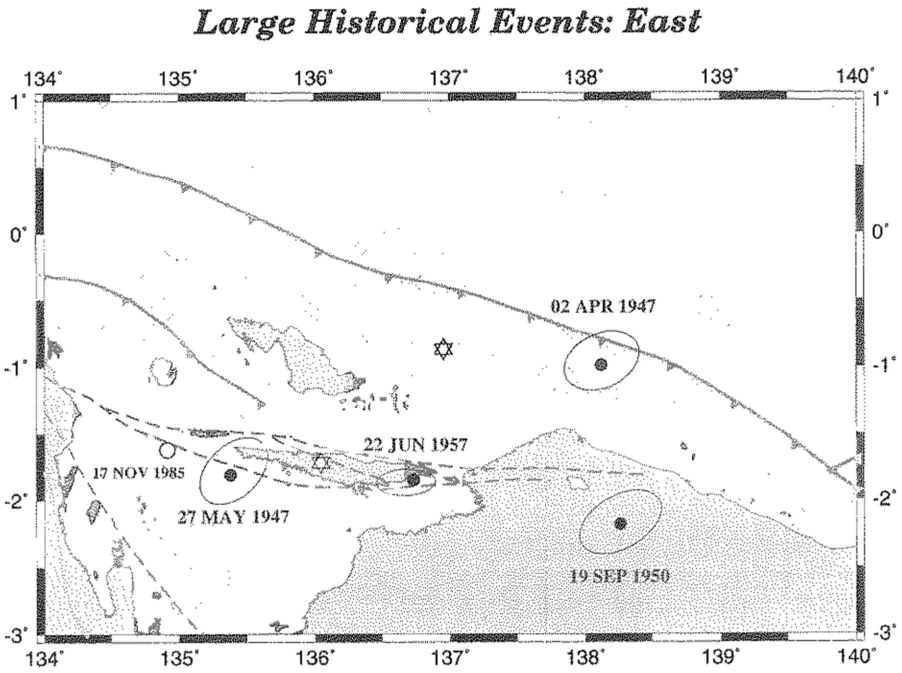

Figure 8
Same as Figure 7 for the eastern part of the study area. In addition, the recent event of 17 November 1985 on the Sorong Fault is shown as an open circle. The stars of David identify the 1979 and 1996 large shocks.

January 1968; $m_b = 4.8$, and 17 January 1974; $m_b = 5.4$) also belong to the Sorong system.

North of the Sorong Fault, in the central segment of the Transition Province, we find 23 events, which can be organized in three families: first a single moderately large event ($M_{PAS} = 6.13$) event happened on 07 April 1957, at the exact location of the future 1996 shock. A group of six events runs from the western end of Biak to the north of the Pandaidori Islands. The third group is composed of a large event on 04 December 1972 ($m_b = 6.1$), and 12 aftershocks in the following week, this cluster being 20 km north of the Sorong Fault. SENO and KAPLAN (1988) showed that the mainshock has a thrust mechanism (Fig. 9). Two shocks in 1987 and 1969 also occurred at the same location, with a sixteenth event relocating to the south of the Sorong fault system.

● *The 1979 Sequence*

The relocation of the 55 events of the 1979 sequence resulted in the correction of a few hypocenters, notably a handful of deep solutions proposed by the ISC (down to 384 km, clearly an unrealistic figure). The fundamental result is that significant seismicity following the 1979 mainshock took place not only along one fault plane (including the various braided strands of the Sorong system), but also in a cluster approximately 55 km to the NNE, in the vicinity of the Pandaidori Islands, the same region that became active immediately following the main Biak event (Dmowska *et al.*, 1996; Taylor *et al.*, 1998). Figure 10 shows that there is no obvious migration of the seismicity, i.e., the activity develops at Pandaidori within one day of the mainshock, and lasts at both locations during our full study period. While depths are often unresolved by the data set, a number of good solutions suggest that focal depths reach about 40 km in the south cluster along Yapen, and extend to 55 km in the north under Biak and Pandaidori Islands.

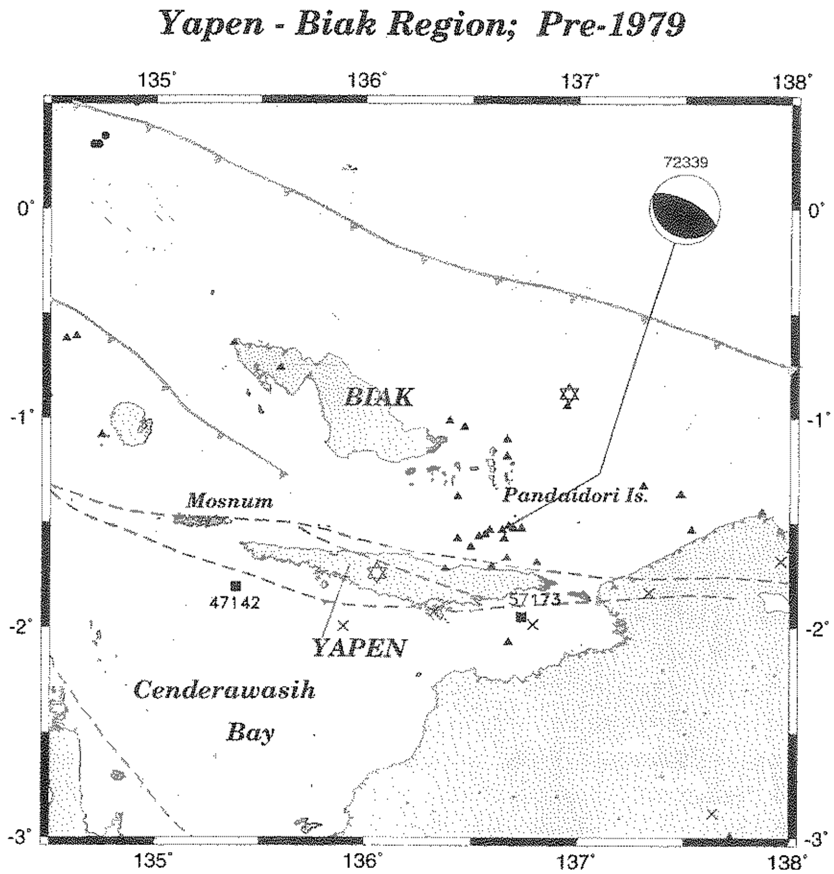

Figure 9
Seismicity of the Biak–Yapen region before the 1979 earthquake (note its generally very low level). Symbols as in the previous figures; the cluster of activity south of the Pandaidori Islands consists mostly of the 1972 event (focal solution by Seno and Kaplan, 1988) and its aftershocks.

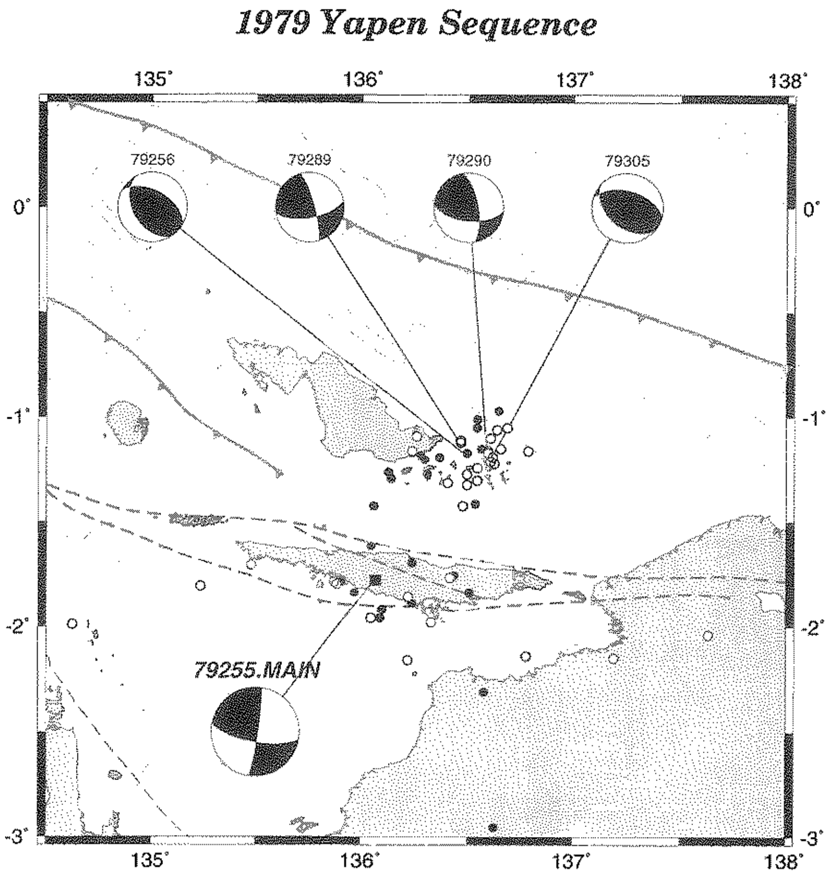

Figure 10
Relocated epicenters of the Yapen sequence, defined as all events taking place between 12 September 1979 and 31 December 1980. Solid dots indicate events on 12, 13 and 14 September 1979, open dots afterwards. All four available CMT solutions are shown.

The four CMT solutions available for this sequence (with moments from 1.5×10^{24} to 1.8×10^{25} dyn-cm) are shown on Figure 10. It is noteworthy that the largest event following the mainshock is located at the southeastern tip of Biak Island, and involves thrust faulting, as does the last event with an available CMT solution (on 01 November 1979), located about 25 km to the southeast, in the Pandaidori Islands. As mentioned by TAYLOR *et al.* (1998), all four events at Pandaidori share a compressional axis (sub-horizontal in the N36 ± 8°E azimuth), which is also close to that of the main 1979 and 1996 events. As shown on Figure 11, this geometry is strikingly similar to that of the Landers–Big Bear 1992 episode in Southern California, which has also been modeled as an example of triggering by stress transfer (KING *et al.*, 1992). Finally, we note that some post-mainshock seismicity (six events in total) aligns on a trend paralleling the Sorong Fault, about 30 km to the south of Yapen.

Once we consider the Pandaidori post-mainshock activity as resulting from triggering by stress transfer (TAYLOR *et al.*, 1998), the conventional aftershocks of the 1979 Yapen earthquake are restricted to the southern cluster of events on Figure 10, extending approximately 75 km along the Sorong system and 35 km across it (we recall that this system is braided across Yapen Island). The rupturing fault plane would have a total area of $\sim 3000\ \mathrm{km}^2$, and the seismic displacement could be ~ 2 m, enough to generate a substantial local tsunami, even from horizontal slip, given the vicinity of shorelines (TANIOKA and SATAKE, 1996). Two events at the extreme western tip of Yapen (23 September 1979 and 17 June 1980) define residual seismicity extending to the epicenter of the large 1947 shock.

• *The Biak–Yapen Region in the Intervening Years: 1980–1996*

We present on Figure 12 the available CMT solutions for the Biak–Yapen region between the two major events. The background seismicity is also shown, with the same geographical conventions as in the other figures. It is characterized mostly by strike-slip earthquakes along the two strands of the Sorong Fault system (three events in the south along the southern shore of Yapen and two in the straits between Yapen and Biak). Three more events took place in or around Yapen: one strike-slip on the southern shore, but with a rotated mechanism, and two thrust faulting events on 29 May 1984, which probably represent convergence along transverse segments of the braided Sorong system inside the island. All this activity is of small magnitude, with only one event reaching 10^{25} dyn-cm. In the Transition Province, we note two thrust faulting events, one east of Biak and one in the epicentral area of the future 1996 earthquake.

• *The 1996 Biak Sequence*

The 1996 Biak sequence was discussed in detail and modeled in the framework of Coulomb stress transfer by TAYLOR *et al.* (1998), who used a single asperity of dimensions 100×50 km, to model the geometrical partitioning between thrust faulting aftershocks (on a line parallel to the trench and running through the epicentral area of the mainshock), strike-slip post-mainshock events (mostly at Pandaidori Islands, and as far south as the northern shores of Yapen) and normal-faulting post-mainshock events (mostly under Biak Island, to the southwest of the mainshock epicenter). Since their study was completed, only one new CMT solution was published, a thrust faulting, presumably "true" aftershock, located north of Biak, on 03 August 1997.

More recently, MASTURYONO *et al.* (1998) have reported the results of the operation of a network of 10 portable seismic stations in the aftermath of the 1996 event, which suggests that the rupture extended along 300 km of trench, as far west as 134½°E, i.e., to the location defined in Section 2 as the western cluster of seismicity, at the presumed termination of the NGT. Based on the depth distribution of aftershocks, these authors have also argued that the 1996 Biak earthquake may not represent the subduction of Caroline lithosphere under New Guinea, but rather be an intraplate event inside the downgoing slab.

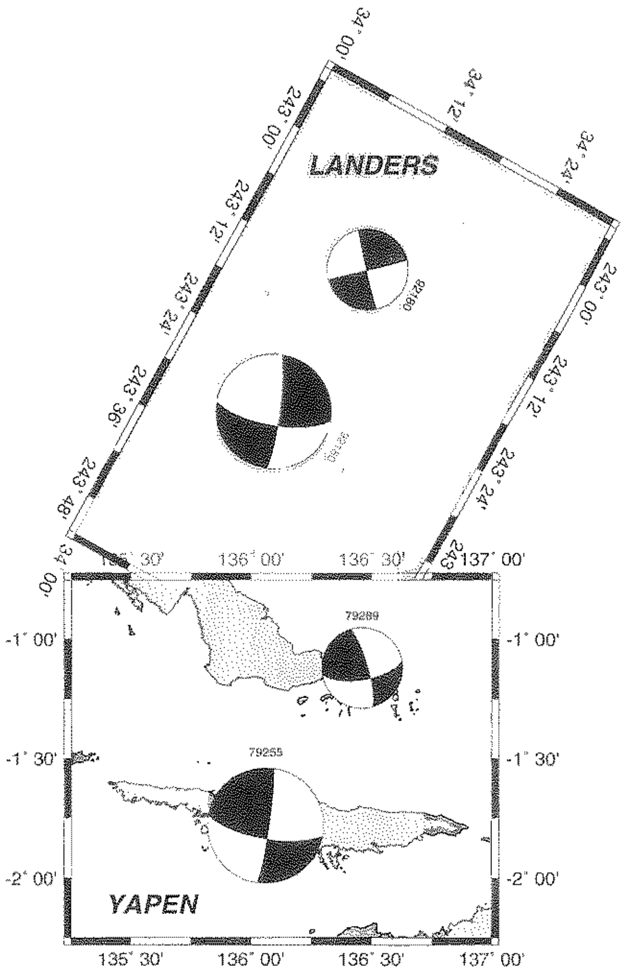

Figure 11

Comparison of geometry of stress transfer for the Yapen and Landers earthquakes. *Top:* Geometry of the Landers mainshock (28 June 1992, 11:57) and of the triggered Big Bear event (28 June 1992, 15:05). *Bottom:* same as top for the Yapen mainshock and the triggered event on 16 October 1979 in the Pandaidori Islands. The top map has been rotated 119° clockwise to make the strike of the Landers event (N341°E) coincide with that at Yapen (N100°E). The two mechanisms are then practically identical, except for their opposite polarity. Note the similar relation in location and orientation of the triggered event.

5. Conclusions

The results of our study can be summarized in three main conclusions:

The Sorong Fault System

The combination of recent seismicity and our historical relocations suggest that the entire Sorong system is seismically active, from the Mamberambo Belt in the east to the western end of Cenderawasih Bay, and possibly into the Bird's Head, for a total distance of at least 420 km, and possibly 750 km, thus alleviating some of HAMILTON's (1979) concerns about the level of seismic activity of this major feature. The eastern end of the Sorong Fault merges into the Mamberambo Thrust Belt system, around 138.6°E, where both thrust and strike-slip mechanisms are

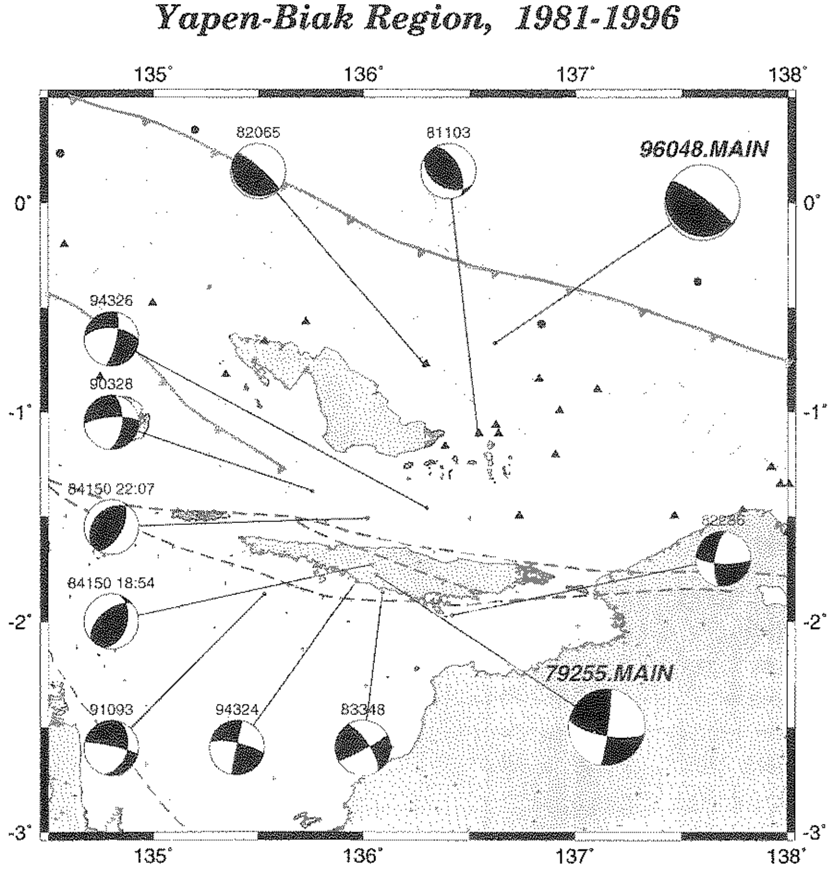

Figure 12
Same as Figure 9 for the time window separating the two large shocks.

documented (Fig. 5). Immediately to the west, the Sorong system is identified in the seismicity with the small events of 23 July 1981 and 24 March 1989, and the larger earthquake of 08 April 1931 north of Lake Rombebai. Major activity involves the 1957 mainshock at 136.7°E, whose aftershocks reach across the straits into the Bird's Shoulder, only 60 km west of the lake. Farther west, the 1979 earthquake and its true aftershocks cover 75 km along Yapen Island, with residual seismicity extending to the western tip of Yapen, and coinciding with the epicenter of the event on 27 May 1947. Moment magnitudes indicate that this event could have been as big as the 1979 Yapen earthquake; in the absence of aftershocks, we speculate that its rupture may have extended to the epicenter of the next large shock along the fault, on 17 November 1985 ($M_0 = 5 \times 10^{26}$ dyn-cm). This event was interpreted by PUNTODEWO *et al.* (1994) as expressing movement along the so-called "Bird's Neck Fault," striking ~N250°E to the narrowest segment of the Bird's morphology. Its strike-slip mechanism along azimuth N271°E is in a direction intermediate between the trend of the Sorong and proposed Bird's Neck Faults, and an exact association with either of them remains speculative.

To the west of this region, the situation is less clear. On the basis of our relocations and their Monte Carlo ellipses, it would be possible to associate 6 of the 7 earthquakes shown on Figure 6 with the Sorong Fault through the Bird's Head; on the other hand, all but one of the relocations are generally north of the Sorong system, and a better association might involve the Koor Fault, as defined along a 90-km segment in the Bird's Head, and a possible prolongation at sea east of 133°E. Ellipses for the two events of 26 April 1944 and 19 July 1934 tangent the Manokwari Trough, but it is unlikely that all events would belong there. Seismic moment estimates obtained for three of the seven events indicate a larger total moment release than during the 1979 Yapen shock, suggesting perhaps a similar level of activity for the two segments of the Sorong Fault.

Activity on the New Guinea Trench

The occurrence of the 1996 Biak earthquake has profoundly changed our understanding of the seismicity of the NGT, which must be considered as an active subduction segment. We show that some level of seismic activity is indeed documented more or less continuously from $134\frac{3}{4}°$ to $139\frac{3}{4}°$E. In the northwest, the subduction probably stops at the junction with the Ayu Ridge, where some focal mechanisms (but not all) would suggest that the convergence is transformed southwest into the Manokwari Trough. Seismicity at a very low level (2 earthquakes with $m_b \leq 5.3$) is resolved along the central segment of trench before the occurrence of the great Biak earthquake. Similarly, seismicity in the Transition Province merges continuously with the cluster of true 1996 aftershocks (as determined by their location and thrust faulting mechanism). It is probable (MASTURYONO *et al.*, 1998) that the

Biak shock ruptured most of the trench segment from 134$\frac{3}{4}$°E to 137$\frac{1}{2}$°E. East of this zone, we document a relatively large trench earthquake at 138°E on 02 April 1947. Scaling laws would suggest that, at $M_0 = 3 \times 10^{27}$ dyn-cm, this earthquake involved a 75-km section of trench, extending to 138$\frac{3}{4}$°E. At that longitude, abundant seismicity expresses the general confluence of the trench, the Transition Province seismicity, and the abutment of the Sorong system into the Mamberambo Thrust Belt to the east. While three relatively poorly located events suggest some low level of activity on the easternmost section of the NGT, this roughly 100-km long segment may well constitute a seismic gap with the potential for an earthquake of moment $\sim 7 \times 10^{27}$ dyn-cm. At 139$\frac{3}{4}$°E, the NGT intersects the West Melanesian Trench and the tectonic regime may change.

This leaves the case of the large shock of 1914; this event is very poorly located, but is most likely at neither of the two published epicenters (NEIC and ISS). On account of its tsunami, we propose to locate it in the New Guinea Trench, north or northwest of Biak. In the absence of adequate understanding of the size of the 1914 earthquake, it may prove futile to further speculate on the relationship of the two events (1914 and 1996) to a possible earthquake cycle along the NGT, and hence on the duration of the latter and the recurrence time of major events along the NGT: Large uncertainties presently plague our estimates of both the component of plate motion expected to be taken up at the NGT (from a maximum of 9 cm/yr of convergence (DEMETS *et al.*, 1990) to 4.0 cm/yr as suggested by PUNTODEWO *et al.* (1994)), and the co-seismic slip during the 1996 earthquake (from 8 m (STEVENS *et al.*, 1996) to possibly 12 m locally in the main asperity (DMOWSKA *et al.*, 1998)). At any rate, it is clear that seismicity at the New Guinea trough takes the form of a few very large earthquakes, and its seismic quiescence prior to 1996 should have been regarded as a "seismic gap."

Stress Transfer at Pandaidori Islands

The triggering of the post-Biak sequences at Pandaidori Islands (as well as in the western part of Biak Island) has been modeled conclusively by TAYLOR *et al.* (1998) as due to stress transfer into the overriding plate. By analogy with the Landers–Big Bear geometry, we argue that a potentially similar mechanism may have triggered the 1979 post-mainshock seismicity at Pandaidori Islands. The concentration of seismicity following both mainshocks at precisely the same location in the Pandaidori Islands remains an interesting property. The occurrence of the 1972 swarm, only 35 km to the south, also suggests that the whole region may constitute a zone of weakness where release of stresses built-up in the overriding plate takes place preferentially.

Finally, the short time span between the 1914 earthquake and the large event in 1916 leads to a natural speculation that the latter, if located to the north of its Monte Carlo ellipse, may have been triggered by stress transfer in the aftermath of the former. This suggestion cannot be discounted, but it remains an unlikely scenario, given the absence of any tsunami report in the region following the 1916 event (for which GUTENBERG and RICHTER (1954) suggested a larger magnitude than in 1914), strongly suggesting an on-land epicenter in the Bird's Neck.

Acknowledgments

I thank my friends at Harvard, Renata Dmowska, James Rice and Mark Taylor, for stimulating discussions on the mechanism of stress transfer. I am grateful to colleagues in many observatories who sent copies of historical seismograms, and I wish in particular to pay tribute to the late Rev. Ramon Cabré, S.J., who on this and many other occasions, sent copies of the excellent La Paz records. Rob van der Hilst provided a customized tomographic profile. Jim Schwartz helped construct a few new focal mechanisms. Many years ago, Mitchell Heineman sorted out historical earthquakes of Irian Jaya for a B.S. project at Yale, and his files have proven invaluable for the present project. The figures were drafted using the GMT software by WESSEL and SMITH (1991). The paper was improved by the comments of Renata Dmowska and an anonymous reviewer.

Appendix

Relocation of Other Significant Earthquakes

We detail here the relocation of significant historical (and a few recent) earthquakes.

- *7 July 1919; Bulletin Location: 2°S; 137°E*

With only 4 P times (those at Melbourne and Riverview mutually incompatible) and 3 irregular S times, the earthquake cannot be meaningfully relocated.

- *23 November 1919; Bulletin Location 0°N; 135°E (NGT Cluster)*

The earthquake is grossly mislocated, and despite a generally poor data set, it must have taken place inside the eastern part of Papua New Guinea, around 5°S; 143°E. The ISS epicenter remains 750 km from the Monte Carlo ellipse (drawn for $\sigma_G = 15$ s).

- *01 March 1921; Bulletin Location: 0°N; 135°E (NGT Cluster)*

This event is poorly constrained (with only 4 stations); it relocates at the southern extremity of the western Caroline Ridge (0.83°N; 132.11°E) but its Monte Carlo ellipse (computed for with a generous $\sigma_G = 20$ s) does not reach past 134°E; the event is most unlikely to be associated with the cluster.

- *10 October 1921; Bulletin Location: 0°N; 135°E (NGT Cluster)*

The ISS proposes two entries for this event: one in the NGT cluster, the other at 5°S, 135°E, assuming a depth of 413 km, more than 300 km deeper than the deepest known CMT solution under Irian Jaya. We relocate the event to 3.07°S; 139.43°E, using a constrained depth of 40 km; all attempts to use a greater depth were unsuccessful. The epicenter is poorly constrained, but the Monte Carlo ellipse is oriented east–west and reaches neither of the two ISS epicenters. The event is most likely associated with the zone of abundant seismicity south of Jayapura.

- *05 April 1922; Bulletin Location: 2°N; 137°E*

The earthquake relocates to the south of Cenderawasih Bay, and its Monte Carlo ellipse ($\sigma_G = 10$ s) cannot reach the ISS epicenter on the Sorong system.

- *20 October 1923; Bulletin Location: 4°N; 139°E*

The data set for this event is small and inconsistent. If we disregard the times at Batavia, the remaining four times converge on an intermediate-depth focus in the Philippines. We keep this interpretation but it remains speculative. Any other combination fails to converge satisfactorily.

- *15 January 1925; Bulletin Location: 0°N; 135°E (NGT Cluster)*

With only 3 P and 3 S times, forming an inconsistent data set, this event could not be relocated.

- *22 March 1925; Bulletin Location: 1°S; 140°E*

A satisfactory solution (4.97°S; 141.13°E; $h = 100$ km) is obtained in an area of documented intermediate-depth seismicity under the Central New Guinea range, by assuming that Perth was 1 minute early and discarding the S time at Adelaide.

- *17 July 1925; Bulletin Location: 2°S; 137°E*

A data set of 9 (out of 12) P times converges to a mediocre solution ($\sigma = 3.5$ s) at 3.03°S, 137.15°E at the southern border of the Meervlakte Basin, and the Monte Carlo ellipse ($\sigma_G = 8$ s) cannot reach the Sorong system to the north.

- *17 September 1927; Bulletin Location: 0°N; 135°E (NGT Cluster)*

With the exception of the times at Batavia, which cannot be reconciled, the solution converges relatively well to a location at 2.42°S; 134.09°E. While the Monte Carlo ellipse ($\sigma_G = 7$ s) is 400 km long, it is oriented SSE–NNW along the Bird's Neck, and does not reach the ISS epicenter.

- *03 October 1930; Bulletin Location: 0.5°N; 135.0°E (NGT Cluster)*

This earthquake is given by the ISS at 2°N; 135.5°E, inside the Caroline plate. The data are very scattered and no reliable relocation could be achieved.

- *05 April 1931; Bulletin Location: 1°S; 140°E*

The times at Adelaide (P) and Melbourne (P and S) must be corrected by one minute. Then, an acceptable solution is found at 0.82°S; 140.43°E, which would make this event intraplate. However, the Monte Carlo ellipse shows no resolution in the NE–SW direction, and we prefer moving the solution to 1.8°S; 139.3°E, where abundant seismicity is documented.

- *08 April 1931; Bulletin Location: 2°S; 137°E*

With the exception of the P time at Perth, the entire data set of 16 stations converges on 1.67°S, 137.96°E ($\sigma = 3.9$ s), along the Sorong Fault in the Bird's Shoulder. The Monte Carlo ellipse ($\sigma_G = 6$ s) extends approximately 200 km in the east–west direction, suggesting that the earthquake remains significantly east of the 1957 series.

- *05 January 1932; Bulletin Location: 3°N; 134°E*

The ISS list two possible solutions, the second one (1.8°N; 129.3°E) suggested by Batavia, neither of them explaining the full data set. We prefer moving the first epicenter approximately one degree west, to the Western Caroline Ridge. The Monte Carlo ellipse ($\sigma = 7$ s) confirms this interpretation.

- *01 September 1932; Bulletin Location: 2°S; 137°E*

This event is poorly constrained in the north–south direction. While all relocations efforts converge on a southern location at 3.3°S, 136.8°E, the tip of the Monte Carlo ellipse ($\sigma = 8$ s) does reach the extremity of the Sorong system in the Bird's Shoulder. It is more likely, however that the event belongs to the southern border of the Meervlakte Basin.

- *29 May 1940; Bulletin Location: 1°S; 141.5°E*

Except for an erroneous *S* time at Adelaide, the data set converges superbly to a more southern location, at 2.10°S; 139.32°E, in the Jayapura seismic belt.

- *17 July 1957; Bulletin Location: 2°S; 137°E, and 09 August 1957; Bulletin Location: 2.02°S, 136.74°E*

Both of these events are aftershocks of the large earthquake of 22 June 1957 at the eastern tip of Yapen. They both relocate on the Sorong system, at 1.82°S, 137.34°E ($\sigma = 1.77$ s on 19 stations) and 1.97°S, 136.79°E ($\sigma = 2.49$ s on 84 stations), respectively.

- *04 November 1963; Bulletin Location: 0.90°S; 139.70°E*

While our best solution (0.95°S; 139.65°E) essentially confirms the ISS one, it is poorly constrained in the NNE–SSW direction, and we prefer a location around 1.25°S, 139.5°E, on the eastern segment of the New Guinea Trench, and inside the Monte Carlo ellipse ($\sigma_G = 2$ s).

- *18 November 1979; Bulletin Location: 1.73°S; 139.69°E*

Both the NEIC (201 km) and the ISC (287 km) depths are excessive, and neither leads to an acceptable solution ($\sigma = 6.76$ and 6.18 s, respectively). Both solutions are crucially controlled by the *P* times at Mould Bay (importance 0.93), which we believe is a mis-associated *SKS* phase from a Tongan event preceding the Indonesian one by 11 minutes. When the MBC time is ignored, the solution converges superbly to a shallow focus further south into New Guinea.

- *23 September 1982; Bulletin Location: 0.31°N; 141.29°E*

The data set of 10 *P* times is poorly fit by both the NEIC solution and the ISS one (1.4°S; 141.3°E; $\sigma = 4.36$ s), which further requires a depth of 107 km, whereas no other deep focus is known in the area north of 3°S. Our Monte Carlo tests

($\sigma_G = 2$ s) show that the only solutions at shallow depths are indeed intraplate, in the vicinity of 0°S; 141°E. We report this solution but regard it as tentative.

- *24 October 1984; Bulletin Location: 0.32°S; 137.67°E*

We confirm the location of this event at 0.39°S; 137.57°E. The only strong residual (−12.3 s at South Ridge, Fiji) probably results from a mis-association of the reading with the wrong earthquake. The Monte Carlo cluster ($\sigma_G = 1$ s) is about 35 km (NNW–SSE) by 50 km (ENE–SSW).

- *14 March 1988; Bulletin Location: 1.06°S; 139.56°E*

The data set has very little resolution in the north–south direction. The time at Mount Isa (QIS) is generally incompatible with the other stations. When QIS is deleted, the earthquake moves 17 km north of the Bulletin epicenter, but we prefer to locate it as 1.3°S; 139.6°E, inside its Monte Carlo ellipse ($\sigma_G = 1$ s) and in the active segment of the New Guinea Trench.

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