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THE SEISMIC ZONE OF THE PAPUAN FOLD BELT

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Improved regional seismograph coverage in the 1970s has enhanced the resolution of the seismicity of the southern highlands of Papua New Guinea. Two zones can be defined. The Southern Highlands Seismic Zone follows the Papuan Fold Belt and extends from Kerema on the Gulf of Papua through the Star Mountains region into Irian Jaya. A second zone, the Mount Hagen Seismic Zone, plunges to the north-northeast from the Southern Highlands Seismic Zone south of Mount Hagen to intersect the intermediate-depth seismicity beneath the Ramu- Markham Valley. The southern highlands earthquakes reflect continuing Pliocene–Quaternary thrust faulting in the crust of the Indo-Australian Plate, brought about by the collision of the Indo-Australian and South Bismarck Plates over the sinking Solomon Sea Plate. Relief of compressive stress is through fracturing of the continental plate margin. The zone of fracture is now manifest in the Papuan Fold Belt. Seismic risk in the Southern Highlands Seismic Zone is less than that of the north coast, New Britain, and Bougainville, but is still high. The once-a-year largest earthquake is of magnitude 4.7, the ten-year earthquake magnitude 6.2, and the 30-year earthquake magnitude 6.9, which compare with the Californian figures of 5.7, 6.9, and 7.4, respectively. Large earthquakes are expected to occur along the zone in the future and their effects could be severe.

Introduction

On 19 January 1922, a magnitude 7.5 earthquake with its epicentre near Kikori occurred beneath the southern foothills of the central ranges of Papua New Guinea. The earthquake was felt strongly 200 km to the southwest. The Meteorological Observer at Daru reported that village houses were damaged in the southwest Papua region, that the sea was disturbed as if boiling, that at Sumai village (exact location not known) a six foot high wave swept over the village, and that people were terrified (see Fig. 1 for localities).

On 2 November 1931, a magnitude 6.5 earthquake occurred near Kerema. The Resident Magistrate reported that a number of village houses collapsed, trees crashed, and long cracks appeared in the ground.

On 3 March 1954, a magnitude 7 earthquake occurred in the Tari–Doma Peaks region, where it was felt at Modified Mercalli Intensity 7 (Dent, 1974; Everingham, 1979). The earthquake was felt from Daru on the south coast to Wewak in the north. A magnitude 5.5 earthquake in the same locality on 6 September 1977 caused landslides, which blocked the Tari–Margarima road.

On 25 June 1976, a magnitude 7.1 earthquake killed an estimated 420 people in Irian Jaya, near the border with Papua New Guinea (UNDRO, 1976). Landslides swept away or buried many villages and gardens. Fifteen small villages were completely destroyed and 70 more were damaged. The epicentre was 130 km northwest of the Star Mountains, and the area of destruction came to within about 60 km of the Papua New Guinea border near the Star Mountains. A second magnitude 7 earthquake occurred four months later, on 29 October 1976, killing many more people.

On 19 January 1981, another earthquake in Irian Jaya, 200 km west of the Star Mountains, was responsible for the deaths of over 300 people. The earthquake magnitude was 6.5. The devastated region was visited by H. Letz of the Freie University, West Berlin, in co-operation with the Indonesian Government, in February 1981 (Letz, personal communication).

These large earthquakes were not isolated events on the southern edge of the main seismic zone of northern New Guinea. Rather, they were events within a discrete seismic zone, here termed the Southern Highlands Seismic Zone. This zone coincides with the southern slopes of the central ranges and extends from the region of Kerema, on the Gulf of Papua, through the Star Mountains into Irian Jaya (Fig. 2; Ripper & McCue, 1982).

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Papuan Fold Belt

The seismic zone coincides with the southern slopes of the central ranges, a region characterised by long northwest–southeast ridges of moderate relief, rarely more than 1500 m high, under heavy jungle cover, becoming more rugged in the west, and surmounted by several Quaternary stratovolcanoes (Dow, 1977). This region is part of a distinct geological structural unit, the Aure Tectonic Zone (Thompson & Fisher, 1965), which incorporates the Papuan Fold Belt (Bain, 1973). Bain described the Papuan Fold Belt as a belt of sub-parallel folds and faults, 50–70 km wide and 1000 km long, which bounds the northern and eastern limits of the Fly Platform. Broad synclines and tight, commonly faulted, anticlines in the northeast give way to overthrust anticlines in the southwest. Tertiary limestone has been considerably shortened by both folding and overthrusting from the north or, in the Aure Trough, from the east. Bain considered that some thrust faults clearly extend to considerable depth in the Mesozoic sequence and possibly into the Palaeozoic basement.

Jenkins (1974) interpreted the thrusts as resulting from gravity-induced horizontal sliding towards the southwest, away from an anticlinal uplift in the northeast. Davies (1979) rejected the gravity sliding mechanism for the development of the thrusts. He maintained that the thrusts are now recognisable as a classic foreland thrust belt, crustal shortening being north–south and northeast–southwest. According to Davies, thrusting commenced in the Pliocene and continued into the Quaternary, the axes of thrust activity and of uplift migrating southwards to the present location through the Star Mountains.

An essential difference between the two hypotheses is that Jenkins interprets the thrusts as being confined to depths above about 7 km, while Davies postulates that they extend to depths of about 25 km. Both hypotheses envisage the thrusting processes as continuing, as the existence of the seismic zone would seem to confirm.

Volcanism in the highlands and south of the highlands has continued from late Pliocene through the Pleistocene. Two volcanoes currently show signs of activity, Doma Peaks near Tari, and Mount Yelia near Menyamya (Mackenzie, 1976). Thus, the tectonic uplift and thrusting have occurred concurrently with the volcanism.

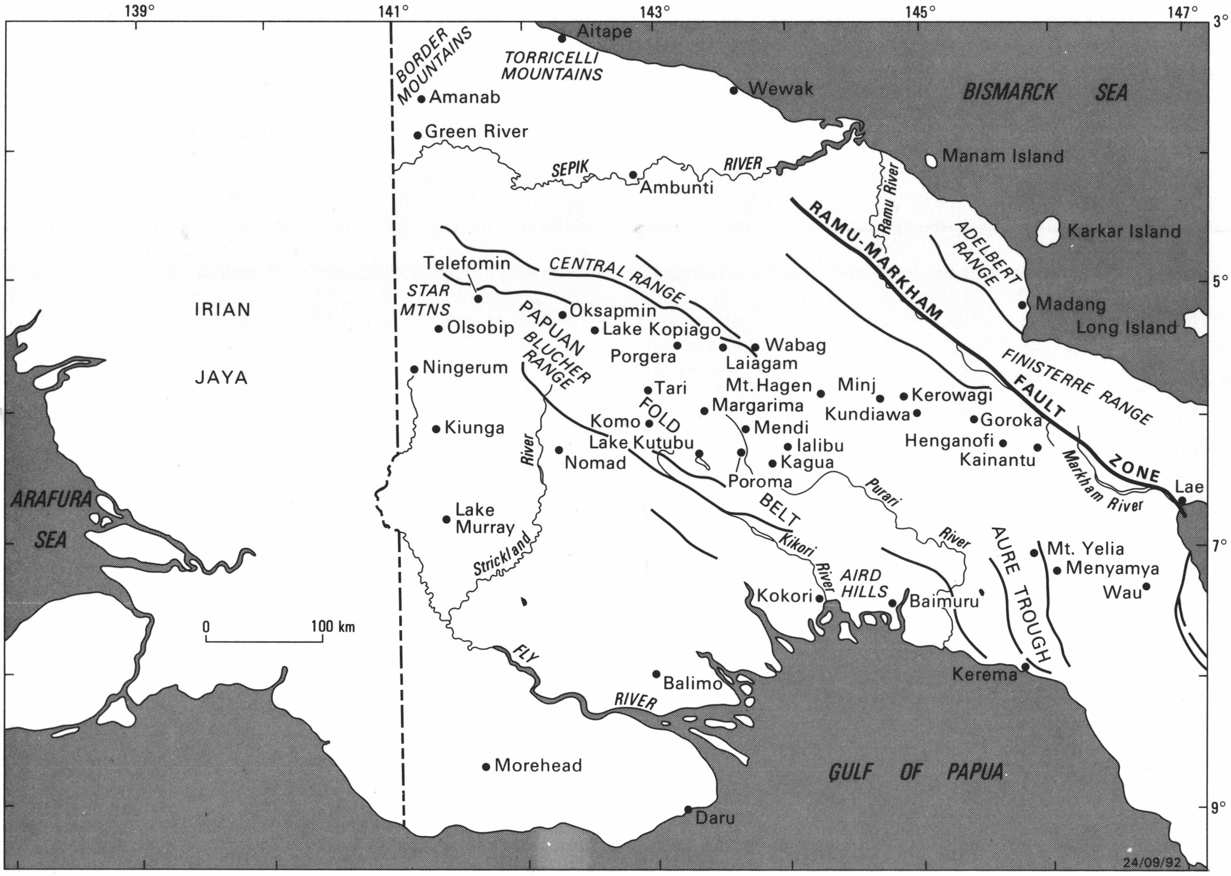

Figure 1. Central New Guinea localities and Pliocene–Quaternary fault zones, showing the Papuan Fold Belt.

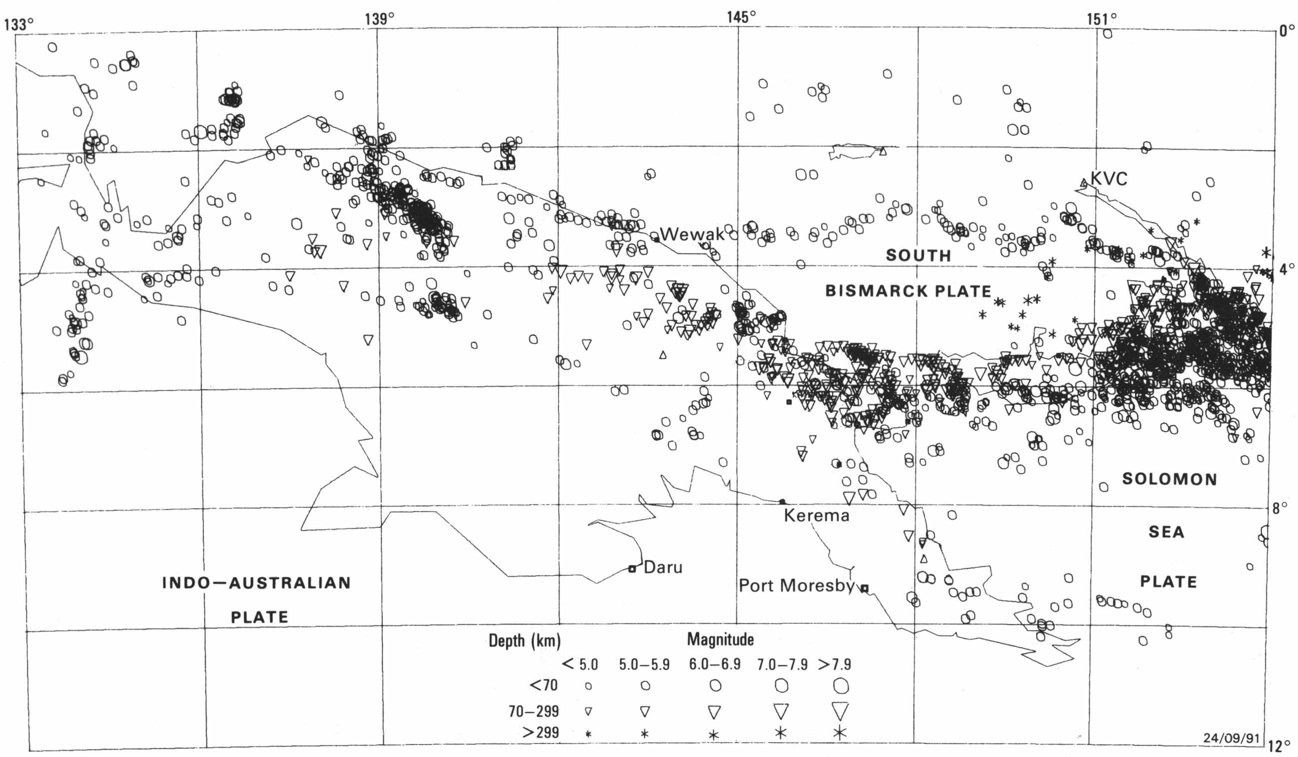

Figure 2. Seismicity of the New Guinea region, 1964–1980.
Fifteen or more stations used in the earthquake locations. The Southern Highlands Seismic Zone and the Mount Hagen Seismic Zone branching off it are clearly apparent.

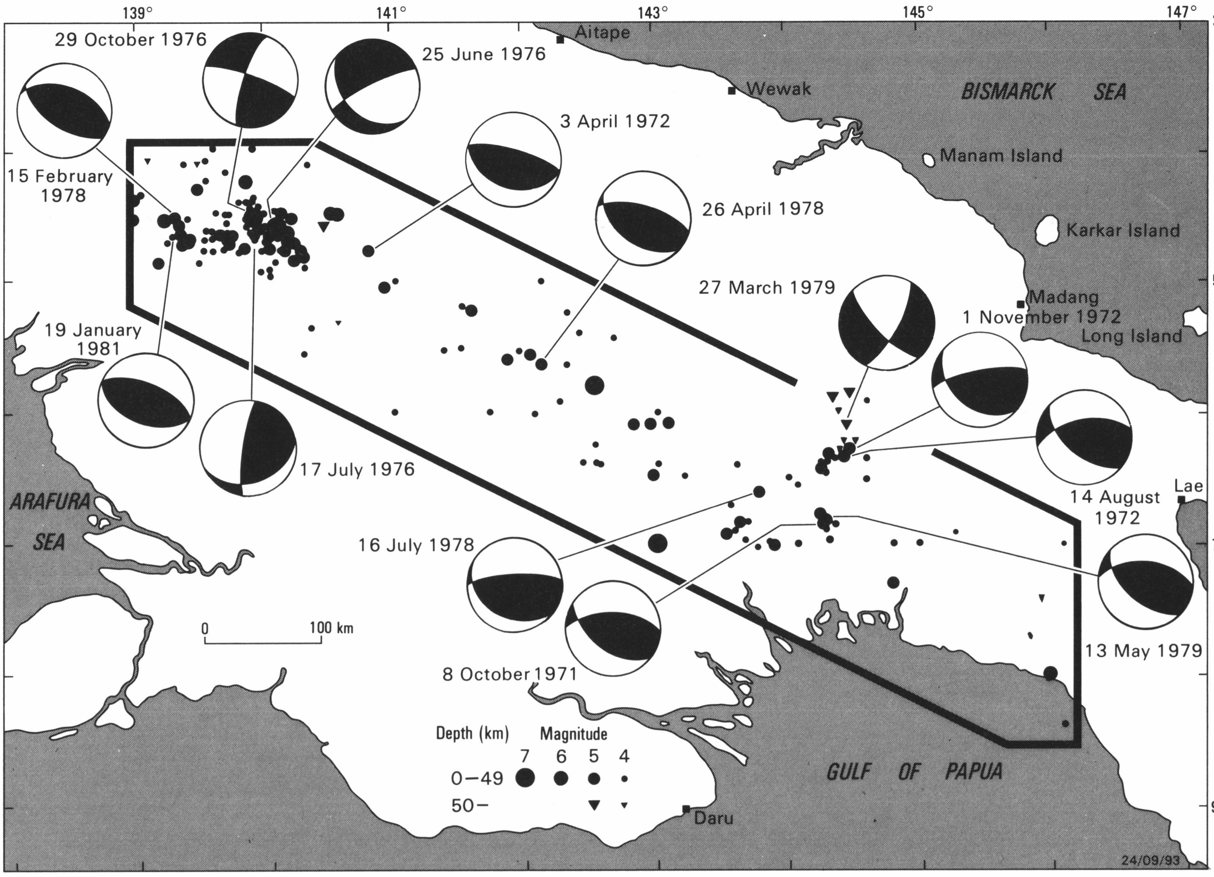

Figure 3. The Southern Highlands and Mount Hagen Seismic Zones.
The position of the NNE-trending Mount Hagen Seismic Zone is shown by the gap in the border around the Southern Highlands Seismic Zone. All known earthquake locations in the zones since 1900 are plotted. Earthquakes of the major seismic zones to the north have been omitted. Earthquake fault-plane solutions taken from Table 1 are superimposed. Solutions with 'black centres' — P-wave compressions — are overthrust; white centres — dip-slip normal; intersection in the centre — strike-slip.

The Southern Highlands Seismic Zone

The Southern Highlands Seismic Zone extends from Kerema on the Gulf of Papua, through the Star Mountains to about 4°S 139°E, and possibly further west-northwest to 136°E. The zone is at least 700 km long and up to 100 km across. The seismic zone is shown in detail in Figure 3. Most of the earthquake hypocentres have been taken from United States Geological Survey Bulletins (USCS, also previously USGS, USNOS, USERL) and International Seismological Centre Bulletins (ISC).

While the locations of earlier earthquakes in the zone may have an uncertainty of a degree or more, those of post-1970 earthquakes should be accurate to about 30 km. Most of the earthquake foci are at depths of less than about 35 km; for many of the depths given by USGS as 'normal, 33 km', the unrestricted computer depth computation was unsatisfactory, but shallow, and the solution was held by the reviewing geophysicist at 33 km. Depths other than 'normal' have either been determined from 'depth phases' (e.g., 13 May 1979) or have an uncertainty factor, normally plus or minus about 10 km. The computed depths would seem to indicate that, although earthquakes may be occurring in the top few kilometres of the crust, earthquakes are also occurring deep within the crust and possibly below it.

Most of the smaller (magnitude 5 or less) earthquakes in the zone, and which serve to define it, have occurred during the 1970s, reflecting not necessarily an increase in seismic activity in the 1970s, but an increased detection capability of the Papua New Guinea seismograph network, more sensitive overseas seismic stations, and improved earthquake location techniques by the USGS and ISC.

Gaps exist where large earthquakes have not recently occurred on the zone. One gap exists to the northwest of Kerema, and another in the Star Mountains region near the border between Papua New Guinea and Irian Jaya. Beyond Kerema, to the east-southeast, the zone either loses its identity or merges with a northerly seismic trend passing through the Wau region and joining the northern zone in the vicinity of Lae.

No earthquake has been correlated with a specific surface Pliocene/Quaternary fault, and no recent earthquake is known to have caused a surface fault scarp in the region. But such a scarp may well pass undetected in the heavy jungle cover or be masked by landslides.

A second earthquake zone, the Mount Hagen Seismic Zone, branches off the main Southern Highlands Seismic Zone at about 6.5°S 144°E, south of Mount Hagen. It trends approximately north-northeast past Mount Hagen, deepening to intersect the intermediate-depth seismicity beneath the Ramu and Sepik Valleys. The position of the zone in Figure 3 is shown by the break in the diagram border and a profile of the zone, showing the increase in depth of earthquakes to the north-northeast is shown in Figure 4. Most of the earthquakes located on the zone occurred in the 1970s and in a two-year period from mid-1971 to mid-1973, but some earlier earthquakes may not have been located. As the width

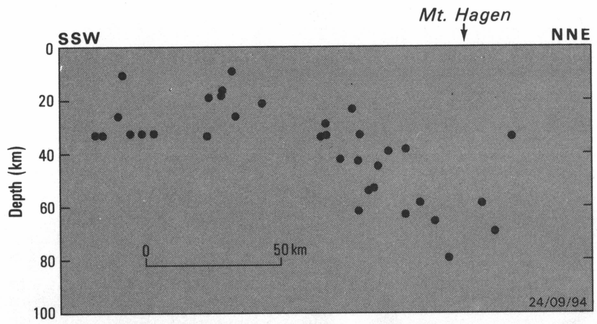

Figure 4. Depth profile of the Mount Hagen Seismic Zone. The width of the profile is less than 70 km. Allowing for location uncertainty, the seismic zone is not a sloping plane, but rather resembles a plunging conduit. Earthquakes in the south-southwest of the diagram are part of the Southern Highlands Seismic Zone. Those of the centre and north-northeast define the Mount Hagen Seismic Zone.

of the zone is less than about 70 km, it is better described as a plunging conduit rather than a sloping plane or Benioff Zone.

Thirteen of the earthquakes on both zones were recorded at sufficient seismograph stations for fault plane solutions to be obtained. Solutions were obtained from P-wave first motions projected onto a Wulff stereographic projection. The first motions were obtained by examination of Papua New Guinea seismograms. Data from stations outside Papua New Guinea were extracted from International Seismological Centre Bulletins and individual station bulletins.

The P-wave first motion diagrams are shown in Figure 5 and the solution parameters in Table 1. The mechanism diagrams from Figure 5 are superimposed on Figure 3. All the first motion diagrams are adapted from Ripper & McCue (1981), and the 1976 and 1978 solutions are based on those by McCue (1981, 1982).

Of the thirteen solutions, nine are overthrusts on a general west-northwest strike. The depths computed for these earthquakes range from 16 km, through 'normal depth' to 45 km, and favour the Davies (1979) foreland thrust concept rather than the gravity-sliding hypothesis of Jenkins (1974).

The first motion diagram of the magnitude 7 Irian Jaya earthquake of 25 June 1976 indicates motion on a normal fault, not easily explained, but the 17 July aftershock appears to be a related 'backlash' event. The 29 October 1976 magnitude 7 earthquake in the same area was not an overthrust, but can be interpreted as a left-lateral fault movement on a west-northwest strike. Hence, neither of the two magnitude 7 Irian Jaya earthquakes had a thrust solution.

One fault plane solution has been obtained of an earthquake at intermediate depth (65 km) in the Mount Hagen Seismic Zone. The compressional stress axis is oriented at 355°, plunge 41°, that is, approximately parallel to the plunge of the seismic zone. The tensional axis of the solution is horizontal and approximately east–west.

Brief descriptions of the solutions

(1) 08 October 1971. Between Kikori and Mount Hagen. Depth 18 ± 7 km. Not a strong solution, but clearly an overthrust with the azimuth controlled by P-wave first motion compressions recorded at seismic stations Port Moresby (PMG) and Lae (LAT). In this solution, and in most of the solutions, PMG records a compression and is ideally positioned to orientate the thrust.

(2) 03 April 1972. Irian Jaya, adjacent to the Star Mountains. Depth 40 ± 13 km. Not a strong solution, there being only two dilatations, and the first motion at Momote seismic station (MOM) is anomalous. But the west-northwest-striking overthrust is essentially the only solution possible, despite the limited data.

(3) 14 August 1972. Southeast of Mount Hagen, on the Mount Hagen Seismic Zone. Depth 44 ± 6 km. An other-thrust solution, with pressure azimuth north-northeast controlled by the P-wave compressions at seismic stations Port Moresby (PMG) and Rabaul (RAB).

(4) 01 November 1972. Same location as the previous shock. Depth 35 ± 5 km. The solution is poor as there are several anomalous station readings, but clearly an overthrust.

(5) 25 June 1976. Irian Jaya, the damaging magnitude 7 earthquake. Normal depth. The solution is reasonable good, and differs significantly from the others. It is dip-slip normal, with the tension axis at shallow plunge to the north and pressure axis plunging steeply southeast. If the plane striking northeast is the fault plane, the southeast side moves relatively up on a normal fault.

(6) 17 July 1976. Aftershock of the 25 June earthquake. Normal depth. A reasonable solution. Fault movement is on either an almost vertical or almost horizontal plane. The polarity quadrants and stress axes are virtually opposite to those of the main 25 June shock, suggesting a backlash effect.

(7) 29 October 1976. A second magnitude 7 earthquake close to the 25 June shock in Irian Jaya. Normal depth. Although there are some anomalous station polarities, the

Table 1. Earthquake fault plane solution parameters.

Ref. No.	Date	Origin Time (UT)	Lat. (°S)	Long. (°E)	Depth (km)	Mag.	Nodal Planes						B Axis		P Axis		T Axis	
							Strike	Dip	Dip Az	Strike	Dip	Dip Az	Az	Pl	Az	Pl	Az	Pl
1	08 Oct 71	14 15 35.9	6.85	144.26	18±7	5.6	091	54	001	127	41	217	284	18	017	09	128	70
2	03 Apr 72	11 43 19.3	4.80	140.80	40±13	5.4	103	66	013	102	24	192	103	00	013	21	196	70
3	14 Aug 72	22 29 27.6	6.31	144.42	44±6	5.6	133	50	223	080	53	350	285	30	015	02	105	60
4	01 Nov 72	21 22 15.4	6.29	144.46	35±5	5.4	077	70	347	128	30	218	266	23	006	27	142	54
5	25 Jun 76	19 18 56.9	4.60	140.09	33	7.0	130	24	220	061	80	331	238	22	130	59	350	32
6	17 Jul 76	05 32 43.2	4.61	139.95	33	6.0	070	17	160	188	81	278	190	15	291	38	084	46
7	29 Oct 76	02 51 07.6	4.52	139.92	33	7.0	108	76	018	014	72	284	323	47	055	15	148	20
8	15 Feb 78	07 00 27.1	4.55	139.31	33	5.5	112	37	022	122	54	212	300	05	207	08	061	80
9	26 Apr 78	10 10 09.6	5.64	142.11	45±5	5.6	106	60	016	124	32	214	290	08	023	15	171	72
10	16 Jul 78	22 13 25.8	6.62	143.79	33	5.5	092	68	002	125	20	215	277	13	013	22	159	64
11	27 Mar 79	10 07 21.8	6.10	144.43	65±4	5.4	030	66	120	137	62	227	177	51	355	41	266	01
12	13 May 79	01 06 42.7	6.84	144.26	•16*	5.5	094	46	004	129	50	219	293	19	202	02	110	69
13	19 Jan 81	18 48 08.9	4.64	139.34	33	6.5	114	51	024	116	40	206	293	02	023	05	203	85

*Depth phases

Th — thrust; Nm — normal; Ss — strike-slip

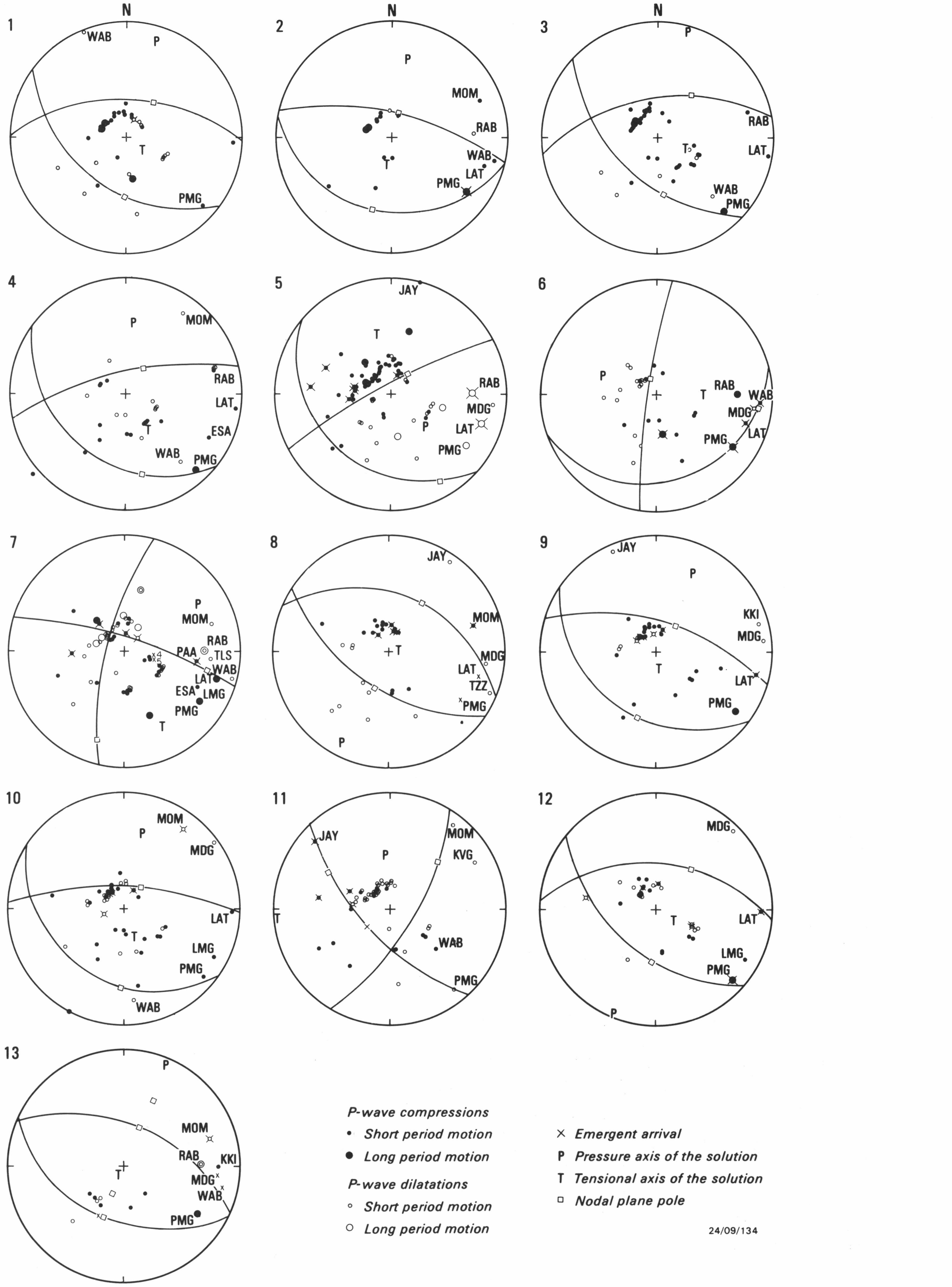

Figure 5. The P-wave first motion diagrams corresponding to the solutions shown on Figure 3.
The numbers correspond to the reference numbers given in the text and in Table 1. Local seismic stations are identified by their codes, ESA—Esa Ala, JAY—Jayapura, KKI—Karkar Island, KVG—Kavieng, LAT—Lae, LMG—Mount Lamington, MDG—Madang, MOM—Momote, PMG—Port Moresby, RAB—Rabaul, TLS—Talasea, TZZ—Tabubil, WAB—Wabag.

solution is strongly strike-slip, pressure axis northeast. If the west-northwest nodal plane is the fault plane, the motion is left lateral.

(8) 15 February 1978. Normal depth. Close to the 29 October 1976 Irian Jaya earthquake, but not an aftershock, since it occurred 16 months later. A west-northwest-striking overthrust, with the Tabubil (TZZ) station compression providing the azimuth control.

(9) 26 April 1978. Blucher Range/Strickland River region, east of the Star Mountains. Depth 45 ± 5 km. Again, a west-northwest-striking thrust, with seismic stations Port Moresby (PMG) and Lae (LAT) providing azimuth control.

(10) 16 July 1978. South of Mendi. Normal depth. A west-northwest-striking thrust, with seismic stations Port Moresby (PMG), Mount Lamington (LMG) and Lae (LAT) providing azimuth control.

(11) 27 March 1979. In the Mount Hagen Seismic Zone. Depth 65 ± 4 km. A reasonable solution, being a combination of strike-slip and dip-slip normal. The tension axis is horizontal, east–west, and the pressure axis plunges to the north.

(12) 13 May 1979. Southeast of Mt. Hagen. Depth 16 km (depth phases). A west-northwest-striking thrust, with azimuth control provided by seismic stations Port Moresby (PMG), Mount Lamington (LMG) and Lae (LAT).

(13) 19 January 1981. Irian Jaya. Normal depth. A west-northwest-striking overthrust with azimuth control provided by the Port Moresby (PMG) P-wave compression. The solution is similar to that issued by the United States Geological Survey Monthly Summary.

Tectonic setting

A simple model to explain the seismicity, faulting, uplift and volcanism of the Highlands is based on Davies' (1979) model of deep crustal thrusting and the collision of the South Bismarck and Indo-Australian Plates over the top of a sinking Solomon Sea Plate. The concept of the Solomon Sea Plate sinking beneath the Ramu-Markham Valley is based on the double-limbed seismic structure beneath the region (Ripper, 1980, 1982), which is preferred to the single-limb models of Jaques & Robinson (1977) and Johnson (1979). Seismicity at depths of greater than 100 km beneath the Ramu-Markham region is indicative of underthrust lithosphere (Denham, 1975). The tectonic model suggested here incorporates the Southern Highlands Seismic Zone into the plate collision pattern of the New Guinea region.

(1) In the middle Miocene, the Indo-Australian Plate was being subducted beneath an island arc system to the north or northeast of New Guinea and Australia (Page, 1976). Collision between the island arc and the margin occurred. The Outer Melanesian Arc, dormant since about the end of the Oligocene, was behind (north of) the island arc in the New Guinea region and not far from it (of the order of 200 km). The region between New Guinea and the Outer Melanesian Arc was to become part of the Solomon Sea Plate in the late Miocene.

(2) In the late Miocene, the Ontong Java Plateau margin of the Pacific Plate, of continental thickness, collided with the Solomon Islands (section of the Outer Melanesian Arc) and subduction of the Pacific Plate beneath the Solomon Islands region was terminated (Kroenke, 1972). Continued convergence of the Pacific and Indo-Australian Plates was accommodated by subduction of the Solomon Sea Plate beneath both major plates. As the plate margins were oblique to the azimuth of approach (plate margin trend approximately NW–SE; azimuth of approach approximately WSW–ENE), an anti-clockwise rotation was also induced into the Solomon Sea Plate, initiating subduction beneath New Britain.

(3) The New Britain subduction extended westward beneath the section of the arc north of New Guinea. The narrow strip of Solomon Sea Plate north of New Guinea was now being subducted northward beneath the Outer Melanesian Arc, and southwestward beneath New Guinea. Volcanism was occurring both in the arc and in New Guinea. The evolution of the northern New Guinea region from late Miocene is shown in Figure 6.

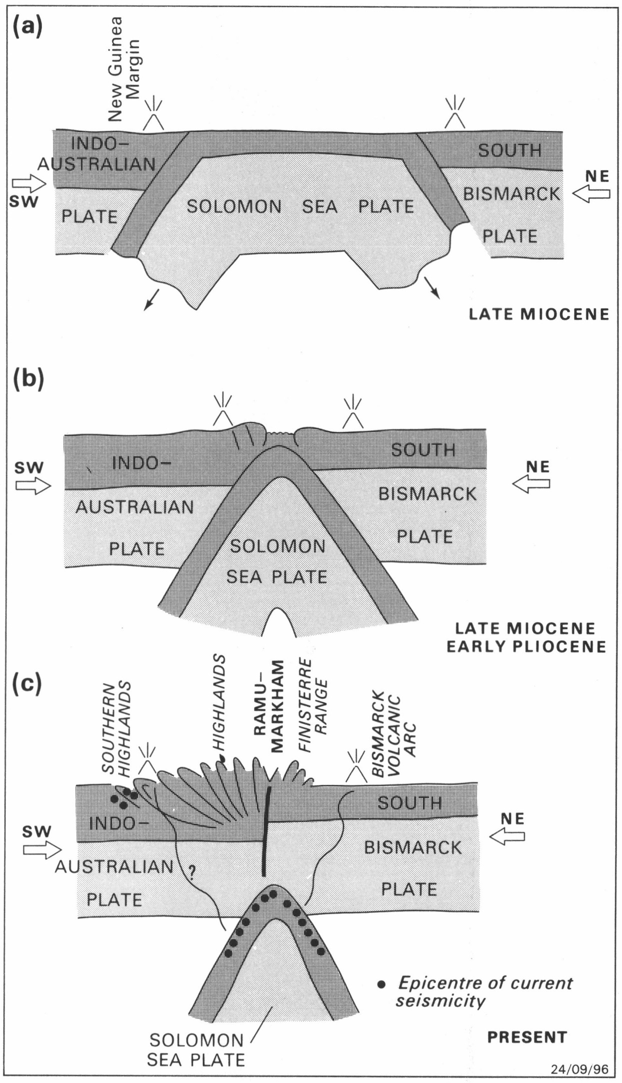

Figure 6. A series of three profile sketches illustrating the collision of the Indo-Australian Plate and the South Bismarck Plate, and the subsequent development of the highlands and southern highlands. (a) — Double subduction of the Solomon Sea Plate was initiated in late Miocene. (b) — Collision of the Indo-Australian Plate and South Bismarck Plate occurred almost immediately. The Solomon Sea Plate began to sink beneath the collision zone. (c) — Continued advance of the two plates applied a horizontal stress in the crystalline crust of the Indo-Australian Plate (northern New Guinea margin) causing faulting on near-vertical thrusts. The thrusting process has migrated away from the plate margin to the region of the southern highlands.

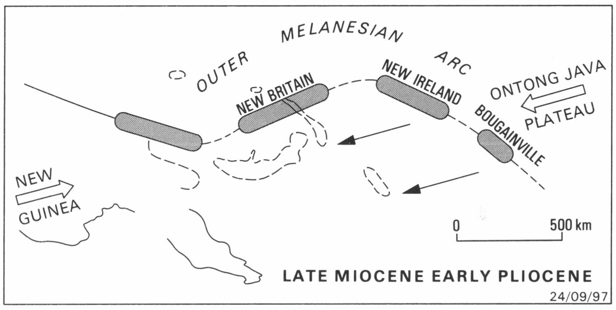

Figure 7. Sketch suggesting the approximate location of the Outer Melanesian Arc relative to New Guinea, at the time of its collision with the New Guinea margin of the Indo-Australian Plate, about late Miocene–early Pliocene.
The large arrows show the azimuth of Pacific/Indo-Australian Plate approach. The small arrows show the movement of New Ireland and Bougainville to their present positions (dotted). Although New Britain has not moved far with respect to New Guinea, its position with respect to New Ireland has changed significantly.

(4) Almost immediately (late Miocene–early Pliocene) the two subduction zones collided, first at the northwest, and progressively to the southeast. The Solomon Sea Plate now formed a suspended or hanging arch beneath the collision zone, whose surface expression is the Ramu-Markham Valley. Subduction slowed because each limb of the subduction zone was anchored to the other. The lithospheric arch was trapped above the aesthenosphere, and could only sink as aesthenosphere was displaced. Figure 6b illustrates this stage of the collision, and Figure 7 sketches the approximate relative positions of the New Guinea mainland and the relevant section of the Outer Melanesian Arc at the time of collision. Mackenzie (1975) suggested a similar sinking double-limbed subduction system, the limbs of which collided earlier, at the end of the early Miocene, and which was not identified as the Solomon Sea Plate.

(5) Convergence between the Indo-Australian and Pacific Plates continued, maintaining subduction of the Solomon Sea Plate at the Solomon Islands margin, and rotation of the Solomon Sea Plate. The virtual cessation of Solomon Sea Plate subduction southwest beneath New Guinea and northward beneath the arc in turn retarded subduction beneath southeast Papua and New Britain. The anti-clockwise plate rotation demanded continued subduction beneath New Britain, however, and this was then accommodated by the initiation of a southeast advance of New Britain past New Ireland (with respect to New Ireland), and associated 'back-arc' spreading behind (northwest of) New Britain. The back-arc spreading New Britain. The back-arc spreading has been described, for example, by Connelly (1976), Taylor (1979), and Johnson & others (1979).

(6) The collision of the arc and northern New Guinea continued. The arc and the New Guinea margin came into direct contact above the sinking Solomon Sea Plate, and compressive stress built up in the continental plate margin and the crystalline continental crust behind the margin. The development of a seismic zone across the Bismarck Sea enclosed a sub-plate, which has been termed the South Bismarck Plate (Fig. 2). The northern New Guinea collision then became a collision between the Indo-Australian Plate and the South Bismarck Plate over the sinking Solomon Sea Plate.

(7) Response to collisional stress was now transmitted to the continental front of the Indo-Australian Plate (Fig. 6c). The continental margin faulted on near-vertical thrusts, north-northeast side up. The thrusting process in the crust has since expanded to the southwest, and is now manifest in the Southern Highlands Seismic Zone and the Papuan Fold Belt. Rapid uplift of the Finisterre Range has occurred above the collision contact.

(8) The Quaternary southern highlands volcanism may originate in the crustal thrusts or deeper down in the Solomon Sea Plate, or as a combination of both. The Solomon Sea Plate is still lying at a depth of about 100 km beneath the Ramu-Markham Valley and is probably the origin of the West Bismarck volcanism (Ripper, 1982).

(9) The intermediate-depth seismicity beneath northwest Ramu Valley and the Sepik Valley (Ripper, 1982) possibly occurs in fragments of the old Solomon Sea Plate (see also Denham, 1975).

To summarise, the southern highlands seismicity, the Papuan Fold Belt, the highlands uplift, and the Finisterre uplift are manifestations of the Indo-Australian/South Bismarck Plate collision over the top of the sinking Solomon Sea Plate. The highlands volcanism may also be associated.

Seismic risk

Gaull (1979) investigated the seismic risk to 20 large towns in Papua New Guinea, and extrapolated his results to include rural areas. He listed the expected effects at each town of all known potentionally damaging earthquakes in Papua New Guinea for the period 1900–1979. He calculated the mean return period for Modified Mercalli Intensities 6 and higher for each town, and then contoured his results for the whole country. Using an empirical relationship, Gaull related intensities to peak ground acceleration. For the towns of Mendi and Kerema on the southern side of the highlands, Gaull obtained return periods of 45 and 55 years, respectively, for intensity 7. His contoured map (Gaull, fig. 23) of estimated maximum intensities for any 50-year period suggests that the Star Mountains should experience intensity 7 about once every 50 years, as for Mendi. Gaull obtained a return period of 60 years for an acceleration of 0.1g peak ground acceleration at Mendi.

It is likely that all New Guinea magnitude 7 or greater earthquakes since 1900 are documented (Everingham, 1974). Recording of earthquakes in the magnitude range 5–7 improved in the early 1960s with the installation of World Wide Standardised Seismographs at Port Moresby, Rabaul, Honiara in the Solomon Islands, and Charters Towers in northern Australia. Combining the two sets of Southern Highlands Seismic Zone data, the 22-year set of largest annual earthquakes 1960 to 1981, and the subset of the magnitude 7.0 or greater earthquakes in the 82 years from 1900 produces a reasonable sample for the analysis of seismic risk. Richter magnitudes measured on the Port Moresby (PMG) Wood Anderson seismographs are used in the magnitude range less than 6, and Surface Wave magnitudes measured world-wide, for the magnitude range 6 and over; above 6, the two scales are virtually equivalent (McGregor & Ripper, 1976).

Figure 8a shows the Type 1 or Gumbel Extreme Magnitude Distribution obtained for the Southern Highlands Seismic Zone, incorporating the two data sets. The method has been described by many workers, including Lomnitz (1974). A Type 1 or Gumbel distribution G(M) is fitted to the set of largest annual values magnitude M. The distribution is given by $P = \exp\{-\alpha e^{-\beta M}\}$ or $-\ln(-\ln(P)) = \beta m - \ln\alpha$ . . . (1), where P is the probability that the largest magnitude in any year is less than M, and α & β are constants.

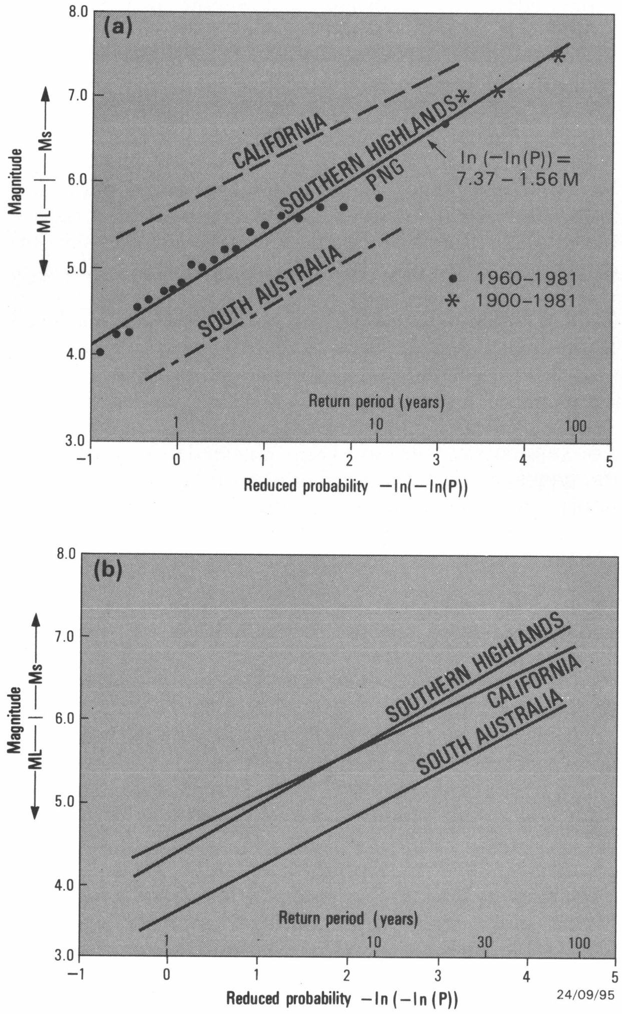

Figure 8. (a) — Southern Highlands Seismic Zone, largest annual earthquakes, 1900–1981 (magnitude 7 only) and 1960–1981.
The magnitude is shown as a function of return period. Also shown are the corresponding plots for California (Lomnitz, 1974) and South Australia (McCue, 1975).
(b) — For a direct comparison of seismic levels, the three seismic zones are normalised to a common area of 100 000 km².
The levels of California and Southern Highlands zones become virtually identical.

The return period T is defined by: T = 1/(1 − P) . . . (2), which is approximated by Lomnitz (1974) as T = { exp (M) } /α . . . (3). Least squares analysis of the Southern Highlands data gives lnα = 7.37 and β = 1.56.

The slope of the familiar recurrence relation 'b' is related simply to β by β = b ln 10 which gives a 'b' value of 0.7, lower than usual, indicating a higher than average ratio of large to small earthquakes. Wyss (1973) has suggested that a low 'b' value is symptomatic of high tectonic stress, which is in keeping with the thrust type focal mechanism obtained for earthquakes on the zone.

Return periods computed using equation (3) are compared (Table 2) with those given by Lomnitz (1974) for earthquakes in California, USA, and by McCue (1975) for South Australia. The first column (a) gives magnitudes computed directly from the relevant magnitude/frequency relationship, whilst those in the second column (b) are normalised to a unit area of 100 000 km².

Table 2. Earthquake return periods for the Southern Highlands Seismic Zone compared with those for California and South Australia.

	Magnitude					
Return period	*Southern Highlands*		*California*		*South Australia*	
T (years)	*(a)*	*(b)*	*(a)*	*(b)*	*(a)*	*(b)*
1	4.7	4.3	5.7	4.5	4.4	3.9
10	6.2	5.7	6.9	5.7	5.3	4.9
30	6.9	6.5	7.4	6.3	5.8	5.6

The once-per-30-year earthquake of the Southern Highlands Seismic Zone is magnitude 6.9, which would cause intensity 7 over a radius of about 80 km (an area of about 20 000 km²), and the 10-year earthquake, magnitude 6.2, intensity 7 over a radius of about 30 km (about 3000 km²).

The effect of comparing the risk per unit area is shown in Figure 8(b). The Californian and Southern Highlands curves are virtually inseparable. The consequences for a building code are clear, since California is rated Zone 3 on the United States Uniform Building Code (U.B.C.) and South Australia is Zone 2 (McCue, 1975). (Zone levels increase from Zone zero, which corresponds to a sufficiently low level of risk that no seismic load need be considered in normal building design). The Southern Highlands zone should be rated at least equivalent to Zone 2 and probably Zone 3 of the U.B.C.

Lomnitz (1974) has defined earthquake risk R_D as the probability of occurrence of an earthquake of magnitude M or more in a D year period, as R_D (M) = 1 − exp (- αD $e^{-\beta M}$) . . . (8). For example the risk that magnitudes 6 and 7 earthquakes will occur somewhere in the Southern Highlands Seismic Zone in the next 50 years are 99 per cent and 81 per cent, respectively. Although overshadowed by the more active seismic zones of the north coast, New Britain, and Bougainville, the Southern Highlands Seismic Zone is thus seen to have a significant seismic risk. Special precautions against future earthquake damage are warranted.

Gaps for magnitude 7 earthquakes in the zone exist in the border region between Irian Jaya and Papua New Guinea, and in the region between Kikori and Kerema. Gaps in the seismic zone are considered to be temporary and thus to have a better chance of being the site of a future large earthquake than the rest of the zone.

Strong motion data

An accelerogram is available of the 25 June 1976 magnitude 7 Irian Jaya earthquake, as recorded at the 'Hongkong' site in the Star Mountains. The duration of shaking exceeded the 43 seconds duration of the MO2 accelerograph recording. The MO2 retriggered, and the strongest shaking was in the second segment of record. The accelerogram is held at the Geophysical Observatory, Port Moresby.

The earthquake produced a maximum acceleration at the Hongkong site of 0.08g at frequency 1.5 hz. The earthquake woke everybody. People were unable to stand. Several landslides were caused, but no damage resulted. The Modified Mercalli Intensity is interpreted as 7. The distance of the Hongkong site from the earthquake epicentre was 135 km.

Conclusions

Two seismic zones are recognised in the southern part of the central ranges of Papua New Guinea. These are the Southern Highlands Seismic Zone, which coincides with the Papuan Fold Belt, and the Mount Hagen Seismic Zone, which branches off the Southern Highlands Seismic Zone south of Mount Hagen and trends north-northeast, deepening to intersect the intermediate-depth seismicity beneath the Ramu-Markham Valley. The Mount Hagen Seismic Zone has the form of a plunging conduit rather than an inclined plane.

Four large (magnitude 7) earthquakes have occurred in the Southern Highlands Seismic Zone this century, in 1922 and 1954 near Mendi, and two in 1976 in Irian Jaya. A magnitude 6.5 earthquake occurred at its eastern end, near Kerema in 1931. Gaps exist in the zone between Kerema and Kikori, and in the Star Mountains border region with Irian Jaya.

Fault plane solutions of earthquakes in the Southern Highlands Seismic Zone are mainly overthrusts that strike approximately parallel to the zone and have pressure axes trending approximately north-northeast–south-southwest. The solutions suggest that the earthquakes represent thrust fault movement in response to a north-northeast–south-southwest compressive stress. Two notable exceptions, however, were the magnitude 7 Irian Jaya earthquakes of June and October 1976, which were dip-slip normal and strike-slip, respectively.

Although no specific correlations between earthquakes and surface faults have been made, the earthquakes presumably occur on the system of east- southeast–west-northwest-trending faults of the Papuan Fold Belt, active through the Pliocene–Quaternary. The very existence of the seismic zone indicates that the fault system is currently active.

Davies (1979) proposed that the Pliocene-Quaternary faults of the Papuan Fold Belt are south-facing thrusts, caused by a regional compressive stress. The concurrence of the seismic zone with the region of Pliocene–Quaternary faulting, and the overthrust earthquake fault plane solutions support this.

The seismic zone is here recognised as an expression of the current collision between the Indo-Australian and South Bismarck Plates in the broad tectonic framework of the Indo-Australian and Pacific Plate convergence. Until about late Miocene, the Indo-Australian and South Bismarck Plates were separated in the northern New Guinea region by the Solomon Sea Plate. Double subduction of the Solomon Sea Plate brought the plates into direct contact, with the two subducting limbs of the Solomon Sea Plate sinking beneath the collision (Ramu-Markham) zone in the form of a hanging arch (inverted 'V' shape). Plate approach and stress build-up in the plate fronts continued above the sinking Solomon Sea Plate, and stress relief occurred by the faulting of the continental crust of the Indo-Australian Plate margin in the New Guinea highlands region. The thrusting and uplift have migrated south-southwest into the southern highlands and are now manifest in the Southern Highlands Seismic Zone and the Papuan Fold Belt.

The Mount Hagen Seismic Zone links the intermediate-depth seismicity of the sinking Solomon Sea Plate with the seismicity of the southern highlands. It could well be associated with Quaternary highlands volcanism as it provides a direct link between the subducted Solomon Sea Plate and the zone of Highlands volcanoes.

Return periods, seismic risk parameters and the magnitude frequency relationship b-factor for the southern highlands were determined by an extreme magnitude Gumbel distribution technique. The once-per-year earthquake was found to be of magnitude 4.7, 10-years, 6.2, and 30-years, 6.9. The corresponding figures for California, USA, are 5.7, 6.9, and 7.4, respectively. If a correction is made for the difference in area, the seismic risk of the Southern Highlands is seen to be equivalent to that of California. As California rates Zone 3 on the USA Unified Building Code scale, the Southern Highlands Seismic Zone should rate at least 2 and probably 3.

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