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NOTES ON NEAR EARTHQUAKES, INTERFERENCE, AND THE PROBLEM OF VOLCANIC TREMORS AT RABAUL, NEW BRITAIN

by

J. H. Latter

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NOTES ON NEAR EARTHQUAKES, INTERFERENCE,

AND THE PROBLEM OF VOLCANIC TREMORS AT RABAUL, NEW BRITAIN.

ABSTRACT.

This report discusses the seismic activity in the Rabaul area and it relates to volcanic activity and the local tectonic setting.

It is intended to supplement earlier, more detailed studies of the geological and volcanic aspects of the work in the region (particularly by Dr. N.H. Fisher, L.C. Noakes and G.A. Taylor) by setting them in the light of recent seismic research carried out at Rabaul.

To some extent it is intended to be a compendium of information on many topics which are related to the regional vulcanicity or to the work of the Vulcanological Observatory in Rabaul, so that a comprehensive picture may be given of events as far as they are known to have occurred in the region.

It asks more questions than it solves - although it provides a possible solution to the question of the "anomalous" class of micro-earthquakes on the Rabaul records, and solves the problem of the "sinusoidal harmonic disturbances" which for years has bedevilled workers at Rabaul. Possibly a lesson may be learnt from the fact that this problem was solved more or less by accident, and in spite of, rather than because of an extensive programme of research into the subject.

It is to be hoped that a corresponding degree of luck may be available to solve the other, more weighty, problems that it raises.

NOTES ON NEAR EARTHQUAKES, INTERFERENCE, AND THE PROBLEM OF VOLCANIC TREMORS AT RABAUL, NEW BRITAIN.

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Chapter 1

GENERAL BACKGROUND

GEOGRAPHY OF THE AREA.

The town of Rabaul is situated on the Gazelle Peninsula at the north-eastern end of the island of New Britain, which forms an arc, convex towards the south-east, at an angle of about 56° to the New Ireland-Solomons arc in the north and about 40° to the New Guinea arc in the South.

Rabaul is unique in that it is the only town of comparable size which lies almost entirely within a caldera of Recent age. Its present resident population numbers about 36,000.

The north-eastern portion of the Gazelle Peninsula, east and north of the Keravat and Warangoi Rivers, is comparatively low-lying country, nowhere above 2300 feet, and supports a large native population. It is extensively planted with coconuts, cocoa, bananas, yams, taro and other crops. The indigenous vetetation comprises rain-forest, secondary forest and kunai grasslands.

West and South of the Keravat and Warangoi Rivers the country is more rugged and rises to a maximum height of some 7,900 feet in the south Baining Ranges. In common with the rest of New Britain, excepting only isolated coastal districts, notably around Talasea, this area is sparsely populated and is covered almost entirely in virgin rain-forest.

The islands, New Ireland, whose southern ranges are plainly visible from Rabaul, and Bougainville, which belongs geographically to the Solomons, are alike regions containing rugged topography with scattered areas of settlement. In this respect they resemble the mainland of New Guinea, which, because of its relatively enormous size, has larger coastal plains and highland valleys, both with greater populations, (a point of importance in weighing potential damage due to volcanic eruption), and a number of major rivers which drain wide areas.

The climate is tropical throughout the region and humidity is generally high, even in the highland areas above about 3,000 feet. At Rabaul conditions are normally better, and the rainfall lower, during the season of the south-east trade winds, from about May to October, than during the north-west monsoon season. On the south coast of New Britain the reverse holds true.

2. GEOLOGY.

The north-east end of the Gazelle Peninsula is composed of Recent volcanic rocks which overlie coral limestone of Pleistocene to Recent age. At Rabaul, on the Caldera floor at the east end of Kamerere Street, a borehole, begun at 55 feet above sealevel passed through 98 feet of unconsolidated volcanic meterial before entering coral limestone.

Elsewhere in the town there are sections which show that the volcanic succession falls into two distinct parts; boreholes pass through about 50 feet of unconsolidated pyroclastic deposits, largely andesitic pumice, into an old beach deposit and through into underlying basalt. On the eastern side of the caldera, towards the southern end of the town of Rabaul, the pumice cuts out and basalt flows from Palagiagia and Rabalanakaia craters are exposed.

The lavas and pyroclastic deposits of the older volcanoes, the Mother(Kombiu), and the North and South Daughters (Towanambatir and Turanguna), are dominantly basaltic. These volcanoes were active before the period of caldera subsidence, which was closely succeeded by eruption of Palagiagia.

The three more recent craters, Tavurvur (Matupi), Rabalanakaia and Sulphur Creek produced lavas ranging from basalt to andesite; Vulcan (Baluan) produced andesitic pitchstone and pumice.

Yasuo Miyake and Yoshio Sugiura (37) have published the following analyses of random samples collected from Rabaul volcanoes, comparing them with samples of rocks from Fuji and Aso volcanoes in Japan.

Percentage	Tavurvur (mean)	Vulcan	Kombiu Palagiagia (mean) Rabalanakaia	Aso	(Iwasaki) Fuji	(Iwasaki and Ikawa) Fuji
SiO_2	47.82	61.75	59.98	53.92	49.31	57.87
TiO_2	0.93	1.08	0.91	0.85	0.60	0.82
Al_2O_3	18.89	14.44	14.77	18.67	19.86	17.80
Fe_2O_3	4.28	3.05	2.93	2.69	3.93	3.07
FeO	6.36	3.67	4.17	5.93	6.43	5.31
MnO	0.23	0.12	0.13	0.14	0.22	0.20
MgO	5.45	1.52	2.12	3.80	5.11	2.63
CaO	12.04	7.53	8.93	9.27	11.03	6.80
Na_2O	2.44	3.55	3.58	2.90	1.97	3.52
K_2O	0.55	1.89	2.02	1.86	0.60	1.43
P_2O_5	0.44	0.73	0.83	0.27	0.16	0.27
H_2O-	-	0.05	0.20	0.21	0.51	0.91
H_2O+	0.30	0.08	0.12	-	-	-
TOTALS	99.73	99.45	100.69	100.51	99.73	100.63

At Tawui Point north of Rabaul pumice and tuff overlying about 150 feet of limestone is exposed in cliff sections on the coast. Dr. N.H. Fisher (18) has described the limestone as Pleistocene to Recent in age. Underlying the limestone are beds of brecciated volcanics. East of Kokopo limestone of Pliocene to Pleistocene age is exposed, from Cape Gazelle south to the Warangoi River. Dr. Fisher has pointed out that the evidence at Tawui Point indicates that vulcanism at Rabaul has continued at intervals since the Pleistocene and has been accompanied by uplift. Similar pyroclastic deposits to those at Rabaul occur in Southern New Ireland. Since they are not associated with any recent cones they have been included in the Pleistocene (see (71) "Explanatory Notes to accompany a Geological Sketch Map of Eastern New Guinea" Australian Military Forces Publication, 1945 +).

East and south of the Keravat and Warangoi Rivers Upper Tertiary limestone unconformably overlies the metamorphosed Baining Series, which is regarded as basement in the area. Uplift in the Baining Ranges exceeds 4,000 feet and probably reached a climax at the end of the Tertiary.

No detailed regional mapping has been carried out over the greater part of the Gazelle Peninsula. Recent investigations have been made in the Toriu and Towanakoko Rivers on the south side of the Baining Range and on the granodiorite areas (intrusive in the Baining Series) at Vunalama on the north side, but the results of these surveys have not yet been published. A preliminary treatment of the geology of New Britain is contained in Geological Bulletin No. 3 of the Territory of New Guinea, 1942, by N.H. Fisher and L.C. Noakes (20).

The geological sketch Figure 1 accompanying this report shows in a generalised manner the areas occupied by volcanic rocks of upper Tertiary to Recent age in the Territory of Papua and New Guinea. It includes Mt. Yelia which was identified as a volcano only as recently as 1962. Certain areas, notably Mt. Lamington and the Hydrographer's Range, and the D'Entrecasteaux Islands, show evidence of both long extinct and recent vulcanicity. It is considered probable that volcanic activity began in these areas in the Pleistocene and continued intermittently until Recent times. It is possible that Mt. Yelia may fall into the same category.

3. OCEANOGRAPHY AND REGIONAL STRUCTURE

The main features of the structure of the E. New Guinea area are listed in this section. A discussion of their significance is reserved for Chapter 5, (see also Figure 1).

The Central Highlands and the Owen Stanley Range of New Guinea form the backbone of main late Tertiary uplift in the area. To the south-west is the major downwarp of the Fly-Digoel depression, and to the north-east the Sepik-Ramu-Markham depression. Along this latter occur the epicentres of both shallow and "intermediate" earthquakes (those whose focus lies between 70 and 300 kilometres deep in the earth's mantle are normally classified as "intermediate"), indicating that this zone remains tectonically active. Active also, and the locus for the majority of the mainland New Guinea earthquakes, are the ranges immediately to the north of the Sepik-Markham depression, from the Bewani Mountains in the west to the Sarawaged, Cromwell and Rawlinson Ranges in the east. The zone of the Northern ranges appear to be tectonically continuous with the south-east facing arc of New Britain, which is one of the most active areas in the region. In the western Sepik District, to the north of the Torricelli and Bewani Mountains, which form part of the Northern Ranges, is a low-lying area near Aitape which extends westwards to the Pual and Bewani River depression. Along this line have occurred some of the larger shallow earthquakes of New Guinea. To the north of this zone is the narrow uplift region of the Cyclops-Oenake-Serra Mountains. Bordering the north coast of New Guinea and New Britain from Kairiru Island to Rabaul is the Inner Volcanic Arc of the Bismarck Archipelago. From Manus to the Feni Islands east of New Ireland is the Outer Volcanic arc. Between the two

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\+ A C.14 result of 43 to 48 thousand years was determined for a shaly mudstone containing plants which was drilled at a depth of 30-40 feet from a borehole put down at the new Keravat Gaol. The mudstone underlies pyroclastic deposits.

is the stable area of the Bismarck Sea. To the north and east of the islands of the Outer Volcanic Arc, parallel to the coast of New Ireland, lies a deep oceanic trough. South of central New Britain is another deep trough which runs east-north-east towards the southern end of New Ireland and then curves abruptly to the south-east to run parallel to the south-west coast of Bougainville. Both these troughs are the locus for numerous intermediate and some deep earthquakes (at depths greater than 300 kilometres). A structural map, Figure 1 illustrating these main features is attached to this report.

4. RECENT VOLCANIC CENTRES

For a full account of the individual volcanic centres the reader is referred to "The catalogue of the Active Volcanoes of the World" Part V by N.H. Fisher (21). Omitting the volcanic centres of the Gazelle Peninsula, which are discussed fully in the next section, and enumerating the centres west along the line of the Inner Volcanic Arc, we find:- the Father (Ulawun) and its three neighbouring volcanoes, the North Son, Lolobau Island and the South Son, the North Son appears to be extinct: further west, Galloseulo, Pago, Lollo, Mululus and the volcanoes of the Willaumez Peninsula, Benda, Bola and Garbuna, all of which are dormant, show similarities to the Rabaul volcanoes: basalt, pumice and andesitic pitchstones are represented. Vitu and Unea Islands are extinct volcanoes offset from the main arc.

The group of volcanoes at the western end of New Britain, Bulu, Munlulu, Langila, Talawe and Tangi, of which only Mt. Langila is active, likewise seem to have produced dominantly basaltic material.

Ritter, Umboi and Sakar Islands, which are all dormant or extinct centres, have a characteristic basalt with phenocrysts of olivine and augite. The rock bears strong similarities to a coarse-grained basalt extruded from the South Daughter volcano at Rabaul.

Continuing westwards, Tolokiwa, Crown Island, Long Island, Bagabag Island, Karkar Island, Manam, Bam, Blupblup and Kadovar complete the chain of active or recently active volcanoes of the Inner Arc. Only Long Island, Manam and Bam are active at present. All are basaltic in type: Manam characteristically erupts basalt. An unusual feature of this volcano, which is almost continuously active, is that eruptions of nuees ardentes have been reported from it (see "An Experiment in Volcanic Prediction (56)" by G.A. Taylor).

The only volcanoes of Recent age in the Outer Volcanic Arc are the Manus centres about St. Andrew's Strait, Baluan, Lou, and the recently active Tuluman (where the material is dominantly pitchstone), and possibly Lihir Island to the east of New Ireland.

The New Guinea mainland volcanoes, (discounting those which are considered to be Pleistocene in age, (the Mt. Hagen and Mt. Karimui Groups, and the Papuan volcanoes, Bosavi, Murray and Favenc), with the exception of the recently discovered Mt. Yelia, form a rough arc along the north side of the Owen Stanley Mountains in Papua. Those active or recently active are Mt. Lemington, Mt. Victory, Goropu (or Waiowa volcano) and a number of centres in eastern Fergusson Island in the D'Entrecasteaux Islands. Mt. Trafalgar, and several other peaks to the north-east of Mt. Victory, have also been active in the Recent Era. All these volcanoes extrude andesitic material with some dacites: hornblende-andesite is the dominant lava. From the three centres which have been active in historical times, Mt. Victory, Goropu and Mt. Lamington, eruptions have been Pelean in type, with the formation of domes, except in the case of Goropu.

From its geographical position, Mt. Yelia would seem to belong to the extinct Pleistocene volcanoes of the Central and Western Highlands, its appearance, however, suggests more recent activity. First reports indicate that andesite was among the lava extruded from this centre.+

The three volcanoes on Bougainville, Mt. Balbi, Mt. Bagana and Lake Loloru, of which Mt. Bagana is almost continuously active, (the others being dormant), belong to the Solomons arc, and have affinities with the volcanoes of the Papuan arc. Like the latter, the Bougainville volcanoes appear to be of Pelean type, and form endogenous domes in the craters. Savo Volcano in the British Solomon Islands Protectorate is of the same kind. Andesitic and Dacitic lavas are recorded from these centres.

It is evident that a difference exists between the volcanoes of the Inner and Outer Volcanic Arcs of the Bismarck Archipelago, which appear comparatively basic in composition, and those of the Papuan and Solomons arcs which are dominantly andesitic.

Catastrophic eruptions may originate in either kind, as is shown by the Ritter Island explosion of 1888 and the Mt. Lamington eruption of 1951, and, as mentioned above, G.A. Taylor has shown that even the basaltic volcanoes may produce nuees ardentes.

5. VOLCANIC CENTRES AND THERMAL AREAS OF THE GAZELLE PENINSULA

The sunken caldera of Blanche Bay++ in which Rabaul is situated contains five recently active volcanic centres, with a further three extinct volcanoes outside the caldera wall. Within 10 miles of the Blanche Bay Caldera are two other extinct volcanoes, Watom Island and Mt. Varzin. In the centre of the Gazelle Peninsula is the long extinct Mt. Sinewit Complex, comprising several peaks, apparently of Tertiary age.

The only thermal areas reported outside Blanche Bay are near the Warangoi River.

Mr. N.H. Fisher (18) has postulated that Submarine activity commenced on the site of Blanche Bay, (possibly in the Pleistocene), and that a large volcano was built up, with the Mother, the North Daughter and the South Daughter as parasitic cones on or near its flanks. Basalt flows and extensive boulder beds, agglomerates and tuffs were erupted from these, and possibly other centres. Especially in the upper part of the succession pyroclastic rocks predominate. The Mt. Varzin centre, some miles south of the caldera, is also composed mainly of pyroclastic material. Watom Island is composed largely of basalt flows. It represents a series of major eruptions from the central vent, the last of which was probably catastrophic, blowing most of the upper part of the mountain away. Collapse of material into the central cavity left by these catastrophic eruptions caused general subsidence and formation of the caldera. Evidence suggests that in the later stages of the caldera-formation both Palagiagia and the South Daughter were active, the former blowing a whole section of the caldera wall away and the latter masking the wall with a series of basalt flows. After formation of the caldera a number of eruptions took place from the southern side, possibly from Karavia Bay, whose submarine contours suggest that it was once a great crater. The Beehives are part of an ancient cone of pyroclastic material which was probably formed at about this stage. Probably both Tavurvur and Matupi Island, as well as Vulcan in historical times, were formed by submarine volcanic activity. As late as 1877 it is reported that traces of a crater existed

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+ Recent volcanic centres exist on Mount Giluwe as rift zones of small craterlets on the mountain (lava extruded was basalt), and near Wau (rhyolite). There is a late Pleistocene to Recent crater at Kompiam where the material extruded was basalt. (D.B. Dow (personal communication)) See Figure 1.

++ See Figure 3

in the centre of Matupi Island. A brief summary of eruptions which have taken place in historical times is given in the next chapter.

Present volcanic manifestations in the caldera are confined to fumarolic activity in Tavurvur and Rabalanakaia craters and on the outer flanks of these craters, (where fumaroles extend down to the shore on the west and north-west sides of Tavurvur and to Sulphur Springs on the shore south of Rabalanakaia), and to hot springs and seepages at Sulphur Springs, on the shore at Rapindik, in Sulphur Creek, and in Vulcan Embayment.

The normal level of temperatures in both Rabalanakaia and Tavurvur craters is 98–100° centigrade. At Tavurvur this temperature range is occasionally exceeded by one or two degrees. Fumaroles on the outer slopes of these volcanoes are generally at a slightly lower temperature, except for points in a narrow gully that runs west from Tavurvur crater to the shore.

The temperature of the hot springs and seepages usually varies widely, both from the amount of recent rainfall and the consequent height of the water-table, and, in the case of those points that lie between high and low water mark, from the level of the tide, as well as from possible volcanic causes. The temperatures of points in Vulcan embayment range no higher than 65° Centigrade, while those at Sulphur Creek are generally below 50°C., (they are all below high water mark), those at Rapindik, similarly below high-water mark, lie in the range 45–65°C. Hot springs below high water mark at Sulphur Springs measure from 70–79°C. +

In recent years a survey was carried out to determine the hydrothermal potential of the area with a view to its use as a town power supply, and a report was published by F.E. Studt. (52)

Mr. Studt notes "The most striking hydrothermal feature is the complete absence of hot springs more than a foot or two above sea level. The springs occur typically along the shoreline between high and low water levels, and since the tidal range is only 2-4 feet the distribution is extremely limited."....... After noting that there may be much unseen seepage offshore, he goes on to say "The limited distribution of springs could be due to the presence of a cap-rock of some description, so disposed that the hot water escaping around its edge appears only at the shoreline. But since steam penetrates to the surface a short distance back from the beach, such a cap could not be very impermeable. A much more likely explanation is that there is insufficient thermal-artesian pressure to raise the hot water far above the coldwater table. This implies that there is no great depth of hot water near the coast." He suggests that the hot water rises to the water-table in the zone of very recent subsidence between Rabalanakaia and the Caldera wall and then percolates seawards.

6. SEISMIC HISTORY

The level of seismic activity in the area is high. Felt shocks are numerous, and intensifies up to 9 on the Rossi-Forel scale have been reported. Shocks originating at considerable distances from New Britain are sometimes felt in Rabaul.

C.F. Richter (46) mentions the following earthquakes (Magnitude 7.8 or over) as having occurred in the New Guinea region:-

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\+ In February 1958 Mr. G.A. Taylor drew attention to the fact that one of the seepage points at which hot water emerges onto the foreshore at Rapindik had changed in temperature by no more than one degree in the past eight years.

EPICENTRE

Date	G.M.T.	Latitude South	Longitude East	Magnitude	Depth	Area
7 Oct. 1900	2104	4°	140°	7.8	Shallow	N.N.G.
24 Jan. 1902	2327	8°	150°	7.8	"	Trobriand Is.
14 Sep. 1906	1604.3	7°	149°	8.4	"	E. of Huon Gulf
1 Jan. 1916	1320.6	4°	154°	7.9	"	Feni Is.
6 May, 1919	194112	5°	154°	8.1	"	W. of Buka
20 Sep. 1935	014633	3½°	141¾°	7.9	"	N. of Lumi
30 Jan. 1939	021827	6½°	155½°	7.9	"	S.Bougainville
30 Apr. 1939	025530	10½°	158½°	8.1	"	B.S.I.P.

Apart from the 1916 and 1919 earthquakes, the Gazelle Peninsula has experienced the following severe shocks:-

(Intensities 7 or greater)

EPICENTRE

Date	G.M.T.	Latitude South	Longitude East	Felt	Remarks
24 Feb. 1910	-	-	-	"severe" Rabaul	Followed by heavy swell from south-east
1923				"severe" Rabaul	
1927				"severe" Rabaul	
Dec. 1933	-	-	-	"severe" Rabaul	
28 May 1937	0320	Volcanic origin Vulcan Is.		Int. 8 (R.'F.) Rabaul	Preceded eruption
7 Jan. 1938	1525	? a little W. of S.W. of Rabaul		Int. 7 (R.'F.) Rabaul	
12 Sep. 1940	1320	4.5	153.3	Int. 7-8 (R.F.) Rabaul	Many after shocks
13 Jan. 1941	1628	4.5	152.7	Int. 9 (R.F.) Rabaul	Many after shocks
11 Oct. 1951	0138	4.5	152.7	Int. 7 (M.M.) Pondo	Widely felt
23 Apr. 1953	1626	4.5	153.3	Int. 7 (M.M.) Rabaul	S-P (12")
10 Oct. 1955	0857	5°	153°	Int. 6-7 (M.M.) Kokopo	Mag. 7¼ (Pas.)

Only minor damage is known to have occurred in Rabaul, and no casualties, as a result of these earthquakes. However there have been casualties in at least three of the large earthquakes in the region. The 20th September 1935 shock in the Aitape area killed many hundreds of natives and dislodged millions of tons of rock and soil: a severe earthquake on 30th April 1939 in the British Solomon Islands caused 11 casualties in the Russell Islands; and the earthquake of 13th January 1941 (Greenwich date) caused the deaths of 4 native children in the Central Baining area of the Gazelle Peninsula. Minor damage is not infrequently reported in earthquakes in the region. See Chapter 3 for a full account of seismic activity. See Figure 2 (sketch map showing earthquake epicentres in the Rabaul area).

7. MISCELLANEOUS EVENTS

A variety of phenomena at Rabaul have been correlated, rightly or wrongly, from time to time with volcanic or seismic activity. They may be grouped under the following headings:-

(a) Apparent changes of level

(b) Waterjets, steam explosions.

(c) Tsunamis, and tidal disturbances

(d) Subterranean noises

(e) Submarine noises

(f) Explosions

(g) Lights

(a) Apparent Changes of Level

The phenomena that fall under this heading range from extreme changes of level due directly to volcanic eruption to apparent changes of a few inches, whose reality, in some cases, has yet to be proved.

At the one extreme are the dramatic changes occasioned by the two eruptions of Vulcan. In the 1878 eruption Vulcan Island was built up to substantial proportions in a single night; in 1937 this island was as rapidly linked to the mainland (four days after the eruption began the new crater was 600 feet high and 1600 feet across, and had a basal diameter of 3,400 feet).

Less dramatic, but evidently considerable uplift accompanied the eruption of the Sulphur Creek craters in about the year 1850. Native eyewitnesses of the event, whose testimonies were recorded by Rev. Fr. George Boegershauser,+ M.S.C., early in this century, stated that a large area of land rose during a severe earthquake at about nine o'clock on the morning of a feast. Immediately afterwards eruption commenced at the site of the Sulphur Creek Craters.

At this point it should be noted that there is, of course, no truth in the widespread story that the two rocks in Blanche Bay known as the Beehives (Dawapia Rocks) rose during the 1937 eruption. They are composed of dipping beds of pyroclastic material and once formed part of an ash-cone whose crater lay to the south-east of their position.

The only recorded instance of sudden change in level due to an earthquake was the disappearance of the Matupi Island causeway leaving a depth of about 10 feet of water during the earthquake of 1st January 1916. The causeway rose again about 2 or 3 feet during the earthquake of 5th May, 1919. Following reports of slow changes in the topography of the

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\+ N.H. Fisher (18)

Rabaul Golf Course, stadia readings were made of pegged points in April-May 1956 by a Surveyor of Commonwealth Department of Works. In November 1958 the ground adjacent to the third tee was said to be rising, and a second line of levels was read across the area by Surveyors of the Department of Lands, Surveys and Mines. In March 1959 permanent bench-marks (6 large bolts) were established in the area said to be rising, with the intention that levels should be checked quarterly and after any large earthquakes, from adjacent benchmarks in supposedly stable ground. This was done after a tremor occurred on 16th May 1959: no change in level was detected. Since that date, as far as the writer is aware, there has been no checking of these levels. In January 1938, following the 1937 eruption of Vulcan and Tavurvur, a line of levels was run from Nodup [+] on the north-east coast across Namanula Hill to the Old Government Wharf in Rabaul and thence to Matupi Causeway, Rapindik and Toboi, in order to determine whether an apparent rise in sea level about that time was due to subsidence of the land or to unusually high tides. The Surveyor, an experienced man, had difficulty in closing this survey with the required degree of accuracy, even allowing for cumulative instrumental errors. It has been suggested that slight vertical movement in some part of the area might have been responsible for this irremovable error. Records of this survey were unfortunately lost in the Japanese occupation. More recently, similar unexplained difficulties in closing theodolite levels, in connection with a hydrographic survey in the area, have been attributed, very tentatively, to the same cause.

The only precise indication of change of level so far obtained resulted from a resurvey in January 1940 of points laid out in January 1938 on the foreshore near Matupi Island Causeway. A definite rise of 2.16 inches had taken place over the two year period. There is every indication that this part of Blanche Bay is unstable and alters in level fairly frequently.

Recent measurements of water level at selected points around Blanche Bay have been referred to a continuously recording tide gauge on the Main Wharf. Apparent vertical movements of up to two feet nine inches have been measured. [++] This matter is discussed fully in Section 5 of the next chapter.

(b) <u>Waterjets, Steam Explosions</u>

Numerous instances of waterjets and steam-jets have been reported to the Vulcanological Observatory in Rabaul.

Characteristically the waterjets occur between the Beehives and Vulcan and take the form of a single pulse, which rises to a height of 20 to 60 feet and subsides rapidly leaving no trace of gas ebullition, discolouration or turbidity in the water. They have also been seen to occur between the airstrip and Matupi Island, between Toboi and the site of the Japanese salvage camp, between the Beehives and Matupi Island, in Matupi (Greet) Harbour, in Karavia Bay, and between Tavurvur and the South Daughter in the area of Escape Bay. The majority occurred in 1958 and 1959.

Careful study of these occurrences points to three probable
A. causes for the phenomena [+++] :- three out of the twenty-six waterjets for which precise records exist can probably be linked to the spontaneous rupture of gas-filled tanks in wrecks on the seabottom. Oil slicks were

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\+ Alternative spelling - Nordup

++ A check carried out early in 1963 has cast doubts on the validity of these readings

+++ The reported waterjet on February 19th 1961, (see page 24 under "Explosions"), was probably due to an explosion of wartime ammunition.

observed shortly after the event in each case: such oil slicks are, however, common in the area between the Beehives and Vulcan, where many wrecks are thought to lie, and there can be no certainty that this hypothesis is
B. correct. Seven waterjets seem to have been definitely of natural origin: the list reads as follows:-

1. On 29th November 1958 at 1430 hours L.M.T., Mr. W. Bates of Public Works Department, saw a column of white vapour rise from between the Beehives and Vulcan to about one third of the height of the larger Beehive (174 feet). It lasted about one minute. Minor jets were seen to follow this outburst. The area was inspected the following day but no signs of disturbance were seen. Normal temperatures were recorded on the seafloor at two points (at depths of approximately 20 and 60 fathoms.)

2. On 5th March 1959 at 1724 hours L.M.T., Mr. J. Barrie of the Vulcanological Observatory and Mr. B. Darcy observed a water-jet rise to a height of at least 50 feet near the north-west shore of Vulcan. They were able to reach the area in the Department of Civil Aviation Crash-boat within twenty minutes. Mr. Barrie wrote "- Although the sea was glassy calm no evidence of after disturbance of the water was observed. The sun was too low to distinguish any colour variation in the water. A lack of native activity and/or dead fish precludes the possibility of dynamiting--".

3. On 6th April 1959 Captain Squires of the administration vessel "Mangana" saw four small water jets rising midway between the Beehives and Matupi Island. No inspection was made.

4. On 21st April 1959 at about 1700 hours L.M.T. two natives of the Papuan village on the North Shore of Greet Harbour saw a 60 foot high jet of "water and steam" rising from a point near Tavurvur volcano.

5. On 16th June 1959 at about 0730 hours L.M.T. personnel of Department of Civil Aviation saw a jet about 50 feet high in the vicinity of Tavurvur volcano. It continued for about 10 minutes (the only record of its kind at Rabaul). The report was delayed and investigation was not made until the following day when a large patch of discoloured water was seen on the spot where the jet occurred. Mr. G.A. Taylor wrote:- "the fact that the jet continued for several minutes strongly suggests that it was of the nature of a geyser. Such a phenomenon is not to be unexpected in a thermal area such as occurs in the Rapindik-Matupi area."

6. About the 26th December 1959, Mr. J. Fulford observed on two occasions fairly broad areas of marine disturbance near Vulcan which sent up multiple sprays of water, lasting for several seconds. Mr. W. Tebb, who accompanied Mr. Fulford on one of these occasions, noted that minor outbursts followed the main jet. A bearing on the disturbance, which occurred between the Beehives and Vulcan, indicated that it lay on a line joining the Observatory and the east side of the Beehives. The depth of water in this area is between 40 and 62 fathoms.

7. On 18th January 1960 at about 1615 hours L.M.T., Messrs. L. Berkefield and B. Strange saw a jet rise from the sea about half a mile north of the Vulcan Embayment. This jet was also seen from M.V. "Mangana" which happened to be entering harbour at the time; the master immediately altered course and made an examination of the area within twenty minutes of the time at which the jet was seen. No evidence of the disturbance could be found. No associated seismic

activity was detected on the Observatory Seismographs and the cause of origin of the water jets on these seven occasions remains obscure.

C. Four water jets can definitely be attributed to the dynamite method of fishing which is commonly practised in the islands in spite of the dictates of commonsense and the law.

On the first two occasions (in September 1959) natives on the shore moved into the bush as soon as a party from the Observatory arrived on the scene. One group was seen to be carrying dead fish and the other was awaiting the return of a native in a canoe from the area where the jet occurred.

On the third occasion (1st July 1960) the master of M.V. "Mangana", Mr. A. Savage, saw from his ship, which was lying at anchor off Vulcan Lagoon, a water jet rise 50 feet above a low headland. He rounded the headland and found several natives gathering fish from water 3 to 4 feet deep. They immediately ran away. Finally, in October 1960, Mr. Berkefield investigated a water jet in the same area. As he approached, a group of natives fled into the bush. A further two events which took place close to the foreshore of Vulcan in January 1959 may be tentatively attributed to bombing of fish in shallow water.

It is possible that the natives used a natural event which they knew occurred from time to time in the waters around Vulcan to mask, rather cleverly, their own illegal enterprise.

D. At least ten water jets have occurred to which it is impossible to assign even a hypothetical origin.

E. A remarkable event occurred at about 1230 hours on 27th October, 1957. A small hole opened in a patch of grass between the Bougainville Company's wharf and the main wharf, on the northern foreshores of Blanche Bay, remote from any known thermal areas. A column of white vapour emerged vigorously to a height of 15 to 20 feet. This emission lasted 10 minutes or so and was followed by mild spasms of activity throughout the afternoon. Mr. Strange, whose house was only some 30 yards distant, observed the whole sequence of events. When examined at 2000 hours whisps of vapour could still be seen rising from the hole, and the odour of H_2S was strong. A temperature of 38°C was recorded.

A similar event is said to have taken place at Toleap (Ratavul), about 2 miles from the scene of this occurrence, on the north coast. No date or reliable details of this event have been obtained.

(c) Tsunamis and Tidal Disturbances

Simpson Harbour, which constitutes the north-west part of the elongated caldera in which Rabaul is situated, measures about 6,600 yards in a north-south direction from the main wharf to the North shore of Vulcan, and about 3,300 yards at its maximum width in an east-west direction south of the airstrip. At the narrowest point, where it opens on the south-east side into the larger stretch of water known as Blanche Bay, between the shore of Vulcan and that of Matupi Island, it measures about 2,100 yards. The deeper portion, with a maximum depth of about 60 fathoms lies in a north-west/south-east striking trough between the Beehives and Vulcan. North of a line drawn east-west from the north-west end of the airstrip, the harbour is everywhere less than 25 fathoms deep.

As a result of its enclosed nature and the comparatively steep slope with which it shallows away from the open sea, it might be expected that Simpson Harbour would be an ideal place in which to observe seiches. Tsunamis (seismic sea waves) should also be observed, although the many small islands of the Duke of York Group should afford the town of Rabaul some protection against them. It is evident both from observation and from tide-gauge records made in Simpson Harbour that phenomena of both these kinds occur.+

Following the cataclysmic eruption of Ritter Island in the Dampier Strait at the south-east end of New Britain on 13th March 1888 a tsunami entered Blanche Bay and caused the sea to withdraw as much as 10 feet, at Matupi Island, below the level of the lowest tide. It then rose in several waves to the same height above high water mark (see (18) N.H. Fisher, Geological Bulletin No. 1, Territory of New Guinea.)

Within a few moments of the severe earthquake which occurred at 2320 hours L.M.T. on 1st January 1916, water level in Rabaul Harbour fell 15 feet and rose again rapidly. The causeway linking Matupi Island with the mainland disappeared leaving a depth of about 15 feet.++ Following the earthquake of magnitude 8.1 at 0541 hours L.M.T. 7th May, 1919, water in Rabaul Harbour fell 6 to 8 feet and rose again rapidly. Effects at Kokopo, on the exposed coast outside Blanche Bay were more severe. On 28th May 1937, (the day before the eruption of Vulcan), a severe earthquake of volcanic origin, with intensities up to 8 on the Rossi-Forel scale, took place. It was followed over the next 10 to 40 minutes by vertical fluctuations of 6 feet or more in water level. On the following day, shortly before the eruption commenced, actual elevation of the sea floor occurred; raising a number of reefs above water level.

At 2000 hours on the day of the eruption a rise of 9 feet in water level caused damage on the water front.

A 3½ foot tsunami affected Rabaul Harbour a little over 8 hours after an earthquake at 1708 hours G.M.T. on 4th November 1952.

Tsunami in Rabaul Harbour due to the 1960 Chilean earthquakes began to arrive at 0300 to 0400 hours L.M.T. on 24th May 1960 and continued throughout the day. The greatest rise of water level was about 4 feet above high tide mark, (see Reports by G.A. Taylor and J. Barrie, (57) and J.A. Brooks, (3)).

Seiches were set up in Simpson Harbour as a result of the major earthquake which took place at 0228 hours L.M.T. on 14th January 1941. The waves commenced at 0230 hours and lasted until 0700 hours. They reached a maximum amplitude, trough to crest, of 1 foot between 0300 and 0400 hours. The period of the waves, as measured on a recording tide-gauge, was 10 minutes.

Similar disturbances were noticed on 17th November, 1960 in calm conditions when ripples described as "similar to those formed by one side of a ship's bow" were seen first moving from Matupi Island towards Vulcan, and some time later from the foreshore near Matupi Island in a north-westerly direction towards the head of the bay. The height of the ripple was estimated as 2 to 3 feet, and its speed as 3 - 4 miles per hour. Four days later, during the afternoon of 21st November, an unusual wave was reported moving from Matupi Island towards the Cosmopolitan Hotel in the north-east corner of Simpson Harbour. This, however, coincided with a violent storm from the south and a sudden change in wind from the north-west, and might possibly have been caused by abnormal weather conditions. Unusual tide conditions were also noticed on the east coast of New Ireland and near Talasea on 17th November, 1960.

+ Before the eruption of 1878 tsunamis are said to have occurred, following severe volcanic earthquakes.

++ Probably scouring action and not due to subsidence - Editor.

On 16th November 1961 four waves up to a foot in height approached the main wharf from the south at a speed of 6 - 7 knots, followed by two which travelled from east to west.

Tide gauge records indicate that waves with a period of 10 minutes and low amplitudes are frequent in Simpson Harbour. Periods of 6 minutes are also observed.

Other disturbances in Simpson Harbour commonly take the form of up-welling of sea water. One such was investigated on 6th November 1957 near the main wharf: it was attributed to influx of groundwater into the sea.

Shoals of fish, when seen at a distance of a mile or more, may give the impression that the sea is boiling. An "undulation or heaving" seen in the harbour on 28th January 1959 was attributed to this cause, as a shoal of fish was seen in the area soon afterwards.

(d) Subterranean noises

Rumbling noises have been reported often in New Guinea earthquakes. It is generally considered that earthquake sounds are produced directly by the transfer of elastic wave energy from the ground to the air. Noises of this kind, variously described as sharp reports, deep booms or rumbles, were associated with the major earthquake near Rabaul in January 1941 and with many of its after shocks in the epicentral area.

A tremour on 5th January 1938, which was one of a swarm of possible volcanic tremors characterised by high intensities and very limited area of perceptibility, was accompanied by rumblings in Rabaul. A sharp shock felt at entensity 2 (RF.) on 22nd October 1939 at Vunakanau, some 5 miles south of Blanche Bay, (one of a swarm of about 6 tremors), was accompanied by "underground rumblings".

Underground rumblings were heard at the Rabaul Bowling Green on 2nd June 1938 during a tremor of intensity 4 which was felt in the town. Rumblings of volcanic origin, apart from those frequently associated with actual eruptions, are reported to have been heard at about 1300 hours L.M.T. on the 29th May 1937, about 3 hours before the eruption of Vulcan began; they were heard on Matupi Island and came from the direction of Vulcan. On 14th April 1938, well after activity had ceased, underground rumbling was heard on Namanula Hill. A series of rumblings heard at Rapindik (15th January 1938) was definitely linked with landslips occurring on the flanks of Tavurvur volcano. More recently the only subterranean noises reported have been caused by airlocks in underground water pipes.

(e) Submarine noises

Between midnight and 0100 hours on 7th May 1938 sounds were heard in Simpson Harbour which are considered to have been associated with a gas upwelling in the harbour.

(f) Explosions

On February 19th 1961 at about 2030+ hours G.M.T. natives living near Vulcan were alarmed by a loud explosion which threw objects off shelves and shook houses. The event is stated to have been accompanied by an 80 foot high waterjet, but inaccuracy of stated times makes the correlation doubtful.

+ A small very short period tremor was recorded with initial compression on the Rabaul seismograms at 2038 hours G.M.T.

In all probability this event was an explosion of wartime ammunition.

(g) Lights

Mysterious lights are sometimes reported to the observatory. They are usually proved to be due to grass-fires. One case however was never satisfactorily explained: a glow was seen in the sky above Tavurvur volcano at 0210 hours L.M.T. on 5th November 1957. It was witnessed by many people, but no consistent position for it was obtained.

CHAPTER 2

HISTORY OF OBSERVATION

1. Establishment of Observatory and Instruments used.

Scientific observation of the Rabaul volcanoes began after the eruption of Vulcan and Tavurvur in 1937. Prior to that date, press, private and administration reports are available but no specifically geological or vulcanological reports.

As a result of the eruption of 29th May 1937 Dr. C.E. Stehn, Vulcanologist in the Netherlands East Indies, was called in to advise the New Guinea Administration; Dr. W.G. Woolnough and Dr. N.H. Fisher, Government Geologist of the New Guinea Territory at that time assisted him in his investigations.

Dr. Fisher remained in Rabaul, and an observatory was established on the caldera wall at the present site on the north side of the town. Regular observations of temperatures and conditions in the volcanoes and thermal areas of Blanche Bay were carried out, and investigations were made of other volcanic centres in New Britain.

Tide records were made in Simpson Harbour, and bubble tiltmeters were installed at the Observatory. Mr. C.L. Knight joined Dr. Fisher as Assistant Vulcanologist.

Early in 1940 Dr. Fisher manufactured and installed a seismograph+, similar to those in use at the Hawaian Volcano Observatory, at the Rabaul Observatory and local epicentres of earthquakes were determined so far as possible. In April 1941 an observation post was completed on the caldera wall about 1 km. north of Tavurvur. A seismograph, identical to that at the Observatory, was installed and operated by an Asiatic assistant. When Tavurvur erupted in June 1941 detailed seismic and volcanic observations were made and the course of the activity was charted until the Japanese invasion put an end to this work in January 1942.

Dr. Takashi Kizawa, a distinguished seismologist of the Meteorological Research Institute of Japan, landed in Rabaul in May 1942, and in December 1942 built an observatory on the north side of Sulphur Creek. He used a 3-component Weichert Seismograph, a 2-component

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+ The seismograph comprised 2-component horizontal seismometers (mass about 350 lbs.), with magnification of 120, recording on smoked paper at a speed of 30 millimetres per minute.

horizontal tromometer, and an Omori type seismograph with a period of about 20 seconds, as a tilt meter. During 1943 and 1944 the Sulphur Creek Observatory suffered several direct hits from allied bombing, and in 1944 the seismograph was practically destroyed. A tunnel was dug in February 1945 near the village of Lat Lat near the Caldera Wall west of Vulcan, and a 200 kg. horizontal Weichert + seismograph was built from the remains of the Sulphur Creek instruments. Later an 80 kg. vertical Weichert and a 20 kg. horizontal Omori (magnification 25-30) were built. Two 18 kg. C.M.O. horizontal tromometers were also in use (magnification, 20: Pendulum period 4-5 seconds), which had been salvaged from the Sulphur Creek building. Observations were continued until October 1945, when the instruments were handed over to the Australian Military Forces.

Dr. N.H. Fisher revisited Rabaul in 1946, but it was not until April 1950 that a resident vulcanologist was appointed. In that month G.A. Taylor commenced duty. He remained in charge of the Observatory until May 1961. Continuous recording using an Omori Seismograph (two component horizontal: magnification, 10) began on 20th June 1950 in temporary quarters at Rapindik.

Regular temperature readings were carried out weekly in the Blanche Bay thermal areas.

After the Mount Lamington eruption in January 1951, J.G. Best took over in Rabaul. Reconstruction of the main Observatory was completed by the end of 1952.

In January 1953 tilt records commenced, using a north-south component bubble tiltmeter at the Observatory. In this month the first seismic monthly bulletin was issued. M.A. Reynolds joined the Observatory staff in November 1953 relieving Best in Rabaul. A three component short-period Benioff Seismograph was installed in November 1953 at the Observatory.

In December 1955 Dr. J.P. Webb, of the Seismology Department, University of Queensland, calibrated and adjusted the seismographs. In this month also J.E. Johnson arrived to take over temporarily from M.A. Reynolds.

In October 1957 a portable Willmore seismograph was added to the instruments at the Observatory. In February 1958 Dr. D.S. Carder of the United States Coast and Geodetic Survey visited the Observatory and gave valuable advice on problems of local interference.

J. Barrie took over as Assistant Vulcanologist from J.E. Johnson in July 1958. Early in October 1958 the Rapindik station was closed (it was by then infested with termites) and the Omori Seismograph was dismantled. In February 1960 2 sets of two component water-tube tiltmeters were set up, at the Observatory and in a tunnel near the Golf Course east of the Sulphur Creek craters. During 1959 the Omori Seismograph was installed in this tunnel, which became known as the Rapindik or Sulphur Creek Instrument Station. A recording tide gauge was installed on the Main Wharf in June 1960. Preliminary velocities of longitudinal waves in Blanche Bay were determined during a geophysical investigation of hydrothermal areas in October 1960, (see Chapter 4, section 3).

In May 1961 the writer, who had replaced J. Barrie in October 1960 as Assistant Vulcanologist, was put in charge of the Observatory, and J.H. Herlihy was appointed to the staff.

On 16th January 1962 the old three component short period Benioff Seismograph was removed from the Observatory and installed in the Rapindik Instrument station. The water-tube tiltmeters were removed,

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+ $V = 40 - 50$, $T_0 = 4 - 5$ seconds.

both from the Observatory and from Rapindik. Work commenced at the Observatory on installation of a United States Coast and Geodetic Survey World Wide Standard Seismograph. This equipment comprises a three component short period seismograph and a three component long period seismograph. Continuous recording on these instruments commenced on 27th February 1962.

On 23rd February 1962 nine tide markers, designed to record the level of maximum high tides, were installed at points around the shores of Blanche Bay.

During March 1962 a vertical Benioff seismometer, recording by means of a Helicorder, was set up in the Observatory.

A water tube tiltmeter, operating at a greater level of sensitivity than previously, was installed at Rapindik during November 1962.

Mr. C.D. Branch took charge of the Observatory in February 1963. Mr. N. Myers commenced work as technical officer in the same month.

Notes on the characteristics of the instruments maintained at Rabaul.

Instrument	Component	Symbol	Tg Galvometer Period	Tp Pendulum Period	M Pendulum Mass	Damping	V Static Magnification	Locality	Remarks
Short Period	Z	Z	0.74 sec	1.0sec.	107.5kg	Critical	12,500	Observatory (04° 11' 33"S. 152° 10'16"E.)	World-wide Standardised Instruments
	NS	N	0.73	0.996	107.5	Ratio Under 100: 1	6,250		
	EW	E	0.75	1.0	107.5	Critical	6,250	"	
Long Period	Z	Z'	99.8	30.18	11.2kg.	Critical	750	"	
	NS	N'	100.0	29.6	10.75	Critical	750	"	
	EW	E'	100.0	29.75	10.75	Critical	750	"	
Benioff, Short Period	Z	Zh	(0.75)	(1.0)	107.5	?	(1.100)	"	Records on Helicorder
Benioff, Short Period (1942 Model)	Z	Zr	0.35	1.26	?(65kg)	Slightly Under	(5,000)	Rapindik (04° 13'S 152°12'E)	Until 16 Jan 1962 at Observatory
	NS	Nr	0.26	1.44	"	"	"		
	EW	Er	0.29	1.45	"	"	"	"	
Omori (Strong Motion)	NS	No	-	3.6	15 kg.	Critical	11.9	"	
	EW	Eo	-	3.8	"	"	10.2	"	
Willmore	Z	Zw	(0.25)	(1.0)	9.15kg.	Ratio between 5: 1 and 10 : 1	(500)	Portable	operated intermittently
	NS	Nw	"	"	"		"		
	EW	Ew	"	"	"		"		

2. Catalogue of Activity and Significant events in the Rabaul Volcanic Area.

The earliest activity of which there is any record occurred in 1767. Captain Carteret sailed through St. George's Channel in that year and noticed a vast column of smoke rising from behind the Mother and the North and South Daughters. N.H. Fisher (18) suggests that either Tavurvur or Rabalanakaia might have been in eruption.

The next recorded eruption occurred in about the year 1850. Father George Boegershauser, M.S.C., of the Roman Catholic Mission at Taviliu, Dr. George Brown (autobiography) (8) and Mr. Wilfred Powell (Wanderings in a Wild country) (40) collected and recorded accounts of native eyewitnesses of the event. The eruption commenced at about 0900 hours on the day of a feast. It was preceded by a severe earthquake and the uplift of a large area of land on the east side of Simpson Harbour. Activity was confined to the small craters at the head of Sulphur Creek (Matanata) which were known as Kururung Maqe, although Tavurvur is said to have given off much greater quantities of steam than normally. The eruption was not large : material thrown out comprised stones and volcanic ash. Basalt is exposed in the walls of the craters.

The 1878 eruption commenced, according to Dr. George Brown, on Monday 4th February at a submarine centre on the north side of Keravia Bay. The previous day very violent earthquakes were felt, followed, on the morning of the eruption, by tsunamis. Immediately before the eruption clouds of steam were seen rising from the water in a direct line between Vulcan and Tavurvur. The severe earthquakes felt around Blanche Bay were barely perceptible at Dr. Brown's home in the Duke of York Islands, about 23 miles away. Some signs of activity must have been apparent at least 5 days before the eruption as natives reported to Dr. Brown on January 30th that it was already taking place. Since, however, any major activity would be clearly visible from the Duke of York Islands it is evident that the eruption proper did not commence until 4th February. Dr. Brown visited the new Vulcan Island, which was some 2000 yards in length and 1,100 yards in width at its maximum dimensions, on 16th February, by which time the eruption was over. Tavurvur erupted violently either at the same time or a few days after Vulcan. Boulders of fresh glassy basalt were ejected with great violence. A new strip of land was formed in this eruption, 20 feet in height, extending 150 yards off shore near Escape Bay. Dr. Brown states that the eruption occurred close to the south wall of what, before the eruption, was a very deep crater with almost perpendicular walls. The old south wall was completely blown away forming the site of the centre of the new crater.

It is reported that prior to the 1878 eruption a native fishing village existed on the Beehives. Dr. Brown noticed on 16th February 1878 that native houses which had previously been well clear of the water were flooded at high tide. Subsidence was evidently considerable. At the present date, (1963), there is a wide expanse of submarine coral lying some 4-5 feet below the surface on the north side of the rocks, especially of the small Beehive. By contrast several small rocks near the north end of Vulcan were raised several feet above their former level.

It is interesting to note that the 1878 crater of Vulcan was almost obliterated by 1955, forming only a shallow depression, much overgrown. The Matupi Island crater was observed possibly in much the same condition by Mr. W. Powell in 1877.

As mentioned earlier, sharp changes of level at Matupi Island Causeway accompanied the great earthquakes of 1916 and 1919. In 1916 the causeway disappeared suddenly leaving a depth of about 10 feet of water and in 1919 rose again suddenly by at least 2 feet, continuing to rise gradually until by 1924 it had regained its pre-1916 level.

The 1937 eruption was preceded by at least three days of very small tremors which were felt in the immediate vicinity of Keravia Bay.

Father George Boegerhauser at Taviliu Mission noticed that the movement was principally in the vertical direction. A very sharp earthquake of maximum Intensity 8 (Rossi-Forel) occurred at about 1320 hours L.M.T. on 28th May 1937, causing landslides around Keravia Bay and development of cracks in the ground on Vulcan Island. During the succeeding 15¾ hours no tremors were felt, but at 0505 hours L.M.T. on Saturday morning, 29th May, a moderately severe shock initiated a whole series of tremors which continued right up to the time at which the eruption began (about 1615 hours L.M.T. on 29th May). Distinctive features of these earthquakes were apparent vertical or circular movement, high frequency and high intensity. They were described as mild at Kokopo, Malabunga and Keravat and were not felt at all at the Warangoi River. The eruption at Vulcan continued for about 27 hours without abating in violence, ejecting material to a height of 25,000 feet or more. Severe earthquakes continued to shake Rabaul for at least the next 36 hours. Tavurvur erupted at about 1320 hours L.M.T. on 30th May, about 21 hours after Vulcan. The eruption was in the nature of a steam explosion which restored the pre-1878 crater. Small subsidiary eruptions occurred at 2 points from ½ to ¾ mile from Tavurvur, to the north-east, and near Escape Bay. For a full account of these eruptions see N.H. Fisher's Geological Bulletin No. 1, Territory of New Guinea, 1939. (18).

Casualties in the 1937 eruption were 505 natives and 2 Europeans killed, as against only 1 native killed in 1878 (the higher casualties in 1937 being due to the S.E. prevailing wind). A north-west wind would carry most of the ash out to sea. Many natives are believed to have been killed in the 1850 eruption. Dr. Fisher calculated that about 400 million cubic yards of material were ejected in 1937 from Vulcan, and 3 to 4 million cubic yards from Tavurvur.+

Since the severe earthquake of 28th May 1937 was definitely established to have been of volcanic and not of tectonic origin, it is certain that it was directly caused by the imminence of the eruption rather than vice versa. For some months after the eruption earth tremors of apparently local origin were felt near Rabaul, particularly in the Toma area. It is considered that these may have been due to readjustments of the volcanic forces after the eruption. Principal events after the 1937 eruption were as follows:-

1. 3rd January 1938 to 8th January 1938; tremors of apparent volcanic origin, up to intensity 6-7 (R.F.) felt in Toma area but hardly felt in Rabaul: apparently terminated by a major earthquake at 0125 hours L.M.T. on 8th January 1938 (Intensity 7 (R.F.) at Rabaul), which probably originated in a W.S.W. direction from the town.

2. 6th to 8th March 1938; a swarm of tremors, apparently of tectonic origin were felt at Keravat and Toma (maximum intensity 4 (R.F.) : during one of these, at 1030 hours L.M.T. 8th March 1938 a sharp puff of steam was emitted from Tarvurvur crater.
   N.B. See Chapter 1, Section 7, 5, in which subterranean noises are briefly discussed. At this stage, shortly after the eruption of 1937, rumblings and similar phenomena at Rabaul were rather frequently reported.

3. 3rd March 1940: 0930 hours and 1015 hours L.M.T., a series of small steam explosions occurred in Tavurvur crater, due to choking of principal vents by downwash material. A thirty to forty foot geyser, with a period of about 10 minutes, was in action on the floor of the crater. This activity culminated during the night of 12th March 1940 and

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\+ Excavation of Mr. Gilbert Renton's house near Vulcan (which was less than one mile from the 1937 crater) in February 1961 showed that the ash which buried it in 1937 was from 5 - 6 feet deep.

between 1200 hours and 1800 hours L.M.T. on 16th March, when steam explosions projected mud, stones and dry dust to a height of several hundred feet above the crater rim.

4. 17th June 1940; minor explosions heard in Tavurvur.

5. July 1940; increase of gas activity in Tavurvur. A series of very active fumaroles developed on the east side of the 1878 crater, highly charged with SO_2.

6. 3rd December 1940; a new vent opened in the 1878 crater of Tavurvur.

7. 7th to 17th December 1940; the principal fumarole[F] in the 1878 crater increased from a maximum temperature of 108°C by approximately 10° daily to a temperature of 224°C. Hardly any change in other fumarole temperatures.

8. Major earthquake of 14th January 1941 (0228 hours L.M.T.) intensity 9 (R.F.) (Upper Warangoi, Keravat area), Intensity 8 (R.F.)(Rabaul). Preceded by severe tilting upwards to the W.S.W.

9. 11th to 18th March 1941; a new fumarole[E] developed 40 yards from the principal one[F] in the 1878 crater of Tavurvur. Temperatures 276°C and 312°C respectively. Over the next month, increased production of gas, especially from vents at the extreme north-east and south-west ends of a narrow cleft running through the centre of Tavurvur.

10. 16th to 22nd April 1941; (E) measured 346°C, (F) at least 320°C.

11. 6th May 1941; both (E) and (F) exceeded the maximum limit of 360°C on the thermometers available.

12. 13th May 1941; gas issuing strongly from all vents and fumaroles in Tavurvur; several landslips in the central area; temperature of 382°C obtained at (E) by pyrometer; (F) measuring 330°C. New fumarole formed (G).

13. 27th May 1941; increased gas production; central plug of basalt in southern crater most active area; (E) measured 384°C, (F) and (G) inaccessible.

14. 3rd June 1941; increased gas from southern wall of crater and a new vent developed on the crater floor; (E) measured 392°C, (F) and (G) inaccessible.

15. 6th June 1941, 0740 hours L.M.T. Tavurvur erupted from the area of the central plug of basalt close to the southern wall where the new vents formed, and within 100 feet of fumaroles (E) and (F) in the 1878 crater. Minor local tremors. The activity was considered to be due to lava rising in the neck of the volcano. Activity declined but remained fairly continuous until:-

16. 12th September 1941; intense microseismic activity consisting of continuous high frequency volcanic tremor, due to rapid sinking of the lava in the conduit. Decline in activity.

17. 22nd October 1941; eruption recommenced at Tavurvur and continued at intervals until observations were broken off following the Japanese invasion in January 1942.

18. October 1943; rise in Tavurvur crater measured at the Japanese Observatory near Sulphur Creek; (S-P) intervals of earthquakes shortened prior to eruption of Tavurvur in this month (date not known).

19. Dr. N.H. Fisher, who visited Rabaul in 1946, wrote, in December 1950, "the state of activity at Tavurvur volcano is comparable with that which existed prior to the 1937 eruption and is much less than during the period 1937-1941."

20. 14th May 1951; fumarole in Tavurvur recorded temperature of 105°C. Two hot springs on the foreshore at Rapindik suddenly ceased to flow. This may have been due to an earthquake which reached Intensity 5 (M.M.) in Bougainville and New Ireland (0828 hours G.M.T. 21/5/51) - epicentre 6.2°S, 154.8°E, depth about 160 kilometers.

    Note: Previous to 1950 the Rossi-Forel scale of earthquake intensities was in general use throughout the Territory. After 1950 it was supplanted by the Modified Mercalli Scale.

21. 23rd April 1953, 16 hours G.M.T.; earthquakes (S-P = 12 seconds) did minor damage in Rabaul: intensities up to 7(M.M.) reported. Epicentre 4.5°S, 153.3°E.

22. March 1954; temperature of 106°C recorded at Fumarole C2 in Tavurvur crater.

23. 28th March, 1955; sharp rise in temperature of point 6 in Tavurvur crater to 108°C. Rabalanakaia temperatures increased also.

24. 15th June 1955; following an earthquake of intermediate depth (100 kilometres), at reported epicentre 3°S, 153°E, at 1536 hours G.M.T., south-east/north-west trending fissures opened in Kamerere Street, Instrumental data at Rabaul indicated that the earthquake originated towards the south-east and this conclusion is supported, though not conclusively, by the fact that the tremor was felt at Intensity 4 (M.M.) at Warangoi Plantation and only at Intensity 2-3 (M.M.) at Rabaul.

25. 5th to 12th September 1955; sharp drop in temperature of fumarole A2 in Tavurvur crater.

26. 10th to 24th October 1955; sudden fall in temperature of hot spring No. 3 in Sulphur Creek. Irregular movement noticed on Observatory tiltmeter on 23rd October.

27. 7th November, 1955; sharp increase in temperature of point No. 11 at Sulphur Springs, and sharp drop in temperature at fumarole A2, Tavurvur crater.

28. 12th to 13th December 1955; irregular movement of Observatory tiltmeter.

29. 16th August 1957; seismic storm commenced at Rabaul. Climax was reached at midday on 23rd August when a shock of Intensity 5 (M.M.) was felt with similar intensity at Rabaul, Kokopo, Warangoi, Namatanai, Londolovit, Aropa and Sohano. The early shocks were from foci east of southern New Ireland, but later shocks appeared to be from the eastern extension of the Warangoi - Keravat Fault. During one of these closer shocks, at 0242 hours L.M.T. on 19th August, one of the most vigorous hot springs at Rapindik dried up suddenly. In all probability this hot spring had been made by the Japanese by boring. Earth movement probably blocked the pipe up which water was rising to the surface.

30. October 1957; small "anomalous" emergent tremors, often possessing an harmonic form, first noticed in large numbers on the seismograms.

31. 27th October 1957; at about 1230 hours L.M.T. a steam-vent developed on the shore between the main wharf and the Bougainville Company's Wharf (see Chapter 1, section 7).

32. 22nd December 1957; swarm of small imperceptible tremors, with S-P intervals of 3-6 seconds, recorded on the seismograph; possibly deeper than normal.

33. January 1958; new upwellings of gas along the foreshore of Greet Harbour near Rapindik. Similar activity observed in 1950, when it was stronger.

34. September 1958; thermal areas in the sea to the south-east of Tavurvur appeared to be more active than usual.

35. 16th June, 1959; steam jet observed for about 10 minutes rising from the sea near Tavurvur volcano. (See Chapter 1, section 7, for other water jets of possible volcanic origin).

36. January 1960; minor fluctuations of temperature in Tavurvur volcano. Some fumaroles were over 100°C for short periods. Thirteen small earthquakes with S-P intervals of less than 5 seconds recorded at the Observatory.

37. February 1960; cumulative tilt since the beginning of January 1960 at Rapindik instrument station amounted to a westerly dip of 13 seconds of arc.

38. June 1960; higher temperatures than usual recorded at point 9A on the beach on the west side of Tavurvur, (90-100°C). Vigorous steaming and much discolouration in the sea at this point.

39. August 1960; down-tilting to the south at the Observatory and to the west at Rapindik amounted to about 5 seconds of arc in each case. "Anomalous" emergent tremors numerous on the seismograms.

40. 31st October 1960; Observatory tiltmeters fluctuated in the north-south plane, and dipped 8 seconds of arc towards the east. This trend continued and by the end of November cumulative tilt in this direction was 10 seconds of arc beyond the normal.

41. 15th November 1960; more than 1,000 energy pulses of unusual type were recorded by the Observatory seismograph during the night (see Chapter 3, section 3).

42. 8th December 1961; point 14 in the gully on the west side of Tavurvur temporarily increased in temperature to 102°C.

43. 2nd to 9th February 1962; point 33 at Sulphur Springs increased from a temperature of 44°C to 70°C, and then decreased gradually to a temperature of 54°C.

44. 23rd February to 20th July 1962; observations on nine tide markers around the shores of Blanche Bay read in conjunction with the tide gauge on the Main Wharf, suggested that vertical movements as great as two foot nine inches had possibly occurred at Tavurvur (see Chapter 2, section 4).+

+ A check carried out early in 1963 has cast doubts on the validity of these readings.

45. August 1962; general levelling off of temperatures at 2 thermal points at Rapindik and 3 at Sulphur Springs, which had previously shown marked fluctuations. The Rapindik temperatures became constant at 66 and 67°C.

46. September 1962; apparent movement at Tavurvur and Namanula Street Wharf, measured by tide markers, amounted to 20½ inches.

47. October 1962; sharp increase of temperature at point 17 on outer slope of Tavurvur. Apparent vertical movement totalling 19 inches at Namanula Street Wharf.

48. 30th October 1962; tremor of possible volcanic origin felt at Rabaul Police Station at 1025 hours L.M.T. (see Chapter 3, section 1, and Plate 1.+

3. Earthquake Report Network

With the co-operation of residents of the Territory, Mr. G.A. Taylor set up a network of reporting stations (initially to obtain volcanic information) which was later extended to cover almost the whole of the Territory of Papua and New Guinea, and which has since been used extensively for reporting earthquakes.

Missionaries, planters and other private persons, and officers of the Administration, render valuable service in reporting changes of volcanic activity, earthquakes and tidal and other disturbances.

Earthquake effects of over Intensity 3 (M.M.), and any changes of activity that appear dangerous, are reported by radiogram to the Vulcanological Observatory in Rabaul, charges, in the case of private persons, being met by the Administration. In this way it has been possible to build up a surveillance network throughout Papua and New Guinea. (See accompanying locality may Figure 1, on which reporting stations are circled and numbered, and Appendix A for the key to the numbers and for the station co-ordinates (given to the nearest 5 minutes of arc).

Information most generally reported, in the case of earthquakes, is Intensity (modified Mercalli)++ duration, and direction of the tremor, if determinable, and any damage that may have been caused. Returns are sent monthly in addition to any special reports by radiogram, and importance is placed on the value of "Nil Returns".

4. Establishment of Marine Datum Level at Rabaul

Before the war Dr. N.H. Fisher established a rough working datum with the aid of a bench mark placed by H.M.A.S. "Moresby" in 1941, near the Burnt Wharf in Rabaul during an hydrographic survey to determine changes due to the eruption of 1937. J.G. Best records "The elevation of the 1941 bench mark is referred to a datum which in turn is referred to average mean low sea level and average mean high sealevel. From these two levels a mean sea level was calculated, the accuracy of which is not known as the duration of the readings was not specified." (Unpublished report J.G. Best 16th February 1953).

In 1948 A United States ArmySurvey Unit placed a benchmark near the Namanula Street Wharf. This bench mark is referred to mean sea level which was calculated from a continuous record of tide levels over a 12 month period: it should thus be reasonably accurate.

++ For an explanation of the Modified Mercalli Scale see Appendix L

A third mean sea level datum was calculated from all available tide gauge records, in 1951. The surface of the Observatory instrument pier is referred to extreme low water mark (it is 604.73 feet above this datum).

Mr. Best found evidence to suggest changes in strand line level during the years 1941 to 1951. He calculated that mean sea level rose by an average amount of 0.47 feet yearly over a total of 3.3 feet between 1941 and 1948 (he discusses the possibility that subsidence of bench marks due to bombing during the war years could have caused some or all of this apparent increase, and discounts it). For the period 1948 to 1951 he calculates that mean sea level remained approximately stable, or at the most underwent a slight decrease.

He points out that, since no appreciable world wide rise in sea level is known to have occurred between 1941 and 1948, the change must have been due to subsidence. Tilt changes (see Chapter 2, Section 2) have sometimes been considerable in the area, and in addition later recording by means of a tide gauge on the main wharf has established the fact that high tides in December 1962 reached a higher level than any recorded since June 1960 when tide gauge recording recommenced.

It is well known that tide levels vary at different times of the year, being a few inches higher during the north-west season than at other times of the year. The town of Rabaul is protected from the north-west and exposed to the south-east, so that the explanation can hardly lie in the banking up of greater volumes of water in Blanche Bay due to the agency of the wind. It may however lie in the movement of large volumes of water into the Bismarck Sea area from the north-west Pacific. Since St. George's Channel is only a little over 20 miles wide at its narrowest point, it is possible that not all this water could escape at once. A build-up of water to a depth of a few inches above normal in Blanche Bay would then be expected.

The maximum amount of change of level to be expected due to earth tides is believed to be of the order of a foot. If differential movement between water and land is taken into account at times of maximum and minimum earth tides presumably a change in mean sea level would be observed. This however, would appear to be too small to account for the measured differences.

Although sudden alterations in level in the Blanche Bay area have been reported it is only recently that the possibilities have been explored of other more gradual changes taking place over wide areas of the caldera floor. As long ago as 1938 levels were run in order to provide a check against future movement (see Chapter 1, section 7), but owing to the war and the loss of records the work was never pressed to a conclusion. On 23rd February 1962 regular weekly readings commenced of 9 tide markers situated around the shores of Blanche Bay, Greet Harbour and Simpson Harbour (see accompanying locality map Figure 3). The markers were installed with a view to recording the highest levels reached by tides, the mechanism involving floats, which travel up with rising tide inside a box measuring some 5 feet in length, but on withdrawal of the tide are left suspended on numbered nails.

No reliable results were achieved, principally because the floats were either trapped underwater or escaped being held by the nails and were carried down by the tide. Also damage to the boxes due to weather and marine conditions sometimes allowed the floats to escape altogether. It was decided to use the boxes purely as markers, and with this in mind a datum was established for the boxes with an accuracy of about ½ inch, using the continuously recording tide gauge on the main wharg as a control.

Weekly timed readings of water level at the markers were referred to the tide gauge record and corrected to an arbitrary datum. Changes of level were then readily apparent. It is considered that in calm weather accuracy of the method is ± 1 inch while in choppy conditions accuracy deteriorated to ± 3 inches. Even considering these rather wide limits results have been startling, particularly since almost all the readings have been made in calm conditions. Movements + of the following order were detected between 23rd February and 20th July 1962; - up to 2 feet 9 inches of vertical movement occurred at the tide stick below Tavurvur volcano, most of the movement being in the sense of the ground rising, and most of it occurring during March; movement at Sulphur Springs closely paralleled that at Tavurvur but the total range was only 1 foot 10 inches; movement at Matupi Island (near the western side of the Causeway) totalled 1 foot 4 inches in the same sense; movement at Karavia Bay and Vulcan paralleled that at Tavurvur, total range 1 foot 8 inches and 11 inches respectively, until 4th May, when an apparent rise of sea level of about 9 inches took place (at this time the Tavurvur - Matupi Island area appeared to be moving in the opposite sense): apparent movement at the Small Beehive ranged through 8 inches, and the box at Sulphur Creek, which was removed owing to damage, on 29th March 1962, recorded 12 inches in the same sense as the larger movement at Tavurvur.

On 25th May 1962 boxes were installed near Toboi and at the Namanula Street Wharf, thus providing points close to the tide gauge on the main wharf, which, for the purposes of this investigation, was assumed throughout to be undergoing no vertical movement. This assumption is unlikely to be correct in view of the apparent movement at the other markers, but it enables a graph to be drawn using an arbitrary level (the three foot mark on the tide gauge record) to which the markers are corrected. The three foot mark on the tide gauge records represents a height of water approximately three feet above extreme low water. In practice tide rarely falls below the one foot mark on the records.

During August ground apparently rose at all tide boxes, from a minimum of 6 inches at Toboi to a maximum of 1 foot 4 inches at the Small Beehive. This trend continued until 28th September, by which time total movement was 12 inches at the Small Beehive, 14 inches at Vulcan, and 17 inches at Keravia Bay. At Tavurvur an apparent sharp fall of about a foot took place between 14th and 21st September followed by a sharp rise of ground amounting to 20½ inches between 21st and 28th September. This trend was paralleled at Sulphur Springs and at Matupi Island to a much smaller extent, while an almost exactly similar movement of 20½ inches occurred at Namanula Street Wharf. At Toboi a sharp rise of ground amounting to 14½ inches took place between 7th and 14th September. This excellent correlation of results appeared to continue during October when an apparent rise of ground took place at all points except Toboi, reaching a maximum on 5th October. Greatest movement occurred at Namanula Street Wharf, and least at Keravia Bay. This was followed by a fall in all areas except Toboi and Keravia Bay, reaching a maximum on 12th October (greatest movement, at Namanula Street wharf, totalled 19 inches). A second rise of ground with a maximum on 19th October took place at Namanula Street (where movement totalled 21½ inches), Matupi Island, Sulphur Springs and Tavurvur. There was then a return towards datum level, with the sharpest movement again taking place at Namanula Street Wharf.

Few apparent ground movements took place during November. The greatest was an apparent fall of ground on the eastern side of the harbour, amounting to 9½ inches at Namanula Street and Matupi Island and to 7 inches at Tavurvur. As before, results correlated well with one another.

\+ The tide markers were re-zeroed early in 1963 using radio-controlled readings. Since then there has been only one movement of any size (an apparent movement of 8 inches at the Main Wharf only). Some doubt has thus been cast upon the previous results.

Similar movements, which by then had come to be considered normal, took place during December. In January 1963 overall apparent movement at Toboi totalled 9½ inches (previously Toboi had been one of the least mobile points).

Despite the remarkable rnage of movement and the speed with which it is traversed, the writer is of the opinion that no cause other than actual ground movement can account for the observations. Gross error can easily occur but the remarkable correlation between different markers would seem to indicate that, although some of the large movements may have been exaggerated by errors of reading, movements are in reality taking place.+

The alternative hypothesis that there is a lag in the times of high and low water at different points in Blanche Bay would seem to be negated by the apparent large relative movements between the tide gauge and the marker at Namanula Street Wharf. Even before installation of this latter marker the conclusion was reached in discussion with officers of H.M.A.S. "Paluma" that such a lag could only account for a small proportion of the observed movement since if a lag occurred at all, the time intervals must of necessity be very small. Under certain weather conditions there is a marked build-up of water in the inner parts of Blanche Bay, but since most of the observed fluctuations have taken place in calm weather it is not considered that this can account for anything but a small proportion of the results.

It is hoped that, as soon as a sufficiently accurate theodolite becomes available, a night survey of levels can be carried out, and checked at regular intervals. This should certainly confirm or deny the reality of the observations. An even more reliable check, which would also serve as a permanent recording of fluctuations of level, would be the installation of a second tide gauge on Namanula Street Wharf.

Fresh observations of mean sea level were made by the R.A.N., Hydrographic Department, during the recent survey of Blanche Bay by H.M.A.S. "Paluma". Tide gauge readings from early May to August 1962 were used in the determination. Results have not yet been published.

Through the courtesy of the Hydrographer, R.A.N., Garden Island, the writer was given the opportunity of comparing the preliminary unpublished charts of H.M.A.S. "Paluma's" soundings with those made in 1941 by H.M.A.S. "Moresby". Results appear to tally well in all parts of the harbour area; however the deepest part of Greet Harbour to the north-west of Tavurvur volcano, which gave 33 to 36 fathoms in the 1941 survey, in 1962 gave only 30 to 31. The difference could certainly not be due to material deposited in the comparatively minor eruption of 1941, nor does it seem likely that much depth of material was deposited in the 1943 eruption. However it could possibly be due to slumping of sediments on the slopes of the depression and to redeposition of material. It may, on the other hand, reflect a genuine rise in level of 18 to 30 feet.

A submarine bank about 500 yards offshore to the north-north-east of Vulcan Point (the point on the east side of the embayment) was charted in far greater detail by H.M.A.S. "Paluma" than by H.M.A.S. "Moresby". The slight differences may have been due to selective sounding in 1941, when the minimum depth recorded was 18 fathoms. H.M.A.S. "Paluma" recorded small areas showing 16 fathoms.

Both surveys agree that the narrow trough between the Beehive and Vulcan is 60 fathoms deep. Similarly no change was observed in the maximum depth of 69 fathoms between Vulcan and Matupi Island.

\+ The tide markers were re-zeroed early in 1963 using radio-controlled readings. Since then there has been only one movement of any size (an apparent movement of 8 inches at the Main Wharf only). Some doubt has thus been cast upon the previous results.

CHAPTER 3

DESCRIPTION OF THE NEAR EARTHQUAKES AND MICROEARTHQUAKES OF THE RABAUL AREA.

1. Near felt Earthquakes and their foreshocks and aftershocks

Reference to the map Figure 4, which accompanies this report depicting internationally determined epicentres for earthquakes in the region over a period of 31 months from July 1960, will make it clear that Rabaul lies close to some of the most seismically active areas in the Territory. A high proportion of the earthquakes which are of sufficient magnitude to be recorded at distant stations are felt close to their point of origin.

A fundamental distinction between tremors of tectonic and those of volcanic origin must be made. Tectonic earthquakes are believed to be caused by yielding of large masses of rock often at great depth to stresses, which have accumulated slowly due to fundamental processes that affect a wide area, such as mountain-building. In a tectonic earthquake intensity characteristically falls off slowly with increasing distance from the epicentre, and shocks may be felt over great distances (more than 200 miles in some of the larger New Guinea earthquakes+). By contrast, volcanic earthquakes are related purely to movement of gas or magma in the conduit of a volcano, to collapse in the vent, or to movements in the magma column below. They are thus characteristically shallow phenomena which yield much less elastic energy than tectonic earthquakes. The intensity of volcanic earthquakes falls off very rapidly with distance. Movement is often noticeably more in the vertical plane than the horizontal, whereas in the case of a tectonic earthquake the reverse is generally the case.

Earthquakes of both classes occur in the Rabaul area. Those of volcanic origin, which are always directly related to volcanic activity or to impending activity, are rare. Almost all the shocks felt in Rabaul are to be classed as tectonic. They are numerous, usually exceeding 50 in a single year. Volcanic earthquakes may occur in the Talasea area.

A. Earthquakes of Volcanic Origin: The severe earthquakes in Blanche Bay which preceded the eruption of February 1878 were barely felt in the Duke of York Islands only some 20 miles away. It is thus almost certain that they were of volcanic origin. As mentioned in Chapter 2, section 2, Dr. Fisher has pointed out that the earthquakes were directly consequent upon increase of pressure in the volcanic vent.

With regard to the earlier eruption in about 1850 at Sulphur Creek it is impossible to say whether the severe earthquake which preceded the eruption could have been due to normal tectonic processes which, by the opening of fissures or the sudden shifting of load, caused the eruption to follow. However, from the evidence it appears that the earthquake was accompanied by considerable uplift in the area which erupted, and further that eruption followed hard on the heels of the earthquake. The probability is accordingly strong that this earthquake, too, was of volcanic origin.

The severe earthquake which occurred on the day before the 1937 eruption was undoubtedly of volcanic origin since it was described as of mild intensity as near as Kokopo and Toma. Furthermore the elastic waves were not recorded on seismograms at Riverview and elsewhere at comparable

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+ the 24th March 1962 earthquake for example (see Figure 6).

distances, whereas they certainly would have been, had an earthquake producing intensities as high as 8 (R.F.) been of tectonic origin (c.f. the effects of the January 1941 earthquake which was felt as far as Talasea, and was recorded at most of the world seismograph stations). Similarly the swarm earthquakes which occurred both before and after the eruption were of volcanic origin: the fact that their motion was chiefly in the vertical plane at Taviliu has already been commented upon.

Other tremors of possible volcanic origin in the area have been mentioned in Chapter 2, section 2, but for the sake of convenience they are listed again as follows:

1. 3rd to 8th January 1938; tremors up to intensity 6-7 (R.F.) felt in the Toma area but hardly felt in Rabaul. Apparently terminated by a major earthquake at 0125 hours L.M.T. on 8th January 1938. It is a matter for conjecture as to what the subterranean connection is, if any, between the Toma area and Blanche Bay, and whether this swarm of volcanic tremors had anything to do with the presence of the apparently extinct volcano, Mt. Varzin, nearby.+

2. 6th June 1941; minor tremors of probable volcanic origin accompanied the eruption of Tavurvur. Apparently none were felt before the eruption. No intensity greater than 3 (R.F.) reported. Volcanic tremors occurred some days after the eruption at 1321 hours L.M.T. on 10th June (Int. 2 (R.F.)), at 1733 hours L.M.T. on 17th June (Int. 2 (R.F.)), and at 1137 hours L.M.T. on 22nd June (Int. 1-2 (R.F.)).

3. 18th November 1941; strong explosive activity in Tavurvur crater accompanied by volcanic tremors felt at intensities 2-3 (R.F.) at the Observation Post near the volcano: a total of 54 tremors noticed. Activity continued with accompanying earthquakes until the next day.

4. 3rd October 1962; tremor of possible volcanic origin was felt at Rabaul Police Station at 1025 hours L.M.T. (Intensity 1-2 (M.M.)). The records of this tremor on the Observatory seismograms are of an unusual appearance, high frequency and low amplitude the tremor was not felt elsewhere and its amplitude on the Observatory records show that ground movement was far too small to be perceptible. The energy of the disturbance must thus have fallen off very rapidly, since the Observatory is only about 2 miles from the Police Station. This tremor was recorded as a small indeterminate shock at Rapindik, but a high level of industrial interference makes the record virtually useless. The tremor was recorded about 1.5 seconds earlier at the Observatory than at Rapindik.

The classification of this tremor as of volcanic origin is suspect. It may possibly have been due to collapse of a wartime dug-out some distance beneath the ground. No evidence of this was ever found. If collapse of a tunnel or some kind of slumping was the cause of this earthquake it must have been considerable, since disturbances of this kind are not normally recorded on the seismograms at distances approaching 2 miles.

In the course of the next week 2 remarkable reports were received from Mr. R. Murphy of the Department of Posts and Telegraphs. At 0745 hours L.M.T. on the 2nd November 1962, and at 0940 hours L.M.T. on 8th November 1962, severe tremors were reported to have been felt at the Transmitting

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\+ A series of small earthquakes felt at Vunadidir on 4th January 1961 may have been of volcanic origin. They were not recorded at Rabaul or felt elsewhere. See Chapter 3, Section 1, subsection (d). Similarly tremors felt at Taliligap which are not recorded or felt elsewhere may be of volcanic origin. See Appendix J and Chapter 5, Section 2.

Station in Tavur Street. On each occasion the movement was strong enough to shake the aerial masts and disturb the aerial wires. No evidence for either of these disturbances could be found on the Observatory seismograms, or the Rapindik seismograms (on the first occasion the record was unreadable), or on Willmore seismograph records which were recorded at the Police Compound only a few hundred yards away. The event is tentatively attributed to minor tunnel collapse close to the building.

B. <u>Earthquakes of Tectonic Origin</u>: Curiously enough in recent years few epicentres of felt shocks in Rabaul fall on the Keravat - Warangoi line of weakness that traverses the Gazelle Peninsula. Shocks felt in Rabaul characteristically come from shallow or intermediate foci in the area of the southern end of New Ireland, Wide Bay or Jacquinot Bay on the south coast of New Britain, or the Nakanai region of central and northern New Britain. Large shocks off the western coast of Bougainville, and large shallow earthquakes occurring in the Bismarck Sea are also sometimes felt in Rabaul. Some intermediate and deep earthquakes are felt widely over the Bougainville - New Britain - New Ireland area. Earthquakes originating in south-western New Britain are rarely felt; those originating on the New Guinea mainland are very seldom if ever felt at Rabaul. The reverse does not however hold true. The very severe earthquake of Magnitude 7¼ (Pas.) which occurred at 0857 hours G.M.T. on 10th October 1955 (Intensities up to 6-7 (M.M.) at Kokopo), whose epicentre was given as 5°S. 153°E., was felt with intensity of 3 (M.M.) at Popondetta. Similarly a very widespread felt shock at 1008 hours G.M.T. on 12th November 1955, which was felt at intensity 3 (M.M.) in Rabaul, (epicentre given as 5°S, 152½°E), was felt also at Esa'ala (Intensity 2 (M.M.)) in the D'Entrecasteaux Islands. A remarkable earthquake at 0347 hours G.M.T. on 4th February 1960, which was mentioned as the strongest earthquake at Rabaul for some years (Intensity 4-5 (M.M.)) was felt with intensity 4-5 (M.M.) at Losuia in the Trobriand Islands, and in the British Solomon Islands. It is thought that these unusual cases represent earthquakes with deep foci and high magnitudes.+

Isoseismal lines drawn for such earthquakes are often extremely irregular.

A point worth mentioning is that earthquakes felt at Rabaul are characteristically felt at slightly higher intensity at Taliligap, on the outer side of the caldera wall on the south-west side. The volcanic ash on which both localities are built is not noticeably less consolidated at Talilicap than it is at Rabaul, and the effect may in part be due to loss of energy in earthquake waves crossing the caldera wall.

Sometimes anomalies in the internationally determined epicentres are found. An example is the earthquake of 2147 hours G.M.T. on 3rd December 1960. Instrumental data at Rabaul gave an S-P interval of 18 seconds (Omori) in the south-easterly direction (Benioff). The epicentre was placed almost at Rabaul, 4.2S, 152.1°E, at a depth of 40 kilometres. The shock was not felt.

(a) <u>Deep Earthquakes</u>

Some earthquakes occurring in the "Deep" range, that is below a depth of 300 kilometres, are felt at Rabaul when of great magnitude. A total of 5 which are known to have deep foci have been felt in the Territory of Papua and New Guinea since the beginning of 1955; they are :-

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+ This relationship does not always hold. An earthquake of magnitude 6¾ which occurred on 31st July 1960 at about 0255 hours G.M.T. at 5.6°S. 150.0°E. (depth 25 kilometres) was felt at Rabaul (Intensity 4 (M.M.)) and very widely as far as Wanigela.

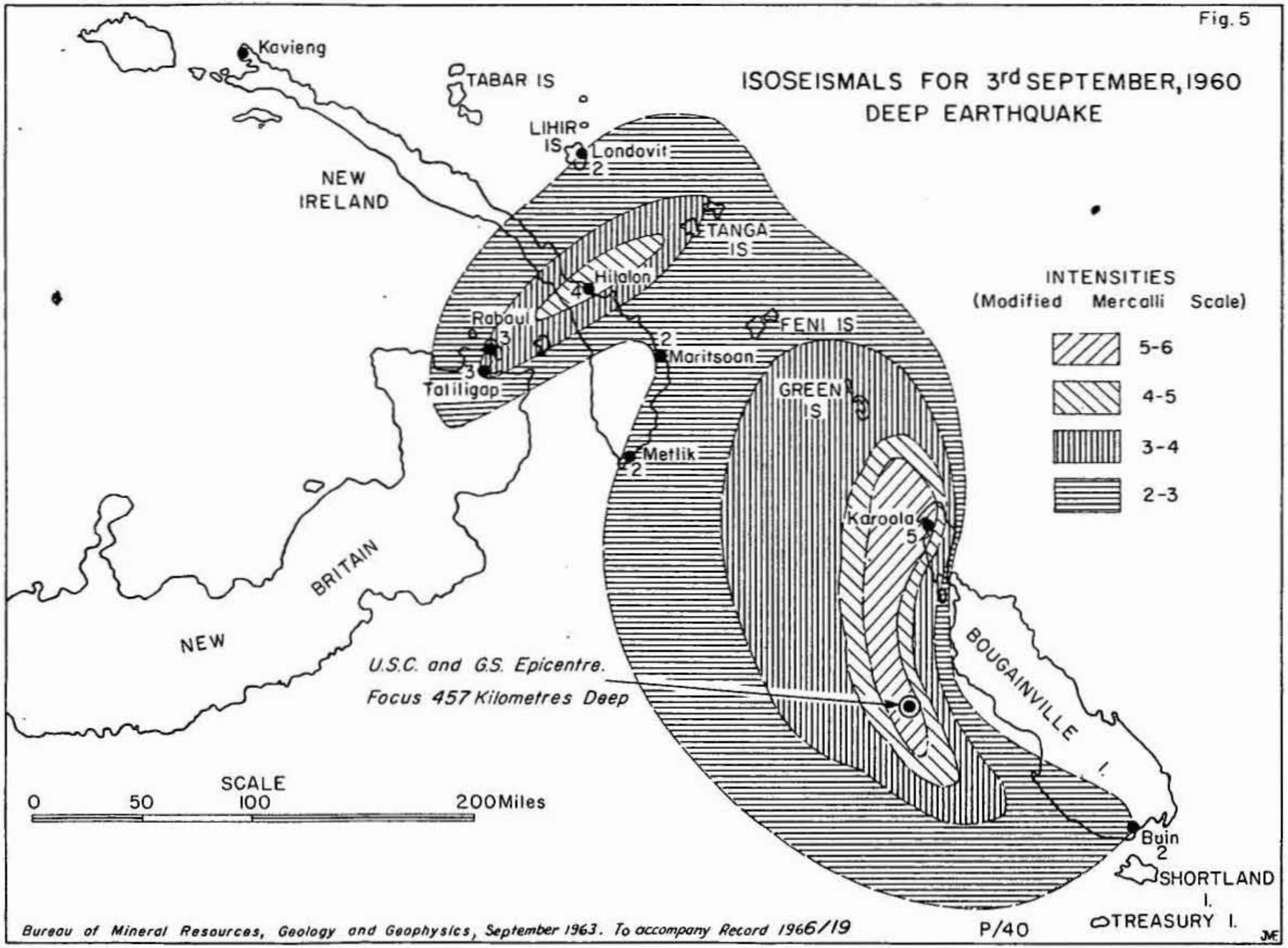
Fig. 5
ISOSEISMALS FOR 3rd SEPTEMBER, 1960
DEEP EARTHQUAKE
INTENSITIES
(Modified Mercalli Scale)
5-6
4-5
3-4
2-3
Kavieng
TABAR IS
LIHIR IS
Londovit
2
NEW IRELAND
TANGA IS
Hilalon
4
Rabaul
3
Taliligap
3
2
Maritsoan
FENI IS
GREEN IS
Metlik
2
Karoola
5
NEW BRITAIN
BOUGAINVILLE I.
U.S.C. and G.S. Epicentre.
Focus 457 Kilometres Deep
SCALE
0 50 100 200 Miles
Buin
2
SHORTLAND I.
TREASURY I.
Bureau of Mineral Resources, Geology and Geophysics, September 1963. To accompany Record 1966/19
P/40

Magnitude	Date	G.M.T.	Epicentre	Depth	Felt at
7–7¼ (Pas.)	31 Jan.1956	0917	4°S, 152°E	400 kms	Rabaul (Int. 3 (M.M.))
	1 June 1959	1233	6°S, 154°E	400 kms	Rabaul (Int.2 (M.M.))
(this followed an earthquake at the same depth closer to Rabaul (4°S 153°E) which was not felt.					
6½–6¾ (Pas.)	3 Sep.1960	1241	6.1°S, 154.5°E	457 kms.	Karoola (Int.5 (M.M.)) Rabaul (Int.3 (M.M.)) etc.
	23 Nov.1960	0411	4.9°S, 153.8°E	516 kms	Londolovit (Int.1–2 (M.M))
5½ (Pas)	22 Dec.1960	2102	6.8S. 155.3°E	469 kms.	Rabaul (Int.1–2 (M.M.)) Buin?

It is often difficult to draw ososeismal lines for earthquakes in the Rabaul area, owing to the large areas of sea and the irregular distribution of reporting stations on the islands. It is particularly difficult in the case of deep earthquakes, when the localities where the shocks are perceptible are often a great distance apart.+ One thing however emerges from the attempt to do so, and that is that north-west/south-east is the preferred direction in which deep earthquake energy is transmitted. The same feature can be noticed in the isoseismals of intermediate earthquakes which occur in the same zones as the deep ones.

The zone of deep earthquakes in the region parallels the line of the Solomons arc, passing west of Bougainville and along the north-east coast of New Ireland. Another area of deep shocks occurs to the north-west of the Gazelle Peninsula, some of the epicentres lying very close to Rabaul (see map, Figure 4, accompanying this report).

The significance of these facts is discussed in Chapter 5, section 3.

It is a curious fact that the deepest earthquake recorded over the period from January 1955 to January 1963 (that of 23rd November 1960 at a depth of 516 kilometres) should be one of only five felt out of a total of 18 recorded (see Chapter 3, section 2 for a list of the deep earthquakes which have not been felt).

The recognition of phases in felt earthquakes from seismograms is generally difficult owing to the strong motion experienced, but near deep felt earthquakes may often be recognised from their shallower counterparts by the sharpness of the P and S groups and by the relatively feeble registration of the surface waves. These differences are best seen on the long period seismograms and on the records of strong motion instruments such as the Omori. For a fuller discussion of the appearance of deep earthquakes on the records see Chapter 3, Section 2 and Plate 2.

An indication of unusual depth may be given, in the case of a large earthquake, by apparent anomalies in the arrival times at other seismograph stations in the region, and by unusually widespread felt reports showing uniform low intensity. A further indication of deep focus may be the fact that the increased distance travelled by shock-waves of deep earthquakes results in a longer wave period than that from shallower

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+ See accompanying sketch map, Figure 5, showing the area over which the deep earthquake of 3rd September 1960 was felt.

earthquakes at similar epicentral distances. There have been no instances of earthquakes in the deep range having caused any damage in the New Guinea area.

(b) Intermediate felt Earthquakes

Earthquakes are commonly classified as of Intermediate Depth if their foci lie between depths of 70 and 300 kilometres.

They are of common occurrence in the east New Guinea area, the majority of those identified being felt, often at considerable distances from their epicentral areas. In the period 1955 to 1962 (inclusive) 233 intermediate focus earthquakes were identified, of which 142 were reported felt; in the period covered by more accurate depth determinations on the part of the U.S. Coast and Geodetic Survey (i.e. from 27th July 1960 to the end of 1962) 168 intermediate earthquakes were identified, of which a total of 103 were felt. See Appendix B for a complete list of the intermediate earthquakes felt over the period.

The main line of Intermediate focus epicentres on the New Guinea mainland follows the Sepik Valley east to the Bismarck Range and continues along the Markham Valley to the Huon Gulf. In addition intermediate earthquakes occur in the Finisterre Mountains, along the coast from Madang to Finschhafen, in the Wau area, and at scattered points off the north-east coast of Papua.

To the west of Madang they are of rare occurrence in the line of the Inner Volcanic Arc. They become dominant in the zone stretching from Long Island along the length of New Britain and across southern New Ireland. They occur most commonly to the east of southern New Ireland, and the zone continues from there along the west coast of Bougainville. Scattered epicentres occur in the Bismarck Sea to the south-west of New Hanover, and along the main range and off the east coast of Bougainville.

The most widely felt earthquakes in the region are generally those of intermediate focus. Thus the earthquake of 24th March 1962, which occurred in the Bismarck Range (5.7°S. 145.0°E) at a depth of 111 kilometres, was felt as far away as Port Moresby. It was evidently of great magnitude since intensities as high as 7-8 (M.M.) were reported, although lower intensity was reported in the epicentral area. See figure 6 showing isoseimals for the 24th March 1962 earthquake.

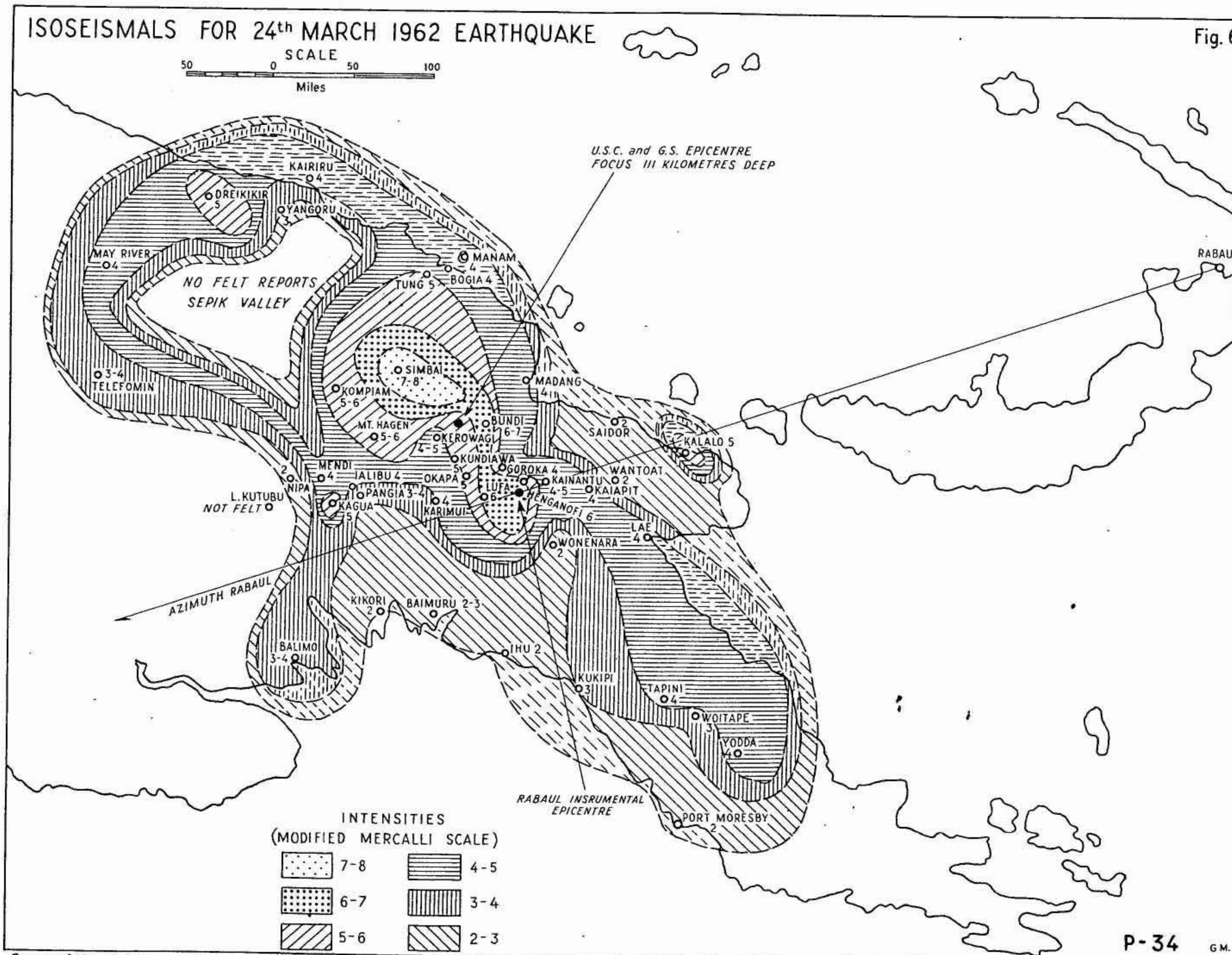
Intermediate earthquakes, and to a lesser extent, shallow earthquakes, occurring in the area 7°S. 156°E., to the south of Bougainville, are often felt at Rabaul, more than 300 miles away+. In a similar way, elongation of isoseismals parallel to the regional structure occurs throughout the E. New Guinea area. As in the case of deep earthquakes, isoseismals are characteristically hard to draw.

Earthquakes in this depth range may cause damage if they are of sufficient magnitude. Minor damage has been reported from Simbai, Bundi, Tari, Angoram and Namatanai, due to earthquakes originating at depths of about 100 kilometres.

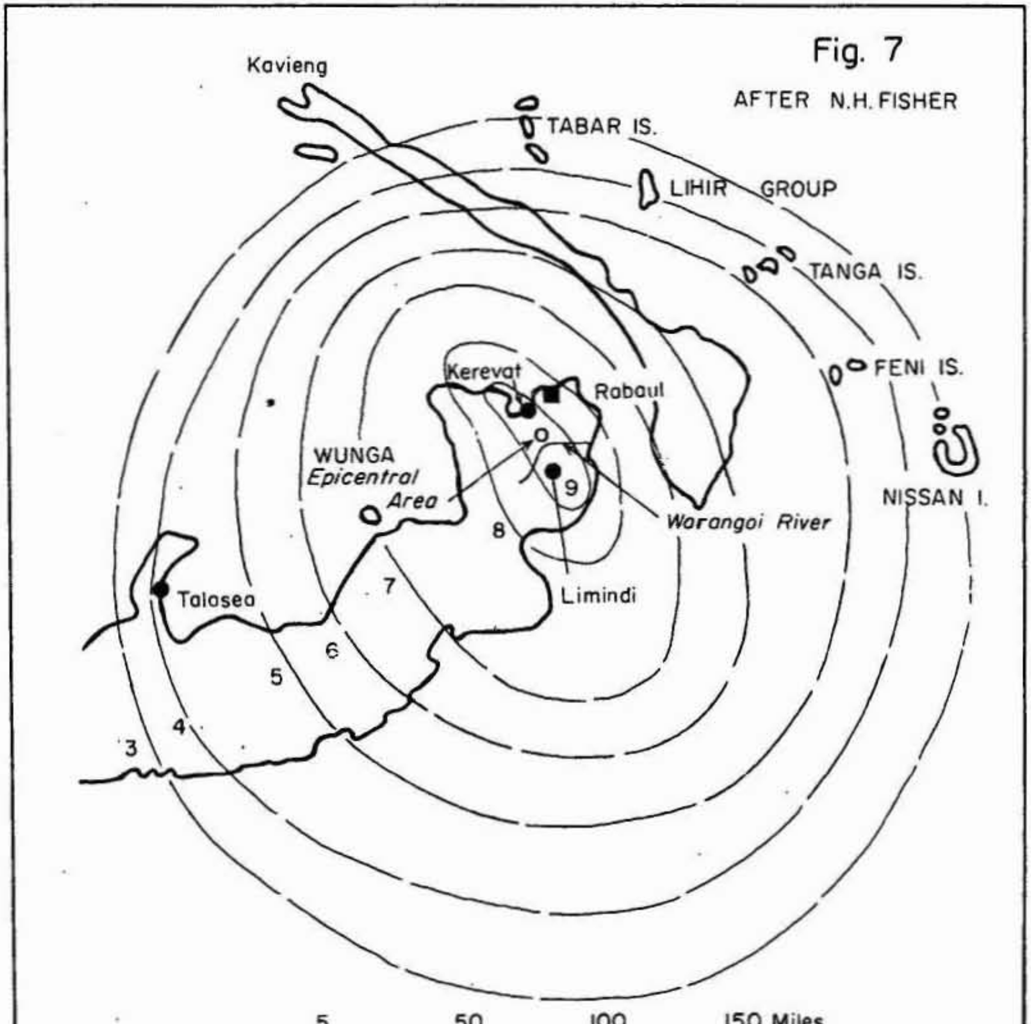
See Plate 3, which depicts a felt earthquake of probable intermediate focus.

+ 12th November, 1958. 7°S 156°E. h about 100 kms. felt Rabaul Int. 1 (M.M.)

26th March, 1959. 7°S. 155½°E. h about 60 kms. felt Rabaul Int. 1 (M.M.)



Bureau of Mineral Resources, Geology and Geophysics, September 1963. To accompany Record 1966/19



ISOSEISMALS FOR 14th JAN. 1941 EARTHQUAKE
(Intensities Rossi - Forel Scale)

Bureau of Mineral Resources, Geology and Geophysics, October 1963. To accompany Record 1966/19 P/33

(c) Shallow Felt Earthquakes

The majority of earthquakes identified as shallow (foci at depths of less than 70 kilometres) are felt near their point of origin. From June 1955 to the end of 1962, 162 shallow earthquakes are known to have occurred in the region, and felt reports were received for 101 of them. During the period covered by more accurate depth determinations (27th July 1960 to the end of 1962) 147 shallow earthquakes were identified, of which a total of 86 were reported felt. (See Appendix C).

The zone of shallow earthquakes follows that of the intermediate ones east from the Sepik to the Ramu valley. Thence it reappears at the coast in Astrolabe Bay and passes east from Madang to the south-west end of New Britain, where it divides near Kandrian+, one arc swinging to the south-east and one crossing the Whiteman Ranges to the north coast near Talasea. Shallow earthquakes are frequent in Central North New Britain (the Nakanai and Pomio areas). Towards the south-west end of the Gazelle Peninsula this zone intersects the zone of shallow earthquakes which extends in a broad sweep from the area of Hollandia, along the north New Guinea coast to the mouth of the Sepik, and thence south of Manus and New Ireland to parallel the west coast of Bougainville. Isolated epicentres occur to the north of New Ireland and to the east of Bougainville, and, on the New Guinea mainland, as far to the south-west as Lake Kutubu and as far to the south as Kokoda. Shallow earthquakes occasionally occur far to the east near Woodlark Island (see Figure 4).

Although direct instrumental evidence is lacking, it is probable that the greatest earthquakes experienced in the New Guinea region (see Chapter 1 section 6), have had shallow foci. As already mentioned, such earthquakes have frequently caused damage and occasionally casualties. By far the best documented instance of what is assumed to have been a shallow focus earthquake is that of January 14th, 1941. See N.H. Fisher (15). This earthquake, which was generally reported as the worst ever experienced in the region, was felt with an intensity of 9 (R.F.) in the epicentral area about Wunga Village, 21 miles south-south-west of Rabaul. Damage was extensive in villages near the epicentre and huge landslides occurred damming up river valleys. Water, mud and sand were ejected from cracks and fissures on the coast near Keravat and not water was brought up in the Kabaira area at the north-east corner of Ataliklikun Bay. Evidence collected by Dr. Fisher suggested that movement had taken place on a fault system running from Ataliklikun Bay through the Warangoi valley with downthrow to the south-west.

The shallow focus earthquakes most commonly felt in Rabaul originate in the Open Bay/Wide Bay area of New Britain or to the south of Jacquinot Bay, to the west of the Gazelle Peninsula, or in the area of Southern New Ireland. The very large earthquakes at very shallow focus (15 to 25 kms), which commonly occur in the Bismarck Sea are rarely felt in Rabaul or Kavieng. Seismograms show that these earthquakes have usually long period surface waves with amplitudes characteristically greater than the P and S waves. This fact probably accounts for the rarity with which they are reported felt, since, although human beings begin to notice shaking when the acceleration approaches 1 gal. (1 $cm/sec.^2$), perceptibility decreases as the period of the shaking increases.

Isoseismals for shallow earthquakes usually show elongation parallel to the regional structure, but to a lesser extent than those for intermediate or deep earthquakes (see Figure 7, reproduced from N.H. Fisher (15), depicting isoseismals for the January 14th, 1941, earthquake).

\+ For these localities see Appendix A and Figure 1.

Shallow earthquakes of high magnitude occur most commonly in the Bismarck Sea to the south of Manus Island, and off the north New Guinea coast between Wewak and Aitape. The 20th September 1935 shock near Aitape, as already mentioned, caused damage and many casualties. Two earthquakes of magnitude 7, on 30th July and 1st August 1962, caused seismic sea waves and damage to small boats and native houses on Kairiru Island, and in the Schouten Islands. An earthquake of magnitude 6¼ - 6½ which occurred to the S. of the Manus group on 26th October 1961 disturbed standing water on Tong Island about 100 miles to the north-east. Its depth of focus of 14 kilometres was the shallowest of all the earthquakes in the region for which a definite depth has been determined, with the exception of an earthquake with a focal depth of 13 kilometres which occurred in the same area on 31st July 1960.

(c) <u>Foreshocks, Aftershocks and Earthquake swarms</u>

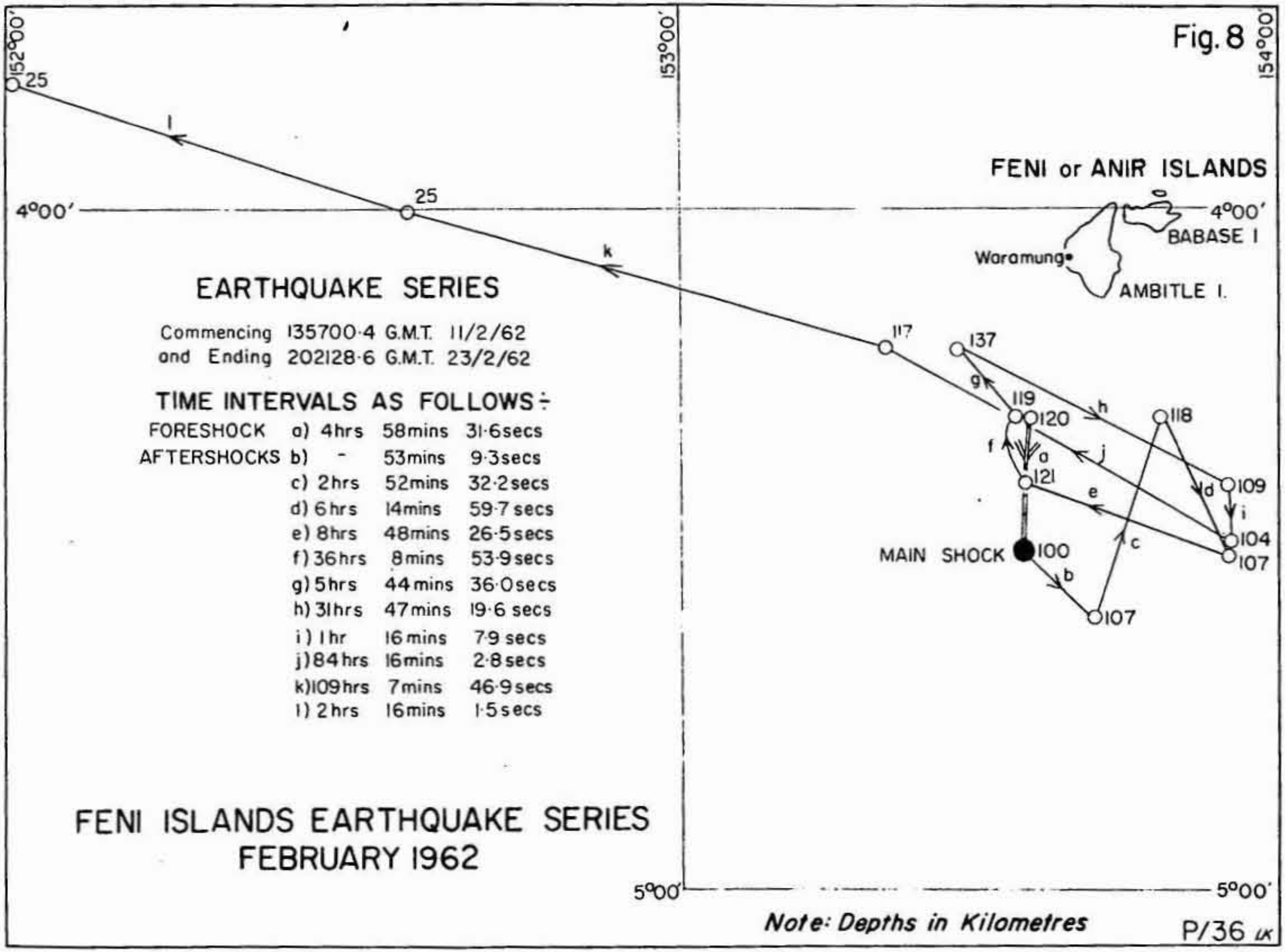
Earthquake swarms of both volcanic and tectonic origin are experienced from time to time in the Rabaul region.+ Multiple events of this kind may be classified under the following headings:-

1. <u>Swarms of Volcanic Tremors which usually precede, accompany and follow volcanic eruption</u>. Unlike the well-known case of the Ischian earthquakes of 1881-1883, there have been no instances at Rabaul of volcanic earthquakes which have not been directly connected with an eruption. In the Talasea area, on Willaumez Peninsula, Central New Britain, however, tremors of apparent volcanic origin are frequently reported. These are characteristically felt at intensities up to 5 (M.M.) at Lagenda, Volupai and Talasea, but not at neighbouring localities such as Walindi, Numundo or Cape Hoskins. The Willaumez Peninsula comprises a number of dormant volcanic centres, one of which, in Lake Dakataua, is known to have been active during the last century. Numerous hot springs, mud-pools and geysers are found in the Talasea-Lagenda-Volupai area and nearby at Pangalu village, and it is probable that the tremors occur in underground magma chambers related to these thermal areas. Swarm tremors of possible volcanic origin have been reported from Esa'ala in the D'Entrecasteaux Islands off the S.E. end of Papua. These so far have had no apparent effect on dormant Recent volcanic centres in the vicinity - See M.A. Reynolds and G.A. Taylor (44, 45, 53). A short series of small shocks which were felt over a 10 minute period at Vunadidir, near Rabaul, on 4th January 1961, (Intensities up to 2 (M.M.)), may have been of volcanic origin since they were not recorded on the Rabaul seismograms. Similarly tremors which are not recorded at Rabaul are sometimes reported felt at Taliligap.

2. <u>Fore shocks and Aftershocks related to a principal earthquake, usually of high magnitude</u>. Large earthquakes in the region are commonly followed by aftershocks, many of which may be felt at intensities up to about 5 (M.M.). Less commonly they are preceded by foreshocks. An example of a series of this kind are the earthquakes of 11th to 19th February 1962, in the Feni Island area to the east of southern New Ireland, (see Figure 8). The principal earthquake of Magnitude 6 was preceded by one foreshock which was felt at intensity 4-5 (M.M.) at Keravat. 8 aftershocks were felt up to intensity 4-5 (M.M.) at Rabaul. Numerous others were recorded but not felt. The series ended with two more distant aftershocks on 23rd February about 100 miles to the north-west.

   The great earthquake of January 14th (L.M.T.) 1941 was followed in the next 24 hours by well over 200 aftershocks, and aftershocks continued to occur for more than a month after the event.

\+ See Appendix D



Bureau of Mineral Resources, Geology and Geophysics, October 1963 To accompany Record No 1966/19

A swarm of tectonic earthquakes, felt at intensities up to 5 (M.M.) in Rabaul, occurred between 16th and 23rd August 1957. Early epicentres lay to the east of southern New Ireland, later ones from an eastern extension of the Warangoi-Keravat fault line, and the series was terminated by a major earthquake at 6°S. 154½°E (Mag. 6½).

From time to time swarms of very small earthquakes with sharp P and S groups and S-P intervals of from 1½ to 6 seconds are recorded at Rabaul. Such earthquakes appeared frequently on the records between November 1957 and March 1958. A short-lived swarm of similar small tremors occurred on 26th May 1959 and others were recorded during January 1960. (See Appendix I). The writer believes that these are small tectonic tremors originating from 8 to 30 miles from Rabaul. Some may be deep focus earthquakes directly under the Rabaul Caldera, but there is no direct evidence in support of this conclusion other than the sometimes poor development of surface waves on the records. The tremors are quite distinct from the more frequent "anomalous" emergent swarm tremors which are discussed fully in Chapter 3, section 3.

3. Pairs of Earthquakes of approximately the same magnitude.
Richter (46) in his Elementary Seismology mentions New Britain as one of the areas which "habitually produce complex earthquakes at a relatively high level of magnitude". Many interesting cases of this phenomenon occur. For example, on 4th July 1956 an earthquake at 5°S. 153°E. was followed 12 minutes later by one at 5°S. 152°E. Both were felt at Rabaul (Intensities 3 and 1-2 (M.M.) respectively). On 4th July 1957, 2 earthquakes occurred at 5°S. 152°E. separated by 24 minutes. Both shocks were felt at Pomio (Intensity 4 (M.M.)) and at Rabaul (Intensity 2 (M.M.)). They were followed by aftershocks. On 18th January 1962 a pair of earthquakes occurred separated by only 3 minutes with different depths at epicentres given as 5.3°S. 153.7°E. and 4.2°S. 153.6°E. (See Appendix D).

(d) Visible Effects of Faulting

Apart from effects due to shaking (damage to watertanks slumping, landslides etc.), cases are also known from the district of effects due to earthquakes which are probably the direct surface expression of faulting.

Under this heading may be grouped the opening of cracks and fissures in the ground, changes of level, and those cases of severe tilting which have definitely been linked with earthquakes.

The following instances may be quoted:-
(for changes of level see Chapter 1, Section 7)

(1) In 1936 subsidence took place near the head of Korsagi Creek in the south-east Baining Ranges on a low ridge 1200 to 1500 feet above sea level, some 2½ miles west-south-west from Ramasaka village and 16 miles south of the most southerly part of Ataliklikun Bay. The area was investigated by Dr. N.H. Fisher+ in October 1937. He found that subsidence was taking place on a fracture or a series of fractures striking north-west to north-north-west and apparently dipping steeply to the north-east (downthrow side). The area involved was 45.8 acres, the length approximately 800 metres and the width 220 metres. It was first observed in November 1936 and probably commenced the previous month in the north-west corner of the area, whence subsidence preceded south-east at a rate of approximately 100 metres per month. Maximum displacement was about 100 feet. Dr. Fisher concluded that the subsidence was due to local adjustment brought about by faulting along a general south-east/north-west direction, with solution cavities in underlying

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\+ N.H. Fisher (16, 17).

limestone assisting the collapse of overlying strata. Dr. Fisher pointed out that the area was directly on a line joining Rabaul and the Father Volcano with direction of fracturing at right angles to this line and parallel to a direction of weakness traversing Rabaul Harbour.

(2) Immediately prior to the eruption of Vulcan on 29th May 1937 cracks appeared in the ground on Matupi Island in a direction trending towards Vulcan Island. They were inspected by Administration officers on the afternoon of the eruption. They were undoubtedly due to the severe volcanic earthquakes of 28th and 29th May.

(3) Actual rupture of conglomerate, shales and sandstones took place (see N.H. Fisher (15)), during the earthquake of January 14th 1941 in the Baining region. Close to the probable epicentre an area of 400 by 500 yards on the side of a small valley slipped across a tributary of the Undal River, leaving a steep rock face at one end about 300 feet high. No other direct surface expression of faulting was found, but subsidence took place around the shore of Ataliklikun Bay, supporting the idea of downthrow to the west.

Tilting[+] at the rate of about 1 second a day was recorded upward to the west-south-west at Rabaul Observatory for about a month prior to this earthquake. This ceased immediately after the shock and for a fortnight (during most of the aftershocks) the tilt was upwards to the north with practically no movement on the east-west component (a condition which was also shown some months prior to the earthquake). (N.H. Fisher (15)).

(4) 1536 hours G.M.T. 15th June 1955 - Following an earthquake to the east-north-east at 3°S. 153°E (h = 100 kms.), which was felt at intensity 2-3 (M.M.) in Rabaul, south-east/north-west trending fissures appeared in Kamerere Street, Rabaul. The earthquake was felt more strongly (Intensity 4) at Warangoi Plantation than in Rabaul.

(e) Seaquakes

Seaquakes, or earthquakes felt at sea, are occasionally reported from the New Guinea region. They are noticed only in the case of high magnitude shocks, since otherwise insufficient energy is transmitted into the water as elastic waves from the underlying rock. They have been reported for earthquakes in the Bismarck Sea near Manus Island and in the Schouten Islands, and at least one has been reported for the Rabaul area, (the earthquake of 9th September 1950 near the Duke of York Islands was felt as a sharp bump on board one of the Administration vessels which was returning to Rabaul at the time).

(f) Periodicity of Earthquakes

A rough periodicity is evident in earthquakes in the region. Monthly numbers of U.S.C. and G.S.[++] and B.C.I.S. epicentres[++] have over the past three years shown a peak in the early part of the year. This tendency is not, however, brought out in the 1955-1959 period (for which the evidence is not so good). Earthquakes in the Rabaul area tend to be more numerous during the "north-west" or rainy season than during the

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\+ During the last 10 days of October 1960 a similar tilt, amounting to a dip of 8 seconds to the east, was recorded at the Rabaul Observatory. This trend continued more slowly in November, reaching a total of 10 seconds (or a third of the tilt recorded in 1941) by the end of the month. It then returned to normal. It is possible that the reversal of this trend was related to the earthquake of Magnitude 6¼ which took place near the Weitin River fault zone in southern New Ireland at 0450 hrs.G.M.T. on 24th November 1960. (See Appendix B, Intermediate Felt Earthquakes)

++ United States Coast and Geodetic Survey, Bureau Central International de Seismologie.

normally drier "south-east" season (See Figures 9, 10). +

A similar tendency has been noticed in California where minor earthquake activity often increases towards the end of the year, about the beginning of the rainy season. It has been attributed to the shifting of large air masses and the consequent change of load on the earth's surface. This may also be true in part for the New Guinea area, where the effect is probably accentuated by increase in weight of ground water beneath the surface.

Figures 11, 12, illustrate earthquake frequency in the area as related to lunar and solar periodicities. It is evident that a poor correlation exists between earthquake frequency and the periods of new and full moon, particularly close to the equinox. The eight most distinct peaks on the figures are as follows:-

Peak	Lunar Correlation	Solar Correlation
August, 1957	2 days after Full Moon	1 month before spring equinox
April, 1958	2 days before Full Moon	2 weeks after autumnal equinox
May, 1959	5 days before New Moon	1 month before winter solstice
February, 1960	2 days after Full Moon	1½ months before autumnal equinox
March, 1961	Full Moon	1 week before autumnal equinox
February, 1962	New Moon	5½ weeks before autumnal equinox
May, 1962	Full Moon	1 month before winter solstice
December, 1962	Full Moon	10 days before summer solstice

See Appendices E and F for a thorough correlation of earthquake frequency maxima with lunar periodicity and for a probability table covering these correlations.

From these appendices (see particularly last column of the probability table), it is apparent that the new moon was the most favourable phase for earthquake frequency in the region over the period 1957 to 1962. Other phases of above average favourability are listed. It will be seen that the full moon, the last quarter and the phase moon minus two days together came second to the new moon in favourability over the period, while the first quarter ranked no more than fifth in the order of favourability. This result supports Davison's conclusions to some extent (9, 10) viz. "if the earthquakes are due to movements connected with the elevation of the crust we should expect the maximum of the 29.6 day period to coincide with new moon and those of the 14.8 day period with new and full moon. If they are caused by the depression of the crust the maxima of the 29.6 day period should coincide with full moon and those of the 14.8 day period with the first and last quarter."

Evidently no simple relationship exists in the New Guinea area between frequency of earthquakes and lunar periodicity, and in all probability earthquakes in the region are triggered both by depression and by elevation of the crust by tidal forces. Mr. G.A. Taylor's highly successful correlations of volcanic eruption with lunar and solar periodicities (56),

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\+ Figures 9 and 10 should be treated with caution. The curve for Energy Release is based on the numbers of earthquakes of given magnitude (before 1963 this means, less than magnitude 5½). It is purely qualitative and is only designed to give an impression of monthly seismicity.
The "curves" for Progression were drawn by linking earthquakes, which it is considered could have been genetically related, in the order in which they occurred. No conclusions are drawn.

show that a delicate state of equilibrium often exists between the opposing forces of upsurge of magma and the confining pressure of the crustal rocks. He has shown that minor changes in the strength or direction of the earth tides may upset this equilibrium and trigger volcanic eruption. It is probable that in a similar way rocks that have accumulated strain due to fundamental tectonic processes such as mountain building may reach a state of delicate equilibrium in which the small extra stress due to the action of earth tides may trigger an earthquake and relieve all or part of the accumulated strain. Where the restraining pressures are not great or when the accumulation of strain proceeds rapidly rocks will tend to succumb to the deforming forces and an earthquake will result before the maximum of force is exerted by the earth tides. When strain accumulates very rapidly, as must often be the case in a tectonic area as active as New Guinea, fracture will occur with resulting earthquakes without regard to lunar or solar periodicities.

An attempt is made in Chapter 5, section 2, to apply results of this thinking to earthquakes in different areas in the East New Guinea region.

A complete statistical study would be necessary to determine how far lunar and solar periodicities affect the overall picture of earthquake frequency in the region, and to what extent their effects may be cancelled out by purely tectonic processes.

The matter is bound up with the whole subject of progression of earthquakes from one area to another, and the rapidity with which this progression takes place. This study is hampered by the lack of sufficient magnitude determinations for earthquakes in the region. Thus energy release can only be roughly estimated at present. Events are set down in figures 9 and 10 which illustrate, in a generalised way, energy release, progression and monthly periodicity in regional New Guinea earthquakes for the period October 1955 to February 1963.

A fuller discussion of the few conclusions which can safely be drawn at this stage is reserved for Chapter 5 section 2.

An attempt has been made to determine whether any particular time of day is favourable to the occurrence of earthquakes in New Guinea (see figure 13). The times of occurrence of earthquakes are plotted in periods of 12 minutes throughout the day and the resulting curve is smoothed by averaging each total with the adjoining two. A total of 764 earthquakes with known epicentres in, or felt in, the Territory of Papua and New Guinea during the period 1957 to 1962 was used in compilation of the diagram. For those whith reported epicentres origin times were used, while for those felt in the Territory P-arrival times at Rabaul were used.

Results indicate that there is little if any correlation between time of day and the occurrence of earthquakes. The most disturbed period appears to be between sunrise and midnight with minor peaks of earthquake frequency around 1700 hours (L.M.T.) (0700 hours G.M.T.), and between 2030 and 2230 hours (L.M.T.) (1030 -1230 hours G.M.T.). The period between midnight and sunrise appears to be rather less favourable to occurrence of earthquakes. It is not considered that the evidence warrants drawing any conclusions regarding diurnal periodicity at this stage.

2. NEAR EARTHQUAKES CHARACTERISTICALLY NOT FELT

a. General: For the purposes of this paper earthquakes referred to as "near" are those whose epicentres lie at an angular distance of not more that 12° (= 12°) from Rabaul. The area considered thus extends from a little beyond the international boundary with West New Guinea through the Territory of Papua and New Guinea to include the greater part of the western and central British Solomon Islands Protectorate.

It is generally considered that small earthquakes, or those which are characteristically not felt, originate in the same way and from the same causes as earthquakes of greater magnitude. That is to say, they are caused by the yielding of large masses of rock under accumulated strain, due primarily to fundamental tectonic processes. At depths near 100 kilometres rocks should yield by plastic flow rather than by fracture, but the evidence indicates that intermediate and deep earthquakes are, like most shallow earthquakes, due to compressional shearing fracture. Richter (46) suggests that this apparent anomaly is due to the fact that, although slowly accumulating strains will be relieved by flow before they can arrive at fracture, more rapidly accumulating strains may progress until fracture is reached.

Near earthquakes are recognised on the Rabaul seismograms by their characteristically sharp P and S groups & short wave periods. Until the installation of long period instruments in February 1962, the S phase was seldom recognisable on the seismograms except in the case of very small earthquakes. The old short period Benioff seismograph generally recorded a sharp P phase (sometimes preceded by an emergent P phase +) after which the movement of the light spot would become so rapid that its trace failed to record on the film. The strong motion Omori Seismograph rarely recorded any local earthquakes except those at or near the level of perceptibility ++. Thus for a large proportion of the earthquakes recorded, the only data which could be derived from the records was the nature and time of the first P arrival.

The improvements to the instrumentation at the Rabaul Observatory in February 1962, and particularly the installation of the 3-component long period Vela Standard equipment, have enabled the times of most S arrivals to be read. The chances of deriving reliable local epicentres are thus greatly improved.

Up to the present time no consistent work has been done on recording wave periods or arrival times of phases other than the P, S and L waves +++. The direction of first arrivals is generally noted.

\+ The aftershocks of the major earthquake on 10th October 1955 had unusually long-period beginnings. They were quite unlike the usual Rabaul near earthquakes.

++ Teleseisms are never recorded on the Omori seismograph unless they are of exceptional magnitude. A notable case was that of the great Assam earthquake of 142002 hours G.M.T. on 15th August 1950, which recorded on the Omori for more than 80 minutes with surface waves of remarkable amplitude and exceptionally long period.

+++ Phases that approximately fit arrival times for PcP and Scs are occasionally recorded at Rabaul at epicentral distances ranging from 1 to 5 degrees.

136 earthquakes of known epicentre in the Territory of Papua and New Guinea, for which directions of first movement at Rabaul have been recorded, are listed in Appendix G, and are plotted geographically in Figure 14. It was hoped that a study along these lines might indicate the degree of continuity in sense of faulting in any particular area. Figure 14 however shows largely random distribution of epicentres for which initial compressions and dilatations have been recorded, and this probably indicates that few areas consistently produce a single type of earthquake. The available evidence is very incomplete, and does not warrant drawing any conclusions at present. It is interesting to note however, that all epicentres in the Wide Bay area to the south-east of the Gazelle Peninsula have up to now recorded with initial dilatations at Rabaul, as have the majority of deep focus earthquakes in the Bougainville - New Ireland - New Britain area for which directions of first movement have been recorded.

Travel times and depths of discontinuities are not accurately known for the Rabaul area: thus identification of $\overline{P}$, P^{+} and Pn and the corresponding S phases is not made as a matter of routine. However sharp initial P phases, at epicentral distances less than about 120 kilometres, are probably to be classes as direct P waves, while the emergent long-period P, which is commonly recorded at epicentral distances of about 200 to 300 kilometres, is almost certainly Pn (the P phase refracted under the Mohorovicivc discontinuity). This latter is commonly followed by a sharper impulse of greater amplitude and shorter period which is probably $\overline{P}$, the direct wave through the crust which is also known as Pg or P_1. A false S phase, arriving earlier than the true S, is sometimes recorded at Rabaul.

Sharp arrivals in the P and S groups which are regarded at Rabaul as reflected phases are very commonly recorded. Typically they do not fit standard travel time tables (Jeffreys and Bullen, Eiby and Muir). This matter is discussed in Chapter 3, section 3, in connection with the "anomalous" class of small local tremors. Explosions in the caldera area at Rabaul characteristically show apparent reflected phases also.

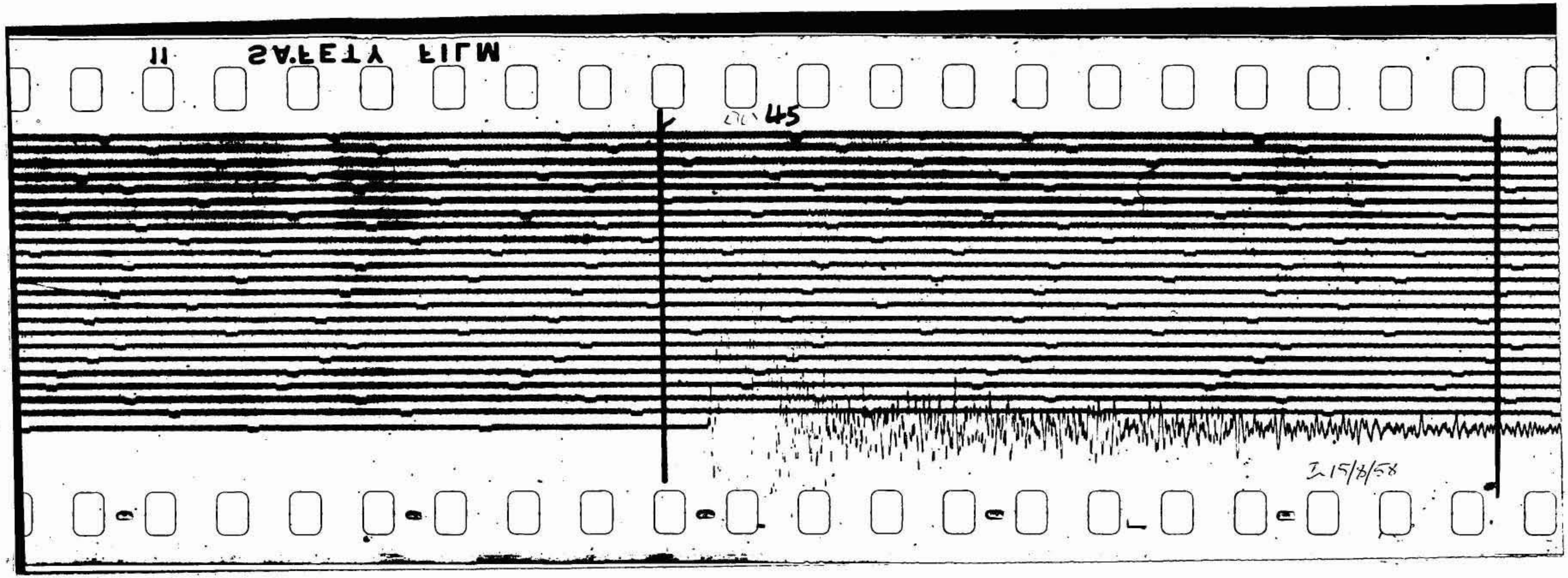
b. <u>Deep Earthquakes</u>: A total of thirteen earthquakes of known deep focus which were not reported felt, occurred in East New Guinea between June 1955 and February 1963++. They are listed, as follows:-

Date	G.M.T. Origin Time	G.M.T. Arrival (P)	Epicentre	Depth (Kms)	Magnitude	Direction of first Movement	Remarks
8.12.55	173600	173654	4°S.152°E.	500	-	Comp.	Phase on Omori at P+43½"
15/9/56	103309	?	4°S.151°E.	400	7 - 7¼	-	
15/8/57	204520	:204631½	4½°S.155°E.	500	-	Dil.to E.S.E.	
26/2/58	001756	:001841	3°S.152½°E.	300	-	Dil. to E.S.E.	
1/6/59	053130	:053230	4°S.153°E.	400	-	-	impulse on Benioff at 053313.Followed by deep earthquake at 6°S.154°E.Felt
25/2/60	205605	205703.0	7°S.154°E.	300	-	-	
15/10/60	121203.0	121337.9	7.7°S.157.5°E.	366	-	-	Western B.S.I.P.
21/11/60	042954.7	:042954.0	3.4°S.152.3°E.	371	-	-	Followed by deep earthquake, felt, 2 days later
6/2/61	192933.2	:193028.2	4.8°S.154.2°E.	470	-	Dil.to S.E.	Phase on Omori at P+44"
2/3/61	110110.6	:110209.1	3.9°S.154.5°E	407	-	Dil.to N.E.	Greatest amplitude (Omori on EW component
1/12/61	065510.9	065554.8	3.9°S.152.5°E	342	-	Comp	
21/4/62	142144.9	142221.5	4.4°S.151.2°E.	334	-	Dil	
27/8/62	055910.4	0600(12½)	5.7°S.154.9°E.	370	-	-	

+ Phases that approximately fit arrival times for PcP and Scs are occasionally recorded at Rabaul at epicentral distances ranging from 1 to 5 degrees.

++ A further 5 earthquakes of known deep focus were felt in the region over this period. They are listed in Chapter 2, section 1.

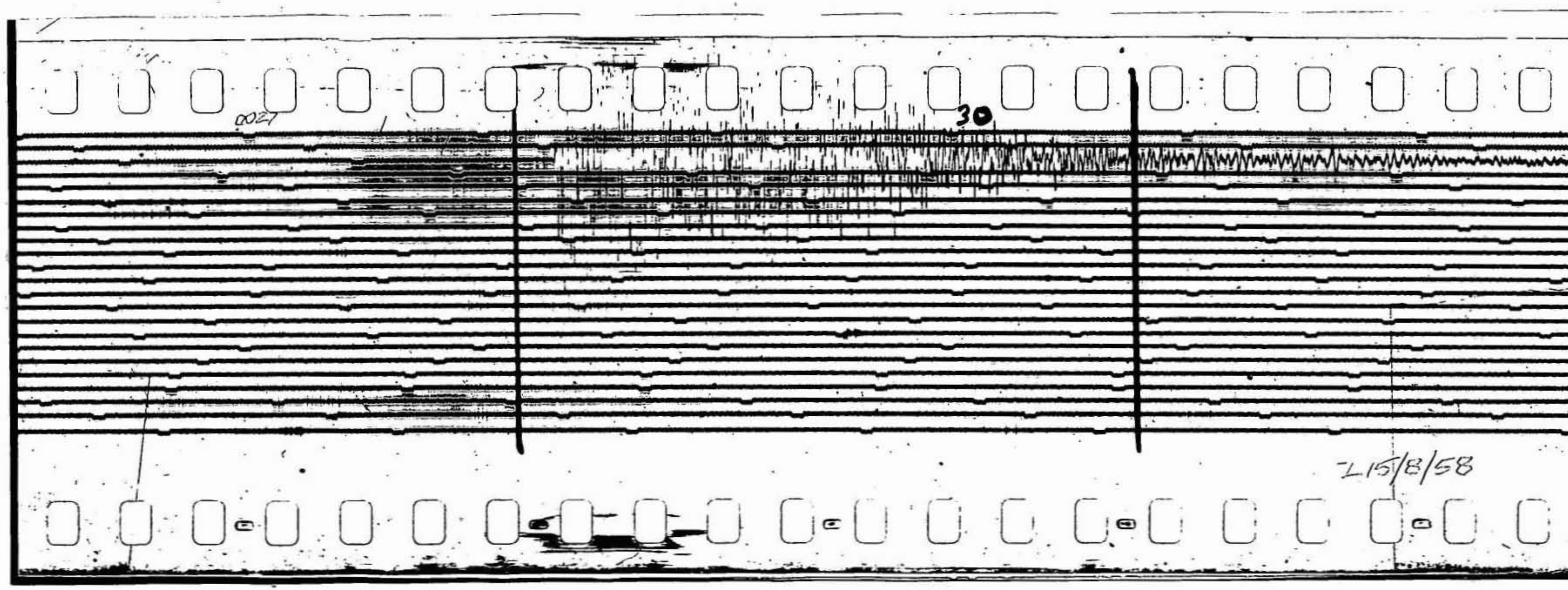
PLATE 1.



Rabaul Observatory

Old Benioff Seismograph record 15/8/58 (Times G.M.T.). Epicentre not reported. Unusual shock at 2234, felt Rabaul Intensity 3 (M.M.). Appearance suggests deep focus (relative preponderance of P and S group over L waves). Note vehicle interference on Observatory Road at 0841.

PLATE 2.



Rabaul Observatory

Old Benioff Seismograph record 15/8/58. 0227 Central New Britain Earthquake; epicentre 6°S, 150½°E, Felt Walindi (Int.4 (M.M.), Felt Rabaul (Int. 3 (M.M.) etc. $\Delta = 2^{\circ}30'$. Note vehicle interference at 1524 hours, and 2217 hours.

The distribution of these deep earthquakes, together with those that have been reported felt, follows a broad arc from the area of the islands north of central New Ireland and the Bismarck Sea, west of the Gazelle Peninsula and across southern New Ireland to Bougainville and the western Solomon Islands. At its widest point, the Bougainville area, the zone is about 200 miles across. The evidence of the far greater number of intermediate and shallow focus earthquakes which occur in the same area indicates that relief of strain by earthquake rarely takes place at depths exceeding 300 kilometres. As already mentioned, this may be due to the fact that at such depths rocks yield by plastic flow unless rapid accumulation of strain takes place.

Evidence on the mechanism of deep earthquakes in the region is lacking at present, but the similarity in tectonic environment between New Guinea and Indonesia suggests that earthquake mechanism may also be similar in the two regions. Ritsema (47) has found that, although strike slip commonly occurs in shallow earthquakes in Indonesia, deep earthquakes are commonly accompanied by dip slip. The regional structural problem is discussed briefly in Chapter 5, section 3.

Small earthquakes which are believed to have occurred at deep focus are recorded from time to time at Rabaul. They are characterised by short-period sharp P and S onsets with no distinct phases in between. The amplitude of the P waves sometimes exceeds that of the S waves. Surface waves are very poorly recorded.

Plate 1 shows an example of an earthquake of probable deep focus recorded on the vertical component of the Benioff Seismograph.

Plate 1 on page 38.

(c) Intermediate Earthquakes: The majority of earthquakes recorded on the Rabaul seismograms are probably intermediate in depth. Those for which epicentres have been calculated lie in the main inland earthquake zone paralleling the north coast of New Guinea, and in the arcuate continuation of this zone along the line of New Britain, Southern New Ireland and Bougainville. Probably the majority of intermediate earthquakes recorded at Rabaul originate in the zone stretching from Wide Bay to Open Bay across the South end of the Gazelle Peninsula and in the area of the "nose" of the earthquake zone, to the east of southern New Ireland, (See Figure 4).

Intermediate focus earthquakes on the records are characterised by sharp P and S phases, often with indeterminate phases in between, and no strong development of surface waves.

Plate 2 illustrates an earthquake of known epicentre but unknown depth which probably lies in the Intermediate depth range. The earthquake, which was felt widely in New Britain, occurred between the Nakanai and Whiteman Ranges in the central part of the island. Note the sharpness of phases and the comparatively poor development of surface waves.

Earthquakes originating at distances over 150 kilometres from Rabaul generally show an emergent P phase (Pn) followed by a sharp short period phase ($\overline{P}$). This feature, which is illustrated in Plate 2, is common to earthquakes in the intermediate and shallow focus range.

Plate 2 opposite this page.

(d) Shallow Earthquakes: Shallow earthquakes, which are recorded almost as frequently as intermediate earthquakes on the Rabaul seismograms, are characterised by comparatively strong development of surface waves.

They occur in the same zones as the Intermediate earthquakes, and further south off the coast of Central New Britain. In addition, however, there is a marked development of shallow earthquakes in a zone that diverges from the zone of mainland New Guinea shocks near Wewak and passes across the Bismarck Sea to the south of Manus and New Ireland.

These Bismarck Sea earthquakes give rise to surface waves of unusually long period and high amplitudes. They are frequently of great magnitude and have caused damage in the vicinity of Wewak and the Schouten Islands. Commonly, however, shocks of about Magnitude 6 occur in the area which are not reported felt+.

Plate 3 illustrates an earthquake of this type which was felt at Tong Island and Lorengau in the Manus Group on 26th October 1961 at 0039 hours G.M.T.

All Bismarck Sea earthquakes of known epicentre, excluding those of Intermediate focus from the area 3½°S. 149½°E., are listed in Appendix H. Numerous earthquakes, having the same characteristics, have been recorded at Rabaul, for which no epicentres have been determined. Many of these probably also originated in the Bismarck Sea.

A study was made of these earthquakes when they were first recorded in June 1957 by J.E. Johnson, who was Assistant Vulcanologist at Rabaul at the time (see J.E. Johnson B.M.R. unpublished notes, October 1957). Since that date no detailed analysis of this class of earthquake has been made (as will be evident from the amount of detail lacking in Appendix H), beyond routine analysis for the Rabaul Provisional Bulletins.

Mr. Johnson raised several interesting points in connection with the 1957 Bismarck Sea earthquakes. He pointed out that they characteristically occurred in groups of two or three separated by intervals ranging from a few minutes to a few hours. He also drew attention to the fact that the P waves are often poorly developed, and to the appearance of a prominent short period phase which may be superimposed on the L waves three to six minutes after the onset of P. Both these features can be distinguished on the seismogram illustrated in Plate 3.

The short period phase superimposed on the L waves has been identified as a T wave, due to propagation of energy through water. As Mr. Johnson pointed out, the expanse of the Bismarck Sea has affected the recording of the L waves. Similar phases have been recorded at the seismological station at Honiara in the British Solomon Islands from shallow submarine earthquakes (J.C. Grover, personal communication). Several phases of this kind can be distinguished on the record illustrated in Plate 3.

The calculated arrival times have been found to agree very closely with measured arrival times at Rabaul. A strong emergent phase which looks like the onset of the L waves is commonly found to agree closely with the calculated arrival time for S. Surface reflexions such as SSS are sometimes recorded. Duration of this class of tremor on the records is sometimes unusually long.

(e) Minor Swarm Earthquakes of Tectonic origin: In addition to the swarm earthquakes discussed in section 1 of this chapter and listed in Appendix D, swarms of microearthquakes are recorded from time to time on the Rabaul seismograms. Appendix I is a compilation of all earthquakes which were listed on the Rabaul work-sheets between March 1955 and February 1963 with S-P intervals of 10 seconds or less. The majority will be seen to have occurred in the second half of 1957. This distribution is biased by the fact that Messrs. J.E. Johnson and M.A. Reynolds

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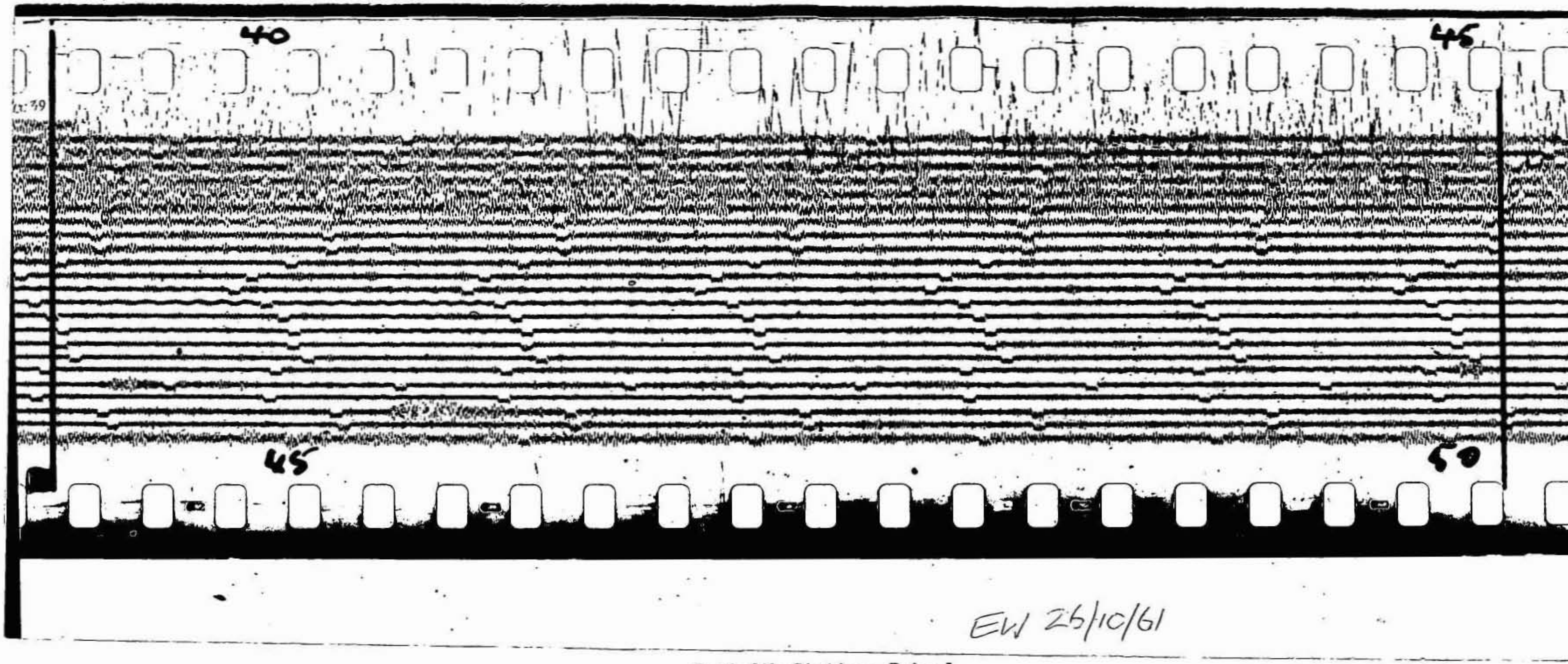
+ For example, the earthquake of Magnitude 6-6¼ which occurred at 000324 G.M.T. on 7th May 1959, at 3½°S 148½°E. This earthquake was preceded by foreshocks on the previous day, and was followed by 2 big aftershocks. None of the series was reported felt.

Plate 3 opposite

PLATE 3.



Rapindik Station, Rabaul.

Old Beinoff Seismograph E.W. Record 26/10/61. Bismarck Sea Earthquake at 0039. Epicentre at 3.1°S, 147.4°E, depth = 14 kilometers. Felt at Tong Island (Int.3 -4 (M.M.)), where it disturbed standing water, and at Lorengan (Int. 3 (M.M.)). Note high level of industrial and vehicle interference at Rapindik.

who were attached to the Rabaul Observatory during this period, recorded such tremors with more diligence than has been shown either before or since. Tremors of small S-P interval were, however, unusually plentiful during 1957: hence the interest that was shown in them.

As will be seen from Appendix I the majority of the recorded tremors have S-P intervals of between 8 and 10 seconds. This puts them at an epicentral distance of between 44 and 55 miles from Rabaul if a near surface focus is assumed for the earthquakes. S-P intervals as small as 1 second have been recorded however, and in February 1961, 2 tremors were recorded with even smaller intervals. Even if one assumes a surface focus for these tremors, their epicentres must have been within 5 miles of the Observatory, and since some of them have the appearance of deep shocks (e.g. an earthquake of S-P = 2.4 sec. on 12th December 1955, and the swarm of small tremors that occurred on 22nd December 1957) their foci probably lay directly under Rabaul.

This matter is discussed more fully in the next section in connection with the "anomalous" emergent tremors that are frequently seen on the records.

In passing it should be mentioned that some of the tremors listed in Appendix I have the appearance of explosions. Where this is so the fact has been noted in the "Remarks" column. These tremors may have been due to explosions of wartime ammunition, although no explosions were reported at the times concerned.

It has been suggested that some of the small tectonic shocks may have been due to slumping of marine sediments on the sea-bed in the vicinity of Rabaul. This has been found to occur in California where the shocks have characteristic long period beginnings, due presumably to a more gradual movement of the unconsolidated sediments than would occur in the case of earthquakes in consolidated rocks. However, the majority of the small tremors recorded at Rabaul have short period beginnings and are very similar in form to larger earthquakes of known tectonic origin, the only differences being the small S-P intervals and the fact that S and L max (M) occur very close together. It is probable that they represent small movements on faults in the Rabaul area. Certain small disturbances with long period beginnings do occur frequently on the records but the writer is of the opinion that they are due to small earthquakes at greater distances from Rabaul than those discussed above, of which only the surface waves are of sufficient amplitude to be recorded.

Mr. G.A. Taylor has on a number of occasions pointed out that the origin of small disturbances of this kind will not be known accurately until the satellite Observatory stations are re-established in the Rabaul Caldera.

3. MICROSEISMS, "ANOMALOUS" MICROEARTHQUAKES, AND OTHER MINOR NATURAL DISTURBANCES

General

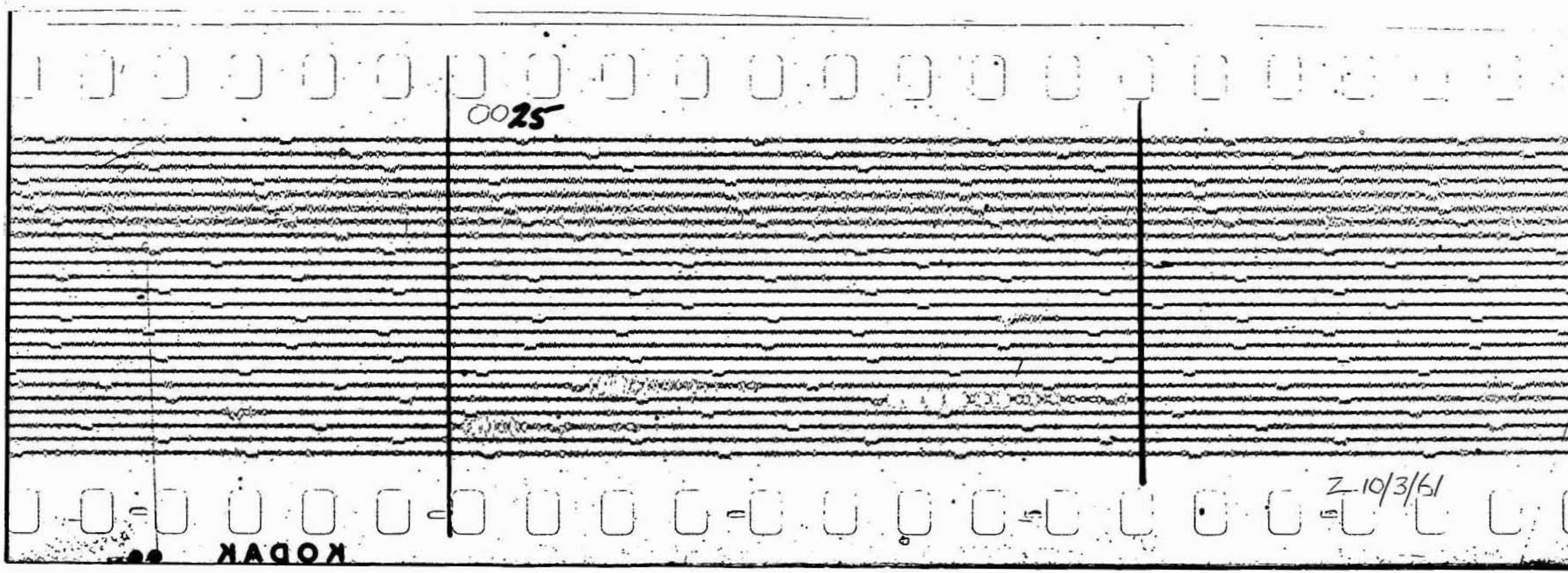
In addition to continuous microseismic activity due mainly to meteorological causes and to the movement of the sea, a number of other small disturbances are recorded from time to time on the Rabaul Seismograms which are not sufficiently similar to known tectonic earthquakes to enable them to be assigned without reservations to the same category. They may be classified under the following headings:-

(a) Volcanic Tremor (b) Microearthquakes with characteristically harmonic+ form, including those with poorly developed harmonic form, and (c) isolated medium to long period pulses and emergent phases. Disturbances of these kinds are discussed separately in this section. Those in classes (b) and (c) are referred to at Rabaul as "Anomalous Swarm Tremors" or respectively class (b) as "Harmonic" and "Semiharmonic" Tremors and class (c) as emergent pulses. They are not to be confused with the

+ The term "harmonic" appears to be used in this context to describe a wave train of almost constant period with a more or less smoothly varying amplitude. - Editor.

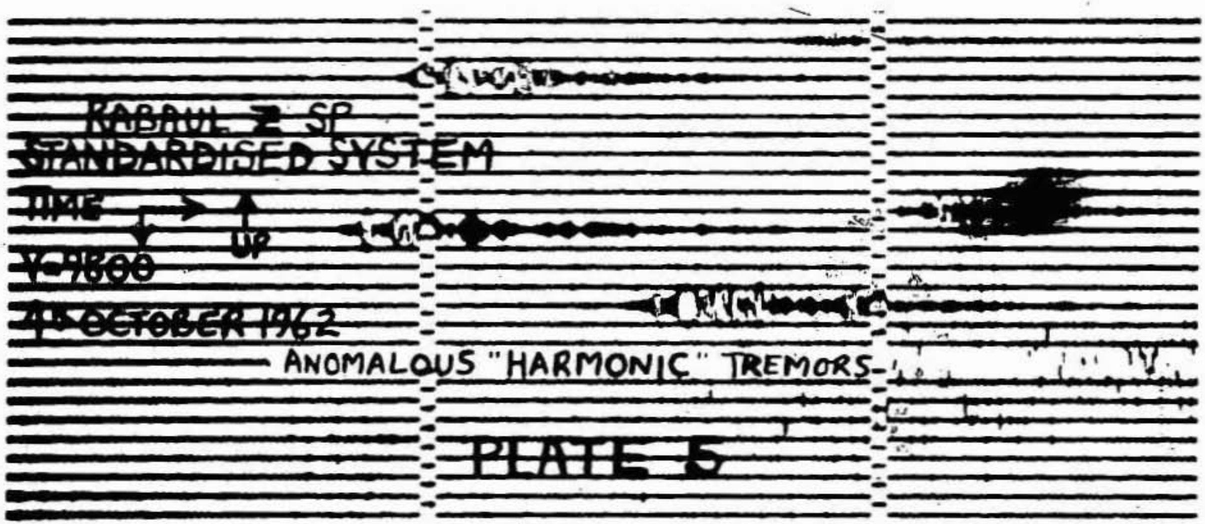
PLATE 4.

"ANOMALOUS" HARMONIC TREMOR 1920 HOURS. G.M.T.



Rabaul Observatory

Old Benioff Seismograph Z Record 10/3/61.


RABAUL Z SP
STANDARDISED SYSTEM
TIME
UP
4th OCTOBER 1962
ANOMALOUS "HARMONIC" TREMORS
PLATE 5

old Benioff Seismograph was calibrated properly for the first time, thus altering the appearance of earthquakes on the records.

It has been suggested that the characteristic harmonic appearance of the tremors may be due to the response of an underdamped seismograph to local tectonic tremors. Before the calibration of the old instruments in December 1955 most tectonic earthquakes recorded in a characteristically harmonic way, although the pattern of the shocks were entirely different to that of the later "anomalous" harmonic tremors. Furthermore interference of industrial origin (see Chapter 4, section 1) was consistently more sinusoidal in appearance than it was after that date. The instruments were in fact definitely underdamped. At present the instruments are considered to be slightly underdamped. The World Wide Standardised short period seismographs are critically damped with the exception of the NS Component (Ratio 100:1 under).

However, the fact that the anomalous shocks are recorded on both sets of short period instruments+, as well as on portable Willmore Seismographs, with a type of signature quite distinct from that of normal tectonic earthquakes, and the fact that their beginnings are almost always emergent while those of tectonic earthquakes are more often sharp, seems to indicate the reality of a class of disturbance that does not conform to the normal type of tectonic earthquake.

Plate 4 illustrates a good example of an "anomalous" tremor of harmonic form. It is of a type described often at Rabaul as "four phase harmonic" on account of the four distinct groups of apparent L waves near the beginning of the signature. Four other, less distinct, groups of phases occur in the coda, and short period low amplitude movement precedes the high amplitude waves.

The tremor depicted in Plate 4 shows a typical onset for this type of shock. Sharp impulses of very low amplitude appear to emerge gradually from the microseismic background in such a way as to make it virtually impossible to identify the arrival time of the wave-train. The onset is, therefore, of the "emergent-impulse" type, ei in seismological parlance, where although the waves have sharp beginnings, it is not possible to pick the exact point at which they emerge from the background impulses. Tremors of less well-defined harmonic form but similar characteristics are referred to at Rabaul as semiharmonic tremors.

Most "anomalous" harmonic tremors at Rabaul have between five and ten indistinct phases which individually lack a smooth outline. Some however, have two distinct smooth groups of maximum amplitude phases: others have three, while a minority have four. A very few have five distinct smooth groups, or as the example in Plate 4, four with up to four more less well-developed groups. Very occasionally a tremor is recorded with only one group of harmonic phases (e.g. 2113 hours G.M.T. 6th May 1961).

The period of the vibrations is normally between ¼ and 1/3 second. However periods greater than 1/3 second and less than ¼ second are not infrequently observed. Occasionally the period of the same vibration differs with different components, being usually shorter on the north-south component of the old Benioff Seismograph than on the vertical or east-west components. Generally the more perfect harmonic form is associated with the vibrations of shorter period (¼ second or less).

Sometimes a tremor may appear harmonic on the vertical component of the old Benioff seismograph while the horizontal components may register little or no harmonic movement. Occasionally the opposite situation is observed.

\+ See Plate 5 for a typical example of the appearance of "anomalous" harmonic swarm tremors on the short period vertical component of the World Wide standardised Seismograph System at Rabaul.

harmonic disturbances of characteristically sinusoidal form which have been found to be due to ships' engines, and which are discussed in Chapter 4, section 1. Microearthquakes without harmonic form and with sharp beginnings are considered as small scale tectonic earthquakes and are discussed in Chapter 3, section 2. They may also be due to explosions in some cases.

(a) Volcanic Tremor:

Continuous oscillations due to volcanic processes such as the rise and fall of magma in the earth's crust are commonly classified throughout the world as volcanic tremor. They may be recorded continuously for periods ranging from a few minutes to several days, and are normally associated with eruptions or impending eruptions. Characteristically, volcanic tremor first appears on seismograms shortly before an eruption, increases in amplitude during eruption and dies away as soon as activity in the crater ceases. Very often the onset of volcanic tremor may coincide with a sharp decrease in the number of felt earthquakes of volcanic origin that normally precede an eruption. Apart from their use as an indication of impending activity, there is some evidence to suggest that the period of the oscillations is related to the viscosity of the magma. Daisuke Shimozuru (51) has found that the predominating period of the vibrations becomes shorter as the viscosity of the magma increases with increasing silica content+.

Although characteristically of shallow origin, volcanic tremor has been noted in Hawaii in connection with swarms of deep earthquakes which are believed to have been related to deep-seated movement of magma: see J.P. Eaton (11).

G.S. Gorshkov (23) has shown that the intensity of the volcanic tremor may reflect the intensity of the eruption that follows.

In the east New Guinea region volcanic tremor has been recorded in connection with eruptions at Manam and Mount Lamington volcanoes (see G.A. Taylor (55, 56)), and at Rabaul in connection with activity at Tavurvur volcano in 1941. Thus continuous vibrations were recorded at the Observation Post near Tavurvur in July 1941, after the eruption of 6th June, 1941. This activity reached a peak over the period July 20th to 23rd and culminated in explosions in the volcano from the 9th to the 11th August, after which seismic activity declined while the eruption became practically continuous. Again, on 23rd November 1941, strong volcanic tremor accompanied explosions at Tavurvur during which bombs were thrown up to one thousand yards from the vent.

No seismographs were installed at Rabaul prior to the 1937 eruption. Therefore it is not known whether volcanic tremor occurred.

(b) "Anomalous" Tremors of Harmonic Form: This extremely important class of tremor on the Rabaul seismograms attracted attention in August 1960, when they first made a strong appearance on the records. They were first recorded in small numbers, in December 1955, and continue to the present time. Their origin is unknown.

They have been recorded both on the old 3 component Benioff Seismograph, on portable Willmore Seismographs and on the short period instruments of the World-Wide Seismograph System. A possible reason for their apparent absence before December 1955 may be that in that month the

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+ From Daisuke Shimozuru (Bull.Volc.Soc.Japan, Feb.1961)

Volcano	Period of Vibrations in Seconds	SiO_2 percentage in magma
KILAUEA	0.5 - 0.7	47
ASO	0.3 - 0.5	53
PARICUTIN	0.1 - 0.2	55 - 59

Between February 1st and May 10th 1961 an attempt was made to locate the origin of these disturbances by use of a portable Willmore Seismograph. Unfortunately only one such instrument was available, and this limited the usefulness of the experiment. Furthermore at that time the World-Wide Standardised Seismograph System had not been installed at Rabaul. In spite of this lack of instrumentation, however, some valuable results were obtained.

It was found that characteristic harmonic tremors on the old Benioff Seismograph at the Observatory did not necessarily appear harmonic when recorded on the Willmore Seismograph at other localities. Conversely harmonic tremors on the Willmore records frequently appeared conspicuously unharmonic on the Benioff records. A diversity of origin was inferred for many of the disturbances on account of the varying response at any one locality to disturbances which were recorded with uniform amplitude at the observatory.

Figures 16-18 represent graphically the results of this experiment. Figure 15 illustrates the frequency of the tremors in relation to numbers of tectonic earthquakes in the Rabaul area, and to lunar and solar periodicities, over the period 10th May 1960 to 10th May 1961. This period was chosen owing to the large numbers of "anomalous" tremors that occurred between August and October 1960, and as being the period at the end of which the most detailed work was carried out. On 11th May 1961 the old Benioff seismograph was removed, cleaned and re-calibrated, while structural alterations were made to the Observatory Vault.

Figure 15 shows that there was no obvious correlation between frequency of earthquakes in the Rabaul area and frequency of "anomalous" tremors over the period. A possible correlation exists between the 1960 solar spring equinox and the sharp peak in "anomalous" tremors at the beginning of October. The increase in the number of tremors began about the time of the August new moon and reached a peak ten days after the September new moon. The correlation is, however, most probably coincidental, since the increases commenced before the August new moon but did not reach a maximum until after the September new moon, when by reason of the equinox the tides were in fact stronger. No peak was observed at the 1961 spring equinox and frequency of "anomalous" tremors remained low until March 1962+.

Figure 16 illustrates diurnal periodicity in the times of occurrence of the "anomalous" tremors over the period 1st February to 10th May 1961. A total of 807 shocks was used in compilation of the diagram. Times of occurrence were grouped into half-hourly periods and the resulting totals were smoothed by averaging them with the totals adjoining on either side of them.

Results indicate no strong correlation between time of day and times of occurrence of the tremors. A preponderance of the shocks occurred at night with a peak shortly after midnight. Although it is not considered that the evidence warrants drawing any conclusions from this apparent frequency relationship, it is interesting to note that it is almost exactly the reverse of the situation for tectonic earthquakes (see Chapter 3, section 1, sub-section g, and Figure 13), where the majority occurred between sunrise and midnight with peaks just before and after sunset.

Figure 17 illustrates period and amplitude of "anomalous" tremors recorded at the Observatory between 1st February and 13th April 1961 on the north-south and east-west horizontal components of the old Benioff seismograph. The radial lines give approximate directions of the disturbances based on the ratio between their amplitudes on the north-south and east-west records. The standard value for these ratios was determined at Rapindik instrument station using a number of horizontal seismometers

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\+ Increase in this month may represent an approximate correlation with the autumnal equinox.

arranged in different orientations to record explosions in the harbour off the north-west end of the airstrip. See Chapter 4, section 3 for a full discussion of these experiments and their results.

Accuracy falls off very rapidly (see section quoted above) with distance of the disturbance from the recorders. However, the marked preponderance of tremors that fall to the right of the north-south/east-west ratio line 1: 1.4 indicates that their points of origin lay roughly in an east-west direction from the Observatory. Smoothing of the results (see Figure 17A) has tended to spread this preponderance over an area of 10 degrees on each side of the east-west line. The resulting area in which, or beyond which, "anomalous" harmonic tremors probably originate in shown shaded in Figure 17B.

Figure 18 shows the results of the experiment with the portable Willmore seismograph. Average ratios of amplitudes measured on the vertical component Benioff and Willmore seismographs were plotted for each locality on which the Willmore was operated. The resulting mean lines about which the amplitude ratios fell are plotted on Figure 18+. The two heavy lines enclosing a shaded area represent the spread of ratios obtained when both instruments were operated side by side at the Observatory. Lines running to the left of this area represent amplitudes on the vertical Willmore seismograph which are smaller than would have been recorded had the instrument been operated at the Observatory, while those running to the right of the area represent larger amplitudes. Thus it may be inferred that, while the former represent disturbances that originated closer to the Observatory than to the portable station, the latter represent cases where the Willmore was the closer to the point of origin.

No allowance is made for the different response of the Willmore seismograph at different localities. However an estimate can be made of the effect of this variable, and it is evident that it cannot materially alter the picture as shown in Figure 18. Characteristics of the various sites are listed hereunder (for their geographical position see Figure 3):-

Locality	Seismometer Base	Background noise characteristics
Rapindik Station	Cement Block in tunnel (unconsolidated Ash & boulders)	High background and high level of industrial and vehicle interference (near road)
Tavurvur Tunnel	Rock Ledge in tunnel (Basalt)	Near road, but low background
Vulcan Barge Tunnels	Rock ledge in tunnel (Pumice)	Near road, much interference, high background
Lat Lat	Sandy Floor in Tunnel (Pumice)	Isolated station : low background
Lakunai	Cement Floor of Blockhouse (on Basalt)	Moderate background
Toleap	Cement Floor of Chicken House (Old Beach Deposit)	Moderate to high background. High level of vehicle interference.
Paluat	Cement Floor of Empty Residence (old Beach Deposit)	Moderate to low background
Malaguna Road Quarry	Rock ledge in open Quarry (Basalt)	Moderate to high background. Much industrial interference.
Watom Island	Rock Ledge below inland cliff (Coral Limestone)	low background
Observatory	Isolated cement Block (Basalt)	Moderate to low background

\+ The complete picture is far too complex to portray on a single graph, and has therefore been simplified to show mean lines only.

The following additional sites were used during the experiments of October to December 1962 (see Chapter 4, sections 2 and 3):

Locality	Seismometer Base	Background noise Characteristics
Namanula	Cement Block (tented) (Pumice)	Moderate Background
Police Compound (Gaol)	Cement floor of Shed (Elluvium)	Moderate to high background and level of interference
Matupi Island	Cement Floor, School Storeroom (Volcanic Ash)	Moderate background
Page Street	Cement floor of Garage (Elluvium)	High background and level of interference
Racecourse	Cement floor of Clubhouse (Volcanic Ash)	Moderate to low background
Nodup	Cement floor of Schoolroom (Old Beach deposit)	Moderate to low background
Nonga	Cement floor of Hospital (Old Beach deposit)	Moderate background. Fairly high level of interference
Sulphur Springs	Cement Block (tented) (Volcanic Ash)	Moderate to low background

The operation of the old Benioff seismograph at Rapindik Station since January 1962 has established the fact that the noise level is much higher there than at the Observatory (see Plate 3). From a comparison of the relative amplitudes of microseisms at the Observatory and at Rapindik during periods when artificial interference was at a minimum it is evident that response to earth tremor is greater at the latter. This was expected from the position of the station which lies within the caldera in the side of a small crater (one of the Sulphur Creek group): whereas the Observatory on top of the caldera wall, lies on a basalt floor.

A very approximate order of response at the various stations is from low amplitude to high, as follows:-

Tavurvur Tunnel, Lat Lat, Observatory, Namanula, Paluat, Racecourse, Sulphur Springs, Lakunai, Nodup, Nonga, Rapindik, Matupi Island, Police Compound, Toleap, Page Street, Vulcan Barge Tunnels.

Accordingly, any correction made to Figure 18 on the basis of varying response at different stations would have the effect of moving the lines to the left except in the case of those tremors recorded at Lat Lat or Tavurvur Tunnel. Thus the only material alterations to be made would be:

(a) to shift the line marked "some small harmonics (Observatory), sharp tectonic tremors (Lat Lat)" to such a position that it might fall to the right of the shaded area : the line marked "some semiharmonics (Lat Lat)" would now fall well to the right of the shaded area,

and (b) to shift the lines marked "Toleap" and "Paluat" to the left. It is probable however, especially in the case of Paluat, where response to earth tremor does not appear to be much higher than at the Observatory, that, when corrected, these lines would still fall well to the right of the shaded area.

Conclusions to be drawn from this study are therefore as follows:-

Fig. 19

ATTENUATION OF "ANOMALOUS" TREMORS

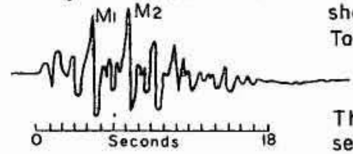
Z component old Benioff seismograph
standard magnification (approx. 15,000)

Semiharmonic Pulses, Medium to Long Period, Recorded on the vertical component of the old Benioff Seismograph at the Rabaul Observatory. This disturbance was recorded as a long-period semiharmonic shock on the vertical Willmore Seismograph at Tavurvur Tunnel, which, from a consideration of relative amplitude relationships, was closer to the source than the observatory. This shock thus represents attenuation of a semiharmonic tremor.

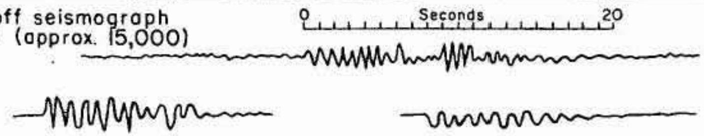
1.

0806 Hours G.M.T. 13th April 1961

Trace amplitude M1 15 1/4 mms.



Z component old Benioff seismograph
standard magnification (approx. 15,000)



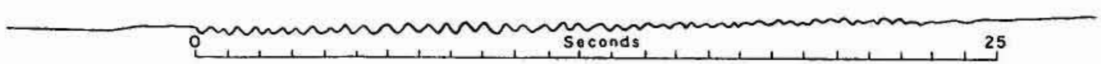
"Tavurvur" or "Matupi" type harmonic shocks on the observatory records.

12th April 1961

2.

Long-Medium Period Pulses, Semiharmonic, Recorded on the old Benioff Seismograph (vertical component) at the Rabaul Observatory. These disturbances were recorded on the vertical Willmore Seismograph at Tavurvur Tunnel as harmonic shocks. Amplitude relationships show that they originated considerably closer to Tavurvur Tunnel than to the observatory. They represent a further stage in attenuation of a small tectonic earthquake than in 1. pictured above.

3.



15th April 1961

"Anomalous" Harmonic Shock on the Benioff Seismograph at the Rabaul Observatory recorded at Vulcan Barge Tunnel on the vertical Willmore Seismograph. This does not represent much attenuation, being very similar to Willmore Records at the observatory of characteristically harmonic shocks.

Z component, Willmore Seismograph, $\frac{1}{10}^{th}$ sensitivity.

Bureau of Mineral Resources, Geology and Geophysics *September, 1963* P/35 JMF.

To accompany Record 1966/19

(1) "Anomalous" tremors may alter in appearance when recorded at different sites

(2) They do not all originate in the same area. This applies particularly to some semiharmonic tremors.

(3) The only localities found which are closer than the Observatory to the area of origin of the majority of the harmonic and semiharmonic tremors were found to have originated closer to Lat Lat than to the Observatory.

(4) Furthermore many medium to very short-period harmonic tremors and some semiharmonic tremors, were found to have originated closer to Tavurvur Tunnel and Rapindik Station than to the Observatory. All tremors in this class were however of very small amplitude on the Willmore records and there is reason to suggest that some were due to local interference in the caldera area. See Chapter 4, section 1 (See also Figure 19).

With regard to these conclusions the following points should be noted:

The way in which "anomalous" tremors alter in appearance at different sites is as follows:-

(a) Characteristic harmonic shocks at the Observatory may record as medium to long-period pulses at Rapindik. Conversely harmonic shocks at Rapindik may appear as medium period pulses at the Observatory. See Figure 19 (Sketch of medium period wave-trains at the Observatory of a type that are recorded as harmonic tremors elsewhere.

(b) Similarly, harmonic tremors at a number of other stations, particularly Tavurvur Tunnel, Lakunai and Paluat, may record as short to medium period pulses at the Observatory. Some short period tectonic tremors at these sites and at Vulcan Barge Tunnels record only as pulses at the Observatory.

(c) A number of harmonic wave-trains recorded at Rapindik, Tavurvur Tunnel, Paluat, Vulcan Barge Tunnels and Toleap were not picked up on the Benioff seismograph at the Observatory. They were almost certainly due to vehicle interference, a number of definite correlations having been established between vehicles and this type of movement on the Willmore records. Movements of this kind may be almost Sinusoidal in form.

(d) Tremors described as "very short period tectonic" at the Observatory are probably of similar origin to those described as "Harmonic" since the former may record on the Willmore Seismograph at Rapindik as "short to medium period pulses" and the latter as "medium period pulses".

(e) Some large semiharmonic tremors at the Observatory were recorded at Paluat as short to medium period pulses.

(f) In spite of the changes of form listed above, tremors frequently appear harmonic both at the Observatory and at the Vulcan Barge Tunnels, Paluat, Lat Lat and other stations. The majority of those tremors that appear harmonic at the Observatory appear also harmonic in Tavurvur Tunnel and at Rapindik.

(g) From the available evidence it appears likely that the same "anomalous" disturbance can record at different stations in the following ways (passing from an imaginary station close to the source to successively more distant ones):-

1. Short or very short period <u>tectonic</u> shock with distinguishable P, S and L phases.

2. Semiharmonic shock, with appearance suggesting a tectonic tremor, but some approximation to the harmonic class of shock (onset generally ei, no easily distinguishable P and S groups). See Plate 6

3. Harmonic shock, as described at the beginning of this section and illustrated in Plates 4 and 5.

4. Short period harmonic pulses. These pulses are generally poorly harmonic in character, of short duration and comparatively low amplitude.

5. Medium period pulses. These are again poorly harmonic and of short duration. As the period increases the amplitude falls off. See figure 19.

6. Long period pulses. Very low amplitude pulses with periods of about one second, sometimes greater. Such pulses appear to represent "anomalous" tremors when they approach the limit of reception.

If this hypothesis is correct, a relationship can be established between the source of the majority of the "anomalous" tremors and the stations at which the Willmore seismograph was operated.

With the instrument operating at Vulcan Barge Tunnels disturbances were found to agree closely with those recorded when the Willmore was operated at the Observatory; i.e. the Observatory and the Barge Tunnels are probably roughly equidistant from the area of origin of the disturbances.

With the Willmore at Rapindik and at Lakunai a definite "step-down" in form of the "anomalous" tremors is evident. Many shocks that are characteristically harmonic at the Observatory are less clearly harmonic when recorded at Rapindik and Lakunai are therefore probably further than the Observatory from the source of origin of the tremors.

Except for the disturbances which may possible be due to interference and a few tectonic tremors which evidently originate closer to the Willmore than to the Observatory, there is good agreement on the whole between the form of shocks at the Tavurvur Tunnel and the Observatory, thus suggesting that the two stations may be equidistant from the area of origin.

The appearance of "anomalous" tremors on the Toleap and Paluat records strongly suggests that the Willmore was a good deal closer than the Observatory to the source. They characteristically record as small tectonic tremors of somewhat unusual appearance (they tend to have harmonic form but sharp beginnings. Often they show a number of well defined phases that may be reflections (see later in this section)).

Some semiharmonic shocks at the Observatory, however, record at Toleap and Paluat as medium period pulses. These probably originated from another source closer to the Observatory than to the two portable stations. Some harmonics at the Observatory appear almost sinusoidal at Paluat and Toleap. It is possible that this form is due to transmission of the waves through a water layer in much the same way as probably occurs with interference due to ships' engines (see later discussion).

There is generally better agreement in form between harmonic shocks at Paluat and the Observatory than that between shocks at the Observatory and Toleap, where they tend to record with an even sharper tectonic appearance, thus suggesting that Toleap may be closer to the area of origin than Paluat.

At Lat Lat most Observatory harmonic shocks are shorter in period and appear more like tectonic shocks. However a few appear as if they

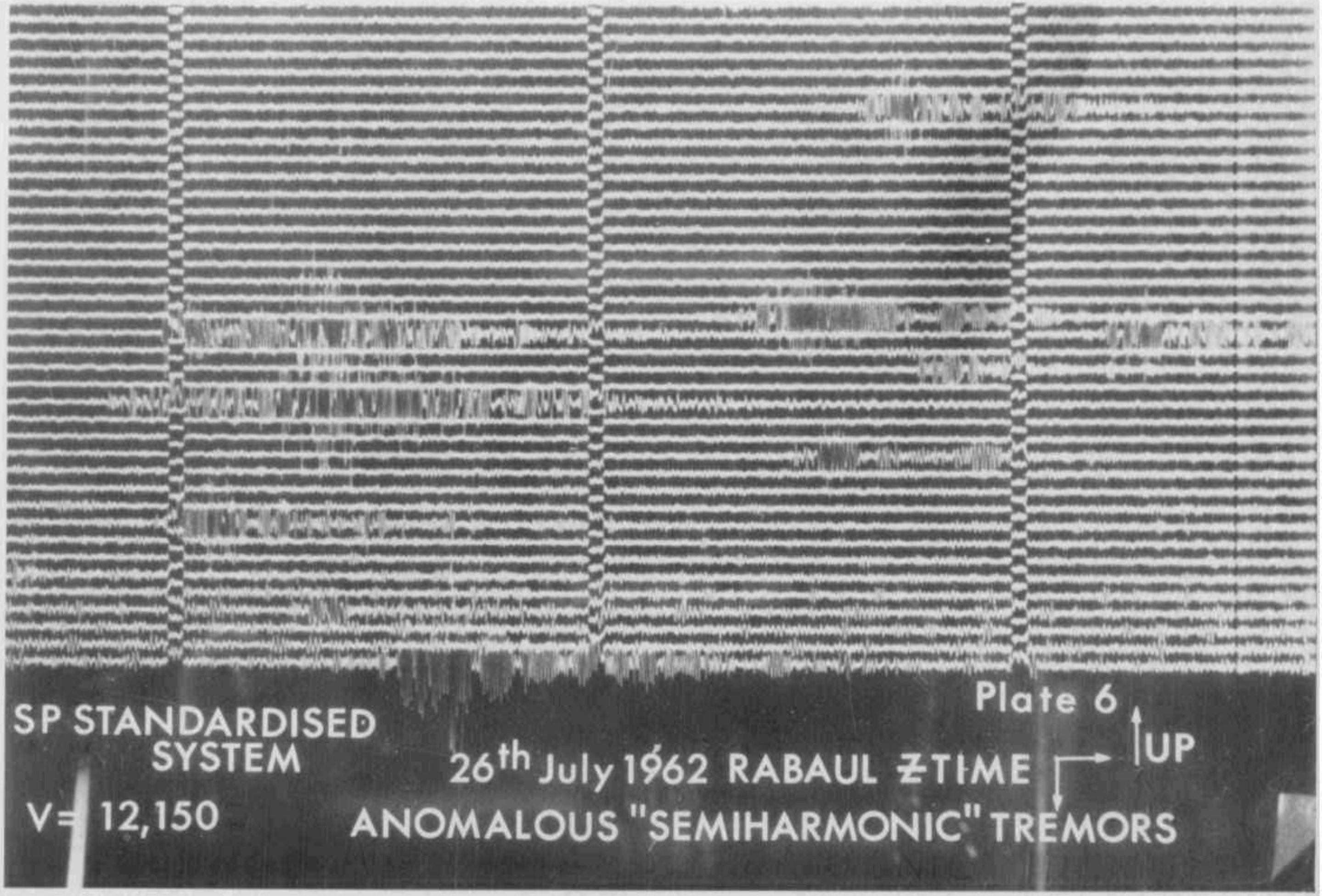


Plate 6
UP
SP STANDARDISED
SYSTEM
V= 12,150
26th July 1962 RABAUL Z TIME
ANOMALOUS "SEMIHARMONIC" TREMORS

originate closer to the Observatory. Hence there is probably some diversity of origin, most originating closer to Lat Lat.

Insufficient results were obtained at Malaguna Quarry and on Watom Island with the Willmore seismograph to enable any conclusions to be drawn.

A different line of enquiry, that of establishing the times of arrival of the disturbances at various stations, was attempted in May 1961.

It is not considered that much reliance can be placed on the results owing to difficulty in picking the precise moment of onset.

It was found that the "anomalous" disturbances reached the Observatory between 0.1 second and 1.2 seconds before they recorded at Toleap. In other cases, however, no movement was detected at Toleap up to 11 seconds after onset at the Observatory: therefore early waves were probably below recording threshold on the Willmore seismograph, and first arrival may well have been at Toleap.

With the instrument at Paluat it was found that arrivals were 1.6 to 1.7 seconds earlier at the Observatory on the only two tremors which had sufficiently sharp beginnings to measure. Onset of the L waves was commonly earlier at Paluat than at the Observatory by about 1½ seconds. A similar situation was observed at Toleap.

Poor though this evidence is, it supports the conclusion reached above that Toleap may have been closer to the origin of the tremors than either Paluat or the Observatory.

In February 1963 an attempt was made to determine arrival times for "anomalous" tremors by means of the World Wide Standardised instruments at the Observatory, the old Benioff Seismograph at Nonga. The experiment was inconclusive as no truly harmonic "anomalous" shocks occurred.

Two small tectonic shocks were recorded at Nonga earlier than at the Observatory or at Rapindik, as follows:-

4/2/63	Nonga	iP	143509.0
	Observatory	iP	09.1
	Rapindik	iP	09.8
5/2/63	Nonga	iP	132010.5
	Observatory	(P)	10.9
	Rapindik	Almost Nil recorded	

One small semiharmonic shock was recorded at Nonga 0.4 seconds earlier than at the Observatory (this suggests origin North or north-west of Nonga). This shock was not recorded at Rapindik.

One small tectonic shock, of partial harmonic form was recorded at the Observatory 0.5 seconds earlier than at Rapindik and 0.6 seconds earlier than at Nonga. This is consistent only with arrival from a north-easterly direction at the Observatory.

The remaining disturbances recorded were medium period pulses which arrived on three occasions at Nonga before they arrived at the Observatory, and on two occasions at the Observatory before Nonga. Not much reliance can be placed on these five determinations owing to the difficulty of picking the precise moment of onset of an emergent pulse.

In December 1962 a portable Willmore seismograph (single component vertical) was operated for some time at a site near Sulphur Springs (see Figure 3), and an attempt was made by use of the permanent instruments at the Observatory and Rapindik to determine arrival times for "anomalous" tremors. Few, however, occurred, and owing to difficulties with timing, no useful results were achieved.

During this experiment very few disturbances recorded at Sulphur Springs appeared to originate closer to that locality than to the Observatory or Rapindik. For a time an instrument was operated also at the Racecourse, and a similar lack of small tremors confined to that area was noticed. In both cases the only disturbances which appeared to originate near the areas concerned could be put down to probable vehicle or ship interference.

A study of the records of the bomb disposals explosions on 30th November and 1st December 1962 was made in order to attempt to locate the source of origin of the few "anomalous" tremors that occurred during the period. These records were made under exceptional conditions of time control and with the maximum number of instruments operating. Thus they were particularly favourable to a study of amplitude relationships and times of onset of "anomalous" tremors.

On 30th November three "anomalous" tremors occurred during the period covered by the "test" records. The first, at 1343 hours G.M.T., was recorded at the Racecourse as a primarily vertical disturbance with a harmonic coda. It was recorded as medium period pulses at the Observatory, Namanula and Matupi Island+. On the assumption that most of the energy was transmitted as longitudinal rather than transverse waves (which has been found to be the case with recent explosions in the caldera++) the source of origin of this disturbance must have been in a north-south direction from the Racecourse and probably no more than 1-2 miles distant. Thus it could have originated between the Beehives and Vulcan, beneath Vulcan crater, or in Karavia Bay. It may have been due to some form of interference, possibly marine. The second and third disturbances, at 1406 and 1441 hours G.M.T., were well recorded as harmonic tremors at the Observatory and at the Racecourse, and rather less clearly recorded at Namanula and Matupi Island. A study of their relative amplitude characteristics indicates that they probably originated west of the Racecourse in the area of Ataliklikun Bay.

Two other strongly harmonic disturbances occurred on 30th November. The first, at 1324 hours G.M.T. probably originated in the Harbour rather closer to Namanula than to the Racecourse, and may have been due to marine interference, since it bore some similarity to known cases of such interference. It may have been linked to the tremor which was recorded strongly at the Racecourse 19 minutes later (i.e. a small ship may have been moving in the harbour over this period). The second disturbance was strikingly sinusoidal in form and of long duration (5 minutes). It was recorded with maximum at 1423 hours G.M.T. only on the north-south component instrument on Matupi Island (the east-west component was partly jammed). It was not recorded at the Observatory, Rapindik, Namanula or the Racecourse, at all of which instruments were operating in good order at the time. It is virtually certain that this disturbance was set up by ships' engines, probably in the open sea to the east of Blanche Bay. An attempt was made to discover whether any ship was known to have been in the area that night, but this was unsuccessful.

On 1st December two small harmonic "anomalous" tremors were recorded with fairly high amplitudes at the Observatory and at Nonga. The first, at 1349 hours G.M.T., which was not recorded at Namanula or Nordup+++, originated, from relative amplitude considerations, to the west of Nonga.

\+ Rapindik records are not available at this time for study.

++ For a full discussion of the relative amplitude method of determining directions See Chapter 4 section 3.

+++ Rapindik records are not available at this time for study.

The second, at 1402 hours G.M.T., which was recorded at Namanula and Nordup as a semiharmonic disturbance as well as at the Observatory and at Nonga, gave clear amplitude ratios at all four stations. The directions implied gave a small triangle of error for the point of origin about one mile to the north-west of the North Daughter volcano. If correct, this is an interesting location for an earthquake, and, although the records were only poorly harmonic in form, it does not lend support to the theory that harmonic form is due to transmission of earthquake energy in a water layer.

Much more complete information will be available as soon as the satellite stations are re-established around the Blanche Bay caldera. Until then, the source of the "anomalous" tremors must remain largely in doubt.

At the present stage, however, the overwhelming likelihood is that the majority of these tremors originate off the north coast to the west of the Rabaul Observatory. The available evidence and the conclusions which can most reliably be derived from it are summarised on the sketch map in Figure 18a.

On this diagram are plotted directions obtained from analysis of first motion at the Observatory (and relative +amplitudes of the same shocks) on the few occasions when an estimate could be made of the direction of first motion. Most are from a swarm of small harmonic shocks with unusually sharp beginnings which commenced on 6th May 1961. Their value is accordingly limited, as they cover only a short period.

A study of the evidence which was used to compile Figure 18 shows that low amplitude semiharmonic pulses characteristically fall on the same mean ratio lines as semiharmonic shocks of larger amplitude. This almost certainly indicates that they come from the same source and obey a simple law of attenuation. The same holds for many small harmonic shocks of almost sinusoidal appearance and harmonic shocks of larger amplitude. Similarly there is an area of medium to long period pulses at all sites which aligns with "anomalous" shocks of larger amplitude, thus confirming belief that these too represent "anomalous" tremors near the limit of reception. Furthermore, while there is a marked scatter of tectonic shocks away from the mean lines at high amplitudes, there is very little scatter apparent for lower amplitude "anomalous" tremors.

Estimated epicentres and directions as plotted on the sketch-map in Figure 18a should be treated with caution owing to the difficulty of determining directions of first movement. There is not likely to be any great error in the relative amplitude estimates of direction, the only likely errors being in which quadrant the tremors fall - thus the quadrants should be treated as mirror images of each other; tremors that have been plotted in one quadrant may have originated in another at the same angle to north-(or south).

As will be seen from Figure 18a a majority of the tremors appear to originate in the north-west quadrant. This is in keeping with the other evidence - the scarcity of determined directions in the south-east quadrant is strong negative evidence against the location of the "anomalous" tremors concerned within the caldera.

As mentioned above, the accumulated evidence very strongly suggests that the great majority of "anomalous" tremors originate in an area to the west of the Observatory off the north coast of New Britain. Some however probably originate outside the caldera to the north east of Rabaul in St. George's Channel, or to the south east of Rabaul off the entrance to Blanche Bay. These latter shocks characteristically record as semiharmonic disturbances at stations in the vicinity of Rapindik and as medium period pulses at the Observatory.

+ Times of L. max. may differ on different components at the one station for the same shock.

"Anomalous" shocks which were determined as having originated closer to Lat Lat than to the Observatory probably came from the area of Ataliklikun Bay (west of Keravat).

The writer considers that the only type of earthquake that fits the evidence collected on the "anomalous" tremors is a shallow shock which attenuates rapidly. Very small magnitude and an epicentral distance of between ten and forty miles from Rabaul (in a westerly direction) are postulated for the great majority of the shocks. The characteristic harmonic and sometimes sinusoidal form, the writer believes, is due to transmission of the wave energy through water, in a manner analogous to the marine interference due to ship's engines which is discussed in Chapter 4, Section 1.

The harmonic part of the shocks is probably made up entirely of L waves, and part of the effect may be due to T waves in much the same way as occurs in the case of the Bismarck Sea earthquakes+ discussed in section 2 of this chapter. Apart from the lack of sharp beginnings, the "anomalous" harmonic shocks show some affinity to small shocks generated by explosions in Simpson Harbour, where much of the energy is transmitted through water. In passing, it should be noted that they also show some affinity to the small earthquake of possible volcanic origin which was felt at the Rabaul Police Station on 30th October 1962.

Consistent with the "anomalous" tremors being normal, very shallow, very small tectonic earthquakes, rather than, for example, volcanic tremors, is the variation in period which is commonly observed. This, together with the presence of low amplitude emergent phases preceding the harmonic part of the shock, strengthens the impression that the harmonic phases are surface waves and that the P and S groups are probably lost in the microseismic background.

"Anomalous" tremors, in common with explosions and small tectonic tremors in the area, characteristically show well defined phases which may be crustal reflections. No analysis of these has been carried out, but they are listed hereunder for reference purposes:-

Some characteristic Second Arrivals commonly recorded at Rabaul from explosions in the Harbour area:-

Phase	Period	Amplitude	Records best on	Most often recorded in
P + 1.6-2 sec.	less than ¼ sec.	usually small	-	Explosions in Simpson Harbour
P + 2.5-3++ sec.	¼ - 1/3 sec.	usually small	-	Explosions in Simpson Harbour
P + 4.8-4.9 sec.	1/3 - ½ sec.	higher than preceding two	-	Explosions in Simpson Harbour
P + 8 sec.	½ sec.	Maximum amplitude	EW	Explosions in Simpson Harbour
P + 11 Sec.	½ sec.	Usually secondary maximum (Not so common as P + 8 sec. phase)	EW	Explosions in Simpson Harbour
P + 2.5-3 sec	Less than ¼ sec.	small	NS, EW	Explosions, Vulcan area
P + 6.0 sec.	¼ sec.	small	Z	Explosions, Vulcan area
P + 20-21 sec.	1/3 sec.	Maximum	Z, EW	Explosions, Vulcan area

\+ Many Bismarck Sea earthquakes have short period harmonic motion in the Coda

++ P max. in the Japanese salvage explosions in Simpson Harbour occurred between P + 1 and P + 2 seconds.
L max. generally occurred for explosions near Matupi Island at P + 23 seconds, and for explosions near Namanula Street Wharf at P + 11 seconds.

Characteristic second arrivals in tectonic earthquakes

Phase	Epicentral Distance ( )	Remarks	
P + 0.9-1 sec.	1°30'-2°	Examples	18/4/59, 16/5/59
P + 2-2½ sec.	4°10'-4°30'	"	19/8/58, 20/8/58
P + 3 sec.	4°20'-6°45'	"	26/3/59, 17/8/58
P + 4 sec. (May be Pg)	2°15-6°50'	"	12/7/59, 7/5/59, 5/7/59, 7/9/58
(Sg is also sometimes recorded at Sn + 5 secs.)			
P + 5 sec.	3°10'	"	28/4/59
P + 6 sec.	4°50'	"	9/7/59

Characteristic Second Arrivals commonly observed in "anomalous" tremors at Rabaul.

Phase	Type of Tremor	Remarks
P + 1.9-2 sec.	Harmonic	
P + 4-4½ sec.	Harmonic or short period tectonic	
P + 7.1-7½, 8 sec.	Harmonic	Strong reflection from Mohorovicic discontinuity
P + 10½-11, 12½ sec.		
P + 15 ½ sec.	Harmonic	N.B. P + 16.9" (Nr) was observed on the record of the possible volcanic tremor on 30th October, 1962.
P + 19 sec.	Harmonic	P + 19.1" (E Observatory) and P + 19.2" (Er) were observed on the record of the same tremor
P + 22-23 sec.	Harmonic	

In connection with the reflected phases listed above it should be noted that a Bureau of Mineral Resources Geophysical Party, which carried out a survey at Rabaul in September-October 1960, recorded strong reflections from a layer which was believed to lie at about 15 kilometres below the surface.

Records of similar Swarm Earthquakes from other localities

Austin E. Jones in a remarkably interesting paper on seismic phenomena at Hawaii (31) mentions a number of earthquake types that show a remarkable similarity to the "anomalous" swarm tremors at Rabaul.

Figure 21 is a sketch after Wadati (62) taken from Mr. Jones' paper. It illustrates a classification, based on pairs of reflected phases, of local earthquakes in Japan.

The concepts involved may be invaluable to a proper understanding of the local earthquakes at Rabaul, where Wadati's conclusions, drawn in a similar tectonic setting, probably apply.

By application of Wadati's ideas in Hawaii Jones classified near earthquakes by the number of pairs of phases that they showed. His illustrations, reproduced in the right hand column of Figure 21, are very similar in form to many of the small earthquakes recorded at Rabaul. In particular, they resemble many of the "anomalous" tremors.

Wadati's illustrations, shown in the left hand column of Figure 21 are equated by Jones with his types from Kilauea. Wadati's oceanic type, with its well developed sinusoidal form, is remarkably similar to the class of interference due to ships' engines at Rabaul, and to those "anomalous" tremors that are unusually sinusoidal in form. Most of the "anomalous" tremors appear to agree most closely with Jones' K3 and K4 classes (Wadati's "inland type").

Jones illustration of "spasmodic tremor" at Hawaii bears a close resemblance to the medium to long period pulses, which at Rabaul, probably represent "anomalous" tremors near the limit of reception. Jones' conclusions regarding "spasmodic tremors" are as follows:- he states, "Spasmodic tremor is of two kinds. The first begins, waxes, wanes and ends with no distinguishable changes; the second shows sharp changes, indicated by P and S. These are undoubtedly the records of small shocks, as has been indicated time and time again by their correlation in time of day with some earthquake in other parts of Hawaii. One thousand to fifteen hundred spasmodic tremors are recorded during the year, most of them being of unknown origin."

These conclusions are strong additional evidence for the hypothesis that the "anomalous" tremors at Rabaul may be of normal tectonic origin.

The instrumental set-up in Hawaii in 1938 was better equipped to determine local epicentres than that at present in Rabaul. Jones was able to show that some correlation existed between different types of earthquakes as shown by their number of paired (P and S) phases and their locations and depths of origin. He found that the K1 earthquakes were centred beneath Kilauea, indicating increasing depth of focus there. Very few occurred above the dip angle of 20^{o} from the recording station, and most at a dip angle of about 32^{o}. K2 type earthquakes appeared to originate most commonly about a dip angle of 20^{o} and the K3 type at a higher level in the crust, up to a dip surface of about 9^{o} from the station. The overall picture that he found was one of decreasing depth of focus with increasing number of pairs of phases. Consequently Wadati's "oceanic type" is most probably of very shallow origin. Jones suggests that this type may indicate a complex of layers beneath the floor of the ocean. The sinusoidal appearance of this class of earthquake suggests to the writer that they may represent cases in which the influence of the water layer has become dominant.

An interesting point mentioned by Jones is that earthquakes with epicentres in the vicinity of Kilauea crater have the pecularity of one pair of phases at all angles of dip when the origin is in the crater and away from the walls, although shocks that originate near the crater walls or outside the crater at shallow depth often generate two or more pairs of phases. He explains this situation by suggesting that there is probably one recent fill inside the crater which is all of the same kind of rock, with two distinct layers outside.

It is not possible to analyse the Rabaul tremors to this extent since the operation of only two fixed seismograph stations (at the Observatory and Rapindik) makes the location of earthquake origins in three dimensions both difficult and unreliable.

W.A. Lynch (34) has reported a class of small unidentified earth tremor from Fordham, New York. It is of frequent, though spasmodic occurrence. It remains constant in form and period (0.7 seconds), does not seem to be artificial and has been detected at all hours of the day and night, (see Figure 22) G.R. Robson and K.G. Barr (48) have reported small

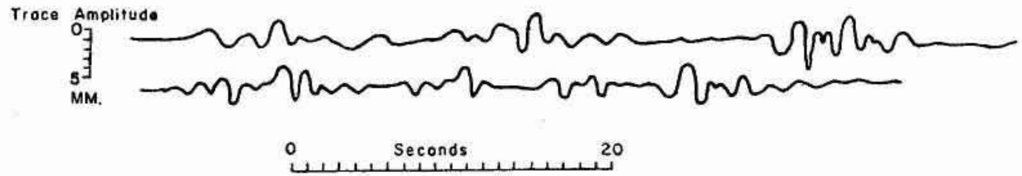
EMERGENT PULSES ON OLD BENIOFF SEISMOGRAPH

Fig. 20

RABAUL OBSERVATORY

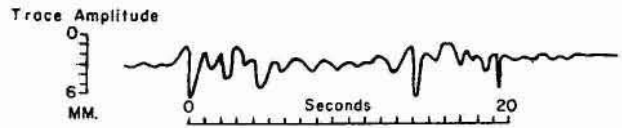
15th NOVEMBER 1960 STANDARD MAGNIFICATION (Approx. 15,000)

N.S. Component



(Approximate scale : no time marks on the record)

E.W. Component

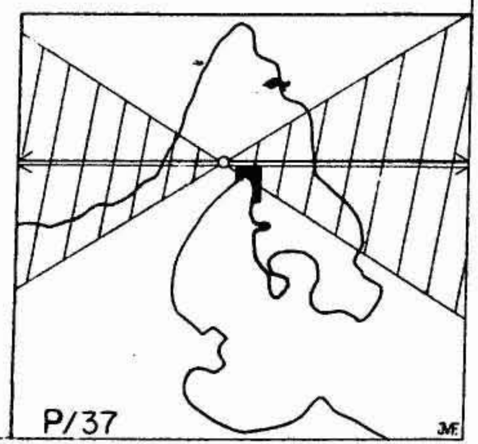


(Approximate scale : no time marks on the record)

Z Component

Only very slight, very short period movement, but pendulum partly jammed.

Sketch-map of Rabaul showing maximum area of probable origin of disturbances of 15th November 1960, based on amplitude ratios. Most probable direction is east/west (marked by a double line.)



Bureau of Mineral Resources, Geology and Geophyics *September, 1963*

To accompany Record 1966/19

unidentified earth tremors on the volcanic island of Dominica in the West Indies. These tremors differ from the "anomalous" tremors at Rabaul in having a sharper onset and a more constant form. Robson and Barr state, - "each tremor consists of an approximately sinusoidal ground motion of 0.3 seconds period. The first swing is always down, the first and eighth swings are maxima, and there are about twelve swings in all. ......They are quite unlike the tremors produced by near earthquakes or by explosions on land or at sea. Factories, quarries and other possible artificial sources for the tremors.... have been investigated and eliminated." They go on to say that the tremors tend to occur in bursts lasting up to twelve hours, the average period between bursts having been seven days. As at Rabaul, an attempt was made to determine the origin of the tremors by operating portable Willmore seismographs in the area, and by comparison of amplitude ratios and arrival times.

Indications were that the sources could lie on a circle which passed through the town of Roseau, on the island of Dominica; seismic velocities were calculated as lying in the range 150 m./sec. - 740 m./sec., depending on the location of the sources on the circle. An estimate of 750 m./sec. was made for the velocity of longitudinal waves in the sand and gravel on which the town of Roseau is built.

Robson's and Barr's illustration of one of these unidentified earth tremors is reproduced in Figure 22. It is similar in appearance to the class of "Short period pulses" on the Rabaul records which has been tentatively correlated with "anomalous" tremors approaching the limit of reception (but closer than medium or long period pulses).

Robson and Barr estimated the energy release at the source as about 10^{14} ergs for the largest tremor recorded. They were unable to find any evidence of a connection between the tremors and volcanic activity on the island, which contains several active thermal areas and some extinct volcanic centres, all of which are some distance from the apparent source of the tremors. They conclude by stating "we cannot put forward an alternative explanation for their origin."

At Rabaul the possibility of a volcanic origin for some of the small disturbances which were recorded more strongly at Tavurvur tunnel and at Rapindik than at the Observatory (see previous discussion in this section) cannot be entirely discounted. As at Dominica, no evidence has been found that they are related in any way to volcanic activity, but, should they be related, the lack of positive evidence would be in no way surprising. Small movements related, for example, to the upflow of hot water near the caldera wall behind Rabalanakaia, as postulated by Mr. Studt (52)+, might easily take place without any noticeable change in gas emission or temperature in the thermal areas.

Thus, although the balance of evidence at Rabaul is strongly in favour of a tectonic origin outside the caldera for the majority of the "anomalous" tremors, the possibility remains open that a minority of the tremors may be of tectonic origin within the caldera (probably related to movements taking place near the walls), or of direct volcanic origin, either beneath the present craters or at depth below the harbour area.

Apart from the swarms of small tectonic shocks which probably originated at depth below the Rabaul caldera (see Chapter 3, section 2, subsection e), and the few known earthquakes of volcanic origin (see Chapter 3, section 1, subsection a), the most likely disturbances which could fit directly into the volcanic category at Rabaul are those which occurred on 15th November 1960.

Figure 20 illustrates the form of these disturbances, which have not been recorded at Rabaul either before or since, although they approximate in form to a few of the medium period "semiharmonic"

\+ See Chapter 1, section 5.

pulses+ recorded.

The 15th November 1960 disturbance took the form of an almost continuous microseismic wave train of low amplitude and periods averaging 1 second. The only instrument in operation at the time was the old Benioff seismograph at the Observatory. The disturbance was recorded on all 3 components of the instrument, but particularly strongly on the horizontals. The greatest trace amplitude (2 to 6 mms.) were recorded on the east-west component, on which the period tended to be slightly shorter and the pulses sharper than on the north-south component (trace amplitudes 2 to 5 mms.). The vertical seismometer was not swinging perfectly freely and recorded only very slight, very short period microseismic movement. Most of the pulses were sharp but the onset of groups of pulses was emergent. More than one thousand such pulses were recorded during the night of 15th November 1960. Unfortunately there was a fault in the timing circuit and no time marks were emplaced on the records.

The records have been shown to a number of experienced seismologists all of whom declared that they had never seen a similar disturbance.

Unless the disturbance can be attributed to a temporary state of instability of the instruments due to some unknown cause, the conclusion appears inescapable that it was due to volcanic activity of some kind in the Rabaul area, or, conceivably, to rather distant tectonic activity of the same kind as that which causes the "anomalous" tremors, but differing markedly in duration.

The writer tends to favour the latter explanation on the sole grounds that the ratios of the north-south/east-west amplitudes++ indicate that the majority of the pulses seemed to originate in an east-west direction from the Observatory, taking the transmission of energy as having occurred as longitudinal waves. This evidence on its own is not strong, owing to the apparent polarisation of seismic waves in the direction of the caldera wall, which may tend to magnify amplitudes in the east-west direction (see Chapter 4, section 3). Furthermore, although the disturbance bears some slight similarity to a few of the "anomalous" tremors, this similarity is not marked, and it is evident that if the disturbance was of tectonic origin it must have originated in a different area or at a different depth, or have been due to some special circumstance. No unusual meteorological conditions prevailed that day, and no tremors were recorded elsewhere which could have been in any way related to the disturbance. Possible evidence for its having been of volcanic origin is its long duration (about ten hours) and its constancy of form over that period. It could, in fact, have been due to pulsating of magma in an underground chamber. Similar pulses with longer period (4 to 5 seconds) were recorded at Aso volcano in Japan during the 1929-1933 period of activity, and these increased in amplitude, period and frequency of occurrence before the severe eruption of December 1932.

\+ For example, the "semiharmonic" medium period pulses which occurred at 1926 hours G.M.T. on 7th May 1961. These were recorded with a trace amplitude on the Z component old Benioff Seismograph at the Observatory of 5.2 mms., and on the portable Willmore Seismograph (Z component) at Toleap of 1.2 mms., this amplitude ratio indicates that the pulses originated much closer to Toleap than to the Observatory.

++ Three examples of amplitude ratios of pulses that could be definitely identified on the 2 horizontal components (no time marks)

Trace amplitudes N:E	Ratios N:E	Probable Angle from north-south
13½ : 22	1: 1.629	90^o
17 : 19	1: 1.118	$58½^o$
20½ : 29	1: 1.415	90^o

(c) Microseisms

No research or analysis has been done on the microseisms recorded at Rabaul. Their general characteristics however, are as follows:-

1. An almost continuous "background" of microseisms on the Rabaul records is believed to be due to the movement of the sea against the coast. The Observatory is about 2 miles from the gently shelving beaches near Pila Pila, to the north-west, and about 3½ miles from the more rugged north-east coast between Tawui Point and Nordup (see Figure 3). Period of this microseismic background usually varies between 1½ and 4½ seconds, and is occasionally longer. Amplitude increases notably during periods of bad weather.

2. A short period microseismic movement (period about ½ second) may be superimposed on the longer period continuous background. It appears to be due mainly to wind. The Observatory is situated on an exposed ridge, well covered with timber at distances of about 100 yards from the instrument vault. Especially during the "north-west" season winds are often strong and the records hard to read. Actual shaking of the Observatory building and its tall aerial mast, together with movement of trees transmitted through their roots, combine to cause long intervals of vibration, particularly on the horizontal component instruments.

3. A shorter period movement (¼ - ½ second) can be correlated with rainfall at the Observatory.

4. Short sharp isolated pulses in a disturbed microseismic background have been correlated with lightning flashes in the vicinity. Similarly, short period vibrations may be due to thunder, which frequently shakes the Observatory building with considerable force.

These remarks apply also to the Rapindik instrument station, which, however, while a good deal more susceptible to industrial and atificial interference than the Observatory, is less prone to the influence of the weather on account of its lower altitude and more sheltered position.

4. CORRELATION OF SEISMIC PHENOMENA WITH OTHER EVENTS

There have been few correlations of seismic activity with other events, whether volcanic, thermal, tidal or related to changes in level at Rabaul, which can be said convincingly to point to interdependence of one set of phenomena or another. The following cases may be quoted:-

On the one hand are those events which have been without question related to, caused by+ or which have caused, major earthquakes. These include changes of level and tsunamis due to, and volcanic eruptions preceded by, high magnitude earthquakes. They have already been enumerated and discussed earlier in this paper, and will not be repeated here.

On the other hand a number of comparatively minor events, which, although many have been already mentioned in earlier sections, are for the sake of clarity listed again hereunder:-

1. 8th March 1938, 1030 hours L.M.T. During one of a swarm of apparent tectonic tremors felt at Keravat and Toma (maximum intensity 4 (R.F.)) a sharp puff of steam was emitted from Tavurvur crater.

2. 12th November 1940. 2, possibly 3, local tremors occurred on or about this date. The temperatures of fumaroles in the 1878 crater of Tavurvur rose to 110½°C. By the end of the week they had dropped to 103°C.

3. Following the major earthquake of 14th January 1941 (0227 hours L.M.T.) new hot springs were formed at the south side of Vulcan not far from the Karavia Bay hot springs++ which had been in existence since the 1937 eruption. Hot water was brought up in the Kabaira area, but the temperatures soon became normal. Hot water is also said to have been thrown out on Watom Island, but this occurrence was never confirmed.

Dr. N.H. Fisher (15) points out that this earthquake appears to have been the culminating phase in a period of intense seismic activity in the area. He states:- "on September 12th 1940 a major earthquake originated about 70 miles south-east of Rabaul, and in general the seismic activity for a considerable period was much greater than normal. Over the same period there was a gradual increase in the manifestations of latent volcanic activity at Tavurvur ....". He goes on to say: "It seems certain that the seismic activity and the general increase in volcanic activity at Tavurvur which burst into eruption again on June 6th 1941.... , were in a general way related. In December 1940 the temperatures in the fumaroles in Tavurvur crater, which up to that date had not exceeded 100°C, began to rise at an average rate of about 10° per day for more than a fortnight... . The morning before the shock the temperature was found to have risen 22° to 284°C.,+++ and it remained at that figure for about a month showing no change immediately following the actual shock. Subsequently the rise in temperature continued slowly until at the time of the beginning of eruptive activity it had reached nearly 400°C."

Tilt measured at the Observatory showed a sharp change at the date of the earthquake. For a month previously a very severe tilting had been taking place upwards to the west-south-west at a rate of about one second of arc per day. This ceased immediately after the earthquake, the east-west component remaining static for a fortnight, and the north-south showing a fall to the south, which may have been due to collapse of the caldera wall

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\+ cases of damage are not listed.

++ These hot springs no longer exist (1963). To the writer's knowledge they have been cold at least since 1960, and probably much earlier.

+++ On 28th January 1941 a fumarole measuring 283°C., in the 1878 crater of Tavurvur was noticed to have extended in area.

near the Observatory.

4. On 22nd August 1941 (more than 2½ months after the eruption of Tavurvur volcano) a marked increase in seismic activity took place over a 12 hour period, more than 100 tremors being recorded in this time. Increased volcanic activity accompanied the tremors (it was stated (Rabaul Times, Aug. 1941) to have been easily the most intense since the June outburst). A partial blackout due to ash fall occurred in Rabaul.

5. Seismic activity was low over the period 27th to 28th August 1941. It increased on the 29th August, 126 tremors being recorded in 24 hours, and then declined. Eruption recommenced on 2nd September 1941.

6. 12th September, 1941. At 1000 hours L.M.T. microseismic activity (volcanic tremor) increased and continued for 16 hours. It was accompanied by rapid shaking which lasted for several minutes. This was believed by Dr. Fisher to be due either to rapid rise or to rapid fall of lava in the conduit. Activity in the volcano declined. There was some return of spasmodic volcanic tremor on 18th and 19th September 1941, but on the whole both seismic and volcanic activity remained at a low level until 22nd October 1941. Mild dust emission took place on 7th October 1941, accompanied by weak volcanic tremor.

7. 22nd October 1941 - Continuous eruption recommenced at 0807 hours L.M.T. Small volcanic tremors occurred. On 28th October 7 tremors were definitely correlated with explosions in the vent. The crater became quiescent on 4th November, but small volcanic tremors continued.

8. 15th November 1941. At 1800 hours L.M.T. explosions commenced again in Tavurvur crater. On 16th November over 200 tremors were recorded at the Observation Post, most being correlated with explosions in the vent. Strong explosive activity continued until the end of November; it was accompanied by strong volcanic tremor.

9. Spasmodic volcanic tremor and discrete shocks occurred on 2nd December 1941 when the volcano was emitting only steam and gas. Eruption, accompanied by volcanic tremor, recommenced at 1250 hours L.M.T. on 4th December ending at 1630 hours on the same day. On 23rd December stronger seismic activity was recorded at the Observation Post.

10. In October 1943 Dr. Takashi Kizawa observed that before the eruption of Tavurvur a rise in tilt occurred in the direction of the crater, and that small earthquakes occurred, the S-P intervals of which shortened immediately before the eruption. The maximum tilt was recorded at the time of the eruption, after which the crater area fell gradually.

11. 14th May 1951. One of the fumaroles in Tavurvur volcano reached a temperature of 105°C. During the month two hot springs on the foreshore at Rapindik suddenly ceased to flow. An earthquake occurred at 0828 hours G.M.T. on 21st May 1951 at 6.2°S. 154.8°E. (depth about 160 kilometres), being felt up to intensity 5 (M.M.) in Bougainville and New Ireland. It is not known whether these events are in any way related.

12. 15th June 1955. Following an earthquake at 3°S. 153°E (h=100 kms) cracks opened in Kamerere Street.

13. An earthquake of Magnitude 7¼ (Pas) occurred at 0857 hours G.M.T. on 10th October 1955. It was widely felt (at Warangoi up to intensity 7-8 (M.M.), and at Rabaul, intensity 5 (M.M.)). The epicentre was given as 5°S. 153°E. Between 10th and 24th October

1955 a sudden fall in temperature took place at point No. 3 in Sulphur Creek. Irregular movement was noticed on the Observatory tiltmeter on 23rd October.

14. 7th November 1955. A sharp increase in temperature took place at point No. 11 at Sulphur Springs, and a sharp drop at fumarole A2 in Tavurvur crater. 4 earthquakes with S-P intervals ranging from 18-25 seconds occurred between 1st and 14th November, with epicentres between 5-5½°S 152-153°E (on 1st, 10th, 12th and 14th November respectively).

15. 12th-13th December 1955 - Irregular movement of the Observatory tiltmeter took place. An earthquake occurred on 8th December 1955 at 1736 hours G.M.T. with epicentre given as 4°S. 152°E. and depth of focus as 500 kilometres. (A small shock with an S-P interval of 8½ seconds occurred at 1904 hours G.M.T. on 15th December 1955).

16. 18th August 1957, 1642 hours G.M.T. During one of the closer shocks of a seismic storm which commenced on 16th August 1957 one of the most active hot springs at Rapindik dried up suddenly. This spring had been tapped by the Japanese by means of a bore-hole - it was suggested that the earth movement probably blocked the pipe which was bringing the hot water to the surface.

17. 27th October 1957. A steam vent opened on the shore of Simpson Harbour near the Bougainville Company Wharf. Although none were recorded on that day, from September 1957 to March 1958, numerous small tremors with S-P intervals less than 10 seconds occurred (see Appendix 1). This seismic activity was particularly strong towards the end of December 1957. In January 1958 new upwellings of gas occurred along the foreshore of Greet Harbour near Rapindik.

18. Small disturbances resembling minor tectonic tremors were recorded at the same times as two waterjets were seen in Simpson Harbour (27th February 1959 and 23rd April 1959). There is no certainty that the events were in any way related.+

19. January 1960. Minor fluctuations of temperature occurred in Tavurvur volcano, some fumaroles exceeding 100°C for short periods. 13 small earthquakes with S-P intervals of less than 5 seconds were recorded at the Observatory.

20. August 1960. Downtilting of about 5 seconds of arc took place to the south at the Observatory and to the west of Rapindik. "Anomalous" tremors were numerous on the seismograms.

21. During the last 10 days of October 1960 marked tilt changes at the Observatory occurred as follows:-
the north-south component fluctuated through 7 seconds of arc and returned to normal : the east-west component dipped 8 seconds to the east. This trend continued until the end of November, by which time the down tilt to the east was 10 seconds of arc beyond the normal. ++

\+ During September 1959 another waterjet occurred which was accompanied by a tremor on the seismic records. This was a very short period signature similar to that obtained from an explosion. Numerous waterjets occurred which were unaccompanied by any such tremors.

++ A tilt in the same direction amounting to about 30 seconds of arc preceded the major earthquake of 14th January 1941.

On 15th November 1960 an unusual long period disturbance was recorded on the seismograph at the Observatory. Its direction of origin is believed to have been in an east or west direction from the Observatory. It could have been related in some way to the tilting.

22. 2nd-9th February 1962. Point No. 33 at Sulphur Springs increased in temperature from 44°C to 70°C. After 9th February it decreased gradually to a temperature of 54°C. A series of tremors commencing on 4th February in the area 5.2-5.7°S. 150.9 - 152.1°E. at depths about 80 kilometres culminated at 1855 hours G.M.T. on 11th February with an earthquake of Magnitude 6 (Berk.) at 4.5°S 153.5°E. (depth 100 kilometres). This was widely felt (at Rabaul, Intensity 6 (M.M.)). On 10th February a tremor of possible volcanic origin was felt at Taliligap (Intensity 4-5 (M.M.)).

23. Between 21st and 28th September 1962 an apparent sharp rise of ground of 20½ inches was indicated by readings of the tide stick at Tavurvur. Previous to this rise a sharp apparent fall had taken place.

On 12th September 1962 a small tremor occurred which was not recorded or felt elsewhere. Its S-P interval was 7½ seconds. Between 23rd September and 4th October a number of felt tremors occurred, the epicentres of which lay in an area between 4.0 - 5.9°S and 151.0 - 152.7°E (depths of focus ranging from 33 to 71 kilometres).

24. An apparent rise of ground took place at all tide sticks, except Toboi, reaching a maximum on 5th October, 1962. A small tectonic tremor with S-P interval of 9.5 seconds was recorded on that day.

25. An apparent rise of ground totalling 21½ inches reached a maximum on 19th October 1962 at Namanula Street Wharf, Matupi Island, Sulphur Springs and Tavurvur. Between 18th and 21st October three small tectonic tremors with S-P intervals of respectively 8.5 sec. 3.5 sec. and 10 sec. occurred. A sharp increase of temperature took place about this time at point 17 on the outer slope of Tavurvur Volcano. On 30th October 1962 a tremor of possible volcanic origin (that illustrated in Plate 1) was felt at the Rabaul Police Station. A second tremor, of possible volcanic origin since it was not recorded or felt elsewhere, was felt at Vunalama some 22½ hours later (Intensity 1 (M.M.)).

Although most of the cases listed above do not constitute more than remotely possible correlations between events, they are set down partly for completeness and partly to illustrate the extreme difficulty in correlating events of this kind.

With improved instrumentation at Rabaul it should be possible to determine local epicentres accurately enough in three dimensions to estimate whether events are coincidental or interdependant on one another. At the present stage of knowledge of seismic activity in the area it is not possible to determine cause and effect in more than an occasional sequence of events, and little can be done except to list possible cases in which some degree of causality may apply.

CHAPTER 4.

SEISMIC NOISE ON THE RABAUL SEISMOGRAMS, AND METHODS OF IDENTIFYING IT.

1. Description of Types of Seismic Noise on the Records

Identification of interference on the seismograms is an important part of the work carried out by the Rabaul Observatory. In order to evaluate what, if any, volcanic tremors occur in connection with the local volcanic centres, it is essential to identify, if not to eliminate, interference on the records.

Since 1950 a considerable amount of work has been done on the problem, chiefly by G.A. Taylor, M.A. Reynolds, J.E. Johnson, and J. Barrie. Elaborate tests have been carried out to determine to what extent vehicles and the Rabaul power house cause interference on the records. In January 1963, after months of work, it was at last discovered, primarily by Mr. James A. Hileman of Texas Instruments Ltd., that a striking class of disturbance on the seismograms was due, not to subterranean volcanic activity as had been previously believed, but to movement of shipping in Blanche Bay and Simpson Harbour.

The following seven classes of interference have been distinguished on the Rabaul records. They are due to:-

a) Industrial activity (including operation of heavy machinery, reciprocating engines in the power house, etc.)

b) Vehicles

c) Ships

d) Aircraft

e) Explosions of various kinds; including disposal of wartime ammunition and quarry blasts.

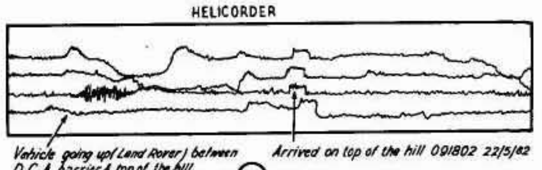
f) Movement of persons near the instruments

g) Instrumental defects

These seven classes are now described severally:

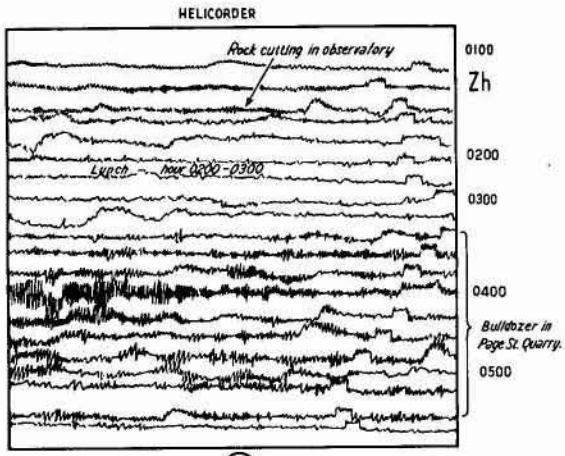
a) Industrial Activity. This class of interference on the records falls into two parts. On the one hand there is prolonged vibration which may be continuous for many hours and which is due to movement of vehicles and activity in working hours, and on the other there is the continuous operation of heavy reciprocating engines at the Power House. This latter potential source of interference has been critically examined by G.A. Taylor and has been found to have a surprisingly small effect on background noise level both at the Observatory and at Rapindik.

On the other hand the effect on the seismograms due to activity during working hours in the town is generally marked. It takes the form of continuous vibrations with period roughly constant on any one day but differing slightly from day to day and at varying localities. Normally it consists of a high noise level punctuated every two or three seconds by small groups of pulses of higher amplitude. The period of this kind of interference ranges from 0.4 to 0.7 seconds and is most commonly around 0.6 seconds. Plate 3 illustrates industrial interference of 0.6 seconds period at the Rapindik Instrument Station. Working hours are covered on the Seismograph by the top 7 lines and the bottom 2 lines. It will be noticed that it takes about one hour for the interference to build up to maximum amplitude. The onset of the



VEHICLE INTERFERENCE

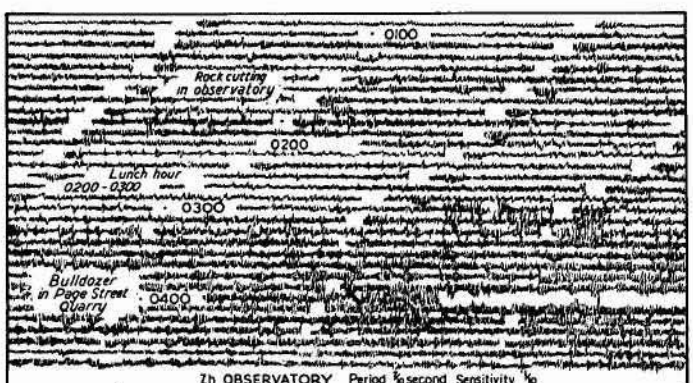
①



②

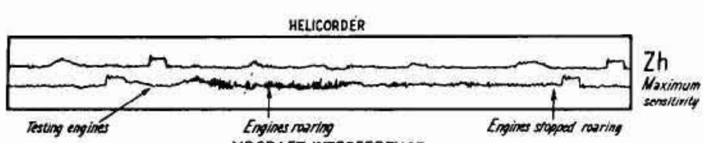
No's. 2 & 3 INDUSTRIAL INTERFERENCE

[Note: No's 2 & 3 illustrate the signatures of two kinds of noise recorded at the Observatory on 2 different instruments using vertical components. Between 0100 and 0200 hrs. GMT noise caused by operation of a rock-cutting machine in the workshop (particularly well shown on the Willmore record 3). Between 0330 and 0745 hrs. GMT noise is caused by a bulldozer operating in the Page Street quarry about ½ mile south of the Observatory. Note the quiet trace during lunch-hour]



Zh OBSERVATORY Period ¹⁄₁₀ second Sensitivity ¹⁄₁₀
VEHICLE INTERFERENCE

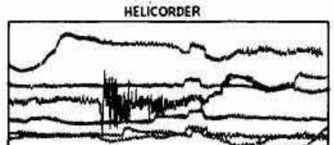
③



AIRCRAFT INTERFERENCE
Magnification about 1100

④

[Note: Effects at the Observatory apparently due to a D.C.3 aircraft testing engines prior to take-off at Lakunai airstrip, Rabaul. 1950 hrs. GMT. 28/5/62.]



EXPLOSION OF WARTIME AMMUNITION, NEAR VULCAN. Magnification abt 1100

⑤

Bismarck Sea earthquake at 0039 hours is somewhat obscured by the high level of interference. Compare Plate 4 which illustrates industrial interference recorded at the Observatory, where effects due to this cause are generally much less than at Rapindik. The interference illustrated is of 0.45 seconds period, and working hours cover the top 7½ lines and the bottom 2 lines on the Seismograph.

From time to time "industrial" interference is recorded which has a long-drawn out sinusoidal appearance on the records. The period of this is usually constant at about 0.5 seconds. Examples of this interference are illustrated in Plate 3 on the old short period Benioff Seismograph.

Operation of bulldozers in the Page Street quarry at the bottom of the caldera wall about half a mile from the Observatory has a marked effect on the Observatory seismograms. Plate 7 (Nos. 2-4) illustrates records made during earth moving operations in the Page Street quarry and also effects due to the operation of a rock-cutting machine in the Observatory workshop. The records are on the vertical components of the helicorder, Willmore seismograph and short period world-wide standardised seismograph respectively.

As already mentioned, effects due to the operation of power house machinery are practically indistinguishable on the seismograms. At G.A. Taylor's request, the reciprocating engines were mounted on insulated platforms, and this has cut down the amount of short period energy transmitted into the rock to the point where it attenuates below the microseismic level of noise before it reaches the Observatory. The new Power House is situated on unconsolidated material inside the caldera about half a mile from the Observatory. Tests using a portable Willmore Seismograph were made in November 1958 to determine the extent of interference at the old Power House, which was distant about a mile and a half from the Observatory, and in March 1961 at the new Power House. In April 1961 generators were installed in an automatic Power Plant on Observatory Hill. These were also mounted on anti-vibration platforms and no appreciable change in noise level was detected at the Observatory. Correlations have frequently been attempted between interference on the seismograms and periods during which the Power House generators have been running in bad adjustment. The only effects seen were due to switching on or off engines at the Power House and took the form of power surges on the Helicorder, which was out of adjustment. There was no appreciable effect on the seismometers.

A check was carried out in May 1962 to see whether any interference was caused by generators in the Coconut Products Ltd. Power House. Periods during which these engines were unsynchronised were scrutinised for interference effects on the records. In general no correlation was established. However between 0900 hours L.M.T. on 22nd May and 1400 hours L.M.T. on 23rd May 1962, when No. 1 engine, which vibrates more than the others, was on load, a very slight thickening of the trace was detected on the short-period Benioff records at the Observatory. Furthermore about 15 minutes after an engine was started up at Coconot Products Ltd., a low amplitude long-drawn out Sinusoidal harmonic disturbance commonly appeared on the Rapindik records.

It is known that movement of traffic, construction and other forms of "industrial" activity may cause local settling and tilting which is detectable on long-period seismographs (Richter, (46). W.A. Lynch in a paper on the effects of traffic and other disturbances on a seismograph at Fordham in New York state (34), mentions that there is a long-period component of traffic disturbance (period about one minute) to which the long-period galvanometer responds at its resonance frequency.

Something of this kind probably occurs in Rabaul, but is normally masked by the much more pronounced movement due to activity in the Observatory building. It is also known that the long period instruments can be effected by the resonance set up from time to time by the movement of shipping in Rabaul Harbour. This is discussed later in this section.

b) Vehicles. A distinct type of signature is produced by vehicles moving within about a quarter of a mile from a seismometer. This type of interference is characterised by very short periods (0.1 – 0.2 seconds). A typical example is shown in Plate 7 (No. 1); it was caused by a Landrover travelling uphill between the barrier at the Department of Civil Aviation parking bay and the top of the Observatory road. Note the spiky gradual emergence of the interference.

A characteristic feature of vehicle interference may be an apparent reversal on the records, so that the interference looks like an earthquake backwards. The example shown in Plate 1 (0841 hours) illustrates this tendency. Instead of running from left to right on the record the disturbance looks as if it runs from right to left.

Another example is shown on Plate 2, (1524 hours).

Effects are generally confined to the short-period seismographs. However there is a slight tilting effect on the long-period instruments, mainly on the horizontal components, when a Landrover is driven from the top of the Observatory Hill down to the Observatory building. This effect is much less than that produced by entering the building on foot.

Effects on the short-period seismographs are usually well-marked and can prove troublesome since they may mask other movement on the records.

Interference is generally detectable at the Observatory when a vehicle is about half way between Tunnel Hill and the turn-off to the Assistant Vulcanologist's residence, at which point it may assume proportions sufficient to mask other activity.

In passing it may be noted that a small grass motor mower can be detected up to about three-quarters of a mile from the Observatory. The effect is a very low amplitude, roughly "harmonic"+ wave train.

c) Ships. Under certain special conditions which are not yet properly understood, the movement of ships' engines in Simpson Harbour and nearby waters may cause a striking form of interference on the seismograms.

This type of interference is characteristically almost perfectly "harmonic" and takes the form of a series of sinusoidal "envelopes". Disturbances of this kind are referred to at Rabaul as "sinusoidal harmonics". Their origin was discovered only in January 1963.

Previously it had been thought that they might be due to movement of magma in underground chambers, and a great deal of work was done in trying to locate their source. This took the form of trying to record the disturbances on portable Willmore seismographs near the volcanoes and of analysis of their arrival times and amplitude ratios. All known forms of interference were eliminated, including the berthing of ships at the Main Wharf. It was not until a suggestion was made by Mr. James A. Hileman of Texas Instrument Ltd., that the cause could be ships at some distance offshore that a correlation was attempted between the disturbances and the records of the Harbour Master at Rabaul. It was quickly found that an exact correlation existed in a high proportion of the known events.

Plate 8 illustrates the most striking example of this phenomenon

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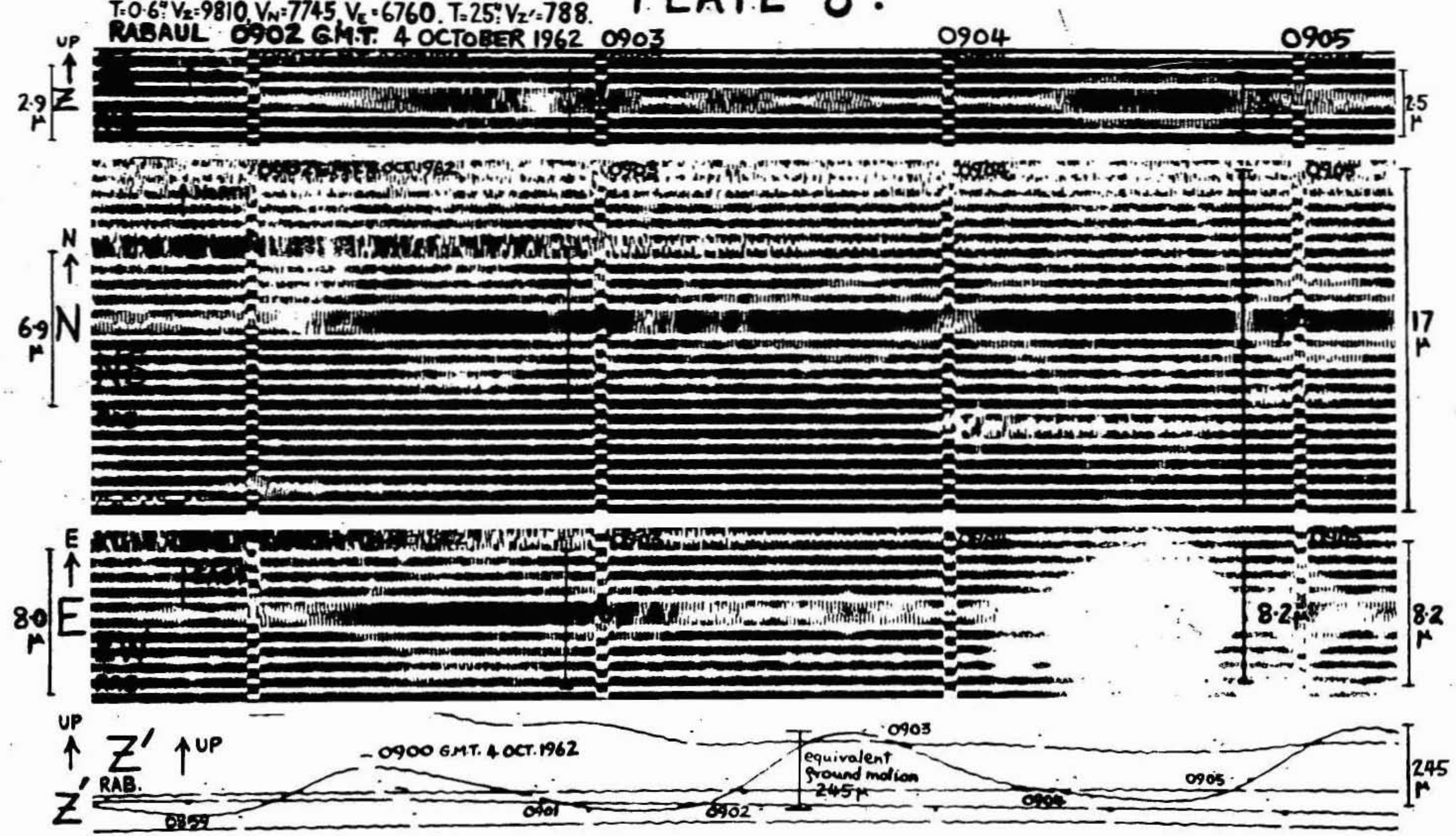
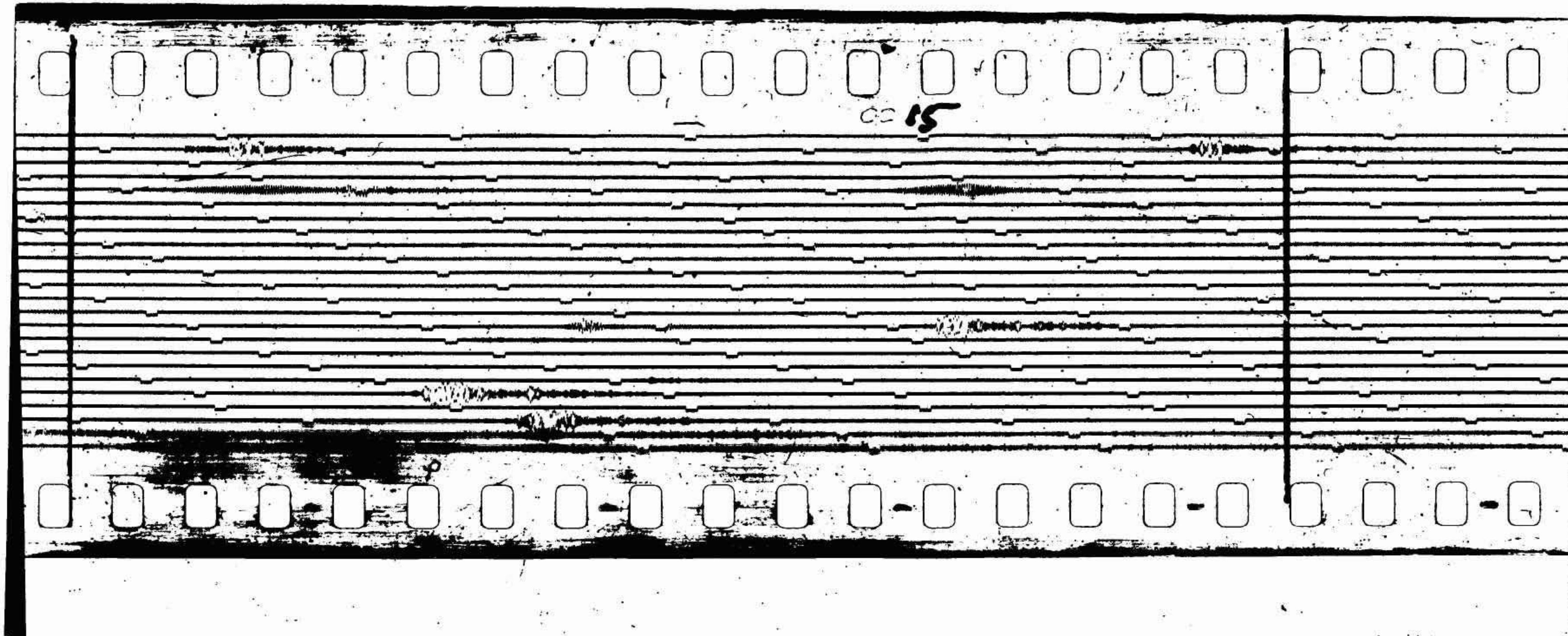
\+ "Harmonic" is used here to describe a vibration of constant period and fluctuating amplitude – editor.

PLATE 8.



3 COMPONENT SHORT PERIOD AND Z LONG PERIOD RECORDINGS OF "SINGING" CAUSED BY M.V. "SOUTHBANK" AT RABAUL.

PLATE 9.



Rabaul Observatory

M.V. "Eastbank" in the area one mile north of the Beehives (probably stationary).
Old Benioff Seismograph Z record 30/4/61. Illustrates "Ship Singing" at 0410 and 0413, a small tectonic tremor (S-P interval, 11½ seconds), at 0111, and "Anomalous Harmonic" Tremor at 0115, 1411, and 1907. The disturbance at 1409 is of unknown origin.

ever recorded at Rabaul.+ It occurred on 4th October 1962 between 0902 and 0906 hours G.M.T. and is believed to have been due to M.V. "Southbank", which cast off at 0845 hours and passed the Beehives at about 0900 hours G.M.T. on her way out of Blanche Bay. The disturbance reached its maximum amplitude at 090430 hours G.M.T. at which time "Southbank" was probably close to the Beehives.++

Appendix K is a catalogue of recorded harmonic sinusoidal disturbances at Rabaul. It is complete from January 1954 to January 1963 except for the periods January 1956 to January 1960 and 10th May 1961 to 16th September 1962. A total of 122 disturbances are listed, of which 59 can be correlated with the movement of shipping in Rabaul Harbour, with 48 there is no correlation, and with 15 there is either no record of ships' movements for the dates concerned or the records have not been examined. Of the 48 cases for which there is no correlation 7 are known to have occurred while ships were in port at anchor (it is probable that their engines may have been running), and 2 can probably be correlated with movement of the Observatory temperature-run boat which visits the Beehives - Vulcan area between 8 and 9 a.m. on Fridays. Furthermore 3 of the 15 cases for which the records have not been examined can be attributed to the Observatory temperature-run boat also. Thus 71 out of 110 disturbances for which records of ships' movements exist have been found to correlate well with these movements, and 39 show no correlation. Since, however, movement of small inter-island boats was not recorded, it is at least possible that these remaining instances could be correlated with them.

A study of Appendix K shows that of the 55 cases, in which a fairly accurate estimate can be made for the position of the ship considered to have been responsible for the disturbance, the great majority represent instances in which the ship was moving away from the wharf towards the "leads" position (roughly one mile north of the Beehives). Thus 28 of the 55 were apparently caused by ships moving from the wharves to the "leads", and a further 12 were caused by ships moving from the "leads" to the wharves.

There are 4 cases in which the disturbance was apparently caused by ships' engines when the vessels were tied up to a wharf, usually shortly before sailing: those concerned were "Delos" and "Southbank" at the main wharf, "Chitose Maru" at the Wreck Wharf, and "Ivybank" at an unspecified wharf. 2 vessels, "Asuma Maru" and Laganbank" apparently caused disturbances when anchored in midstream.

7 disturbances, including the major one caused by "Southbank" which is illustrated in Plate 8, were apparently caused by vessels moving between the "leads" and the entrance of Blanche Bay. A further 2 were caused by vessels coming into harbour, on the seaward side of the "leads". The two largest ships to have entered Rabaul Harbour in recent years, "Oronsay" and Orcades", both caused sinusoidal disturbances, "Oronsay" at the "leads" at the moment of sailing, and "Orcades" near the Beehives on her way out of Rabaul Harbour.

The two vessels which caused disturbances at the greatest distance from the wharves were "Lederwaal", at 30 minutes outward bound from the "leads" (she may in fact have remained stationary for some time), and "Langkoeas", 16 minutes outward bound from the "leads".

\+ Plate 9 is a more typical example of marine interference. It was recorded on 30th April 1961 on the old Benioff seismograph at the Observatory (on all 3 components) and on a vertical Willmore seismograph at Rapindik. It was due to M.V. "Eastbank" in the area north of the Beehives.

++ An intersection based on relative amplitude ratios at the Observatory and at Rapindik (see pp. 76-77) gave an intersection in Simpson Harbour (see figure 24) in an area of between 22 and 25 fathoms depth sloping gently to the east, with about ½ mile of water at a comparable depth in that direction.

The great majority of disturbances occurred when vessels were between 3 and 13 minutes outward bound from the wharves, which would put their position in the general area of the Beehives.+

Characteristics of the sinusoidal vibration are as follows:- the duration of any one event may range from about half a minute to more than three quarters of an hour. Trace amplitudes may vary widely (see Appendix K). Periods of the vibrations range from 1/6 to 1¼ seconds and may vary in any one disturbance. Overlap or mutual interference between vibrations of two different periods has been frequently observed. This usually takes the form of short period vibrations between 1/5 and 1/3 second which start on a background of longer period vibrations (about 2/3 second), which may persist for sometime. Overall period of the sinusoidal "envelopes" depends on amplitude of the vibrations; it varies between 4 and 180 seconds, but is most commonly between 10 and 30 seconds.

The larger sinusoidal disturbances can affect the horizontal components of the long-period standard seismograph. A minute "hedgehog" effect, with amplitude no greater than the width of the trace and vibrations perfectly harmonic in form, has been observed on several occasions. There is a single striking instance of an apparent effect on the vertical long-period component. A remarkable wave train of period 2 minutes 45 seconds occurred over nearly the same time during which the major disturbance of 4th October 1962 was recorded. The long waves commenced at 0859 hours G.M.T., about 2 minutes before the short period seismographs recorded the movement, and ended at 0925 hours about 10¾ minutes after the short-period movement had apparently ceased. Their maximum trace amplitude was 14 mms. : as this lessened at the end of the disturbance the period increased to 3 minutes 35 seconds. Such an event on the vertical long period seismograph is unusual. It bears some resemblance to the effect of movement of people in the Observatory building but is of far greater regularity. It was established that there was nobody in the Observatory++ at the time. Its occurrence at this time could have been coincidental, but the writer can suggest for it no alternative explanation, other than that there was a long period component in the oscillations.

The similarity between many of the sinusoidal disturbances and regular vibration caused by an undamped galvanometer suggests that the phenomenon is essentially one of resonance. A disturbance is apparently set up in the water by the movement of a ship's propellors, causing it to resonate. At or near resonance frequency this movement couples to the underlying rock and is transmitted probably as both body and surface waves. The actual amplitude of the disturbance probably depends on the number of revolutions per minute of the propellors which will determine the time at which resonance takes place. The recorded amplitude presumably depends on the peak frequency response of the seismograph.

The period of the disturbance must depend ultimately on the dimensions of the water layer in which resonance occurs. Since it is known that most cases have occurred when ships were on the wharf side of the Beehives, where the water is not more than 50 fathoms deep, and moreover that the phenomenon can occur close to the shore in water not more than 10 fathoms deep, it is evident, when the period of the waves is considered, that the disturbance must be set up in a dominantly horizontal direction.

\+ Reliable amplitude ratios and derived directions were obtained for the disturbances of 28th September and 4th October 1962. The intersections are plotted on Figure 24. See also Chapter 4 section 3. The disturbance of 28th September occurred in about 33 fathoms of water over a westerly sloping trough about ½ mile wide, which deepens off to the north to 36 fathoms. See footnote on p. 65 for 4th October disturbance.

++ This is confirmed by the horizontal components which showed no effects due to persons in the building.

At the limiting velocity of sound in water, 1½ kilometres per second, a vibration of 1/6 second period (the smallest observed) would not resonate in a vertical direction in water less than 375 feet (62½ fathoms) deep, while vibrations of 1 second period, which are commonly observed, would require a depth of water of 2,250 feet.

From the approximate area through which most of the ships are passing when resonance occurs the distance to the shore is roughly as follows:- in a westerly direction 5,300 feet, in an easterly 4,700 feet, to the north 8,100 feet and to the south 11,000 feet. These distances are all greatly in excess of what would be required to set up the observed periods of the vibrations. Even the longest period observed would require only about 1,800 feet.

Thus there appear to be two possible solutions to the problem. Either the resonance takes place in a horizontal plane across the deepest part of Simpson Harbour north of the Beehives, vibrating for example at about the level of the 35 fathom line for the 1 second period oscillation, and at about 45 fathoms for the 1.6 second period waves, or there is a near surface propagation of waves from the ship to an obstruction such as the Beehives. Although the exact position occupied by ships when resonance occurred is not known, it is probable that in most cases they were more than 1000 yards from the Beehives, which would rule out this latter solution.

In passing it should br noted that there is of course no perceptible effect on the tide gauge records due to marine interference phenomena. The greatest actual ground movement recorded was a little less than .008 mms. on 4th October 1962.

The estimated position of ships that have caused resonance in the Harbour make it clear that the phenomenon can occur in varying depths of water and at varying positions. From the fact that interference can be caused both by ships leaving and entering the Harbour it is evident that there is no single direction in which the energy must be propogated in order to cause resonance.

The evidence of the relative amplitudes on the horizontal components both at the Observatory and at Rapindik indicates that the energy which is transmitted from the water to the shore or underlying rock is propagated both as longitudinal and transverse waves. A study of Appendix K will show that maximum amplitude recorded has more often been on the north-south component at the Observatory. Maximum amplitude has, however, been frequently recorded on the east-west component at the Observatory and the north-south component at Rapindik. Before the origin of the disturbances became known a very careful analysis of their wave motion was carried out. Evidence was found that the maximum amplitude oscillates from one component to the other. The maximum phase of the disturbance caused on 21st October 1962 by "Orcades" leaving Rabaul Harbour was recorded on the north-south component of the Willmore seismograph at Namanula at a time when the east-west amplitude was almost zero. Similarly, the maximum east-west amplitudes occurred when the amplitude on the north-south component was almost zero.

The conclusion was reached that most of the energy was transmitted as longitudinal waves, but that an important part was transverse. Much of the energy near the beginning of the disturbances was apparently in the vertical sense (see Plate 8, Z component, 090240 hours G.M.T.)

A certain consistency was evident in the order in which first arrivals and maxima occurred at the various stations. Both first arrivals and maxima occurred generally at the Observatory before they did at Rapindik (or at Namanula). The disturbance of 30th April 1961 (see Plate 9) was unusual in that the first arrival at 0401 hours G.M.T. occurred at Rapindik well before anything at the Observatory, although the sinusoidals that followed closely afterwards at 0410 and 0413 hours were recorded earlier and better at the Observatory than at Rapindik. Apparent anomalies of this kind led to the conclusion that the tremors originated within the caldera area and were recorded only close to their point of origin. Since the maximum effects at the Observatory and Rapindik showed no relation to observed travel times in the area, it was thought that activity probably started in one area and migrated to another after a lag of a minute or more. All this appeared to strengthen the hypothesis that the tremors were due to subterranean volcanic activity. Finally the conclusion was reached that the point of origin lay either in the north-east part of the caldera or in the area north of the Beehives, depending on whether the movement was respectively transverse of longitudinal. It was noted that the average order of first arrivals at the stations was almost exactly the reverse of the order in which maxima occurred at the stations. This fact lent support to the idea that both transverse and longitudinal waves occurred.

After it had been discovered that shipping was responsible for the disturbances, a Willmore seismograph was operated (on 31st January 1963) at a site on the small Beehive during a period of 18 hours in which "Bulolo" and "Lindenbank" left harbour and "Shansi" and "Fleetbank" berthed. However no sinusoidal interference was recorded at the Observatory and the instruments on the Beehives failed to produce a readable record.

It is to be hoped that future operation of a Seismograph at this locality may be able to shed some light on the nature of the special circumstances without which, and in the great majority of cases of ships entering and leaving port, no disturbance is registered at the Observatory or at Rapindik.

Analogous disturbances to the "sinusoidal harmonics" at Rabaul have been recorded in other parts of the world.

Mr. Hugh Doyle and his fellow workers in the Geophysics Department of the Australian National University in Canberra, who were kind enough to give the writer the benefit of their advice on this problem, pointed out that similar vibrations are commonly recorded on the N.S.W. network of instruments. They have been correlated both with heavy trucks on highways in the vicinity of the seismometers and with trains on the Canberra-Sydney main railway line.

Plate 10 illustrates a high-amplitude disturbance caused by the evening train from Canberra to Sydney passing Inveralochy Seismograph Station, N.S.W., at about 1 mile distance, and an almost sinusoidal disturbance which was probably due to a freight train or to a heavy truck on the highway.

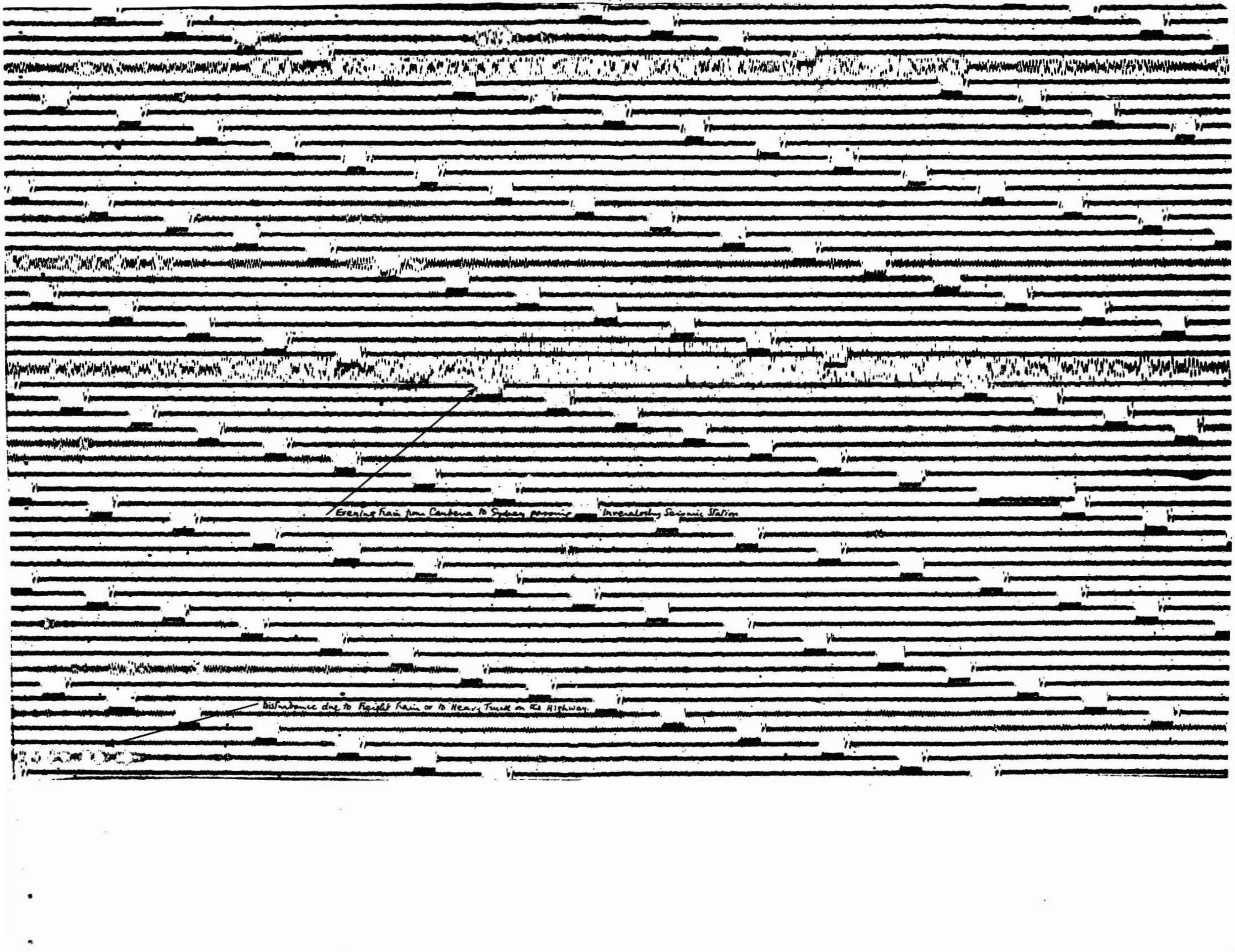
This latter movement has a period of 1/5 second and its similarity with the Rabaul marine interference is somewhat misleading on account of the much greater recording speed of the Inveralochy seismograph.

Mr. Doyle has also found that explosions of depth charges at sea some 150 miles from the seismometers are recorded with nearly sinusoidal movement. He suggested that this might be due to the effect of the water layer on the transmission of the energy. He pointed out that such a phenomenon was well-known in explosions carried out during offshore seismic surveys.

Many investigations have been made of this phenomenon, which is commonly referred to as "singing". "Singing" has been defined as "the phenomenon that produces sinusoidal seismic records, or records showing simple combinations of sinusoids".

G.C. Werth, D.T. Liu, and A.W. Trorey (63) found that the simple concept, that singing was due entirely to water-borne energy repeatedly reflected by the surface and the bottom in the area of the explosion, failed to fit their experiments. They found that an area in which singing occurred could grade into one where shooting gave clear reflections untroubled by singing without any change in depth. In the area that they

PLATE 10



Evening Train from Canberra to Sydney passing Inveralochy Seismic Station
Disturbance due to Freight Train or to Heavy Truck on the Highway.

PLATE 11

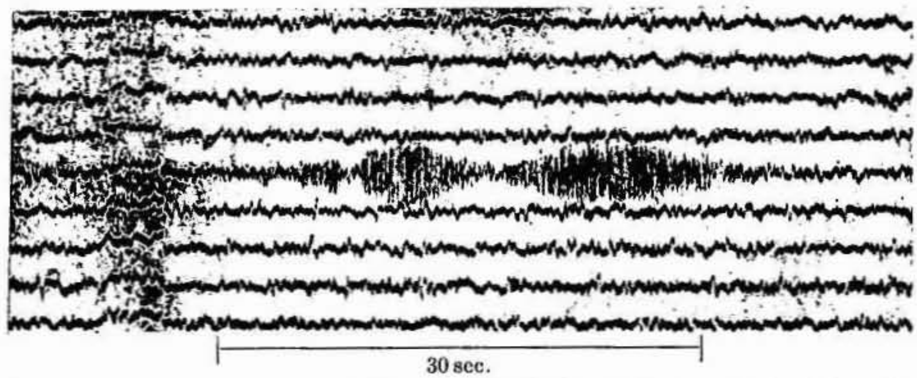


Fig. 3. Maximum phase written by heavy freight train passing about 400 yd. from the seismic station at 35 to 40 mi. per hr.

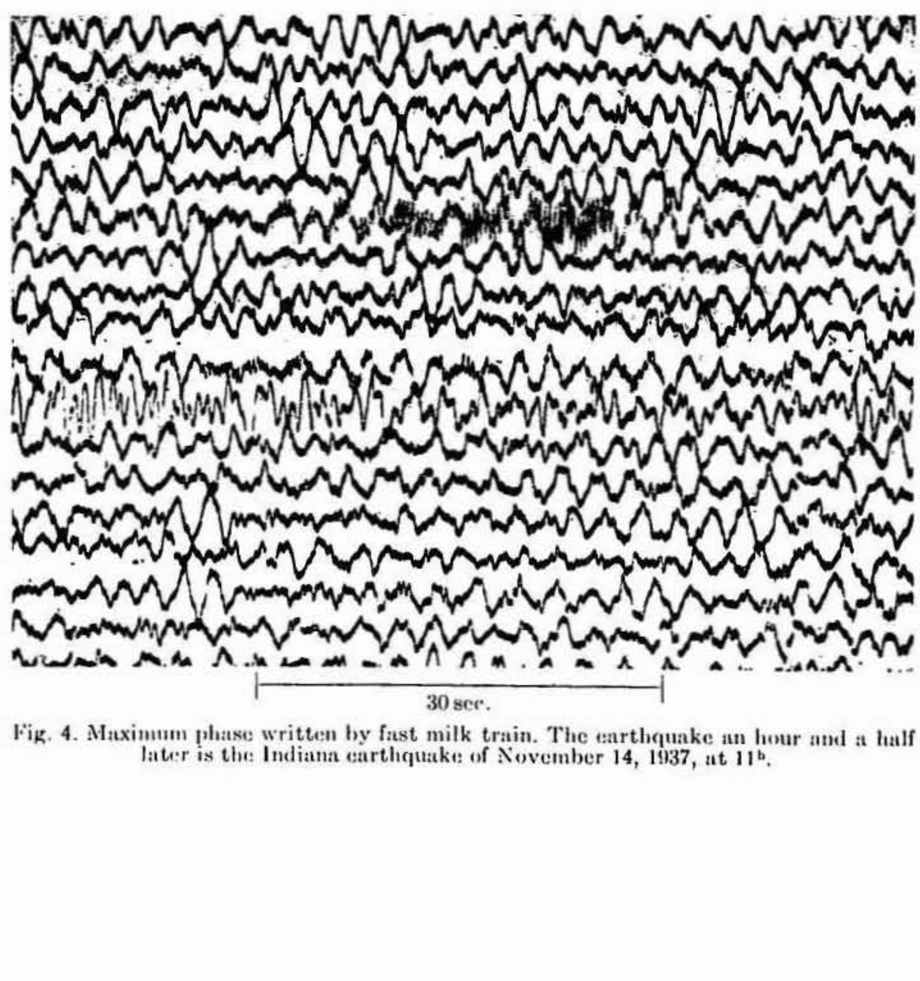


Fig. 4. Maximum phase written by fast milk train. The earthquake an hour and a half later is the Indiana earthquake of November 14, 1937, at 11^h.

studied they found that the frequency corresponded to the third harmonic of a fundamental, the wave length of which was four times the depth of the water.

They proposed that the reflections, following the shot, themselves excite an accoustic resonant layer formed by the surface of the water and the bottom. D.T. Liu (32) showed that energy remaining solely in the water after an explosion could not be responsible for singing after ½ second or so had elapsed, and that an extended source of some kind was necessary to account for the phenomenon.

Werth and his co-authors pointed out that ordinary ocean waves of the standing type, as proposed by M.S. Longuet-Higgins (33) as a source of microseisms, could provide such an extended source, and that reflections from deep reflectors could provide another.

At Rabaul the movement of ships' propellors is of course an extended source. Werth (et al.) deduced an amplitude depth relationship which gave a maximum amplitude at 1/3 of the depth and at the bottom, and a minimum at the surface and 2/3 of the depth. This relationship was worked out in rather shallower depth than that part of Simpson Harbour where most of the marine interference appears to originate.

M.M. Backus in a paper entitled "Water Reverberations - their nature and elimination" (1) points out that purely water-confined energy should give average velocities of about 5,000 feet per second. He found that the average figure lay between 6,000 and 8,000 feet per second (it was determined for the Persian Gulf as about 7,000 feet per second to a depth of about 1,000 feet. He concluded that much of the effects were due to reflections from the rocks below the ocean floor. Owing to the presence of an energy trap caused by the strong flat reflecting surface of the water-air interface and a strong bottom reflector, which is present in many areas, a pulse, such as that caused by dynamite exploded in the water, is reflected successively in the non-attenuating medium bounded by the two strong reflecting surfaces, with a time interval equal to the two-way travel time, and an amplitude decay dependant on the reflection coefficients.

There is some evidence at Rabaul for the validity of this idea of a strong bottom reflector, in the strong vertical pulses that are sometimes seen early in the sinusoidal disturbances. Thus the strong pulse at 090239 hours on 4th October 1962 (see Plate 8, Z component) may have represented a genuine structural layer in the underlying rock. According to Backus' paper subsurface energy should become dominant early on the record.

That not all strong developments of sinusoidals are marine evident in a paper by William A Lynch on local disturbances recorded at Fordham, New York State (34). Heavily laden freight trains of about 20 wagons travelling at 35-40 m.p.h. register up to 1½ miles from the seismograph station, which at its closest point is about 400 yards from a railway. The maximum phase is sometimes strongly sinusoidal and bears a close resemblance to the marine sinusoidal interference at Rabaul (see Plate 11). The upper illustration is so similar that the overall period of the "envelopes" (about 15 seconds) is even the same as numerous examples of Rabaul marine interference. The period of the individual vibrations, however, is only about 0.15 seconds which is substantially less than that recorded in Rabaul marine interference. Again, the similarity is somewhat misleading on account of the greater drum speed of the Fordham recorder.

Mr. Lynch states that, while sometimes the period remains constant throughout the passage of the train, at other times the period diminishes and the amplitude increases as though resonance were reached.

It is proposed that the sinusoidal marine vibrations at Rabaul should from now on be termed "ship singing" in order to keep descriptions of the phenomenon in line with previous researches.

d) Aircraft. Aircraft testing engines on the Rabaul airstrip at Lakunai, about 3 miles from the Observatory, have been tentatively correlated with small movements at the Observatory and Rapindik.

Plate 7 (No. 4) shows a possible correlation between movement on a vertical component Benioff seismometer (recording on a Helicorder) and a D.C. 3 aircraft testing engines at the south-east end of the airstrip prior to take-off. The disturbance was also recorded on the world wide standardised short period instruments at the Observatory. The period is a little less than 1/3 second.

It has been suspected for sometime+ that some of the long-drawn out, low amplitude, sinusoidal industrial disturbances recorded both at the Observatory and at Rapindik, have been caused by aircraft engines testing on the airstrip. It is possible that some of the low amplitude disturbances listed in Appendix K were due to the same cause. Their times often correspond well with aircraft taking off at Lakunai.

This correlation has, however, never been established beyond doubt.

e) Explosions. Quarry blasts and explosions of wartime ammunition are frequently recorded on the Rabaul instruments. Plate 7 (No. 5) represents the explosion of about 1000 lbs of ammunition at a site near the Racecourse on the south side of Vulcan. It shows a rather longer period movement than that which is characteristic of explosions, being about 3/10 second, whereas the majority of explosions have periods of less than 1/5 second. It is also unusual in showing an initial dilatation whereas most explosions record with a sharp compression. As already mentioned in a previous section explosions show certain characteristic reflected phases at Rabaul (see page 52). They always show a well developed P phase. It is not known to what extent, if any, actual airwaves due to explosions affect the Rabaul instruments. They have been recorded on seismograms in other parts of the world, especially those due to volcanic explosions among the gases emitted from a volcano. It is probable that the effect would be similar to that described above (page 57) for thunder.

Quarry explosions in the caldera wall on the south-east side of the North Daughter, about 1¼ miles from the Observatory, have a remarkably small effect on the seismograms. The normal daily explosions cause small, very short period oscillations with the greatest trace amplitude characteristically on the east-west component of the short period Benioff seismograph, thus suggesting that most of the energy is transmitted along the caldera wall as Rayleigh or longitudinal waves. Actual ground movement is usually about .0003 mms.

Explosions of dynamite in the harbour during Japanese salvage operations were recorded with high amplitudes at the Observatory. Explosions in Karavia Bay are, however, very weakly recorded.

Explosions carried out during a seismic survey at Rabaul in October 1960 (see G.A. Taylor, B.M.R. unpublished report, Travel Times, October 1960) were remarkable for development of sinusoidal movement in some cases. This occurred with shots south of Matupi Island 32 seconds after P arrival. The period of the P phase was about 0.18 seconds.

\+ A low amplitude long-drawn out sinusoidal at 1951 hours G.M.T. on 21st July 1954 may be correlated tentatively with an aircraft on the ground. It was recorded best on the vertical component of the old Benioff seismograph at the Observatory (trace amplitude of 1¾ mms.). It was recorded very weakly on both horizontal components.

f) Movement near Instruments. On short period instruments the effects of persons moving in the vicinity of the seismographs resemble those depicted in Plate 7 (No. 3) on the Willmore vertical component (recorded during rock-cutting in the Observatory workshop). The interference characteristically takes the form of short period isolated pulses. A minute harmonic disturbance of 3 seconds duration was recorded on the vertical Willmore seismograph, when the Observatory was entered.+

On the long period instruments, however, there is a very marked effect, due probably to a minute tilting of the Observatory building. The entrance of even one person into the building characteristically causes the two horizontal long period components to "drift" so that the trace is quite sharply offset by about 15 mms. The effect is detectable even when a person does not enter the building but merely walks around outside. It is most marked when the darkroom (immediately above the instrument vault) is entered or when movement is on the steps that lead down to the vault.

There is usually no effect on the vertical component of the long-period seismograph.

g) Instrumental Defects. Numerous cases of so-called interference are in reality associated with instrumental defects. Chief among these is an under-damped or undamped galvanometer which may accentuate sinusoidal oscillations. These were frequent on the very early records at Rabaul (November 1953 to February 1954) and were fairly common up to about the end of 1955. They can usually be identified by the fact that they occur on only one component.

Sometimes the vibrations take the form of intermittent thickening of one of the traces which may persist for several hours. In this case the fault is usually a loose galvanometer connection.

For a time the Helicorder at the Observatory was operated with the A.C. balance circuit out of adjustment. During this period the automatic cutting-in of the water-pumps at the Observatory and the Vulcanologist's residence caused a sharp dip followed by a bulge on the record. A deflection also usually occurred when pumping stopped.

Switching the air conditioner on or off had a similar effect, while the cutting-in and out of the condenser in the air-conditioning caused a very marked pulse on the record.

2. Travel Time Tests and Results.

No travel times have been accurately determined in the Rabaul area. Recently, however, J.A. Brooks has published independant values for the velocity of P_n and S_n waves in the New Guinea-Solomon Islands region (4). He obtained a mean surface velocity of 7.95 kms. per sec. for P_n waves and 4.35 kms. per sec. for S_n waves. From his results he postulated the existence of a low velocity channel at a depth of about 125 kms. below the area, in which P wave velocity is 7.6 kms. per sec. and S wave velocity 4.20 kms. per sec.

There have been three attempts at Rabaul to measure the velocity of seismic waves directly, none of which have been entirely successful.

On 6th October 1959 an Army bomb disposals squad blew up 3 large bombs on the west side of Tavurvur volcano. G.A. Taylor attempted to record the moment of detonation by means of a stopwatch and a chronometer. The human factor, concerned with the effect of a loud explosion imminent at close range, is too great to record such an event with the necessary accuracy. The attempt was abandoned, and on the next occasion recourse was had to a

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+ Passing within 10 yards of this instrument caused a harmonic vibration of period about 0.12 seconds.

system of radio-controlled time-checks and triggering of the explosions by means of a chronometer.

These second tests have been described by G.A. Taylor (unpublished report, October 1960). They were carried out at Rabaul during a seismic survey by the Geophysical Section of the Bureau of Mineral Resources during September and October 1960. Velocities determined from explosions at shot-points+ from Karavia Bay to Pila Pila covered a wide range, 4,800 - 1,200 feet per second. Most values, however, lay between 7,000 and 10,000 feet per second and the average value was about 8,000 feet per second. (approx. 2.6 kms. per sec.).

During the third set of travel time tests, which were carried out at Rabaul between 29th November and 1st December 1962 in conjunction with an Army bomb disposals squad, an attempt was made to improve the accuracy of timing by carrying out time-checks with a portable Zenith radio in the field. A chronometer and shot box were again used to detonate the explosions.

The shot point used was on the east side of Tavurvur volcano close to the road to Escape Bay. It was determined by the Department of Lands, Mines and Surveys as 7,443 metres on a bearing of 133 degrees 30 minutes from the Observatory. Good time control was maintained throughout the experiment. It was considered that by using a stopwatch, reading to 1/10 second, in conjunction with a radio time signal, the time on all chronometers was known with an accuracy of ± 50 milliseconds.

All available instruments were installed at various locations around Blanche Bay. These locations were changed, in most cases, after each of the three explosions; the maximum number of instruments were operated with three components in order to learn as much as possible about the relative amplitude relationships as well as about the travel times. The Rabaul Police Department kindly undertook to maintain radio contact with the Observatory so that the shots could be visually monitored by means of the Helicorder ++ in order to ensure that no earthquakes spoilt the records. Finally the explosions were timed for after midnight so that the background level of noise should be as low as possible.

Unfortunately on 29th November, before the Police had been requested to assist, when the radio contact was in the hands of a local Taxi company, liaison broke down at the critical moment and the explosion was detonated during an earthquake. On this occasion the mechanism of the shot box worked perfectly.

On 30th November the shot box circuit was incorrectly linked and consequently the time of the explosion was not recorded. On 1st December the spark jumped the chronometer contacts and detonated the explosion a few seconds before the contacts closed. This occurred during a countdown by the writer with the aid of a stopwatch so that the time of the detonation was known within half a second. Charges were all of the order of 1,000 lbs of high explosive.

Useful results were obtained from the explosions of 30th November and 1st December, since the difference in the arrival times at the various stations, particularly between the Observatory and Rapindik, could be used to determine approximate travel times. The difference in arrival time between Rapindik and the Observatory was measured as 0.45 seconds (2 determinations): on 30th November a lower figure of 0.20 seconds was obtained but the reading was suspect.

+ Shotpoints are marked on the locality map, figure 3.

++ The only Observatory instrument on which the actual recording of earthquakes can be watched as they occur.

Using the best fit for the differences in arrival time between Rapindik, the Observatory, Nonga, Nordup, Matupi Island and Namanula, and the values given below+ for the distances between the stations, the following approximate velocities were deduced:-

for P, 21,800 feet per sec. = 6.65 kms. per sec.
for S, 16,700 feet per sec. = 5.09 kms. per sec.++
for L, 6,800 feet per sec. = 2.07 kms. per sec.

for a strong reflection (? mantle reflection) 4,100 feet per sec. = 1.25 kms. per sec.

It would be advantageous, if future tests are conducted, to operate a seismograph as close as practicable to the shot point, so that in the event of advanced firing by the shot box-chronometer circuit, the origin-time of the explosion may be read directly from the records.

It is unlikely that really good results can be expected unless seismographs with much higher recording speeds can be used.

Recent experiments in New Zealand (see G.A. Eiby and R.R. Dibble (12)), to determine velocities in the area were carried out using paper speeds of 50-195 mms. per second with time marks emplaced on the records every 1/50 or 1/100 second.

Recent studies in the United States have indicated that in the eastern Pacific area there is good agreement between observed arrivals and the Jeffreys-Bullen tables beyond an epicentral distance of 20 degrees. As far as has been determined in the Rabaul area, this is true also.

3. Methods Based on Locating Directions of Tremors

A considerable amount of work has been carried out on the Rabaul records to determine to what extent the measurement of trace amplitudes+++ on two horizontal component instruments can give a true direction of origin for an earthquake. Three series of dynamite explosions were carried out in Simpson Harbour specifically to test amplitude relationships, and in addition much information was derived from records of bomb explosions designed primarily to record travel times, from Japanese salvage explosions, and from quarry blasts and other minor explosions in the caldera area.

A workable relationship between direction of origin and amplitude ratios was obtained. It was used successfully to determine the source of the sinusoidal disturbances before it was known that they were due to "ship singing", and it has been applied, the writer believes with success, to the study of the "anomalous" swarm tremors.

The study of amplitude relationships and directions based on the first movement of a disturbance is notoriously unreliable. Richter (46) points out that considerable error may result in the estimation of directions from first movements owing to horizontal refraction in regions of complicated structure. That this occurs in New Guinea is certain. The major earthquake of 24th March 1962 (see Figure 6) was recorded with clear directions and amplitudes of first movement on the Rabaul long and short period instruments

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+ Station	Approx. distance from Shot point	Instrumentation
Observatory	24,300 feet	3 comp. Standardised short period instrument
Rapindik	11,950 feet	old model 3 comp. short period Benioff
Namanula	16,250 feet	3 comp. Willmore
Matupi Island	10,150 feet	2 comp. Willmore (horizontals)
Nordup	16,950 feet	2 comp. Willmore (horizontals)
Nonga	36,500 feet	3 comp. Willmore

++ This high value is undoubtedly due to incorrect interpretation of the records - Editor

+++ It should be noted that throughout this paper the term 'amplitude' refers to peak to peak measurements of vibrations, not peak to midpoint of the trace (amplitude ÷ 2).

and a reliable S-P interval was obtained. However the epicentre that was derived from these readings was offset 6 degrees from the U.S.C. and G.S. epicentre. Similar results are often found for earthquakes in southern New Ireland. An interesting contrast with the earthquake of 24th March 1962 was the case of the Aitape earthquake which occurred 2 days earlier, at 1513 hours G.M.T. on 22nd March 1962. This earthquake was recorded with initial dilatation to the north-north-west on the short period instruments (nearly 90 degrees in error) but the direction (and S-P interval) as determined on the long period instruments gave an epicentre which was less than 10 miles distant from that given by the U.S.C. and G.S. A possible reason for this apparent anomaly between the two earthquakes may lie in the fact that whereas the line joining Rabaul and the epicentre of 24th March crosses first the Baining Ranges of the Gazelle Peninsula and then the line of the Northern Ranges of New Guinea (Finisterre Mountains), that joining Rabaul and Aitape (No. 2 on Figure 1), on the far north west coast of New Guinea, crosses only open sea between the two points. If this hypothesis is correct it indicates that horizontal deflection of earthquake waves is at a minimum in this direction, which, from the point of view of the determination of direction made for the anomalous tremors, is encouraging, since these were found to lie along almost exactly the same azimuth.

Horizontal deflections have proved troublesome in other parts of the world. Sassa in Japan found deflections of as much as 40 degrees in the ficinity of Aso volcano and correlated them with a system of great fractures (49).

Austin E. Jones in Hawaii noted that the variation of static magnification between 112 and 120 on his seismographs produced an error of 2½ degrees in the directions as determined by vectors of the amplitudes of first movement, and that actual errors due to other sources were 5-10 times this. Accordingly he used directions only as a check on locations made by other means (30). He also experimented with the amplitude ratios of P to S, which he plotted against distance from the Observatory. However, his results seemed to indicate that the ratio might be a constant and thus of no value. Furthermore, he derived an experimental ratio of the periods of S to P of 1.732 which enabled the periods of the S waves to be deduced, even if unreadable, from the periods of the P waves. This result he found, did not apply to teleseisms where the S period is many times that of P. He attempted to derive a depth or distance function from this period change but was unable to find a constant relationship.

At Rabaul it was discovered early that simple plotting of vectors for earthquakes based on the relative horizontal ratios yielded hopelessly misleading results. Near earthquakes were often misplaced up to 20 degrees from their true locations. This lead to a search for a reliable amplitude ratio in the limiting case when one horizontal seismometer is at right angles to the direction of an earthquake and the other is parallel to it.

Figure 23 shows the results that were obtained from 3 series of test explosions in Simpson Harbour. For the first and second series, which were carried out on 15th December 1962, the maximum number of Willmore seismometers available were operated as horizontal instruments at varying angles to the direction of the explosions. The explosions were carried out by Commonwealth Department of Works at a point near the middle of Simpson Harbour, 3300 yards due south of the Observatory and due west of Rapindik instrument station, and near the Beehives 5450 yards due south of the Observatory. Explosions were alternately 8 and 6 sticks of dynamite.

Figure 23 shows the wide spread of amplitude ratios obtained at various angles to the explosions at the Beehives, and the very small spread for ratios obtained from the midpoint harbour explosions. Only the amplitude ratios of L max (the maximum phase on the records) are plotted on Figure 23.

The third series of explosions were carried out, again by Commonwealth Department of Works, on 22nd December 1962, after an unsuccessful series on 19th December. Each explosion was of 4 sticks of dynamite close offshore at the north-western end of Lakunai airstrip, 950 yards due west of Rapindik instrument station, where all available instruments were installed as horizontals in a wide variety of orientations. Good readings were obtained on almost all components.

A wide spread of ratios was obtained (see Figure 23) but averaged readings agreed fairly well with those obtained in the earlier series of tests. The line marked "Best result" is the mean position of the lines representing the average distribution of ratios determined from the north-south/east-west components of the old Benioff Seismograph and the north-south/east-west and north-north-west/east-south-east components of the Willmore Seismograph. It is suggested that it should be used in any attempts at direction finding in the Rabaul area.

Figure 23a has been drawn from the actual angular errors which have been found using the ratio curve marked "Best results" in Figure 23. It includes data derived from quarry explosions and the bomb disposals series of explosions between 29th November and 1st December 1962, as well as from the 3 series of explosions described above. An attempt was made to use amplitude ratios derived from the old Benioff horizontal records at the Observatory made during the 1960 Bureau of Mineral Resources travel time tests. Ratios were found to be apparently random at distances greater than about 5,000 yards. For certain localities, notably the area of the Burnt Wharf on the east side of Simpson Harbour, ratios did not conform to pattern at distances as small as 2,300 yards. The determined ratios do not apply outside the caldera where the limiting value appears to lie in the vicinity of 1:5 rather than 1:1.4. Evidently the method is too inaccurate to be employed at distances greater than about 4,000 yards from the source disturbance. Beyond this point there is no relationship between distance and degree of error to be expected. A study was made of a total of 40 Japanese salvage explosions at two of the sites nearest to the Observatory (No.s 5 and 8, see Figure 3). At site No. 8 at the north-west corner of Simpson Harbour, only about 1,850 yards from the Observatory, all ratios were found to be unusually low, and the majority of the explosions gave the ratio 1:1, which is to be expected for disturbances at an angle of 45^{o} to the seismometers.

This result can be explained by postulating that the dominant north-south longitudinal waves were refracted horizontally at some point in their passage to the Observatory. The only likely point for this to occur would be the caldera wall, which on other evidence has been suspected of having a polarising effect on seismic waves.

Ratios derived from the explosions at Site No. 5, in the north-east part of Simpson Harbour, about 2,000 yards from the Observatory, were found to agree in a number of cases with the experimental ratios derived from the airstrip explosions. However in some cases the angular divergence was as great as 29^{o}. In all cases the north-south amplitude was increased at the expense of the east-west one (the reverse of the situation for site No. 8). This situation is probably due to a structural feature in the area (a possible one would be the presence of a dominantly north-south striking fault along the east side of Simpson Harbour).

The study of the Japanese explosions confirms the conclusions reached previously that most energy, at least from explosions, is transmitted as longitudinal waves.

In this connection it is interesting to note that G.A. Eiby and R.R. Dibble (12) in New Zealand found that the S phase in explosions carries less energy than the P. At Rabaul the P phase is also strong. Maximum amplitudes appear in the L waves which are dominantly longitudinal.

The structural implications of this study were so interesting that the writer searched previous determinations of amplitudes for an explanation of the directional bias noticed in the results from some areas.

Japanese salvage explosions at a total of 7 sites were studied, together with records of the 1960 and 1962 travel time tests. Results are plotted diagramatically on Figure 24. The strongest indication of the presence of some structure is in the north east corner of Simpson Harbour, where the results from two Japanese salvage sites consistently showed higher amplitudes on the north-south component at the Observatory, whereas the highest amplitudes were to be expected on the east-west component. By contrast the explosions at sites 1-3 showed a pronounced bias in the east-west direction.

Not all the 1960 seismic survey explosions give consistent results with the Japanese salvage explosions, particularly around Matupi Island and in Greet Harbour. It is interesting, to note that an explosion carried out in Sulphur Creek gave a strong bias to east-west directed energy as recorded at the Observatory.

The only marked effect of the 1962 bomb disposals explosions west of Tavurvur was on the Observatory, Rapindik, Namanula and Nordup stations. The bias was to the north-south at the Observatory and Rapindik, and very markedly to the east west at the other two stations.

It is probably this kind of effect that causes a station to the north of an explosion point to show highest amplitudes on the east-west component. The apparent refraction by the caldera wall may in fact be refraction along faults cutting the Rabaul caldera, and it is possible that the structural pattern within the caldera may be complex.

The alternative explanation, that explosion energy is transmitted both as longitudinal and transverse waves, either of which may cause maximum ground amplitude at a station, is the writer believes, carrying the idea of the existence of surface waves whose maximum amplitude oscillates from one component to the other rather too far. All the evidence indicates that, although waves of this type exist, maxima are always produced by longitudinal waves, so that the greatest amplitude at any station should be on the component which is most nearly parallel to the direction of origin of the disturbances. Any apparent anomaly has most probably a structural explanation.

The apparent structural anomalies naturally limit the usefulness of the amplitude ratios illustrated in Figure 23. Probably the high error with increasing distance away from the source is largely to be explained on structural grounds. Furthermore, the relationship having been determined mainly at Rapindik, where evidence of bias exists, the limiting ratio is itself probably not applicable to the whole of the Rabaul caldera.

The recent cases of ship singing in Simpson Harbour provide a clear indication that areas in which bias is shown in one direction may give place close by to areas showing bias in the other.

Thus the disturbances of 28th September, 4th October, 12th October and 21st October 1962 were recorded at the Observatory without bias. With the exception of 4th October when the indicated direction was due south, the other 3 disturbances gave identical ratios of 1.35:1, which correlates with an angle of 6° from the north-south direction. On the other hand although the singing on 28th September, 4th October and 12th October (for "Fern Star") gave no bias at Rapindik, that on 12th October (for "Southbank") and on 21st October gave a pronounced bias to the north, which was repeated at Namanula. On 28th October the ship singing recorded with pronounced bias to the east at the Observatory and to the north at both Rapindik and Namanula.

The conclusion is inescapable that there is an area in the middle of Simpson Harbour in which structural features have a pronounced effect on the directions of transmission of seismic waves, at one point causing strong bias to the north at Rapindik, and at another no bias, and at one point strong bias to the east at the Observatory, and at another no bias.

"Fern Star" and "Southbank" must have been in different positions between the main wharf and the "leads" when singing was caused, unless they were facing different ways and the transmission of the singing was strongly directional. On the face of it this latter hypothesis seems the most probable, but unfortunately, as the exact position of the ships are not known, the question must remain unsettled.

The intersections derived for the origin of the singing on 28th September and 4th October 1962, which were apparently recorded without bias at both the Observatory and at Rapindik, are plotted on Figure 24.

An attempt was made at Rabaul to use the apparent travel time of the L max phase on the records, which gave a consistent figure of 900 feet per second in the bomb disposals series on 30th November and 1st December 1962, as an indicator of distance travelled from the origin point of a disturbance. The L max - P interval was taken for a number of explosions and a plot was made of this interval against distance in the caldera.

An approximate figure of L max - P = 48 seconds was derived for the greatest L max - P interval consistent with the origin of a disturbance within the caldera. This figure is not reliable since evidence was found in a study of explosions at the Japanese salvage sites 2 and 4 that the apparent velocity at which the maximum phase travelled could be as low as 750 feet per second.

In conclusion, it is evident that there is no simple relationship between direction of origin of a disturbance and amplitude ratios on horizontal seismometers at Rabaul. A workable relationship can be deduced, but errors average as much as 15 degrees at 5,000 yards. This confusion is attributed to refraction of simple wave trains at structural interfaces in the caldera with consequent distortion of amplitudes on the records.

CHAPTER 5.

CONCLUSIONS AND RECOMMENDATIONS

1. STRUCTURE OF THE AREA IN THE LIGHT OF REGIONAL SEISMICITY

a) Depth of Discontinuities

Depths to discontinuities in the Rabaul area are not known. Recent studies by J.A. Brooks of the Geophysical Observatory in Port Moresby (4) have indicated the existence of a low velocity channel at a depth of about 125 kilometres (where velocity of P is about 7.6 kms/sec.), but no accurate figures are available for the depth of the Mohorovicic discontinuity.

From preliminary analysis of the records made by the Bureau of Mineral Resources seismic field party at Rabaul in 1960 it seemed that the depth to a discontinuity was about 15-20 kilometres. Strong reflections were received from a layer at about that depth. It is probable that the phase identified as "mantle reflection" at Rabaul during the 1962 bomb disposals tests was reflected from the same layer.

It is frequently found that arrival times at Rabaul and Port Moresby do not agree with the standard tables or with U.S.C. and G.S. epicentres. This is particularly noticeable in the case of Port Moresby where arrivals from earthquakes in areas north and east of the main axis of New Guinea often seem to indicate unusually slow velocities. There is frequently better agreement between travel times determined at Rabaul and Djakarta, and Rabaul and Manila, than there is between Rabaul and Port Moresby.

It should be noted that there are at present no detailed gravity readings available for the greater part of the area.

Gutenberg (25/26) has suggested that the low velocity layer suggested a layer of weakness, and Richter (46) has pointed out that this correlates well with the placing of earthquake foci at that depth. Certainly in New Guinea and the surrounding area the majority of earthquakes occur at intermediate depth (70-300 kms.)

In many other parts of the world most ordinary earthquakes originate above the Mohorovicic discontinuity,+ but taking this level as 15-20 kms., in the New Britain area it is evident that very few earthquakes, which are large enough for their epicentres to be reported, originate above this level. The shallowest so far recorded, at a depth of 13 kms., below the Bismarck Sea, is barely below the estimated limits. It is unlikely that all Bismarck Sea earthquakes showing the characteristically strong development of surface waves originate above the discontinuity, since depths of focus for these earthquakes extend down to over 40 kilometres (see Appendix H).

It is probable that the class of "anomalous" earthquakes recorded at Rabaul originate above the discontinuity. Their similarity to the K3-K4 type earthquakes described by Austin E. Jones (31) after Wadati(62), by analogy, may indicate that they originate, assuming an

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\+ C.F. Richter (46) gives the following range of depths for the Mohorovicic discontinuity for various types of tectonic setting:- beneath the oceans, 10-11 kms. (as low as 6 kms. in some places), beneath continents, 30-40 kms., and in the root zones of continents, 50-60 kms., New Zealand, about 30 kms. Hawaii (J.P. Eaton (11)), 14.8 kms.

epicentral distance of about 40 miles from Rabaul, at a depth of about 12 kilometres.

b) Structural evidence in the Rabaul area from Seismic data

Figure 2 represents a possible interpretation of the structure in the Rabaul area. All known epicentres in the area as well as these estimated at Rabaul, have been plotted; most of the faults are hypothetical. However there is geological evidence for the pair shown near Ramasaka in the south-east Baining Ranges (N.H. Fisher (16/17)) and for the Warangoi - Keravat fault, the Wide Bay - Open Bay fault, and the Weitin River - Tambakar River fault.

There has been no attempt to show structure in the area of the Father volcano, or to link this area with the volcanic centres at Rabaul. It is possible, however, that the north-east/south-west trending fault zone at Ramasaka may continue down the line of the Toriu River to the Father volcano. There is no geological evidence for this, and recent field work in the area has rather tended to accentuate the importance of north-south/east-west lineaments transverse to the direction of the New Britain arc, (Dr. E.K. Carter and Mr. E.J. Best, (Personal communication)).

The hypothetical fault line, shown running from the north of the Duke of York Islands to an intersection with the Wide Bay/Open Bay fault, is marked by a considerable number of epicentres, of which the largest was the earthquake of 9th September 1950 near the Duke of York Islands. It appears to be tectonically active, whereas the Warangoi-Keravat fault which it displaces has had no recorded movement on it for some time. From geological evidence, even the great earthquake of January 14th 1941 occurred well to the south of the latter fault.

There is at present no direct evidence of the mechanism of faulting in the area, beyond the geological evidence quoted by Dr. N.H. Fisher in his account of the 1941 earthquake,+ in which downthrow was to the west. It is not known whether there was a strike-slip component in the faulting.

The evidence that can be adduced in support of any structural analysis of the area is very limited. The two most active areas in the north New Britain-New Ireland region are evidently in Wide Bay and to the east of southern New Ireland. There appears to be an area around Namatanai, possibly an extension of the Duke of York Islands fault, in which earthquakes, in the deep and intermediate range occurring between New Ireland and Bougainville, are characteristically felt. This fact probably has a structural explanation, and the area may be near the intersection of two or more faults.

2. GENERAL SEISMICITY AND VULCANICITY

The great majority of the earthquakes which occur in E. New Guinea fall into the category described by G.S. Gorshkov in Kamchatka (23) as 'volcano-tectonic'. That is to say they are all directly caused by tectonic processes but all occur in zones which have an intimate relationship with those of the volcanoes in the region.

Earthquakes occurring in the Western Highlands (area No. 23, Figure 4), and near Wau, represent, as it were, relict movement in areas which were once characterised by active volcances. They are analogous with H.H. Hess' serpentine belts, which he described as "fossil orogenies". (28).

A minority of the E. New Guinea earthquakes are volcanic, due directly to the expression of volcanic forces in the crust. Those which

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+ (15)

have been felt in the Rabaul area have already been listed (page 26 and following). They are of rare occurrence and almost always have an immediate and direct connection with impending eruption. However minor volcanic tremors may occur near Taliligap, Vunadidir and Toma without surface expression of volcanism. They are probably related to movements of magma at depth.

Elsewhere in the Territory it is possible that the pattern of volcanic earthquakes follows that of eruptions, with the exception of two areas, the Willaumez Peninsula on the north coast of New Britain and Fergusson and Normanby Islands in the D'Entrecasteaux Group. In both these areas "volcanic" earthquakes, characterised by small radius of perceptibility in which intensities are often high, and by failure to be recorded at the Port Moresby and Rabaul seismological stations, are fairly frequently reported. Dormant or extinct volcanoes are to be found in both localities. Between August 1961 and November 1962 a close watch was kept on Mount Victory, on the north coast of Papua, to determine whether any movements were taking place which might indicate impending renewal of activity. The volcano has been dormant since a violent Pelean eruption in about the year 1890, in which a large number of people were killed. A Willmore seismograph was installed at Utan Plantation near Wanigela, together with a pair of tiltmeters, the instruments being maintained and operated by Mr. and Mrs. A.A. Imlay, the manager of the plantation and his wife. No volcanic earthquakes were definitely identified, although movements were registered by the tiltmeters which were consistent with rise and fall of the mountain.

Volcanic earthquakes have preceded and accompanied activity at Mount Lamington, Manam, Bam, Tuluman and Langila[+] volcanoes, and earthquakes of possible volcanic origin have occurred near Bagana and Balbi on Bougainville.[++] None are known in connection with the Father volcano, where, if they occur, they should be reported felt at Ulamona, some ten miles distant.

It may be noted that earthquakes described and illustrated by G.S. Gorshkov (23) in connection with the eruption of Bezymianny volcano bear a remarkable similarity to some of the "semiharmonic" "anomalous" tremors at Rabaul. Their origin, however, is considered to be entirely different.

The degree to which "volcano-tectonic" earthquakes effect, or even cause, volcanic eruption is one of the major fields of vulcanology. Mr. R. Priam[+++] has recently found a connection between earthquakes in the deep and intermediate range and volcanic eruption in the New Hebrides (42). G.A. Taylor is working on this problem, at present in New Guinea.

A point of great practical importance is how to distinguish between purely volcanic earthquakes and 'volcano-tectonic' earthquakes when both are recorded close to a volcano.

In an area such as New Guinea where there may be a great distance between seismographs, the criterion of failure to register at other stations may be inadequate. It becomes a vital matter to know the accurate depth of focus of the earthquake. This cannot usually be determined without a network of at least three stations.

\+ (53-56)

++ Rabaul Final Bulletins.

+++ G.S. Gorshkov notes that earthquakes at depths of about 50 kms. affected the course of the eruption at Bezymianny (23).

J.P. Eaton (11) has written, on Hawaian volcanism, "earthquakes identify regions where the rock is yielding to the strain before the encroaching magma or to the wholesale deformation caused by its retreat". They also identify regions in which strains are being accumulated due to long drawn out, deep seated tectonic processes, and regions in which readjustment is taking place due to alterations of load or to movements in other areas.

This raises the whole problem of progression in earthquakes. In any study of this kind it is almost impossible to separate causality and coincidence. However, after some years it is to be hoped that a pattern in New Guinea earthquakes may emerge, which may lead to a better understanding both of the connection which exists between widely separated areas, and the way in which the relief of strain in one region may build it up in another.

At the present time only the roughest estimate can be made of the rate at which strain accumulates in different parts of the region, of the areas which are most affected, and of the amount of energy which is released by earthquakes. Areas in which earthquakes are most frequent are not necessarily those in which the most strain is being accumulated. The confining pressure of the overlying rock must vary widely in different areas and at different depths, and the previous history of a locality will determine how it withstands the slow accumulation of pressure.

Thus areas which are cut by numerous faults on which previous movements have often taken place will withstand stresses less firmly and yield sooner than those where structure is more massive and fewer lines of weakness in the rocks exist. However, unless stresses are directed into a weaker environment, leaving the massive rocks as a bastion round which the weaker structures are wrapped, the time will come when the load has reached such gigantic proportions that the rocks will ultimately yield, producing a major earthquake.

Thus without exact measurements of the strain present in the rocks, which is still beyond the power of seismology to achieve, it is rash to state that any area is unlikely to produce a major earthquake, particularly in a region as tectonically active as New Guinea, where records go back such an insignificant number of years.

At the present time it is impossible to say more than that there undoubtedly is a connection of the most direct kind both between earthquakes in different parts of the region and between earthquakes and volcanic activity. Time and time again it has been noticed at Rabaul that earthquakes in Bougainville are followed by earthquakes in the Sepik district or along the north New Guinea coast.

The deformation of the region by faulting, expressed as earthquakes, and by plastic yielding of the rocks at depth, is a continuous process. The accumulation of strains and their relief in one area eases the stress in another and accentuates it in yet another, building it up slowly so that even the slight effect of the sun and moon can probably cause the ultimate fracture, and perhaps with it the renewal of a cycle of volcanic activity.

It is this that makes the study of seismology of such absorbing interest to a geologist.

3. <u>GENERAL DISCUSSION OF GEOGRAPHICAL RELATIONSHIPS</u>

The seismically active zones of E. New Guinea may be correlated to some extent with geological processes of known age. These range from the extinct vulcanicity of the Mount Hagen and Wau areas to the current faulting that is apparently taking place near the deep trenches to the south-west of Bougainville and the north-east of New Ireland.

A glance at Figure 4 immediately suggests that the tectonic features of the region as revealed in earthquake epicentres are not as simple as one would expect from many standard accounts of island arc structures in the Pacific.

H.H. Hess and J.C. Maxwell (28) describe the main features of the region as the expression of two great orogenies, that of the late Jurassic, and of the late Cretaceous to Tertiary. The axis of the former period of orogeny they place following the main range of New Guinea and the line of the Louisiade Archipelago to a point north of Rennell Island in the Solomon Islands. That of the latter period they place following the line of the north New Guinea coast along the south coast of New Britain to south of New Ireland where it continues to the south-east as the Solomons arc. They point out that the New Britain, Solomons and New Hebrides arcs all have the peculiarity of facing away from the Pacific into the Solomons Sea.

It is evident from the epicentres of current earthquakes that the present seismic zone is not everywhere constant in dip. South west of Bougainville the trace dips nearly vertically. Shallow, intermediate and deep earthquakes occur with epicentres superimposed on each other. In New Britain, on the other hand, the seismic trace appears to dip fairly gently to the north-west. Benioff and others have postulated that these seismic traces are gigantic thrust planes, and this hypothesis is supported in the New Guinea - Solomon Islands region by the presence of ultrabasic belts and by much other geological evidence. Thus Dr. R. B. Thompson (58) has shown that ultrabasic belts in the Solomon Islands were emplaced along arcuate thrust planes. There are two such zones, a major one with ultrabasic outcrops in Choiseul and Santa Ysabel and a minor one with outcrops in Guadalcanal and San Cristoval.

Similarly the ultrabasics, which outcrop on the New Guinea mainland on the north side of the Owen Stanley Range and in the vicinity of the Bismarck Range, probably indicate the locus of an ancient axis of orogeny.

Recent volcanoes normally follow a zone along the inside of the arcuate structures, and this relationship is brought out in Bougainville and New Britain, where structure is comparatively simple. Both represent regions overthrust to the south west and south east respectively, and both show characteristic foredeeps. Since movement was, and possibly still is, to the south west and south east respectively in these two areas, one would expect the zone of volcanism on the inner sides of the arcs to be tensional environments.

Evidently the tensional zone behind the New Britain arc extends to the north west to the vicinity of Wewak, where it is cut off by the line of the outer volcanic arc of the Bismarck Archipelago. This arc, although convex to the north, has on its northern side a wide zone of Pleistocene Volcanics with remnants of Tertiary volcanics further south. Movement to the north-east is not consistent with the present pattern, so that the direction of thrusting has either changed since the Pleistocene, or the Outer Volcanic Arc, represented by the Admiralty Islands and New Ireland, has been faulted out of its original position. It is at present marked, across the northern margin of the Bismarck Sea by a line of shallow earthquakes. It is therefore probably not a major thrust plane. The explanation that it is due to the presence of a tensional environment behind the New Britain arc is unlikely since it follows the line of the outer arc more closely. The conclusion seems inescapable that it is the last relic of some ancient structure of which New Ireland was also a part.

Similarly the New Guinea mainland shows no simple arcuate structures. It is not, as it is often described, a northward fronting tectonic arc. The present active zone of the Sepik-Ramu-Markham valley is the locus of deposition of much material and is probably a zone of subsidence, rather than thrusting, accompanied by possible large strike-slip movements. The area is not at present associated with volcanics, the Inner Volcanic Arc being genetically part of the New Britain Arc. Extensive uplift has occurred up to Recent times along the north coast of New Guinea.

The extensive vulcanism in the New Guinea Highlands (Mount Hagan to Wau) and the Papuan Plateau (Mt. Bosavi) suggests block rather than arcuate structures. However the Tertiary Volcanic deposits of the Northern Ranges represent an ancient arc, much broken up by later faulting. The absence of deep earthquakes beneath the New Guinea mainland probably indicates that the major thrust planes in the area are no longer active.

The Papuan arc has also been much broken up by faulting. It fronted originally to the north, as is shown by the presence of Tertiary volcanic rocks near the south coast. There are few earthquake epicentres in this area. An interesting feature of the northern scarp of the Owen Stanley mountains in Papua is the presence of apparent strike slip faults of very Recent appearance. There are many such minor instances of the apparent discordance between conspicuously young topography and the areas in which earthquakes are taking place.

There is an urgent need in New Guinea for a great deal of research into the problem of the mechanism of the regional earthquakes, which at present is unknown. As a sideline of such a study it would be possible to delimit the areas of compressional and tensional environment which would greatly aid the study of present day seismicity.

4. RECOMMENDATIONS

(a) Instrumental Requirements

The setting up of a three-station net to cover the Rabaul caldera, which is already on its way to completion, should solve many of the outstanding problems encountered at Rabaul. For the first time it will be possible to locate the origin of earthquakes accurately in three dimensions.

With all three stations operating on standard time from the Observatory, and modern instrumentation in the form of Benioff Seismometers, it should be a simple matter to determine times of arrival of the "anomalous" tremors. Within a short space of time enough information should be collected to superside that which has been presented in this paper, and to confirm or deny the conclusions that have been reached regarding westerly origin of these tremors.

A three-station net should also confirm the dominant longitudinal nature of transmission of earthquake energy in the area, greatly assist in determining the rate of dissipation or fading out in one direction, establish to what extent refraction by structural interfaces within the caldera distort seismic waves, and identify the strong "mantle reflection".

If standard time channels can be provided for other, perhaps temporary, sites+ in the caldera, the Willmore seismographs that were used to determine most of the data in this paper could be used to supplement the permanent stations. The study of the origin of the Dominica tremors (see page 55) was carried out using a 4-5 station net (G.R. Robson, personal communication), and obviously the more stations that are available the more reliable will be the results.

The Japanese geophysicist, Dr. Takashi Kizawa, who made observations at Rabaul during the war, noticed that S-P intervals of earthquakes, apparently of volcanic origin, shortened before the eruption of Tavurvur in 1943. His tiltmeters at the Sulphur Creed Observatory recorded their greatest variation prior to the start of activity, with upward movement of the crater followed by gradual collapse after eruption. Dr Kizawa is at present working on the 1943 Rabaul records.

\+ Also the permanent site suggested for Rabalanakaia crater.

In the operation of tiltmeters at Rapindik and the Observatory a number of difficulties have so far been encountered, which have led to some of the results being of dubious value. Thus tilt readings in the north-south direction at the Observatory have probably been influenced to an unknown extent by caldera collapse, a purely secondary process due mainly to weathering and unconnected with any fundamental changes which may be taking place within the caldera.

At Rapindik failure of the rubber connecting hoses and sealing rings caused erroneous readings between July and December 1961, amounting to a cumulative apparent rise in the direction of Vulcan of 25 seconds of arc. In the same month a fall to the south of 3 seconds at the Observatory was attributed to caldera collapse.

There is an urgent need for a seismograph with a fast paper speed of recording, in excess of 60 mms. per second, for study of travel times at Rabaul. The present instrumentation is inadequate for really accurate determinations of this kind.

G.S. Gorshkov (23) suggested in a recent paper that vulcanological observatories should be equiped with barographs and microbarographs. The former are capable of recording explosion waves of powerful near eruptions, and the latter those of weak local explosions and powerful distant ones. An anemometer would be of value in studying the Rabaul microseisms.

G.A. Gamburtsev (22) has suggested an interesting method of determining directions of earthquakes based on "azimuth seismic stations", or seismometers arranged in particular directions. It is not certain that his results would apply, but the paper is mentioned in case a programme of research should ever be initiated into the subject at Rabaul.

Finally, if there is reason to believe that differential movement is in fact taking place in the caldera, it would be invaluable if a second continuously recording tide gauge were installed, for example on Namanula Street Wharf.

(b) Analysis of Small Tremors and Disturbances

It would be of great value both to future research at Rabaul and to those seismologists in other parts of the world who are interested in the seismic problems of New Guinea, if periods and trace amplitudes of phases, particularly at the beginning of earthquakes, could be recorded as a matter of routine. Recent research in other parts of the world has tended to stress the importance of period changes, especially in the field of determination of earthquake mechanisms.

Great importance is also attached to periods in such work as that of Daisuke Shimazuru (51) on volcanic microseisms (recorded not further than 600 metres from the craters).

At present little is known of the structural layering in the New Guinea area so that any recording of such phases as Pn, Pg, P^+ etc., is likely to be of great value. It may be possible to distinguish volcanic and 'volcano-tectonic' earthquakes (see Chapter 5, section 2), both by the period of the vibrations and by the reflected phases that occur.

The earthquakes described by G.S. Gorshkov in Kamchatka (23)++ as "volcanic" were strikingly different from his "volcano-tectonic" ones, which had a sharp beginning in both P and S with a period of about 0.2 seconds. They showed a more emergent beginning in both P and S, longer periods, and "a peculiar maximum phase after preliminary phases". Unless

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++ This paper, in quarto typescript form, should be in the Rabaul Observatory close to the point of origin they are not felt so readily as 'normal', "volcano-tectonic" earthquakes, on account of their longer period.

Useful results have been achieved in Hawaii, Japan and California (see Austin E. Jones (30)) by measurement of the natural period of the ground, through studies both of microseisms and of local earthquakes. Variations have been attributed to differences in underlying structures.

J.P. Eaton (11) attaches importance to a study of the phaseless seismic unrest which he calls "spasmodic tremor" (similar to "harmonic tremor"). In Hawaii it characteristically accompanies the deep earthquakes for many hours during each swarm, "providing additional evidence that these swarms are related to movement of magma at depth".

Care should be taken in any future study of the "anomalous" tremors if determinations based on relative amplitude ratios are used. The writer has found that there are a number of pitfalls associated with this line of approach. The rapid decay of energy in one direction may distort amplitude ratios at a recording station, and refraction by structural planes may alter the directions from which energy from a disturbance would ordinarily reach a station. However, providing recordings can be made as close as possible to the source, and at all events within 5,000 yards, it should be possible to use results determined in the 1962 series of tests to estimate directions of tremors.

If a catalogue, for example of the daily numbers, of the "anomalous" tremors can be kept, it is possible that over some years a pattern may emerge relating them to local tectonic earthquakes or to lunar-solar periodicities. As Figure 15 shows, no such correlation has yet been established for these tremors.

If the conclusions regarding origin of the "anomalous" tremors to the west of Rabaul are correct, it should be possible to confirm them by operating a Willmore seismograph for a time at a site on Watom Island or, for example, near Cape Liguan.

As a major project, it would be of enormous value to determine the systematic mean deviation from standard travel time tables (Jeffreys and Bullen, Eiby and Muir), by means of a statistical analysis of arrival times from known epicentres (see J.A. Brooks (4)). The amounts by which Rabaul arrivals vary from the tables may not be the same as that which applies at Port Moresby. Accuracy of the U.S.C. and G.S. epicentres are given as + ¼ degree. Ultimately it should be possible to construct a special set of travel time tables for Rabaul in the same way as has been done in New Zealand (Eiby and Muir+) and New South Wales (H. Doyle).

With regard to the problems presented by "interference" at Rabaul, little is still known of the effects due to aircraft, both on the ground and in the air++. Nor has it been definitely confirmed that small ships can cause "ship singing". In particular there is evidence to suggest that this phenomenon may have been caused by the movement of the Observatory temperature-run boat, but no definite correlation has even been established.

It would be of the greatest interest if "ship singing" could be recorded on a seismograph on the Beehives. As already mentioned, an attempt to do this early in 1963 was unsuccessful. Before any final analysis of the phenomenon can be made, the exact positions of the ships responsible, their orientations, and, probably, the number of revolutions per minute of their engines, would have to be ascertained.

\+ These tables contain a description of the methods employed in New Zealand in determining local epicentres.

++ Effects due to aircraft passing overhead are sometimes visible on seismograms recorded at the Australian National University in Canberra. (H. Doyle, personal communication).

(c) Relative Importance of Seismic, Geological and other Methods of approach.

A wide variety of approaches are possible in the study of local earthquakes, interference and volcanic tremors at Rabaul. The complementary methods of regular measurements of temperature and continuous seismic recordings have been used with success for many years, supplemented by measurements of tilt and observation of gas emission at the volcanoes+.

Owing to the lack of staff and the very high pressure of work at Rabaul and elsewhere in the Territory, there has been little work carried out on the detailed geology and structure of the caldera area. The survey carried out by Mr. F.E. Studt (52) to explore the possibilities of using hydrothermal power at Rabaul raised many interesting questions regarding local structure which have never been satisfactorily answered.

His suggestion that magnetic and resistivity surveys of the area might help to delimit areas in which the greatest amount of leaching has taken place was implemented in 1960 during the seismic survey. They were of value in mapping underground extensions of the thermal areas.

Final results of the seismic survey carried out in 1960 were published as B.M.R. Record No. 1962/9 ("Rabaul Geothermal Investigation, New Britain, 1960" by W.A. Wiebenga and E.J. Polak). Three major shear planes (running N/S or NW/SE) were located near Sulphur Springs. Seismic velocities ranging from 2000 to 11,000 feet per second were encountered.

A careful study of apparent tidal movements at Rabaul may be invaluable as a method of detecting relative movements in different parts of the caldera. Information derived by this means is hard to come by unless the most accurate theodolite surveys can be carried out. Such a survey, as suggested in the past by G.A. Taylor, may be a conclusive way of proving or disproving small movements, particularly if carried out by night when difficulties due to refraction do not apply.

The results of the recent oceanographic survey of the Rabaul caldera by H.M.A.S. "Paluma" will, when they are released for publication, provide data by which an exact analysis of ship singing may be possible.

An extremely interesting line of approach, and one which would be of great value in an area such as Rabaul is the absolute measurement of rates of movement in regions which are tectonically active. The suggestion was made some time ago at Rabaul that measurements be carried out regularly with a tellurometer between New Britain and New Ireland in order to measure the differential movement, if any, between the two islands. This could be carried out, for example, at six monthly intervals, and after any large earthquakes in the region. Regular readings across St. Georges Strait from Cape Gazelle to the New Ireland coast north of King Bay might give some indication as to whether strike slip movement was taking place on the north-south trending Duke of York Islands Fault. If successful this method could be applied elsewhere in New Guinea.

Movement of this kind has been discovered in other parts of the world, for example Greenland is known to be moving in the direction of the North American continent, and Japan to be moving into the Pacific at the rate of two metres per century. (Ting Ying H. Ma and Chia Lin Pan (59)). It is possible that in an area as active as New Guinea gradual movement might be very much faster, and after earthquakes sudden movements might be detected.

+ An improvement in temperature measurement by the use of recording thermographs has already been suggested at Rabaul.

Changes might also be shown in the Rabaul caldera after near earthquakes (cf. the case of the cracks in Kamerere Street) and these might be detectable by re-surveying the marks set up many years ago on the Golf Course from, for example, the bench mark near the Burnt Wharf.

Geological evidence regarding mechanism of faults in the Rabaul area is very meagre at present. It is not known whether there has been any consistency in sense of faulting in the recent geological past. Field work might adduce evidence for or against strike slip faulting in the area. In this respect a greater degree of discussion with the Wau Geological Office would be of great value. D.B. Dow and others have been working on the problem of strike-slip faulting for some time.

At present little is known of the similarity or dissimilarity of the mainland New Guinea structures with those of New Britain and New Ireland. The possibility that New Guinea may have been influenced by block faulting which has deformed earlier arcuate structures, does not seem to have a parallel in the islands of the Bismarck Archipelago where the arcuate structures are still apparently active. The possibility that New Ireland, which is discordant to the New Britain arc, may have moved from its original position and orientation, might be confirmed or denied by geological mapping in the southern part of the island, where a great area is covered by Pleistocene volcanic rocks which may show signs of later deformation from a particular direction.

The author hopes to be able to make some determinations of focal plane mechanism on selected earthquakes in the region, and this may help to establish the type of faulting that is taking place.

The present trend for increasing numbers of earthquakes to be reported in the Preliminary Determinations of Epicentres at the U.S.C. and G.S. with estimated magnitudes may allow a quantitative approach to the problem of energy release in New Guinea+. This will benefit future studies of periodicity in earthquakes, which remains one of the fundamental problems of seismology.

Apart from helping to delimit areas in which earthquakes may be triggered by tidal effects due to lunar and solar periodicities, a study along these lines may show that initial compressions and dilatations may be correlated with compressional and tensional periodicities. Times of new moon and other phases, not merely dates, may show a correlation with earthquakes, and there may be a particular position of the moon in the sky relative to the sun which is optimum for earthquakes. The major earthquake of 24th May 1962 occurred almost at the equinox. A statistical study should show to what extent such events are coincidental and to what extent they may be said to be caused by the stresses concerned.

The writer is of the opinion that in most fields in which coincidence appears to be a major factor, a pattern of causality may one day emerge.

\+ With appropriate instruments, such determinations could usefully be undertaken in Rabaul.

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NOTES TO APPENDICES ON METHODS OF READING SEISMOGRAMS

RELATIVE ACCURACY AND NOTATIONS USED.

Accuracy of Reading Seismograms

Where possible seismograms are read to 1/10th second, decimals being used in writing times thus determined. In other cases the order of accuracy is to the nearest half second. In order to make it plain which standard has been used a reading of ten and a half seconds would be written 10.5 seconds and 10½ seconds respectively. Sharp phases are prefixed 'i', emergent phases 'e', very sharp phases of high amplitude 'i:' and sharp phases which emerge gradually from the microseismic background 'ei'. Periods are read to the nearest 1/10 second, and trace amplitude to the nearest millimetre. Actual ground motion in terms of μ is not normally determined. Before March 1st, 1962, time marks usually ended on the 60th second. Since that date, to bring them into line with the world wide standardised system, they have commenced on the 60th second.

2. Conventions and Notations

The sense of ground movement on the seismograms is as follows:

Component	Trace	Ground movement
Vertical	Upwards	Upwards (Compression)
North-South	Upwards	To North
East-West	Upwards	To East

The following notations are used:-

Dil. or D. Dilatation (to epicentre)
Comp. or C. Compression (from epicentre)

Z, Z, Zr, Zw, Zh	Vertical component instruments	) See Chapter 2,
N, N, Nr, Nw	North-South component instruments	) Section 1 for
E, E, Er, Ew	East-West component instruments	) locations and constants.

Tg Period of galvanometer M.M. Modified Mercalli Scale of intensity
Tp Period of Pendulum R.F. Rossi-Forel Scale of intensity
M Mass of pendulum G.M.T.= 10 hours behind L.M.T. (Local mean time)
V Static magnification of recording system.

3. Timing

Minute and hour marks are placed on the records either by electronic clock (as in the case of the world wide standardised Seismograph System) or by chronometer (the old Benioff Seismograph At Rapindik, and the portable Willmore Seismographs), or by Synchronome clock (the old Benioff Seismograph up to February 1962, at the Observatory). Times are checked to an accuracy of 1/10 second, once daily, by means of radio time signals from Stations JJY or WWV. A much high order of accuracy is possible in the case of the world wide standardised instruments (± 5 milliseconds). When a stop watch is used in conjunction with a Chronometer an accuracy of ± 50 milliseconds can be achieved. Minute marks are usually 3 seconds in length. However, on some early records they are 1½ seconds in length. Hour marks are recognised either by the absence of the 59th minute mark or by the presence of an additional mark at half a minute past the hour.

APPENDIX A.

CO-ORDINATES OF STATIONS IN THE EARTHQUAKE REPORTING NETWORK

Key to Fig. 1	Place	Lat. Sth.		Long. East	
109	Abau	10°	10'	148°	40'
1	Aiome	05	10	144	45
2	Aitape	03	10	142	20
152	Amanab	03	30	141	00
110	Ambunti	04	15	142	50
3	Angoram	04	05	144	05
4	Arawe	06	05	149	05
5	Aropa	06	25	155	50
6	Atitau	04	45	145	20
7	Awala	08	50	148	05
8	Awelkon	05	40	147	50
9	Baluan	02	35	147	20
10	Baniara	09	45	149	55
11	Beara	07	30	144	50
12	Bialla	05	20	151	05
13	Bogia	04	15	144	55
14	Boku	06	35	155	20
15	Buin	06	50	155	45
111	Bundi	05	40	145	15
16	Bwaruada	09	55	151	10
112	Cape Gloucester	05	30	148	30
113	Cape Hoskins	05	25	150	25
17	Chimbu (=Kundiawa)	06	00	145	00
149	Chuave	06	05	145	05
18	Daru	09	05	143	15
81	Doilene (=Rangarere)	04	15	151	35
114	Dreikikir	03	35	142	50
115	Dyaul Island	02	55	150	55
116	Erave	06	40	144	00
19	Esa'ala	09	45	150	50
20	Fead Islands	03	25	154	45
21	Finschhafen	06	35	147	50
22	Fyfe Bay	10	35	150	00
23	Gaima	08	20	142	55
117	Garaina	07	55	147	05
118	Garove	04	40	149	30
24	Gavit	04	10	151	40
25	Gehua (= Sinaeada)	10	20	150	25
154	Gembogl	05	50	145	10
26	Goroka	06	05	145	25
27	Green R.	03	55	141	10
155	Gumine	06	10	144	55
28	Henganofi	06	15	145	35
151	Hilalon	03	50	152	40
119	Ialibu	06	20	144	00
29	Ihu	07	55	145	25
30	Ioma	08	20	147	50
120	Jimi R.	05	20	144	20
158	Kabwum	06	10	147	10
31	Kaiapit	06	15	146	15
32	Kainantu	06	15	145	55
121	Kairiru	03°	20'	143°	30'
33	Kairuku	08	50	146	35
153	Kalalo	06	00	147	10
122	Kambubu	04	35	152	20
34	Kandrian	06	15	149	35
123	Karimui	06	30	144	50
35	Karkar	04	40	146	00
36	Karlai	05	05	152	00
37	Karoola	05	10	154	35
38	Kavieng	02	35	150	50
39	Keravat	04	20	152	00
40	Kerowagi	05	50	144	50
41	Kiep	05	10	152	00
42	Kieta	06	15	155	40
43	Kikori	07	25	144	15
44	Kilenge	05	30	148	20
45	Kiunga	06	05	141	15
47	Kokoda	08	50	147	45
46	Kokopo	04	20	152	15
124	Kompiam	05	20	143	55
156	Koroba	05	45	142	45
125	Kulumadau	09	00	152	40
17	Kundiawa (= Chimbu)	06	00	145	00
49	Kunua	05	45	154	45
50	Lae	06	45	147	00
89	Lagenda (near Talasea	05	20	150	05
126	Laiagam	05	30	143	25
48	Lake Kutubu	06	25	143	20
51	Lake Murray	07	00	141	30
52	Lindenhafen	06	10	150	35
53	Lingalinga	05	35	149	45
54	Lolobau Island	04	55	151	10
55	Londolovit	03	05	152	40
56	Longau	01	15	144	15
127	Lorengau	02	00	147	15
57	Losuia	08	30	151	05
58	Lufa	06	20	145	15
59	Lumi	03	30	142	05
60	Madang	05	15	145	50
159	Malala	04	25	145	20
160	Malekolon	04	00	153	40
62	Manam Is.	04	05	145	05
63	Maprik	03	40	143	05
150	Maritsoan	04	15	153	05
61	May River	04	35	141	35
64	Mendi	06	10	143	40
65	Menyamya	07	10	146	00
128	Metlik	04	45	153	00
66	Minj	05	50	144	40
67	Misima Island	10	40	152	45
68	Morobe	07	45	147	35
69	Mount Hagen	05	50	144	15

APPENDIX B.

INTERMEDIATE FOCUS FELT EARTHQUAKES - E. NEW GUINEA REGION

June 1955 to December 1962.

Date	GMT. Origin Time	First Motion	GMT. Arrival P	O=OMORI B=BENIOFF S-P	(Modified Mercalli) Scale Intensity Felt.	Lat.°S. Long.°E Epicentre	Kms. Depth	Mag.	Remarks
12/7/56	054007	C	054034½		Rabaul 1.		150		
21/11/56	074949		-	8"(O)	Namatanai 5.				
					Rabaul 2.	4 152½	100		
23/8/57	133351		133435		Rabaul 2.	6 154	100		
26/8/57	195333	D	195417		Rabaul 2 etc.	5½ 154	100		
15/9/57	184220		e184259½		Rabaul 4 etc.	6 153½	150		
1/10/57	071226		071315		Rabaul 1				
					Londolovit 1-2 etc	5½ 155	100		
4/6/58	094739		094922		Okaoa Kaiapit 3 etc	2 145	150		
19/7/58	063019		e063334		Lumi 2.	4 138½	150		
12/8/58	231217	D	!231248		Rabaul 2 etc.	6 152	100		
13/8/58	215631	C	!215710		Rabaul 2-3 etc.	4½ 154	200		
20/8/58	224805		224908½		Kainantu 4.	5 149	250		
22/8/58	221656	D	221728	32"(O)	Port Moresby,				
					Chuave 2.	5 149	250		
28/9/58	125025	C	!125050		Rabaul 2.	5 153½	100		
4/10/58	004936	D	005140		Angoram 5 etc.				
					widely	4½ 143½	100		
12/11/58	103947		104050		Rabaul 1,				
					Warangoi?	7 156	100		
24/12/58	011317		!011402		Kandrian 1.	6½ 150½	100		
8/1/59	040646		!040721	! 21"	Pomio 2.	5 151½	150		
24/1/59	153356		153424		Rabaul 2,				
					Rangarere 3.	- -	100		
9/2/59	211318		!211353		Rabaul 4 etc.	5 154	100		
20/4/59	032752		!032852		Lingalinga 5 etc.	6 149½	100		
28/4/59	130057		!130113		Rabaul 2 etc.	5 152½	100		
18/5/59	054009		095037		Taliligap 2.	4½ 153½	100		
28/5/59	222715		222948		Ambunti 5 etc.	4 141½	100		
8/8/59	235605		235656		Karoola 6,				
					Rabaul 3.	6 155	100		
4/9/59	085255		!085308.1		Pondo 5,				
					Rabaul 2-3 etc.	4½ 152	100		
23/10/59	034332		034402.6		Londolovit,				
					Pomio 3.	4 154	150		
5/11/59	054523		!054540.8		Rabaul 2-3 etc.	4½ 153	100		
20/11/59	105659		!105723.2		Rabaul 2 etc.	4½ 153	100		
24/1/60	121623		e121808		Mendi 3	4½ 143½	100		
4/2/60	092723		e092731.3	26"(O)	Rabaul 3 etc.	5 154	100		
8/2/60	091945		!092024.8		Rabaul 3 etc.	5 155	100		
10/2/60	154454		!154529.3		Rabaul 2.	4½ 154½	100		
11/2/60	082858		082949.5		Rabaul 2 etc.	6 155	100		
12/3/60	021456		!021530.0		Rabaul 1 etc.	4 152½	150		
18/3/60	121651		e121715		Rabaul 2.	4½ 152	150		
4/4/60	124530		!124549.9		Rabaul 2 etc.	5 152	100		
27/5/60	201000		!201016.0		Taliligap 2.	5½ 153	150		
18/7/60	014329		!014334.7		Rabaul 4 etc.	4½ 151	200		
27/7/60	141006.6		!141122.1		Kaiapit 2.	5.5 147.3	205		
31/7/60	070437.1		!070518.2	35"(O)	Rabaul 2 etc.	6.0 150.0	93	6	
1/8/60	162855.0		!162912.5		Rabaul 2 etc.	4.8 152.6	77		
21/8/60	005925.2		!010012.6		Wataluma 3 etc.	5.5 149.5	177		
14/9/60	155901.7		-		Buin 2.	6.5 155.1	100		
17/9/60	125856.4		125942.5		Buin 2.	6.3 154.4	134		
1/10/60	114403.6		!114424.2		Rabaul 1-2 etc.	4.7 153.3	90		

APPENDIX B.

Date	GMT. Origin Time	First Motion	GMT. First Arrival P	O=OMORI B=BENIOFF S-P	(Modified Mercalli) Scale Intensity Felt.	Lat.°S Epicentre	Long.°E Epicentre	Kms Depth	Mag.	Remarks
4/10/60	095116.1		e095213.1	49½"(O)	Torokina 2.	7.5	155.3	134		
12/10/60	182935.1		i183031.5		Kandrian 2-3	6.1	148.6	119		
13/10/60	184030.3		i184056.5	c20"(O)	Rabaul 2-3 etc.	3.8	152.4	213		
22/10/60	222219.8		-		Chuave 2 etc.	4.6	144.3	170		
25/10/60	093647.9		e093746		(Torokina 2)?	6.5	155.3	100		
23/11/60	012430.1	D			Rabaul 3,					
		(SW)	i012453.5	c18"(O)	Taliligap 4	5.0	153.3	79		
23/11/60	094250.6		094416.6		Bwaruada 2.	10.3	152.3	70		Slight rumbling
24/11/60	045015.8		i045037.3	c17"(O)	Taliligap 6,					
					Rabaul 4-5 etc.	4.6	153.0	87	6¼	
27/11/60	131011.0		131135.2		Awelkon 1.	5.6	146.4	100		
1/12/60	204950.4		i205020.5		Taliligap 1-2	4.5	154.0	117		
31/12/60	210601.7	D								
		(SE)	i210626.8		Taliligap 1-2	5.0	151.4	136		
5/1/61					Tari 6 etc.widely	4.1	143.0	108	6¾-7	
14/1/61	063242.5		i053405.9		Gavit 2, etc.	5.4	152.9	81		
27/1/61	135515.6	D	i135534.4	c18"(O)	Taliligap 2,					
		(SW)			Rabaul 1-2	5.5	151.9	118		
16/2/61	140013.6		ei140112½	56½(B)	Buin 3.	6.9	155.1	162		
17/2/61	185504.3	D			Rabaul 2-3,					
		(SE)	i185524.0		Taliligap?	4.4	153.0	108		
20/2/61	141727.3	D	141755.3	16"(O)	Rabaul 2,					
					Taliligap?	5.0	153.4	107		
21/2/61	035027.6		035125.3		Buin 2.	6.5	154.8	213		
2/3/61	091902.8		092003.8	50.0"(OB)	Buin (2?)	6.5	155.8	138		
7/3/61	231159.6	C	i231222.1	14"(O)	Karoola 5,					
		(ESE)			Rabaul 3, etc.	4.7	153.2	90		
8/3/61	032716.2		032940.7		Aitape 3 etc.	4.0	141.8	217		
13/3/61	100656.0		e100814		Awelkon 1.	5.5	146.7	75		
15/3/61	130102.2	D	i130117.7	c.10"(O)	Metlik 4,					
		(SE)			Rabaul 3 etc.	4.4	152.5	99		
4/4/61	103511.1	D	i103557.3		Kandrian 4,					Kandrian
		(SW)			Rabaul 1-2 etc.	5.9	149.4	124		rumbling.
13/4/61	215128.4		215033.3		Buin 1.	6.7	154.7	192		
7/5/61	002540.8		002624.6		Karoola 5 etc.	6.1	154.4	123		
9/5/61	110626.2		110711.3		Karoola 3.	6.2	154.5	110		
14/5/61	122436.8		(122604.3)		Awelkon 2.	6.3	146.2	79		Willmore records only
14/6/61	025949.3	C	i030010.6		Rabaul 2 etc.	5.5	151.9	98		
		(SW)								
24/6/61	161923.7		162108.4		Kundiawa 4 etc	4.6	144.9	212		
14/7/61	010710.9	D?	i010734.5	20"(O)	Pomio 2-3,					
					Rabaul 1-2 etc.	5.4	151.9	77		
9/8/61	230041.6		230108.8		Rabaul 1-2	5.7	151.4	90		
13/9/61	030535.9		i030720.7		Kundiawa 4 etc.	5.6	144.8	100		
28/9/61	173710.1	C								
		(SE)	i173731.8		Rabaul 2 etc.	5.5	152.2	113		
9/10/61	102741.4		102852.4		Madang 2 etc.	5.9	147.7	71		
10/10/61	082554.6		082623.6		Karoola 3,					
					Rabaul 2.	5.4	154.3	154		
16/10/61	175504.8		175622.0		Kaiapit 3.	5.6	147.2	190		
17/10/61	032809.7		-		Vanimo 3-4	2.9	141.0	87		
25/11/61	141123.2		141215.7		Boku 4, Rabaul 1.	6.3	154.8	83		
26/11/61	190402.8		e190518½	64½"(B)	Bwaruada 2-3	9.3	150.0	109		
3/12/61	210320.2		-		Ambunti 4-5	4.1	142.3	88		
9/12/61	223900.2	D	223947.8		Cape Gloucester 2.	6.0	149.3	123		
24/12/61	112632.2		e1128(28)		Tung 2-3	4.7	144.2	95		

APPENDIX B.

Date	GMT. Origin Time	First Motion	GMT. Arrival P	O=OMORI B=BENIOFF S-P	(Modified Mercalli) Scale Intensity felt.	Lat.°S Epicentre	Long.°E Epicentre	Kms. Depth	Mag.	Remarks
27/12/61	231826.9		231921.0		Kandrian 3	5.7	148.9	155		
8/1/62	170318.9	C	:170432.7		Awelkon 3-4 etc.	6.4	147.3	104		
15/1/62	182112.8		182233.9		Henganofi 3-4 etc.	6.0	146.8	140		
18/1/62	154225.5		e154254		Rabaul 1-2	5.3	153.7	83		
18/1/62	154540.9		1546(19.0)	20"(O)	Rabaul 3.	4.2	153.6	127		
22/1/62	213020.2	C(SW)	:213035.4		Rabaul 3 etc.	4.3	152.5	104		
27/1/62	202804.0		(e202951)		Tung 3-4 etc.	5.1	144.2	145		Willmore
2/2/62	033248.3		(033404½)		Kabwum 2, Lae, Kainantu 1	5.4	147.3	161		records only " "
4/2/62	125951.8		:(130013)	16½"(O)	Rabaul 4 etc.	5.3	151.6	81		" "
4/2/62	161640.9		:(161703½)	10"(O)	Pomio 4, Rabaul 3etc.	5.7	152.1	85		" "
8/2/62	114913.9		-		Vanimo, Amanab 3.	3.2	141.3	87		
11/2/62	135700.4		135726		Keravat 4-5 etc.	4.3	153.5	120		
11/2/62	185532.0		185559½		Rabaul 6 etc.	4.5	153.5	100	6	
11/2/62	194841.6		194908½		Rabaul 1	4.6	153.6	107		
11/2/62	224113.8		224145		Rabaul 1-2	4.3	153.7	118		
12/2/62	134440.0		:134508½		Rabaul 2.	4.4	153.5	121		
14/2/62	015333.9		:015359		Taliligap 1	4.3	153.5	119		
14/2/62	073809.9		:073836		Rabaul 1-2	4.2	153.4	137		
15/2/62	152529.5		152557	17.4"(O)	Rabaul 4-5 etc.	4.4	153.8	109		Many after-shocks
19/2/62	045740.2		:045804½		Rabaul 2 etc.	4.2	153.3	117		
23/2/62	114052.8		e114203	63½"(O)	Awelkon 3-4 etc.	6.3	147.0	80		
9/3/62	083127.6		e0832(16)		Boku 1.	6.4	154.7	117		
9/3/62	220735.6		220958¼		Kalalo 6 etc.widely	5.8	146.4	76		
24/3/62	125930.9	C(NW)	e130115	83"(B)	Simbai 7-8, Bundi 6-7 etc. very widely	5.7	145.0	111		
26/3/62	152041.8	D(SW)	:152158.5		Lae 3-4	5.5	148.1	122		
1/4/62	121109.2	C(SW)	121318		Koroba 6 etc. very widely	4.2	143.6	80		
3/4/62	154012.1		e154220		Ambunti 4 etc.	4.5	143.2	80		
8/4/62	042840.5		e043109		May River 3 etc.	4.1	141.5	115		
6/5/62	071014.1		071039.9		Rabaul 1	5.7	151.6	98		
7/5/62	045638.4		045839.3		Kerowagi 3.	4.1	143.7	113		
22/5/62	220336.0	D	220354.4		Palmalmal 5-6 Rabaul 4 etc.	5.5	152.0	100		
23/5/62	063400.4	D(SW)	:063423.8	18.2" (B)	Rabaul 2-3 etc.	5.4	152.0	70		
25/5/62	094033.9	D(SW)	:094047.4	16½"(B)	Ulamona 1-2	5.4	151.7	129		
9/6/62	102540.3		102701.5		Kalalo 3.	5.9	147.0	72		
19/6/62	033201.8	C	:033223.2	28"(B)	Rabaul 2 etc.	5.6	151.5	130		
22/6/62	145539.8		e145707	92"(B)	Lae 5 etc.	6.9	147.0	70		Sound effects Kaiapit
26/6/62	080534.5		e080653		Lae 2, Awelkon 1.	4.8	146.9	82		
27/6/62	122140.0		122200.7		Taliligap 2.	4.6	151.4	110		
2/8/62	132642.4		:132652.8		Doilene 4, Rabaul 3 etc.	4.8	152.1	79		
5/9/62	111706.7		111958		Amanab 3.	3.3	139.9	110		
23/9/62	070145.7		:070201.3		Gavit 4, Rabaul 2.	4.9	151.9	71		
3/10/62	115721.8		115919.7		Simbai 3, etc.	4.5	144.6	108		
7/10/62	123530.9		123726.5		Tung, Yangoru 2 etc.	4.9	144.3	75		
23/11/62	104157.6		1044(28)		Telefomin 2-3	4.0	142.3	100		
30/11/62	230751.6		230926.5		Okapa 3 etc.	5.5	145.9	79		
4/12/62	103427.8		:103513.9		Kandrian 3-4 etc.	6.1	149.9	83		
9/12/62	142704.1	D	:142733.4		Rabaul 2.	4.7	153.7	117		
12/12/62	100848.5		:100918.2		Rabaul 5, Kunua 2, etc.very widely	4.8	153.8	94		
19/12/62	125619.9		e125651½		Rabaul 3 etc.	4.7	154.0	98		
21/12/62	012631.5		e012653½		Rabaul 2.	4.2	152.9	150		
21/12/62	173556.1		-		Taliligap 3	4.6	153.8	95		
22/12/62	232759.5		232824.9		Rabaul 1.	5.1	151.2	105		
30/12/62	181621.4		181650		Boku 4, Rabaul 3.	4.7	153.7	116		

APPENDIX C.

SHALLOW FOCUS FELT EARTHQUAKES, E. NEW GUINEA REGION

June 1955 to December 1962

Date	GMT. Origin Time	First Motion	GMT. Arrival P	(O=OMORI B=BENIOFF) S-P	(Modified Mercalli Scale Intensity felt	Lat.°S Epicentre	Long.°E Epicentre	Depth KMs	Mag.	Remarks
10/10/55	085744		085810		Rabaul 5, Kokopo 6-7 etc. V.widely	5.	153	Shallow	7¼	Minor Damage
12/11/55	100747		100833	25"(0)	Karoola 4, Rabaul 3 etc.	5.	152½	60		
20/3/56	094136		094201	23"(0)	Warangoi 4-5 Rabaul 3 etc.	5.	152½	60		
4/7/56	094845	D	094908		Rabaul 3 etc.	5.	153	60	6¼-6½	
10/12/56	164821	D(ESE)	164837	12"(0)	Rangarere 4-5 Rabaul 3 etc.	5.	152	60		
2/5/57	015009	D(SE)	015032		Warangoi 3 etc.	4½.	153	60		
8/9/57	131855	D(SSE)	131913		Kokopo 5, Rabaul 3 etc.	5.	152	60		
12/2/58	063459		!063528½		Rabaul 4 etc.	5½.	151	60		
12/2/58	072137		!072200		Rabaul 3 etc.	5½	151½	60		
26/3/59	022412		022527		Rabaul 1	7	155½	60		
1/5/59	145657		!145726		Rabaul 3 etc.	5.	154	60		
16/5/59	061623		!061653		Rabaul 4-5 etc.	4½.	153½	60	6¾	
16/5/59	073118		073149		Rabaul 1	4½.	153½	60		
22/7/59	230227		!230250		Warangoi 6 Rabaul 4 etc.	5.	152½	60		
2/11/59	200332		!200405.8		Rabaul 3 etc.	5½.	151½	60	6¾	
31/7/60	025546.2		!025631.4	35"(0)	Rabaul 4, etc. v. widely	5.6	150.0	25	6¾	
21/8/60	001801.5		002006.3		Manam Is. 3 etc.	4.3	143.3	39		
6/9/60	123516.1		123707.5		(Chuave 2-3)	4.9	145.1	38		
23/9/60	211956.2		!212103.5		Awelkon 2	5.6	147.3	60		
10/11/60	144447.3		e144756.2		Vanimo (?Int.)	2.6	139.4	25	6¾	
1/12/60	101144.6		101322.4		Madang 4 etc.	5.7	145.9	45		
2/12/60	043728.2	D	!043808.9		Taliligap 2-3, Rabaul 1	6.6	152.5	33		
29/12/60	134234.6		e134403		Saidor 4-5 etc.	5.5	146.1	57		rumbling
2/1/61	205159.3		ei205246		Taliligap 2	6.8	150.3	62		
27/1/61	005214.6		ei005313½		Torokina 3, Rabaul 1	6.4	154.7	23		
6/2/61	214513.5		e214620½	(48")(0)	Buin 6, Rabaul 2-3 etc.	6.8	155.3	59		
6/2/61	215733.4		ei2158(46)		Boku 2-3 etc.	6.4	155.0	25		
8/2/61	192554.9	C(NW)	!192624.7	(34")(0)	Rabaul 1	5.9	151.8	51		
13/2/61	134557.7		e134714½		Buin, Torokina 2	6.9	155.7	25		
3/3/61	094616.7	D(SW)	!094732.6		Tapini 3, etc.	5.7	147.4	25		
12/3/61	040903.3	C(E)	!040953.8		Karoola 3	5.3	155.4	64		
15/3/61	101455.5	C(NW)	!101518.6		Rabaul 2-3 Kavieng 2	3.3	150.7	21	6	Bismarck Sea
28/5/61	023020.8		023212.9		Tung 4 etc.	4.9	145.0	59		
28/5/61	104717.5		104916.1		Tung 4	5.1	144.8	25		
31/5/61	191557.0		(191619.2)		Palmalmal 6, Rabaul 4-5 etc.	5.3	151.6	56	5½-5¾	
2/6/61	043652.3				Henganofi 4 etc.	5.5	146.4	32		
3/6/61	055512.6	C(SW)	055531.7		Rangarere 4, Rabaul 2-3 etc.	4.3	151.1	18		
3/6/61	091432.1	C(NW?)	!091452.5		Rangarere 3, Rabaul 2	4.3	150.9	25		
21/6/61	073334.4		073509.2		Wau, Tapini 3	7.7	146.7	25		
7/7/61	131043.8		131133.0	33.4¼(0)	Walindi, Volupai 4, Rabaul 2-3 etc.	5.7	149.7	57	6-6¼	
13/7/61	012244.4		e012356		Awelkon ?	5.9	147.4	54		
13/7/61	103155.6	C	!103226.2	17.6"(0)	Keravat 5, Rabaul 2 etc.	5.5	150.8	25		

APPENDIX C.

Date	GMT. Origin Time	First Motion	GMT. Arrival P	(O=OMORI B=BENIOFF) S–P	(Modified Mercalli Scale) Intensity felt.	Lat.°S Long.°E Epicentre		Depth kms.	Mag.	Remarks
17/9/61	232206.3		232321.2		Sag Sag 4	5.9	147.4	45		
11/10/61	040239.5				Vanimo 3	2.5	140.9	18	18	
12/10/61	082410.0	C	:082436.0		Rabaul 3 etc.	5.6	151.9	41		
14/10/61	111528.2	D	:111556.1		Ulamona 2	5.1	150.7	35		
26/10/61	0038203	D	003924.0		Tong Is. 3–4 etc.	3.1	147.4	14	6¼–6½	Bismarck Sea.
20/11/61	190806.6		e191005		Mendi, Simbai 4 etc.	5.0	144.4	65		
26/11/61	181218.9				Kainantu 2	5.6	146.3	52		
4/12/61	053318.5		053342.1		Cutarp 3–4, Rabaul 3	5.2	151.6	59		Cutarp rumbling
14/12/61	071023.2		e071304		May River 4, etc.	3.1	140.9	44		
27/12/61	022548.2				Aitape 3	2.7	141.3	22		
29/12/61	100033.1	D	100125.3		Boku I.	6.3	154.5	44		
15/2/62	005945.1		010120½		Wanigela 4–5etc.	8.9	147.7	60		
23/2/62	180527.1		:180533½	7.5"(O)	Rabaul 4 etc.	4.0	152.6	25		
23/2/62	202128.6		:202135½	7.5"(O)	Rabaul 4–5 etc.	3.8	152.0	25		
24/2/62	193433.6		e193606½		Kainantu 5 etc.	5.5	146.1	40		
27/2/62	013903.6		e0140(08½)		Boku 3	7.1	155.2	25		
28/2/62	051954.1		e0522(44)		Vanimo 2	2.5	140.5	25		
28/2/62	204422.4		e204709½		Vanimo 2	2.9	140.7	25		
14/3/62	151732.7	C (SW)	151747.8		Karlai 3, Rabaul 1–2	4.9	152.4	57		
22/3/62	151303.9	D (NNW)	:151524½		Aitape 5 etc, widely	3.2	142.3	25		
2/4/62	183352.4		e183516		Kalalo 5 etc.	6.1	146.7	60		
6/4/62	065052.6	D	065305		Ambunti 5 etc.	4.2	143.3	63		
21/4/62	211801.7		e212002½		Kompian 3, Manam Is. etc.	6.5	144.6	42		
23/4/62	210604.2	D	:210706.2		Walindi 2 etc.	5.9	148.4	51		
26/4/62	024410.8	C	024528.5		Awelkon I.	5.8	147.3	68		
11/5/62	045243.4				Kikori 3	6.4	143.6	37		
11/5/62	070552.5		070707.5		Finschhafen 3–4	6.6	147.7	42		
22/5/62	231546.1	D	:231606.0		Pomio 3 etc.	5.0	151.3	65		
23/5/62	050347.0	D(SW)	:050408.5		Gavit 2 etc.	5.4	151.9	55		
23/5/62	064328.0	D	:064353.9		Taliligap, Karlai 1	4.9	150.8	44		
24/5/62	021135.8		:021201.9	19.0" (B)	Rabaul, Lolobau Is.3–4	5.4	151.9	55		
25/5/62	010958.1	D (SW)	011021.8	16.2" (B)	Doilene 3, etc.	5.6	152.2	25		
2/6/62	091848.1	D(NE)	:091909.5		Rabaul 1–2	5.4	151.7	53		
3/6/62	134237.3		134341.1		Lae 1–2	6.4	148.1	32		
18/6/62	234231.3	C	:234356.9		Pomio 5, Rabaul 3 etc.	4.8	151.8	47	6¾	
24/6/62	030147.6		0303(23)		Lae 4–5 etc.	6.8	146.8	50		
27/6/62	033001.9		0330(55.3)		Kandrian 4 etc.	6.1	148.8	55		
17/7/62	231209.0		e2313(30)		(Ioma 4)	7.8	148.1	42		
18/7/62	012102.8		:012116.8		Rabaul 3–4 etc.	4.3	152.9	51		
19/7/62	005213.9				Taliligap 3–4 etc.	5.1	153.6	49		
30/7/62	171644.4		e 171849		Kairiru 6 etc. widely	3.3	143.9	25	7	Bismarck Sea

APPENDIX C.

Date	GMT Origin time	First Motion	GMT Arrival P	(O=OMORI B=BENIOFF S-P	(Modified Mercalli Scale) Intensity Felt	Lat. °S	Long. °E	Depth Kms.	Mag.	Remarks
31/7/72	021905.2		e0221(25)		Wewak 2	3.2	144.1	20		Bismarck Sea
1/8/62	043657.6		e043902		Kairiru 6 etc. widely	3.2	143.7	33	7	"
1/8/62	103242.7		!103259		Rabaul 1-2	3.8	153.1	51		
26/8/62	233038.0		233325½		May R. Green R., Amanab 2	3.7	140.1	50		
27/8/62	232845.2		232935.1		Walindi 3	6.0	149.5	48		
11/9/62	003312.0		003404.2		Walindi 3	6.1	149.4	62		
12/9/62	181842.9		182021		Bogia 4 etc	4.4	145.4	32		
27/9/62	182652.5		!182702.4		Doilene 3 etc.	4.0	151.2	51		
30/9/62	104910.3	D	!104832.0		Doilene 5, Rabaul 3 etc.	5.2	152.7	33		
30/9/62	105837.0		!105831.1		Rabaul 2 etc.	5.9	151.0	50		
1/10/62	150722.1		!150745.2		Karlai 3 etc.	5.5	151.9	49		
4/10/62	203438.7	D	!203500.2		Karlai 3, Rabaul 2	5.1	151.9	33		
6/10/62	213757.4				Gembogl, Kundiawa 2	5.3	145.0	43		
6/11/62	212647.8	D	!212705.0	11"(B)	Gavit 3, Rabaul 2 etc.	4.9	152.7	68		
15/11/62	162509.4	D	162640.0		Lae 6 etc.	6.9	146.7	40		
20/11/62	101111.2		101157.9		Karoola 4 Rabaul 2-3	6.1	154.5	69		
11/12/62	182330.8	D	!182401.9		Talíligap 2	5.3	150.6	58		
15/12/62	142235.2		142246.8		Doilene 5, Rabaul 3 etc.	4.6	152.1	53		
27/12/62	140202.1		e140347		Bogia 4 etc.	4.9	145.1	35		

The following severe tremors in the 1950-55 period were probably shallow:

Date	GMT Origin time	GMT Arrival P	Intensity Felt	Epicentres	Remarks
9/9/50	1024		Rabaul 4-5	Duke of York Is.	Swarm
11/10/51	0138		Kokopo 5, Rabaul 4	Minor landslips	Rabaul-Kokopo road. Minor damage
24-25/12/52	0815-1800(25")		Kokopo 6-7. Rabaul 5.	c.100 miles	Swarm
23/4/53	1625	162533	Rabaul 7	Earthfalls and cracking of ground Observatory Hill.	
5/2/54	0921		Rabaul 5	Landslides on Namanula and Tunnel Hills	

PRINCIPLE MULTIPLE EARTHQUAKES AND EARTHQUAKE SWARMS

RECORDED FROM THE NEW BRITAIN AREA

N.B. - This Appendix excludes "Anomalous" Swarm Shocks

GMT. Date From	To	Felt Intensity	Epicentre	Remarks
3/2/1878	-	"very violent"	Vulcan area	Preceded 1878 eruption of Vulcan
26/5/37	29/5/37	"Severe" up to 8 (R.F.)	Vulcan area	Preceded 1937 eruption of Vulcan
29/5/37	31/5/37	"severe"	Vulcan area	Continued for at least 36 hrs. after eruption
3/1/38	7/1/38 (1525) hrs.	Toma 6-7 (R.F.)	Toma area	Volcanic. Hardly felt in Rabaul.
(terminated by a major earthquake, Int. 7 (R.F.) at Rabaul)				
13/2/38 (0805)	13/2/38 (1405)	Keravat 3-4 (R.F.)	Keravat area	Probably tectonic swarm
6/3/38	8/3/38	Keravat and Toma up to 4 (R.F.)	-	Swarm of probable tectonic origin
22/10/39	-	Vunakanau, up to 2 (R.F.)	-	Swarm of 6 tremors. Rumbling heard.
12/9/40 (1320)	-	Rabaul 7-8 (R.F.)	c.70 miles S.S.E.	Over 100 aftershocks (50-100 miles SSE).
13/1/41 (1627.6)	13/2/41	Keravat area (R.F.)	Wunga	222 aftershocks recorded between 13/1/41
1738 hours and 14/1/41 hours: in the 4 successive weeks 323, 78, 44 and 33 respectively.				
9/9/50 (1024)	-	Rabaul 4-5 (M.M.)	c.25 miles ENE (near Duke of York Is.)	30 aftershocks felt at Rabaul; more in Duke of York Islands.
24/12/52 (0815)	25/12/52 (1800)	Kokopo, up to 6 (M.M.) Rabaul, up to 5 (M.M.)	c.100 miles from Rabaul	46 tremors recorded (36 felt at Kokopo, 12 at Rabaul). Tectonic
23/4/53 (1600)	-	Rabaul, up to 7 (M.M.)	4.5S 153.3E	Swarm of tectonic earthquakes (S-P 12")
19/5/54 (2307)	-	Pomio 4 (M.M.) Rabaul 3 (M.M.)	c.100 miles from Rabaul	11 aftershocks
26/8/54 (1845-55)		Kokopo 4, 3, 1 (M.M.)	-	Swarm of 3 tremors; felt in Rabaul also
10/10/55 (0858)	-	Kokopo 6-7 (M.M.) Rabaul 5 (M.M.)	5S 153E	Almost continuous aftershocks 2-3 hrs.
4/7/56 (0948)	4/7/56 (1000)	Rabaul 3 (M.M.) etc.	Rabaul 1-2 (M.M.)	5S 153E/5S 152E Pair
17/7/56 (1416)	17/7/56 (1510)	Rabaul 2 (M.M.)/Not felt		4S 151½E (both) Pair.
4/7/57 (1411)	4/7/57 (1435)	Pomio 4 (M.M.) Rabaul 2 (M.M.) (both)		5S 152E/? Pair Aftershocks follow

APPENDIX D.

GMT. Date From	To	Felt Intensity	Epicentre	Remarks
16/8/57	23/8/57 (0200)	Rabaul 5 (M.M.) etc.	6S 154½E Mag. 6½	terminated seismic storm. Early epicentres were E. of Southern New Ireland, later ones from east of the Warangoi-Keravat fault.
10/12/57(?)		Mag. 6¾ earthquake	Bougainville	Over 70 aftershocks recorded next 3 days
22/12/57		-	-	+ 18 very small shocks recorded (S-P3-6")
17/4/58		Warangoi, up to 2 (M.M.)	50-100 miles S.E. of Rabaul	Swarm of 9 small shocks
12/2/58 (0635)	12/2/58 (0722)	Rabaul 4 etc./Rabaul 3 etc. (M.M.)	5½S 151E/5½S 151½E	Both 60 kms. pair.
4/4/58 (0223)	5/4/58 (2026)	Rabaul up to 4 (M.M.)	5½S 152E	14 tremors felt
26/5/59 (0710-0950)		Rabaul, up to 2 (M.M.)	c.25-30 miles S.W. of Rabaul	20-30 small shocks (S-P5-6")
31/7/60 (0256)	31/7/60 (0705)	Rabaul 4 etc./Rabaul 2 etc. (M.M.)	5.6 150.0/6.0.150.0 25 kms. Mag.6¾ / 93 kms. Mag.6	Pair
3/6/61 (0555)	3/6/61 (0914)	Rangarere 4/Rangarere 3	4.3.151.1 h.18/ 4.3.150.9h.25	Pair. Also felt Rabaul
11/2/62 (1357)	19/2/62 (0457)	Rabaul up to 6 (one shock)	area of 4.3 153.5 h.c.110	Swarm of 11 earthquakes comprising 1 Foreshock, main shock (Mag.6) and 9 aftershocks. Numerous other minor aftershocks from same area (S-Ps 15-20")
18/1/62 (1542)	18/1/62 (1545)	Rabaul 1-2/Rabaul 3	5.3S.153.7E h.83/4/2S 153.6E. h.127	Pair, followed by 2 aftershocks
22/5/62 (2203)	25/5/62 (0940)	Palmalmal 5-6/first shock	Area of 5.5, 152.0 h.25-129 kms.	Series of 8 good-sized earthquakes with numerous aftershocks.
26/7/62 (0503)	26/7/62 (0701)	Not felt	5.5S.151.1E h93/5.3S 150.8E.h.71	Pair
23/9/62 (0702)	4/10/62 (2035)	Doilene up to 5, Rabaul up to 3	4-6S.151-152E h.33-71 kms.	Series of 6 earthquakes

+ N.B. Swarm tremors with very small S-Ps continued to be recorded commonly up to March 1958.

APPENDIX E.

CORRELATION OF EARTHQUAKE FREQUENCY MAXIMA WITH LUNAR PERIODICITY

NEW GUINEA 1957-1962

Period	14.8 day maxima	29.6 day maxima
July 1957	New Moon	
	Full Moon + 1	Full Moon + 1
Aug. 1957	-	-
	Full Moon + 2	Full Moon + 2
Sept.1957	-	-
	Full Moon	Full Moon
Nov. 1957	Full Moon +1	Full Moon +1
	New Moon	
Dec. 1957	Full Moon +1	Full Moon +1
	Last qtr.	
Jan. 1958	-	-
	1st. qtr.	1st. qtr.
Feb. 1958	Last qtr.+ 1	-
	New Moon + 3	
Mar. 1958	Last qtr.+ 1	
	Full Moon -2	Full Moon- 2
(April)	Full Moon -2	Full Moon -2
April '58	New Moon -3	New Moon - 3
May 1958	(Last qtr.+ 3)	
	New Moon +3	New Moon +3
June1958	Full Moon +2	-
	1st.qtr.	1st. qtr.
July '58	-	-
	Full Moon - 2	Full Moon -2
Aug. '58	New Moon	New Moon
	1st.qtr. - 2.	
Sept.'58	Last qtr.+ 2	
	1st.qtr.- 1	1st.qtr. - 1.
Oct. '58	Last qtr.+ 2	(Last qtr.+2)
	1st.qtr. + 2	(1st. qtr.+2)
Nov.'58	Last qtr.- 2	Last qtr.- 2
	-	-
Dec.'58	-	-
	1st.qtr. -3	1st.qtr.- 3
Jan.1959	New Moon	New Moon
	Full Moon + 3	-
Feb.1959	Full Moon + 3	-
	Last qtr.- 2	Last qtr -2.
Mar.1959	New Moon + 2	-
	Last qtr.	Last qtr.
Apr. '59	Full Moon + 1	-
	(Last qtr.+ 2)	
May. '59	1st.qtr.- 3	1st.qtr.- 3
	Last qtr.+"	Last qtr.+2
June '59	New Moon	-
	Last qtr.-1	Last qtr.- 1
July '59	1st.qtr.+ 2	-
	Last qtr.	Last qtr.
Aug.1959	New Moon + 3	-
	Last qtr.- 3	-
	New Moon	
Sept.'59	1st.qtr.+ 3	-
	Full Moon +1	Full Moon+ 1
Oct. '59	Full Moon+ 2	Full Moon +2
Nov. '59	Full Moon -2	-
		(Full Moon +2)
	New Moon+2	(New Moon +2)
Dec. '59	Full Moon+ 2	Full Moon+ 2
Jan. '60	Full Moon+ 1	-
Feb. '60	Full Moom +1	Full Moon +1
	1st.qtr.	
Mar. '60	Last qtr.+ 2	Last qtr.+2
	New Moon + 1	-
Apr. '60	Full Moon+ 3	Full Moon+ 3
	Full Moon +2	-
June '60	New Moon - 1	New Moon - 1
July '60	New Moon	-
	1st. qtr.	1st. qtr.
Aug. '60	Last qtr.-1	Last qtr.- 1
Sept.'60	New Moon -3	-
	1st.qtr.+ 3	1st.qtr.+ 3
Oct. '60	New Moon- 3	New Moon -3
	1st.qtr. - 1	
	last qtr.	
Nov. '60	1st.qtr.- 1	1st.1tr,- 1.
	Last qtr.-2	Last qtr.- 2
Dec. '60	New Moon	
	Full Moon + 4	Full Moon +4
Jan. '61	New Moon + 3	
	New Moon + 3	
Feb. '61	1st.qtr.+ 1	1st.qtr.+ 1
	Last qtr.	
Nov. '61	New Moon + 4	-
	Full Moon	Full Moon
	Last qtr.+ 2	
Apr. '61	1st.qtr.- 1	
May '61	Full Moon-3	Full Moon -3
June '61	1st.qtr.+2	1st.qtr.+ 2
	Last qtr.-3	last qtr.- 3
Jul. '61	Full Moon	
	Last qtr.+ 1	Last qtr.+ 1
	1st.qtr.+ 1	
Aug. '61	Last qtr.- 2	Last qtr.- 2
	1st. qtr.- 3	
Sept.'61	New Moon- 2	New Moon - 2
	New Moon + 2	
Oct.1961	Last qtr.+ 1	Last qtr.+ 1
Nov. '61	Last qtr.- 2	
	1st.qtr.+ 3	1st.qtr.+ 3
Dec. '61	Last qtr,	
	Full Moon - 1	
Jan. '62	Last qtr.+ 3	
	1st.qtr.-1	1st.qtr.- 1
Feb. '62	New Moon	New Moon
	Full Moon - 2	
	Full Moon + 2	Full Moon + 2
Mar. '62	Full Moon - 2	
Apr. '62	Last qtr.	
	Full Moon -2	Full Moon - 2
May. '62	New Moon - 2	
	Full Moon	Full Moon
June '62	Last qtr.+ 4	
	Full Moon - 3	
	Last qtr.- 1	Last qtr. - 1
July '62	Full Moon - 2	
Aug. '62	New Moon- 2	New Moon - 2
	Full Moon	(Full Moon)
	Last qtr.+ 1	Last qtr.+ 1.
Sept.'62	(1st.qtr. - 3)	
	(1st.qtr. + 2)	
Oct. '62	New Moon	New Moon
	1st. qtr.	
	Last qtr.	
	(New Moon + 1)	(New Moon + 1).
Nov. '62	(1st.qtr.+ 2)	(1st.qtr.+ 2)
	Last qtr.+ 3½	
Dec. '62	Full Moon	Full Moon
	Last qtr.+ 2	

APPENDIX F

PROBABILITY TABLE FOR LUNAR CORRELATIONS (SEE FIGURES 10 AND 11)

(Total number of correlations = 123 (63 for 29.6 Day Period)

(Average or expected number of correlations = 4 per Phase (2 for 29.6 Day Period)

LUNAR PHASE (DAYS)	NUMBER OF CORRELATIONS	VARIATION FROM EXPECTED NO. OF CORRELATIONS	FAVOURABILITY OF PHASE AND REMARKS		
			14.8 Day Period	29.6 Day Period	Overall
New Moon	10 (4*)	+ 6 (+ 2*)	1 (Most favourable)	3*	1st
New Moon + 1	1 (1*)	- 2 (- 1*)			
" " + 2	2	- 2 (- 2*)			
" " + 3	5 (1*)	+ 1 (- 1*)	5		5th
" " + 4	1	- 3 (- 2*)			
" " + 5	4 (2*)	Nil (Nil*)	6 (Average)	5* (Average)	Average
" " + 6	2	- 2 (- 2*)			
" " + 7 (First Quarter)	5 (3*)	+ 1 (+ 1*)	5	4*	5th
" " + 8	5 (3*)	+ 1 (+ 1*)	5	4*	5th
" " + 9	2 (1*)	- 2 (- 1*)			
" " + 10	5 (3*)	+ 1 (+ 1*)	5	4*	5th
" " + 11	3 (2*)	- 1 (Nil*)		5* (Average)	
" " + 12	3 (1*)	- 1 (-1*)			
" " + 13	8 (3*)	+ 4 (+ 1*)	2	4*	2nd
" " + 14	4 (2*)	Nil (Nil*)	6 (Average)	5* (Average)	Average
Full Moon	6 (6*)	+ 2 (+ 4*)	4	1* (Most Favourable)	2nd
Full Moon + 1	4 (3*)	Nil (+ 1*)	6 (Average)	4*	5th
" " + 2	5 (5*)	+ 1 (+ 3*)	5	2*	3rd
" " + 3	2 (1*)	- 2 (- 1*)			
" " + 4	1 (1*)	- 3 (- 1*)			
" " + 5	2 (1*)	- 2 (- 1*)			
" " + 6	5 (4*)	+ 1 (+ 2*)	5	3*	4th
" " + 7 (Last Quarter)	4 (4*)	Nil (+ 2*)	6 (Average)	3*	4th
" " + 8	8 (2*)	+ 4 (Nil*)	2	5* (Average)	2nd
" " + 9	4 (3*)	Nil (+ 1*)	6 (Average)	4*	5th
" " + 10	7 (3*)	+ 3 (+ 1*)	3	4*	3rd
" " + 11	3	- 1 (- 2*)			
" " + 12	5 (2*)	+ 1 (Nil*)	5	5* (Average)	5th
" " + 13	4 (3*)	Nil (+ 1*)	6 (Average)	4*	5th
" " + 14	1 (1*)	- 3 (-1*)			

Plain Figures are plotted for Correlations in the 14.8 day period;

* denotes correlation also in the 29.6 day period.

APPENDIX G

DIRECTIONS OF FIRST MOVEMENT FOR EARTHQUAKES OF KNOWN EPICENTRE, NEW GUINEA REGION, 1956-1962

Date	1st Movement	Epicentre	Depth (Kms)	Remarks
9/6/56	dil	5 S. 152 E.	-	Felt
4/7/56	dil.	5 S. 153 E.	60	Mag. $6\frac{1}{4}$ - $6\frac{1}{2}$ Felt
10/12/56	dil. to E.S.E.	5 S. 152 E.	60	Felt
20/4/57	dil. to E.N.E.	6 S. $147\frac{1}{2}$ E.	-	Felt
28/4/57	Comp.	6 S. 155 E.	-	Felt
2/5/57	dil. to S.E.	$4\frac{1}{2}$ S. 153 E.	-	Felt
4/7/57	dil. to E.S.E.	5 S. 152 E.	-	Felt
4/7/57	comp. from S.E.	?	-	Felt. Aftershock
21/7/57	dil. to E.S.E.	$4\frac{1}{2}$ S. 153 E.	-	Felt. Mag. $5\frac{3}{4}$
27/7/57	comp. from S.S.W.	$6\frac{1}{2}$ S. $151\frac{1}{2}$ E.	-	Not felt
5/8/57	dil. to N.W.	5 S. 154 E.	-	Felt
15/8/57	dil. to E.S.E.	$4\frac{1}{2}$ S. 155 E.	500	Not felt
16/8/57	dil.	5 S. 154 E.	-	Felt
16/8/57	dil.	5 S. 155 E.	-	Felt
17/8/57	dil.	5 S. 155 E.	-	Felt
18/8/57	Comp.	$4\frac{1}{2}$ S. 153 E.	-	Felt
19/8/57	Comp.	$4\frac{1}{2}$ S. 153 E.	-	Felt
26/8/57	dil.	$5\frac{1}{2}$ S. 154 E.	100	Felt
4/9/57	Comp.	4 S. $151\frac{1}{2}$ E.	-	Felt
8/9/57	dil. to S.S.E.	5 S. 152 E.	60	Felt
5/11/57	Comp.	6 S. 150 E.	-	Felt
2/1/58	dil. to E.S.E.	5 S. 152 E.	-	Felt
12/2/58	dil. to S.S.E.	$5\frac{1}{2}$ S. 151 E.	60	Felt } Pair
12/2/58	dil. to S.S.E.	$5\frac{1}{2}$ S. $151\frac{1}{2}$ E.	60	Felt } Pair
22/2/58	Comp.	6 S. 147 E.	200	Felt
25/2/58	Comp. from S.S.E.	6 S. $151\frac{1}{2}$ E.	-	Not Felt
26/2/58	dil. to E.S.E.	3 S. $152\frac{1}{2}$ E.	300	Not felt
15/3/58	dil. to S.	5 S. 152 E.	-	Felt
28/3/58	dil.	6 S. 153 E.	-	Felt
2/4/58	dil.	$5\frac{1}{2}$ S. $154\frac{1}{2}$ E.	-	Felt
4/4/58	dil.	$5\frac{1}{2}$ S. 152 E.	-	Felt
4/4/58	dil.	$5\frac{1}{2}$ S. 152 E.	-	Felt
4/4/58	dil.	$5\frac{1}{2}$ S. 152 E.	-	Felt
17/4/58	Comp. from S.	$5\frac{1}{2}$ S. 152 E.	-	Felt
23/4/58	Comp. from S.E.	$5\frac{1}{2}$ S. 153 E.	-	Felt
23/4/58	dil.	$4\frac{1}{2}$ S. 153 E.	100	Felt
14/5/58	dil.	$4\frac{1}{2}$ S. 153 E.	-	Felt

Appendix G. (Contd.)

Date	1st Movement	Epicentre	Depth (Kms)	Remarks
7/6/58	Comp.	5 S. 150½ E.	150	Not felt
10/8/58	dil.	3½ S. 150½ E.	-	Felt
12/8/58	dil.	6 S. 152 E.	100	Felt
13/8/58	Comp.	4½ S. 154 E.	200	Felt
22/8/58	dil.	6 S. 149 E.	250	Felt
2/9/58	dil.	5½ S. 145½ E.	-	Felt
28/9/58	Comp.	5 S. 153½ E.	100	Felt
4/10/58	dil.	4½ S. 143½ E.	100	Felt
21/10/58	dil.	5½ S. 147 E.	-	Felt
29/10/58	Comp.	4½ S. 153½ E.	-	Felt
4/11/58	dil.	6 S. 147½ E.	-	Felt
31/6/59	Comp.	5 S. 152½ E.	-	Not felt
12/2/60	dil.	4½ S. 153½ E.	-	Not felt
17/2/60	dil.	5 S. 142½ E.	-	Felt
23/11/60	dil (to S.W.?)	5.0 S. 153.2 E.	79	Felt
2/12/60	dil	6.6 S. 152.5E.	33	Felt
3/12/60	dil. to S.E.	4.2 S. 152.1 E.	40	Not felt
4/12/60	Comp.	5.3S. 148.8 E.	43	Not felt
22/12/60	Comp. from S.E.	6.8 S. 155.3 E.	469	Felt. Mag. 5½
31/12/60	dil. to S.E.	5.0 S. 151.4 E.	136	Felt
3/1/61	dil. to N.W.	6.2 S. 150.9 E.	113	Not felt
27/1/61	dil. to S.W.	5.5 S. 151.9 E.	118	Felt
6/2/61	dil. to S.E.	4.8 S. 154.2 E.	470	Not felt
8/2/61	Comp. from N.W.	5.9 S. 151.8 E.	51	Felt
17/2/61	dil. to S.E.	4.4 S. 153.0 E.	108	Felt
20/2/61	dil.	5.0 S. 153.4 E.	107	Felt
2/3/61	dil. to N.E.	3.9 S. 154.5 E.	407	Not felt
3/3/61	dil. to S.W.	5.7 S. 147.4 E.	25	Felt
7/3/61	Comp. from E.S.E.	4.7 S. 153.2 E.	90	Felt
12/3/61	Comp. from N.E. or E.	5.3 S. 155.4 E.	64	Felt
13/3/61	Comp. from S.E.	5.2 S. 153.3 E.	25	Not felt
15/3/61	dil. to S.E.	6.0 S. 151.6 E.	79	Not felt
15/3/61	Comp. from N.W.	3.3 S. 150.7 E.	21	Felt. Mag. 6
15/3/61	dil. to S.E.	4.4 S. 152.5 E.	99	Felt
15/3/61	Comp. from S.E.	4.6 S. 153.4 E.	18	Not felt
18/3/61	dil to S.E.	4.8 S. 153.8 E.	157	Not felt

Appendix G. (Contd.)

Date	1st Movement	Epicentre	Depth (Kms)	Remarks
4/4/61	dil. to S.W.	5.9 S. 149.4 E.	124	Felt
16/4/61	dil. to W.	3.5 S. 149.5 E.	109	Not felt
2/5/61	dil. to S.E.	5.3 S. 151.5 E.	81	Not felt
7/5/61	dil. to S.E.	5.3 S. 151.2 E.	76	Not felt
3/6/61	Comp. from S.W.	4.3 S. 151.1 E.	18	Felt
3/6/61	Comp. (from N.W.?)	4.3 S. 150.9 E.	25	Felt
14/6/61	Comp. from S.W.	5.5 S. 151.9 E.	98	Felt
16/6/61	Comp. from N.W.	5.7 S. 150.7 E.	121	Not felt
13/7/61	Comp.	5.5 S. 150.8 E.	25	Felt
14/7/61	dil. ?	5.4 S. 151.9 E.	77	Felt
17/7/61	dil. to S.E.	5.4 S. 152.4 E.	64	Not felt
11/8/61	dil.	5.3 S. 152.4 E.	79	Not felt
24/8/61	dil. to S.W.	6.0 S. 149.9 E.	96	Not felt
28/9/61	Comp. from S.E.	5.5 S. 152.2 E.	113	Felt
9/10/61	Comp.	5.2 S. 153.7 E.	204	Not felt
12/10/61	Comp.	5.6 S. 151.9 E.	41	Felt
14/10/61	dil.	5.1 S. 150.7 E.	35	Felt
26/10/61	dil.	3.1 S. 147.4 E.	14	Felt. Mag. $6\frac{1}{4} - 6\frac{1}{2}$
1/12/61	Comp.	3.6 S. 152.5 E.	342	Not Felt
9/12/61	dil.	6.0 S. 149.3 E.	123	Felt
29/12/61	dil.	6.3 S. 154.5 E.	44	Felt
8/1/62	Comp.	6.4 S. 147.3 E.	104	Felt
22/1/62	Comp. from S.W.	4.3 S. 152.5 E.	104	Felt
24/2/62	Comp.	5.6 S. 153.6 E.	25	Not felt
14/3/62	Comp. from S.W.	4.9 S. 152.4 E.	57	Felt
21/3/62	dil.	6.6 S. 150.1 E.	25	Not felt
22/3/62	dil. to N.N.W.	3.2 S. 142.3 E.	25	Felt. Large earthquake
24/3/62	Comp. from N.W.	5.7 S. 145.0 E.	111	Felt. Large earthquake
26/3/62	dil. to S.W.	5.5 S. 148.1 E.	122	Felt
1/4/62	Comp. from S. or S.W.	4.2 S. 143.6 E.	80	Felt. Large earthquake
(3/4/62	dil.	10.6 S. 164.9 E.	36	Mag. $5\frac{1}{2}$. B.S.I.P.)
6/4/62	dil.	4.2 S. 143.3 E.	63	Felt
21/4/62	dil.	4.4 S. 151.2 E.	334	Not felt
23/4/62	dil.	5.9 S. 148.4 E.	51	Felt
26/4/62	Comp.	5.8 S. 147.3 E.	68	Felt
(22/5/62	dil. to S.E.	12.3 S. 166.6 E.	151	Mag. $6\frac{1}{2} - 6\frac{3}{4}$. B.S.I.P.)
22/5/62	dil.	5.5 S. 152.0 E.	100	Felt
22/5/62	dil.	5.0 S. 151.3 E.	65	Felt
23/5/62	dil. to S.W.	5.4 S. 151.9 E.	55	Felt
23/5/62	dil. to S.W.	5.4 S. 152.0 E.	70	Felt
23/5/62	dil.	4.9 S. 150.8 E.	44	Felt
25/5/62	dil. to S.W.	5.6 S. 152.2 E.	25	Felt

APPENDIX H.

BISMARCK SEA EARTHQUAKES WITH KNOWN EPICENTRES OCCURRING IN THE PERIOD JUNE 1955 TO FEBRUARY 1963.

Date	GMT Origin Time	GMT P.Arrival	Direction of First Motion	Epicentre	KMS Depth	S	L	T	Period of L Waves	Remarks (Felt etc.)
8/6/57	032333	032404	-	3°S.147½°E.	-	-	e0325.8	e0329.0	5-8"	Not felt, D = 5°
8/6/57	060747	060835½	-	2½°S. 150°E	-	-	e0609.6	e0610.5	5-7"	Not felt, D = 2°48'
**12/7/57	205618	205717	-	3°S. 148½°E	-	-	e2058.1	e2100.4	4-5½	Not felt D = 4°
4/8/57	003912	e004057½	-	3½°S.145°E	-	004222	e0043.0	-		Felt Manam Is.etc. D =7°10'
18/2/58	200844	e201000	-	3°S.147½°E	-	-	e2011.6	-	-	Not felt D = 4°48'
17/5/58	070225	070348	-	3°S.147½°E	-	-	(e070507 (e070542	-	-	Not felt D = 4°48'
22/5/58	150800	150934	-	3°S.146°E	-	(iPPP151000)	e1511.5.	-	-	Not felt D = 6°16'
25/6/58	093630	093821	-	3°S.144½°E	-	-	-	-	-	Mag.6¼ - 6½. Felt Chuave etc, D=7°45' Nuku.
10/8/58	180553	!180608½	Dil.	3½°S.150½°E	-	-	-	-	-	Felt Rabaul D = 1°52'
17/8/58	180105	e180244	-	3°S 145½°E	-	-	i180548	-	-	Not felt D = 6°46'
31/10/58	190254	190440	-	3½°S.143½°E	-	-	(e190626 (e190706	-	-	Not felt D = 8°42'
1/11/58	033836	033911	-	3°S. 150°E	-	-	-	Recorded	-	Felt Kavieng D = 2°28'
1/11/58	060647	060829	-	3½°S.143½°E	-	-	-	-	-	Not felt D = 8°42'
7/5/59	000324	000426	-	3°S. 148½°E	-	e0005(18)	-	Recorded	-	(Foreshocks.Not felt. (Mag. 6 - 6¼. D = 3°50'
7/5/59	090346	090428	-	3½°S.149½°E	-	e0905(08)	-	-	-	Not felt D = 3°
7/5/59	111716	111758	-	3½°S.150°E.	-	e1118(34)	-	-	-	Nor felt D = 2°20'
21/6/59	032810	032911	-	3°S.146°E.	-	e0330.3	-	-	-	Not felt D = 6°10'
12/9/59	015347	e015518	-	3°S.146½'E.	-	-	e0157.8	-	-	Not felt. Many aftershocks.
12/9/59	070145	e070310	-	3°S.147°E	-	i070431.0	e0704.6	-	-	Not felt. Many aftershocks.
13/9/59	043805	e043929	-	3½°S.146½°E	-	e0441.0	e0441.2	-	-	Not felt
14/11/59	103356	i103450.3	-	3°S.148½°E.	-	103443	e103545	-	-	Not felt
10/2/60	215045	i215103.6	-	3½°151½°E	-	-	-	-	-	Felt Rabaul.
27/4/60	171130	171305.7	-	3½°S.146½°E.	-	i171326.7	e171439	i171807.6	-	Not felt
28/4/60	050807	051001.2	-	3½°S.144½°E.	-	e051149	e151219	-	-	Not felt. D = 7°50'
20/5/60	002322	e002534	-	3½°S.147½°E	-	-	-	-	-	Not felt.
25/7/60	213646	e213749	-	3°S.148°E.	-	-	e2138.7	-	-	Not felt.
31/7/60	184613.9	184715.1	-	2.8°S.148,2°E.	13	-	-	-	-	Not felt.
15/3/61	101455.5	!101518.6	Comp.	3.3°S.150.7°E.	21	-	-	-	-	Felt Rabaul,Kavieng.Mag.6
26/3/61	202905.7	203054.7	-	3.1°S.146.2°E.	25	i203138½	e203245	-	-	Not felt.
3/6/61	055512.6	055531.7	Comp.	4.3°S.151.1°E.	18	-	-	-	-	Felt Rangarere,Rabaul.
3/6/61	091432.1.	!091452.5	Comp.	4.3°S.150.9°E.	25	-	-	-	-	Felt Rangarere,Rabaul.
25/8/61	055141.5	e0553(02)	-	0.7°S.148.2°E.	-	-	-	-	-	Not felt.
17/9/61	171359.1	-	-	3.6°S.143.4°.E	44	-	-	-	-	Not felt.
20/9/61	190337.1	e190327	-	3.6°S.150.9°E.	30	-	-	-	-	Not felt.
12/10/61	060125.5	-	-	2.9°S.144.9°E.	25	-	-	-	-	Not felt
26/10/61	003820.3	003924.0	Dil	3.1°S.147.4°E.	14	i004030.2	i004133.2	Several apparent T waves recorded.	2.4"	Felt Tong.Is.amd Lorengau Mag.6¼ - 6½
28/5/62	030807.4	e030940	-	3.3°S.146.0°E.	25	i031058	e031157	-	-	Not felt.
2/6/62	053536.1	053714	-	3.5°S.145.3°E.	42	i053857	e0540(00)	-	-	Not felt.
1/7/62	015615.6	015640	-	3.8°S.150.4°E.	24	-	-	-	-	Not felt.
22/7/62	234927.0	e235102.6	-	3.5°S.145.6°E.	28	-	-	-	-	Not felt.
30/7/62	171644.4	e171849	-	3.3°S.143.9°E.	25	i172021	-	-	-	Felt widely.Mag 7.
31/7/62	021905.2	e0221(25)	-	3.2°S.144.1°E.	20	-	-	-	-	Felt Wewak.
1/8/62	043657	e043902	-	3.2°S.143.7°E.	33	-	-	-	-	Felt widely.Mag.7.
8/8/62	054202.8	e053958	-	3.5°S.150.5°E	19	e05324	-	-	-	Not felt.
9/10/62	201438.3	201531.9	Dil.	3.2°S.148.2°E.	33	-	-	-	-	Not felt.Mag. 6¼
12/10/62	043438.9	043616.3	Comp.	3.4°S.145.3°E	36	i043733	i043620	-	-	Not gelt.
3/11/62	043409.6	e043524	-	2.7°S.147.4°E.	33	i043620	-	-	-	Not felt
24/11/62	172259.5	172355½	-	2.5°S.148.9°E.	32	i172452.3	-	-	-	Not felt.
11/12/62	180958.6	e181157	-	3.9°S.143.6°E.	33	-	-	-	-	Not felt.
21/1/63	115615.3	115655.5	Comp.	2.7°S.150.1°E.	50	-	-	-	-	Not felt.
28/1/63	1212---	-	-	2.6°S.149.9°E.	33	-	-	-	-	Felt Mussau.
12/5/57	215845	215942	-	3.°S.148½°E	-	-	e2200.3	e2203.0	5-8"	Not felt D = 4°.

APPENDIX I

CATALOGUES OF EARTHQUAKES RECORDED AT RABAUL WITH KNOWN S-P

INTERVALS OF NOT MORE THAN TEN SECONDS

Date	GMT Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt	Remarks
2/3/55	013707	(8)	B	to N.E.		
14/4/55	223133	(9)	B			
9/5/55	0102½				Rabaul	(int.2-3) Within 20 miles of Rabaul
7/8/55	010559½	(8)	O	Dil/to S.		(Possibly foreshocks of
9/10/55	210916	(10)	O			(earthquake of 10/10/55.
9/10/55	232646	(10)	O			(Mag. 7¼
22/10/55	152330.3	(4)	B	Compression		
23/10/55	164313.4	9	B	Comp.from S.S.W.		
27/10/55	114923.1	(8.1)	B	Comp. from S.W.		Deep?
1/11/55	153838.2	4.8	B	Compression		
20/11/55	022046.0	3	B	Dilatation		
2/12/55	184951.9	7.3	B	Comp. from 302°		
8/12/55	0549 CBM	8	B			
12/12/55	132212.4	4.7	B	Comp. from S?.		
12/12/55	140420.2	4.8	B	Comp. from 145°		
12/12/55	203146.6	2.4	B	Compression		Possibly deep
14/12/55	large No. of shocks	(7)	B	None clear		
15/12/55	190337	8½	B			
18/12/55	082256.4	6½	B	iP! Comp. from 28°		
18/12/55	224715.8	7	B	Comp. from 36°		
19/12/55	103623.0	7	B	Comp. from 124°		
26/12/55	082130.3	6	B	Compression		
27/12/55	043711.5	2	B	Dilatation		Explosion? v. short period beginning
29/12/55	120824.9	6	B	Dilatation		
31/12/55	023917.0	1.7	B	Dilatation		"
4/1/56	110154.6	6½	B	iP! Dil to 148°		
6/1/56	020128.3	7.8	B	Compression		
1/2/56	103031.2	(6.2)	B	Dilatation		
10/2/56	003719.9	(3½)	B	Compression		
16/2/56	065650.2	8	B	Dil. to 158°		
13/3/56	233310	10	O	-	Rabaul,Warangoi	(Int. 4) 4°S. 153°E
2/5/56	104731	6	B			
2/5/56	114610	10	B	Comp. from N.E.		
4/11/56	200811	10	O		Rabaul	(int.1)Not recorded elsewhere
21/11/56	0750	8	O		Namatanai (Int.5) Rabaul (Int.2)	h=100 kms. 4°S 152½°E.
21/12/56	141635	10	O	Comp. from S.E.	Tol (Int.3) Bialla (Int.2)	Deep
17/4/57	194648	9	B	Compression		
29/5/57	0013009	9½	B	Dil. to S.E.		
8/7/57	105910½	3½	B			
22/7/57	163935	9	B			
6/8/57	115002	10	B			
9/8/57	100118	10	B			
9/8/57	193216.3	9.7	B			
17/8/57	093738½	9½	B			
27/8/57	133141	10	B			
3/9/57	192643	8	B			
4/9/57	113924	8½	B			
4/9/57	114023	7½	B			

APPENDIX I

Date	GMT Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt	Remarks
4/9/57	120346	8	B	Compression		
"	120633½	8	B			
"	120726½	8½	B	Compression		(N.B. Shock 122650½ felt Rabaul (Int.3) Epicentre 4°S 151½°E
"	131608	4	B			
"	211933	10	B			
5/9/57	030718½	8½	B			
9/9/57	140244	8½	B	Dilatation		
"	203614½	10	B	"		
14/9/57	090253	9	B			
20/9/57	105357	10	B	Dilatation		
21/9/57	073537½	6	B			
"	132313½	10	B			
25/9/57	175205½	8	B			
26/9/57	0428(05)	10	B	eP, eS.		
5/10/57	052332½	8	B	Dilatation		
7/10/57	040503	10	B			
10/10/57	180457½	9½	B	Dilatation		
"	183723	8½	B			
14/10/57	062602	8½	B	iP! iS!		
"	142608	9	B			
16/10/57	115226	8	B	eS		
"	204946	9	B			
19/10/57	192341½	8	B			
"	192806½	6	B			
21/10/57	133124½	10	B			
"	232250½	(5)	B	Compression iP!		
23/10/57	125907	9	B			
"	192018	5	B	Compression		
29/10/57	123236	10	B			
"	141100	10	B	Compression iS!		
"	161509½	8½	B	Compression	Warangoi (Int.1-2)	
2/11/57	181735	9	B			
"	214754	8	B			
3/11/57	175404½	8½	B	Dilatation		
4/11/57	010736½	9	B			
"	150454	3	B	Dilatation		
"	215722	8	B			
5/11/57	004603	2	B			iS!
"	152314	9	B			
"	161257	4½	B			
"	173704½	4½	B			
6/11/57	153327½	8½	B			
"	1546(51)	6	B			(eP)
7/11/57	100232	6	B			
"	100455	8	B			
"	142327½	4½	B	Comp. from N.W.		
8/11/57	174452	10	B			
"	230748	10	B			
9/11/57	082829	9	B			
11/11/57	212557½	8	B	Compression		
13/11/57	134409	8½	B			
14/11/57	094827½	10	B			eS
15/11/57	133322	10	B			
21/11/57	191253½	2½	B	Dilatation		eiP. very small shock
22/11/57	025258½	4	B			
23/11/57	175421½	9	B			
"	192036½	9	B			
25/11/57	200642½	8	B			

APPENDIX I.

Date	GMT Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt	Remarks
26/11/57	064553	10	B	Dilatation		iS!
27/11/57	115120½	9	B	Dil.to E.N.E.	Rabaul(Int.1.)	?Not recorded elsewhere
28/11/57	011650	9½	B			
"	235143½	9	B			
30/11/57	213800½	10	B			
1/12/57	104853	8½	B			
"	161110	6½	B			
2/12/57	185355½	8	B			
3/12/57	115717½	6	B			
6/12/57	092606½	9	B			
"	110404½	6½	B			
7/12/57	062913	8	B			
"	075746	8½	B			
"	134014	6	B			eS
"	212444	10	B			
9/12/57	143647	9½	B			
"	180701	8½	B			
10/12/57	105553½	8½	B			
12/12/57	004029½	3½	B			Similar to blast
15/12/57	040928	3	B			
"	050619	7½	B	Dilatation		iS!
"	100652½	9½	B			
17/12/57	071543½	9	B			
"	171418	9½	B			
18/12/57	162609	6½	B			
20/12/57	001104	10	B			iS! Similar to blast
22/12/57	024921	5	B			)
"	140154½	5½	B			)
"	144249½	5½	B			)
"	165909½	2½	B	Compression		) iS!
"	182548½	7	B			) Several of these
"	192122½	5	B			) small tremors
"	192939½	4	B			) appear deeper
"	193540½	3	B			) than normal
"	193610½	5	B	Compression		)
"	194055½	5½	B			)
"	194227½	5½	B			)
"	204345½	4	B			)
23/12/57	172134	5	B			
24/12/57	025529	8	B	Compression		Deep?
"	160853	6	B			
25/12/57	202725	10	B			
26/12/57	040034	10	B			
"	075739	9	B	Dilatation		
"	145206½	9	B			eS
27/12/57	074517½	(9)	B	Dilatation		
29/12/57	060152	9	B	Dilatation		
"	093216½	7½	B	Compression		
"	173558	9	B			eP
30/12/57	103901	9	B	Compression		
"	143404	9	B			
"	165059	9	B			
"	234110	10	B	Comp.from N.N.E.		
31/12/57	052934	9	B			
1/1/58	074248½	2½	B			
2/1/58	100136	7	B			
"	185540½	9	B	Compression		
3/1/58	142938½	8	B	Compression		
4/1/58	131944½	9	B	"		
"	224943½	10	B	"		

APPENDIX I.

Date	GMT. Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt	Remarks
5/1/58	012912	4.8	B	iP!		
"	013514	9	B			
"	123642	8	B			
"	174033½	8½	B			
6/1/58	080326	3	B			
7/1/58	080114½	8	B			
"	102424½	9	B			
9/1/58	100932	7	B			
"	222237	6	B			
10/1/58	160241½	8½	B			
11/1/58	192129	9	B	Compression		
12/1/58	032608½	9	B			
13/1/58	052335	10	B	Dilatation		
15/1/58	015215½	1½	B			
"	080315	8	B			
"	091103	10	B			
"	233805	8½	B			
18/1/58	043117½	1½	B			
19/1/58	002344½	10	B	Dil.toS.E.iP!		
13/3/58	065432	4	B			
19/3/58	125358	4	B			
22/3/58	001711	8	B			
6/3/59	165052	10	B		Rabaul (Int.1)	Deeper than normal. Not recorded elsewhere
19/3/59	142942	8	B	iP!	Rabaul (Int.1)	Not recorded elsewhere
2/4/59	162607	(7)	B	iP!		
15/4/59	164155	(9)	B	iP!		
26/5/59	094954	5-6	B	From S.W.	Rabaul (Int.2)	Not recorded elsewhere S-P measured from aftershocks.
4/1/60	062003.7	10	O		Rabaul (Int.3) etc. 4½°S. 153½°E.	

(N.B. 13 small earthquakes of S-P less than 5" were recorded during January 1960).

Date	GMT. Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt	Remarks
27/3/60	233229.2	6.0	B	iP!	Rabaul (Int.1)	Not recorded elsewhere
2/4/60	141516.4	6.1	B	iP! iS!		
20/12/60	131444.2	5.8	B	Compression	Rabaul (Int.1)	Not recorded elsewhere
1/2/61	2025	(½)	B	V.short period, possibly volcanic?		
10/2/61	2228	(4)	B			
11/2/61	1431	(9)	B			
"	151517.0	(2½)	B	Comp. from N.W.		
12/2/61	163933.9	(9)	B	Dil. to (N.W.?)		
13/2/61	2042	(1)	B	Possibly volcanic?		
15/2/61	081903.0	(2)	B	Dil. to N.E.		
"	1510449.9	(8)	B	Comp. from N.N.E.?		
"	1548	(5)	B	Harmonic		
16/2/61	042826.1	(2)	B	Dil. to (S?) Possibly volcanic?		
17/2/61	0754	((½))	B	Harmonic		
18/2/61	194357.7	6	B	Dilatation		
21/2/61	1013	1	B	Possible volcanic		
"	213237.1	9¼	B	Dilatation		
23/2/61	0917	(10)	B			
1/3/61	001723.8	(4)	B	Dil. to ((N.)W?).		
"	004306.9	(5)	B	Dilatation		
"	123105.9	(10)	B	Dil. to W.S.W.?		
2/3/61	0308	(8)	B			
4/3/61	224227.8	9	B	Comp. from E.N.E.		
5/3/61	0318	(4)	B			
"	2236	(8)	B			
6/3/61	034724.5	(4)	B	Comp. from (N)W.		
"	102935.7	(4.3)	B	Comp. from N(E).		
"	165629.6	9.3	B	Dil. to N(W).		

APPENDIX I.

Date	GMT. Arrival Time	S-P (Seconds)	Omori or Benioff	Direction of first movement	Felt.	Remarks
6/3/61	173111.0	(4)	B	Dil. to (S)W.		
7/3/61	001023.3	(4)	B	Compression		
"	031032.9	(8)	B	Dil. to S.W.		
"	053415.6	5½	B	Dil. to N.W.		
8/3/61	095219.9	4.4	B	Compression		
9/3/61	110723.3	3.6	B	Dil. (to W?)		
10/3/61	093522.2	7	B	Comp. from (S.E.?) iP!		
"	174138.7	7	B	Comp. from N.W. iP!		
12/3/61	135550.0	(6)	B	Comp. from (S.E.?) iP!		
"	142955.7	(2½)	B	Comp. from N(W?)) iP!		
15/3/61	130117.7	(10)	O	Dil. to S.E. iP!	Metlik (Int.4) Rabaul (Int.3) h= 99 kms. 4.4°S 152.5°E	
15/3/61	150554.4	(10)	B	Dil. to (E.?)		
17/3/61	221108.1	10	B	Dil. to S.E.		
18/3/61	112531.5	(1½)	B	Dil. to (S.E.?)		
8/4/61	0516	8½	B			
"	215644.9	10	B	Comp. from (S.W.?)		
14/4/61	184349.6	7.4	B	Dilatation		
22/4/61	122743.8	9½	B	Dilatation		
5/5/61	1438.8	(7½)	B	Compression		
6/5/61	140329.4	7.6	B	Compression		
7/11/61	162947	8	B		Very small shock. Not recorded elsewhere	
4/2/62	161703½	10	O	iP!	Pomio (Int.4) Rabaul (Int.3) etc. 5.7°S, 152.1°E, h= 85 kms.	
23/2/62	180533½	7½	O	iP!⅜	Rabaul (Int.4) etc. 4.0°S, 152.6°E, h= 25 kms.	
"	202135½	7½	O	iP!	Rabaul (Int.4-5) etc. 3.8°S, 152.0°E. h= 25 kms.	
24/2/62	103203	7	B			
"	142828½	7	B	Compression		
"	145931	7	B	"		
1/3/62	194149.4	9.1	B			
3/3/62	191014.0	7½	B	Dilatation		
15/3/62	1035(27)	7.	B	eP		
(26/3/62	152158.5	7.5	B	Dil. to S.W.)		
1/4/62	193458½	8½	B	Dilatation		
16/4/62	2200(16)	8½	B	eP		
29/4/62	124754.2	9.3	B	iP!		
7/5/62	094004.1	9.9	B	Compression	Taliligap (Int.2-3) Rabaul (Int.2) also Londolovit and Ulamona	
4/8/62	085805.2	(9)	B			
12/9/62	222344	7½	B			
5/10/62	105048.8	9.5	B	Dilatation		
18/10/62	072644.8	8.5	B	Compression iP!		
19/10/62	221303.5	3½	B	Dilatation iP!		Possibly deeper than usual
21/10/62	095546.4	10	B	Dilatation iP!		
25/20/62	083828.6	9.4	B	Dilatation		
30/10/62	224528½	3	B	eiP	Vunalama (Int.1) Not recorded elsewhere	
9/11/62	112724.8	6	B			
3/2/63	015220.5	9.5	B	iP!		

APPENDIX J.

EARTHQUAKES WITH REPORTED EPICENTRES OR FELT IN THE RABAUL AREA

MAY 1960 - MAY 1961.

Date	GMT Time	Epicentre	Kms. Depth	Magni-tude	(Intensity Modified Mercalli Scale) Felt	Remarks
27/5/60	2010	5½°S 153°E	150		Taliligap 2	
2/6/60	0747	5½°S 151½°E+			Rabaul 4-5 etc.	Deeper than normal
3/6/60	0738	5½°S 151°E			Rabaul 3 etc.	
10/7/60	2105	+			Taliligap 2	Not recorded
12/7/60	1347	+			Taliligap 3	Rec. only at Rabaul
18/7/60	0143	4½°S 151°E	200		Rabaul 4 etc.	Deeper than normal
"	0708	+			Taliligap 2	Not recorded
"	1046	+			Rabaul 2	Rec. only at Rabaul
27/7/60	(1512)	+			Taliligap 2-3	Time reported as 1635
31/7/60	0256	5.6°S 150°0E	25	6¾	Rabaul 4 etc.	V. widely as far as Wanigela
"	0705	6.0°S 150°0E	93	6	Rabaul 2 etc.	
"	1821	+			Taliligap 3	Not recorded
1/8/60	1629	4.8°S 152.6°E+	77		Rabaul 2 etc.	
2/8/60	2234	+			Rabaul 2	Rec. only at Rabaul
6/8/60	1046	+			Taliligap 2	Not recorded
10/8/60	0745	+			Taliligap 2	"
"	1909	+			Taliligap 1	"
24/8/60	0427	6.2°S 150.4°E	66		Not felt	
3/9/60	1242	6.1°S 154.5°E	457	6½-6¾	Karoola 5 Rabaul 3 etc.	
17/9/63	1512	3.6°S 149.5°E	220		Not felt	Deep Dismarck Sea
25/9/60	1705	+			Taliligap 5-6 Rabaul 2-3	Recorded Charters Towers
1/10/60	1144	4.7°S 153.3°E+	90		Rabaul 1-2 etc.	
7/10/60	1415	+			Taliligap 1-2	Not recorded
13/10/60	1841	3.8°S 152.4°E+	213		Rabaul 2-3 etc.	
24/10/60	1710	6.0°S 150.0°E	122		Not felt	
11/11/60	1942	+			Taliligap 1.	Rec. only at Rabaul
(15/11/60	- Large number of unusual pulses throughout the day)					
21/11/60	0430	3.4°S 152.3°E+	371		Not felt	
23/11/60	0125	5.0°S 153.3°E	79		Taliligap 4 Rabaul 3	
"	0412	4.9°S 153.8°E	516		Londolovit 1-2	
24/11/60	0451	4.6°S 153.0°E+	87	6¼	Taliligap 6, Rabaul 4-5	
1/12/60	2050	4.5°S 154.0°E	117		Taliligap 1-2	
2/12/60	0438	6.6°S 152.5°E	33		Taliligap 2-3 Rabaul 1	
3/12/60	2148	4.2°S 152.1°E+	40		Not felt. Epicentre probably wrong. Possibly about 5.3°S 152.8°E.	
18/12/60	2055	5.4°S 152.7°E+	62		Not felt	
20/12/60	1315	+			Rabaul 1 S-P 5.8" Rec. only at Rabaul.	
20/12/60	2220	4.3°S 152.1°E+	154		Not felt	
21/12/60	0253	+			Rabaul 1	Rec. only at Rabaul
22/12/60	2103	6.8°S 155.3°E	469	5½	Rabaul 1-2	(Buin)?
31/12/60	2106	5.0°S 151.4°E+	136		Taliligap 1-2	
2/1/61	2052	6.8°S 150.3°E	62		Taliligap 2	
3/1/61	1803	6.2°S 150.9°E	113		Not felt	
4/1/61	0520	+			Vunadidir 2	Not recorded. Series of small shocks
13/1/61	1734	+			Taliligap 2-3	Not recorded
14/1/61	0534	5.4°S 152.9°E	81		Gavit 2 etc.	

APPENDIX J.

Date	GMT Time	Epicentre	Kms. Depth	Magnitude	(Intensity Modified Mercalli Scale) Felt	Remarks
27/1/61	0553	6.4°S 154.7°E	23		Torokina 3, Rabaul 1	
"	1355	5.5°S 151.9°E	118		Taliligap 2, Rabaul 1-2	
6/2/61	1930	4.8°S 154.2°E	470		Not felt	
"	2146	6.8°S 155.3°E	59		Buin 6, Rabaul 2-3 etc.	
8/2/61	1926	5.9°S 151.8°E	51		Rabaul 1	
17/2/61	1855	4.4°S 153.0°E+	108		Rabaul 2-3,? Taliligap	
20/2/61	1418	5.0°S 153.4°E	107		Rabaul 2,?Taliligap	
3/3/61	2002	+			Rabaul 2.	Recorded Brisbane
4/3/61	0226	Dil (to NW?) +			Rabaul 2	Recorded only at Rabaul
7/3/61	2312	4.7°S 153.2°E	90		Karoola 5, Rabaul 3 etc.	
8/3/61	0926	Comp. from N.E.+			Rabaul 2	Rec. only at Rabaul
13/3/61	0451	5.2°S 153.3°E	25		Not felt	
15/3/61	0058	6.0°S 151.6°E	79		Not felt	
"	1015	3.3°S 150.7°E+	21	6	Rabaul 2-3 Kavieng 2,	Bismarck Sea
"	1301	4.4°S 152.5°E+	99		Metlik 4, Rabaul 3 etc.	
"	1612	4.6°S 153.4°E	18		Not felt.	
4/4/61	1036	5.9°S 149.4°E	124		Kandrian 4, Rabaul 1-2 etc.	
19/4/61	0557	5.5°S 152.9°E	111		Not felt	
22/4/61	1900	3.5°S 150.1°E	91		Not felt	Intermediate Bismarck Sea
26/4/61	0620	5.7°S 151.1°E	34		Not felt	
2/5/61	0643	5.3°S 151.5°E+	81		Not felt	
7/5/61	0026	6.1°S 154.4°E	123		Karoola 5 etc.	
"	1451	5.3°S 151.2°E	76		Not felt	
9/5/61	1107	6.2°S 154.5°E	110		Karoola 3	

+Shocks marked with an asterisk are those with probable epicentres less than 1° from Rabaul. They are plotted on Figure 15 as open circles, all other shocks are plotted as closed cirles.

APPENDIX K.

CATALOGUE OF HARMONIC SINUSOIDAL DISTURBANCES, RABAUL, OTHER THAN CLEARLY INDUSTRIAL DISTURBANCES.
JANUARY, 1954 - JANUARY, 1963.

<u>A</u> = UNUSUALLY PERFECT EXAMPLE. A = PERFECT SINUSOIDAL ON ALL 3 COMPONENTS. B = PERFECT SINUSOIDAL ON AT LEAST ONE COMPONENT.
C = IMPERFECT HARMONIC SINUSOIDAL. D = POOR HARMONIC SINUSOIDAL

GMT DATE	COMPONENT G.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ENDS	L.M.T. MAX. AMPLITUDE AT	COMPONENT MMS MAX AMPLITUDE (TRACE)	SECONDS PERIOD	SECONDS OVERALL PERIOD ENVELOPES	CLASS	SHIP	REGISTERED TONNAGE	L.M.T. LEFT WHARF	L.M.T. "LEADS" (OFF BEEHIVES)	L.M.T. BERTHED WHARF	REMARKS
26/3/54	093536	1935	-	-	3½(Z)	½	4-5	C	No records of shipping exist for 1954-1955.					A little less than
"	1849	0449(27/3)	0450	-	1½(Z)	½		C	"		"			A little more than
21/7/54	1951	0551(22/7)	-	-	1¾(Z)	-	-	C	"		"			
1/9/54	2223½	0823½(2/9)	0825	-	3½(Z)	1/3	4	C	"		"			
14/11/54	2328	0928(15/11)	0930	-	5¼(Z)	½	5	D	"		"			
15/11/54	1220	7220	-	-	5 (Z)	2/3	35	B	"		"			
6/6/55	0916	1916	-	-	2¾(Z)	1/3	-	D	"		"			
28/7/55	2323	0923(29/7)	-	-	8 (E)	2/3	44	A	"		"			
1/8/55	2109	0709(2/8)	-	-	7¾(N)	½	14	(A)	"		"			
Seismograms read for harmonic Sinusoidal disturbances to the end of 1955. No further readings made until January 1960 except for the following fourcases:														
19/1/56	2249	0849(20/1)	-	-	small	-	-	(A)	Nil					Friday morning (Observatory temperature boat?)
28/1/56	0617	1617	1619	-	4½(Z)	½	16	<u>A</u>	Nil (M.V.Funing berthed 0800 hours L.M.T. main wharf).					
19/12/57	0800	1800	-	-	-	-	-	(A)	Ivybank	4448	1815	1840		
"	1945	0545(20/12)	-	-	-	-	-	(A)	Nil					
5/1/60	201321(N)	0613(6/1)	0616½	061504	8(N)	1/3,¾,1	-	A	Chungking	3084	0610	?		
10/1/60	203233(Z)	0632(11/1)	06333	063252	6½(N)	½	-	B	Asuma Maru 7	2060	-	1930(10/1)	0830(11/1)	Anchorage (leads)1930(10/1) 0830(11/1).
13/1/60	225136(N)	0851(14/1)	0852	085146	23½(N)	¼.1/3	-	B	Nil					
17/1/60	124035(N)	2240	224420	224226½	2½(N)	2/3	-	A	Nil					
"	215424(N)	0754(18/1)	075742	075521	10½(Z)	1/3	--	<u>A</u>	?					
28/1/60	205216(N)	0652(29/1)	065350	065233½	5¾(E)	¾	-	B	Chefoo	3130	-	?		0600-0730 Main wharf.
2/2/60	080602(N)	1806	180635	180621	8(N)	½	13-16	B	?					
5/2/60	221127(Z)	0811(6/2)	081300	081205	9¼(N)	½	12-37	B	?	-	-	-		Friday morning,probably Observatory Temperature boat.
12/2/60	220643(N)	0806(13/2)	080709	080658½	6 (N)	½	30	B	?					"
19/2/60	220757(N)	0807(20/2)	080841	080814	5¾(N)	½	38	C	?					"
26/2/60	150523(N)	0105(27/2)	012555	010527½	5½(N)	1/6,1/3	4-19	C	?				-	-
"	220814(N)	0808(27/2)	080849	080826½	6¼(N)	½	35	D	Nil					"
12/3/60	065932(Z)	1659	174717½	-	7½(E)	1/3,½	-	A-B	Nil (However Lisbank, Stanvac Nairobi and Chitose Maru were in port)					
"	220626(Z)	0806(13/3)	-	-	-	-	-	A-B	Nil					
18/3/60	195550(N)	0555(19/3)	055819	no clear max.	5¼(E)	½- ½	30-36	A	Chitose Maru Delos *	1532 2211	0530 -	?		*Delos probably caused the disturbance. 0545-0630 Main Wharf.
19/3/60	105306(N)	2053	205647	205422	6¼(N)	½	20	B	Delos	"	2100	-	-	Main wharf
21/3/60	220736(N)	0807(22/3)	080809	080756½	17½(N)	2/3	14	B	Tung Fengi	3782		0700	0830	Main wharf
22/3/60	1433(07)(N)	0033(23/3)	-	003440	3¾(N)	2/3,4/5	23	B	Foylebank	3219	(22/3)2345	0045	-	Wreck wharf
23/3/60	083740(N)	1837	183(8)46	183806	5¾(E)	2/3	-	C	Tung Fengi	3782	1800	1845	-	Main wharf
16/4/60	2107(25)(Z)	0707(17/4)	071026	070926	7½(E)	Overlap 1/3,2/3	15-16	<u>A</u>	Southbank	3523	0700	-	0830	Moved from Main Wharf to Toboi.
18/4/60	082823(E)	1828	183937	183101	43½(E)	2/3	15-19	<u>A</u>	Southbank	3523	1745	1930	-	Toboi

2...

GMT DATE	COMPONENT G.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ENDS	L.M.T. MAX. AMPLITUDE AT	COMPONENT MMS MAX AMPLITUDE (TRACE)	SECONDS PERIOD	SECONDS OVERALL PERIOD	CLASS	SHIP	REGISTERED TONNAGE	L.M.T. LEFT WHARF	L.M.T. "LEADS" OFF BEEHIVES	L.M.T. BERTHED WHARF	REMARKS
23/4/60	225516(E)	0855(24/4)	090200	085915	5½(N)	2/3	25	A	(Southbank*	3523	0715	-	0930	Toboi to Wreck Wharf.
									(Citos	2104	0815	0835	-	Main wharf?
									(Aros *	2067	0845	0900	-	Wreck wharf.
									*Southwark or Aros probably caused the disturbance.					
30/4/60	213627(Z)	0736(1/5)	0739(21)	073720	14(E)	2/3-4/5	15-18	C	Southbank	3523	0730	0745	-	Main wharf.
10/5/60	080538(Z)	1805	180853	180623	10½(E)	2/3	16-32	B	Laganbank	3219	1750	1815	-	Toboi. Harmonic again at 181341(Z.N.)
15/5/60	1403(31)(E)	0003(16/5)	000426	000356	4¼(E)	1/3-2/3	15	B	Laganbank	3219		(0740(15/5) (0800(16/5)	-	At anchorage
17/5/60	141121(ZE)	0011(18/5)	001256	001151	7 (E)	2/3- 1	6-(17)	B	Sinkiang	1763	2355(17/5)	0020(18/5)	-	Main wharf
21/5/60	205736(E)	0657(22/5)	070201	070219	4½(E)	1/3-2/3	-	C	Laganbank	3219	0645	-	0800	Main wharf to Toboi (Harmonic again at 0730(E).
2/6/60	201008(N)	0610(3/6)	061342	061121	3(E)	½ 2/3	-	C	(Malacca*	2192	0600	0615	-	Wreck wharf
									(Chekiang	3131	0615	-	0700	Main wharf to Wreck wharf.
									(Bulolo	3319	-	?	0715	Main wharf
									* Malacca probably caused the disturbance.					
4/6/60	0638(17)(Z)	1638	165247	165212	10½(N)	¼,1/3,2/5	-	C	Bulolo	3319	1630	1645	-	
									Alkwaar *	6914	-	1545	1715	Main wharf.Intermittent harmonic.
									*(Alkwaar probably caused the disturbance).					
15/6/60	125017(E)	2250	225156	225121	7(N)	2/3	14-30	A	Delos	2211	2215	2250	-	Main wharf
10/7/60	204510(N)	0645(11/7)	064600	064537	20½(N)	¼, ¼	23	B- C	Schelde Lloyd	4692	(0545 (0700	0715	-	Main wharf
13/7/60	1403(24)(N)	0003(14/7)	001027	000407	5¼(N)	¼	-	C	Sinkiang	1763	0000	0015	-	Wreck wharf
27/7/60	143917 (NE)	0039 (28/7),	004133	004029½	21(E)	2/3	13	B	Citos	2104	0035	0055	-	Main wharf
29/7/60	130842(N)	2308	231825	231816	3¼(N)	¼, ½	18	C	(Chitose Maru	1532	(30/7)0020	0040	-	Wreck wharf *
									(Stanvac Sydney		-	-	0800(29/7) **	
									*Harmonic again at 002139(20/7) **Pumping operation continuous until daylight hours (30/7).					
9/8/60	154127(Z)	intermittent until 0141(10/8)	015730	(014156 (015707½	9(E) 9½(E)	2/3.2/3	(20)	C B	Nessbank	3321	2330(9/8) -0145(10/8)		0200	Toboi
21/8/60	214612½(E)	0746(22/8)	075357	no clear max.	9 (E)	-	-	D	Nil	-	-	-	-	Saturday morning.
23/8/60	215903½(E)	0759(24/8)	0805	"	7¾(N)	½	-	D	Nil					
27/8/60	152132(N)	0121(28/8)	(0124)	012336	3 (E)	1/6. 2/3	-	D	Nessbank	3321	0115	0140	-	Toboi
3/9/60	153305(N)	0133(4/9)	(0158)	014927	48(E)	1/3.3/4	-	B	Name not recorded		-	0152	-	Anchorage (Intermittent (harmonics
6/9/60	081303(E)	1813	(1915)	181328	40(E)	¾, 1	24	B	(Shansi *	1826	1745	1830	-	Main wharf
									(Nayadis	4785	-	1835	1915	(Anchorage mid-stream)
									* Shansi probably caused the disturbance.					
7/9/60	201913(E)	0619(8/9)	(062620)	(062347	27(E)	¾ 1	19-27	C	(Shansi	1826	0600	0625	-	Main wharf
again	203129(E)	-	gradually (	(063147	17¾(N)	1	-	C	(Nayadis	4785	-	0545	0630	Main wharf
15/9/60	14(1900)(Z)	00(19)(16/9)	0025¾	002135	4¾(N)	1/5. ½	-	C	Westbank	3523	2330	(15/9)0045	-	Wreck wharf
24/9/60	142328½(E)	0023(25/9)	004129	002413	18¼(N)	1/5.2/3	-	C	Carranbank	3645	2330(24/9) 0030	(25/9)0100	- -	Main wharf
									Unusual overlap of periods.					
30/9/60	204247(N)	0642(1/10)	064542	064333½	19(E)	¾	9,14,27.	A	Mataram	5866	0545-0615	0645	-	Main wharf
15/10/60	0818(18)(E)	1818	183050	182729	22½(N)	½, 1	14-18	A	(Soochow	1808	1805	1820	-	Main wharf
									(				Intermittent harmonics	
									(Oronsay*	15, 122	-	1830	-	Anchorage
									*Oronsay probably caused the disturbance.					
23/10/60	081230(N)	1812	obscured by earthquake 181305		8¾(N)	½	-	C	Nil.	-	-	-	-	

3...

GMT DATE	COMPONENT G.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ENDS	L.M.T. MAX AMPLITUDE AT	COMPONENT MMS MAX AMPLITUDE (TRACE)	SECONDS PERIOD	SECONDS OVERALL	CLASS	SHIP	REGIS-TERED TON-AGE.	L.M.T. LEFT WHARF	L.M.T. "LEADS" OFF BEEHIVES	L.M.T. BERTHED WHARF	REMARKS
1/11/60	080135(N)	1801	1816½	180526½	38(N)	½,2/3,¾.	13,23,34.	B	Southbank	3523	1810	1825	-	Main wharf
										Intermittent harmonics (perfect on on N.E.)				
3/11/60	140607(Z)	0006(4/11)	gradually	000646	14(E)	1/3	(10)	B -C	Kanimbla	6225	0010	0025	-	Main wharf
9/11/60	071910(Z)	1719	?	172010	20(N)	2/3. ¾	(13)	(B)	Southbank	3523	1715	1730	-	Main wharf
13/11/60	080523(N)	1805	(1810)	1807(07)	22(E)	¾	-	(B)	Bintang	4957	1755	1815	-	Main wharf
29/11/60	124325(NE)	2243	224929	224606	7(E)	1/3 ½,2/3	-	B	Nil. From 1/1/61 main Sinusoidals only are listed. Complete lists between 1/2/61 and 10/5/61.					
23/2/61	0418	1418	-	-	8(E)	-	-	A	Nil (However Restormel was at anchorage all day.)					
"	1409	0009(24/2)	0014	?	19(E)	4/5 (also shorter period.		A	Citos	2104	0000	0015	-	Main wharf
26/3/61	0654	1654	-	-	3½(Z)	-	-	(A)	Nil. (Recorded on Z Willmore at Observatory.				(No N.E. Records)	
27/3/61	1502	0102(28/3)	0103	?	11(E)	-	-	A	Delos	2211	0100	0115	-	Main wharf
30/3/61	1431	0031(31/3)	-	?	9(N)	-	-	A	Nil. (However, Inchstaffa, Vedarbank, and Soochow in port).					
5/4/61	2133	0713(6/4)	-	-	15(N)	-	-	(A)	{Malacca {Chengtu	2192 3084	- -	? ?	0715 0730 No.Z. record.	Wreck wharf Main wharf
8/4/61	0608	1608	1610	-	5½(N)	very short	-	A	Chengtu	3084	1600	1615 Recorded Z Willmore Obs.	-	Main wharf
8/4/61	1941	0541(9/4)	-	-	7(N)	-	-	C	Nil.			" "		
"	2249	0849(9/4)	-	-	5(N)	-	-	B	Nil.			Nil on Willmore at Obs.		
13/4/61	0705	1705	1706	-	11(N)	short	-	B	Nil			Nil on Willmore Obs.at Tavurvur Tunnel.		
"	1604	0204(14/4)	-	-	5(N)	long	-	B	Cedarbank	3218	0200	0215 Nil on Willmore, Tavurvur Tunnel.	-	Wreck wharf.
"	2019	0619(14/4)	-	-	11½(N)	-	-	(B)	Nil	-	-	Nil on Willmore, Tavurvur Tunnel.		
14/4/61	1045	2045	2048	-	6(Z)	-	-	(B)	Langkoeas	5552	2030	2030 Trace on Willmore, Vulcan Tunnel.	-	?No NE Records
16/4/61	2203	0803(17/4)	-	-	3¼(Z)	-	-	(B)	Nil	-	-	-		?No NE Records.
17/4/61	0248	1248	-	-	4.9(Z)	-	-	(C)	Nil.	-	-	- Recorded on Willmore,Vulcan Tunnel.		No NE Readings.
"	0524	1524	-	-	5¾(Z)	-	-	(A)	Nil	-	-	- Nil on Willmore, Vulcan Tunnel.		No NE Readings.
"	2115	0715(18/4)	0719	-	7(Z)	-	-	(A)	Nil	-	-	do.	do.	
"	2348.5	0948(18/4)	-	-	4¾(Z)	-	-	(A)	Nil	-	-	do.	do.	
18/4/61	0416	1416	-	-	4½(Z)	-	-	(D)	Nil	-	-	do.	do.	
19/4/61	0550	1550	-	-	8¾(Z)	-	-	(A)	Nil	-	-	do.	do.	
20/4/61	0429	1429	-	-	4.3(Z)	-	-	(C)	Nil	-	-	-	-	No.NE Readings.
24/4/61	0454	1454	-	-	4½(Z)	-	-	(D)	Nil	-	-	- Nil on Willmore Lat Lat.	-	No NE Readings.
"	2327	0927(25/4)	-	-	7 (Z)	short	-	(A)	Nil	No Willmore Record.				No NE Readings.
25/4/61	0045	1045	1055	-	4½(Z)	medium	-	(A)	Nil (However Chefoo sailed at 11.30). No Willmore record. No NE Readings.					
"	1616.9	0216(26/4)	0217	-	3½(Z)	Very short	-	C	Nil	- Perfect on Willmore, Tavurvur Tunnel.	-	-		No NE Readings.
"	2026.5	0626(26/4)	0752	no clear max.	3½(Z)	medium	-	(A)- C	Nil (Partlyrecorded on Willmore Tavurvur Tunnel, (very short period).	-	-	-		No NE Readings.

4...

Sheet 4. Appendix K.

GMT DATE	COMPONENT G.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ARRIVAL TIME	L.M.T. HARMONIC ENDS	L.M.T. MAX AMPLITUDE AT	COMPONENT MMS MAX AMPLITUDE (TRACE)	SECONDS PERIOD	SECONDS OVERALL PERIOD ENVELOPES	CLASS	SHIP	REGISTERED TONNAGE	L.M.T. LEFT WHARF	L.M.T. "LEADS" OFF BEEHIVES	L.M.T. BERTHED WHARF	REMARKS
26/4/61	0304	1304	-	-	4.4(Z)	medium	-	(A)	Nil.	Nil on Willmore	Tavurvur Tunnel.		No NE Readings.	
"	1808.0	0408(27/4)	-	-	11 (Z)	short-medium	-	(A)	Nil.	do.	do.		do.	
27/4/61	0104.8	1104	-	-	9.4(Z)	medium-short	-	(A)	Nil	do.	do.		do.	
"	1506	0106(28/4)	-	-	11½(Z)	-	-	(A)	Nil (Malaita sailed 0000)				do.	
30/4/61	0402	1402	1426	Intermittent until 1413	7.6(Z)	0.65 medium-long	32-37	A - A	Eastbank	3516	-	1340	1500	Main wharf.
									Recorded Willmore at Rapindik. No NE Readings. See Plate 11.					
2/5/61	1252.6	2252	-	-	8.6(Z)	-	-	C	Nil (Shansi berthed 1900) Recorded Willmore, Lakunai. No NE Readings.					
3/5/61	1227	2227	-	-	5¼(Z)	-	-	A	Nil. Nil on Willmore Lakunai.					"
5/5/61	0650	1650	-	-	5.8(Z)	-	-	(A)	Lederwaal	-	1600	1620	-	" (No Willmore Rec.)
"	1409	0009(6/5)	-	-	4.0(Z)	-	-	A-B	Nil.	-	-	-	-	" "
"	1446	0046(6/5)	-	-	5.3(Z)	-	-	C	Nil	-	-	-	-	" "
"	1938	0538(6/5)	0541	-	2.9(Z)	-	-	(A)	Nil	-	-	-	-	" "
7/5/61	2018	0618(8/5)	-	-	5.6(Z)	-	-	C	Eastbank	3516	-	0605	0750	"
											?Rec.Willmore, Toleap, Toboi Wharf.			
10/5/61	2011	0611(11/5)	-	-	2.45(Z)	medium-long	-	(A)	Eastbank	3516	0600	-	0700	"
											Rec.Willmore at Obs.Toboi to Wreck Wharf.			
"	212658½	0726(11/5)	0732	no clear max.	3.9(Z)	"	-	(A)	Nil	-	Rec.Willmore Observatory.		No NE readings.	
16/9/62	1418	0018/17/9)	0020	-	1.9(Z)	Helicorder	-	(A)	Roepat	4779	0010	0030	-	No ZNE readings. Wreck wharf.
28/9/62	033639.2	1336	(1338)	133736.8	21(N)	-	-	A	Southbank	3523	-	1310	1415	Toboi wharf. (C.P.L.)
(Recorded on the long period horizontal standardized seismograph at the Observatory, and on all components of the old Benioff Seismograph at Rapindik.)														
4/10/62	090120(N)	1901	191446	190430	60(N)	¾	(180)	A	Southbank	3523	1845	1900	-	Rec.on all instruments. (See Plate 10)
(Remarkably long period waves were recorded on the long period vertical standardized seismograph at the Observatory over the period of this disturbance. (Period = 2 mins.45 secs. Trace amplitude = 14 mines.)														
12/10/62	122938¾(Z)	2229	(2250)	223210 (Rapindik)	16(N.Rap.)	¾, 4/5. 1	-	A	Southbank	3523	2215	2245	-	
"	210036(Z)	0700(13/10)	0705½ Rapindik	070128 "	17(E.Rap)	1, 1½.	-	A	Fern Star	?	0630	0700	-	
									(boarded by Harbour Master			1645 (anchorage)		
21/10/62	070925(N)	1709	-	171139	5(N)	¾. 1	-	A	Orcades,	15839	-	1730	(left harbour).	
								Recorded with unusually long period on Willmore at Namanula.						
28/10/62	085220(N)	1852	-	185342.3	17.4 (N.Rap.)	¾	-	A	Delos	2211	1840	1855	-	Wreck wharf.
30/11/62	1323 (Rapindik)	2323	-	-	1(N)	Willmore at Namanula	-	(B)	Nil. Recorded on all 3 short period components at the Observatory, on the Willmore at the Racecourse and on the Willmore at Namanula.					
"	142150(N)	0021(1/12) (Willmore at Matupi Is.)	002715	0023½	¾(N)	Willmore at Matupi Is.)		(D)	Nil. Recorded only at Matupi Island (Willmore).					
1/12/62	1412(03)	0012(2/12)	005456	004237	6¾ (Z.Rap.)	1/3	5 - 7	B	Nil. Not recorded at Observatory, Nonga, Nordup or Namanula.					
11/12/62	1447(Obs.)	0047(12/12)	-	-	-	-	-	(A)	Beverbank	3321	0030	0040-50	-	
15/12/62	151323 (N.Rapindik).	0113(16/12)	-	-	-	-	-	(B)	Rodsley	3014	Times unknown		-	Recorded only at Rapindik.
16/12/62	103550 (Z.Willmore at Observatory)	2035	203655	203610	1¼ (Z.Willmore at Obs.)	2/3	10-15	A	(Milos*	2294	2030	-	c2035?	Wreck wharf to main wharf.
									(Foylebank	3219	-	2049	-	(Arrival at anchorage).
									*Milos probably caused the disturbance.					
8/1/63	0122	1122 (Z Willmore at Racecourse)	-	1122½	5¼	1/3 (Z Willmore at Racecourse)	(4)	C	Nil)	However "La Perouse" was at anchor in the Harbour, and "Michael Jibson was at the Wreck Wharf.				Rec.only at Racecourse.
"	0154	1154 (Z Willmore at Racecourse)	- -	- -	- -	" " "	" " "	C	Nil)					
"	0449	1449 (Z Willmore at Racecourse	-	-	-	"	"	C	Nil)	(No record at Sulphur Springs.)				

Sinusoidal harmonic disturbance are not listed between 10/5/61 and 16/9/62.
Hereafter readings are taken from the world-wide standardised seismograms recorded at the Observatory.

APPENDIX L.

MODIFIED MERCALLI INTENSITY SCALE.

1. Not felt except by a very few under especially favourable circumstances.

2. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

3. Felt quite noticeably indoors, especially on upper floors of buildings but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations like passing of lorry. Duration estimated.

4. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors, disturbed; walls make cracking sound; sensation like heavy lorry striking building. Standing motor cars rocked noticeably.

5. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

6. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

7. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; some chimneys broken. Noticed by persons driving motor cars.

8. Damage slight in especially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

9. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

10. Some well-built wooden structures destroyed; masonry and frame structures and their foundations destroyed; ground badly cracked. Rails bent. Landslips considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks of rivers, etc.

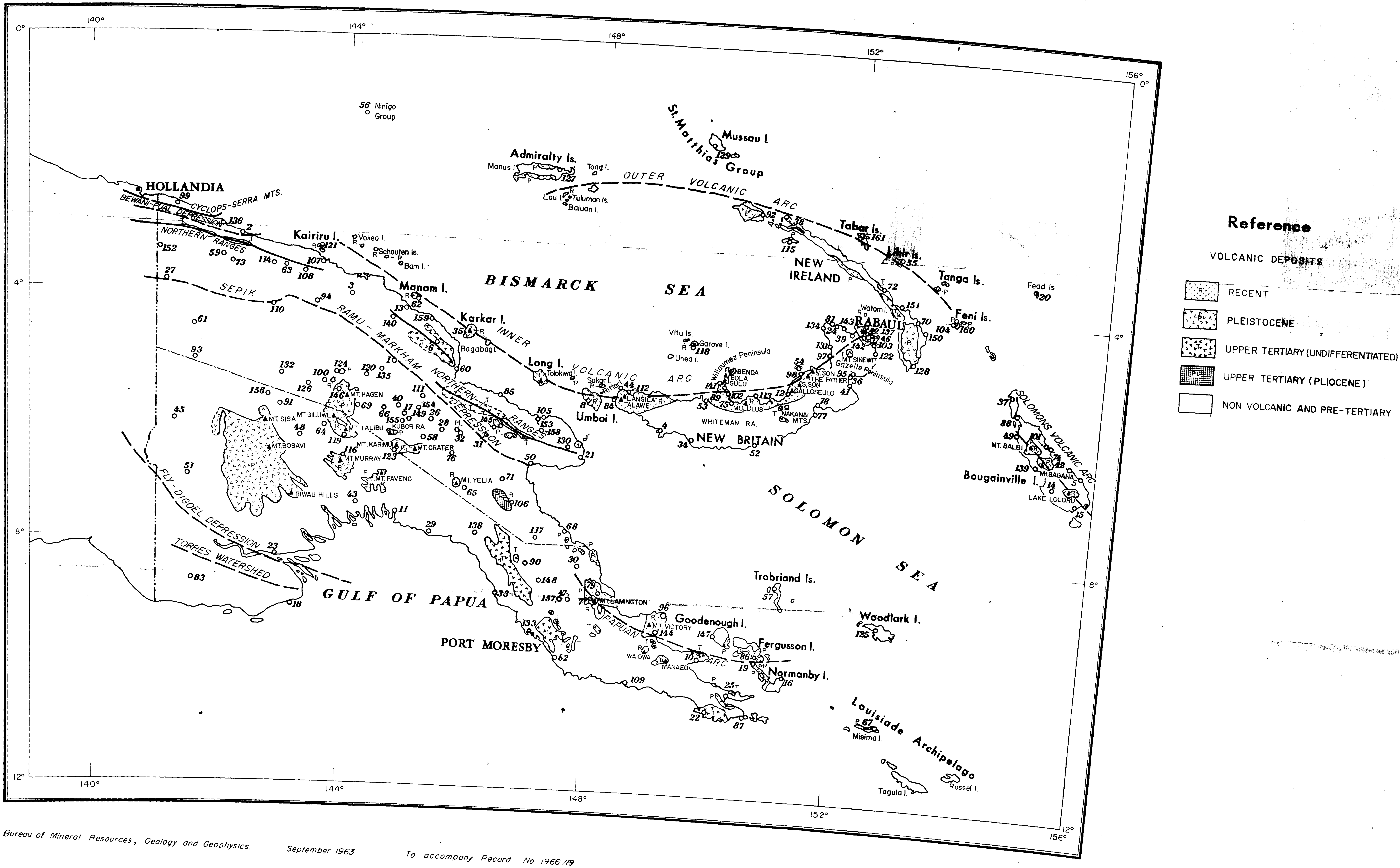
11. Few, if any, masonry structures remaining standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and landslips in soft ground. Rails bent greatly.

12. Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward in the air.

VOLCANIC DEPOSITS AND GENERALISED STRUCTURE, TERRITORY OF PAPUA AND NEW GUINEA

Figure 1

(SEE APPENDIX A FOR KEY TO LOCALITY NUMBERS)



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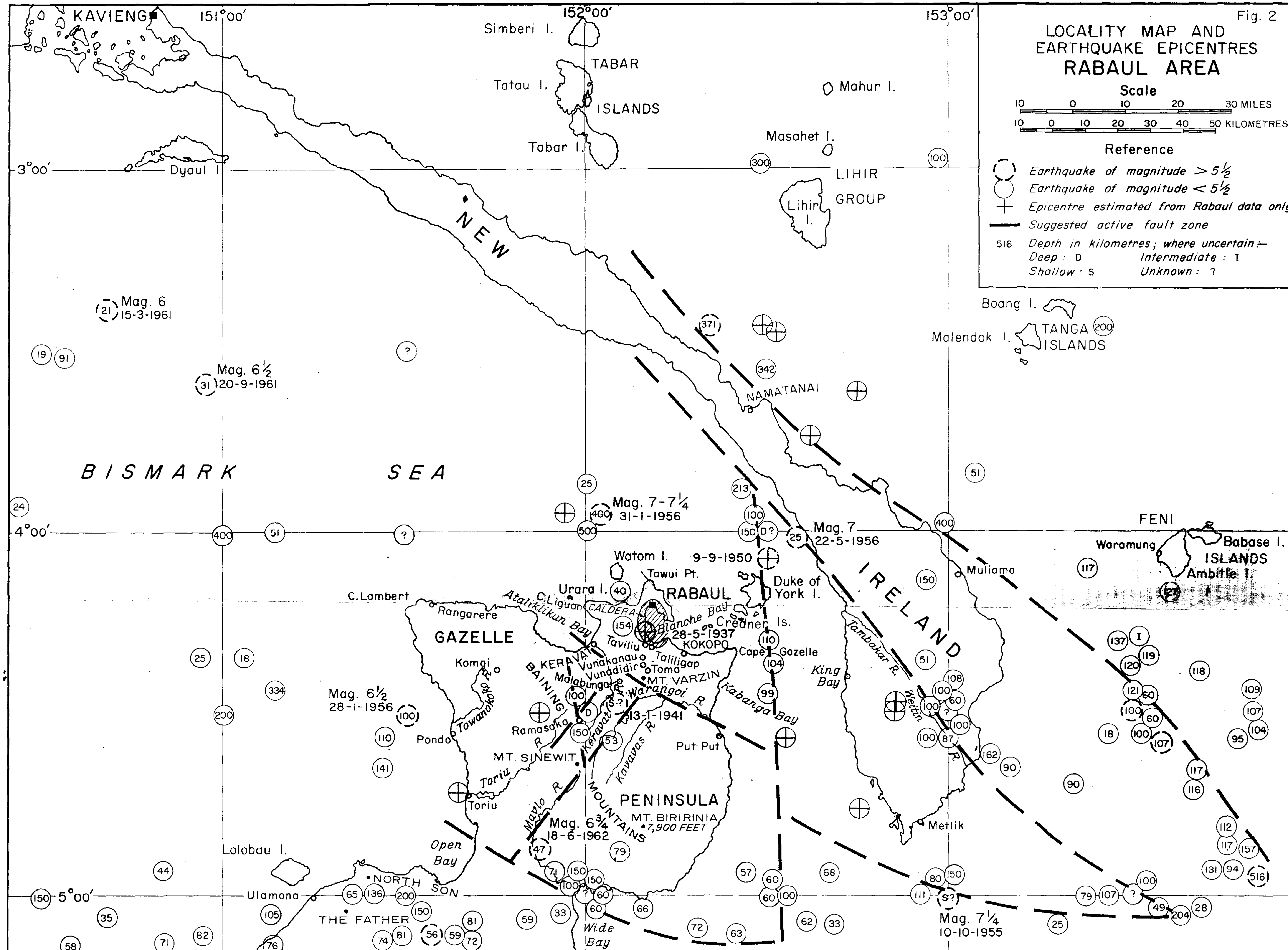

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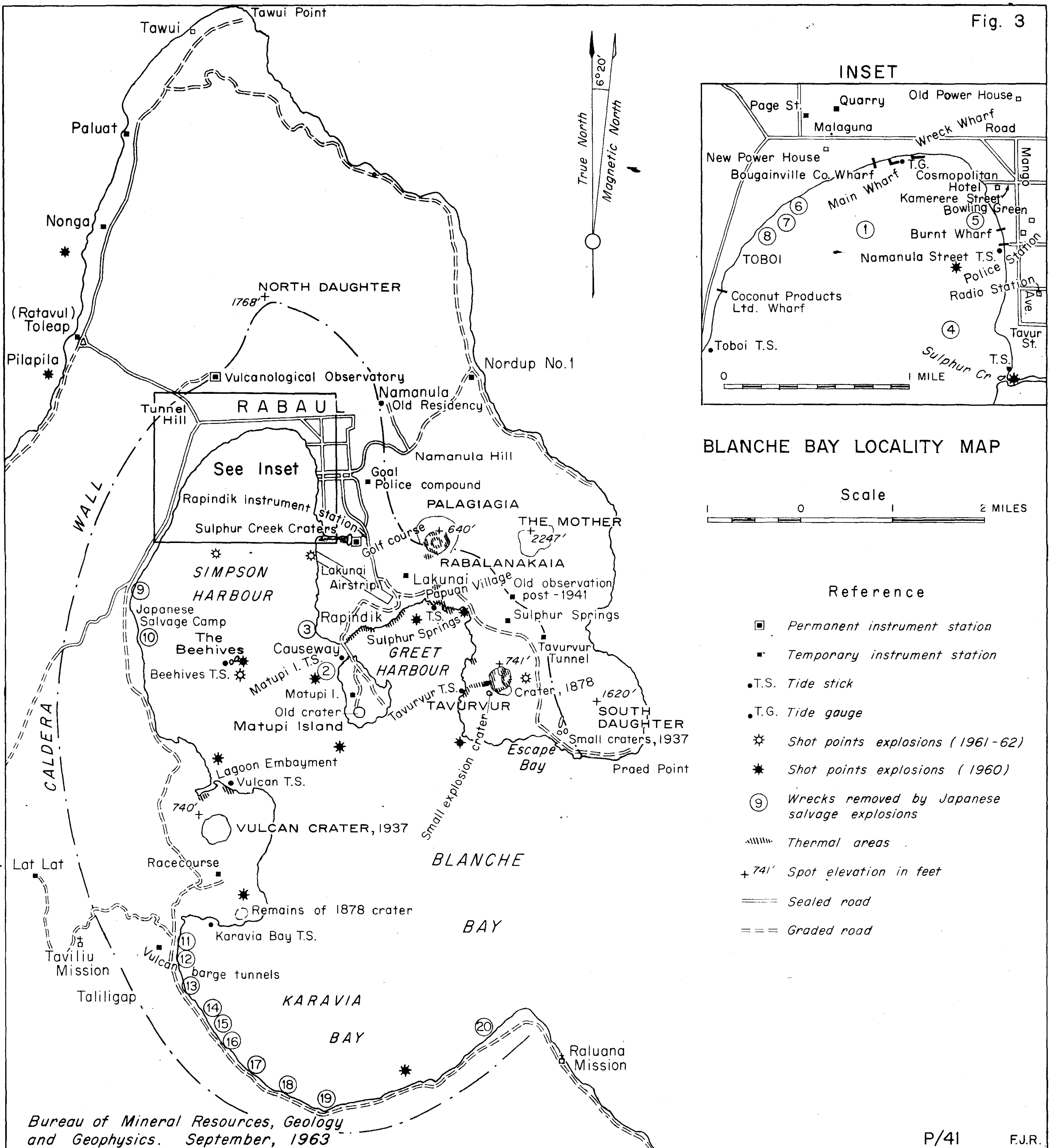
Fig. 3



BLANCHE BAY LOCALITY MAP

Scale

1 0 1 2 MILES

Reference

- Permanent instrument station
- Temporary instrument station
- T.S. Tide stick
- T.G. Tide gauge
- Shot points explosions (1961-62)
- Shot points explosions (1960)
- (9) Wrecks removed by Japanese salvage explosions
- Thermal areas
- +741' Spot elevation in feet
- Sealed road
- Graded road

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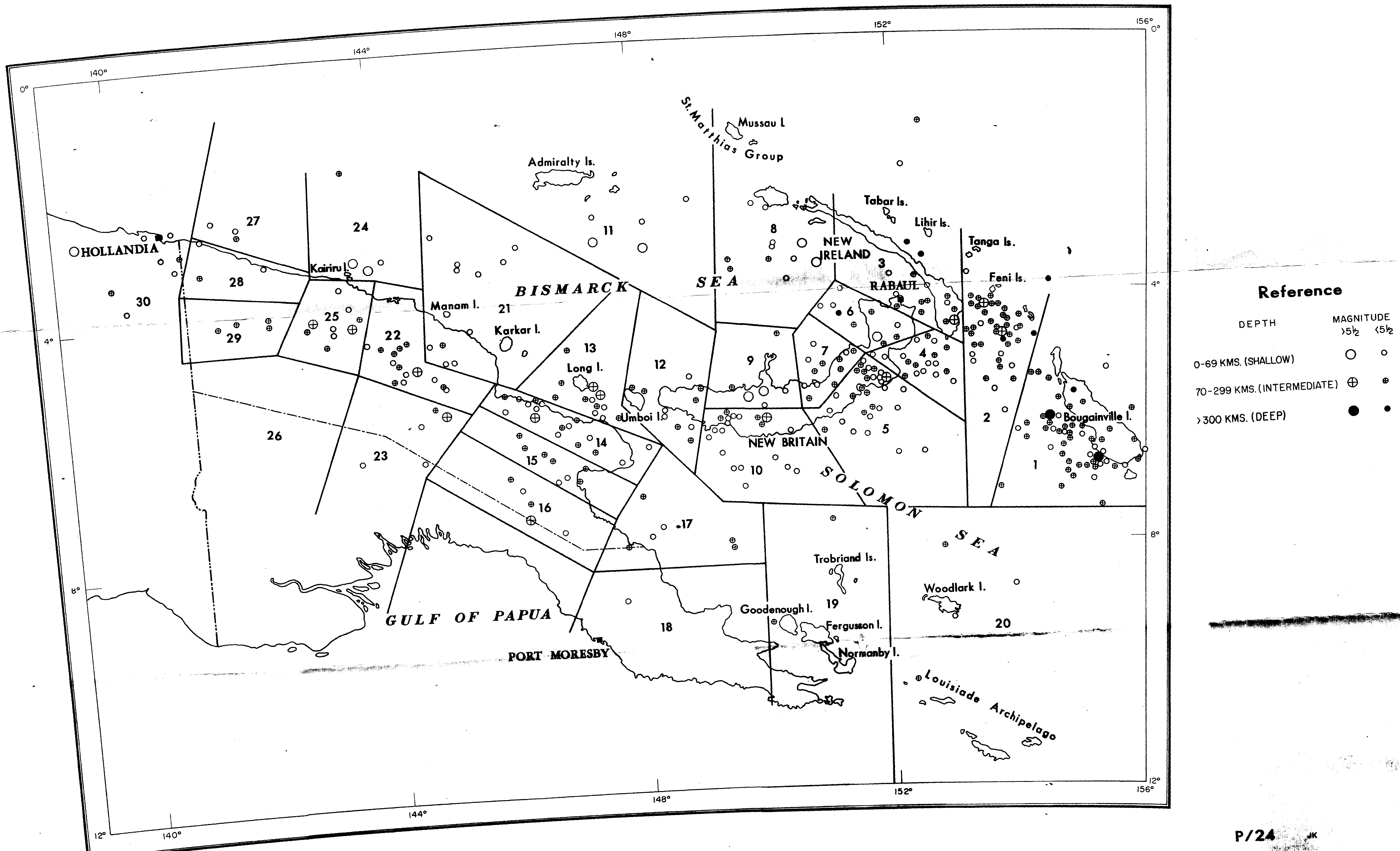
Figure 4

U. S. C. AND G. S. EPICENTRES FOR THE PERIOD 27/7/60 TO 14/3/63



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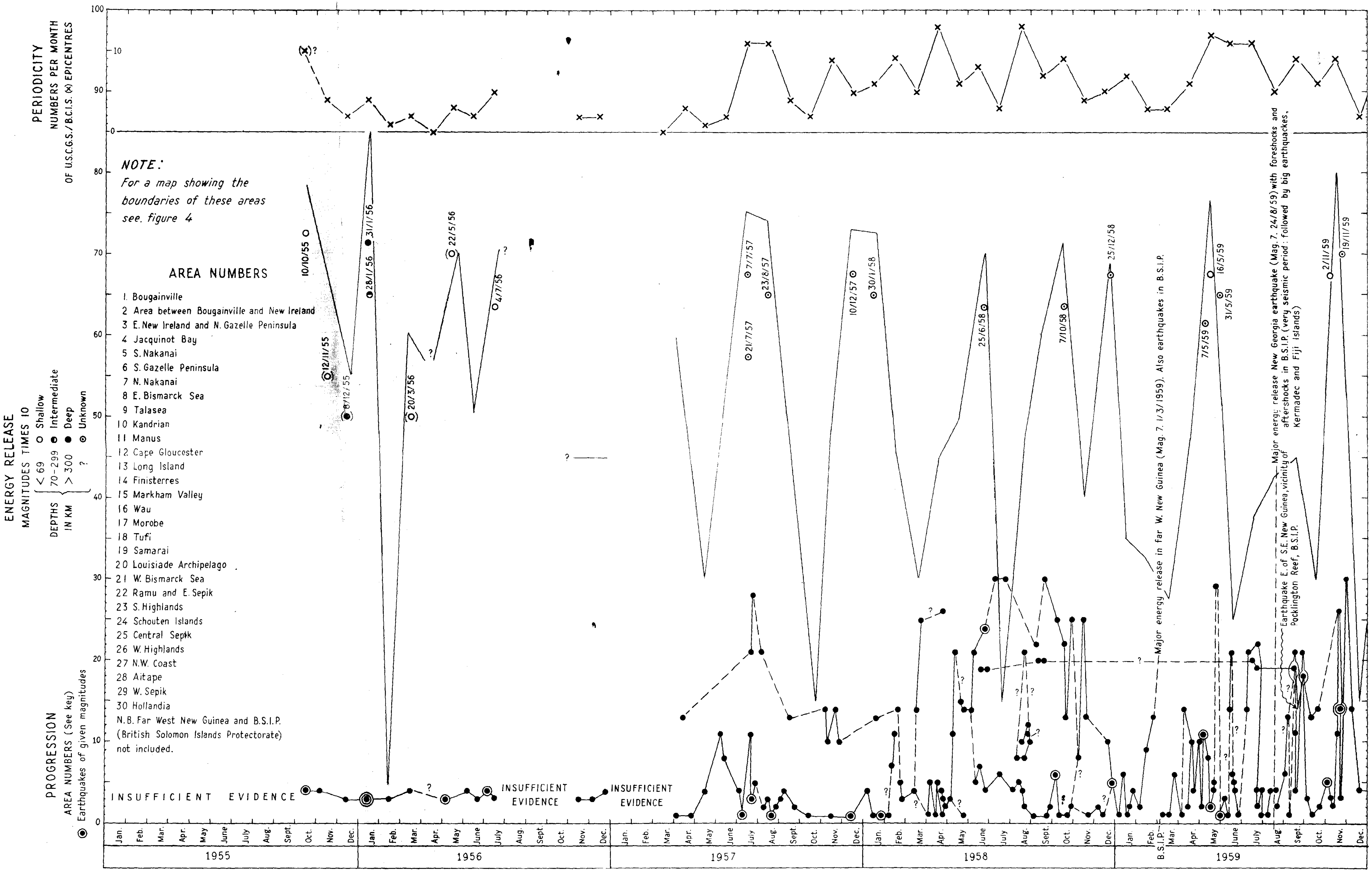
ROUGH GRAPHICAL ESTIMATE OF ENERGY RELEASE, PERIODICITY AND PROGRESSION OF E. NEW GUINEA EARTHQUAKES, 1955-1959

Fig. 9



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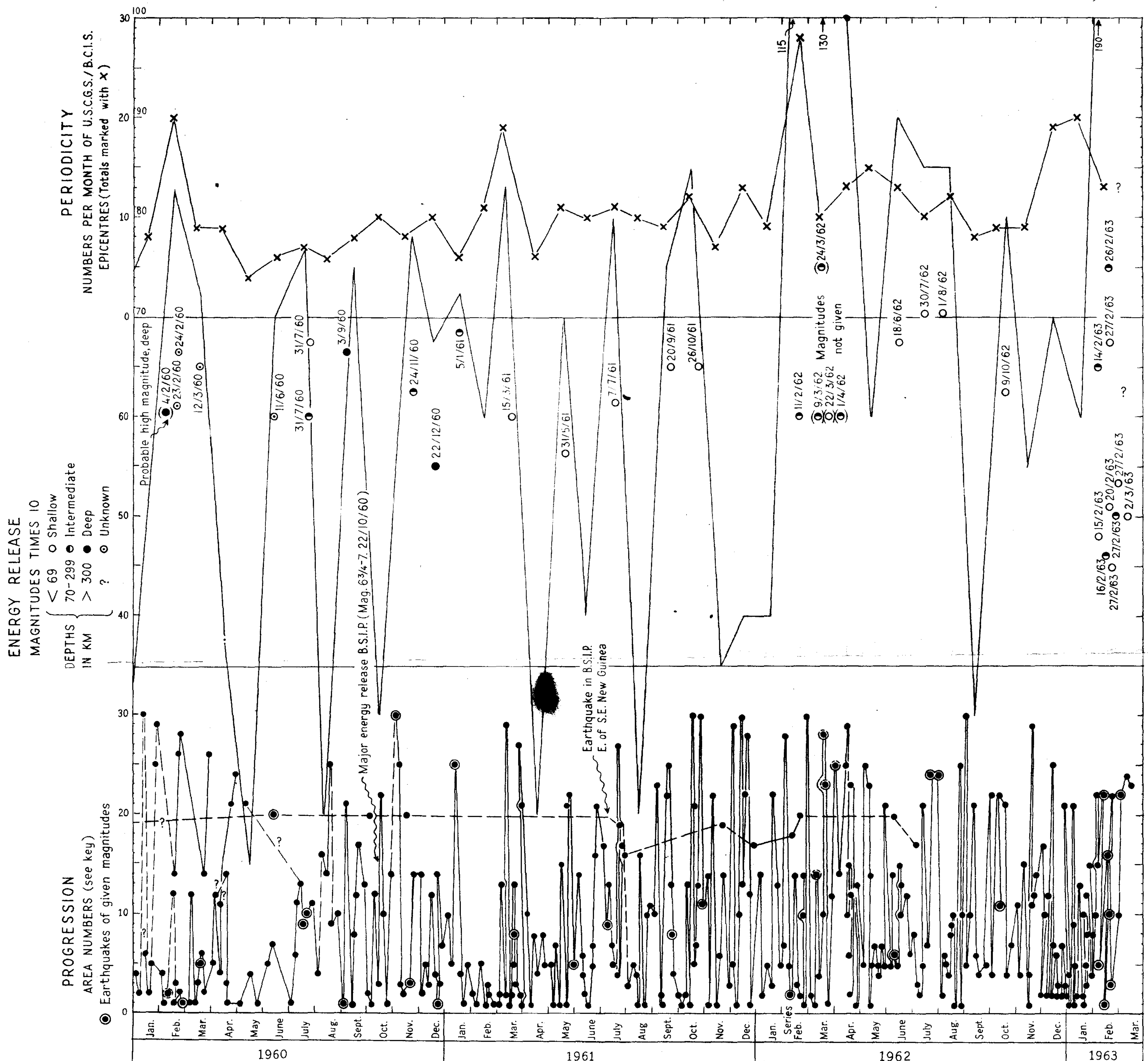
G.M.

ROUGH GRAPHICAL ESTIMATE OF ENERGY RELEASE, PERIODICITY AND PROGRESSION OF E. NEW GUINEA EARTHQUAKES, 1960-1962

Fig. 10



AREA NUMBERS

1 Bougainville
2 Area between Bougainville and New Ireland
3 E. New Ireland and N. Gazelle Peninsula
4 Jacquinot Bay
5 S. Nakanai
6 S. Gazelle Peninsula
7 N. Nakanai
8 E. Bismarck Sea
9 Talasea
10 Kandrian
11 Manus
12 Cape Gloucester
13 Long Island
14 Finisterres
15 Markham Valley
16 Wau
17 Morobe
18 Tufi
19 Samarai
20 Louisiade Archipelago
21 W. Bismarck Sea
22 Ramu and E. Sepik
23 S. Highlands
24 Schouten Islands
25 Central Sepik
26 W. Highlands
27 N.W. Coast
28 Aitape
29 W. Sepik
30 Hollandia

N.B. Far West New Guinea and B.S.I.P. (British Solomon Islands Protectorate) not included, unless earthquake felt in T.P.N.G.

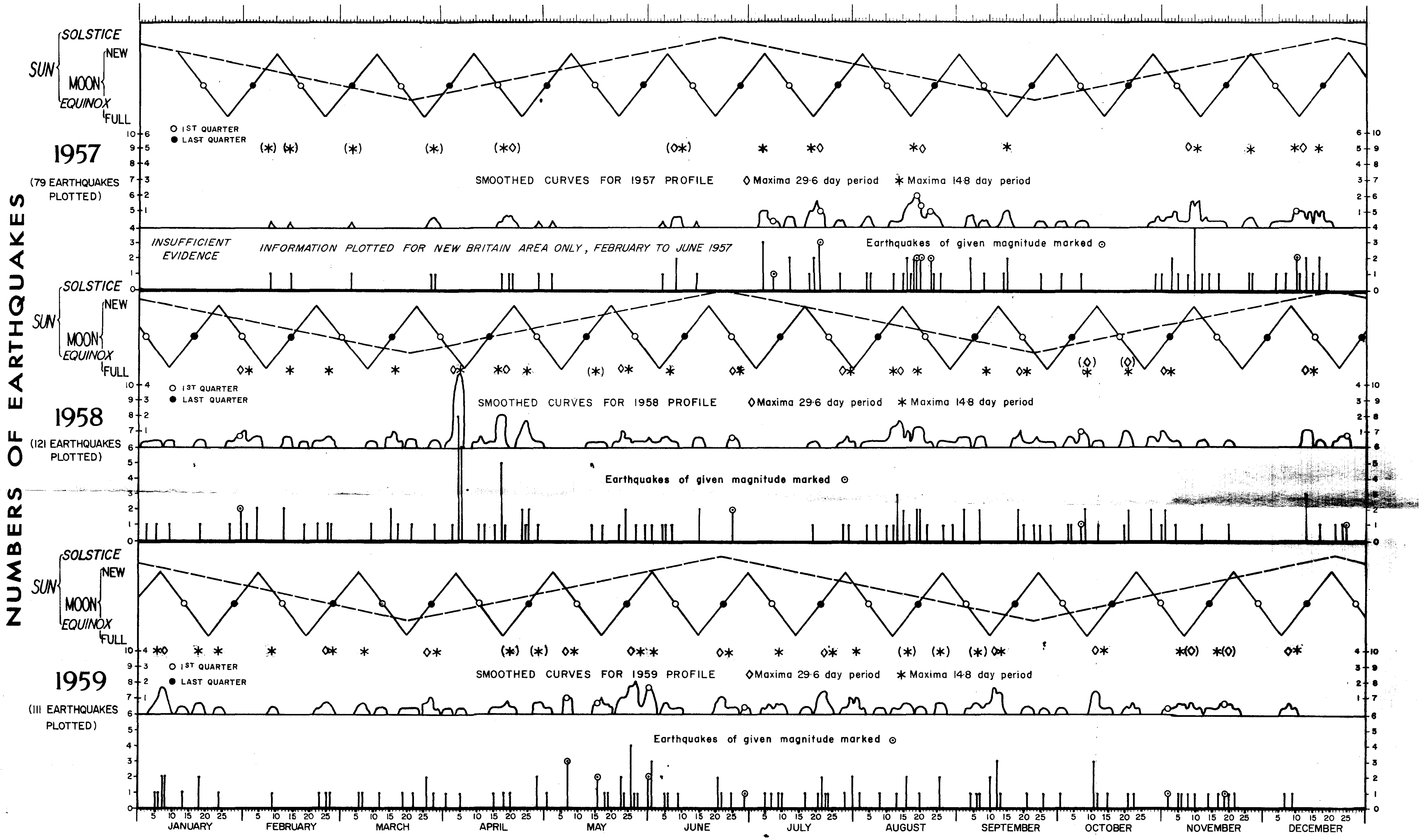
NOTE:
For a map showing the boundaries of these areas see figure 4

Bureau of Mineral Resources, Geology & Geophysics, October, 1963. To accompany Record 1966/19

P-30 G.M.

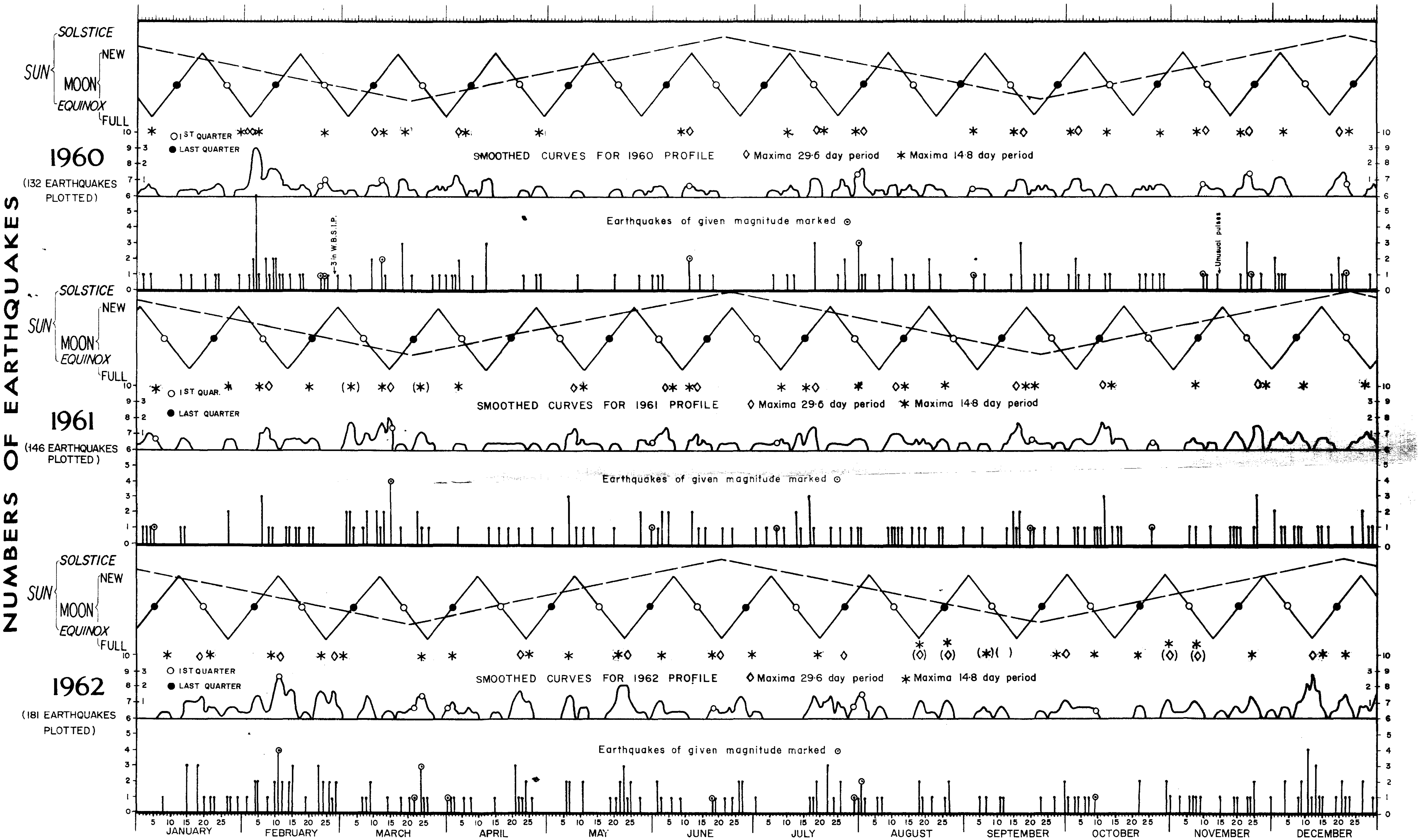
DAILY AND MONTHY PERIODICITY IN EAST NEW GUINEA EARTHQUAKES, 1957-1959

(ONLY EARTHQUAKES WITH REPORTED EPICENTRES, OR THOSE FELT IN THE TERRITORY OF PAPUA AND NEW GUINEA, INCLUDED)



DAILY AND MONTHY PERIODICITY IN EAST NEW GUINEA EARTHQUAKES, 1960-1962

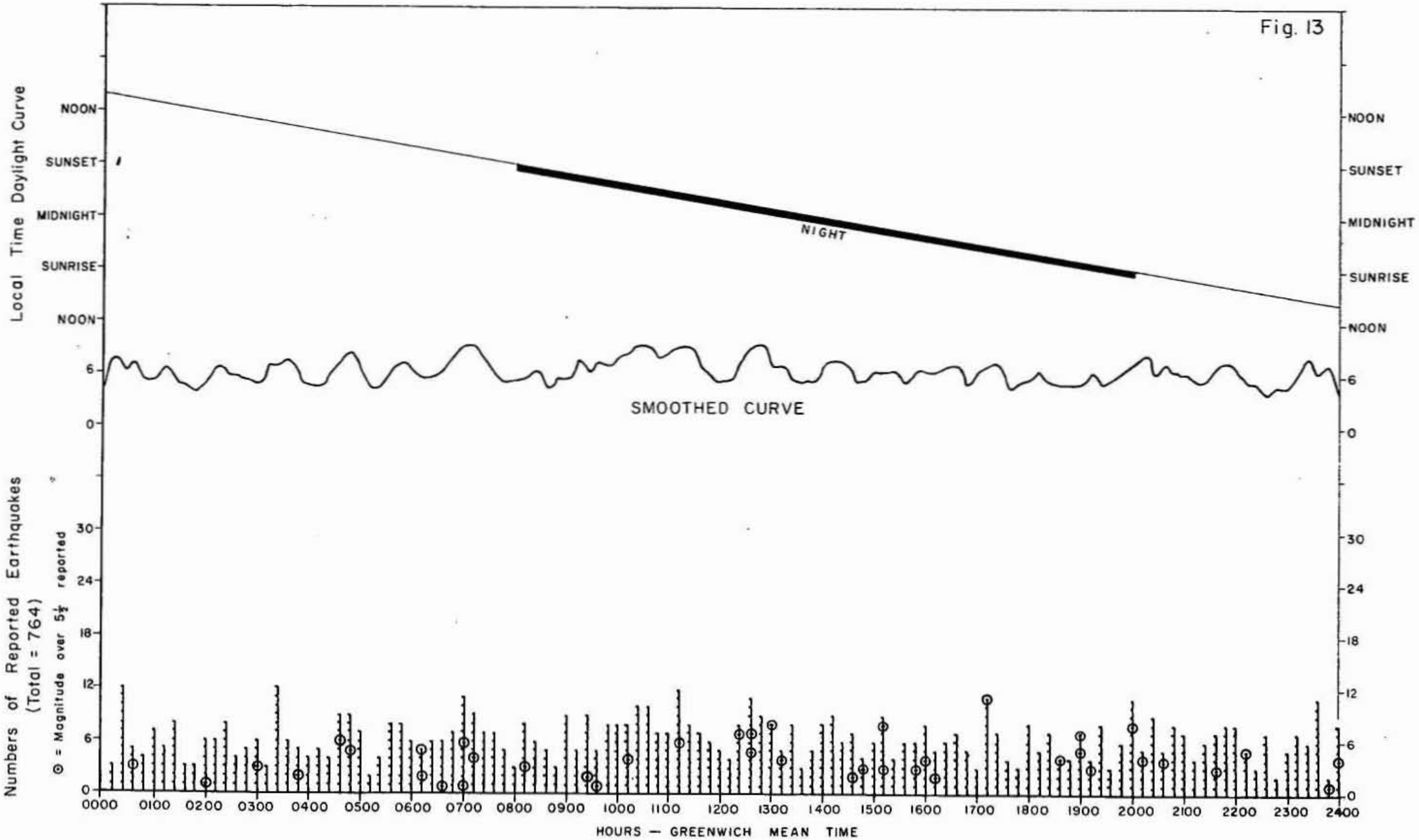
(ONLY EARTHQUAKES WITH REPORTED EPICENTRES, OR THOSE FELT IN THE TERRITORY OF PAPUA AND NEW GUINEA, INCLUDED)



691 EARTHQUAKES PLOTTED FOR PERIOD 1958-1962 (AVERAGE LEVEL = 1 every 2·6 days)
770 EARTHQUAKES PLOTTED FOR PERIOD 1957-1962 (1957 INCOMPLETE YEAR, AVERAGE LEVEL = 1 every 2·8 days)

Bureau of Mineral Resources, Geology and Geophysics   October 1963   To accompany Record No 1966/19

P/26   JK

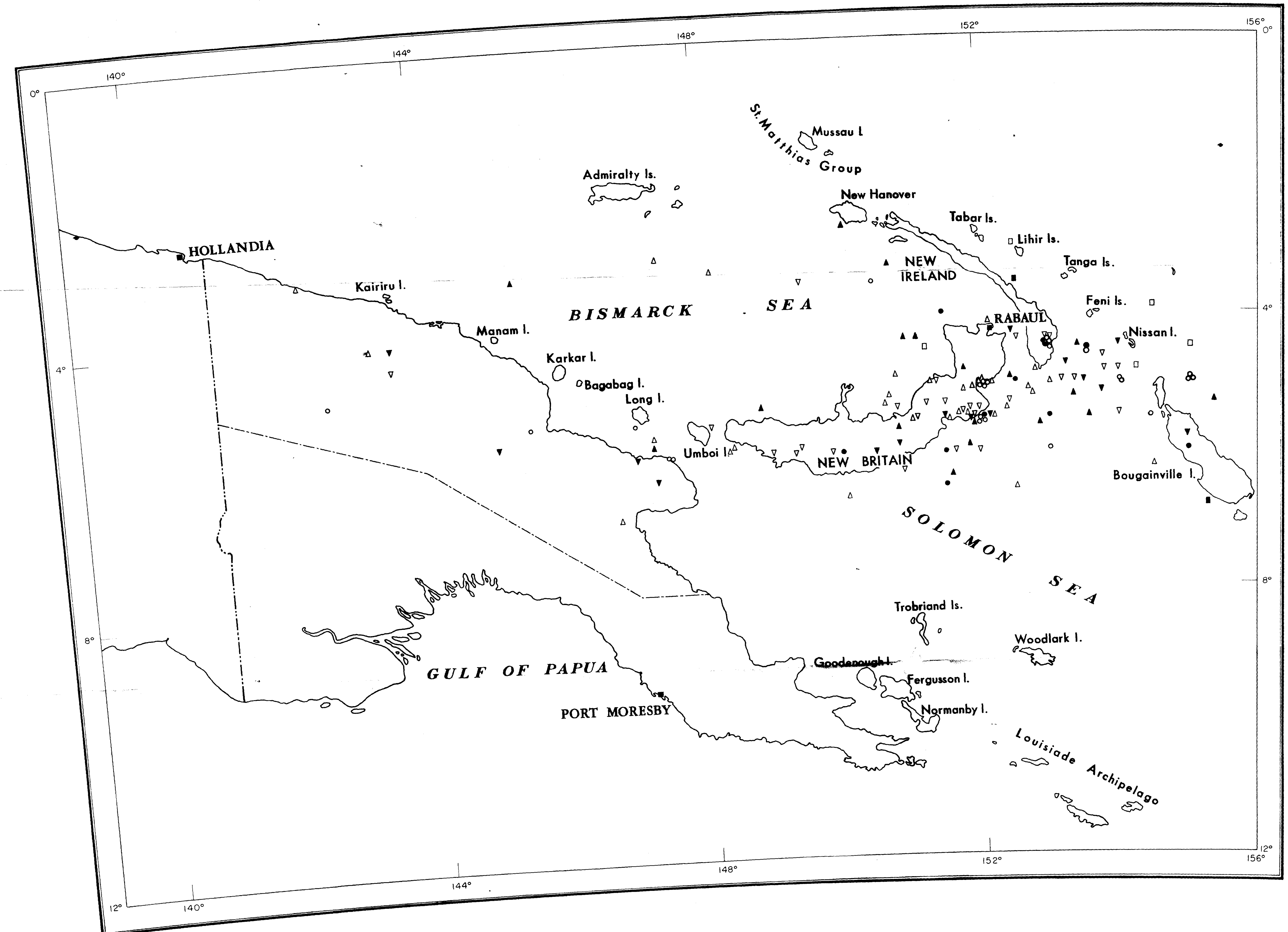


DIURNAL PERIODICITY DIAGRAM, EARTHQUAKES FELT OR WITH REPORTED EPICENTRES IN THE TERRITORY OF PAPUA AND NEW GUINEA 1957 TO 1962

Figure 14

RECORDED COMPRESSIONS AND DILATATIONS AT RABAUL FROM EARTHQUAKES AT EAST NEW GUINEA EPICENTRES

JUNE 1956 TO JANUARY 1963



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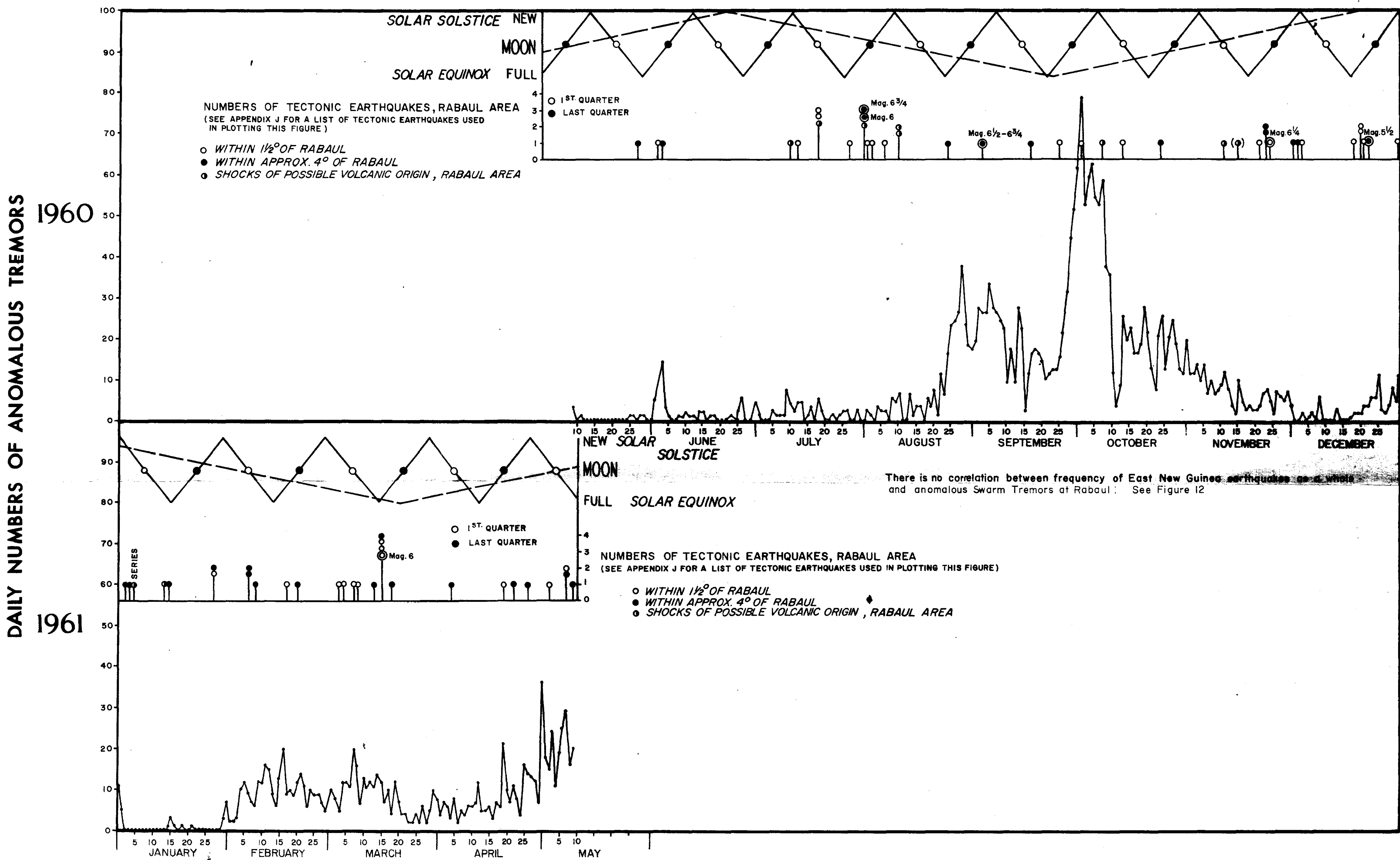
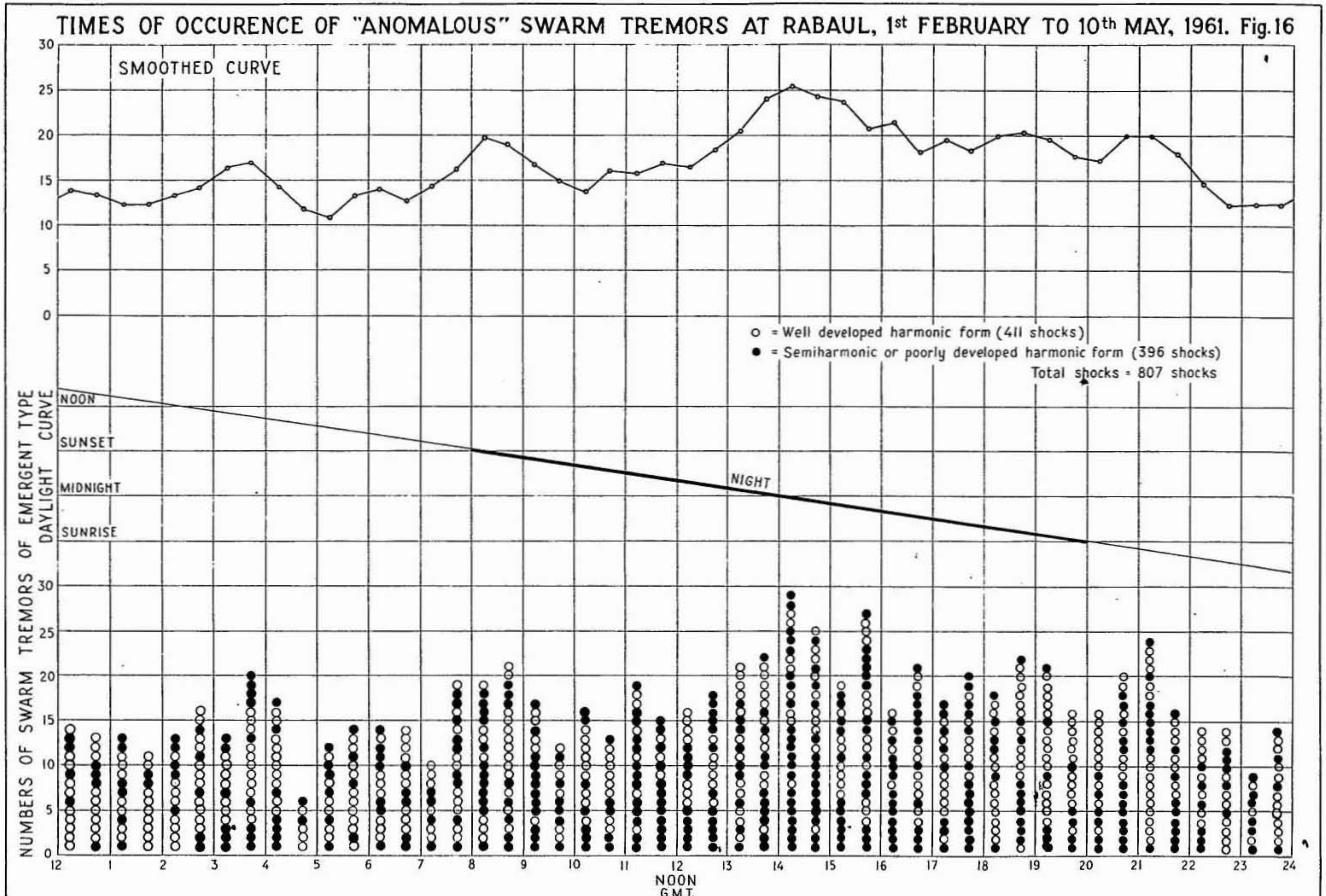
P/25 JK

Figure 15

FREQUENCY OF "ANOMALOUS" SWARM TREMORS, RABAUL





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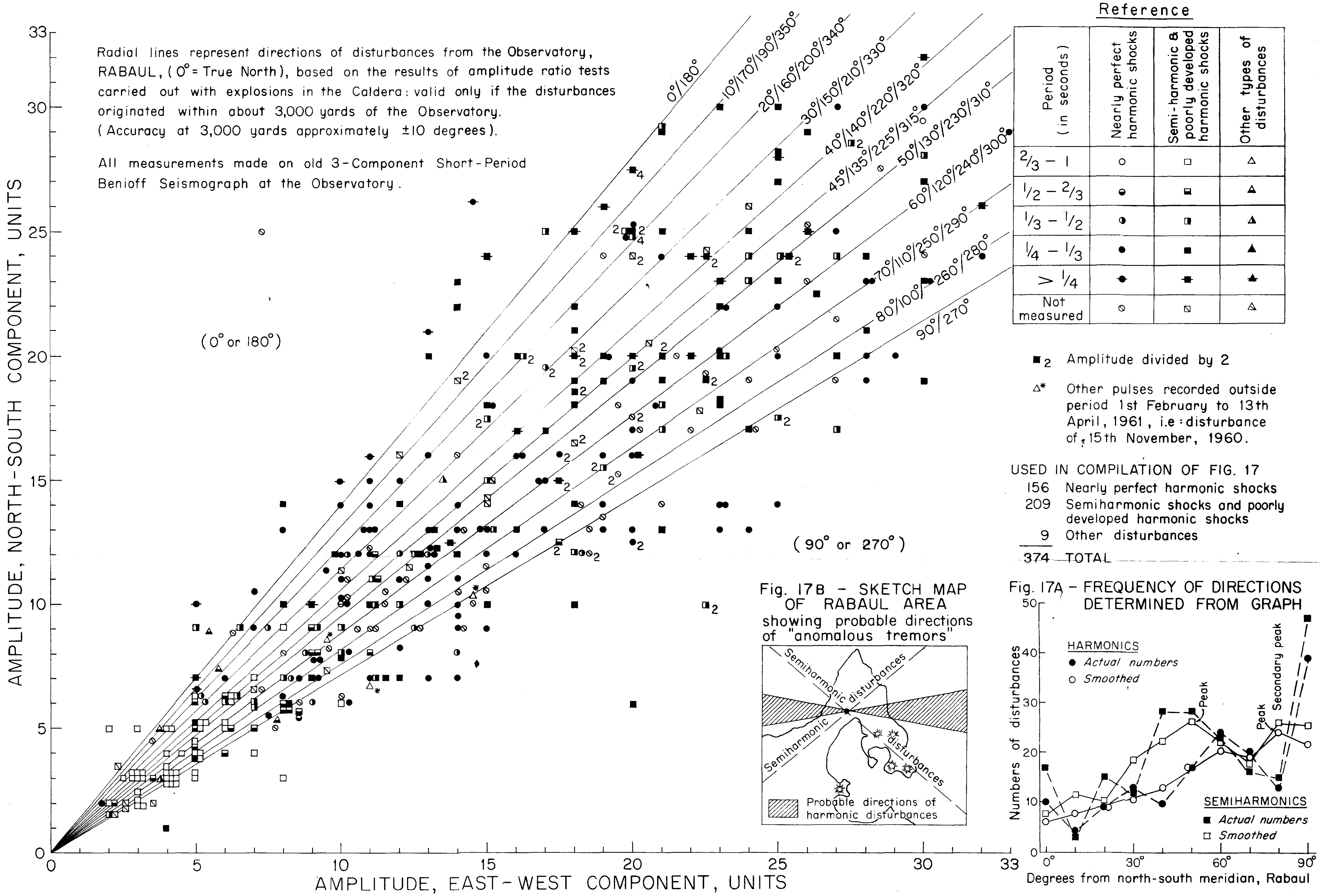
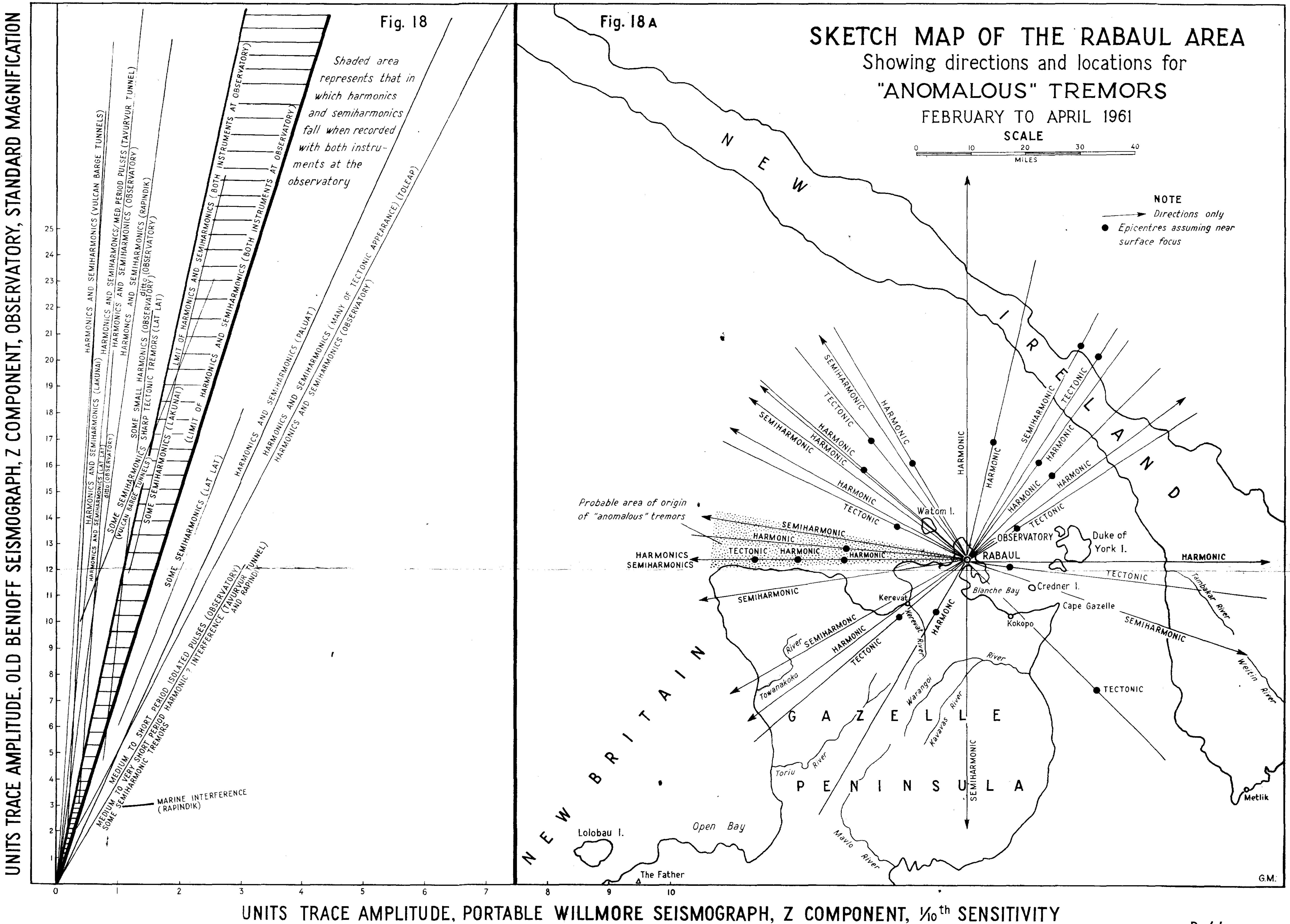
PERIOD AND AMPLITUDE OF "ANOMALOUS" SWARM TREMORS, RABAUL — 1st February to 13th April, 1961

Fig. 17



RELATIVE TRACE AMPLITUDES OF "ANOMALOUS" TREMORS AT RABAUL OBSERVATORY AND PORTABLE STATIONS. VERTICAL COMPONENT



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SKETCH OF LOCAL EARTHQUAKE TYPES, JAPAN AND HAWAII

AFTER K. WADATI ("THREE KINDS OF EARTHQUAKES OBSERVED IN JAPAN", 4TH PACIFIC SCIENCE CONGRESS PROC. 2A) AND AUSTIN E. JONES ("EMPIRICAL STUDIES OF SOME OF THE SEISMIC PHENOMENA OF HAWAII", Bull. Seis. Soc. Amer. 1938, Vol 28 No 2, p. 313)

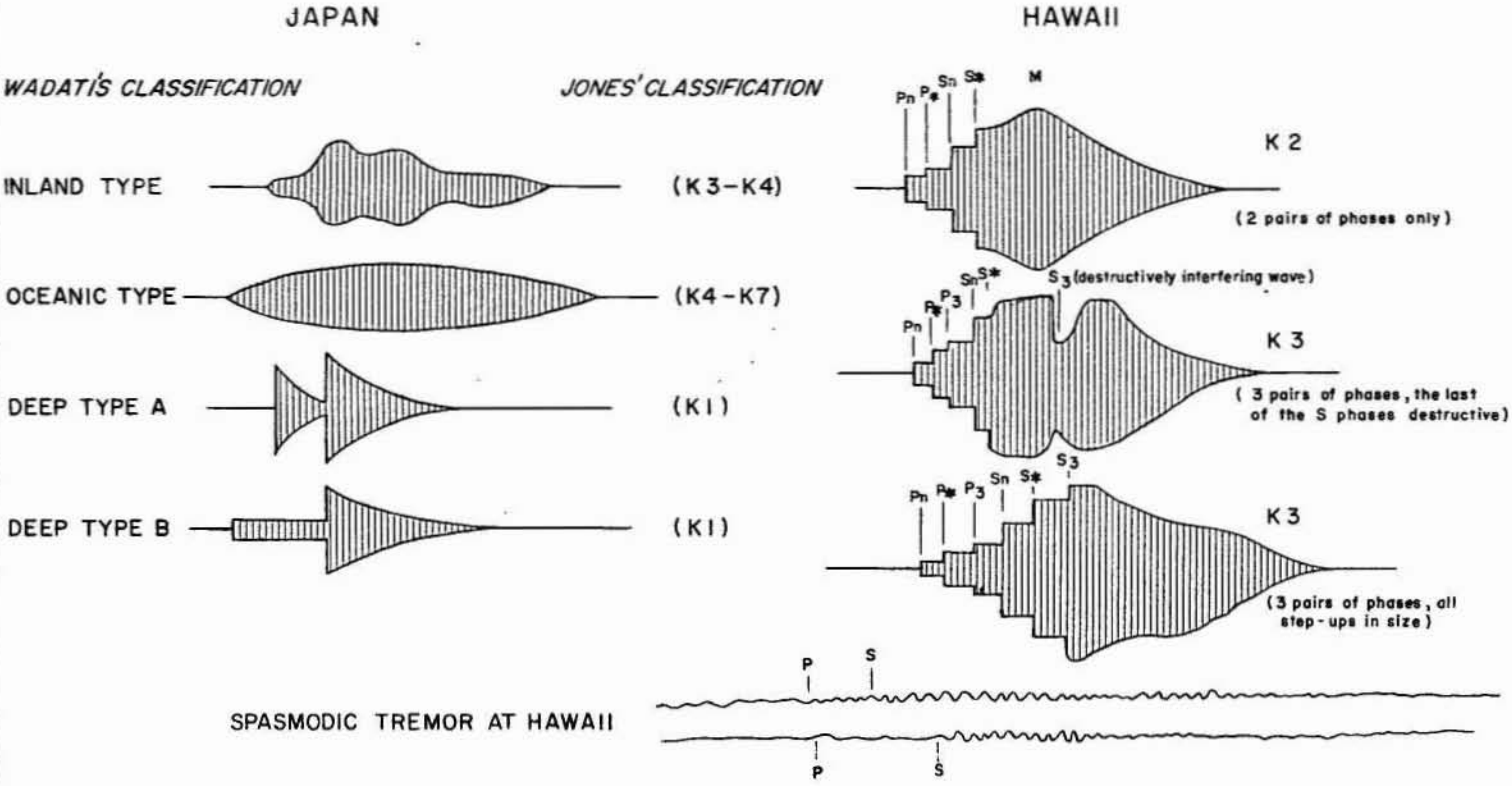
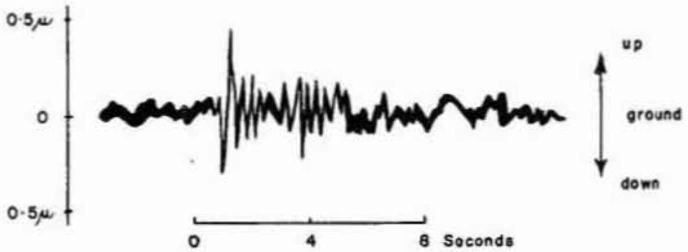


Fig. 22

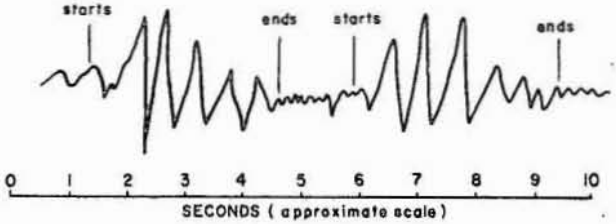
UNIDENTIFIED EARTH TREMOR RECORDED AT THE SEISMIC RESEARCH UNIT'S SEISMOGRAPH STATION AT ROSEAU, DOMINICA, WEST INDIES ON SEPTEMBER 11TH 1959

(From note by G. R. Robson and K. G. Barr, in Nature (Geophysics) October 22. 1960)



UNIDENTIFIED EARTH TREMOR RECORDED AT FORDHAM, NEW YORK, U. S. A. ON A VERTICAL BENIOFF SEISMOGRAPH

(After William A. Lynch, "Traffic and other Local disturbances registered at Fordham by the vertical Benioff Seismometer". Bull. Seis. Soc. Amer. 1938. No 28 p. 217)



(This is the only example recorded of two of these spasmodic tremors grouped together.)

EXPERIMENTALLY DETERMINED AMPLITUDE RATIO/DISTANCE GRAPH AND EXPECTED DEGREE OF ERROR

FIGURE 23

EXPERIMENTAL RESULTS SHOWING HORIZONTAL AMPLITUDE RATIOS OBTAINED FOR PAIRS OF SEISMOMETERS ARRANGED AT RIGHT ANGLES TO EACH OTHER AND AT DIFFERENT ORIENTATIONS TO THE SOURCE EXPLOSION.

THE LINE MARKED "BEST RESULT" SHOULD BE USED. FROM IT A MEASURED RATIO, BETWEEN AMPLITUDE ON TWO HORIZONTAL SEISMOMETERS AT RIGHT ANGLES TO ONE ANOTHER, CAN BE CONVERTED TO THE ANGULAR DIVERGENCE OF A DISTURBANCE FROM THE DIRECTION PARALLEL TO THAT OF THE SEISMOMETERS SHOWING THE GREATEST AMPLITUDE

ACCURACY ± 10 DEGREES AT 3,500 YARDS. THUS ONLY SUITABLE ACCURATE DIRECTION FINDING WITHIN THE CALDERA AREA AT RABAUL, AT DISTANCES LESS THAN 4,000 YARDS. IT DOES NOT APPLY OUTSIDE THE CALDERA

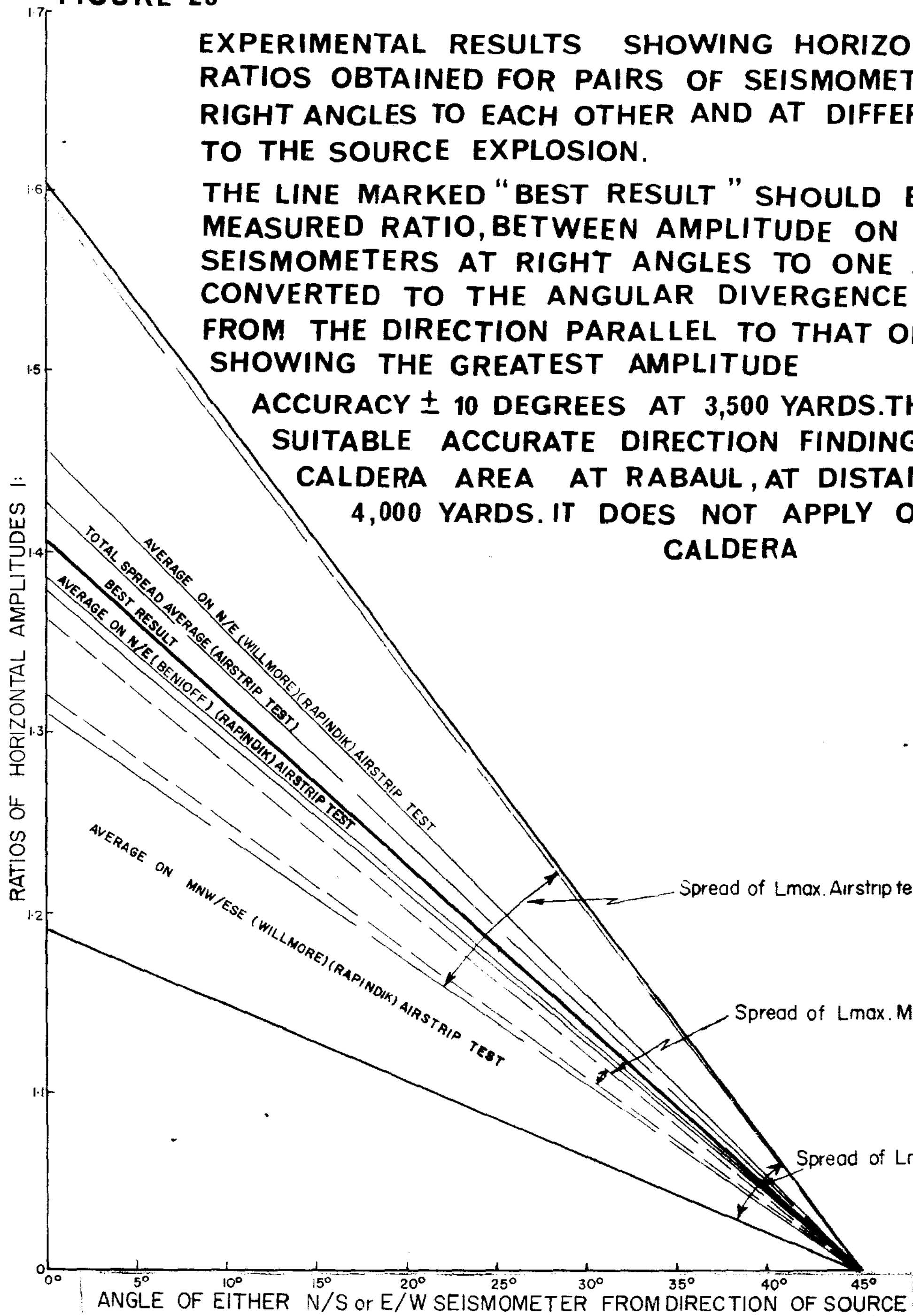
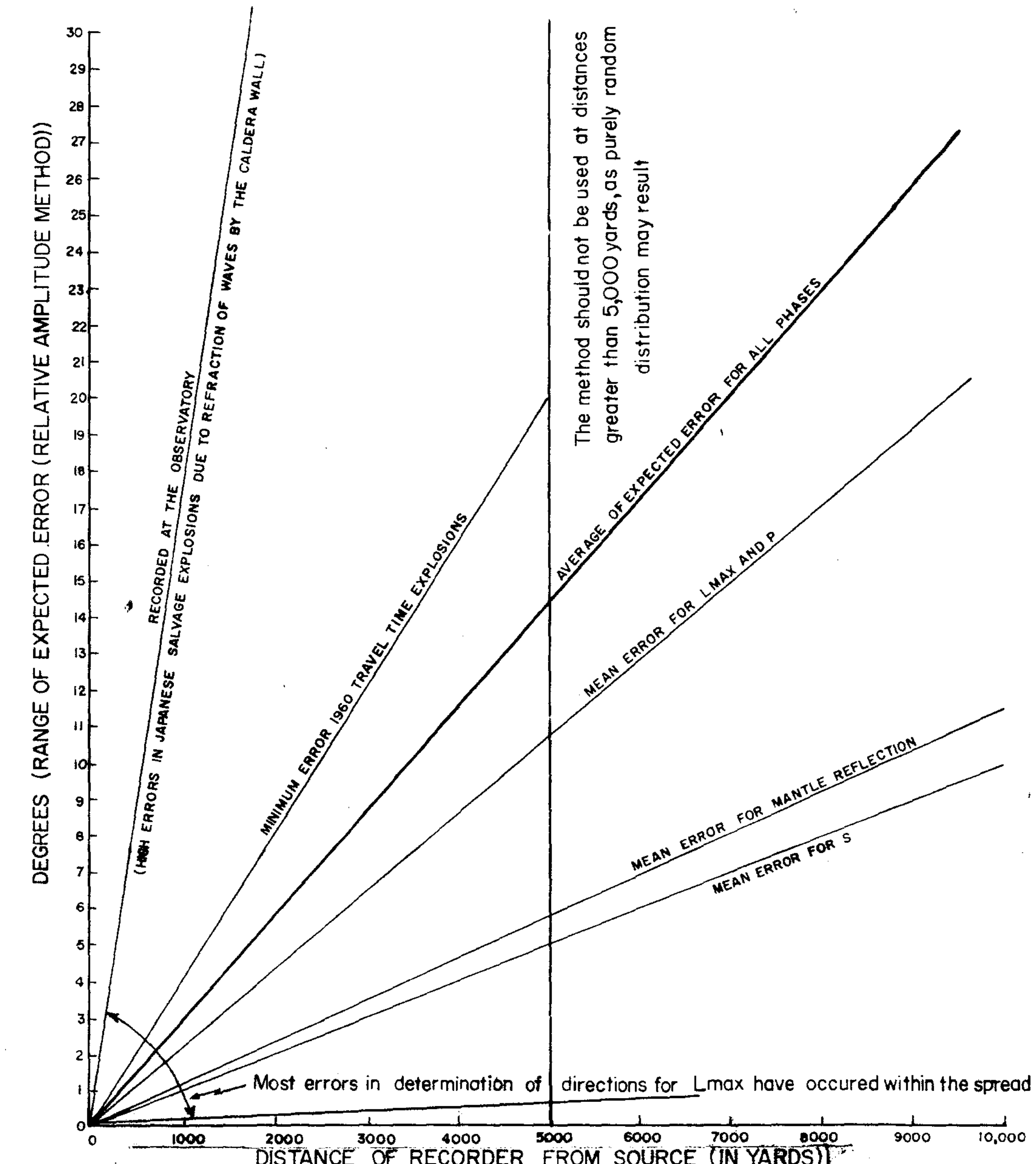


FIGURE 23a

DIAGRAM SHOWING ACTUAL SPREAD OF ERRORS OBTAINED BY USING THE AMPLITUDE RATIO CURVE IN FIGURE 23 MARKED "BEST RESULT"



Bureau of Mineral Resources, Geology and Geophysics. March, 1963. To accompany Record 1966/19

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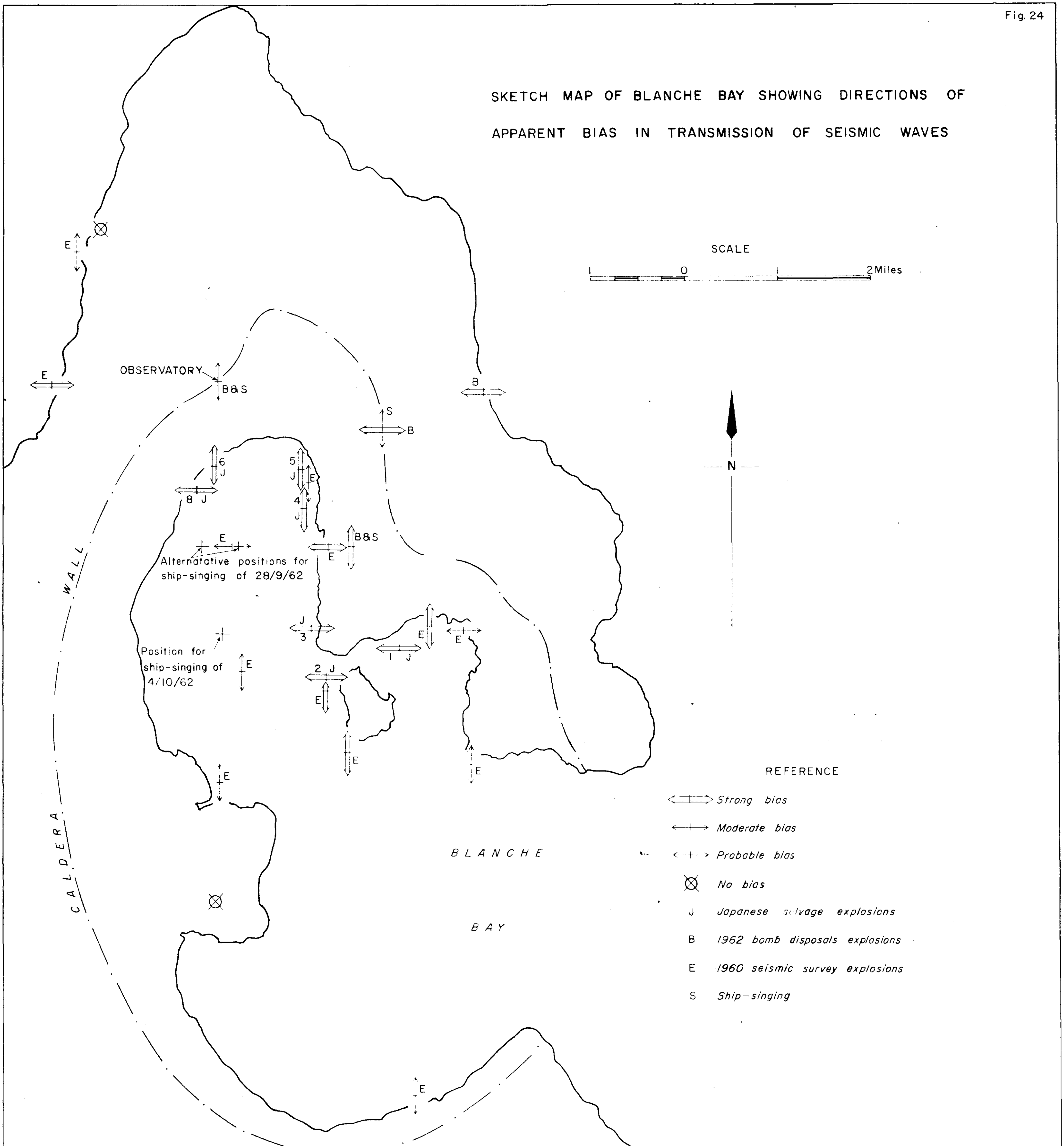
Fig. 24

SKETCH MAP OF BLANCHE BAY SHOWING DIRECTIONS OF APPARENT BIAS IN TRANSMISSION OF SEISMIC WAVES



Bureau of Mineral Resources, Geology and Geophysics, February 1964. To accompany Record 1966/19

JVF.