COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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Earthquake Activity and Seismic Risk in Papua & New Guinea

BY

J. A. BROOKS

Issued under the Authority of the Hon. David Fairbairn
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MINISTER: THE HON. DAVID FAIRBAIRN, D.F.C., M.P.

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SUMMARY

A comprehensive analysis has been made of seismic activity in the Territory of Papua & New Guinea. The activity is very high, comprising five to ten percent of the world's total earthquake occurrences. Earthquakes potentially large enough to cause considerable damage occur within the Territory at an average rate of about ten per annum.

Data on the distribution and frequency of occurrence of earthquakes have been used to zone the Territory according to probable maximum intensities of shaking during periods of 100, 50, and 25 years.

Seismic activity during the last 50 years tends to exhibit a periodic variation. Evidence suggests that general trends of seismic activity in some parts of the Territory, as well as in the area as a whole, may be predictable because of this feature. In 1963 the whole region is apparently strained to an extent not surpassed in the last 30, possibly 50, years; the next four or five years may therefore be a period of relatively high seismic activity.

Comment is made on the desirability of earthquake engineering investigations in certain circumstances. Emphasis is placed on the need for care in the selection of construction sites in relation to local geology, if seismic effects are to be minimised.

The need for more seismographs and seismoscopes is mentioned.

1. INTRODUCTION

The purpose of this Report is to assess known facts about the seismicity, or degree of earthquake activity, in various parts of the Territory of Papua & New Guinea.

The Territory, consisting of the Australian Territory of Papua and the United Nations Trust Territory of New Guinea, is situated between the equator and latitude 12^{o}S from the meridians 141^{o} to 160^{o} E. It covers almost one million square miles, of which about one-fifth is land area (Plate 1). The population of almost two million is more than 98 percent indigenous.

Partly because of the highly mountainous and very rugged nature of the terrain, with its consequent effect on communications and transport, the rate of economic and cultural development has until recent years been relatively slow. However, all phases of development are now increasing rapidly, resulting in a marked expansion in the size of established towns, an increase in the number of civil engineering projects, and the establishment of secondary industries on a small scale.

Papua & New Guinea is situated in the circum-Pacific belt of earthquake activity (Plate 2), and is one of the most active seismic areas of the world. It has been estimated that between five and ten percent of the total number of large earthquakes occurring in the world are located within or near the borders of the Territory (Gutenberg & Richter, 1954, p.22). Earthquakes ranging up to high magnitudes are frequently felt in New Guinea and some parts of Papua. This activity, then, is an ever-present potential cause of damage to constructions of various kinds; it is therefore desirable that its nature be understood by as many as possible.

The seismic data which have accumulated over the last 50 years are the only available material from which the pattern and degree of future seismic activity may be estimated. As several major constructional projects are being planned for the Territory, it seems that an assessment of future seismic activity would be of particular value.

It is intended that these data will provide general background information to authorities engaged in design and construction of buildings and engineering projects in the Territory, and also other authorities interested in : (a) risk of damage by earthquakes to construction of various kinds, and (b) safety precautions that must be taken to minimise these risks. It is hoped that the list of references on specific subjects given in Appendix 1 will be of use to those seeking specialised information.

It is generally appreciated that the time of occurrence of individual earthquakes cannot be predicted, despite the efforts of seismologists for many years. Although the possibility of being able to predict earthquakes in the foreseeable future is regarded as remote by the most eminent of those who have commented on the matter (e.g. Richter, 1958, ch. 4), there is general agreement that before this aim can be achieved, increased knowledge of the causes and precise nature of earthquakes is required. It is hoped that the data in this Report will be useful for any such studies.

Appendix 3 is included for the benefit of those unfamiliar with the terminology and general practices of seismology.

2. SEISMOLOGY IN THE TERRITORY

Seismological recording is generally undertaken for one or more of five purposes:

(a) To ascertain the degree of earthquake activity (seismicity) in a given region and the extent of any areas subject to damage.

(b) To determine the effect of earthquakes on structures of different types, and so provide information for aseismic design purposes.

(c) For vulcanological prediction purposes.

(d) To determine the local physical characteristics of the Earth's crust.

(e) To contribute to world-wide research programmes.

Discussion will be related to (a) and (b) as the remaining three points are outside the scope of this Report.

At present there are only two routine seismological stations in Papua & New Guinea: Rabaul Vulcanological Observatory was established in 1939 to provide data of type (c) and to a lesser extent (e); Port Moresby Geophysical Observatory began operating in 1958 chiefly for the purpose of providing data of type (e), but data from both observatories are now important for purpose (a).

Both stations have recently been re-equipped with new, more sensitive instruments as part of a world-wide seismological standardisation programme.

Studies of type (a) require data such as epicentre, depth, and magnitude of both small and large earthquakes. Earthquakes cannot be located accurately by less than three observing stations suitably placed with respect to the earthquake epicentre; thus many more than three should operate in a region the size of the Territory if its seismic activity is to be effectively analysed.

Prior to 1958 there existed detailed instrumental information of only the largest earthquakes that occurred. Seismic data on the small and moderate earthquakes, which occur more frequently, can even now be evaluated only very approximately - such events are recorded within a limited radius and often by less than three stations. Thus an assessment of past seismic activity must be based entirely on data concerning earthquakes large enough to have been recorded at distant observatories.

The revised building code for the Territory (1963), does not stipulate special requirements for areas where seismic activity, and hence the probability of structural damage, is higher. In 1961 the Commonwealth Department of Works adopted the practice which applied the recommended lateral force requirements of the Structural Engineers Association of California to construction in the Trust Territory of New Guinea (not Papua).

This Report provides a firmer basis for deciding regions where special regulations are necessary. However, these would not replace the need for special on-site investigations for costly structures erected in highly seismic areas, particularly those on which the degree of public dependence is high. The Californian recommendations cited above clearly state that in other areas the coefficients might require revision.

Specific investigations in the Territory for engineering reasons would:

(a) Test the value of Californian aseismic design regulations, and

(b) Enable more specific measures to be enacted where necessary.

Two primary requirements that must be satisfied before compiling aseismic design data relating to particular events, or events in a specified area, are: (a) location of earthquakes, and (b) record of ground acceleration for a particular earthquake. The former can be computed only from routine seismological station recordings; it has already been mentioned that there are too few stations currently in operation. The latter data can be satisfactorily provided only by accelerometers, of which there are none in the Territory at present.

The value of data that could be provided by earthquake engineering investigations might well justify the moderate cost of installing the required equipment in selected areas of the Territory.

3. DISTRIBUTION OF EARTHQUAKES IN THE TERRITORY

The broad tectonic features of the region have been briefly discussed by Gutenberg and Richter (1954, p.50) who differentiate three structurally different regions: (a) principal groups of the Solomon Islands, (b) Bismarck Islands arc, including New Britain and New Ireland, and (c) the region of Central New Guinea.

This Report is concerned primarily with describing the regional seismicity as it affects areas under development and takes the form of an analysis of the magnitude, frequency, and energy release associated with large earthquakes.

Plate 3 illustrates the positions of the epicentres of all earthquakes of magnitude 6 or greater that have occurred since 1906, according to available records (See Table 1, Columns 1-5).

As the latitudes and longitudes of most epicentres prior to 1945 and those from 1956 to June 1960 are quoted to the nearest degree or half degree, the distribution of epicentres on Plate 3 in many places shows an artificial alignment along meridians or parallels. The accuracy of epicentres listed depends on the quality and quantity of data available in each case. Although the accuracy was not as good for some of the earlier shocks as for more recent ones, the errors do not affect the general regional distribution of epicentres presented by Plate 3.

On statistical grounds it is felt that an assessment of the general seismicity should be based on shocks of magnitude 6 or greater because lists of shocks of smaller magnitude are very incomplete. Nevertheless it should be borne in mind that small earthquakes occur in far greater numbers than the larger shocks considered here; though they are rarely a cause of excessive damage, they do contribute to the seismicity. It is possible that in a few isolated areas the general picture of the seismicity presented by Plate 3 may be somewhat incomplete. This would be so in an area where no shocks of magnitude 6 or over have yet occurred but where shocks of lesser magnitude have been reported. An example of this is the islands near the south-eastern tip of Papua; only one shock of magnitude greater than 6 has been plotted in this area, but it is known that smaller shocks have frequently occurred there during the last few years.

An idea of the relative frequency of occurrence of shocks of different magnitude is given by the following equation which roughly represents world-wide frequency of occurrence:

$$\log_{10} N = A - bM$$

where N = number of shocks of magnitude M or greater per year.

For this equation Richter (1958, p.359) gives the values:

$$A = 8.2 \text{ (approx.)} \qquad b = 1.0$$

i.e. the world as a whole has an annual average of one earthquake of magnitude 8 or greater, ten of magnitude 7 or greater, etc.

Statistics giving relative frequency of shocks of small and large magnitudes in the Territory have been compiled only from Port Moresby Observatory records for the period August 1958-April 1960; these are presented in Table 2 and Plate 4. Because of the low sensitivity of the Wood-Anderson seismographs, from which magnitude determinations have been made, not all shocks of magnitude below 5 occurring throughout the Territory would be recorded in Port Moresby, which is up to 9 or 10 degrees from the region of epicentres near Bougainville, New Ireland, and the Sepik District. Therefore the trend of the log N versus M curve is unreliable for values of M less than 5.

It will be noted from Plate 4 that the frequency of occurrence of Territory earthquakes follows the world-wide trend for shocks M = 5 or greater. Considering that the data on Territory earthquakes listed in Table 2 cover less than two years' observations, it is surprising that they indicate such a smooth frequency distribution and conform so closely to the estimate of five to ten percent of world occurrences given by Gutenberg and Richter. If we accept Richter's values for A and b, this implies that the Territory of Papua & New Guinea has an annual average of just less than one earthquake of magnitude 7 or greater, ten of magnitude 6 or greater, one hundred of magnitude 5 or greater, etc.

It will be seen (Plate 3) that large earthquakes have occured over almost the whole of the land area of the Territory of Papua & New Guinea with the possible exception of Manus Island, the Western Highlands District, and the southern part of the Morobe District. These areas, however, have sometimes felt severe effects of larger earthquakes in adjoining areas; Modified Mercalli intensities in the range IV to VII were reported from the Western Highlands and Morobe Districts on 19th November 1959. It would therefore be safe to assume that no part of the Territory of New Guinea is free from risk of damaging vibrations caused by earthquakes. New Britain and Bougainville particularly are very liable to strong shocks.

In an unpublished summary of New Guinea seismicity Fr O'Leary, formerly chief of the Riverview College Observatory, has recorded frequent instances when intensities of VII-VIII on the old Rossi-Forel scale were felt.

A feature evident from Plate 3 is the occurrence of earthquakes at depths between 70 and 300 km in mainland New Guinea from the south-eastern Sepik District to the Madang and Eastern Highlands Districts. Generally it is found that deep earthquakes are felt over a much wider area than shallower ones of the same size. For example the earthquake on

19th November 1959 in Table 1 was felt over almost the whole of mainland New Guinea. Therefore, although these deep earthquakes have occurred less frequently than the shallow ones in New Britain and Bougainville, they could cause damage over a wider area. However, for shocks of equal magnitude, epicentral intensities will generally become less as focal depth increases.

Plates 5-7 illustrate earthquake frequency per square degree per century computed according to the method outlined in Appendix 2. The contour lines clearly illustrate that parts of New Britain, New Ireland, and Bougainville have experienced more shocks than any other area in the Territory.

In Appendix 4 an analysis is made of the rate of occurrence (per century) of earthquakes of varying size by comparing Territory statistics with world-wide statistics, both of which are listed by Gutenberg and Richter (1954, pp.16-22). This suggests a rate of 115 shocks per century of magnitude 7 or greater, and more than 1000 shocks of magnitude 6.0-6.9. The numbers used are statistically small (especially those for large shocks) and the conclusions reached express only a probability; nevertheless, the expected century totals appear reasonable. Some confirmation of their apparent reliability is given by an integration of the areas enclosed by contours in Plates 5 and 6, from which century rates of occurrence are directly calculated. These figures are derived from activity 1930-1959, i.e. a different period from those used by Gutenberg and Richter.

	Plate 6 ($M \geq 7.0$)		Plate 5 ($M \geq 6.0$)			
Area (square degrees)	36.5	5.6	59.5	10.8	5.4	1.8
Average earthquake frequency per century	2.5	7.5	5	15	30	50
Total earthquakes per century calculated from above figures	133		712			
Total earthquakes per century derived in Appendix 4	115		955 or 1155+			

Agreement for larger shocks (magnitude 7.0 or greater) is excellent. Considerably less, but still fair, agreement results from the comparison of corresponding data for shocks of magnitude 6.0 or greater; the discrepancy amounts to something over 400 shocks per century. Two factors would contribute to this:

(a) Gutenberg and Richter's statistical data for shocks of magnitude 6.0-6.9 were derived from the period 1932-June 1935, for which they felt their records were most complete. Reference to Plates 13 and 18 will show that, for the Territory, this was a period of higher than average activity. Therefore, when extrapolated for a century (as in Appendix 4, Class c shocks) an excessively large number of earthquakes results. Comparison of estimated strain release for a century computed at the average rates 1930-1962 and 1932-1935.5 provides one means of estimating that the figure of 1155+ tabled above is high by perhaps 100 to 150 shocks.

(b) It is most likely that not all shocks of magnitude 6.0-6.9 (particularly in the range 6.0-6.5) that occurred between 1930 and 1962 have been listed.

This is almost certainly true between 1940 and 1946 when, of 29 earthquakes listed, more than two-thirds exceed magnitude 7. This abnormally high proportion suggests that the estimate of 712 determined from Plate 5 may be too low by as much as 200.

It is concluded therefore that earthquakes of Richter magnitude 6.0 or greater probably occur at an average rate of about 900-1000 per century - i.e. 9-10 per annum - within the borders of the Territory. Of these, about one shock per annum could be described as a major earthquake.

4. AN ATTEMPT TO DELINEATE SEISMIC REGIONS OR ZONES

In order to express earthquake risk, seismic regions have been mapped both in the Soviet Union and the United States (Richter, 1959).

In this Report risk is defined in terms of the maximum level of potentially damaging ground motion that a particular location can expect in a specified number of years. Plates 8-10 indicate areas within which various maximum degrees of shaking (intensities, Modified Mercalli scale, 1956 version) may be anticipated during time intervals 100, 50, and 25 years. The sections of this scale relevant to the present discussion are (Richter, 1958, p.137):

'Intensity VI:

Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D (see note following) cracked. . . Trees, bushes shaken.

Intensity VII:

Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices. . . Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

Intensity VIII:

Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

Intensity IX:

General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations. . .).

Frame structures if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

Intensity X:

Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.'

which refer to:

'Masonry A: Good workmanship, mortar and design; reinforced especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B: Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C: Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D: Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally'.

The following kinds of data may be used as a basis for defining zones of differing seismic risk as prescribed above:

(a) Reported felt intensities over a long period of time.

(b) Detailed geological data.

(c) Earthquake statistics, both frequency and magnitude, provided the numbers involved are sufficiently great.

Felt intensities

Macroseismic reports of many of the large earthquakes that have occurred in the last 60 years are available but unfortunately there are only a few individual reports in each case. This can be attributed to the sparsely populated country and communication difficulties, which make the reliable operation of any reporting system a major problem. Unfortunately, too, the method of reporting which has been in use does not allow the resulting data to be reliably assessed for these purposes. It is most desirable that observers report felt effects rather than their own individual estimates of intensity. In the latter case there is a very strong possibility that reports of a single shock will be inconsistent with each other and that reports from time to time at the same location will lack consistency. Detailed comment on this question has been made by Richter (1958, p.141) and others. In the circumstances, available reports of intensities felt throughout the Territory must be regarded as insufficient, both qualitatively and quantitatively, to provide a basis fo zoning purposes.

In the foreseeable future the number and disposition of potential observers is unlikely to increase sufficiently to permit the establishment of a comprehensive intensity-reporting network. A more objective approach would be to make use of simple mechanical seismoscopes as intensity indicators (e.g. the USCGS seismoscope; see Appendix 1, items 8 and 9). Their low initial cost and simple method of recording make them ideal instruments for operation by completely untrained observers. Such instruments would serve a double purpose in providing engineering data.

Geological data

Intensities of shaking are very dependent on the geological characteristics of the site in question, and any form of seismic zoning must therefore take account of these factors. For example, it is generally accepted that at a given distance from an epicentre, the worst shaking will probably be experienced on unconsolidated sediments (e.g. Duke & Leeds, 1959). Richter (1959) considers the allocation of different intensities largely on the basis of geological foundation is quite a practical procedure in some circumstances and has based his micro-regionalisation of California on detailed geological maps.

Existing geological maps of the Territory are not detailed enough to enable this type of information to be uniformly and generally used as a controlling factor in the construction of any seismic zoning maps. At best, areas that include Quaternary sediments can be roughly designated as localities which, for a given distance from an epicentre, are probably subject to more intense shaking than other areas.

Earthquake statistics

Therefore the most reliable (and complete) data on which any assessment of seismic risk can at present be based in the Territory are earthquake magnitude statistics. These can be used to express risk in terms of either ground acceleration or intensity, together with frequency of occurrence. Both of these parameters are subject to substantial qualification when used for this purpose, as they are dependent on local geology and earthquake energy radiation characteristics. Maximum values of acceleration are not as useful now as formerly, in view of the recent and more realistic approach to the solution of aseismic design problems - viz: to use dynamic rather than static methods. On the other hand the concept of intensity, although defined on a generally broad and subjective scale, is more familiar to the layman, is a useful qualititive measure for this purpose, and consequently has been adopted to express seismic risk here. Moreover, expected intensities in a given locality can be compared with past reports. Plates 8-10 can therefore be described as intensity zone diagrams.

Earthquake statistics refer not to the history of every point in an area but to the occurrence, at determinable points, of events of a certain intensity. To express the risk of earthquake damage at every point in the neighbouring region, some assumption must be made about the area affected by the earthquake. For the purpose of this Report, the assumption is made that the epicentral intensity applies to all points in the square degree centred on the epicentre. Assumed lower intensities of more distant points are ignored. In other words, the average number of times that a given point will experience a certain intensity is equal to the average number of times an earthquake with that epicentral intensity occurs in an area of one square degree (about 12,000 sq.km) centred on the same point during the specified period. This assumption is discussed in Appendix 5.

Therefore the contours of Plates 8-10 can also be interpreted as showing for every point the intensity that will be experienced on an average once during the specified period of time. The three maps illustrate the changing probability of values of intensity for three different intervals of time.

In Plates 8-10 therefore the Territory is subdivided by contours into areas of 'expected highest intensities' within specified periods of time. These lines indicate highest (i.e. in the region of the epicentre) values of intensity from the largest earthquakes that occur, on the average, once during the time interval considered. It is assumed that an earthquake of this intensity will occur at least once in the areas between each contour line under consideration and the next-'highest' line. The mathematical probability that one earthquake producing the intensity indicated by the contour lines will occur in a given square degree during the time interval concerned is 63 percent.

Subdivisions of the intensity zone maps (Plates 8-10) are purely statistical boundaries determined from a superimposition of corresponding contours of equal frequency, from Plates 5-7. The shaded portions designate areas within which earthquakes of the maximum intensities indicated can be expected to occur at least once per square degree during the period indicated, based on frequency of occurrence during the last 50 years.

Magnitudes have been assigned equivalent epicentral intensities (I_o) that should empirically represent maximum intensities on 'average' ground. Accelerations could be chosen with equal validity, but would probably imply a numerical accuracy that is not present. The equation used is:

$$M = 1 + 2I_o/3 \quad \text{(Gutenberg \& Richter, 1956)}$$

which represents nominal 'average' ground conditions in California.

It will be seen that expected maximum intensities range from VI to X. The subdivision from IX to X is largely of academic interest, as 'to the engineer, designing for possible IX is already enough of a problem; the added risk of X or over makes little practical difference.' (Richter, 1959).

For large areas of the Territory, where intensities above VIII are indicated, little or no significant increase in intensity would be worth specifying on geological grounds. However, some increase in expected maximum intensities, where these are indicated as VI, would definitely be warranted in alluvial areas; each proposal for construction in these regions should be given special individual consideration.

Reported cases of M.M. intensity VI or greater are plotted in Plate 11. These cover the period 1916-1937, a single earthquake in 1941 (Fisher, 1944), and the period 1954-1962. Although incomplete, the reports do permit some comparison to be made between observed intensities and the intensity zone maps. Agreement is good, but this of course is not conclusive justification of the maps or the method. The single questionable event is a reported intensity of R.F. IX (M.M. VIII) at Kerema in 1931. This is in agreement with the 100-year map and in view of the probable alluvial foundations is not at variance with the 25- and 50-year maps. In fact it served very well to illustrate the care necessary when proposing construction on such ground. Details of the basis of this report are not available, but it is doubtful whether it represents more than a single estimate rather than a careful assessment of many reports in a single area.

5. STRAIN ACCUMULATION AND RELEASE

A useful method of diagrammatically representing the amount of strain released by an earthquake has been devised by Benioff. By first assuming a relation between magnitude and energy release, Benioff computed a 'strain rebound increment' proportional to the square root of the amount of energy theoretically released by each shock. The procedure (see Appendix 2) is dependent on a number of assumptions but it has been used in various ways by Benioff, Ritsema, and others to demonstrate the accumulation and distribution of strain release over a period of time in several regions of the world, and as an aid in describing the seismicity of a given area.

Contours of strain rebound displacement factor per square degree are superimposed on a map (Plate 12). This is a quantity proportional too the total strain release integrated over all earthquakes in an area, divided by the area in square degrees. Although not absolute quantities - owing to the fact that the constant C involved in the conversion of energy to strain rebound (see Appendix 2) is unknown - the values form a valid basis for comparison of affected areas with each other, subject of course to acceptance of the basic assumptions referred to above.

The general similarity in the shape of the contours in both Plates 5 and 12 is evident and illustrates that those areas with a high frequency of shocks experience the largest strain release. This is to be expected if the period of time considered is sufficient to smooth those anomalies produced by a single earthquake large enough to intensify considerably the strain rebound values of an area while contributing only a small increase to the frequency factor. Examples are the shocks of 30th April 1939, 10.5°S 158.5°E, magnitude 8, and to a lesser degree 20th September 1935, 3.5°S 141.5°E, magnitude 7.9. Thus erroneous conclusions could be drawn from strain rebound charts if assessments of the seismic activity of any given area are made in this fashion using too few events.

It has been demonstrated by Benioff and others that the rate of strain release in certain large areas is more or less constant over long periods of time. Data on earthquake magnitudes have been available only since the start of the century, i.e. over the last 60 years, but this period may represent only a small fraction of the time interval required to assess reliably the morphology of regional tectonic stress patterns. Mountain building is an extremely slow process and its growth rate can possibly be expected to bear some relation to the degree of concomitant seismic activity. Consequently, patterns of seismic activity may not be truly significant indicators of future conditions until they can be observed over extremely long time intervals.

The progressive total of strain release has been charted for the whole Territory and for a number of areas of limited extent (Plates 13-17 and Table 1, Col. 7-11). For Plate

13 the geographical borders of the Territory have been taken as arbitrary limits, and progressive annual totals only have been plotted, rather than each individual earthquake.

The restricted areas (Plates 14-17) were chosen to cover the main centres of development and to serve as random samples for assessing the consistency of seismic activity in small areas within the main zone of activity.

Plate 13 indicates a marked change after 1930; there is little doubt that this is a consequence of the paucity of seismological data relating to events before then. The following conclusions are therefore drawn from data for 1930-1962.

Plate 13

The mean rate of strain release is reasonably steady but points of maximum release of strain (peaks) and of maximum accumulation of strain (troughs) can be discerned. When these sets of points are joined the two lines aa' and bb' are seen to be roughly parallel, suggesting that the limits of strain accumulation and strain relaxation are fairly constant. The progressive accumulation and release of strain seem to exhibit a periodic tendency but the significance to be attached now to this observation is open to question, as data for a longer duration are required to verify its reality.

The inference to be drawn from Plate 13 of course is that the region is now strained to its limit and that if the periodic tendency mentioned above is real, the next four or five years (1963-1967) will be a period of higher-than-average activity during which the strain released may total twice to three times the amount released by large earthquakes during the last five years.

Plates 14-17

The extent to which the average rate of strain release in limited areas is a reliable indicator of future activity has not been greatly studied. Benioff (1955) successfully predicted the nature of future activity within a small 'seismically isolated' area of a few square degrees in the Indian Ocean, but the author is not aware of any such studies made within areas of high seismicity.

The following areas (of arbitrary extent, see Plate 3) were chosen for study:

Region A:	Bougainville area	- Lat. $5\frac{3}{4}$ - $7\frac{3}{4}{}^{\circ}$S	Long. 154 - 156 $^{\circ}$E
Region B:	Northern New Britain, Southern New Ireland	- Lat. $3\frac{1}{2}$ - $5\frac{1}{2}{}^{\circ}$S	Long. $151\frac{1}{2}$ - $153\frac{1}{2}{}^{\circ}$E
Region C:	Madang and Morobe Administrative Districts	- Lat. $4\frac{1}{2}$ - $7\frac{1}{2}{}^{\circ}$S	Long. $144\frac{1}{2}$ - 148 $^{\circ}$E
Region D:	Sepik Administrative District	- Lat. 2 - $4\frac{1}{2}{}^{\circ}$S	Long. 141 - 144 $^{\circ}$E

Each region has general tectonic characteristics that distinguish it from the others.

Region A. This consists entirely of portion of the Solomon Islands, suggested by Gutenberg and Richter (1954, p.50) as comprising 'an arcuate structure of the Pacific type'. In this case the 'plane' of earthquake foci dips very steeply and, in fact, may be taken as vertical. Earthquakes in this region may be related to a single major tectonic feature.

Region B. This region is at the junction of the Solomons arc and the 'Anomalous arc of the Bismarck Islands' (op. cit., p.50); two or more major tectonic features may therefore be related to the occurrence of major earthquakes.

Region C. This forms part of the Bismarck Islands arc but consists of an area in which intermediate-depth shocks are predominant.

Region D. This area includes fewer epicentres than the other three - mostly of shallow earthquakes. The tectonic relation with Region C earthquakes is not clear.

Inferred limits of strain accumulation are shown in Plates 14-16. Except for periods of apparent inactivity in Regions A and C beginning 1939, the main trends shown in Plates 14-16 correspond with those for the whole Territory (Plate 13). The comparison is illustrated in Plate 18.

Plate 18

Corresponding diagrams of strain fluctuation are set out on a common time scale in order to compare trends in strain, region by region. They are derived from Plates 13-16 and Table 1 (Col. 7-11), and the rates of strain accumulation were assessed from each graph on the assumption that the rate of strain release corresponds to the rate of strain accumulation. These are indicated on Plates 13-16 together with the period for which each rate applied. Strain accumulation is represented on each plot of Plate 18 as a line sloping upward to the right between earthquakes, which are indicated as vertical lines at the time of occurrence (graphs for regions A, B,and C refer).

TPNG. For convenience, strain relaxation is plotted in annual increments (i.e. the total strain release for each year derived from Table 1, Col. 7). Details of individual shocks would have confused the diagram without affecting the overall pattern of strain fluctuation.

Region A. Plate 14 indicates that strain was released - and, by hypothesis, accumulated - at different rates during the periods 1930-39 and 1948-62. Further, no strain release apparently occurred during 1940-47. The rates adopted for 1930-39 and 1948-62 are indicated as A1-A2 and A3-A4 on Plate 14. These were determined solely by inspection; no attempt was made to fit the data to a regression curve, for two reasons: (a) precision of the rate of strain release is not required, and (b) the degree of precision (or imprecision) associated with magnitude determinations, and therefore increments of strain, does not warrant accurate numerical treatment for this purpose.

It is difficult to concede that no earthquake above magnitude 6 occurred in Region A from 1940-47 (A2-A3). Doubtless some events were unrecorded at Pacific stations during hostilities in the Pacific (1942-45), but any very large events should have been recorded throughout the world. It can only be suggested that statistics for this period are probably incomplete for reasons unknown. Strain during 1940-47 was therefore presumed to accumulate at the average rate 1930-1960 as indicated on Plate 14 and, again, obtained by inspection.

This has resulted in a considerable change in level of the graph for Region A, which could be taken to indicate a highly-strained condition since 1948 and hence the likelihood of a very large earthquake or series of large earthquakes. It is important to note that this is not necessarily or even probably so; if in fact no strain accumulated in Region A during 1940-47, or if strain release occurred but we are not aware of it, then the difference in level on the Region A diagram on Plate 18 would not be real.

Region B. The diagram was compiled in a similar manner, again using two different rates of strain accumulation for the periods 1930-46 and 1946-62 (B1-B2 and B2-B3, Plate 15). It is of interest to note that no prolonged period of apparent inactivity occurred in this region.

Region C. A similar procedure was followed to that used for Region A. An apparently inactive period is again evident and the following rates of strain accumulation were inferred from Plate 16 and are indicated thereon:

1930-39	(C1 to C2).	By inspection Plate 16, C1-C2
1939-46	(C2 to C3).	Average rate 1930-1962, Plate 16 by inspection.
1946-62	(C3 to C4).	By inspection Plate 16 (same rate as 1939-46)

Remarks concerning the portion A2-A3 of the diagram for Region A apply equally to the portion C2-C3 here.

Thus strain fluctuation is compared, region by region, in Plate 18. It is important to state clearly that the aim has been to compare general trends of strain fluctuation rather than absolute changes in level - the latter cannot be reliably inferred from the diagrams presented, and will not be discussed.

Plates 13-18 allow estimation of total strain release for each area discussed, but it does not necessarily follow that the trends indicated in Plate 18 are real. To ascertain the likelihood of this, the series of annual increments of strain release (1930-1962) for TPNG as well as for Regions A, B, C, D were tested for indications of positive conservation by a serial correlation technique (Chapman & Bartels, 1940); i.e. to see whether each sequence consists of a series of values predominantly random in character, or whether groups of high and low values tend to occur together. The table below lists values of

$$\theta(h) = V(h).h/V$$

where h = number of successive annual strain increments grouped together (1, 2, 3, 4, 5)

$V(h)$ = variance of means of groups of h = 1, 2, 3, 4, 5 years respectively

V = variance of sequence for h = 1

h (years)		1	2	3	4	5
TPNG	$\theta(h)$ =	1.00	1.36	1.48	1.50	1.40
Region A	$\theta(h)$ =	1.00	0.98	1.06	1.04	1.05
Region B	$\theta(h)$ =	1.00	1.23	1.30	1.30	1.21
Region C	$\theta(h)$ =	1.00	1.12	1.28	1.24	1.23
Region D	$\theta(h)$ =	1.00	0.93	0.95	0.93	-

Positive conservation is indicated if $\theta(h)$ is greater than 1, and the value of h corresponding to the maxium value of $\theta(h)$ indicates the number of high (and low) annual values tending to occur consecutively in the data. There are indications of positive conservation for TPNG as well as for Regions B and C. The evidence for conservation for Region A is decidedly weak, and for Region D conservation is negative.

The large range of energy is often poorly resolved between the levels corresponding to earthquake magnitudes 6 and 8, where it is frequently described by one of only nine levels of activity. Therefore the negative result of the conservation test in Region D may be due to the fact that fewer earthquakes were recorded from there, and the statistics are consequently poorer.

In the case of TPNG, $\theta(h)$ appears to become asymptotic to about 1.5 for large values of h. This implies some positive correlation between adjacent years, but very little between intervals two years apart. Another statistical test that can be applied is the mean-square difference test (Brownlee, 1960). An estimate of the variance of individual annual strain release is made in two ways: firstly, an unbiased estimate is made from the square of the difference between each annual value and the overall mean; secondly, the variance is estimated from the differences between successive annual values. The latter estimate is lower than the former, with a statistical significance of about two percent, indicating that the amount of strain release in one year is not independent of that released the year before. When the variance is estimated from the differences between annual strain release two years apart, no significant departure from the unbiased estimates of variance is found. The serial correlation, therefore, extends at most over about one year.

Correlation of trends between graphs for TPNG and Regions B and C is particularly striking (corresponding peaks are indicated). It is worth noting that the vertical scale for the Region A, B, and C graphs is only one-fifth of that for the TPNG graph.

It is suggested that there is sufficient similarity to imply a distinct correlation between activity confined to some small regions and the activity throughout the whole Territory. Clearly, at the end of 1962 strain was accumulating throughout the Territory and in Regions A, B, and C. If this pattern of activity continues, one would expect the rate of strain release for say the five-year period 1963-1967 to be higher than the average for 1930-1962; it might amount to 300 units compared with the average of about 200 units (inferred by inspection of Plates 13 and 18).

In terms of earthquakes, assuming the rule $\log_{10} N = A - bM$ (see page 7), the following occurrences might be expected to account for these two amounts of strain release:

Earthquake magnitude range	7.5 or greater	7-7.4	6.5-6.9	6-6.4
1963-1967 inferred	2	5	15	47
5-year period at average rate 1930-1962	1 or 2	3	10	31

It should be stressed, however, that the actual occurrences for the period 1963-1967 remain a matter for conjecture.

6. GROUND ACCELERATION

Ground acceleration is important because it can be used to compute the stresses in fixed structures; therefore it is the basis of all earthquake-resistant design. Accelerations of the order of 0.5g or greater can be expected in the epicentral regions of major earthquakes. Acceleration will become smaller with increasing distance from the epicentre but the relation between these two factors is complicated to a high degree by the local geology.

Although some early building codes specified that structures be built to withstand certain maximum ground accelerations, expressed as a fraction of g, on the assumption that these structures were rigid, methods of estimating actual strains and displacements produced in structures by earthquake ground motion have been developed in recent years, and modern building regulations in seismic areas are based on such information. For the desired calculation of these structural responses, ground acceleration as a function of time must be directly recorded. In certain cases, values of g higher than those experienced on the ground can be induced in parts of some structures because of the elastic characteristics of the structure and the time history of the ground acceleration. The behaviour of structures is described by diagrams, known as response spectrum curves, which indicate how the distance and size (magnitude) of earthquakes affect certain classes of structures.

Accelerations are best measured by seismographs of special design known as accelerometers. These recorders are usually triggered by the initial movement of a shock and record for a pre-set time. According to Hudson (1963) the only measurements of ground acceleration produced by destructive earthquakes have been made in the United States and the degree to which resulting conclusions apply in other seismic areas has not yet been determined. Moreover it is significant that no such records have yet been made in the epicentral region of a destructive earthquake.

It may be some time before such information can be recorded in Papua & New Guinea, although early action to effect this would be highly desirable. Meanwhile two alternatives are possible:

(a) Many countries which have earthquake engineering problems are currently proceeding on the general assumption that aseismic design specifications compiled from data derived from earthquakes in California are valid for their own areas, until accelerometer recordings can be made. This procedure is probably a fairly safe one for constructions of moderate cost. Building codes in seismic areas are so designed that structures will survive the more frequent moderate ground motions without damage but in the rarer event of very strong ground motion, damage would be tolerated provided no danger to life was anticipated (Housner, 1959). This is a compromise approach, but is taken partly because it is impossible to specify the precise extent of the effect of any future ground motion on structures and partly because the cost of incorporating extreme safety factors in buildings is high.

(b) In the absence of any reliable acceleration data or appropriate building regulations, Richter (1958, p.645) points out that a simple 'rule of thumb provision against lateral accelerations' of some specified value 'has repeatedly demonstrated its practical efficiency'. Such provisions although arbitrary could be usefully applied particularly in the case of simple rigid structures.

As mentioned in pages 9-10 above, the intensity zone diagrams (Plates 8-10) could equally well have been designated acceleration zone diagrams, but data expressed in this way could be subject to overinterpretation. However, in the absence of other data, intensities derived from magnitude statistics can serve as a rough guide for protection against lateral accelerations. Thus for areas designated Mercalli Intensity less than VIII in Plate 8 a lateral acceleration of 0.1g is suggested, and for other areas 0.2g. On unfavourable ground these could be arbitrarily increased to 0.2g and 0.3g respectively.

It is worth noting that locations on unconsolidated ground can expect to be more severely shaken than those on solid basement. Richter (1958, p.384) points out that in a given area where earthquakes are general, the geological nature of the site can often have a greater bearing on felt intensity than the distance from the epicentre. This point would have particular application to areas of the Territory where earthquakes occur frequently. The fact that earthquakes are common will mean that, sooner or later, many locations are going to experience heavy shaking. The effects of this can be minimised, in some cases very considerably, by a critical examination and careful selection of site.

7. CONCLUSIONS

The most significant features of the seismicity of the Territory have been analysed. The frequency of occurrence of shocks and rate of energy release (or a factor related to it) are considered fundamental parameters to be included in any quantitative description of the degree of earthquake activity in a given area.

This is the most comprehensive attempt so far made to describe the comparative degree to which various areas in the Territory are subjected to the effects of earthquakes and it is deduced that the areas around the northern end of New Britain, southern end of New Ireland, and southern half of Bougainville are the most severely affected. The Madang-Ramu Valley region is subject to slightly less activity. It is concluded that seismic activity in the five-year period beginning 1963 will be more intense, throughout the Territory and in the above three regions, than it has been during the last five years.

Seismic activity in the Territory of Papua & New Guinea is high by any standards. Its full implications may not receive adequate recognition because of the scattered nature of settlement. However, with increasing development and construction it will become more desirable for authorities to be aware of the level of seismicity in the region. Further, a fuller understanding, by the public, of the general nature of earthquake occurrence may help to reduce public alarm during any series of felt earthquakes.

Construction anywhere in the Territory should be specially designed if seismic damage is to be minimised. Special attention is directed to those areas of New Guinea designated M.M. Intensity VIII and greater on Plates 8-10.

<u>In areas of high seismicity the use of unsuitable building materials and construction methods, chosen for economic reasons at the expense of structural quality, should not be contemplated without due regard to possible consequences.</u> The disastrous result of the Agadir earthquake in Morocco (29th February 1960) is one of many excellent examples of the damage that can be caused by a moderate earthquake under these circumstances (Tillotson, 1960; Rothe, 1960). Magnitude estimates for this earthquake range between $5\frac{1}{2}$ and $6\frac{1}{2}$. Such widespread damage and high intensity are usually associated only with earthquakes of high magnitude.

The importance of siting construction on consolidated geological foundations where possible should also be recognised. If unconsolidated foundations cannot be avoided, due allowance for the increased intensity of vibrations should be made. The degree to which damage at Agadir was accentuated by unsuitable geological foundations in certain areas cannot be clearly analysed, owing to a combination of circumstances. However, it should be noted that there are areas in the Territory where the surface geology, especially alluvial beds, is of a kind generally considered to be subject to larger-amplitude motion than consolidated foundations. Increased risk of damage in such areas should be recognised (Duke & Leeds, 1963).

The general adoption, throughout the Territory, of a building code especially compiled for a seismic region, such as California, would be an excellent step to take in view of the impracticability of directly surveying earthquake engineering data everywhere in the Territory. Specialised surveys for costly projects are strongly recommended, however.

Although the system adopted for reporting felt intensities of earthquakes throughout the Territory would be difficult to improve without considerable reorganisation and additional analytical effort, some attention to this question is warranted; such information provides valuable data for assessing relative seismic hazard. The data provided so far are inadequate to permit firm conclusions to be drawn. Therefore, and in view of the difficulty of obtaining a reliably consistent geographical coverage of reporting stations, consideration should be given to the installation of a large number of seismoscopes (as mentioned under 'Felt Intensities', page 8). This would provide an inexpensive means of assessing the contribution of local geology to the seismic hazard in different areas, would eliminate human-observer inconsistencies, and would provide valuable engineering data. The total cost of providing and installing 100 of these instruments would be of the order of £3000 and their operating cost would be negligible. Such instruments are being used in increasing numbers in many countries that have a seismic risk problem.

The present number of seismograph stations - inadequate to provide basic instrumental data on local earthquakes - could also be increased with little difficulty and at moderate cost. The two very well-equipped stations at Port Moresby and Rabaul would provide the basis for such a network comprising 10 to 15 stations. Recent developments in compact, inexpensive, but highly sensitive visual-recording seismographs have increased the operational reliability of this type of equipment and eliminated the need for costly instrument housing.

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APPENDIX 1

SELECTED BIBLIOGRAPHY ON ENGINEERING AND CONSTRUCTION PROBLEMS CAUSED BY EARTHQUAKES

1. 'Bibliography of Engineering Seismology' by Edward P. Hollis, published by the Earthquake Engineering Research Institute 1958.

An excellent source of reference to publications on the following:

Design and construction in seismic regions; relating to buildings, towers, bridges, tunnels, earthwork, dams, harbours.

Fire protection and insurance problems.

Building codes.

Seismometry and dynamics of structures and soils.

2. 'The Earthquake Engineering Research Institute' - 1960.

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Note: Information on publications of the Earthquake Engineering Research Institute may be obtained from the Secretary of the Institute, 465 California Street, San Francisco 4, California, USA.

APPENDIX 2

CALCULATION OF EARTHQUAKE FREQUENCY FACTOR AND STRAIN REBOUND INCREMENT

Frequency factor

A number is assigned to each unit of equal area to represent the number of shocks that have occurred in that area in a given time. Over the range of latitude of interest (0-10^{o}) the areas of each square degree may be regarded as being sufficiently nearly equal to be used for this purpose. Frequency factors for each square degree were computed for the period 1930-1959. This period was chosen as it affords a reasonably long period of time, over which the regional picture of seismic activity might be expected to be representative. It was also thought desirable to eliminate the years 1906-1930, during which details of many earthquakes of magnitude less that 7 are probably missing. The frequency of shocks has been plotted in this way:

(a) If the epicentre is placed within the boundary of a square degree a frequency number 4 is assigned to that square.

(b) If the epicentre is located on a boundary, 2 is assigned to the squares on either side.

(c) If the epicentre is located at the intersection of two boundaries, 1 is assigned to each of the four squares adjoining.

(d) The frequency factor for each square degree is the sum of the numbers assigned to it divided by four and extrapolated for a given period. These have been plotted and roughly contoured in Plates 5-7 to show lines of equal frequency factor per square degree per century.

Strain rebound increment

This quantity was first proposed as a means of assessing the degree of seismic activity in a given area or region by Benioff (1951). It is defined as the square root of the calculated energy released by an earthquake in the form of seismic waves, multiplied by a constant with dimensions $(\text{energy})^{-\frac{1}{2}}$

Under the assumption that, before the occurrence of an earthquake, the average strain in an area is S, then the stored potential energy may be represented by the equation

$$E = \tfrac{1}{2}\, k S^2$$

where k is a constant depending on the coefficient of elasticity and the volume of rock mass under strain.

It can be assumed that a proportion (P) of this stored energy will be released in the form of seismic waves at the instant of occurrence of the shock (E_W).

$$E_W = \tfrac{1}{2}\, k P S^2$$

Further, assuming that the strain in the region is reduced to zero by the earthquake, the displacement that takes place (presumably along a fault) can then be held to be proportional to S; i.e. S = KD where D is the displacement.

Transposing we find

$$D = CE_W^{\frac{1}{2}} \quad \text{where } C = (2/kP)^{\frac{1}{2}}/K$$

Several expressions for calculating E_W for the assigned Richter magnitude of an earthquake have been developed from time to time. The one used here is

$$\log E_W = 11.4 + 1.5M \quad \text{(Richter, 1958, p.366)}$$

Neglecting the constant factors involved, a strain rebound increment $E_W^{\frac{1}{2}}$ is computed for each shock. The sum of such factors for a number of shocks in a given area can of course only be used for comparison purposes within each area covered by the analysis and not taken as an absolute quantity. The increment relating to each shock is assigned to the square degree in which the shock occurs (or to adjoining squares by dividing by 2 or 4 as the case may be, in similar fashion to the way in which the frequencies were plotted).

While the above procedure is necessarily dependent on the acceptance of a number of assumptions, it nevertheless is considered to be a valid approximate representation of the comparative movements resulting from earthquakes within the area considered. The chief assumptions made are :

(a) That the constant k is uniform throughout the region under consideration.

(b) The fraction of total stored energy released by an earthquake in the form of seismic waves is the same for each earthquake considered.

(c) The radiation of energy in the form of seismic waves is equal in all directions - it is necessary to accept this before using M.

(d) The release of strained energy takes place at one time and not in the form of a series of multiple shocks occurring very close together.

(e) That the equation $\log E_W = 11.4 + 1.5M$ adequately represents the relation beteen magnitude and energy throughout the region. In the absence of any evidence to the contrary, this assumption seems reasonable. However, the correctness of the equation itself as a quantitative expression may well be queried if only because the definition of a uniform scale for deriving M has not yet been adequately achieved.

APPENDIX 3

SOME COMMENTS ON BASIC PRINCIPLES AND TERMINOLOGY OF SEISMOLOGY

Earthquakes occur spasmodically in the upper mantle and the crust, or exterior portion of the Earth, when strains accumulated in the rock masses beneath the Earth's surface are released along lines of weakness. It is well known that earthquakes are most frequent in well-defined belts, which are zones of potential weakness or instability in the Earth's outer regions. The Territory of Papua & New Guinea lies on a zone of prolific seismic activity.

No earthquake is known to have occurred at a depth exceeding about 450 miles, and by far the greater number of shocks originate at a depth of less than about 60 miles, which includes the Earth's crustal layers. The depth of an earthquake has considerable bearing on the intensity with which that earthquake is felt at the Earth's surface.

The amount of energy released by earthquakes varies over a large range. As an indication of the energy released at an earthquake's focus (hypocentre, or point of origin), there can be assigned to each quake a magnitude according to some arbitrarily-defined scale. The most commonly-used scale is the Richter scale. On this scale, the smallest earthquakes felt would have magnitude about 2 - the largest, magnitude 8.5 to 8.8. A hundredfold increase in energy released at the focus corresponds roughly to a step of 1 up the Richter scale.

Knowing the magnitude of an earthquake, it is possible to estimate how far away from the epicentre (or point of the Earth's surface, vertically above the focus) its tremors will be felt. This gives a 'radius of perceptibility', defining an area beyond which the intensity of the tremors at the Earth's surface can be expected to be too small to be felt. The radius of perceptibility is greater for deep shocks than for shallow ones. Therefore, damage from a large deep quake could reasonably be expected to occur over a wider area than that from a shallow one of equal magnitude, although damage near the epicentre of the shallow one may be greater. It should also be appreciated that local geology plays an important part in determining the area over which earthquake effects are felt.

A scale has been devised to enable observers to assess the intensity with which an earthquake has been felt at any one point. This scale does not represent any physical measurement; it is a simple gauge of the extent to which the earthquake was felt. The Modified Mercalli Scale of Intensity has 12 grades, designated by Roman numerals. Most people are familiar with the use of this scale, sometimes quoted for earthquake 'strengths'. Intensity I means that shaking was generally not perceptible to people; V means that it was felt by nearly everybody, with some dishes, windows, etc. broken and unstable objects overturned; VI that it was felt by all, with some instances of fallen plaster or damaged chimneys - this grade is regarded as the lower limit of damage. Damage is total for intensity XII.

It is obvious that any attempt to establish a relation between magnitude and intensity is complicated by such things as distance from the epicentre, depth, and geological structure. A high intensity does not necessarily signify the occurrence of a very large earthquake. However, some idea of the relation can be gained from the fact that the lower limit of damage (i.e. intensity VI) could be expected close to the epicentre of any earthquake having a magnitude of 5 to $5\frac{1}{2}$ and occurring at a shallow depth, or a hundred or more miles from a major earthquake (magnitude higher than 7).

NOTE: The focus of a shallow earthquake lies less than 45 miles below the Earth's surface; that of an intermediate-depth quake, between 45 and 200 miles below the the surface; and that of a deep quake, more than 200 miles below the surface.

APPENDIX 4

A QUASI-STATISTICAL ANALYSIS OF TERRITORY SEISMICITY

The analysis is based on the numerical proportion of earthquakes in the region, to those in the whole world. It is assumed that such a proportion is constant over a long period of time. This assumption is not without some foundation, and the method has been used for similar analyses of seismicity in other regions. However, the conclusions drawn should not be accepted without the reader being mindful of the large number of variables involved in the occurrence of seismic phenomena.

Three classes of earthquake have been used as data. The classification is made on the basis of magnitude. Only shocks of Richter magnitude 6.0 and greater are involved.

Class	a	b	c
Magnitude	$7\frac{3}{4}$ - $8\frac{1}{2}$	7.0 - 7.7	6.0 - 6.9

The most complete summary of earthquakes throughout the world, from 1904-1952 is contained in the book 'Seismicity of the Earth' by Gutenberg and Richter (1954). From this summary, statistics have been derived for the following periods, for which Gutenberg and Richter believe their record to be most complete:

1904-1945 for class a,

1922-1945 for class b, and

1932-June 1935 for class c shocks.

Including all shocks in the above categories, the following totals are given for the specified periods:

Classes a + b	Class c	
	Total (c_t)	except intermediate & deep M 6-$6\frac{1}{4}$ (c_e)
596	538	448

From the data for the Territory, statistics have been derived for earthquakes satisfying the same conditions as those used for the world totals. The numbers of earthquakes of each class, occurring in the Territory, are summarised below:

Class a	Class b	Class c	
		c_t	c_e
6	29	37	33

These represent the following percentages of the world totals:

Classes a + b	Class c c_t	Class c c_e
5.9 %	6.9%	7.4%

From data in 'Seismicity of the Earth' (pp. 16-22) an estimate can be made of the annual rate of occurrence of earthquakes throughout the world. Shocks of all depths are included together. The estimates for a century are:

Class a	Class b	Class c c_t	Class c c_e
270	1680	15,000+	11,400

Application of the percentages tabled above gives expected century totals for the Territory, thus:

Class a + b	Class c c_t	Class c c_e
115	1040+	840

i.e. 1155+ shocks of magnitude 6.0 or greater

955 shocks of magnitude 6.0 or greater, except intermediate and deep shocks of magnitude $6\text{-}6\frac{1}{4}$.

APPENDIX 5

EARTHQUAKE MAGNITUDE, EPICENTRAL INTENSITY, AND AREA FELT

Quantitative empirical treatment of the relation between magnitude, intensity, focal depth, and radius of perceptibility has been attempted by investigators, principally in USA, USSR, and Japan; e.g. Gutenberg and Richter (1942, 1956); Shebalin (1956). The possible errors of applying conclusions reached in these (and other) studies to locations in regions of differing characteristics must be clearly stated, and are stressed by some authors. This would seem even more important in areas where seismicity and geology are known to be different - as is likely in the Territory of Papua & New Guinea.

Earthquake frequencies in the Territory have been discussed in this Report in terms of the number occurring per square degree per century. From this, seismic risk is described by the maximum value (I_o) of intensity that accompanies an earthquake that occurs, on the average, at least once per square degree per centry (see p. 10). Little sound empirical evidence is available for the implied assumption that the epicentral intensity I_o (or an intensity within 1 Modified Mercalli unit, $I_o - 1$, an acceptable 'observational error') is felt over an area of the order of one square degree, 12,000 sq. km.

Only Fisher (1944) has published isoseismals of a Territory earthquake, and one example is clearly inadequate to support any general conclusions regarding the areas over which different intensities are felt. Although such areas will vary widely with change in focal depth and local geology, most interest centres around earthquakes at a 'normal' shallow depth; these result in highest value of I_o, and therefore the highest risk of damage is associated with them. From Fisher's lone example the area affected by R.F. intensities VIII and IX was approximately 7000 sq.km.

As far as can be gauged from recent data, most shallow shocks in the Territory seem to have a mean focal depth of between 30 and 40 km, say 35 km - see the last few depth entries of Table 1, where values were determined by the USCGS computer. Similar limited evidence is provided by Brooks (1962). Of a random sample of 185 shocks, almost 50 percent occurred at a mean focal depth of 65 km or less.

For illustrative purposes only, the result of 7000 sq.km estimated from Fisher's paper can be compared with others, e.g. by using equations (12) and (13) (Gutenberg & Richter, 1942) and the equation $I_o = 1.5M - 3.5 \log h + 3$ (Shebalin, 1956) and thus we may investigate in general terms the effect of changing focal depth, from say 20 to 50 km, on area affected. (No suggestion is thereby made that these equations should be indiscriminately applied to Territory statistics to force numerical results that would not otherwise be available. Supporting empirical information is first required). It should be noted that this procedure ignores effects of practical significance, e.g. as caused by non-uniform surface geology.

Example: Magnitude 7 earthquake

Notation: Gutenberg & Richter (1942)

Definition: Area perceptible to earthquake = πr^2; where r is the distance from the epicentre to the outer limit of M.M. intensity II zone; this isoseismal corresponds to intensity I-II, i.e. intensity "$I\frac{1}{2}$".

h	I_o	R	Maximum isoseismal radii for zones			Approximate area susceptible to intensities		
km	MM units	km	"VI½"	VII	VIII	"VI½"	VII	VIII
				km			sq.km	
20	IX	355	61		29*	11,700		2700*
35	VIII	420		51*			8000*	
50	"VII½"	500	75*			17,500*		

* Corresponding to $I_o - 1$

Thus a change in focal depth from 20 to 50 km results in a lower epicentral intensity by 1½ units but an increase in area perceptible to $I_o - 1$ by a factor of 6. In the above example, the area affected by intensity VI½ increased by 50 percent. Thus a deeper shock can affect a larger area than a shallow-focus shock, although the epicentral area will be more severely shaken in the latter case.

An examination of isoseismals drawn by Fisher suggests a focal depth of perhaps 30-40 km for the New Britain earthquake studied by him. The area of 7000 sq. km estimated to have been affected by intensities R.F. VIII+ seems reasonable therefore, and not inconsistent with figures tabled above. (M.M. VII-IX corresponds roughly with R.F. VIII-IX).

Therefore, from such meagre Territory data as are available, and considering other empirical results, principally from Californian earthquakes, one might reasonably expect the area over which $I_o - 1$ intensity is felt in the Territory to be 6000-12,000 sq.km.

The assumption as to area affected is in practice limited to either one square degree or at least, one half square degree. This is due to the inaccuracy, often ± 1 degree or more, of the epicentral co-ordinates (Plate 3). The choice of one half square degree as the unit area would not be unreasonable, but having regard to possible average focal depth in the Territory is thought to be too small for use as a basis for zone diagrams. Alternatively one square degree is probably on the large side but its use incorporates an arbitrary 'safety factor.'

The effect of having overestimated this area would be that designated areas of Plates 8-10 are probably larger than they would be otherwise - a not-undesirable fault in diagrams of this kind. Moreover the effect of all earthquakes farther than about 65 km (radius of a circle of 12,000 sq.km area) from the epicentre has been neglected. In practice, this would probably have a compensating effect. Therefore, in the absence of more specific observational data from the Territory, the diagrams of Plates 8-10 are based on the assumption that intensity $I_o - 1$ is felt over an area of the order of 12,000 sq.km.

<u>TABLE 2</u>

<u>FREQUENCY OF OCCURRENCE OF EARTHQUAKES;</u>

<u>COMPARISON BETWEEN VALUES FOR WHOLE WORLD AND TERRITORY</u>

<u>OF PAPUA & NEW GUINEA</u>

Magnitude M	Number per Annum* (whole World)		ø Number M Recorded for TPNG, Aug. 1958 - Apr. 1960	Number per Annum TPNG		n/N %
	N	log N		n	log n	
0	1.6×10^{8}	8.2				
1	1.6×10^{7}	7.2				
2	1.6×10^{6}	6.2				
3	1.6×10^{5}	5.2	785	449	2.65	
4	1.6×10^{4}	4.2	587	335	2.52	
5	1.6×10^{3}	3.2	197	113	2.05	7
6	1.6×10^{2}	2.2	22	13	1.11	8
7	1.6x10	1.2	2	1.1	0.04	7
8	1.6	0.2				

* Based on $\log N = A - bM$ where $A = 8.2$, $b = 1.0$ (Richter, 1958, p.359)

ø Recorded at Port Moresby only. Assumed near-surface focus.

Magnitudes estimated from maximum amplitudes on Wood-Anderson seismograph.

TABLE 1

PRINCIPAL EARTHQUAKES IN PAPUA & NEW GUINEA 1906-1962

EARTHQUAKE					STRAIN REBOUND DISPLACEMENT FACTOR $S = E^{\frac{1}{2}} . 10^{-10}$					
						Cumulative Total (S)				
							Region			
Date	Lat. (°S)	Long. (°E)	Depth (km.)	Mag.	S	Whole TPNG	A	B	C	D
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1906 Sep 14	7	149		8.1	75.9	75.9				
1910 Jul 29	5	143	80	6.9	7.6					
Sep 7	6	151	80	7¼	12.6	96.1				
1911 Dec 31	2	143½		7.0	9.0	105.1				
1912 Sep 1	4½	155	430	7	9.0	114.1				
1913 Jun 4	1½	150		7	9.0	123.1				
1916 Jan 1	4	154		7¾	35.5	158.6				
1917 Jul 29	3½	141		7.6	25.2	183.8				
1918 May 20	1	153		6.7	5.3					
Jul 3	3½	142½		7.5	20.9					
Oct 27	2	148	50	7.4	17.8					
Dec 25	7	153	450	6¾	6.4	234.2				
1919 May 6	5	154		7.9	41.7	275.9				
1920 Feb 2	4	152½		7.7	30.2	306.1				
1923 Nov 2	4½	151½	50	7.2	12.6					
Nov 4	5	152		7.2	12.6	331.3				
1925 Jun 9	3	140		7.0	9.0					
1926 Jan 25	9	158		7.4	17.8					
Feb 7	4	152	390	6½	3.8					
Mar 27	9	157		7.2	12.6					
Jul 28	8	157½	50	6½	3.8					
Sep 7	6	146	100	6¾	6.4	341.5				
Sep 16	11½	160	50	7.1	10.5					
1927 Feb 1	6½	155½	60	6.9	7.6					
May 13	2½	143½	50	6¼	2.2	351.3				
1928 Mar 13	5½	153	100	7.0	9.0					
Sep 7	5½	146½	140	6¾	6.4	366.7				
1929 Jun 12	5	143½	110	6¾	6.4	373.1				
1930 Jun 11	5½	150		7.1	10.5					
Sep 30	4½	146		6¾	6.4	390.0			6.4	
1931 Jan 15	3	143½		6½	3.8					3.8
Apr 6	7	155		6¾	6.4		6.4			
Apr 24	6½	155		6.9	7.6		14.0			
Jun 1	4½	152		6¼	2.2			2.2		
Jun 17	6½	146½	140	6½	3.8				10.2	
Jul 23	6½	155	400	6¾	6.4		20.4			
Aug 7	4	142		7.1	10.5					14.3
Oct 23	9	159		6¼	2.2					
Nov 2	8	146		6½	3.8	434.5				
1932 Jan 9	6.2	154.5	380	7.3	15.2		35.6			
Jan 29	6	155		7.0	9.0		44.6			
29	6½	155		6½	3.8		48.4			
30	7½	155		6¼	2.2		50.6			
31	6	155		6	1.6		52.2			
Mar 8	6	154	70	6½	3.8		56.0			
19	3	152	350	6½	3.8					
30	6½	154½	50	6	1.6		57.6			
Apr 12	4	152	100	6¾	6.4			8.6		
Jul 14	3½	154	150	6¼	2.2					
Oct 17	7½	157	100	6¼	2.2					
Dec 24	3¼	145¾		6½	3.8	487.9				
1933 Jan 15	5½	147½	140	6¼	2.2				12.4	
Jun 4	5	146	120	6	1.6				14.0	
Aug 5	9	157½		6¼	2.2					
Sep 27	4¾	151		6	1.6					
Nov 18	7	154½	60	6¼	2.2		59.8			
22	6	151		6¾	6.4					
Dec 12	4½	152½		6¾	6.4			15.0		
24	1	150		6	1.6	509.9				
1934 Feb 3	5¾	151½		6¾	6.4					
9	4	151½		6½	3.8			18.8		
11	6½	154½	80	6½	3.8		63.6			
27	6	154	180	6½	3.8		67.4			
28	5	150		7.2	12.6					
Mar 1	7	148		6½	3.8				17.8	
16	5½	146	120	6¾	6.4				24.2	
20	5½	148		6½	3.8				28.0	
Apr 28	4	152½		6	1.6			20.4		
May 13	5¼	154	100	6¾	6.4					
Jun 9	5¾	147¼	130	6.9	7.6				35.6	
15	6½	148		6	1.6				37.2	
22	3	150		6	1.6					
Aug 4	3	146½		6	1.6					
11	5½	151½		6¼	2.2			22.6		
Sep 25	5	152	100	6½	3.8			26.4		
Nov 18	4	153		6½	3.8			30.2		
Dec 17	2¼	148½		6½	3.8	588.3				
1935 Mar 20	7¾	156		6½	3.8		71.2			
May 21	6	146	140	6	1.6				38.8	
21	6	146	140	6¾	6.4				45.2	
Jun 16	4½	147		6	1.6				46.8	
Sep 20	3½	141¾		7.9	41.7					56.0
20	3¼	142½		7.0	9.0					65.0
Nov 14	4¼	152½	60	6¾	6.4	663.5		36.6		
1936 Feb 8	5¼	145¾	80	6¾	6.4				53.2	
21	5	144½	75	6.9	7.6				60.8	
Mar 22	8¼	157½	60	6.9	7.6					
Apr 2	3	151		6½	3.8					
19	7½	156	40	7.4	17.8		89.0			
May 5	3¼	148½		6¼	2.2					
Jun 10	5½	147	190	6.9	7.6				68.4	
Dec 29	4½	153½	100	7.0	9.0	700.1		45.6		
1937 Jan 4	4	141½		6	1.6					66.6
23	4½	153		7.0	9.0			54.6		
May 12	4½	144	150	6¾	6.4					73.0
31	6½	154	100	6½	3.8		92.8			
Aug 5	5½	150	140	6¾	6.4					
Sep 23	6	154	60	7.4	17.8	745.1	110.6			
1938 May 12	6	147¾		7.5	20.9				89.3	
Jul 23	5	147	120	6½	3.8				93.1	
Aug 30	3¼	143¾		6¾	6.4					79.4
31	4	151½	350	6¾	6.4			61.0		
Sep 7	6½	155	160	6½	3.8	786.4	114.4			
1939 Jan 22	7½	149		6¼	2.2					
30	5½	147	200	6½	3.8				96.9	
30	6½	155½		7.8	35.5		149.9			
Feb 3	10½	159		7.1	10.5					
Mar 2	4	143	130	6.9	7.6					87.0
8	6	155		6¾	6.4		156.3			
Apr 30	10½	158½	50	8.0	50.2					
May 22	3	141		6¼	2.2					89.2
26	3½	140½		6½	3.8					
Aug 25	5	152¾	90	6¾	6.4			67.4		
Nov 10	9	148		6¼	2.2					
17	6	154½	140	6	1.6	858.1	157.9			
1940 Feb 24	3	141½		6¾	6.4					95.6
Apr 24	5	148½		6	1.6					
Jun 7	9¾	151¼		6¼	2.2					
Sep 12	4½	153	40	7.0	9.0			76.4		
Nov 27	3¼	151		6¾	6.4	883.7				
1941 Jan 13	4½	152½		7.0	9.0			85.4		
Feb 9	4	153		6½	3.8			89.2		
May 2	6	152½	80	6½	3.8					
Sep 4	4¾	154	90	7.1	10.5	910.8				
1943 Mar 21	5¾	152¼		7.3	15.2					
Dec 1	4¾	144	120	7.2	12.6					
23	5½	153½	50	7.3	15.2	953.8		104.4		
1944 Jan 7	4½	143½	120	7.1	10.5					106.1
May 19	2½	152¾	50	7.2	12.6					
25	2½	152¾		7.5	20.9					
Oct 5	4½	152½	110	6.9	7.6			112.0		
Dec 27	6½	152	90	7.0	9.0					
28	6	149½	100	6¾	6.4	1020.8				
1945 Apr 23	4.2	152.2	100	6¾	6.4			118.4		
Sep 5	5.2	152.4	50	7.1	10.5			128.9		
22	3.2	148.2	50	7.0	9.0					
Dec 8	6.1	150.5		7.1	10.5					
27	6.1	150.5	40	7.0	9.0					
28	6.1	150.5		7.8	35.5	1101.7				
1946 Jan 17	6.2	147.7	100	7.2	12.6				109.5	
May 3	4.3	153.8		7.4	17.8					
Aug 11	8.2	155.8		6¾	6.4					
Sep 23	6.5	145.8	100	7.2	12.6				122.1	
29	5.1	153.1		7¾	35.5	1180.2		164.4		
1947 Mar 2	5.0	144.5	50	7	9.0				131.1	
May 6	6.6	148.8		7.6	25.2	1214.4				
26	9.2	159.5	450	6¼	2.2					
1948 Jun 18	6.5	155.0		6½	3.8		161.7			
Jul 14	3.6	146.0		6¼ - 6½	3.0					
23	3.6	146.0		6½	3.8					
Sep 26	8.5	158.5	60	6½	3.8					
Oct 21	8.0	155.0		6½	3.8					
Nov 26	5	145	70	7.0	9.0	1237.8			140.1	
1949 Jan 27	3.5	152.5		6½	3.8			168.2		
Mar 16	5.4	151.3	60	7.0	9.0					
17	5.4	151.3	60	7.0	9.0					
Aug 13	0.0	146.0		6½	3.8					
Sep 24	6.2	154.8	60	6¾	6.4		168.1			
Oct 19	6.5	153.2	60	7¼	13.9					
31	5.6	153.6	100	6¾	6.4	1290.1				
1950 Jan 13	4.6	153.6		6½	3.8					
Jun 21	3.6	146.0		6¼ - 6½	3.0					
Jul 29	6.5	155.0	100	7.1	10.5		178.6			
Oct 15	9.7	159.6		6½	3.8					
Nov 6	7.2	155.3		7	9.0		187.6			
8	9.7	159.6		7¼	13.9					
Dec 4	5.1	153.5	100	7.2	12.6	1329.0		180.8		
1951 Jan 8	5.0	150.0		6¾ - 7	7.6					
Feb 17	7.1	146.0	180	7.3	15.2				155.3	
Apr 2	6.2	149.1		6½	3.8					
30	8.3	154.0		6½	3.8					
May 21	6.2	154.8	150	7.0	9.0		196.6			
Jul 16	6.0	146.5	100	6½	3.8				159.1	
Aug 2	4.1	154.8	500	6 - 6¼	2.0					
Oct 11	4.5	152.7	60	6.9	7.6			188.4		
Nov 22	5.2	152.4		6 - 6¼	2.0	1383.8		190.4		
1952 May 9	6.5	155.0	50	7	9.0		205.6			
Aug 14	6.5	155.0		6¼	2.2		207.8			
16	7.2	155.3		6½	3.8		211.6			
Nov 6	5.0	145.5		7¼ - 7½	17.4				176.5	
28	6.5	155.5	100	6¾	6.4		218.0			
Dec 6	8.0	157.0		7¼	13.9					
24	5.9	151.2		7	9.0					
24	5.5	151.5		6½	3.8			194.2		
25	5.5	151.5		6½	3.8			198.0		
25	5.5	152.0		6½	3.8			201.8		
25	5.5	151.5		6¼	2.2	1445		204.0		
1953 Jan 7	5.5	150.5		6.3	2.6					
27	4.5	153.0		6 - 6¼	2.0			206.0		
Mar 9	4.5	153.5		6½ - 6¾	5.4			211.4		
Apr 2	5.0	151.5	60	6	1.6			213.0		
23	4.0	154.0		7½ - 7¾	26.8			239.8		
Jun 18	6.5	155.0		6 - 6¼	2.0		220.0			
Jul 6	6.4	147.3		6¼	2.2				178.7	
Aug 25	4.3	152.8		7	9.0			248.8		
Oct 6	3.5	151.0		6½ - 7	6.4					
Dec 4	3½	141½		6¾	6.4	1509.6				112.5
1954 Feb 5	5.0	153.0		6½ - 7	6.4			255.2		
Mar 3	5.5	142.5		6¾ - 7¼	9.0					
19	5	151		6¼ - 6½	3.0					
Jun 7	3.5	152.5	450	6½ - 7	6.4			261.6		
Jul 13	3.0	151.0		6½	3.8					
Dec 4	5.0	152.5		6.2-6.5	3.2			264.8		
21	3.5	145.5		6¼	2.2					
28	4¾	153.0		6½	3.8	1547.4		268.6		
1955 Aug 16	6¼	155	200	6¾ - 7½	13.6		233.6			
Sep 8	7.0	155.5		6½	3.8		237.4			
11	7.0	155.0		6	1.6		239.0			
Oct 9	5.0	153.0		6.4	3.2			271.8		
10	5.5	153.0		7-7.7	19.6	1589.2		291.4		
1956 Jan 28	4.5	151.1		6½	3.8					
31	3¼	152¼	400	7 - 7¼	11.4					
Mar 19	6.0	150.0		6.4	3.2					
Apr 22	5.8	151.0		6	1.6					
May 19	7.0	156.0		5 - 6.4	1.6		240.6			
22	4.0	152.5	550	6.5 - 7	6.4			297.8		
Jun 24	7.0	155.0		5½ - 6¼	1.6		242.2			
Aug 4	5.0	153.0	60	6.5	3.8	1622.6		301.6		
1957 Mar 18	6	152		6¾	6.4					
Apr 20	6	147½		6½	3.8				182.5	
Jul 7	6½	156		6¾	6.4		248.6			
Aug 23	6	154½		6½	3.8		252.4			
Dec 10	6	154½		6½ - 6¾	5.4	1644.6	257.8			
1958 Jan 30	7½	155½		6½	3.8		261.6			
Jun 25	3	144½		6¼ - 6½	3.0					
Oct 7	5	151½		6¼ - 6½	3.0			304.6		
Dec 25	5½	151½		6¾	6.4	1657.0		311.0		
1959 May 7	3	148½		6 - 6¼	2.0					
16	4½	153½	60	6¾	6.4			317.4		
31	6½	155		6 - 6½	2.2		263.8			
Jun 29	7	155½		6 - 6¼	2.0		265.8			
Aug 17	7½	156		7¼	13.9		279.7			
Nov 2	5½	151½	60	6¾	6.4			323.8		
19	5.9	146.3	100	6¾	6.4	1682.4			188.9	
1960 Feb 4	4½	153½		6½ - 6¾	5.4			329.2		
Jun 2	5½	151½		6½ - 6¾	5.4			334.6		
11	9	152½		6½ - 6¾	5.4					
Jul 31	5.6	150.0		6¾	6.4					
Sep 3	6.1	154.5		6½ - 6¾	5.4		285.1			
Nov 24	4.6	153.0	87	6¼	2.2	1712.6		336.8		
1961 Jan 5	4.1	143.0	108	6¾ - 7	7.5					120.0
Mar 15	3.3	150.7	21	6	1.6					
May 7	6.1	154.4	123	6½ - 6¾	5.4		290.5			
Jul 7	5.7	149.7	57	6 - 6¼	2.0					
Aug 1	9.8	160.5	50	6½ - 6¾	5.4					
Sep 20	3.6	150.9	30	6½	3.8					
Oct 26	3.1	147.4	14	6¼	2.2	1735.1				
1962 Jun 18	4.8	151.8	47	6¾	6.4			343.2		
Jul 30	3.3	143.9	25	7	9.0					129.0
Aug 1	3.2	143.7		6¾	6.4	1756.9				135.4
Sep 12	4.4	145.4	32	6	1.6					
Oct 9	3.2	148.2	33	6¼	2.2					
Dec 12	4.8	153.8	94	6¾	6.4					
19	4.7	154.0	98	6	1.6					
27	4.9	145.1	35	6	1.6	1770.2			190.5	

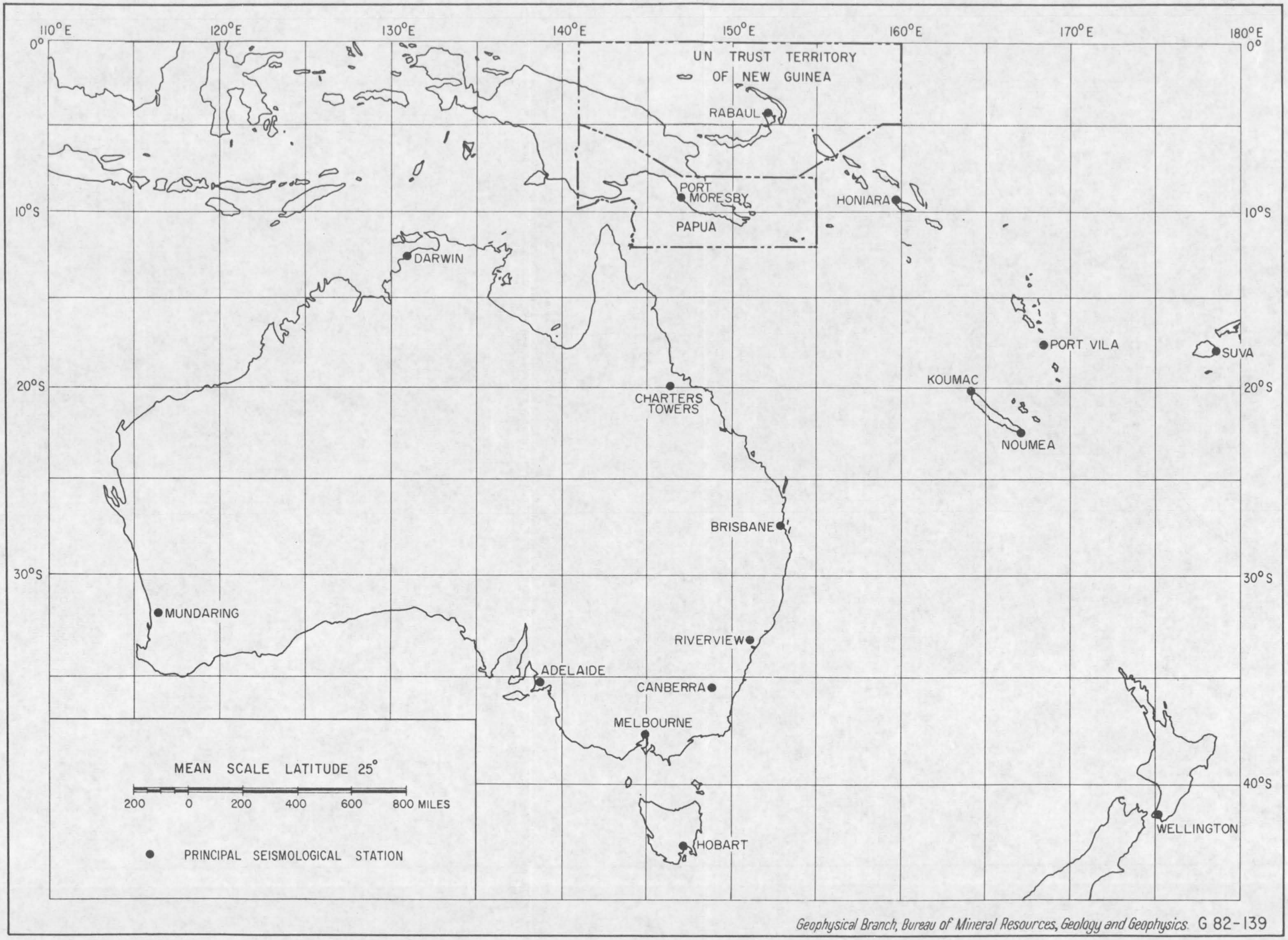
NOTE:

Where discrepancies exist between various data sources, the following order of preference has been observed to select the most reliable data to be listed in the above table.

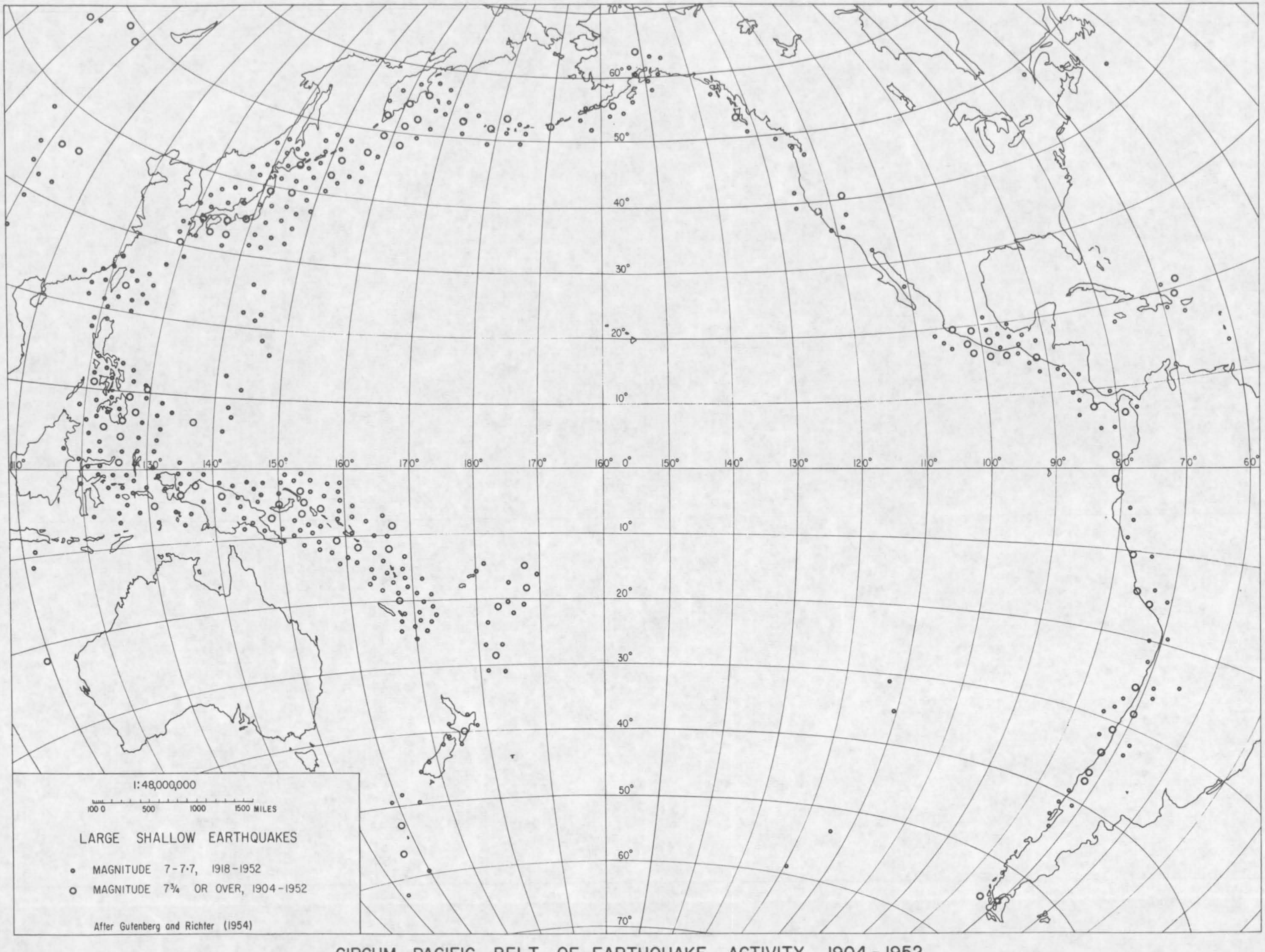
1. 'Seismicity of the Earth' (Gutenberg & Richter, 1954).
2. International Seismological Summary (preferred for epicentres 1945-1952 except 1948 October-December and 1952 October-December which were not available for reference when required).
3. Seismological Bulletin of the International Central Seismological Bureau, Strasbourg.
4. USCGS Preliminary Epicentre Cards.
5. Port Moresby Observatory Seismological Bulletins.

In cases where both epicentre and magnitude have not been listed by a single source, magnitudes have been chosen from alternative sources to keep the entire listing of magnitudes consistent (i.e. determined by the same procedure). Thus the primary source of magnitude ratings, other than "Seismicity of the Earth' has, in general, been the determinations made by the Pasadena Seismological Laboratory. This procedure has been necessary to preserve, as much as possible, the validity of the strain diagrams compiled for long periods of time.

PLATE I

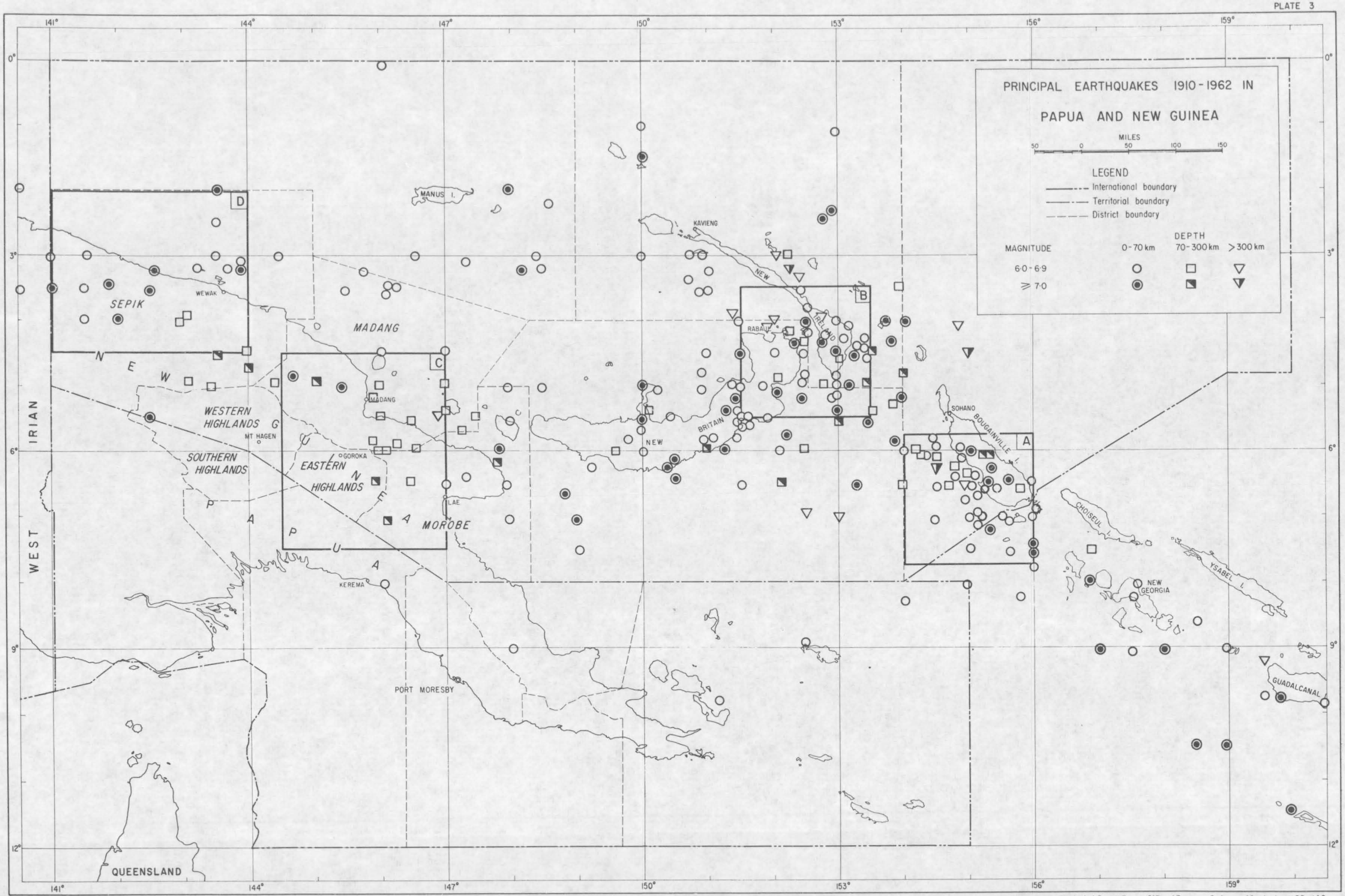


LOCALITY MAP - TERRITORY OF PAPUA AND NEW GUINEA

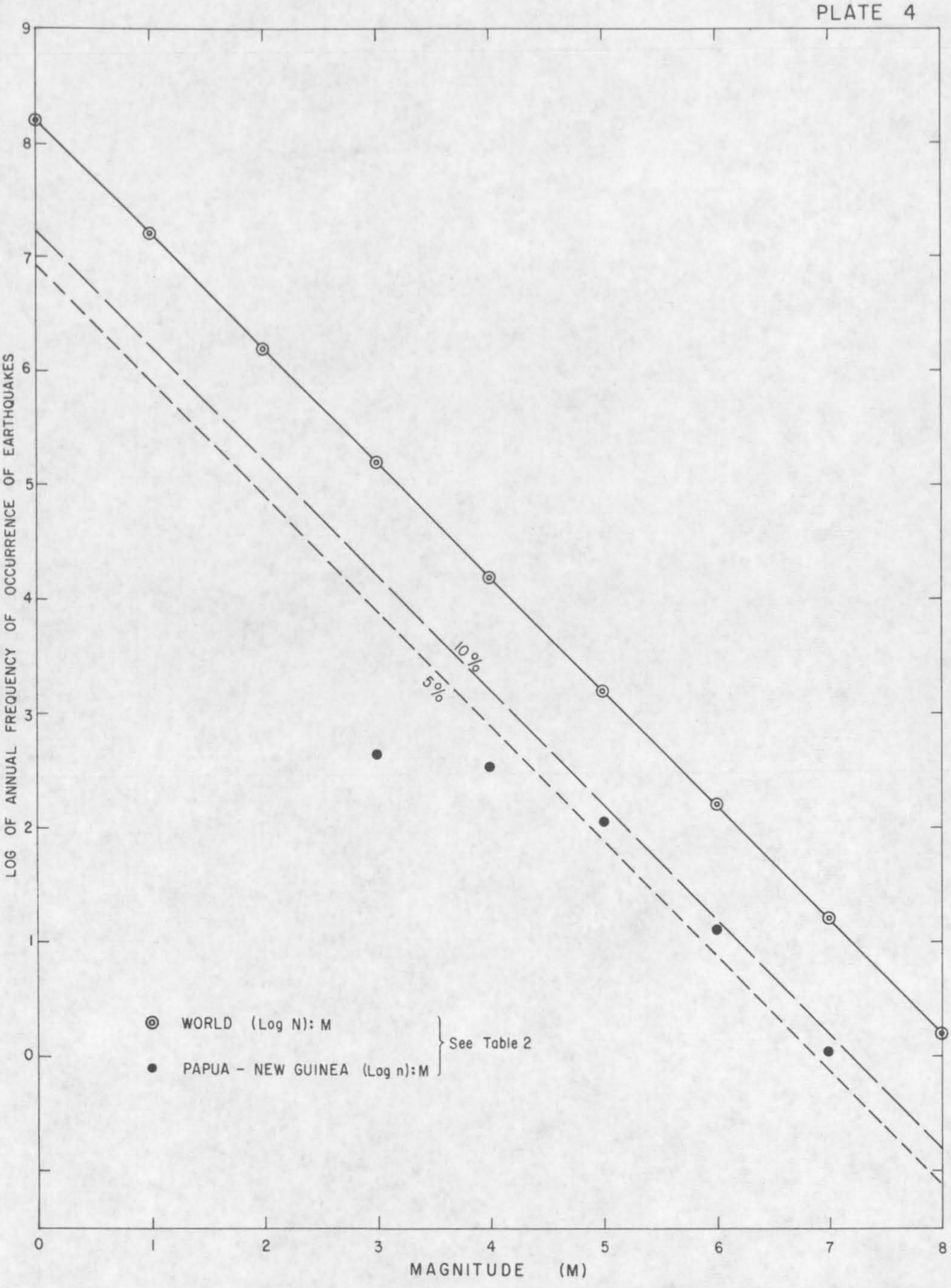


CIRCUM-PACIFIC BELT OF EARTHQUAKE ACTIVITY, 1904-1952

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-141



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-146



MAGNITUDE v. FREQUENCY OF OCCURRENCE

COMPARISON BETWEEN TERRITORY AND WHOLE WORLD

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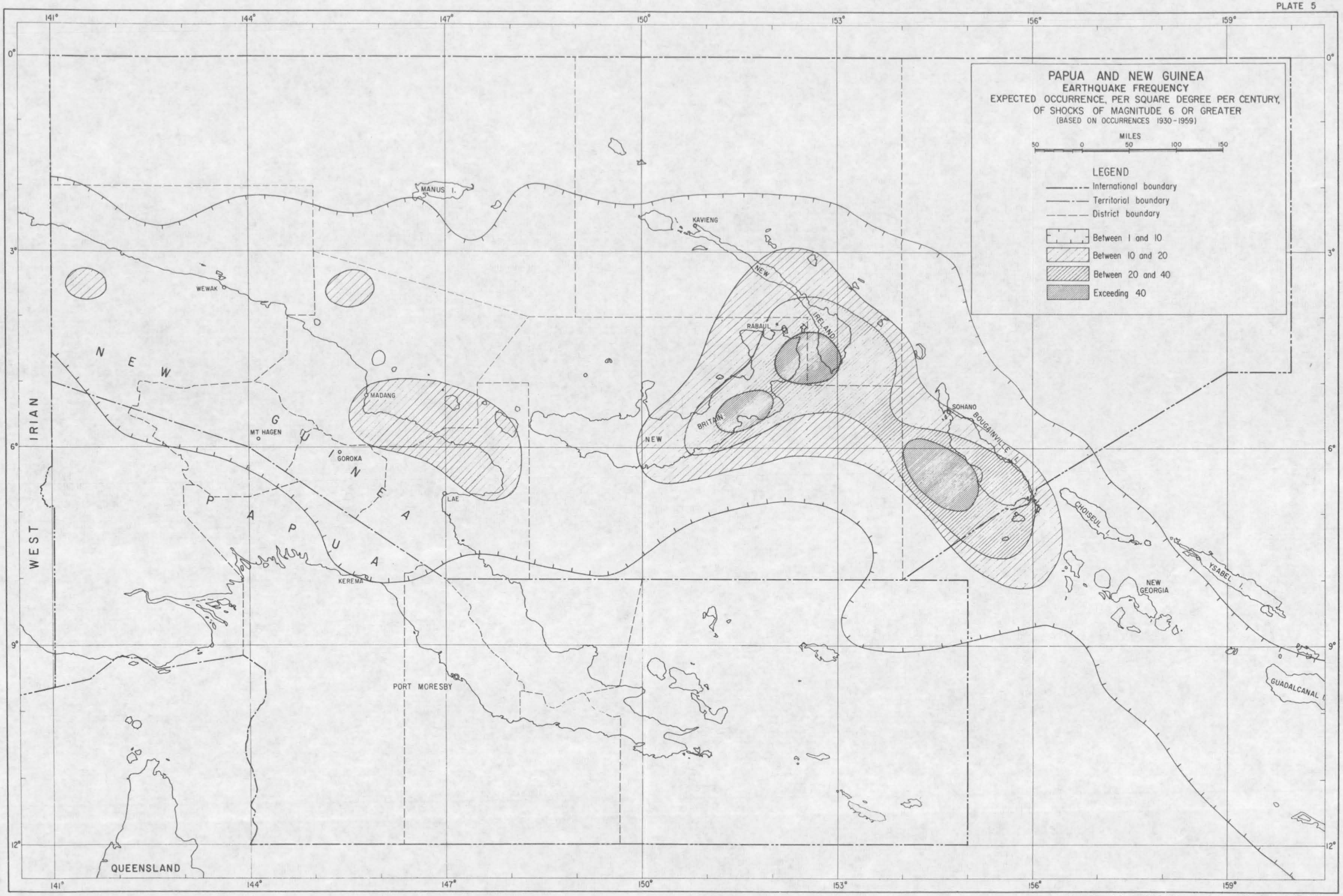
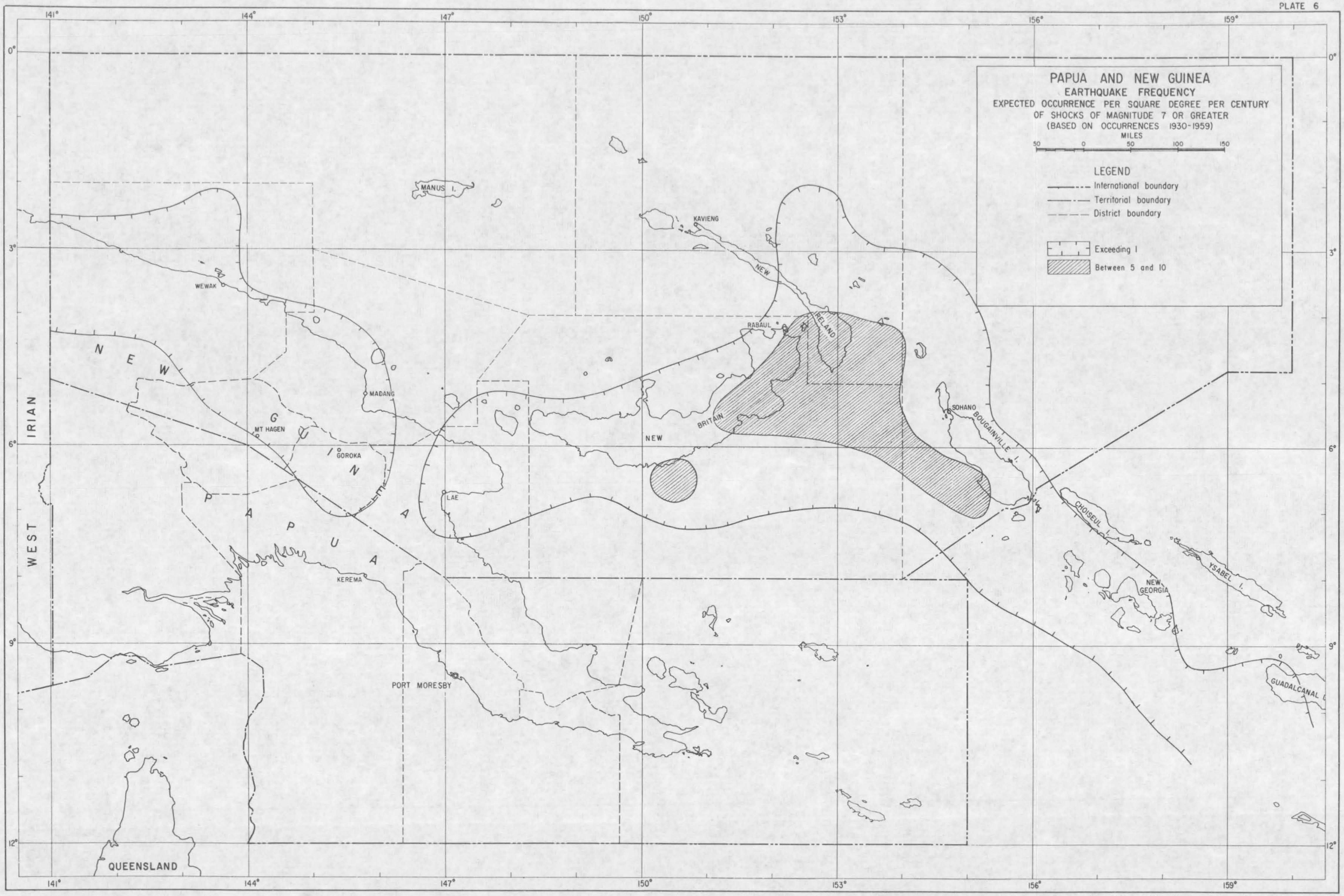
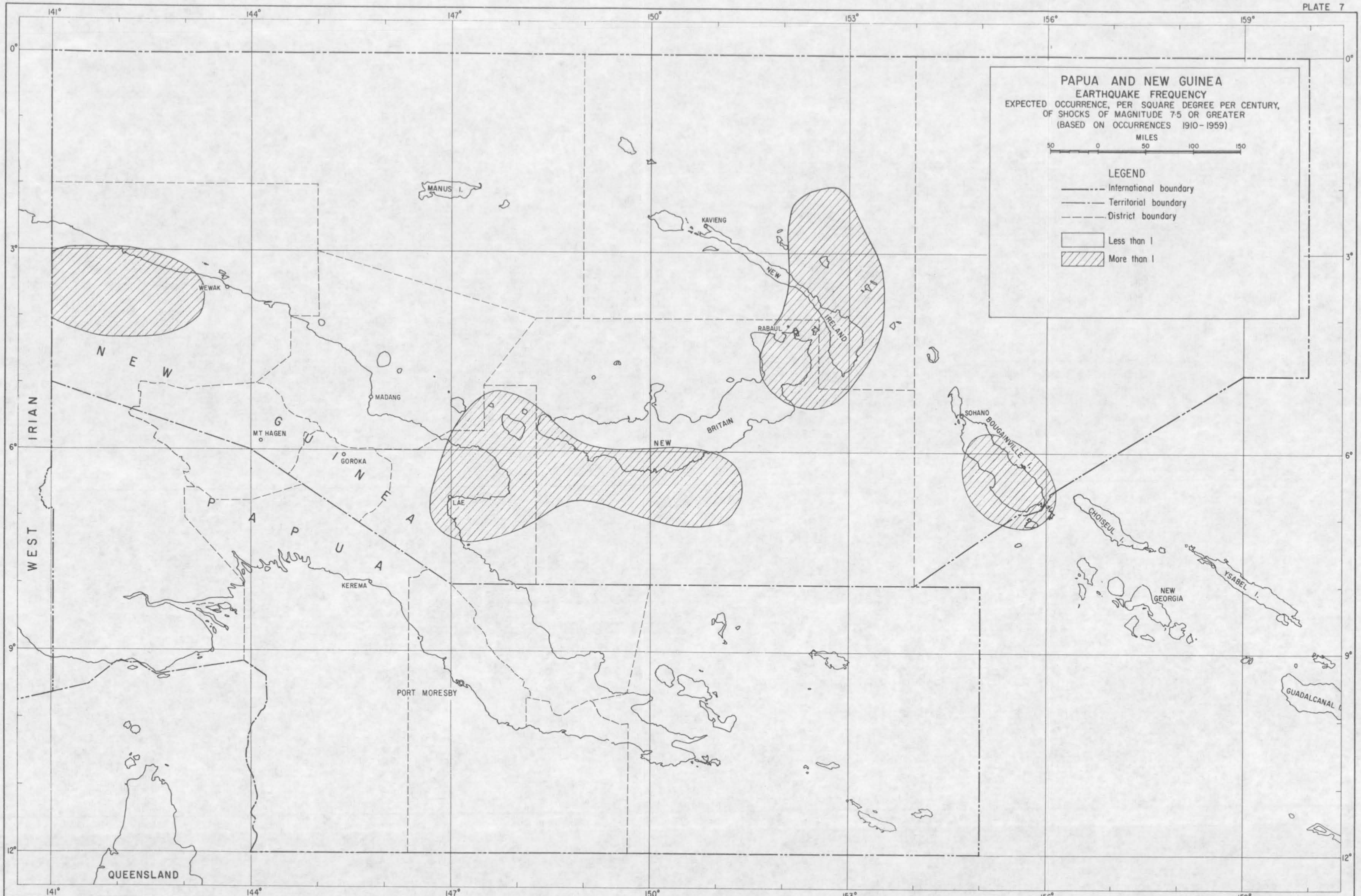


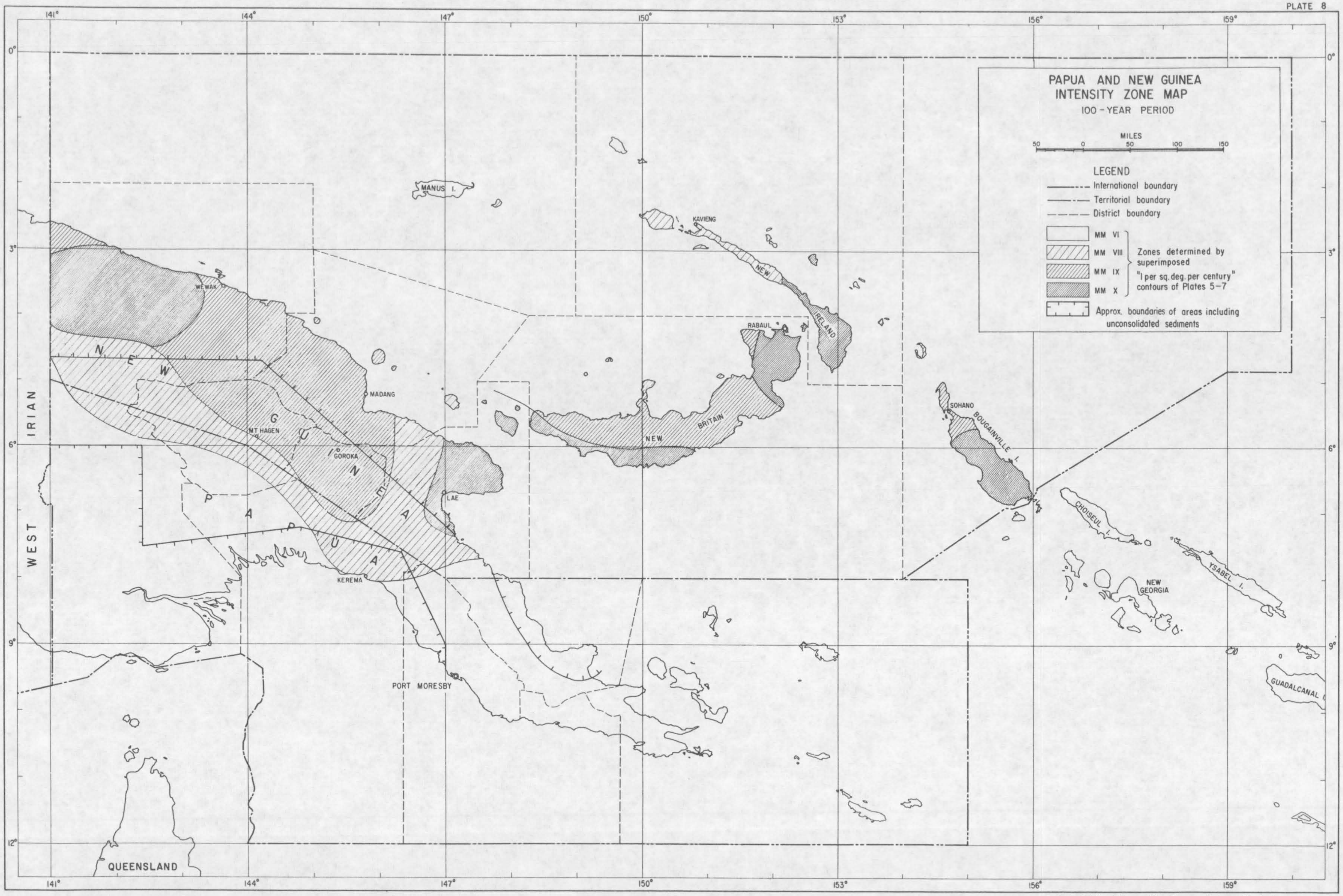
Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-147



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-148



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-149



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G82-150

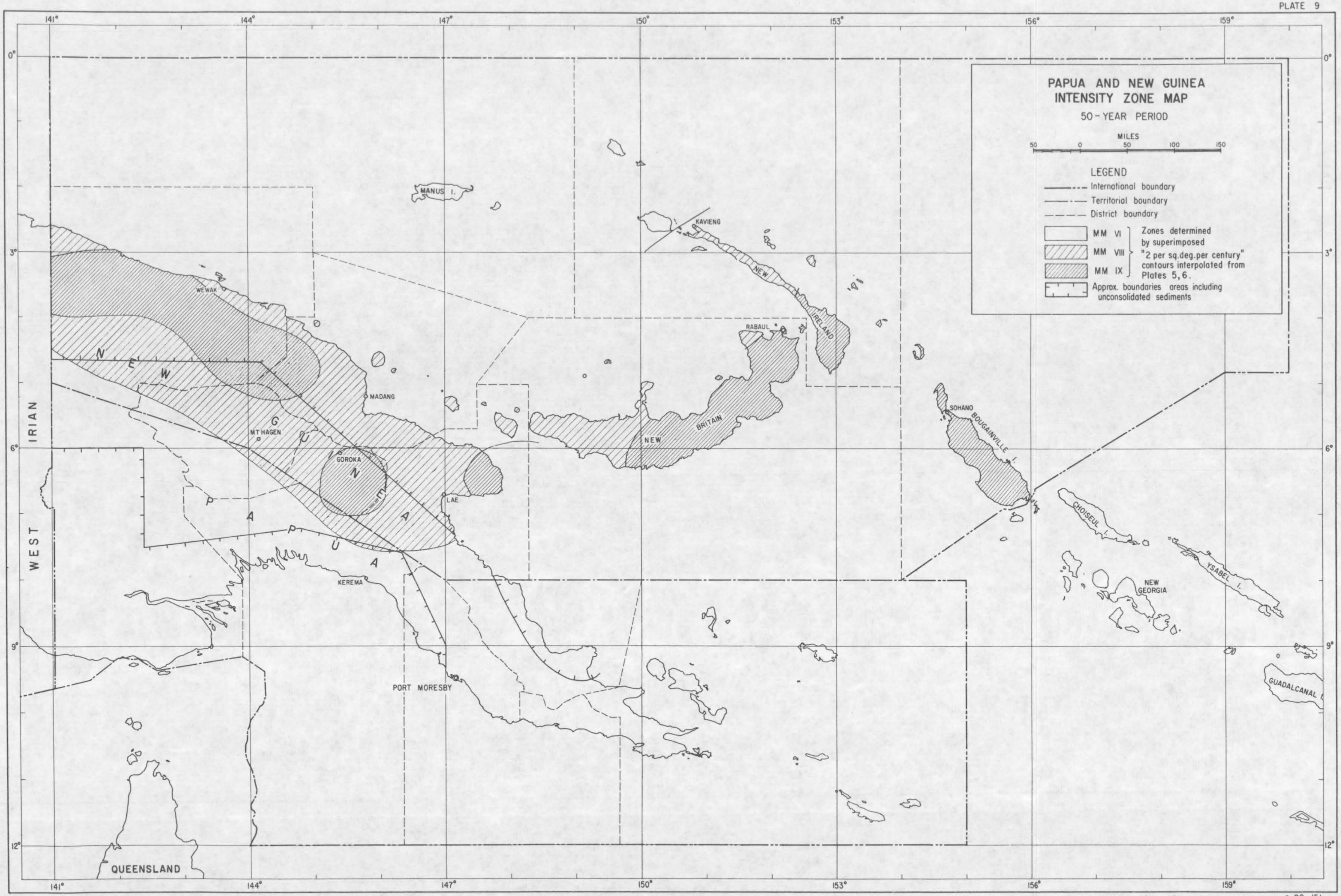


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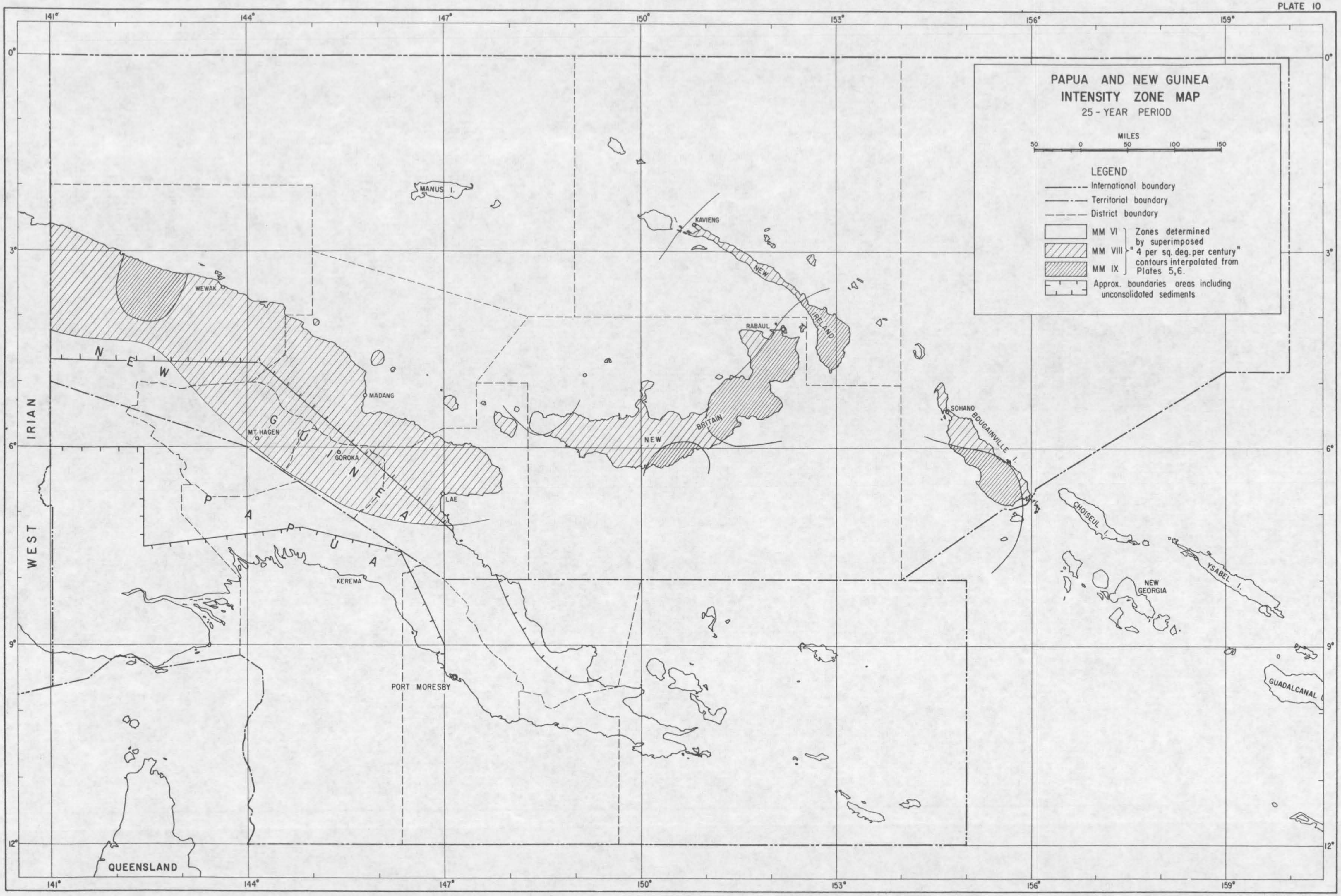
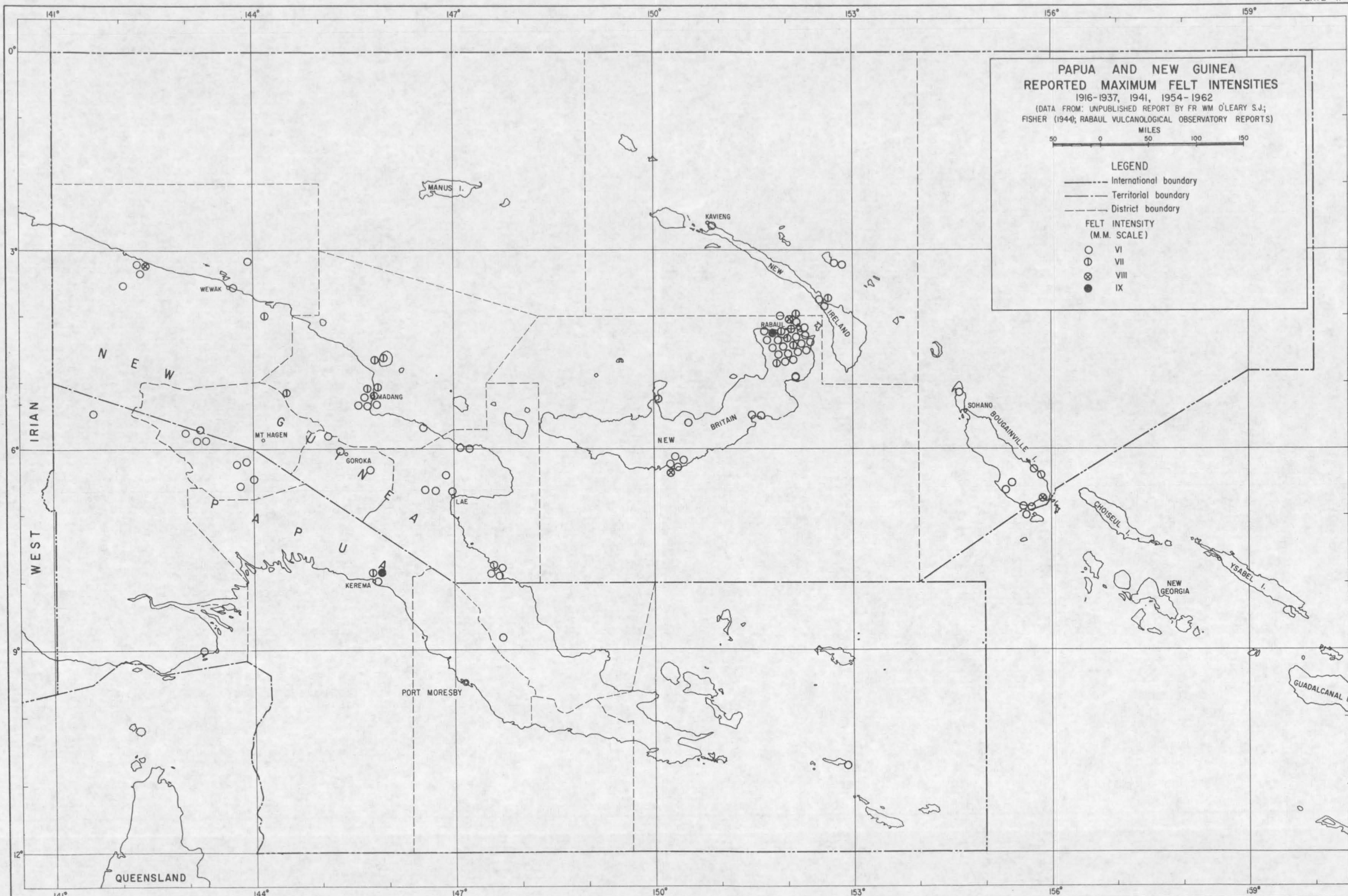
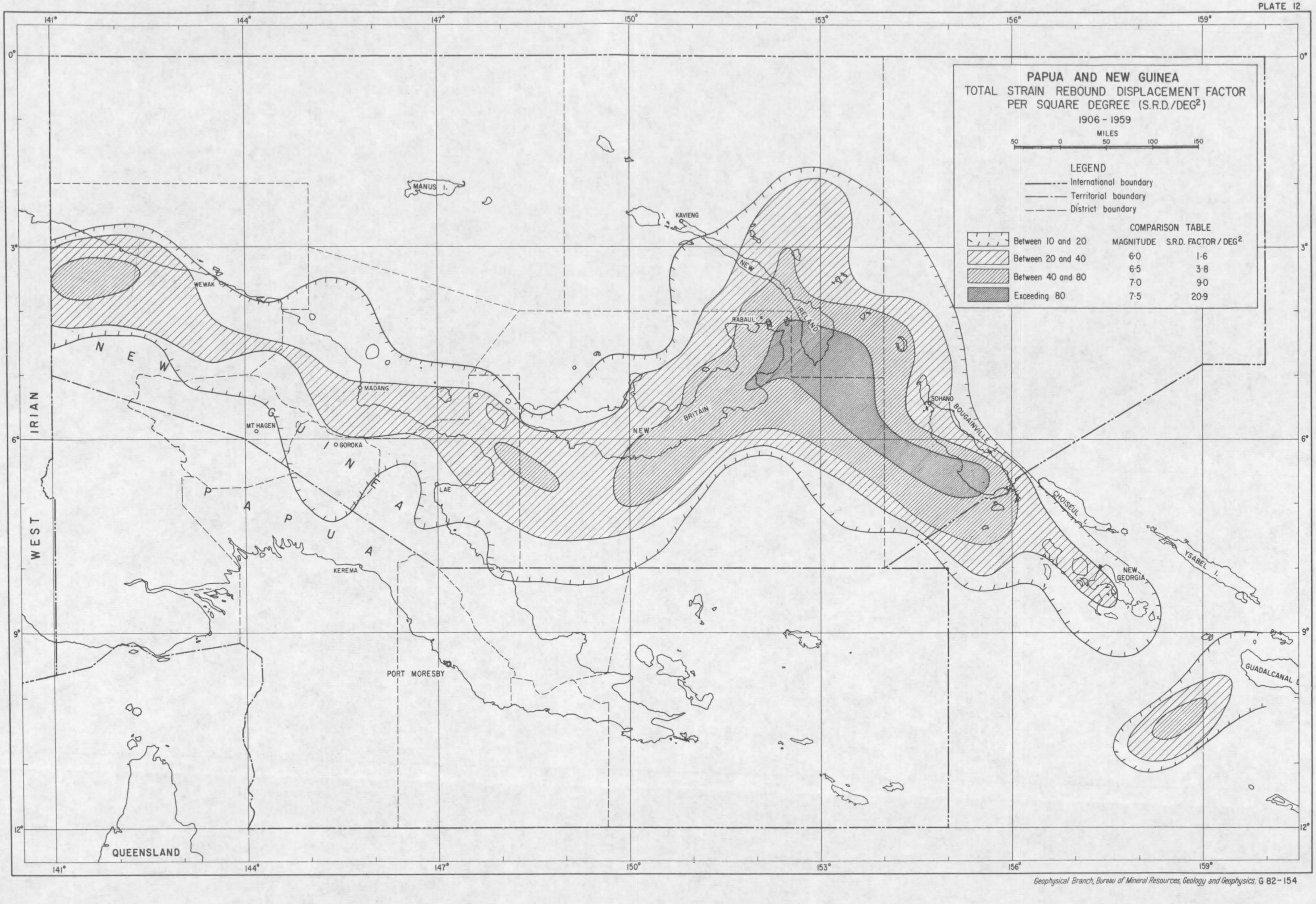
PLATE 10



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 82-152


PAPUA AND NEW GUINEA
REPORTED MAXIMUM FELT INTENSITIES
1916-1937, 1941, 1954-1962
(DATA FROM: UNPUBLISHED REPORT BY FR WM O'LEARY S.J.; FISHER (1944); RABAUL VULCANOLOGICAL OBSERVATORY REPORTS)
MILES
50 0 50 100 150
LEGEND
International boundary
Territorial boundary
District boundary
FELT INTENSITY
(M.M. SCALE)
VI
VII
VIII
IX
141° 144° 147° 150° 153° 156° 159°
0° 3° 6° 9° 12°
MANUS I.
KAVIENG
NEW IRELAND
RABAUL
NEW BRITAIN
SOHANO
BOUGAINVILLE I.
CHOISEUL I.
NEW GEORGIA
YSABEL I.
GUADALCANAL I.
WEWAK
MADANG
MT HAGEN
GOROKA
LAE
KEREMA
PORT MORESBY
NEW GUINEA
PAPUA
WEST IRIAN
QUEENSLAND



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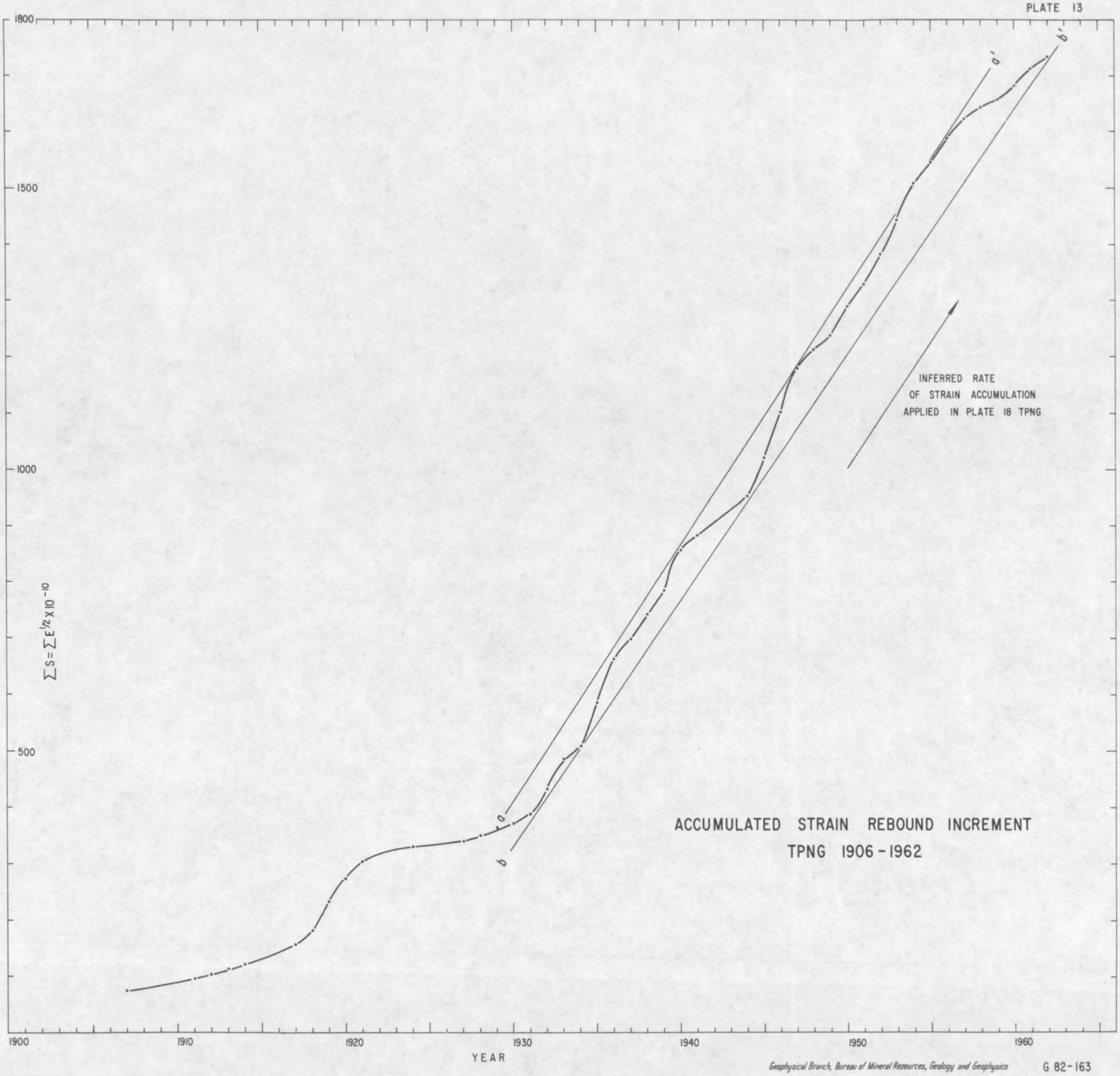

ACCUMULATED STRAIN REBOUND INCREMENT
TPNG 1906 - 1962

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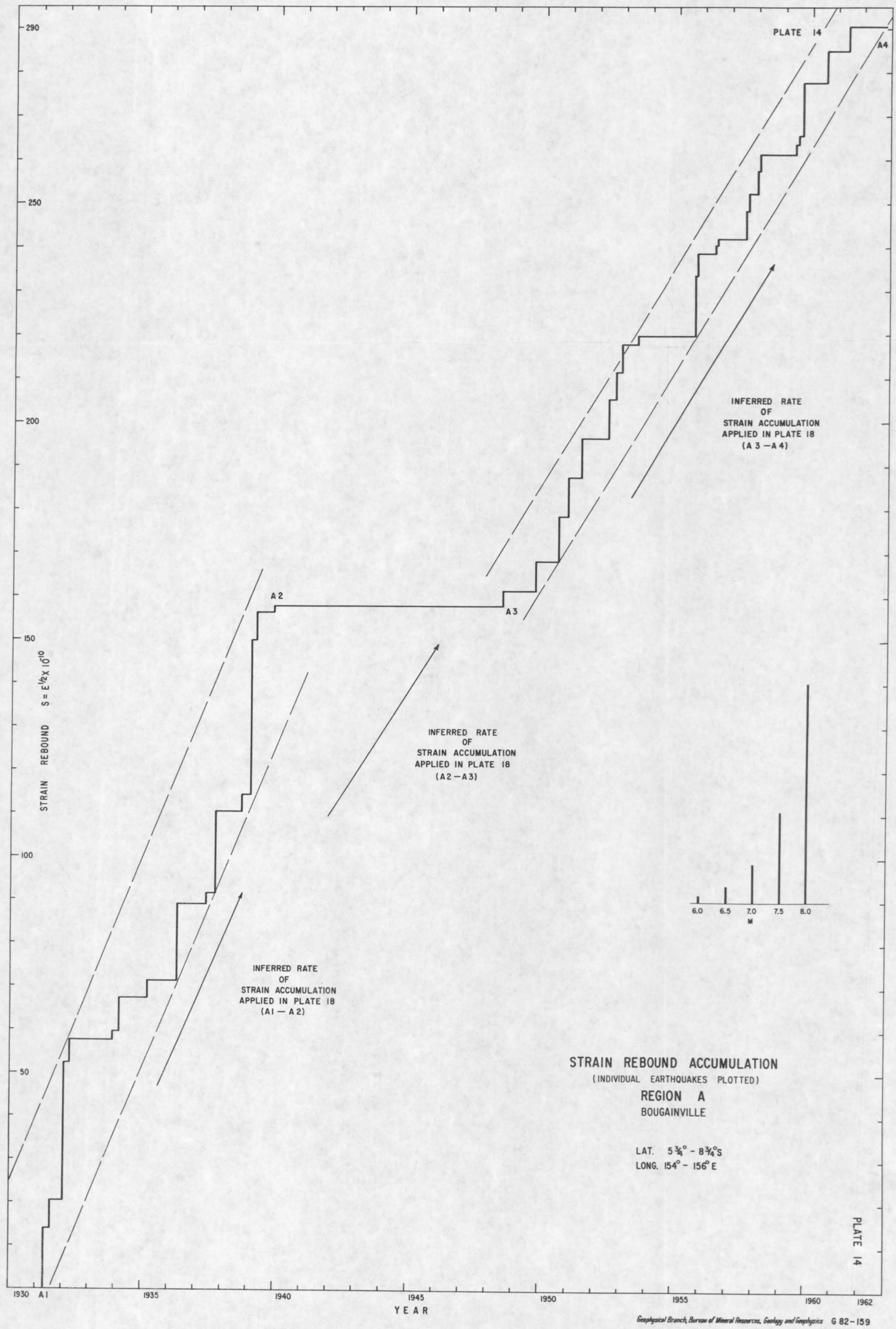
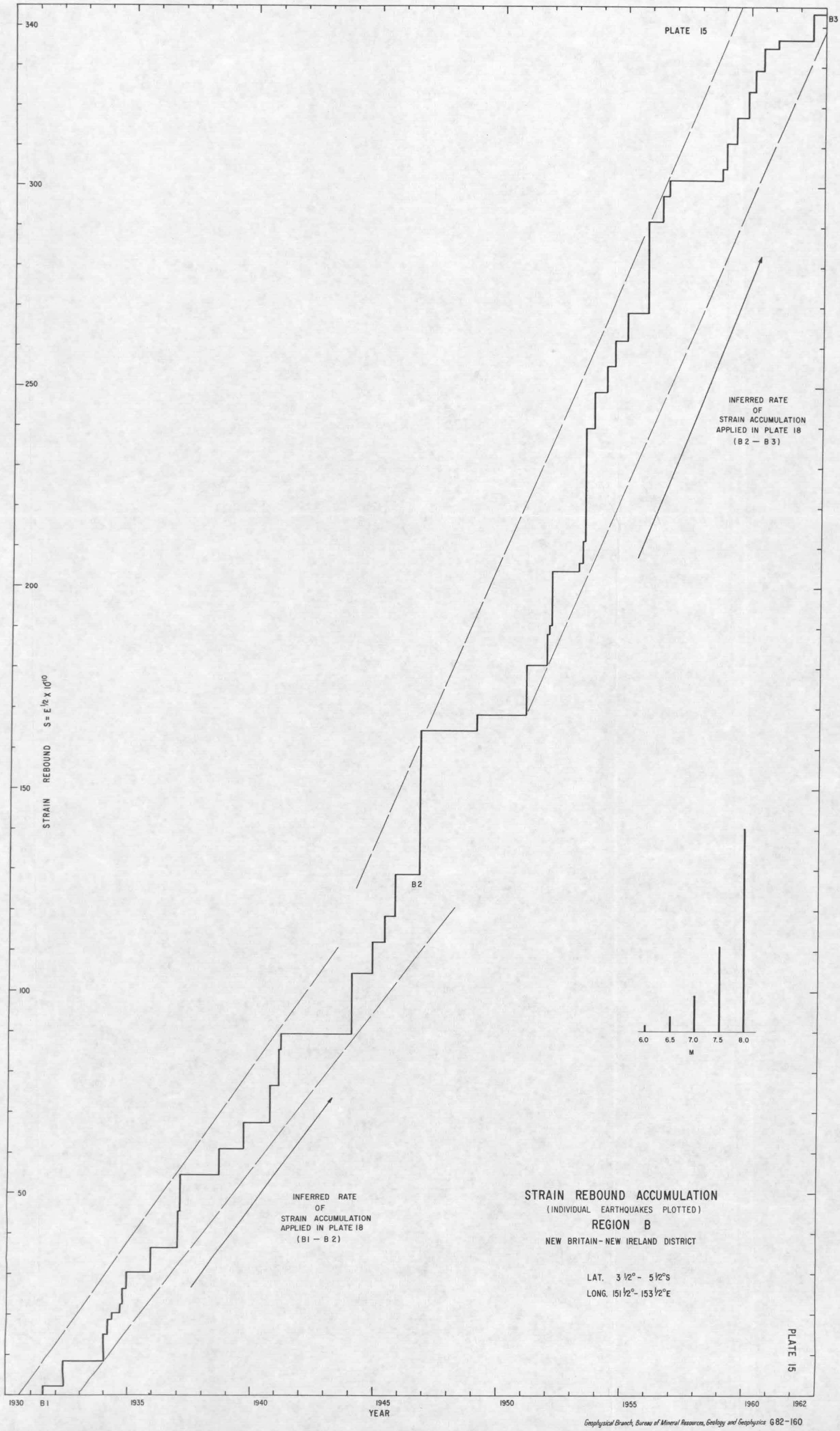
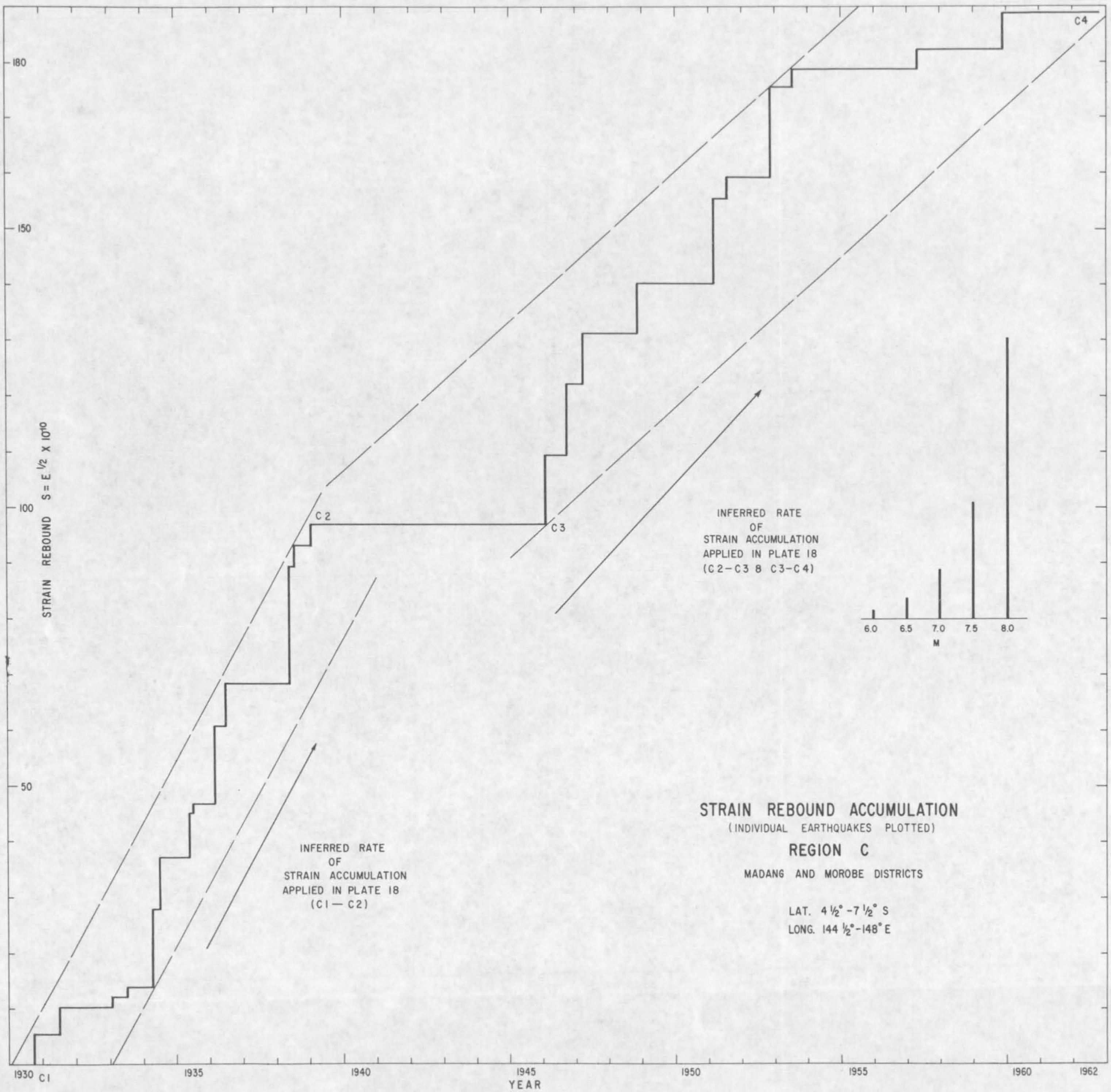


Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics G 82-159



Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics G82-160



STRAIN REBOUND ACCUMULATION

(INDIVIDUAL EARTHQUAKES PLOTTED)

REGION C

MADANG AND MOROBE DISTRICTS

LAT. 4 ½° - 7 ½° S
LONG. 144 ½° - 148° E

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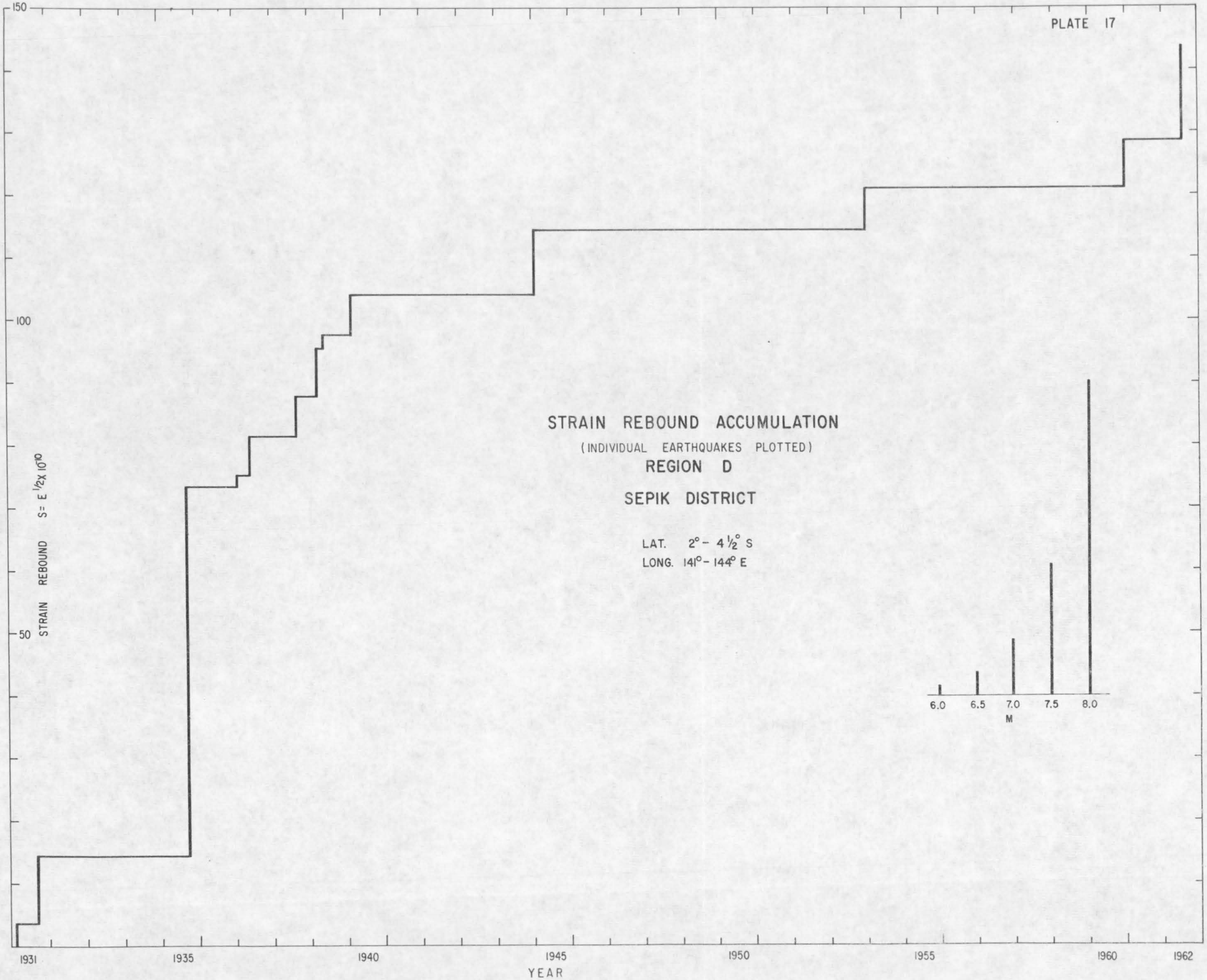

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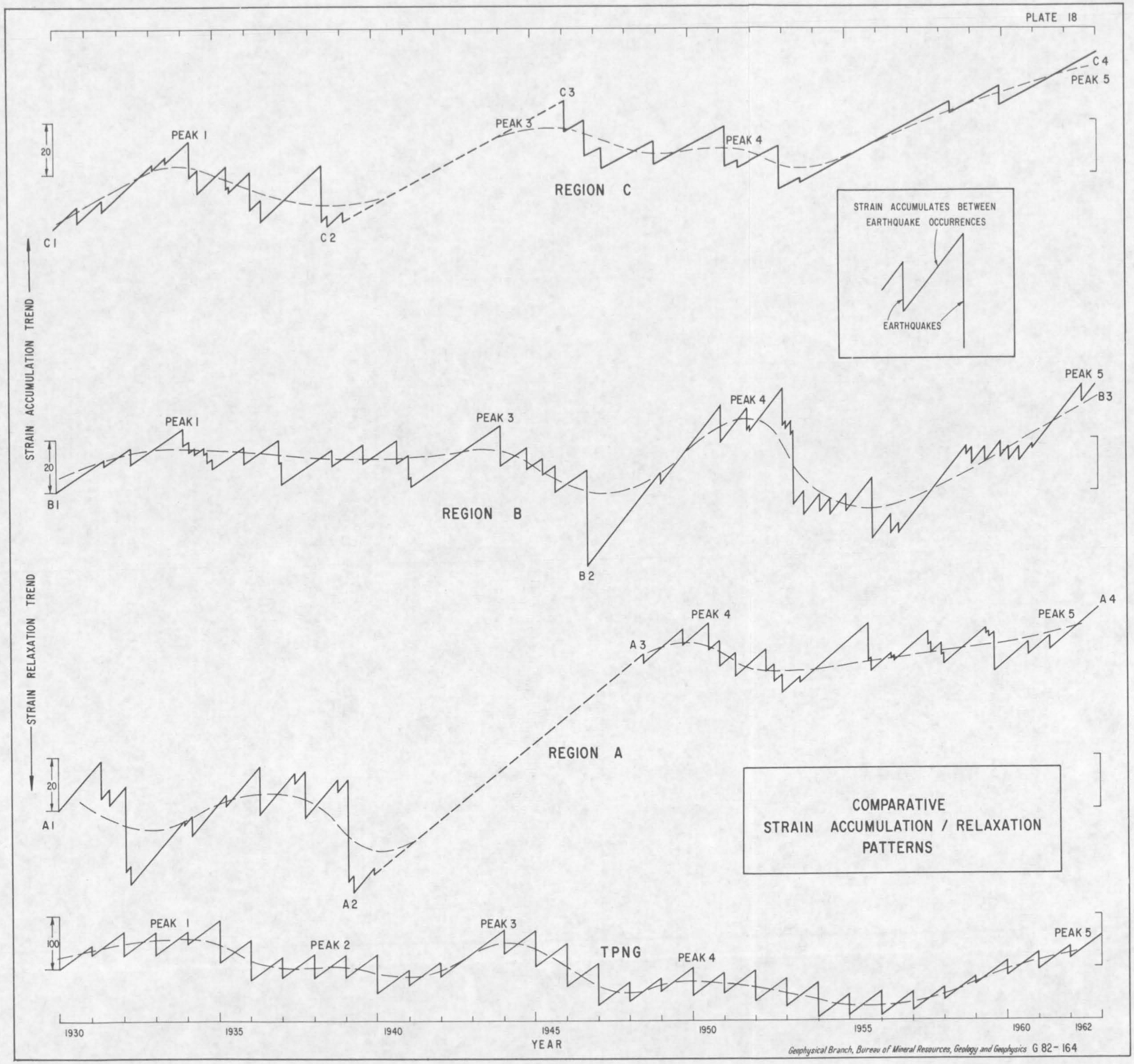

COMPARATIVE STRAIN ACCUMULATION / RELAXATION PATTERNS

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