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Tectonic and Earthquake Risk Zoning*

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Abstract

Quaternary tectonic deformation in New Zealand shows a north-east trend, and this is also shown by historic deformation and earthquakes. A study of Quaternary deformation shows that zones of relative frequency of tectonic movement can be inferred and related to a common median axis. Where tectonic activity is most frequent, destructive earthquakes are expected to be most frequent. Conversely, where tectonic activity is least frequent, destructive earthquakes are expected to be least frequent. With this as a basis, together with a knowledge of the distances to which destructive effects extend from earthquakes of particular magnitudes, zones of earthquake risk are suggested. These are zones of relative frequency of destruction from earthquakes, not of absolute liability to destruction; the boundaries are necessarily somewhat arbitrary as each grades into the next.

Introduction

Though New Zealand is a small country it has not suffered uniformly from past earthquakes. It would be desirable to assess the risk from damaging earthquakes by using an adequately long instrumental record, but systematic instrumental records of large shallow earthquakes cover a period of less than 40 years and extend back only to 1940 for those of magnitude 6 to 6.9. These short-term records provide no justification for detailed seismic zoning in New Zealand, and therefore if the relative frequency of occurrence of major earthquakes in different areas is to be estimated, geological evidence must be used. Most of the historical major earthquakes in New Zealand have been accompanied by measurable tectonic deformation, revealed by warping, tilting or faulting of the earth's surface. Assuming that the present-day geological processes are the key to the past, the geologist infers that earthquakes will have accompanied most of the similar pre-historic deformation shown in the relatively recent geological record, and conversely that major earthquakes will have been rare where there is no measurable deformation. It is not asserted that all surface deformation takes place at times of major earthquakes, or that all major earthquakes are accompanied by surface deformation.

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Given sufficient time, major earthquakes can occur anywhere; but some areas have earthquakes more frequently than others, and some have virtually none. Calculated risks are inherent in any zoning scheme anywhere, and these risks should be assessed in terms of probability of destruction from major earthquakes within a given period of time.

Geological Setting for Late Quaternary Tectonic Movement

In the following discussion various periods of geological time are referred to, and these are listed below. The lengths of time involved are not known exactly but the orders of magnitude are likely to be correct.

Years				
115	Historic	Recent	Late Quaternary	Quaternary
20,000				
500,000				
3 to 5 x 10^6			Early Quaternary	
				Pliocene
11 x 10^6				
				Miocene

The most seismically active regions of the earth are in belts of late Tertiary and Quaternary deformation, and one of these belts runs through New Zealand. The tectonic activity of which the present day earthquakes are a manifestation is not a new phase, but continues from the geologic past.

Pliocene and Early Quaternary sediments were originally deposited almost horizontally and the present dips (angles of slope) of their bedding planes register the sum of the tectonic movements since deposition. Figure 1, on which the dips are shown, indicates the long term tectonic setting in which the Late Quaternary deformation has taken place. This figure shows angles of dips, averaged where many observations are available, of Early Quaternary and Pliocene beds, and is compiled from New Zealand Geological Survey records.

The absence of observations in substantial areas of Figure 1 results from the absence of preserved Pliocene and Early Quaternary deposits that would have registered deformation within those areas. The only one of these which can be reasonably inferred not to have suffered deformation in the Pliocene and Early Quaternary is North Auckland. North of where observations are recorded on Fig. 1, strata even older than Pliocene are not deformed. Thus, two broad Quaternary tectonic regions can be distinguished:

(a) The North Auckland Peninsula. This region has not experienced measurable deformation since the Miocene, and apart from local volcanic activity, appears to have been substantially stable during the Quaternary.

(b) The "Quaternary Tectonic Zone". This comprises the remainder of the country. Its north-west limit can be fairly closely defined from the mouth of the Waikato River through the Hauraki Gulf, but the south-east limit lies beyond the New Zealand coast.

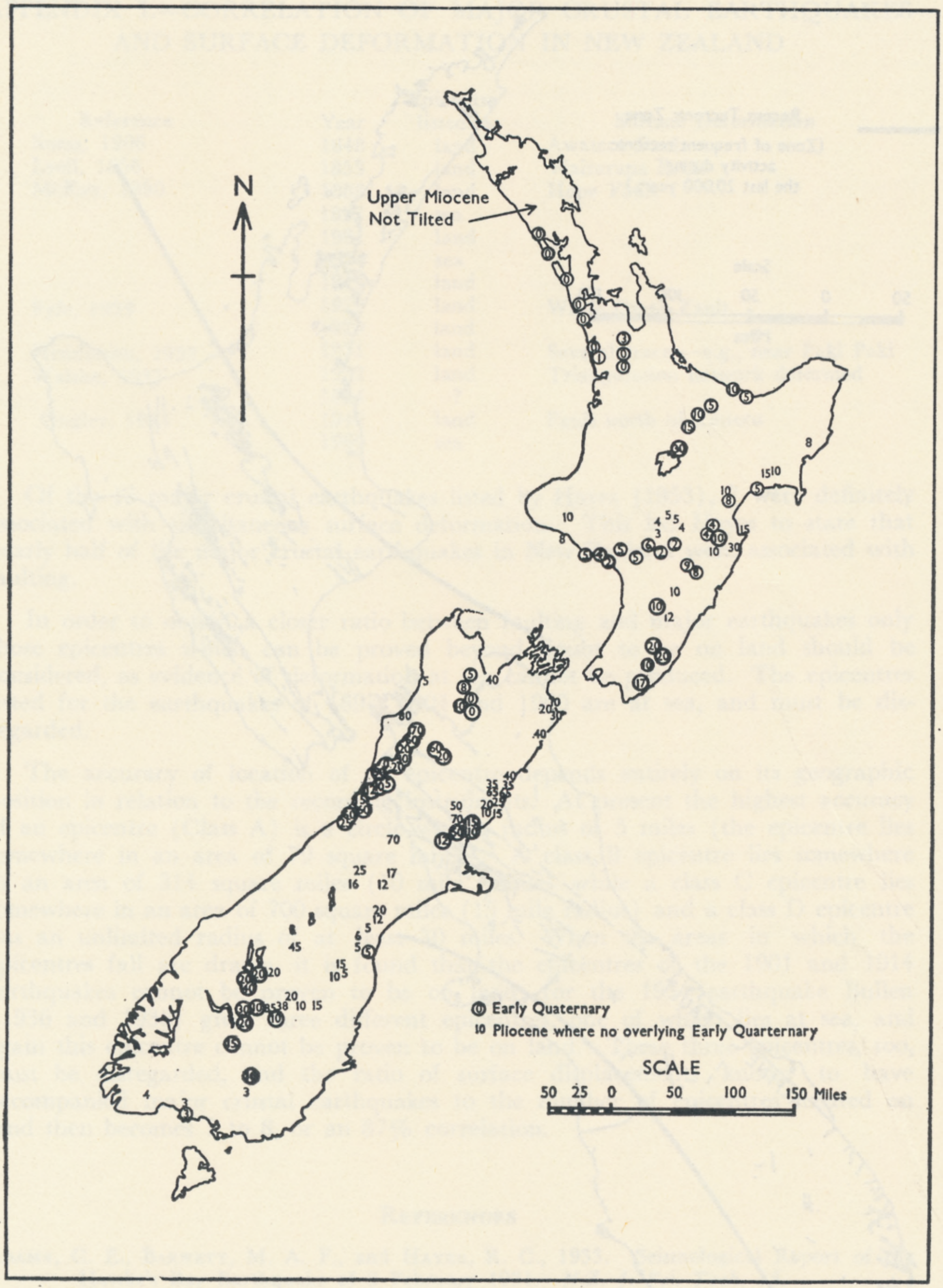

FIG. 1.—Dip Angles on Early Quaternary and Pliocene Beds.

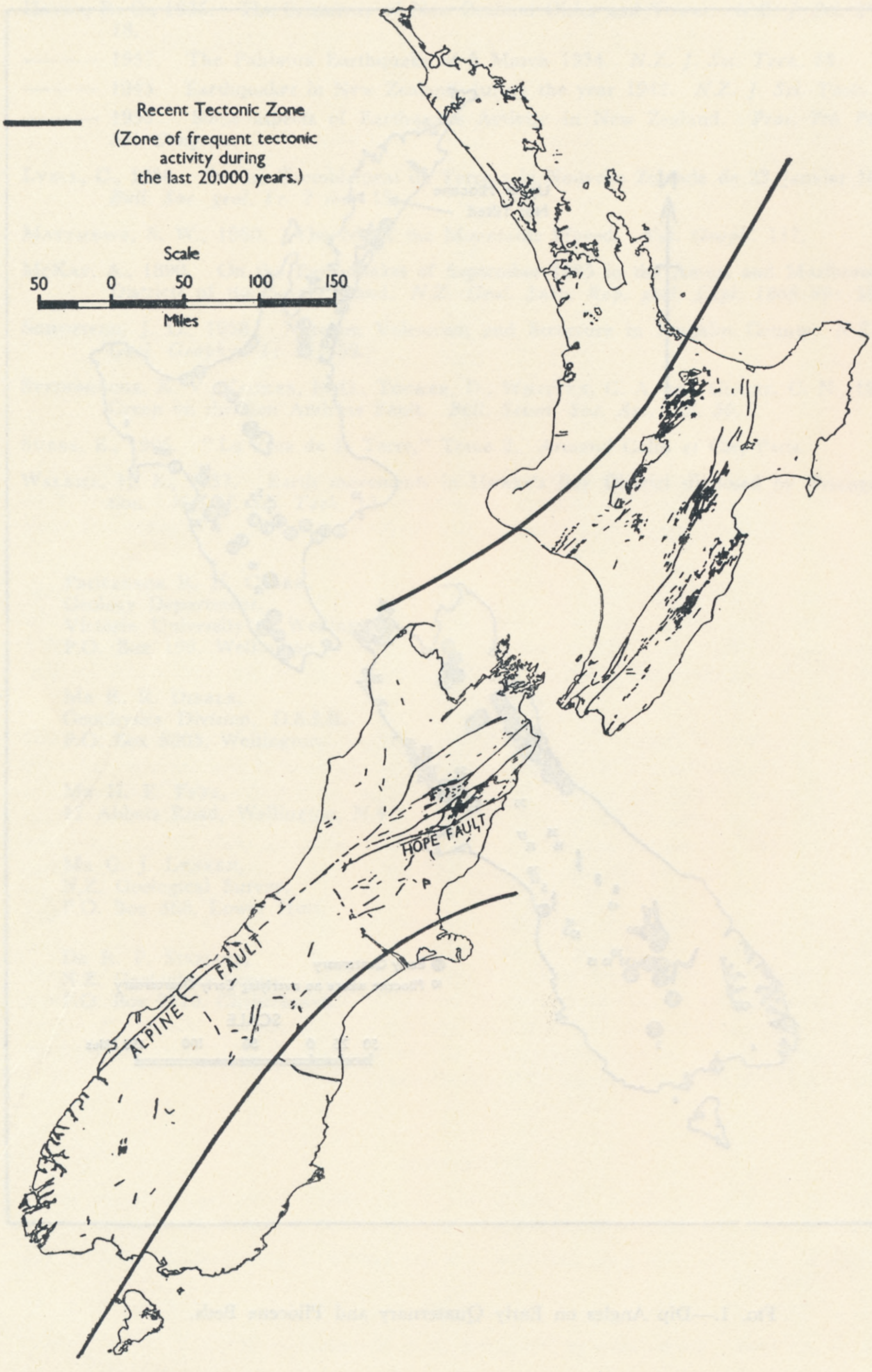

Fig. 2.—Late Quaternary (mainly Recent) Fault Traces.

LATE QUATERNARY TECTONIC DEFORMATION

The principal evidence of Late Quaternary deformation is provided by fault traces on Late Quaternary deposits or topographic features no older than Late Quaternary. These fault traces are shown in Figure 2, compiled by G. J. Lensen from published and unpublished data. To illustrate all that are known, the lengths of some short traces have been exaggerated diagrammatically.

The coverage of the country cannot be perfectly uniform from area to area; fault traces can be easily seen in open country but not in bush country; not all the country is covered by aerial photographs, nor has every photograph been examined. The four-mile mapping programme of the N.Z. Geological Survey has, however, now largely covered the country, and field work and air photograph study have been an essential part of this programme. It is confidently believed that the relative densities of fault traces from region to region will not be significantly changed by further work.

There are two main groups of fault traces. The first covers the central volcanic district and extends south-west to include the set of traces in the Wanganui region. The second group comprises the major transcurrent faults (faults with dominantly horizontal movement) and a great number of minor traces. The greatest of the transcurrent faults is the Alpine Fault, which is active at points along its full length from the Wairau River to Milford Sound and probably further south-westwards just off the Fiordland coast.

The first group differs from the second in that the faulting is dominantly tensional instead of dominantly transcurrent. The tectonic setting of this group is one of tension and volcanic activity; that of the second is one of horizontal shear. Both groups, in different tectonic settings, are adjacent, and show that even a country as small as New Zealand cannot be regarded as a single entity from a tectonic—and hence seismic—point of view.

One consequence of the contrast in tectonic settings is that surface displacement can occur with lower magnitude earthquakes in the tensional region. Thus surface faulting accompanied the Taupo (1922) earthquake of magnitude less than 6, while in the shear region surface faulting is not known to have occurred during earthquakes of magnitudes less than 7. [Magnitude (M), which indicates the amount of energy released at the focus of an earthquake, is distinct from the felt intensity at any particular place, which is measured on the Modified Mercalli (MM) scale.]

In the South Island, comparatively few Late Quaternary fault traces are known north-west of the Alpine Fault, but warping and tilting of Late Quaternary surfaces indicate that several of the major folded structures of north Westland and southern Nelson are active. Although no traces are known from the Grey River to the Cascade River in Westland, elevated marine shorelines show that this part of the region west of the Alpine Fault is also unstable. South and east of the Alpine and Hope faults over 90 per cent of the fault traces lie within 80 miles of these faults. South-east of this 80-mile belt only the trace on the Akatore Fault, south-west of Dunedin, is definitely Recent. Other traces in South Canterbury and North Otago are late Quaternary in age but not Recent.

In the North Island, north-west of the central volcanic district, only a few traces are known, the furthest north-west being those at Bombay, south of Auckland (Schofield, 1958) which are almost certainly associated with local volcanic activity. In the lower Mokau River two parallel traces are the only Recent ones known west of the central volcanic district.

The absence of fault traces in the Gisborne region is striking, particularly as it lies along the north-east trend of the main belt of East Coast deformation. The whole of this belt is tectonically active; judging by terraces, warping in late Quaternary times has taken place, and possibly warping rather than faulting characterises Quaternary deformation in the Gisborne region, as is also the case in parts of California (Matthews, 1960, photo). Factors militating against the formation and preservation of fault traces are considerable thicknesses of intensity fractured and incompetent upper Cretaceous and lower Tertiary beds, and in the southern part of the region a thick sequence of relatively unconsolidated upper Tertiary sediments.

By far the majority of fault traces shown on Fig. 2 are of Recent age, and a "Recent Tectonic Zone"—the zone of frequent tectonic deformation in the last 20,000 years—can be defined on the basis of the distribution of these traces. The Akatore and Mokau traces lie far from the Recent Tectonic Zone, but within the Quaternary Tectonic Zone based on Fig. 1. Thus tectonic deformation has not ceased in that part of the Quaternary Tectonic Zone that lies outside the Recent Tectonic Zone, and the rarity of fault traces there is merely an indication of the rarity of deformation. This emphasises that subdivision of New Zealand in terms of tectonic deformation and of risk of major earthquakes must be based on relative frequency of deformation.

Historic Tectonic Deformation and Earthquakes

Both in New Zealand and overseas, most measured historic surface displacements of the order of feet have been indisputably associated with destructive shallow earthquakes, of magnitude 7 or greater, rarely less except in tensional regions.

In the New Zealand area there have been fourteen shallow earthquakes since 1848, of M7 or greater, and surface displacement during at least seven of them (Fig. 3). Making allowance for the uncertainty of position of many of the epicentres, particularly the older ones, for the three epicentres definitely given as at sea, and for the six epicentres possibly at sea because of low confidence of location, at least 80 per cent of destructive earthquakes were accompanied by surface tectonic deformation (Appendix 1). The deformation comprises surface faulting, warping, tilting and regional changes in level.

Of the instances of historic surface deformation since 1848, six are of faulting accompanied by changes in level, and the seventh, Wairoa, of horizontal movements established by re-triangulation.

The historic deformation and major earthquakes serve to define a "Historic Tectonic Zone".

In California, two instances of "creep" along faults have been recorded, one on the San Andreas Fault (Steinbrugge, *et. al.*, 1960). This creep has been accompanied by only minor earthquakes, the larger ones of which were associated with the larger of the individual small sudden fault movements. Records of such creep are rare in comparison with those of sudden large movements accompanying major earthquakes. No creep has been established on any New Zealand fault, although it cannot be ruled out as a factor producing some fault displacements. It seems improbable that creep at faults amounting to more than a fraction of the known sudden displacements could have gone unrecorded. As in historic times, so in earlier times, faulting was dominant over creep, as is shown by the abruptness and freshness of the fault scarps cutting Recent deposits and recording successive movements.

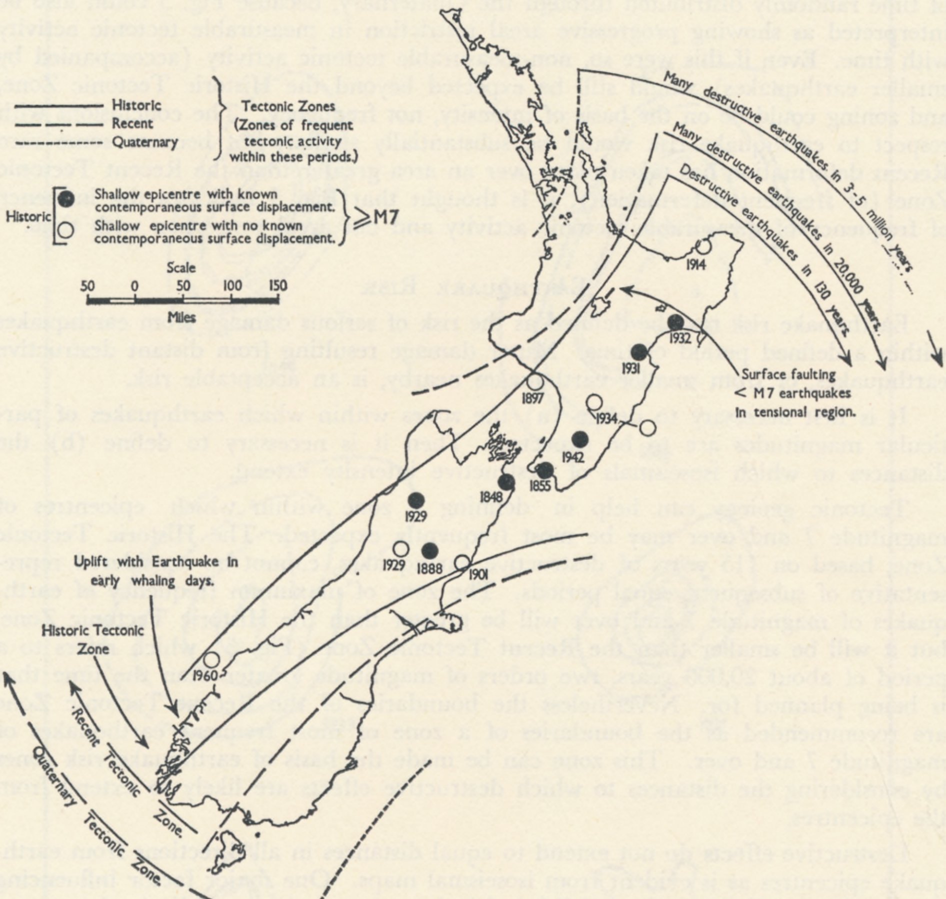

FIG. 3.—Historic Major Earthquakes and Tectonic Zones. Epicentral data supplied by Seismological Observatory.

THE SUCCESSIVE TECTONIC ZONES

The Quaternary Tectonic Zone, that is the zone of measured Quaternary tectonic deformation based on Fig. 1, refers to a period of several million years. If the frequency of deformation varies from area to area within this zone, then the areas prone to more frequent deformation should show as areas within this zone when deformation that has taken place over shorter time spans is considered. The north-east trend of the Historic Tectonic Zone (Fig. 3), shown also in the distribution of late Quaternary fault displacements (Fig. 2), is consistent with the trend showing in Quaternary deformation indicated by the geological structure of the country. This structural trend is the basis for inferring the trend of the Quaternary Tectonic Zone and for inferring a common median axis for the three successive zones shown in Fig. 3.

The progressive restriction of zones with decreasing time is consistent with a maximum frequency of deformation at a median axis, decreasing outwards. Nevertheless it would have been desirable to illustrate this from different periods of time randomly distributed through the Quaternary, because Fig. 3 could also be interpreted as showing progressive areal restriction in measurable tectonic activity with time. Even if this were so, non-measurable tectonic activity (accompanied by smaller earthquakes) would still be expected beyond the Historic Tectonic Zone, and zoning could be on the basis of intensity, not frequency. The conclusions with respect to earthquake risk would be substantially similar, but because some rare Recent deformation has taken place over an area greater than the Recent Tectonic Zone (of frequent deformation), it is thought that Fig. 3 indicates the influence of frequency of measurable tectonic activity and not areal restriction with time.

Earthquake Risk

Earthquake risk may be defined as the risk of serious damage from earthquakes within a defined period of time. Minor damage resulting from distant destructive earthquakes, or from smaller earthquakes nearby, is an acceptable risk.

It is first necessary to define (a) the zones within which earthquakes of particular magnitudes are to be expected. Then it is necessary to define (b) the distances to which isoseismals of destructive intensity extend.

Tectonic geology can help in defining a zone within which epicentres of magnitude 7 and over may be most frequently expected. The Historic Tectonic Zone, based on 115 years of destructive earthquakes, cannot be considered representative of subsequent equal periods. The zone of maximum frequency of earthquakes of magnitude 7 and over will be greater than the Historic Tectonic Zone, but it will be smaller than the Recent Tectonic Zone (Fig. 3) which refers to a period of about 20,000 years, two orders of magnitude greater than the time that is being planned for. Nevertheless the boundaries of the Recent Tectonic Zone are recommended as the boundaries of a zone of most frequent earthquakes of magnitude 7 and over. This zone can be made the basis of earthquake risk zones by considering the distances to which destructive effects are likely to extend from the epicentres.

Destructive effects do not extend to equal distances in all directions from earthquake epicentres as is evident from isoseismal maps. One major factor influencing the incidence of destruction (MM 8 felt intensity, and greater*) is the nature of the ground at the place from which reports are received. The influence of ground conditions on the isoseismals is evident, for example, from the values at Blenheim in the isoseismal maps of the 1929 and 1931 earthquakes; Blenheim lies predominantly on young Post-glacial thick alluvium. In 1929 a value of MM 7 contrasts with MM 5-6 a few miles to the south; in 1931 a value of MM 5-6 contrasts with MM 3-4 a few miles to the north. Thus isoseismals locally reflect bad ground conditions for which additional allowance in assessing risk is essential.

A second major factor causing asymmetry in isoseismals is regional trends of geological structure, as is broadly shown by the available isoseismals for major historic earthquakes (Fig. 4). The north-east axes of the isoseismals are greater than the north-west axes, as is to be expected from the regional structural trends which are north-east in the region within which the historic earthquakes fall. In the Auckland peninsula and in Otago and Southland, the trends are north-west, and their influence should be allowed for.

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* With MM 7 earthquakes there is negligible damage to well-designed and constructed buildings; some chimneys are broken. With MM 8 earthquakes damage is considerable to ordinary substantial buildings, with partial collapse, but is slight to specially designed structures.

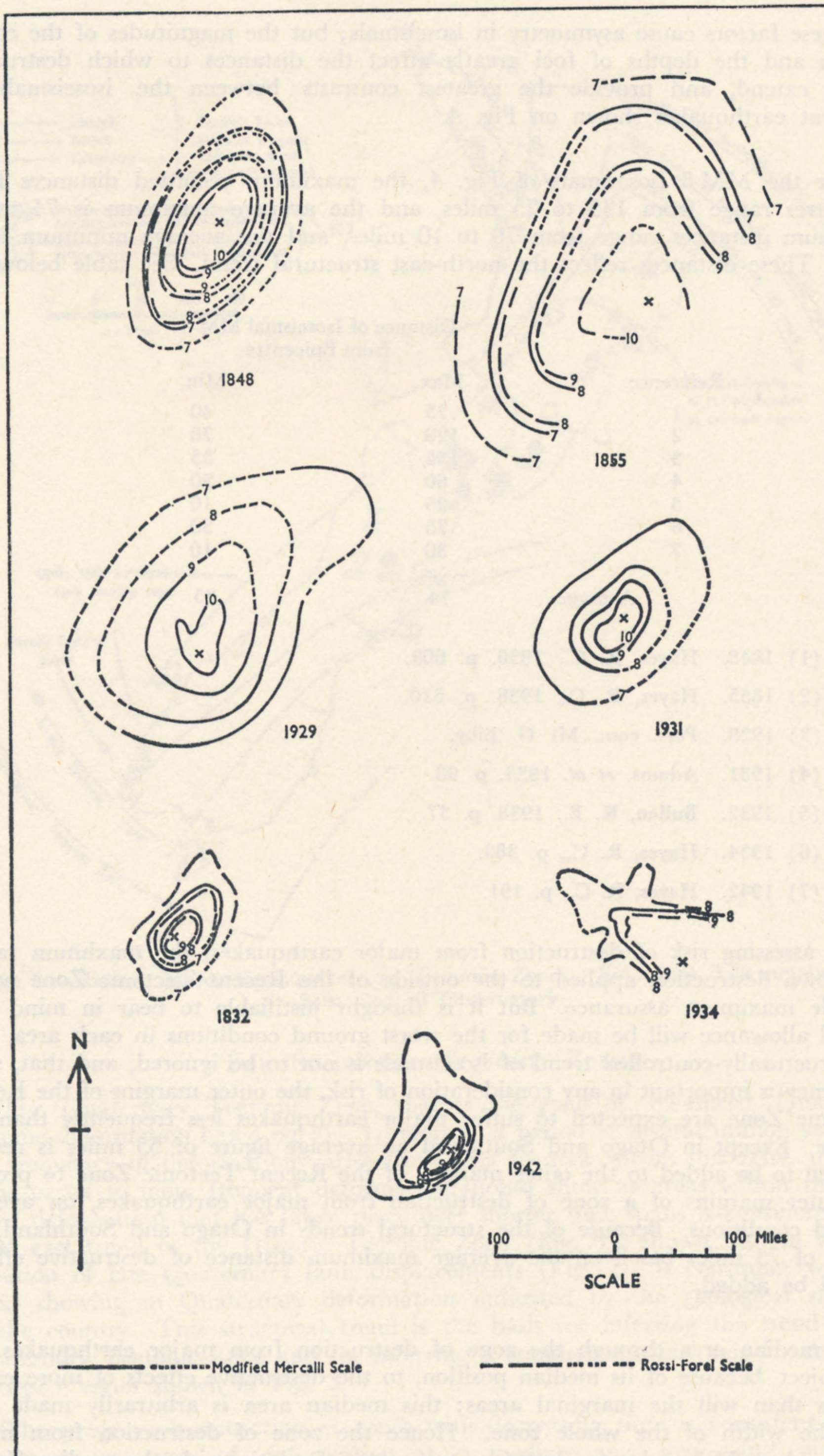

Fig. 4.—Isoseismals of some Destructive Earthquakes in New Zealand.

These factors cause asymmetry in isoseismals; but the magnitudes of the earthquakes and the depths of foci greatly affect the distances to which destructive effects extend, and provide the greatest contrasts between the isoseismals of different earthquakes shown on Fig. 4.

For the MM 8 isoseismals of Fig. 4, the maximum recorded distances from epicentres range from 135 to 25 miles, and the average maximum is 74 miles; Minimum distances range from 70 to 10 miles, and the average minimum is 35 miles. These distances reflect the north-east structural trend. See table below.

	Distance of Isoseismal MM 8 from Epicentre	
Reference	Max.	Min.
1	75	40
2	120	70
3	135	55
4	60	30
5	25	10
6	75	30
7	30	10
Average	74	35

(1) 1848. Hayes, R. C., 1936. p. 609.

(2) 1855. Hayes, R. C., 1936. p. 610.

(3) 1929. Pers. com. Mr G. Eiby.

(4) 1931. Adams, *et al.* 1933, p. 98.

(5) 1932. Bullen, K. E., 1938. p. 37.

(6) 1934. Hayes, R. C., p. 383.

(7) 1942. Hayes, R. C., p. 191.

In assessing risk of destruction from major earthquakes, the maximum radius of known destruction applied to the outside of the Recent Tectonic Zone would provide maximum assurance. But it is thought justifiable to bear in mind that special allowance will be made for the worst ground conditions in each area, that the structurally-controlled trend of isoseismals is not to be ignored, and that, since frequency is important in any consideration of risk, the outer margins of the Recent Tectonic Zone are expected to suffer major earthquakes less frequently than the middle. Except in Otago and Southland an average figure of 55 miles is recommended to be added to the outer margins of the Recent Tectonic Zone to provide the outer margins of a zone of destruction from major earthquakes, on average ground conditions. Because of the structural trends in Otago and Southland, the figure of 75 miles based on the average maximum distance of destructive effects, should be added.

A median area through the zone of destruction from major earthquakes will be subject, because of its median position, to the destructive effects of more earthquakes than will the marginal areas; this median area is arbitrarily made one-half the width of the whole zone. Hence the zone of destruction from major earthquakes (M 7 and over) provides two zones of relative risk, the median Zone 1 flanked by Zone 2 (Fig. 5).

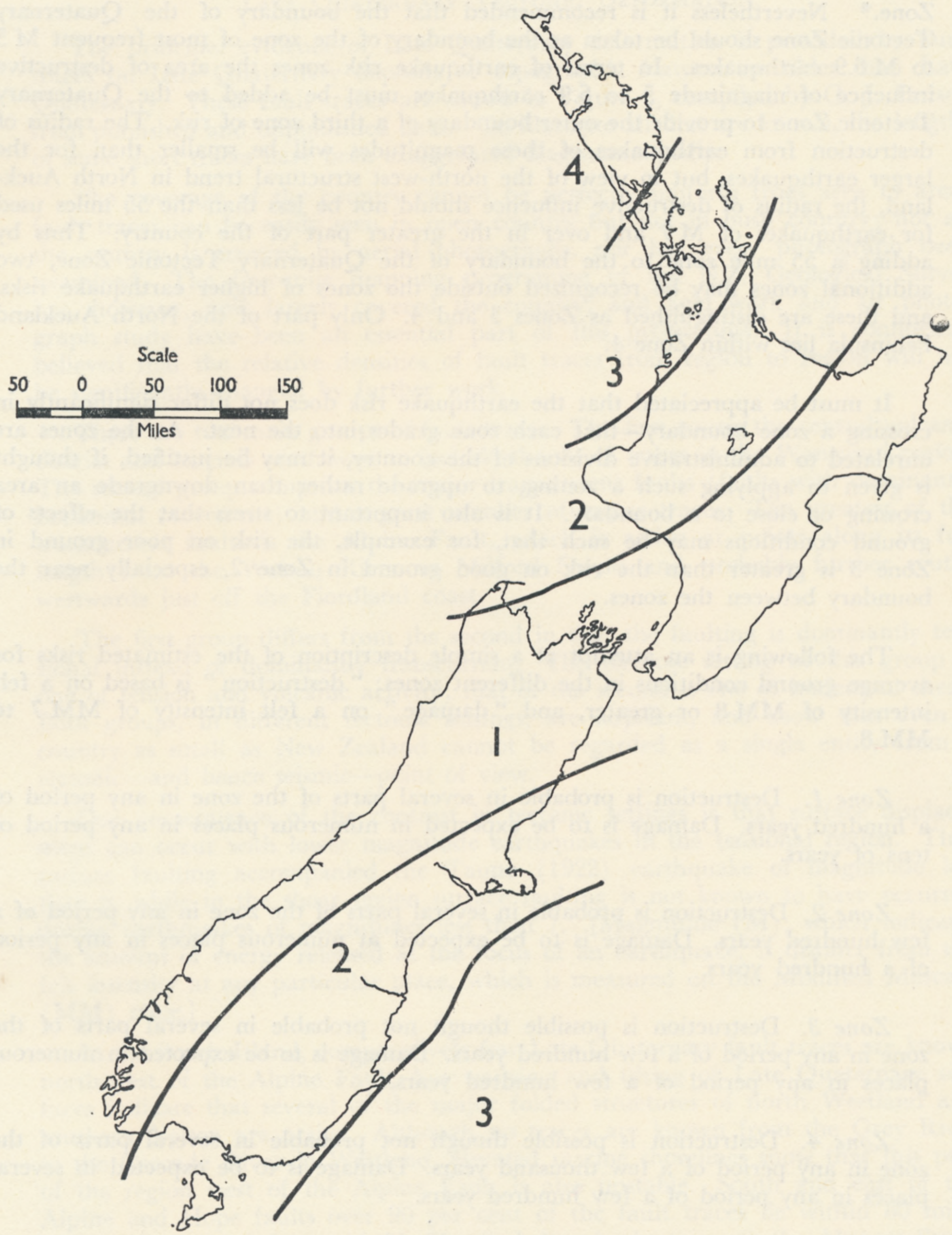

FIG. 5.—Earthquake Risk Zones.

Serious damage may result from smaller magnitude earthquakes—magnitudes 5 to 6.9. The records of earthquakes of these magnitudes (5 to 6.9) indicate that they have a general north-east to south-west distribution pattern and that they do not extend north-west and south-east to the limits of the Quaternary Tectonic

Zone.* Nevertheless it is recommended that the boundary of the Quaternary Tectonic Zone should be taken as the boundary of the zone of most frequent M 5 to M 6.9 earthquakes. In terms of earthquake risk zones the area of destructive influence of magnitude 5 to 6.9 earthquakes must be added to the Quaternary Tectonic Zone to provide the outer boundary of a third zone of risk. The radius of destruction from earthquakes of these magnitudes will be smaller than for the larger earthquakes, but in view of the north-west structural trend in North Auckland, the radius of destructive influence should not be less than the 55 miles used for earthquakes of M 7 and over in the greater part of the country. Thus by adding a 55 mile zone to the boundary of the Quaternary Tectonic Zone, two additional zones may be recognized outside the zones of higher earthquake risks, and these are distinguished as Zones 3 and 4. Only part of the North Auckland Peninsula lies within Zone 4.

It must be appreciated that the earthquake risk does not differ significantly in crossing a zone boundary—that each zone grades into the next. As the zones are unrelated to administrative divisions of the country, it may be justified, if thought is given to applying such a zoning, to upgrade rather than downgrade an area crossing or close to a boundary. It is also important to stress that the effects of ground conditions may be such that, for example, the risk on poor ground in Zone 3 is greater than the risk on good ground in Zone 2, especially near the boundary between the zones.

The following is an attempt at a simple description of the estimated risks for average ground conditions in the different zones; " destruction " is based on a felt intensity of MM 8 or greater, and " damage " on a felt intensity of MM 7 to MM 8.

Zone 1. Destruction is probable in several parts of the zone in any period of a hundred years. Damage is to be expected in numerous places in any period of tens of years.

Zone 2. Destruction is probable in several parts of the zone in any period of a few hundred years. Damage is to be expected at numerous places in any period of a hundred years.

Zone 3. Destruction is possible though not probable in several parts of the zone in any period of a few hundred years. Damage is to be expected in numerous places in any period of a few hundred years.

Zone 4. Destruction is possible though not probable in several parts of the zone in any period of a few thousand years. Damage is to be expected in several places in any period of a few hundred years.

It must be stressed that it is not possible to forecast how soon or where the next destruction or damage will occur in any zone.

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* An earthquake of M 5.0 caused minor damage in November 1963 in northern Northland (Eiby, 1964). This area is in Zone 4 of this paper.

APPENDIX I.—CORRELATION OF MAJOR CRUSTAL EARTHQUAKES AND SURFACE DEFORMATION IN NEW ZEALAND

Reference	Year	Epicentre listed as	Surface Deformation
Suess, 1906	1848	land	Awatere Fault
Lyell, 1856	1855	land	Wairarapa Fault
McKay, 1890	1888	land	Hope Fault
	1897	sea	
	1901	land	
	1904	sea	
	1914	land	
Fyfe, 1929	1929	land	White Creek Fault
	1929	land	
Henderson, 1933	1931	land	Several traces—e.g., near Paki Paki
Walshe, 1937	1932	land	Triangulation network deformed
	1934	?	
Ongley, 1943	1942	land	Fault north of Taueru
	1960	sea	

Of the 13 major crustal earthquakes listed by Hayes (1953), 7 were definitely associated with simultaneous surface deformation. This led Hayes to state that nearly half of the major crustal earthquakes in New Zealand were associated with faulting.

In order to obtain a closer ratio between faulting and major earthquakes only those epicentres which can be proved beyond doubt to be on land should be considered, as evidence of deformation at sea cannot be produced. The epicentres listed for the earthquakes of 1897, 1904 and 1960 are at sea, and must be disregarded.

The accuracy of location of an epicentre depends entirely on its geographic position in relation to the recording instruments. At present the highest accuracy of an epicentre (Class A) is a circle with a radius of 5 miles (the epicentre lies somewhere in an area of 79 square miles). A class B epicentre lies somewhere in an area of 314 square miles (10 mile radius) while a class C epicentre lies somewhere in an area of 700 square miles (15 mile radius) and a class D epicentre has an unlimited radius of at least 30 miles. When the areas in which the epicentres fall are drawn, it is found that the epicentres of the 1901 and 1914 earthquakes cannot be proven to be on land; for the 1934 earthquake Bullen (1936 and 1938) gives three different epicentres, one of which lies at sea, and again this epicentre cannot be proven to be on land. These three epicentres, too, must be disregarded, and the ratio of surface displacements known to have accompanied major crustal earthquakes to the number of epicentres located on land then becomes 7 to 8, or an 87% correlation.

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