ELASTIC AND NON-ELASTIC SURFACE DEFORMATION

IN NEW ZEALAND

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INTRODUCTION

Over the last decade it has become evident that not all surface deformation takes place during earthquakes. Deformation associated with earthquakes and their aftershocks appears to be non-elastic in nature, while in between earthquakes deformation appears to be elastic.

In the past twenty years evidence of non-elastic faulting, folding, warp, shear and tilt has accumulated in New Zealand to such an extent that the coverage shown in fig. 1 is fairly complete.

HISTORIC TECTONIC EARTH DEFORMATION

DISTRIBUTION AND GENERAL NATURE

Reliable records of historic tectonic earth deformation date back less than 200 years, beginning when the first Europeans visited the shores of New Zealand. As the Maoris did not possess a written language only their traditions prevail prior to the last century. New Zealand in those times was only sparsely populated so that only few instances of earth deformation can be gleaned from Maori traditions and some of these can be attributed to volcanic activity.

The nature and distribution of historic earth deformation and their setting within the framework of late Quaternary tectonics have been summarised by Clark et al.(1965). Although the historic earthshifts lie within the zone of frequent post-glacial deformation, the historic record is too short to span the entire width of that zone. The nature of the historic earthshifts however, exemplifies the uniformitarian principle of "The present is the key to the past".

Eleven historic earthquakes (appendix 1) are known to have had associated earth deformation. These include the 1848 Awatere Valley earthquake, during which the Awatere Fault was active (McKay, 1886); features indicating a 20 ft lateral offset at the Saxton River are so fresh that 1848 movement is probable. Of the eleven displacements eight were in the Late Quaternary shear zone, which includes the Alpine Fault and extends from Marlborough northeastwards along and to the east of the axial range of the North Island. Evidence of horizontal displacement was recorded after the Awatere (1848), Glynnwye (1888), Napier (1931) and Wairoa (1932) earthquakes, but only vertical displacement after earlier earthquakes within

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this zone - 15th century and 1855 (Wellington), 1826 (Fiordland) and 1866 (Waipawa) - though horizontal earth displacement may well have occurred also.

Of the remaining three earthquakes, those in 1929 (Murchison) and 1968 (Inangahua) were accompanied by dominantly compressional earthshifts, while that in 1922 (Taupo) by a dominantly tensional series of earthshifts. The nature and trend of Late Quaternary deformation in those regions was thus confirmed.

Some fault traces formed during the Napier and Inangahua earthquakes coincide in strike and presumably in dip with the bedding in the underlying Tertiary sediments; horizontal and vertical movement took place near Inangahua. Typically the traces are staggered, indicating simultaneous failure along more than one bedding plane that provide weaknesses within the sediments. This type of faulting is essentially a continuation of folding. Pre-historic bedding faults of Late Quaternary age occur in the Silver Range in Hawke's Bay, south-west of Inangahua in the Grey-Inangahua Depression in north-west South Island (Suggate, 1957; Young, 1963) and in the Awatere Valley (Lensen, 1960).

REGIONAL DIFFERENCES IN DEFORMATION

New Zealand Shear Belt

The 1848, 1855, 1866 and 1888 earthshifts consisted of surface faulting, the greatest horizontal displacement (inferred to have occurred in 1848) being 20 ft and the greatest vertical movement being 9 ft. Typically, the 9 ft uplift associated with the 1855 Wairarapa earthquake produced a regional tilt of 20" arc in westerly direction of the Wellington shoreline, in keeping with the post-glacial tilting of the marine beach ridges east of Wellington (Wellman, 1967). The 15th century uplift of Petone and Miramar can also be traced into the same set of raised beaches.

In contrast with this faulting, the 1931 and 1932 Napier and Wairoa earthshifts were characterised mainly by plastic surface deformation, and fault traces, if any, were short and insignificant. This is consistent with the Late Quaternary tectonic history, where in the Hawke's Bay-Gisborne regions fault traces are rare and short and are replaced by folds. In this region surface warping and dextral horizontal shear are shown to be dominant by deformed triangulation networks. The distribution and directions of shift of trig stations in the Hawke's Bay-Wairoa area suggest one subsurface north-east-trending fault common to both earthshifts. Thick Tertiary and Quaternary sequences mask the anastomosing Late Quaternary

fault pattern, which is pronounced in the rest of the shear zone, and plastic surface deformation forms the only known evidence of sub-surface faulting.

Although in the shear zone the dominant character of faulting is consistent with the Late Quaternary tectonic history of individual regions, in some areas the vertical component of displacement, which is minor compared with the horizontal, has shown a reversal. Both the 1848 and 1888 earthshifts produced changes in upthrown sides along the strikes of the traces. These historic earthshifts, although inconsistent with the total tectonic history since the onset of the Kaikoura Orogeny, are consistent with the post-glacial displacements along major parts of all Marlborough and some western Hawke Bay faults; flights of faulted terraces along the Branch, Grey and Saxton Rivers clearly demonstrate reversals of vertical throw in post-glacial time (Lensen, 1964a, 1968).

North Westland - West Nelson Compressional Region

Both the 1929 and 1968 earthshifts in this region resulted in pronounced thrusting with sinistral horizontal shear components on north-trending faults, accompanied by regional tilting. Bedding faulting took place in 1968 as discussed above. Comparably, Late Quaternary deformation in this region is demonstrated by warping along fold axes, locally accentuated by thrust or reverse faulting and by tilting along and across the structural trends.

Taupo Volcanic Zone

The 1929 Taupo earthquake swarm produced a swarm of 4 parallel fault traces and movement on the traces was distributed over the duration of the 7-month period. The displacements, which were vertical, produced a six mile wide graben, with a maximum depth of 12 ft, thereby deepening the Late Quaternary graben already present. Thus this earthshift accentuated the Late Quaternary tectonic character of this region, which consists of a series of sub-parallel horsts and grabens within the overall graben of the Taupo Volcanic Zone.

FREQUENCY OF EARTHSHIFTS

As the average periodicity of fault movement in the shear-belt at any one locality may be about 1,000 years (Lensen, 1968) or 1,300 years (Wellman, pers.comm.) the 200 years historic record of earthshifts is too short to deduce any change in rates and distribution of deformation and the associated seismicity. The historic evidence shows a continuation of trend and nature of post-glacial tectonic activity, so that earth deformation and crustal seismicity will probably continue at broadly the same overall rates (Clarke et al.,1965); these rates are, however, different for each of the Late Quaternary tectonic regions of New Zealand.

POST-EARTHSHIFT DEFORMATION

Relevelling following the 1929 (Murchison) and the 1931 (Napier) earthshifts, and repeated relevelling and retriangulation of a quadrilateral after the 1968 Inangahua earthshift, demonstrate continued deformation in the same

sense during the major part of the aftershock sequence followed by a partial recovery both vertically and horizontally towards the pre-earthshift situation.

Subsequent to the Murchison earthshift, tilt continued in the same direction to be followed within one year by a reversal of tilt of a lesser amount. Relevelling one year after the Napier earthshift showed a 5-10 per cent return to pre-earthshift levels.

In the immediate vicinity of the fault at Inangahua, the quadrilateral rotated sinistrally and its area decreased by shortening across and along the fault, in the same sense as that of the main earthshift for the first 4 months after the main shock. Subsequently, as the aftershocks diminished in frequency and intensity, the quadrilateral rotated dextrally and its area increased but by lesser amounts than the previous post-earthshift deformation (Lensen and Otway, in press).

RECENT

The next time unit in which to study deformation is the post-glacial period, the geologically "Recent", a period of about 20,000 years.

The amount of evidence of pre-historic movements in New Zealand in considerable but only really useful if the events can be dated. Radio-carbon dating forms a useful tool but suitable material such as wood, peat and shells in the right localities is relatively rare and the geologist often has to date movements in terms of geological episodes. Suitable episodes in the Quaternary are the periods of glaciation and the intervening interglacials.

In general during glaciations the vegetation level in the mountains was lowered and erosion had increased considerably in the higher regions. Rivers brought down the eroded material in the form of gravel, sand and silt from the frost ridden and ice covered ranges and deposited this debris in valleys as extensive bouldery plains (aggradation).

During interglacials the climate became milder and forest and tussock grew at higher levels and protected the mountain flanks from excessive erosion. The rivers gradually carried less and less material and as they could carry more than they did, they started to carry, erode and remove the outwash gravels of the bouldery plains and cut down into the plains leaving behind a series of slip-off or degradational terraces.

To measure vertical movement a reference surface is required, while to measure horizontal and vertical movement a reference line on a reference surface is required. Faulted flights of terraces, where abandoned channels on the terrace surfaces are preserved, form ideal evidence. If such channels are absent, terrace edges must suffice, although they are less likely to give true horizontal offsets because subsequent lateral river erosion can remove in part or completely any lateral offset caused by faulting (Lensen, 1964b).

Where such terraces are absent offset spurs, ridges and streams can be used, but again such offsets are not necessarily true offsets.

During glaciations, while the outwash gravels were being deposited, any traces of faulting were soon covered by further outwash. Not until the rivers started to cut down did evidence of faulting become preserved. A fault trace on the gravel outwash surface became preserved as soon as the riverbed reached a lower level. Later, as the river successively abandoned lower and lower terraces, fault traces on those terraces became preserved also. The outwash surface being the oldest and highest terrace, the successively lower terraces being successively younger, thus the fault traces on successively lower terraces represent successively shorter periods of faulting.

Flights of faulted terraces are rare and until 1965 were unique to New Zealand. Since then one set of faulted terraces has been found in Japan.

Of the 15 known flights of faulted terraces in New Zealand, the importance of which was first realised by Wellman, the Branch River terraces in the Wairau Valley form the most complex example (Wellman 1955, Suggate 1960 and Lensen 1968). Here the horizontal offsets of 227, 190, 155, 120, 100 and 10 ft for successively younger terraces not only demonstrate that faulting has been an intermittently continuous process at a relatively uniform rate over at least this period, but also that faulting occurred repeatedly along the same plane and the 227 ft lateral displacement of the top terrace must have been made up out of at least 10 separate instances of faulting.

All flights of faulted terraces further demonstrate that the repeated horizontal faulting has always occurred in dextral sense.

Vertical faulting occurred simultaneously with horizontal movement, but unfortunately not continuously in the same sense. The scarp heights of the Wairau Fault across the flight of terraces changes from the oldest (highest) terraces to the youngest (lowest) terraces in the following order: 4, 9, 7, 5 and 3 ft. As the oldest terrace has experienced more faulting than the younger terraces one would expect that terrace to have a fault scarp of more than or at least 9 ft in height if vertical faulting has occurred in the same sense, that is, if the same side of the fault continued to move downwards. This is not the case and a reversal of vertical faulting must be accepted. The 4' scarp is an algebraic sum rather than a simple arithmetic sum of individual vertical displacements.

Such reversals of vertical movement can be demonstrated on flights of faulted terraces in the Grey River, Awatere Valley, Marlborough (Lensen, 1964a), the Saxton River, Molesworth (Lensen in prep.) and Branch River (Lensen, 1968). Similar reversals can be found along the eastern flank of the Ruahine Range in the North Island. All these reversals took place during the "Recent" period.

In general most of the South Island and the eastern part of the North Island have been subjected to dominantly transcurrent faulting with to a smaller extent vertical faulting and reversals of vertical faulting in Fiordland, the Kaikoura Ranges and eastern Ruahine Ranges.

The horizontal displacements do not exceed 250 ft, while the vertical displacements are in the order of 50 ft but generally less, with the exception of the Alpine Fault where the vertical displacement over a period of 13,000 years reached 470 ft near Paringa (Suggate, 1965a).

In the rest of the North Island numerous traces dissect the Rotorua-Taupo volcanic district where the nature of faulting has been dominantly vertical. Horizontal displacements cannot be directly demonstrated with one exemption where a lava flow has been offset both horizontally and vertically by 20 ft (Grindley, 1965).

To the west of the volcanic belt isolated traces occur near Inglewood, Mokau and in the Hauraki Graben; again the displacements are vertical.

LATE HAWERA

So far we have discussed the immediate past, the geologically "Recent" period. Preceding this is the Upper Pleistocene or the Hawera Series. This period is characterised by alternating Glacials and Interglacials, and repeated aggradation and degradation have destroyed much evidence of Upper Pleistocene faulting. Even so, some evidence has been preserved.

While Glacials and Interglacials are due to changing temperatures of the order of 6°, smaller fluctuation in temperature occurred during the glacial periods resulting in the repeated advance and retreat of the glacier ice and the glacial periods can be subdivided into stadials and interstadials respectively.

The flights of faulted terraces so far discussed have been cut into the outwash of the main last stadial of the Last Glaciation which have been given formational names of Loopline, Speargrass, Springston etc. according to the area in which they occur. On some flights of terraces the previous stadial outwash has been preserved also. These terraces are the Waiohine Terraces across the West Wairarapa Fault, near Greytown in the Wairarapa (Lensen, Vella, in press), and the previously mentioned Grey and Saxton Rivers terraces across the Awatere Fault.

The total displacements since the formation of these outwash surfaces vary between 320, 350 and 330 ft horizontally, and vertically, 60, 3 and 18 ft both respectively. The low value of 3 ft at the Grey River terraces is due to reversal of vertical displacement, the maximum vertical displacement reached at least 9 ft.

The total horizontal displacements since the deposition of these outwash gravels about 35,000 years ago, varies generally between 300 – 350 ft, while the vertical displacements vary considerably and, as shown before, reversals have occurred.

EARLY AND PRE HAWERA

Horizontal Offsets:

As faulted flights of terraces formed in the Lower Pleistocene and Upper Tertiary have not been preserved less reliable data, such as offset streams and rivers will have to be used

to assess the total displacement since their formation and both the amount of displacement and the age of the features are generally less accurate.

Horizontal offsets of 5 miles of the Tauwharenikau, Waingawa and other rivers in the Tararua Ranges in the North Island probably started in the beginning of the Pliocene about 7 million years ago, while the 3 miles offset of the Manawatu started at the beginning of the Quaternary, about 2½ million years ago.

Horizontal offsets of conglomerates and volcanics across the Hope Fault (Dr. R. Freund, pers. comm.), horizontal drag of volcanics in the Awatere Valley (Lensen, 1960) and horizontal shift of a limb of a synclinal fold in mid Tertiary beds all suggest a 12 mile displacement since the middle of the Miocene, about 18 million years ago.

The largest proposed horizontal shift in New Zealand is that along the Alpine Fault where the stratigraphy and structure of rocks in the Red Hill region north of the Wairau Fault is strikingly similar to that of the Red Hills and Eglinton Valley in Fiordland. This 300 mile shift was first noted by Wellman (1952) and is now generally accepted by most New Zealand geologists.

The dating of the start of movement and the period in which the main movement took place is however still uncertain. Suggate (1963), Grindley (1963) and others have suggested that the main movement took place in the Rangitata Orogeny (Jurassic - lower Crataceous), and rejuvenation occurred during the Kaikoura Orogeny. Wellman (1964) suggested that the displacement started post-Miocene.

Laird (1968) in his study of the Paparoa Tectonic Zone postulated a N-S Principal Horizontal Stress (direction of principal horizontal shortening) in the Early Tertiary period.

If the Alpine Fault was active during this period, the movement along it must have been in sinistral sense and the 300 mile shift must be regarded as an algebraic sum of dextral movement during the Rangitata (160-100 million years ago) and the Kaikoura (30 million years - present), orogenies and sinistral movement during the intervening period covering Late Cretaceous and Early Tertiary (80-40 million years ago).

Vertical Offsets and Uplift

Vertical displacements along faults vary and are further varied by regional uplift, while erosion is a complicating factor which makes estimates of vertical displacement difficult.

In the North Island along the axial range the vertical displacement varies from 3,500 ft over $2½ \times 10^6$ years in the Ruahines to 8,000 ft over 7×10^6 years in the Tararuas. The volcanic region is characterised by tectonic and volcanic subsidence. The subsidence in the Tectonic depression of the Taupo-Rotorua graben is 12,000 ft over $2½ \times 10^6$ years while that for the Taupo-Reporoa graben is 10,000 ft over 2×10^6 years (Grindley, 1965, p.19).

Sediments placed on the sea floor or in the river valleys are deposited in horizontal or nearly horizontal layers, and if no subsequent deformation occurred they remained horizontal. Any outwash surfaces and any marine beds tilting at more than a few degrees must be regarded as forming evidence of deformation.

In the South Island vertical movement again varies considerably from fault to fault and from place to place along any one fault.

In Marlborough no evidence of horizontal displacement has been preserved over the Lower Pleistocene, Pliocene and Upper Miocene periods, but the total uplift since its emergence in the middle Miocene can be estimated as 24,000 ft over 19×10^6 years. An $8°$ tilt over a distance of 4 miles of Waitotaran (Upper Pliocene) sediments and a $20°$ tilt of Kapitean (uppermost Miocene) sediments over a distance of 6 miles produce rates of uplift of 1 ft/1,000 years and 1.2 ft/1,000 years respectively. In the Buller region Suggate (1965b) gives a value of 12,000 ft over 3×10^6 years, while that for the Southern Alps amounts to 50,000 ft over 2×10^6 years.

The Marlborough Sounds are at present, however, submerging.

In several areas where, because of the presence of thick and relatively soft covering strata, faulting does not reach the surface warping, tilting and folding have taken place in the covering strata.

Prior to the Murchison Earthquake of 1929, the White Creek Fault was not thought to be active because evidence of "Recent" surface faulting was absent. Subsequent work by Suggate (1965b) on the Pleistocene geology of the Buller Gorge area demonstrates that the Late Pleistocene outwash deposits of the Manuka Formation (Waimaunga Glaciation, about 250,000 years old) are warped and faulted, the differential movement amounting to 300-400 ft. Thus the White Creek Fault should have been considered to be potentially active in the "Recent" period.

Fig. 3 shows the amount of dip (deviation from the horizontal) of Early Quaternary deposits; hence shows deformation since these beds were deposited i.e. Late Quaternary deformation. In areas where Early Quaternary deposits are absent, either because they have been eroded off or were never deposited, dip values on the Pliocene beds are given which indicate the amount of deformation during the entire Quaternary, a period of about 2½ million years.

In most of the North Island Late Quaternary deformation values generally do not exceed $20°$, and deformation is in general substantiated by the presence of active fault traces. In the North Auckland region the early Quaternary deposits are still horizontal and very little deformation can have occurred in Late Quaternary. That the absence of deformation in that region is not just temporary is shown by the fact that even Upper Miocene beds are still horizontal, indicating that very little deformation has taken place since the onset of the Pliocene (7 million years ago).

In the South Island the amount of deformation is in general somewhat higher than that

of most of the North Island. On the West Coast of the South Island dip values of 70° indicate that although fault traces are generally absent, deformation has been considerably more than anywhere else in New Zealand.

RATES OF DEFORMATION

Expressed in feet per 1,000 years Suggate (1965) gave a rate of 35 ft for the Southern Alps and 2 ft for the Buller area. The first rate dates back about 13,000 years while the Buller rate covers a time span of 250,000 years approximately.

In the volcanic zone in the North Island Grindley's evidence of 12,000 ft over a period of 2½ million years produces a rate of subsidence of 5 ft/1,000 years.

It would be interesting to see whether such rates of vertical and horizontal displacements have changed or have been constant since the Kaikoura Orogeny began. Unfortunately nowhere has a complete sequence of deposits and evidence of their displacement been preserved at any one single locality.

A composite sequence can, nowever, be compiled along the North Island Axial Ranges and in Marlborough. The evidence over the younger part of the geological column is fairly reliable but that over the earlier part is somewhat subjective although the order of magnitude of values for displacement and age are substantially correct. Values in the table given at the end of the Section are expressed in feet per 1,000 years for horizontal and vertical displacement.

Both in Marlborough and the eastern part of the North Island, the rate of horizontal displacement appears to have increased towards the present. The rate of vertical movement in the North Island would appear to have been relatively constant, while in Marlborough the rate of vertical movement appears to decrease towards the present. The latter decreasing rate is consistent with the "Recent" reversals of vertical movement in that area.

PERIODICITY OF FAULT MOVEMENT

As the historical deformation of New Zealand covers only slightly more than one century, this time span is obviously too short to establish a frequency of fault movement along any one fault.

The values for horizontal displacement of the Branch River terraces of 227, 190, 155, 100 and 10 ft for successively lower and younger terraces indicate the following minimum measurable horizontal displacements that can have occurred along it, namely 37, 35, 35, 20, 90 and 10 ft (the difference between each two successive measured offsets). As the last value of 10 ft is an erosional remnant of an originally larger offset this value cannot be used. The remaining values suggest single horizontal movement ranging between 17 and 20 ft, the first three values each being the sum of 2 horizontal offsets of 17-20 ft while the value of 90 becomes the sum of 5 such off-sets.

Horizontal offsets of the order of 20 ft are known from the San Andreas Fault during the San Francisco Earthquake of 1906 and from the Fair Weather Fault during the 1958 earthquake in Southern Alaska.

The Wairau Fault is the northern part of the Alpine Fault, which is the major fault in New Zealand and is comparable in magnitude with the San Andreas and Fair Weather Faults. Horizontal offsets in the order of 20 ft can be expected to occur along it.

The total horizontal offset of 227 ft can be attributed to 11-12 movements over a period of 20,000 years, or one movement over each period of 1,700-1,800 years.

Any horizontal displacement of, say, 20 ft resulting from a fault movement along a trace of, say, 60 miles length dies out, however, in both directions from the mid point of the movement to become zero at the ends of the rejuvenated section of the trace.

As, however, the total horizontal offsets along a fault trace preserved over the last 20,000 years vary but little along its length, subsequent fault movements must average out the previous horizontal displacements. In the case of our example subsequent movements of 20 ft at both ends of our original trace will produce a continuous trace of 60 miles length showing 20 ft lateral displacement, the subsequent movement at each end affecting half the original trace. *

For this reason it must be assumed that at Branch River two movements occurred over each period of 1,700-1,800 years, or one movement in 850-900 years. The distance to which this particular periodicity can be applied along the Wairau and Alpine Faults depends on the total horizontal displacement of features of the same age distributed along the faults.

The suggested periodicity of fault movement is based on the assumption that lateral offsets of 20 ft did occur. Unfortunately no historic displacement along the Wairau Fault is known. The largest known horizontal displacement occurred in 1888 along the Hope Fault and the maximum value did not exceed 10 ft.

If lateral offsets of the order of 10 ft were to be assumed for the Wairau Fault then the periodicity of fault movement at Branch River is 450 years. Although it can be reasoned that the Wairau Fault is geologically a more important active fault in that it separates older rocks than the Hope Fault and that it is the present continuation of the Alpine Fault and therefore bigger displacements can be expected along the Wairau Fault, the possibility that the Hope Fault is a far younger and now an equally active fault must be considered.

As it is probably fair to assume that the

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*Footnote: It is not necessary for the maximum displacement during the next movement to occur exactly at the point where the previous movement ceased, as further displacements must tend to cancel out any possible discrepancies in displacement. Post-1939 earthquakes in Turkey clearly demonstrated that rejuvenations of fault traces along the North Anatolian Fault occurred at almost the exact point where it has ceased during the previous earthquake.

average horizontal displacement along the
Wairau Fault lies somewhere between 10 and 20
ft a periodicity of faulting between 500 and
900 years is suggested.

ELASTIC DEFORMATION

Throughout history earth deformation prior
to earthquakes has been reported, but few
accounts can now be verified, apart from
obvious large vertical changes immediately
preceding earthquakes. Small changes at larger
time intervals before earthquakes went unnoticed
until the introduction of tide gauges and geo-
detic surveys at the end of last century, but
even then such changes became only evident as
accidental by-products of other investigations.

Apart from some early isolated work in
Japan and California, integrated investigations
designed specifically to detect earth deform-
ation did not start until about 10 years ago.
Since then evidence of precursory changes has
accumulated to such an extent that within the
next 10-20 years the forecasting of major
earthquakes that have their epicentres on land,
has become a distinct possibility. In fact,
several successful forecasts together with some
unsuccessful ones have already been made in
California by Dr. R. B. Hofmann and his team
(1968).

Evidence shows that not all deformation
takes place during sudden fault movement,
folding or tilt at times of earthquakes and
suggests that the type of deformation changes
with time.

The author (Lensen, 1968a) has recognized
four phases in one cycle of earth deformation:
secular, pre-earthshift, earthshift[*] and post-
earthshift, the first two phases being elastic
in nature whereas the others are non-elastic.

Secular, long term, slow deformation occurs
over most of the interval between two sudden
fault movements at any one locality. This
interval has been estimated at 900 years or
longer at some transcurrent faults in New
Zealand (Lensen, 1968b).

Pre-earthshift. At the end of the secular
phase magnitudes of movements increase and
reversals occur until finally the elastic
limit of the earth's crust is reached and
Earthshift occurs in the form of faulting,
folding, tilt, warp or drape and the crust has
yielded non-elastically (brittle or plastic
deformation). This phase is followed by Post-
earthshift deformation, a period of further
but lesser permanent adjustments commonly
resulting in a small reversal with respect to
the earthshift.

Evidence of vertical post-earthshift
deformation is provided by Henderson (1937)
following the Murchison (1929) and by Henderson
(1933) following the Napier (1931) earthquakes.
Continued but smaller amounts of
non-elastic deformation in the same sense as
the earthshifts were followed by small
reversals.

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[*] The word earthshift is chosen because within
the study of earth deformation it is the
earthshift that is measured, and not the
associated earthquake.

Evidence of horizontal post-earthshift
deformation is recorded by Lensen and Otway (in
press) after the 1968 Inangahua earthquake.
The sense of faulting was reverse with a
sinistral strike slip component. After the
earthshift, shortening of the area and sinistral
rotation continued at lesser magnitudes, follow-
ed by a reversal that resulted in extension and
dextral rotation by an even smaller amount.

RATES AND MAGNITUDES OF DEFORMATION

The rates for the 4 phases of earth deform-
ation vary according to the tectonic settings.
Many differences can be expected between
tensional, shear and compressional regimes and
the regime in any one area can change gradually
with time.

Further, the available evidence, although
as yet inconclusive, suggests broadly that the
amplitude of pre-earthshift deformation varies
inversely with the distance from the epicentre
and the depth of the hypocentre, and varies
proportionately with the magnitude of the
coming earthquake. Similarly the time interval
between pre-earthshift deformation and the
future earthquake appears to be directly related
to the magnitude of the future earthquake in any
given tectonic regime.

Thus it would appear that the crust of the
earth is in constant motion at a roughly uniform
rate (secular). This motion appears as a
transverse wave pattern in the vertical plane
and as a longitudinal wave pattern in the
horizontal plane. Suddenly amplitudes increase,
wave-lengths decrease and reversals take place
(pre-earthshift) until an earthshift occurs,
to be followed by post-earthshift deformation
which finally settles down again to secular
deformation of the next cycle.

"Creep"

Active fault creep slippage observed in
California appears to be of an irregular
episodic nature and it may propagate along a
fault and reversals have been observed.

"Creep" thus varies with time and place
along Californian faults, appears to be non-
elastic in nature and may perhaps be regarded
as a special form of earthshift and post-
earthshift deformation.

In detail "creep" appears as longitudinal
oscillation and is thus consistent with the
nature of horizontal deformation discussed
before.

Absence of evidence of elastic deformation
in New Zealand simply indicates the lack of work
to detect such deformation.

Since middle 1969 the N.Z. Geological
Survey has started a programme to monitor such
deformation, in part by surveying 20-30 miles
wide quadrilaterals across active faults. The
Wellington Quadrilateral is shown as an example
(Fig. 3). The N.Z.G.S. 1969 resurvey showed
that elastic deformation had occurred over a
40 year period and that the rate would indicate
a secular phase. By annual observations with
improved instrumentation it will be possible
in time to monitor elastic deformation over
most of New Zealand and to detect pre-earthshift
deformation precursory to major earthquakes

earthquakes which have their epicentres on land. However a major programme to obtain basic data, which may take 10-20 years to collect, is a pre-requisite.

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APPENDIX 1

HISTORIC DEFORMATION

1848 (10 October).

The centre of disturbance was in the Awatere Valley in Marlborough where an eye-witness reported that a great rent was caused

in a chain of mountains and that the fissure, though not more than 18 inches in average width, was traced by reliable observers for at least 60 miles and still continued. Alexander McKay (1886) visiting the area 40 years later confirmed the open rents and fissures still to be seen on the surface along the line of fracture. Unfortunately no measurements of displacement were made after the earthquake but recent work by the author (Lensen, in prep.) at the Saxton River indicates likely displacements of 1 ft vertical and 20 ft horizontal in dextral sense.*

1855 (23 January).

Movement on the West Wairarapa Fault (Ongley, 1943a), caused 9 ft uplift on the coast near Mukamuka east of Wellington and tilted a block of land 30 miles wide and 100 miles long. A horizontal offset shown by a river channel possibly amounted to 40 ft (Lensen and Vella, in press) in dextral sense.

1888 (1 September).

Movement occurred on the Hope Fault where near Glynwye a fence was horizontally offset in dextral sense by 8 ft 6 in. This offset was recorded by McKay (1890), who thus became the first geologist to record horizontal displacement. Previously it has been assumed that faults moved only vertically.

1922 (May-December).

During the Taupo swarm of earthquakes the Whakaipo, Kaiapo and Whangamate Faults moved in successive jumps. The earth block (Kaiapo Graben) between the faults had sunk 3-6 in. in June, 4 ft 6 in. in September and in December at the conclusion of the earthquakes the graben tilted towards the east with a maximum throw of 12 ft (Grange, 1932).

1929 (17 June).

During the Murchison Earthquake the White Creek Fault lifted the Murchison-Inangahua Road 15 ft vertically and shifted it 7 ft horizontally; this time the horizontal movement was sinistral, that is, the west side moved south relatively to the east side (Henderson, 1937).

1931 (3 February).

During the Napier Earthquake a road and fence north of Poukawa were both horizontally offset by 6-7 ft in dextral sense. An average uplift of 4-5 ft occurred over an area of 60 miles by 10 miles, maximum uplift reaching 10 ft (Henderson, 1933).

After the 1931 earthquake one of the central trig. stations (Bluff Hill, Napier) was reoccupied and reobservations showed that movement had taken place. Surrounding stations were reobserved further and further afield until satisfactory agreement within the limit of accuracy of the original observations was

* If the strike of a fault is N-S, then horizontal displacement is called dextral, if the west side moves north relative to the east side, while the displacement is called sinistral if the west side moves south relative to the east side.

obtained. The resulting adjustment indicated undoubted shifts of three stations, Kauranaki, Bluff Hill and Mohaka.

At the same time a second order net was thrown over that district.

1932 (16 September).

Surface breakage occurred as a result of the Wairoa Earthquake but all observed breakage could be explained by slumping etc. However, in 1929 a modern triangulation survey had been carried out in this area and in 1935 third order work near Wairoa was found difficult to adjust in terms of the second order. As this third order was of particularly accurate standard, it was decided to reobserve the second-order work within the first order triagle Mohaka-Whakapunake-Te Kapu. The total relative horizontal displacement amounted to 3.3 links. "The origin of this movement is no doubt the earthquake which occurred on September 16th, 1932" (Walshe, 1937). Although no definite surface displacement could be demonstrated, reoccupation of a triangulation network proved that deformation had occurred in the relatively soft covering strata.
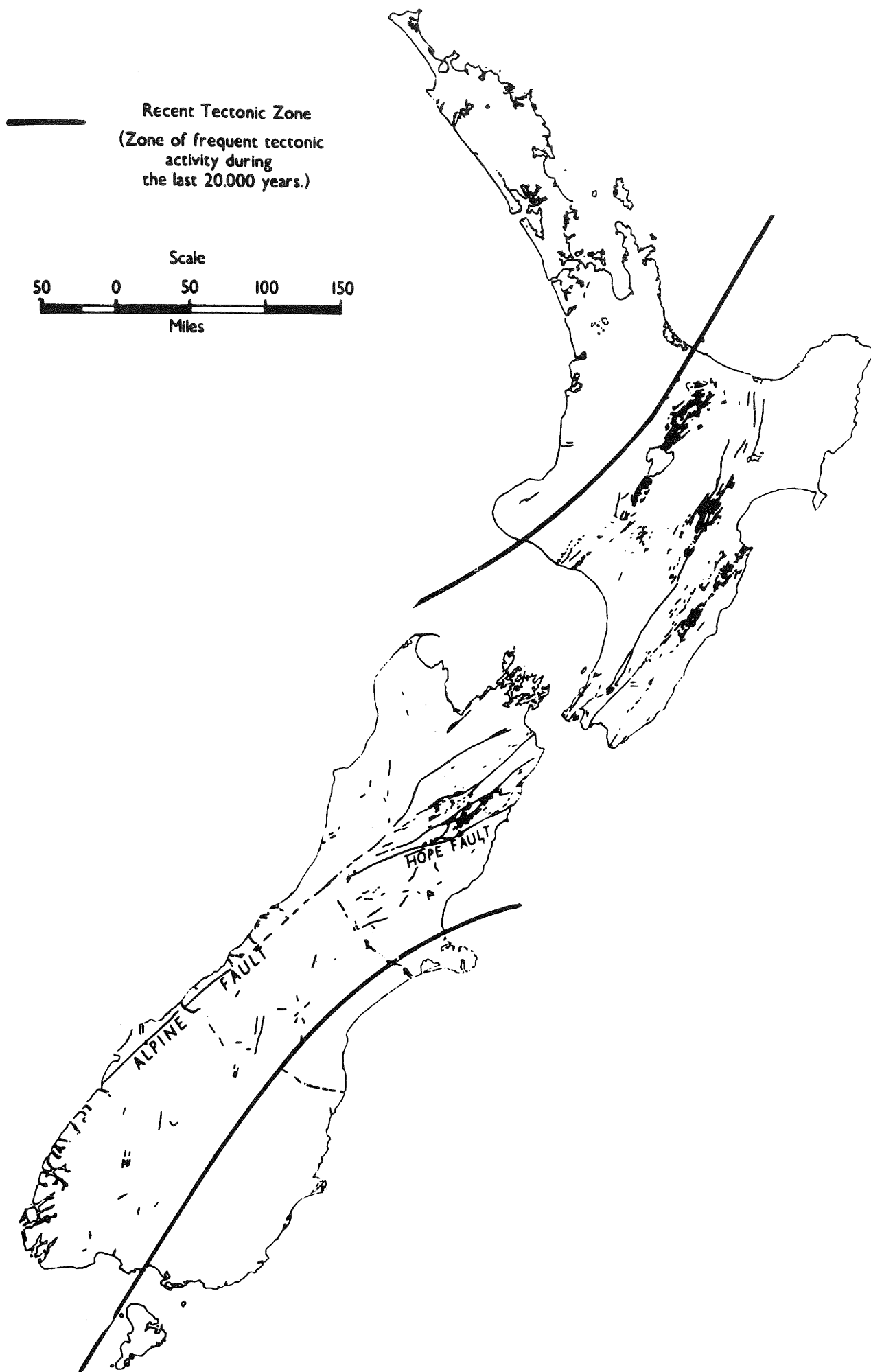
1966 (23 April).

Immediately south of Seddon the railway line became deformed during the Seddon Earthquake and here the inner (lower) line of a ten-chain curve buckled upwards 3" while the outer (higher) line buckled downward 1", resulting in a reversed cant on this curve. Such deformation is inconsistent with slumping, compaction etc. but can be readily explained by horizontal shortening. As the main trunk line south of the disturbed area is nearly parallel to the Hogg Swamp Fault and the main trunk line to the north generally strikes at an angle of about 77° to the strike of the Hogg Swamp Fault in such a way that the western angle is acute, it is likely that this buckling is due to dextral horizontal deformation within the Tertiary sediments that cross the fault. That a surface trace was not found is understandable as the soft relatively plastic, Tertiary covering beds are at least 3,000 ft thick, the magnitude of the earthquake was only 6.2 and the total shortening is a matter of an inch, rather than links or feet (Lensen, 1970).

1968 (24 May).

The Inangahua Earthquake is undoubtedly the most closely studied earthquake in New Zealand. Regional surveys show an area of 400 sq. miles to be uplifted by an average of 3 ft, while that entire area was also deformed horizontally by as much as 3 ft in places. In detail, thrusting and sinistral (anti-clockwise) horizontal shift occurred on the Glasgow Fault, while new bedding faults were formed near Rotokohu and Rough Creek.

All evidence of deformation is consistent with horizontal crustal shortening in 125°-305° direction (Lensen and Otway, in press; Lensen and Suggate, 1968).
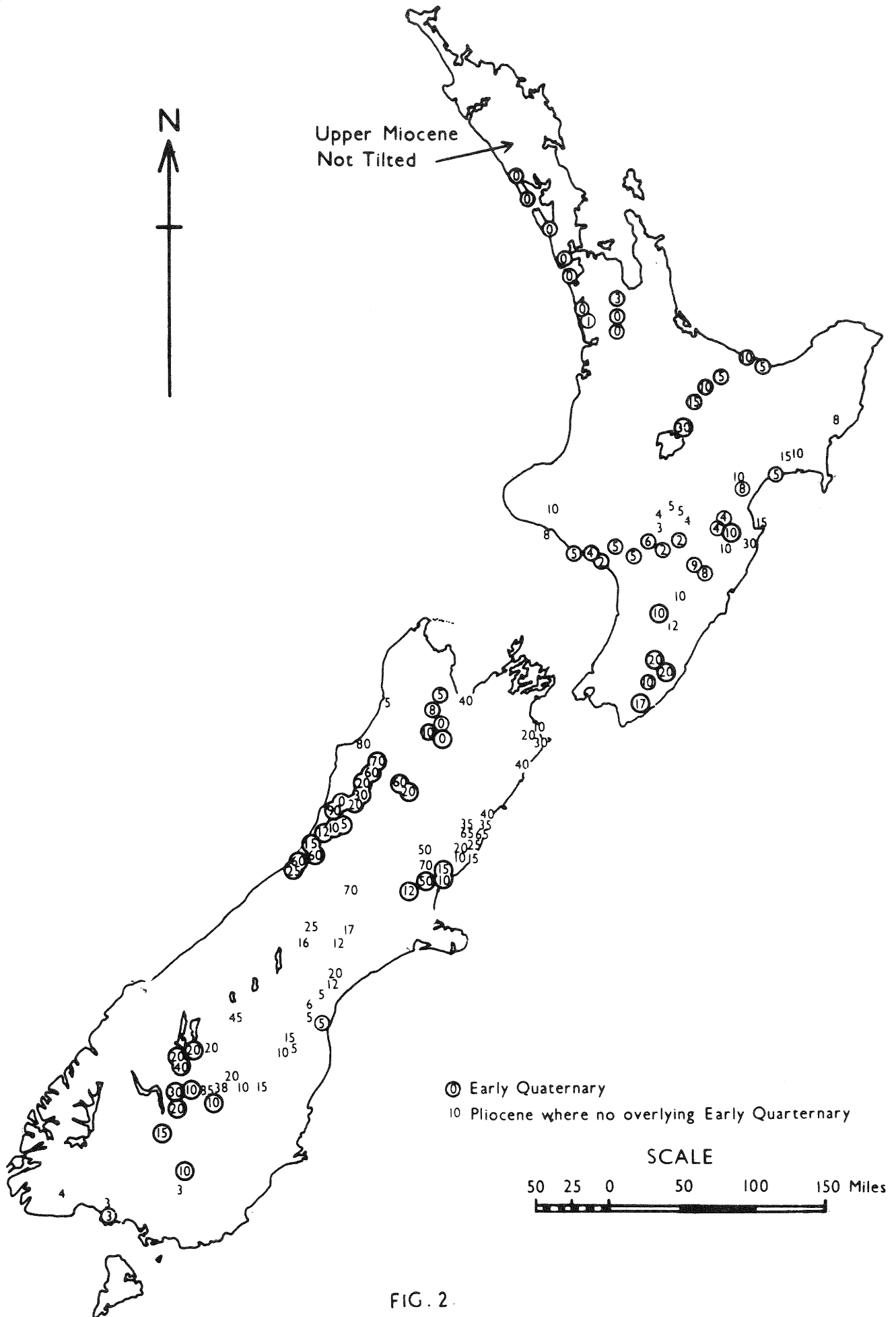
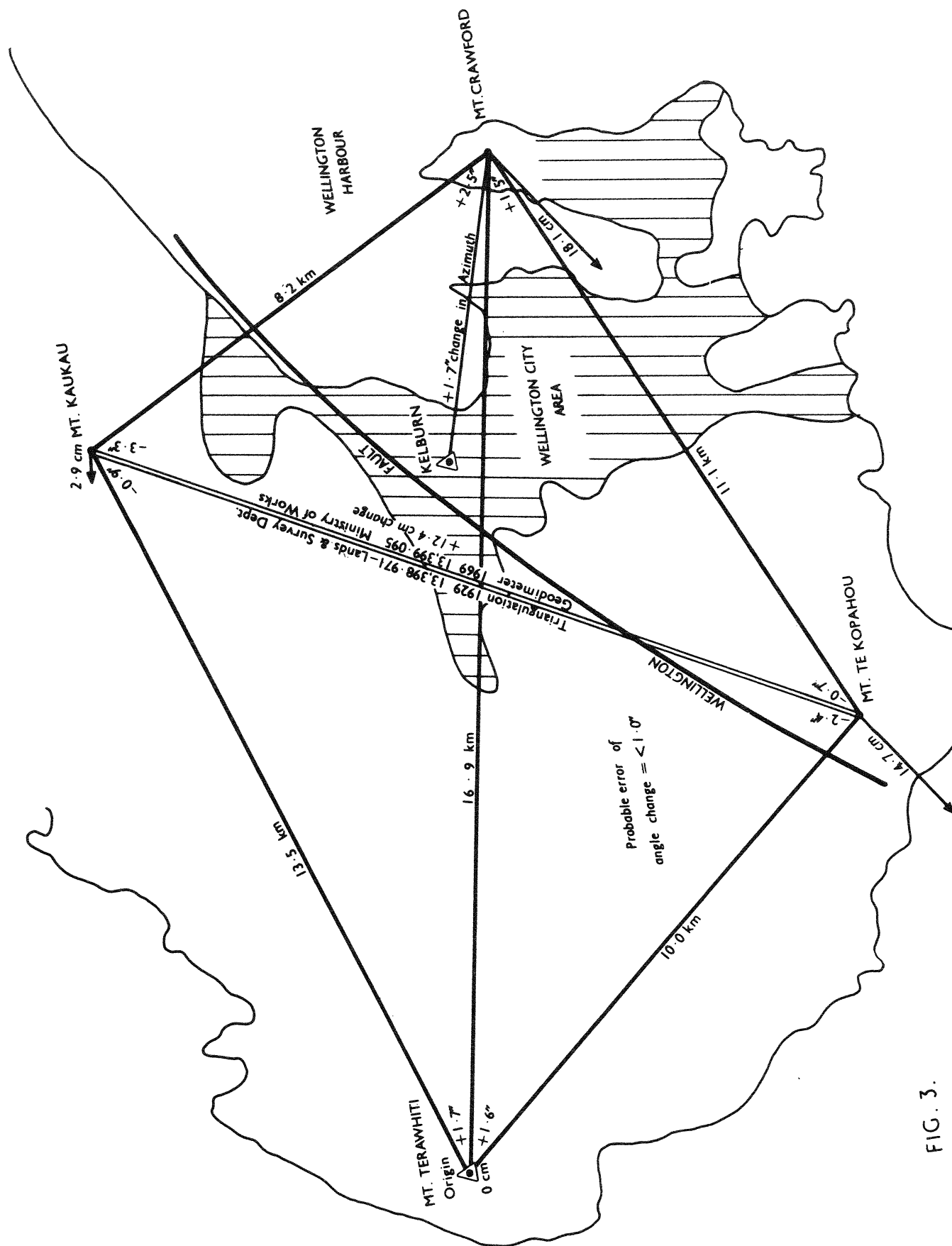Recent Tectonic Zone

(Zone of frequent tectonic
activity during
the last 20.000 years.)

Scale

| 50 | 0 | 50 | 100 | 150 |

Miles

HOPE FAULT

ALPINE FAULT

FIG. 2

MT. CRAWFORD

WELLINGTON HARBOUR

+2.5"

+1.5"

18.1 cm

+1.7"change in Azimuth

KELBURN

WELLINGTON CITY AREA

FAULT

8.2 km

MT. KAUKAU 2.9 cm

-3.3"

-0.9"

11.1 km

Triangulation 1929 13,398.971—Lands & Survey Dept.
Geodimeter 1969 13,399.095 Ministry of Works
+12.4 cm change

16.9 km

WELLINGTON

Probable error of
angle change = <1.0"

-0.7"

-2.4"

MT. TE KOPAHOU

14.7 cm

13.5 km

10.0 km

MT. TERAWHITI
Origin
0 cm
+1.7"
+1.6"

FIG. 3.

	Eastern Ranges North Island			Marlborough		
	Waiohine Range Terraces	Ruahines	Tararuas	Branch Range Terraces	Saxton Range Terraces	Inland Kaikouras
Recent 20,000 years	H = 10 V = 1.1			H = 11 V = .4		
End 1st Stadial Last Glacial 35,000 years	H = 9.1 V = 1.8				H = 9.4 V = .52	
Quaternary $2\frac{1}{2} \times 10^{6}$ years		H = 6.1 V = 1.8				V = 1
Pliocene 7×10^{6} years			H = 5.2 V = 1.6			V = 1.2
Mid. Miocene 18×10^{6} years						H = 3.4 V = 1.5