NEW ZEALAND EARTHQUAKES AND PLATE TECTONIC THEORY

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ABSTRACT

The rates and direction of shear strain from geodetic data and the direction of slip from earthquake mechanism studies in New Zealand are in good agreement with plate tectonic theory. The relative motion of the Pacific and Indian plates in the last 100 years has been accommodated by distributed strain in a belt at least 100 km wide crossing New Zealand from north-east to south-west. Strain rates within this belt exceed $3 \times 10^{-7}$/y and average $5 \times 10^{-7}$/y in Marlborough.

Under the eastern North Island and northern part of the South Island the Pacific plate underthrusts the overlying belt of deformation. Large thrust earthquakes are episodically generated, perhaps by locking of the thrust. Not all relative plate movement is transformed into displacement on faults - a substantial fraction is taken up by aseismic and anelastic deformation within the plate boundary zone. The relative proportion of aseismic and seismic deformation may vary in different regions.

INTRODUCTION

Geophysics Division, D.S.I.R., has published a number of papers in recent years, loosely within the framework of the Earth Deformation Programme initiated by the Royal Society of New Zealand in 1973, that may assist in understanding the processes that lead to earthquakes in New Zealand. While the research is continuing, now is a suitable time to summarise some of the conclusions and current ideas. Most of the findings and data have been published elsewhere in the papers cited in the text. The purpose of the present article is to present a review of these studies for the broader readership of the N.Z. National Society for Earthquake Engineering.

The theory of plate tectonics, formulated around 10 years ago, arose in large part as an explanation for the global distribution and mechanisms of earthquakes. Earthquakes are generally restricted to continuous linear segments that divide the earth's surface into a mosaic of 'plates' that are themselves comparatively aseismic. As the plates move passively over the surface of the earth earthquakes are generated at their boundaries. With suitable seismometers positioned around an earthquake epicentre it is possible to recognise a pattern of compressional or dilational first motions in the wave train proceeding from the focus so that the orientation of the fault plane is known then the direction of slip can be also obtained. Earthquake mechanisms have assisted in the identification of three classes of boundary between plates that are in good agreement with other geological and geophysical information. These are: Rifts, Subduction zones, where a slab of high seismicity can be recognised dipping steeply from near a trench on the sea floor under active andesitic volcanoes to depths of several hundred kilometres; earthquake mechanisms commonly indicate compression normal to the boundary; Transform faults, long steeply dipping faults with lateral offsets of many tens or hundreds of kilometres with earthquake mechanisms of simple shear parallel to the fault. In purely kinematic terms we can refer to these classes as being extensional, compressional or translational boundaries.

The directions of motion across the boundaries between plates can be obtained from the earthquake mechanism and, more importantly, from the trend of transform faults. The rates of motions are given by the separation of linear magnetic anomalies of known age on the sea floor on either side of the mid-oceanic ridges. The separation between the pair of magnetic anomalies identified by the number '3', formed about 5 million years ago gives the average rate in the last 5 million years. This value is probably a good estimate of the present day rate of plate motion as the rate of separation can be shown to be remarkably uniform in time from older magnetic anomalies. Using this type of information from world wide sources, Chase (1978) has computed the relative plate motion vectors for all major plate boundaries.

The importance of plate tectonics to the study of New Zealand earthquakes is that New Zealand lies across the boundary between the Pacific and Indian (or Australian) Plates (Figure 1). According to Chase, the Pacific is moving with respect to the Indian plate around a pole near 60°S and 175°E at a rate of 1.26°/million years. This means that in the vicinity of Wellington the Pacific plate is moving due west at a rate of 50 mm/y, with rates being faster to the north and slower to the south, about 40 and 60 mm/y near the latitudes of Dunedin and Auckland respectively. The 95% confidence limits from Chase's data set would suggest

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that these values are known to about $\pm 7^\circ$ in direction and $\pm 5$ mm/y in rate. It is the stresses developed between the plates that are presumably the ultimate cause of most New Zealand earthquakes. However, in moving from a global to a more regional scale it is readily apparent that the simplified classes of plate boundary are not directly applicable. The shallow seismicity of New Zealand (Figure 2) is fairly spread over a zone at least 100 km wide and there are no clear cut discontinuities that might be identified with extensional, compressional or transtensional boundaries. Moreover the direction of relative plate motion is oblique to the north-east/south-west trend of the boundary indicated by the seismicity so that both compressional and translational components of motion must be present.

The great success of plate tectonics is that it pulls together an immense amount of information including morphology, tectonics and geology - all characteristic of a subduction zone and the heat flow, as well as seismicity. But most importantly it is a quantitative theory with the rates and directions of motion being determined from many independent sources of data. It is in this light that the recent work in Marlborough is very relevant.

GEODETIC STRAIN IN MARLBOROUGH

Bibby (1975, 1976) compared triangulation surveys made in Marlborough during the period 1875-84 with repeated triangulations made in 1951-60. The triangulation covers almost continuously a broad band from Kaikoura to West of the Wairau Valley, a distance of about 100 km (Figure 3). Changes in the observations of angles give estimates of shear strain and measurements were obtained at a number of localities by combining data in parts of the net (Figure 4). An additional survey made in part of the region in the 1920’s allows examination of the possibility that the shear strain varied in time, but no such variation is apparent. From the data in Figure 4 several points are made. Firstly, there is no difference in strain between triangulation made in the 19th and 20th centuries with those made about 1931 show a variation is apparent. From the data of 1875-84 with repeated triangulations made in the 1930’s (Adams and Ware, 1977) (Figure 5). It shallows to depths of about 50 km under the axial ranges of the Tararua and Ruahine Ranges. A shallow dipping zone of high seismicity and gravity anomalies under the east coast of the North Island is the Hikurangi Trench which lies on the extension of the Kermadec and Tonga trenches. Under the North Island is a slab of high seismicity dipping northwards to depths of about 300 km (Adams and Ware, 1977) (Figure 6). It shallows to depths of about 50 km under the axial ranges of the Tararua and Ruahine Ranges. A shallow dipping zone of high seismicity can be identified under the east coast of the North Island rising from depths of about 50 km under the axial ranges at an angle of about 120° and if extended would reach to the Hikurangi Trench (Figure 8). The active tectonic and gravity anomalies of the North Island are all characteristic of a subduction zone and according to plate tectonic theory represents part of the Pacific plate underthrust beneath the overriding Indian plate.

The relative extension and compression we see in the triangulation data is unusual, but is consistent with earthquake mechanisms in the crustal rocks overlying the subducted plate. These too show tension axes normal to the boundary. The extension suggests that the Pacific and Indian plates are totally decoupled along the surface of the subducted slab with the relative plate movement being taken up by an aseismic slip on the surface of the slab.

EPISODIC EXTENSION AND COMPRESSION

Extension normal to the boundary has not always been the rule, however. Comparisons of triangulation made in the 19th century with those made about 1931 show a strong component of compression normal to the plate boundary. It is only after the great 1931 Hawke’s Bay earthquake that extension became evident.

This earthquake, of magnitude 7.9 (Richter, 1958), evidently originated on a north-westward dipping thrust, with a
FIGURE 1: PLATES AND PLATE BOUNDARIES NEAR NEW ZEALAND. THE ARROWS SHOW THE DIRECTION AND RATE (IN MILLIMETRES PER YEAR) OF THE MOTION OF THE PACIFIC WITH RESPECT TO THE INDIAN PLATE BASED ON THE CHASE (1978) POLE — THE POSITION OF WHICH IS SHOWN BY THE SOLID CIRCLE.

FIGURE 2: SHALLOW SEISMICITY IN NEW ZEALAND FOR A TWENTY YEAR PERIOD. THE EPICENTRES ARE ALL EARTHQUAKES REPORTED IN THE NEW ZEALAND SEISMOLOGICAL BULLETINS IN WHICH THE DEPTH OF THE HYPOCENTRE IS RESTRICTED TO 12 KM OR 33 KM.

FIGURE 4: SHEAR STRAIN COMPONENTS CALCULATED FROM RETRIANGULATION DATA PLOTTED AGAINST DISTANCE FROM THE WAIRAU FAULT. THE BARS SHOW STANDARD ERROR. (FROM BIBBY, 1976)


geodetically determined north-west/south-east shortening of about 3 metres. The principal axis of compression at the time of the earthquake was 125° in azimuth, like that of the survey strain prior to the earthquake. A large earthquake in the following year at Waioha showed a principal axis of compression more like those of the present day, around 70°. It was also observed that both before and after the earthquake there was a continuing simple shear strain parallel to the boundary in the geodetic data.

These observations lead to the hypothesis of episodic compressional and extensional phases within the crust overlying the subduction zone along the east coast of the North Island. The simplified structure may look something like that of Figure 7. The motion of the Pacific plate (on the right) with respect to the Indian plate (left) is oblique to the boundary with both parallel and normal components. The parallel component is accommodated by continuous shear strain in steeply dipping fault and shear zones cutting through the overlying crust. The normal component is today taken up by creep or aseismic slip along the subduction thrust. But periodically the subduction thrust locks and the compressional component between the plates is taken up by a compressional strain in the overlying rocks. Eventually the continuing compressional strain leads to rupture on steeply dipping faults releasing the stress and unlocking the subduction thrust for a new phase of aseismic slip.

Episodic compressional and extensional behaviour may also have occurred in the vicinity of Wellington. Repeated surveys in the Wairarapa and near Wellington City since around 1920 show a principal axis of compression oriented at about 115° with a compressional component normal to the trend of the plate boundary. But a repeated survey in the Tararua Ranges 1880-1912 show a compression axis of 070° indicating a component of extension normal to the trend of the plate boundary. Unfortunately this particular triangulation has not been repeated since 1912 so there may be an element of geographic rather than time variation indicated. Surveys near Wellington City in the periods 1912-1931 and 1914-1929 show a principal axis of compression much more nearly east-west than the later north-west/south-east. Together these data may be interpreted as indicating substantial extension normal to the boundary prior to 1920 and substantial compression after that time. The extensional phase suggests that the subduction thrust was unlocked, perhaps following the 1855 Wairarapa earthquake, and that the thrust was latter locked for some reason around 1920. The relative plate movement since that time has been accumulating as strain in the overlying crust. The total plate movement in the last 20 years that has accumulated as strain within the crust is about 3 metres, quite sufficient to produce a major earthquake.

SEISMICITY OF THE WELLINGTON REGION

A permanent telemetered network of sensitive seismometers has been in operation near Wellington since January 1976 with the objective of studying in detail the spatial and time varying distribution of local earthquakes. An analysis of the results to date is given by Robinson (1978). A plot of earthquake epicentres observed in the period January 1976 to September 1977 is shown in Figure 8 and a plot of the depth of earthquakes in north-west/south-east profile in Figure 9. The activity is generally diffuse (Figure 8) and the pattern does not vary much in time. The shallow seismicity (<20 km) does not correlate with major surface faults, a common feature in New Zealand seismicity. In profile the majority of events define a band of relatively intense activity at depths of from 2 to 4 km. Also aseismic creep on faults like that inferred for the subduction thrust at Hawke's Bay, and observed in California, may occur in crustal rocks.

The subducted Pacific lithosphere extends no further south than a line from Kaikoura to north-west Nelson as the intermediate depth earthquakes of the Hikurangi subduction zone are found only well above the band of relatively intense activity at the North Island. In profile the majority of events define a band of relatively intense activity at depths of from 2 to 4 km. Also aseismic creep on faults like that inferred for the subduction thrust at Hawke's Bay, and observed in California, may occur in crustal rocks.
We have two lines of evidence to suggest that a very substantial part of the strain observed geodetically is accommodated by anelastic processes.

1. In Marlborough, Lensen (1975) has observed that the total offset of data features across the major faults amounts to no more than $16 \pm 2$ mm/y displacement rate but the geodetic and plate tectonic rate is three times this at around 50 mm/y. As some of these offsets may have been caused by aseismic creep this suggests that less than one third of the strain will be eventually liberated by earthquakes on these faults.

2. The map of shallow seismicity (Figure 2) shows the seismic activity of the Southern Alps to be comparatively weak. Moreover no earthquake of magnitude greater than 7 has occurred in this region in the last 150 years. Yet we would infer from the geodetic data and plate tectonic theory that the strain rate is as high, if not higher, than in Marlborough. One interpretation is that the seismicity of the last 150 years is not a good guide to long term seismicity and eventually major earthquakes may occur to liberate the accumulated elastic strain. An alternative explanation is that the seismicity has always been low in this region and that only a very small fraction of the strain will ever be released as an earthquake, perhaps less than one tenth as the rocks are deforming in a ductile manner.

At this stage there is no clear evidence to choose between the two hypotheses. Clearly the answer to this question has a bearing on the likelihood of an earthquake in the Wellington region. For although the 3 m compression imposed since the inferred locking of the subduction zone is sufficient to cause a major earthquake only a small fraction of the compression may be available as stored elastic strain and most may be dissipated by anelastic processes like rock folding.

ACKNOWLEDGEMENTS

Figures 2, 7, 8, 9 and 10 have been reproduced with permission from articles originally published in the Geophysical Journal of the Royal Astronomical Society.

REFERENCES


FIGURE 10: SCHEMATIC DRAWING OF THE WELLINGTON REGION. THE LARGE ARROWS REPRESENTS FORCES DUE TO THE LARGE SCALE DRIVING MECHANISM OF PLATE CONVERGENCE WHILE SMALLER ARROWS REPRESENT THE RESULTING STRESS STATES DUE TO A LOCKED REGION EAST OF WELLINGTON RESISTING MOTION. (FROM ROBINSON, 1978).