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Variation in fault behaviour in different tectonic provinces of New Zealand

KELVIN BERRYMAN and SARAH BEANLAND

DSIR Geology and Geophysics, P.O. Box 30368, Lower Hutt, New Zealand

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Abstract—Fault behaviour appears to be different in different tectonic provinces of New Zealand. Uplifted Holocene marine terraces along the east coast of the North Island suggest time-predictable behaviour on reverse faults of the Hikurangi subduction margin. Major dextral faults of the strike-slip fault province in central New Zealand appear to show characteristic slip behaviour. Short normal faults in the Central Volcanic Region show highly variable increments of displacement. Finally, reverse faults of the Central Otago and Northwest Nelson region may have intermittently characteristic patterns of activity. Each of these behaviour patterns has been observed elsewhere, although, where there are good data to constrain the actual dates of palaeoearthquakes, a uniform slip or coupled model best explains most situations. Temporal and spatial clustering of fault rupture and major earthquakes are increasingly being recognized. It is crucial to obtain better dates and to determine the extent of individual rupture segments in order to better characterize fault behaviour. Non-characteristic fault behaviour has serious implications for current methods of seismic hazard evaluation. Seismic hazard studies should utilize specific fault data in preference to assuming a particular fault behaviour model.

INTRODUCTION

PROBABILISTIC models of earthquake occurrence are dependent on the assumption that faults, or fault segments, rupture at more or less regular time intervals, with constant increments of slip. They also assume that the late Quaternary or Holocene pattern of fault activity will continue into the foreseeable future. Although data exist that support such characteristic behaviour (Schwartz & Coppersmith 1984), few attempts have been made to test the validity of the assumptions over a range of fault styles and in different tectonic settings. Preliminary data now exist on the behaviour of faults in several tectonic provinces in New Zealand (Fig. 1). These can be compared with various fault behaviour models, in particular the characteristic earthquake model. The models considered in this paper are (Fig. 2): (a) variable slip; (b) uniform slip; (c) characteristic earthquake; (d) overlap (Schwartz 1989); and (e) coupled (Scholz 1989).

These models express different patterns of slip accumulation along a fault's length through several earthquake cycles and involve variations in displacement at a point per event, slip rate along the fault and earthquake size. In the variable slip model, displacement per event and earthquake size vary unpredictably, but overall the slip rate is constant along the fault. In the uniform slip model, displacement per event and slip rate are constant, but large earthquakes are interspersed with more frequent moderate-sized earthquakes. The characteristic earthquake model invokes constant displacement per event and constant earthquake size, but has variable slip rate along the fault. The overlap model is very similar to the characteristic earthquake model but concerns itself with fault behaviour near the ends of fault segments. In the coupled model (the only model actually based on physical and theoretical modelling), the pattern of earthquake and displacement size is dependent on the frictional properties of individual fault segments. With overall constant slip rate along the fault, each segment experiences equal displacements per event, but the earthquakes have variable sizes as more than one segment may rupture each time. The result is that each segment may have a variable, but non-random pattern of activity.

Another way to represent fault behaviour is to plot the distribution of displacement at a point through time (Shimazaki & Nakata 1980) (Fig. 3). If the overall slip rate at that point is constant, the different types of behaviour conform either to the variable slip model or to the uniform slip, characteristic earthquake and coupled models. The variable slip options can be explained either because a constant upper limit of strain must accumulate before rupture occurs and thus the time of rupture is proportional to the size of the prior event (time predictable), or because strain is released back to a constant level by each event and thus slip is proportional to the elapsed time (slip predictable). Uniform slip, characteristic and coupled behaviour require by definition that increments of slip or time remain constant at a point. As yet only in the coupled models does the vertical axis represent both displacement per event along a fault and recurrence intervals along a fault.

TECTONIC SETTING OF NEW ZEALAND

New Zealand is situated astride the obliquely convergent Pacific–Australian plate boundary in the southwest Pacific. Relative plate motion varies from 60 mm a^{-1} in the northeast to about 30 mm a^{-1} in the southwest where it becomes increasingly oblique (Walcott 1981). The main tectonic elements of New Zealand are (Fig. 1): the NW-dipping Hikurangi subduction zone along the east-

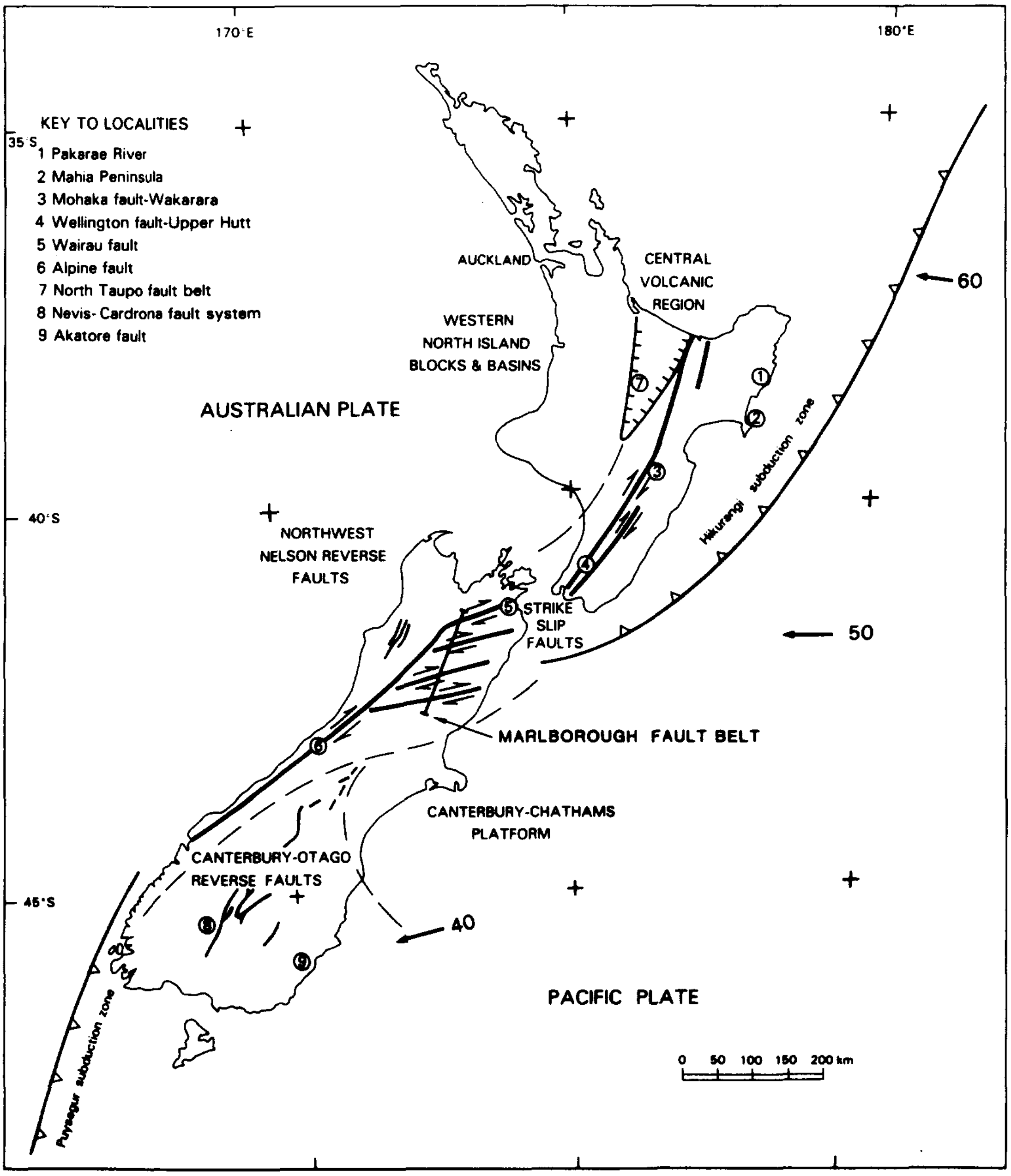

Fig. 1. Tectonic setting of New Zealand. Relative plate motions in mm a^{-1} are from Walcott (1981). Tectonic provinces, shown by dashed boundaries, are based on faulting style. Localities and faults discussed in text are numbered.

ern side of the North Island; the SE-dipping Puysegur subduction zone in the far southwest of the South Island; a transform fault system linking the two subduction zones which comprises the Alpine and Marlborough faults and extends northeast into the North Island as a series of strike-slip faults westward of the Hikurangi margin; and a backarc spreading area known as the Central Volcanic Region which is associated with the Hikurangi subduction zone.

Several different tectonic provinces, based on the tectonic elements outline above, can be defined (Fig. 1). These include two reverse fault provinces which lie in the northwest and southeast of the South Island.

FAULT BEHAVIOUR IN EACH OF THE TECTONIC PROVINCES

Hikurangi subduction zone

Along the east coast of the North Island, the Pacific plate is being subducted beneath the Australian plate at the Hikurangi Trough (Adams & Ware 1977, Reyners 1980, Walcott 1981) at a rate of about 50 mm a^{-1}. A well-developed accretionary prism comprises an imbricate thrust system and associated asymmetric fold structures (Lewis 1971, Lewis & Bennett 1985, Davey *et al.*

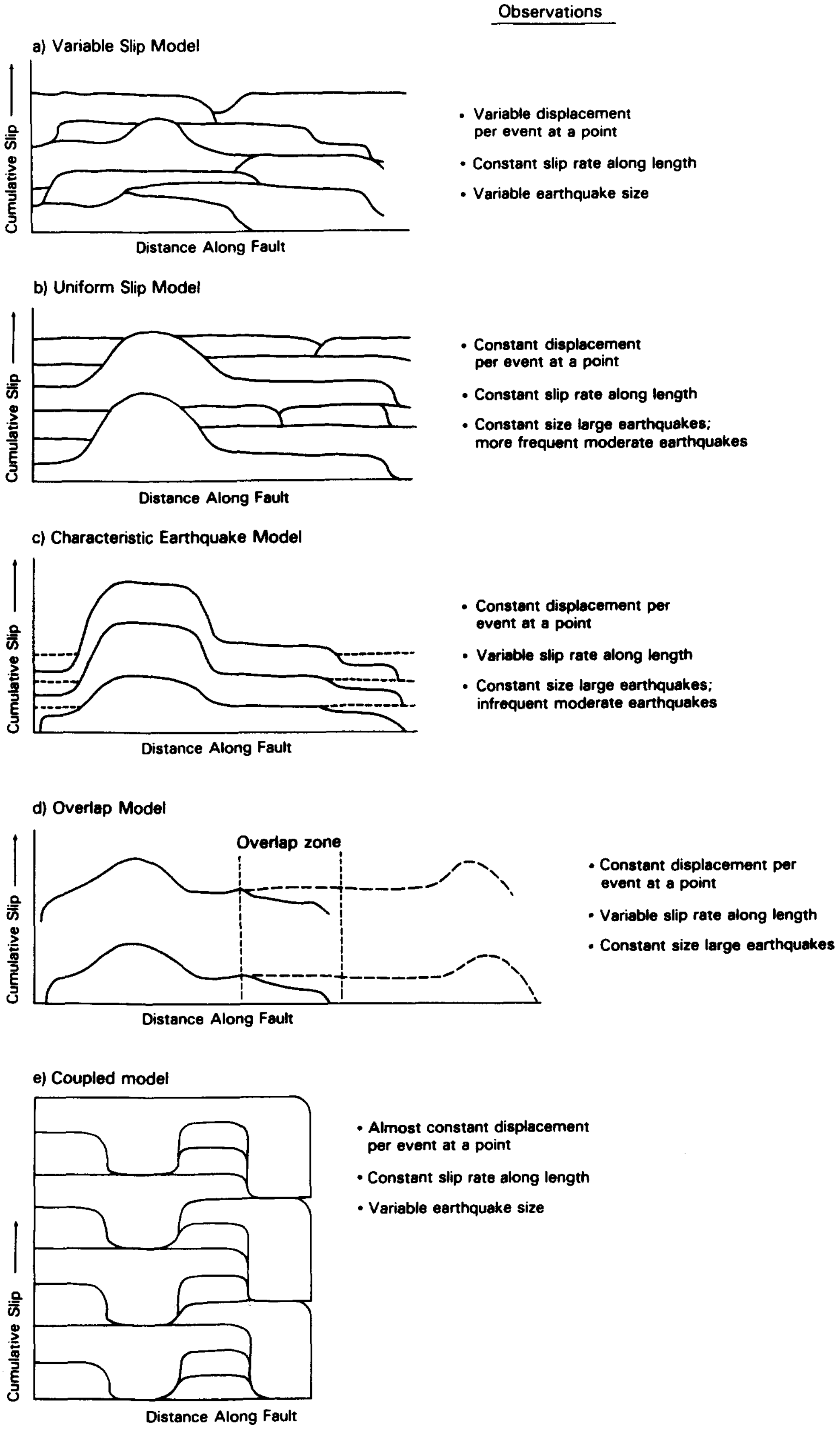

Fig. 2. Models of fault behaviour: (a)–(d) after Schwartz (1989); (e) after Scholz (1989). Only in model (e) can the vertical axis be read as time events as well as cumulative displacement.

1986). The present-day coastline coincides approximately with the highest accretionary ridge where extensive flights of marine terraces attest to rates of uplift as high as 3 or 4 mm a^{-1} (Berryman 1988).

At many localities along the 500-km-long eastern North Island coastline there are sequences of Holocene marine terraces aged 7000 years or less. The highest of these terraces is 27 m above present-day mean sea-level at the Pakarae River locality (Fig. 4). These Holocene marine terraces are interpreted as the result of episodic

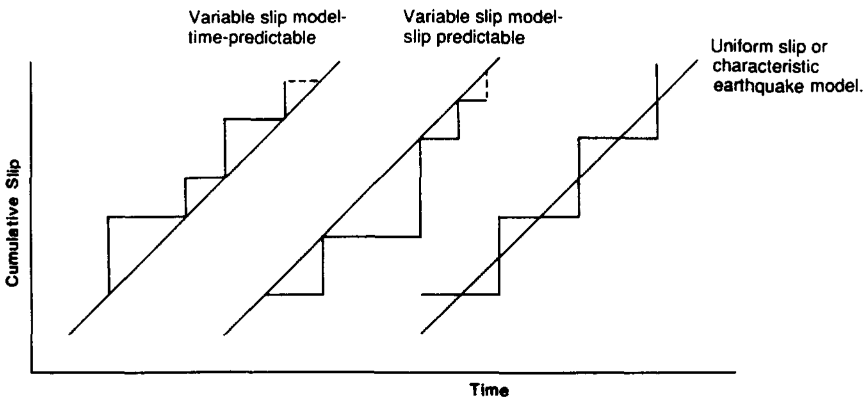

Fig. 3. Models depicting relationships between displacement per event and time between events at a point along a fault (after Shimazaki & Nakata 1980).

uplift associated with large earthquakes. This interpretation is based on characteristic stepped terrace morphology, clustering of ages of terrace deposits within subregions, and the occurrence of co-seismic coastal uplift in New Zealand in historic time (1855, 1931). Differential uplift across structures and distinct age variation at sub-region boundaries are also characteristic. Radiocarbon dates on shell and wood, which occur in beach deposits that overlie marine-cut shore platforms, or in beach ridges, effectively date individual earthquakes.

Different segments of the coastline reveal different earthquake histories (Berryman *et al.* 1989). The intervals between the six events at Pakarae River range from 400 to 1500 years (Fig. 4) and at Mahia Peninsula (five events) from 300 to 1600 years (Fig. 5). At both sites,

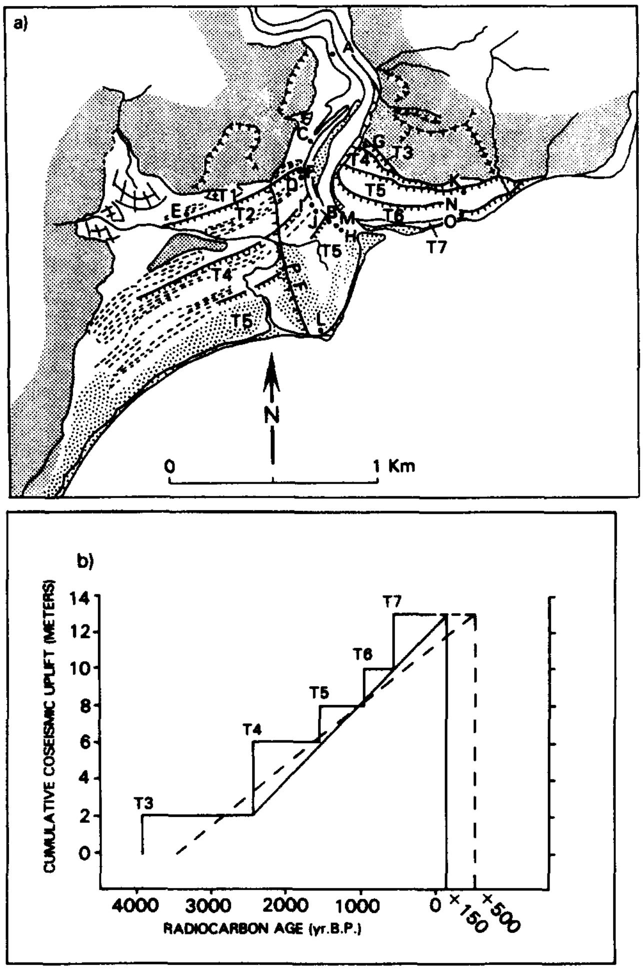

Fig. 4. (a) Geomorphology of the uplifted Holocene marine terrace sequence at Pakarae River. Letters refer to radiocarbon dating sites and PF refers to the Pakarae fault. Location shown on Fig. 1. (b) Age–height relationships of the marine terrace sequence T3–T7 preserved on the east bank of the Pakarae River. Regression lines illustrate how the data conform to a time-predictable pattern (from Ota *et al.* in press).

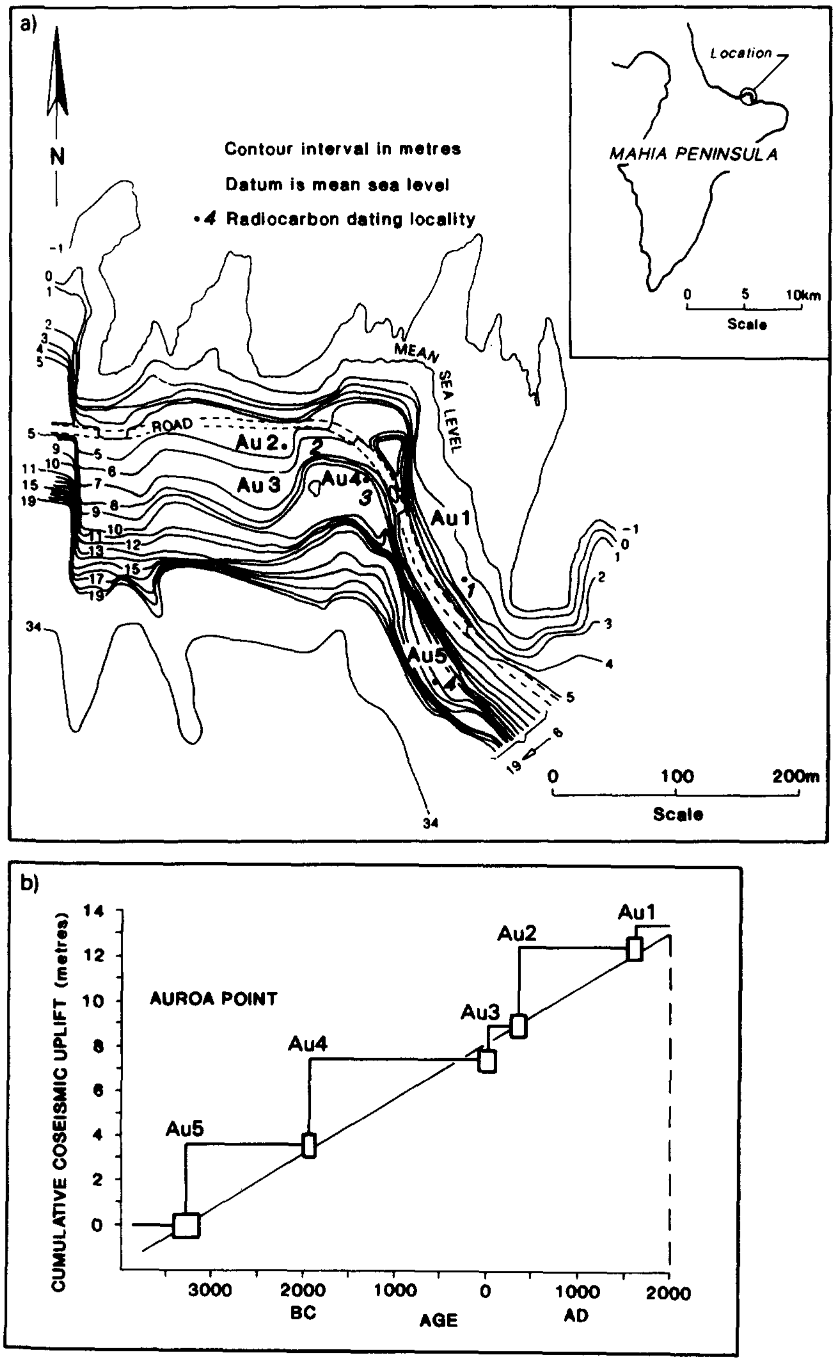

Fig. 5. (a) Geomorphology of an uplifted sequence of Holocene marine terraces at Mahia Peninsula. Location shown on Fig. 1. (b) Age–height relationships. Regression line illustrates how these data fit the time-predictable pattern of uplift.

uplift varies from 1.5 to 4.0 m. Small uplift events are followed by short interseismic intervals and large uplift events by correspondingly long interseismic intervals. Palaeo-earthquake dates from the whole coastal region also show some degree of temporal and spatial clustering (Berryman *et al.* 1989) (Fig. 6).

The faults in the Hikurangi subduction zone responsible for the uplifted terraces at Pakarae River and Mahia Peninsula appear to satisfy time-predictable behaviour (Shimazaki & Nakata 1980). The faults responsible for the Holocene terrace uplifts are considered to be individual local structures of the imbricate thrust system associated with deformation of the continental borderland (Berryman *et al.* 1989). Of the options shown in Fig. 2 only the variable slip model might apply, but less randomness than this is implied by time-predictable behaviour.

Strike-slip fault province

In the northern part of the South Island, several faults branch from the Alpine fault to form the strike-slip fault province extending through Marlborough and the eastern part of the North Island (Fig. 1). The relative plate motion results in almost pure strike-slip (dextral) faulting on NE trends in Marlborough, but a component of

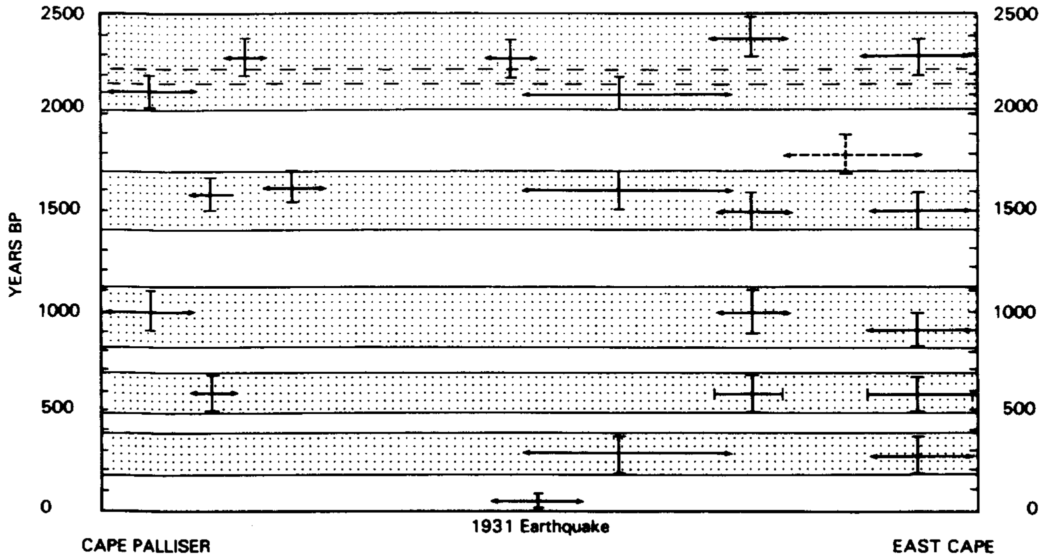

Fig. 6. Coast-parallel plot showing clustering in time (stippled periods) of palaeo-earthquakes in coastal areas of eastern North Island. Each of the symbols represents an earthquake, the length of the symbol representing the length of coastline affected and the height of the symbol showing the dating uncertainty (from Berryman *et al.* 1989).

compression on most faults of the North Island. Representative slip rates are 25–45 mm a^{-1} on the Alpine fault (Wellman 1984, Hull & Berryman 1986), 3.8 mm a^{-1} on the Wairau fault (Lensen 1976), 6.6 (+1.0, −0.6) mm a^{-1} on the Wellington fault in Upper Hutt (Berryman 1990) and about 3 mm a^{-1} on the Mohaka fault (Raub *et al.* 1987). The strike-slip province contains a number of fault strands of several hundred kilometres' length as well as various splay faults and associated folds and reverse faults. The distribution of segment boundaries on the main strands is however, poorly known, and there are very few data available to constrain the timing of palaeoseismic events.

Data on the sizes of individual displacements are available for several of the strike-slip faults and although the rupture lengths and dates of palaeoseismic events are unknown, some conclusions can be made about the patterns of activity on those faults. For example, the Mohaka fault in western Hawkes Bay (Fig. 1) had dextral displacements of 3.5–4.0 m in the last two events (Raub *et al.* 1987).

On the Wellington fault in Upper Hutt (Figs. 1 and 7), a low-level sequence of river terraces less than 15,000 years old records dextral displacement during several events (Berryman 1990). The smallest offset is 3.7 m, measured at an abandoned channel on the second to lowest terrace. Successively higher terrace risers or channels are dextrally offset by 3.7–4.7, 7.4 and 18–19 m (Fig. 7a). These values suggest single event dextral offsets of 3.4–4.7 m during the last five events. Still older terraces record progressively greater dextral offsets (Fig. 7b) and indicate a constant slip rate for the Wellington fault over the past 140,000 years (Berryman 1990).

Additional evidence for constant increments of fault slip in this tectonic province comes from the Wairau fault in Marlborough (Fig. 2), where repeated faulting increments of about 6.0 m have been identified (Lensen 1976), and from the northern end of the Alpine fault, where the past three displacements have measured 7.0 ± 0.5 m (Berryman & Beanland unpublished data).

In each of the above examples there is evidence that successive displacements, at the same locality, are approximately equal. If, like the Wellington fault, the slip rate is constant, then interseismic intervals must also be approximately equal. Such behaviour appears to conform with the original characteristic earthquake model as described by Schwartz & Coppersmith (1984). However, the constancy of slip rate along strike on both the San Andreas fault and the New Zealand examples suggests that strike-slip faults may conform more closely with the uniform slip or coupled models.

Normal faulting province of the Central Volcanic Region

Faulting within the Central Volcanic Region (Fig. 1) is distributed across many short structures, often in zones of multiple parallel strands (Fig. 8). Almost all faults trend northeast and have pure normal movement. Slip-rate data are available on only a few of the faults; but the Edgecumbe fault has a long-term vertical rate of about 1 mm a^{-1} (Beanland *et al.* 1990), and the Paeroa fault has a vertical rate of 3.3 mm a^{-1} (Nairn 1976). Three historical earthquakes, as well as preliminary palaeoseismic studies, provide some information on fault behaviour.

In 1987, the M_S6.6 Edgecumbe earthquake shook the eastern Bay of Plenty in the northeastern part of the North Island (Fig. 8). The main 7-km-long fault rupture occurred on the Edgecumbe fault, which crosses the 1850 year B.P. Taupo pumice alluvium surface of the Rangitaiki Plains. An earlier event on the Edgecumbe fault occurred approximately 800 years B.P., causing a maximum of 1.3 m vertical displacement, whereas the

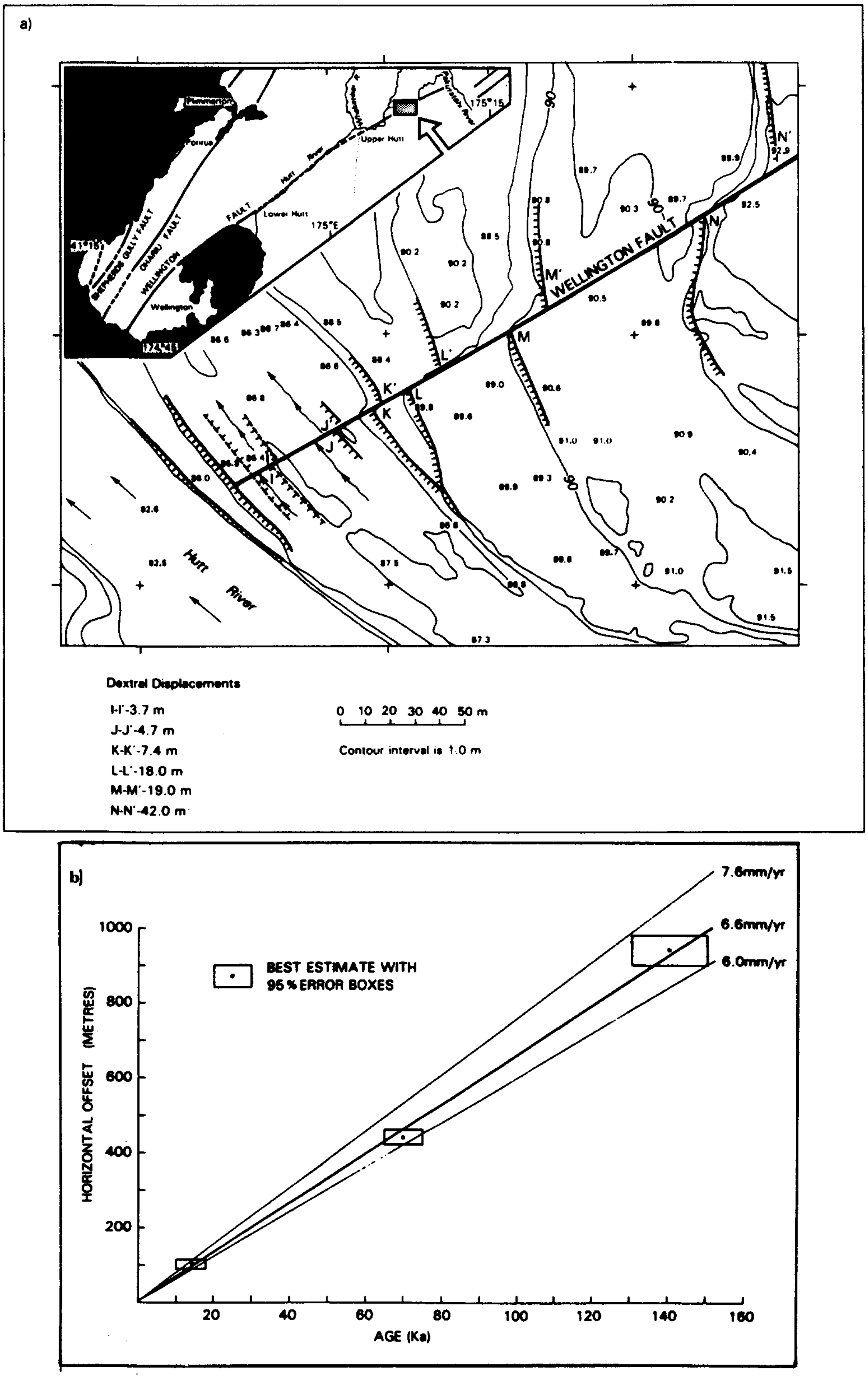

Fig. 7. (a) Displaced geomorphic channels and terrace risers along the Wellington fault at Upper Hutt, southwest North Island (Fig. 1). Inset shows study area in relation to Wellington and to other faults in the region. (b) Slip-rate graph for the Wellington fault at Upper Hutt. Boxes approximate 95% confidence limits and points represent best estimates of offsets and ages.

1987 earthquake had a maximum vertical displacement of 2.5 m (Beanland *et al.* 1989). Ten other fault ruptures were associated with the Edgecumbe earthquake, four of which had vertical separations of the order of 0.5 m. The remainder of the fault ruptures were small; approximately 0.1–0.2 m vertical separation superimposed on pre-existing fault scarps. These observations suggest that the sizes of fault displacements in successive events in the Rangitaiki Plains region are quite variable.

Further south, in the Taupo fault belt (Fig. 8), two earthquakes, or more properly two earthquake swarms, have produced historical fault rupture. The Kaiapo fault (Fig. 8) ruptured in 1922 with about 0.5 m vertical displacement and again in 1983 with 0.05 m displace-

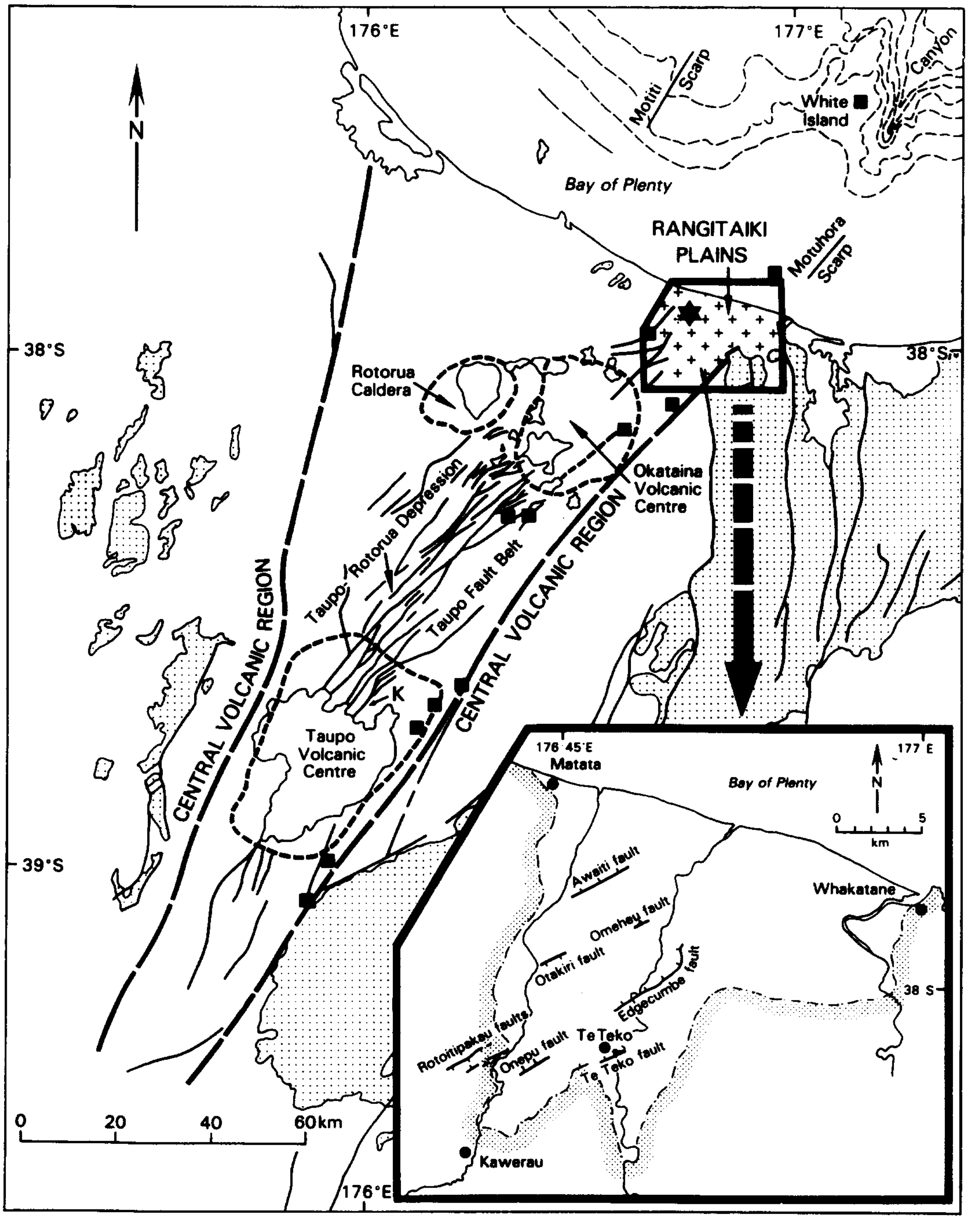

Fig. 8. Distribution of faults in the Central Volcanic Region, location of Taupo fault belt and location of the Rangitaiki Plains, and site of the 1987 Edgecumbe earthquake (★ marks location of Edgecumbe earthquake mainshock). The letter K identifies the Kaiapo fault which ruptured in 1922 and 1983. Filled squares mark andesite–dacite arc volcanoes, outcropping Mesozoic greywacke bedrock is stippled. Inset shows location of fault breaks formed during the Edgecumbe earthquake.

ment (Grindley & Hull 1986). Again, these data suggest non-characteristic fault behaviour, at least in terms of displacement, and the only model that suits is the variable slip model of Schwartz (1989). Whether or not such behaviour is time- or slip-predictable cannot be determined from our data.

Central Otago and Northwest Nelson reverse fault provinces

The Central Otago region is characterized by range and basin topography caused by movement on major reverse fault–fold structures (Figs. 1 and 9). Uplift on these structures occurs at rates of about 1 mm a^{-1} and has done so since about 2 million years ago, accommodating a small component of the relative plate motion. Similar reverse structures are present in Northwest Nelson on the other side of the Alpine fault (Yeats & Berryman 1987).

The Central Otago faults have recurrence intervals of several to tens of thousands of years. Different segments of the Nevis–Cardrona fault system (Fig. 9) for example, have recurrence intervals of 3600–6000 years (Upper Nevis Basin), 4000–9000 years (Cardrona Basin) and

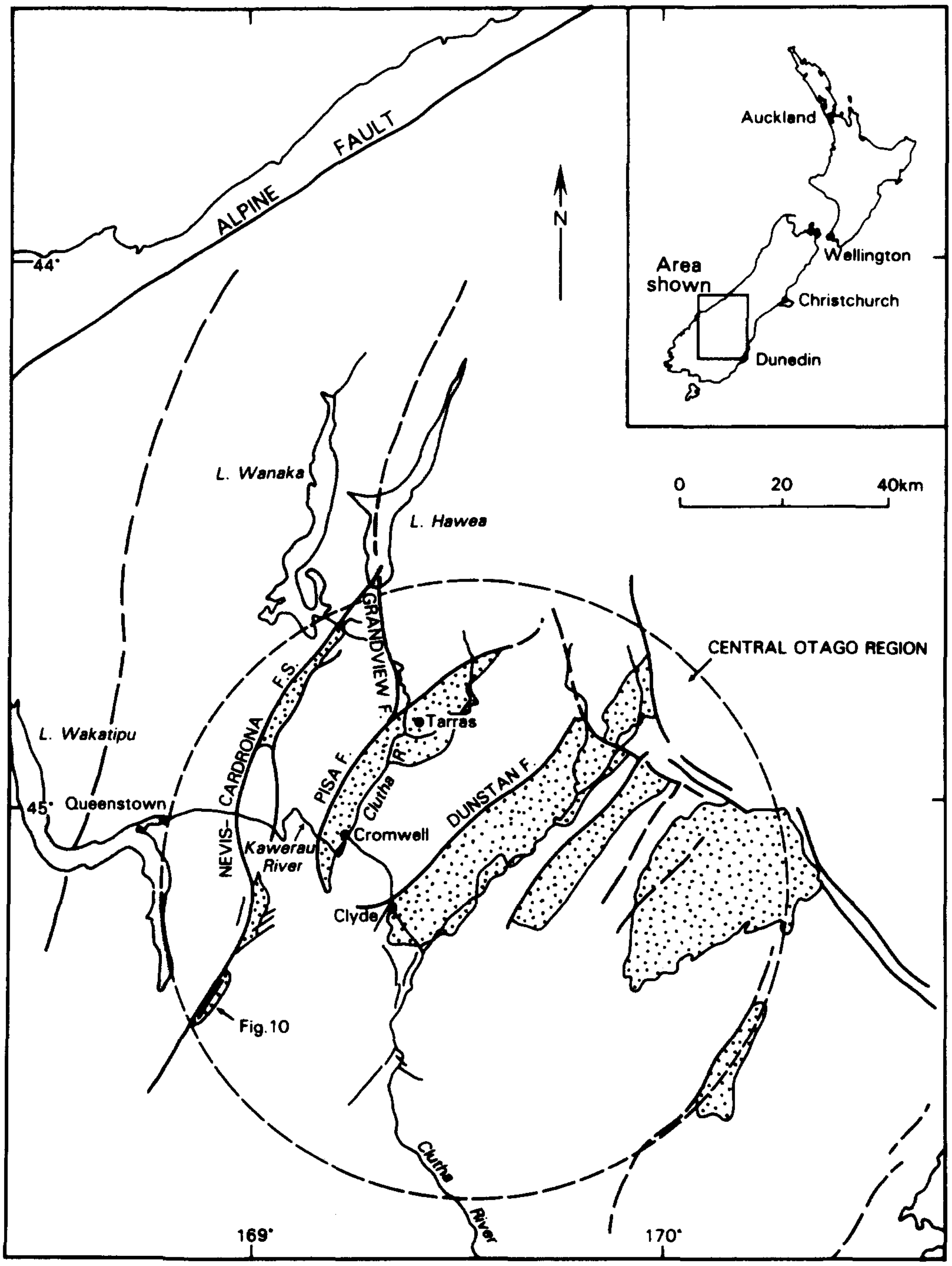

Fig. 9. Central Otago region of the South Island, showing major faults and structural basins (stippled), where Cenozoic sediments are present. Basement rocks, schist and greywacke, are blank. Location of Fig. 10 is shown.

<10,000 years (Lower Nevis Basin) (Beanland & Barrow-Hurlbert 1988). There is some evidence for approximately equal increments of fault displacement, 0.25–0.4 m, in the last four events on the Nevis fault (Fig. 10) (Beanland & Barrow-Hurlbert 1988), and repeated fault ruptures of 1.0–1.5 m have been described from the Akatore fault in east Otago (Makgill & Norris 1983). These data suggest that displacement per event at a point is approximately constant.

On the Pisa fault in Central Otago there is evidence that late Quaternary activity has occurred episodically with periods of activity and quiescence in the order of 10^4–10^5 years (Beanland & Berryman 1989). These conclusions are based on the deformation of a sequence of successively younger late Quaternary glacial fans, outwash or moraine. Older structures are in places overlain by undeformed intermediate-age sediments, while on other strands of the fault, younger fans are offset in several places along the fault zone. The youngest fans and river terraces cut across older faults and folds, and are undeformed. During the latest period of quiescence, since at least 23,000 years ago, the nearby Dunstan fault has been active.

Very few data are available for the faults of Northwest Nelson, but in 1968 a M7.1 earthquake on the Inungahua fault produced a rupture across a late last-glacial

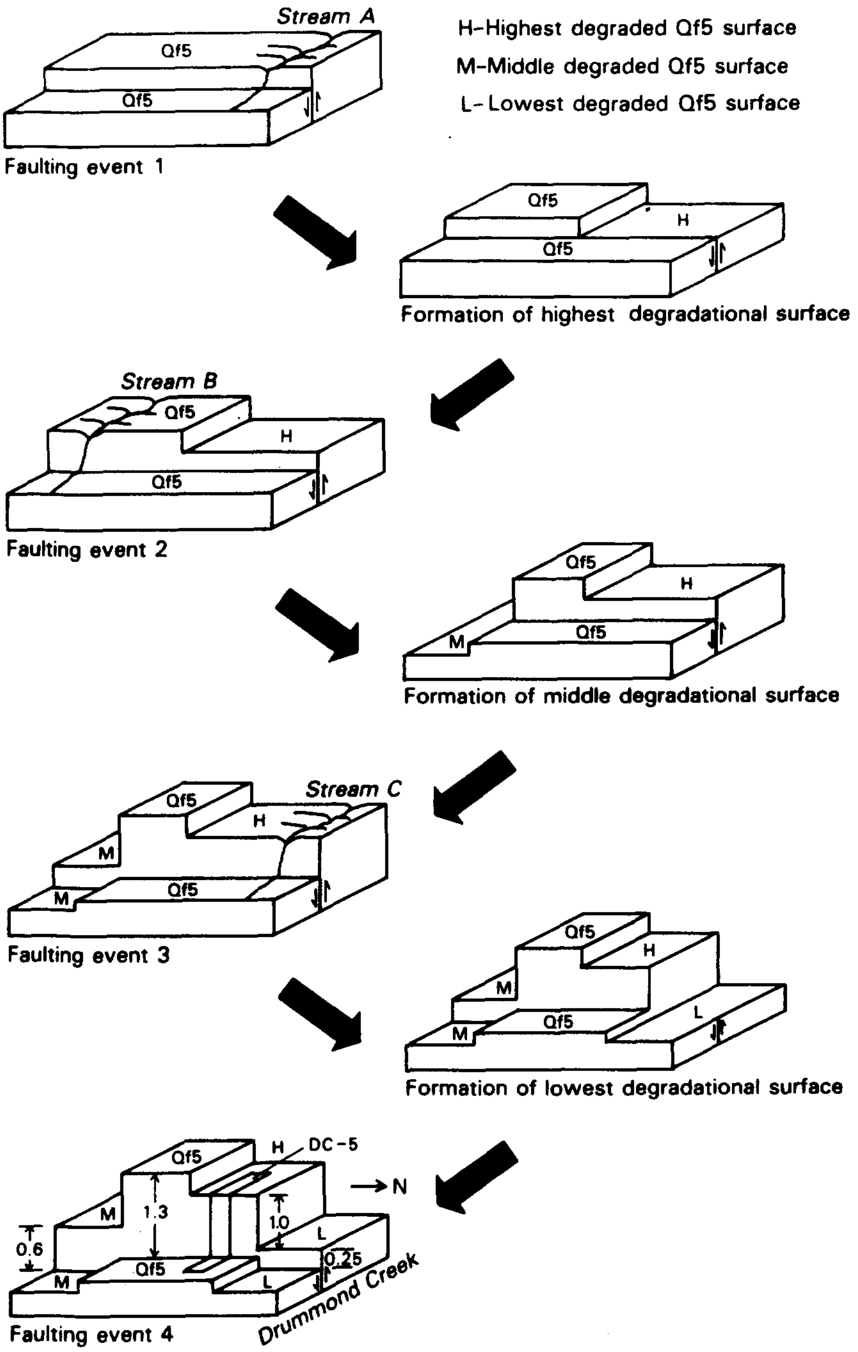

Fig. 10. Schematic representation of faulting and fluvial downcutting events that formed a terrace sequence at Drummond Creek, Upper Nevis Basin, Central Otago (Fig. 9). Increments of faulting range from 0.25 to 0.40 m illustrating near-constant displacements on this strand of the Nevis–Cardrona fault system (from Beanland & Barrow-Hurlbert 1988).

outwash terrace. This doubled the height of the pre-existing scarp. Berryman (1980) concluded that faults in this region have very long recurrence intervals of 6000 to more than 18,000 years. In contrast to Central Otago, Northwest Nelson is a region of high historical seismicity, including the 1929, M7.6 Murchison earthquake which ruptured the White Creek fault. It seems likely that the current phase of activity on faults in Northwest Nelson, noted for their very long recurrence intervals, is an example of temporal clustering. Evidence in Central Otago and Northwest Nelson for long-term periods of fault quiescence followed by episodic bursts of activity, as well as evidence of equal increments of fault slip, suggest an intermittently characteristic behaviour. None of the models discussed so far display such a pattern of activity.

DISCUSSION

Varying fault behaviour in the different tectonic provinces of New Zealand may reflect variation in tectonic setting and fault style. While several fault behaviour models have been discussed in recent years (e.g.

Schwartz & Coppersmith 1984, Nishenko & Buland 1987, Shimazaki & Nakata 1980, Scholz 1989, Schwartz 1989), none satisfactorily explain the full range of observed fault behaviour (Scholz 1989). In this report we attempt only to find similarities between the New Zealand data and well-constrained fault behaviour patterns elsewhere, for the purpose of directing further study and assessing the implications of various fault behaviour models on earthquake hazard assessments.

The fold and thrust belt of the Hikurangi subduction margin is characterized by time-predictable behaviour. While the palaeo-earthquakes identified in the Hikurangi margin occur on local structures rather than the subduction thrust itself, time predictable behaviour has been observed at several other subduction zones around the Pacific. At Cape Muroto, Shikoku Island, Japan, uplifted terraces record as many as eight major earthquakes, the last three or which occurred in historical time and formed one of the data sets for the time-predictable model of Shimazaki & Nakata (1980). Other similar examples include Middleton Island, Alaska, uplifted in the 1964 Alaskan earthquake (Plafker & Rubin 1978), and Mocha Island, Chile, uplifted in the 1835 earthquake (Kaizuka *et al.* 1973). It may be that movements on the local structures in New Zealand are accompanied by rupture on the plate interface, which, if the dip is sufficiently gentle, will not result in significant net regional uplift. Combined interplate and upper-plate motion satisfies geological data in elastic dislocation models of the 1855 Wairarapa earthquake and the 1931 southern Hawkes Bay earthquake (Darby & Beanland 1989, Sykes 1989).

Along-strike clustering of historical subduction zone earthquakes is well documented (e.g. Thatcher 1989), leading to the recognition of seismic gaps in which earthquakes have a high probability of occurrence. New Zealand data suggest similar temporal clustering for palaeoseismic events (Berryman *et al.* 1989) (Fig. 6). Variable uplift in subsequent events implies also that rupture lengths might also be variable and possibly overlapping. Historical events at Cape Muroto also had different rupture lengths. Segment boundaries therefore do not seem to be persistent in this environment and many ruptures may occur by triggering. A fault behaviour model that satisfies all of these characteristics is not yet available.

Some faults within the strike-slip province of New Zealand seem to exhibit characteristic earthquake behaviour. Such behaviour had been recognized on both strike-slip (San Andreas) and normal (Wasatch) faults in the United States (Schwartz & Coppersmith 1984). However, increasingly precise dating at Pallett Creek on the San Andreas fault (Sieh *et al.* 1989), and additional study of the overlapping nature of historical ruptures along that fault, suggest that a uniform slip model may be more appropriate (Schwartz 1989). Scholz's coupled model (1989) predicts a similar pattern of events or cumulative slip to the uniform slip model if sufficient events are sampled.

Many detailed fault studies are now finding evidence for clustering of events at one place in time and overlapping rupture segments (e.g. Rockwell 1989). Even at Parkfield on the San Andreas fault, where an average recurrence interval of 22 years is derived from the last six events, one event occurred only 12 years after the prior event (Bakun & McEvilly 1984). Caution about assuming the characteristic model for strike-slip faults is clearly necessary. Although increments of slip may be constant at a particular locality, fault rupture lengths may be variable.

Many of the normal faults in the Basin and Range Province of the United States do seem to behave according to the characteristic earthquake model, with equal increments of faulting and persistent segment boundaries. The Wasatch fault has now been extensively trenched and many palaeo-earthquakes identified (e.g. Machette *et al.* 1989, Schwartz 1989). Interestingly, such studies are also producing evidence that earthquakes may cluster in time along a particular fault (e.g. Wasatch fault zone; Schwartz 1989) and that a fault segment may experience a long period of quiescence (100,000 years) and then several 'characteristic' events (e.g. Lost River fault zone; Schwartz 1989, and the La Jencia fault of New Mexico; Machette 1986). The latter pattern of activity is similar to that proposed for the Central Otago reverse faults. In Central Otago there are insufficient data to recognize belts of nearly contemporaneous palaeo-earthquakes, such as the historically active Central Nevada seismic zone (Wallace 1984), but perhaps the present high rate of seismic activity in Northwest Nelson will prove to be such a spatial and temporal cluster.

Within the normal faulting province of the Central Volcanic Region, thin and weak seismogenic crust, coupled with major inhomogeneities in the upper crust such as magma bodies, may explain why fault behaviour is irregular. Some extension may occur aseismically. Examples of such erratic behaviour, that is, the variable slip model, are not commonly reported. The Central Volcanic Region is characterized by dense faulting and data on earthquake occurrence for many faults over a large region are needed to discern activity patterns. As discussed for subduction zones and strike-slip faults, triggering may be an important aspect in producing variable slip patterns.

Clearly, New Zealand data are presently insufficient to refine or establish better fault behaviour models, except perhaps in the Hikurangi subduction margin. The apparent differences in behaviour around New Zealand may decrease as more dates and segment lengths are obtained for palaeoseismic events and the dependence of apparent behaviour on different time-scales is better understood. International experience suggests that clustering of earthquakes in space and time is real and is partly dependent on triggering of adjacent faults and fault segments. As more data become available, the uniform slip or coupled models seem preferable to the characteristic model. It also seems likely that dip-slip and strike-slip faults will have real differences in behaviour because the slip direction will affect the persistence of segment boundaries. The inter-relationships between faults in a zone are also likely to be important, especially in accounting for clustered behaviour.

CONCLUSION

Patterns of fault behaviour have major implications for seismic hazard evaluation based on geological studies. While renewal models of earthquake hazard represent a significant advance on models that assume a poisson or random earthquake distribution in time (Schwartz & Coppersmith 1986), probability estimates of future hazard are generally derived from characteristic fault behaviour models. Fault hazard probabilities and earthquake magnitude assessments may be seriously in error in tectonic provinces where fault behaviour approaches the variable or even uniform slip models. Hazard evaluations may need to include thorough geological assessments of typical fault histories within the tectonic region rather than relying on a particular fault behaviour model. Increased efforts to date individual palaeoseismic events and to identify rupture segment boundaries are essential.

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