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SEISMIC HAZARD EVALUATION OF AN ACTIVE FAULT.

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ABSTRACT

Seismic hazard evaluation for the Hope Fault in New Zealand has been carried out based on detailed mapping and reviews of historical earthquake data in several recent studies. Methods used in evaluating seismic hazard and examples from recent studies are presented here.

1. INTRODUCTION

In areas of active faulting the seismic hazard evaluation of faults or fault segments is important. This evaluation involves estimation of earthquake magnitudes and the determination of anticipated displacements associated with the larger events. Such evaluation requires data from various approaches such as analysis of historical events, structural mapping of faults, slip rate determinations, displacement per event determination and dating of previous earthquakes.

This paper outlines some of the approaches that have been used by the author and other workers to collect such data from the Hope Fault in New Zealand.

2. STRUCTURAL ASPECTS OF THE HOPE FAULT

New Zealand lies across the boundary between the Pacific and Australian Plates. Oceanic crust of the Pacific Plate is being subducted westwards beneath the North Island and northern South Island, along the Hikurangi Trench. The velocity of relative plate convergence at the southern end of the Hikurangi Trench has been estimated at 54 ± 9 mma^{-1}, (Figure 1). In the northern South Island, the obliquely convergent relative plate motion is accomodated by the Marborough Fault System which comprises four major active faults, the most southern being the Hope Fault.

The Hope Fault extends 230 km from the Alpine Fault to the Kaikoura coast (Figure 1). A single major fault zone trace is visible for the central 150 km only, with each end consisting of many diverging splays where dextral displacement is dissipated as oblique slip and thrusting movements (Freund, 1971; Van Dissen, 1989).

For most of its length, the Hope Fault cuts Mesozoic Torlesse Supergroup basement rocks, consisting mainly of indurated greywacke and argillite with the active fault plane striking between 070° and 085° and usually dipping steeply to the NNW, (Freund, 1971; McMorran, 1991; Van Dissen 1991). The fault zone consists of a corridor of intensely crushed and sheared basement rocks up to 2 km wide (Freund, 1971; McMorran, 1991). Faults that have been active in the Late Quaternary are generally readily mapped as they displace Late Quaternary glacial and fluvial gravels.

The Hope Fault can be divided into discrete segments on the basis of fault continuity, with segment boundaries being indicated by releasing stepovers, substantial bends in the fault, or splaying of subsidiary faults (see Figure 1). The Hope River segment, which ruptured causing the 1888 Glynn Wye earthquake (Cowan, 1990) is the best example and is probably the best defined segment.

Perhaps the most striking structural feature of the Hope Fault is Hamner Basin, a 15 km wide releasing bend or stepover that separates the Hope River segment from the Conway segment. Such releasing structures tend to reduce the earthquake intensity by limiting the length of fault that can rupture in a single event.

The structural geometry of the Hope Fault varies along its length, from nearly pure strike-slip or transtensional movement (Cowan, 1989) in the central section of the fault, to transpression east of Hamner Basin (McMorran, 1991), and a progressively stronger oblique component towards the coast (Van Dissen, 1991). This change in structural style reflects the varying orientation of the fault plane to the relative plate motion vector, and the proximity to the Alpine Fault in the west and the subduction zone in the east. Variations in the estimated late Quaternary slip rate for the Hope Fault along its length reflect the change in faulting style.

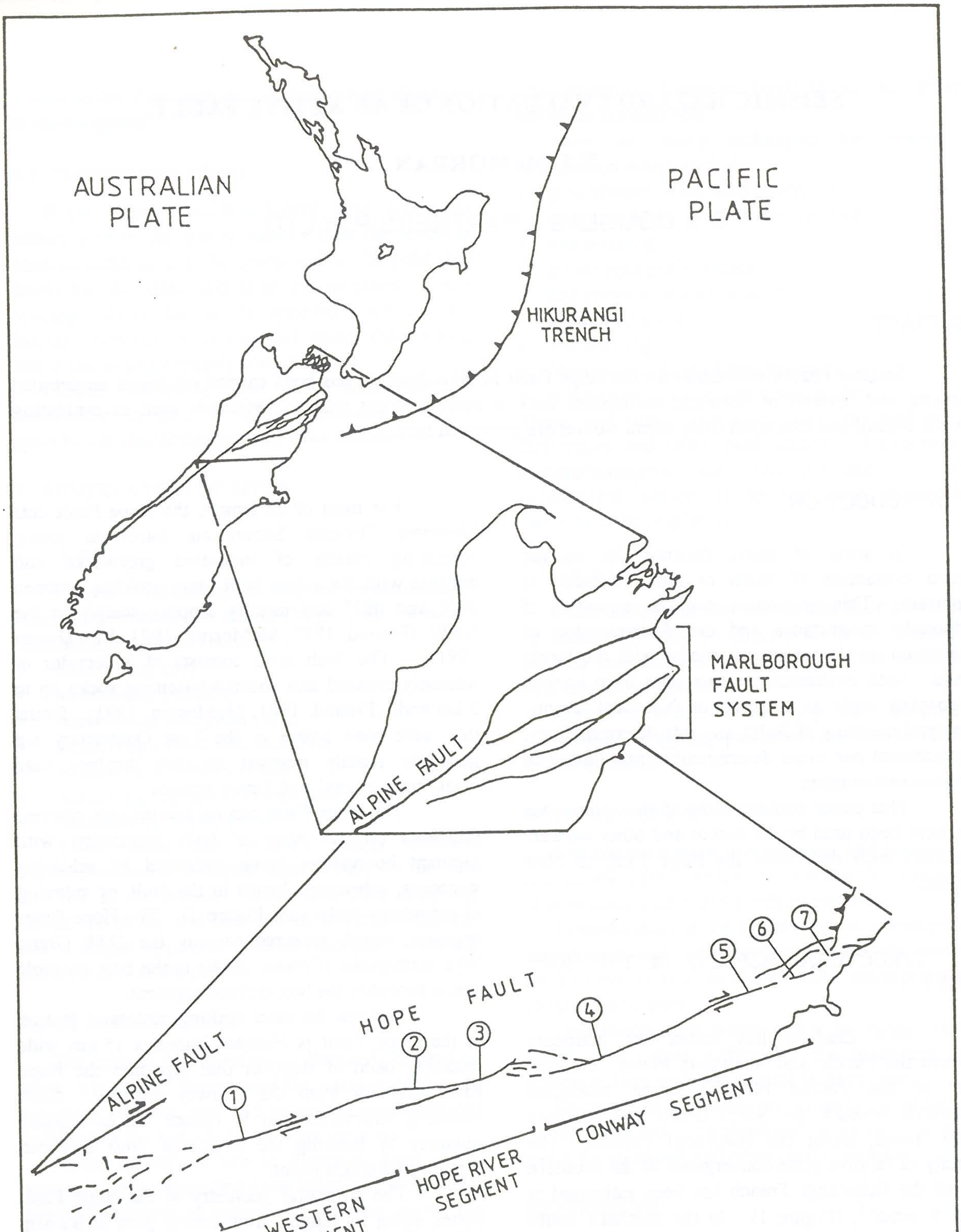

FIGURE 1. SCHEMATIC MAP OF THE HOPE FAULT SHOWING POSSIBLE SEGMENTATION. LOCALITY NUMBERS 1-7 REFER TO TABLE 1 FROM GREGG (1964); FREUND (1971); COWAN (1990); VAN DISSEN (1991)

Offset of geological and geomorphological markers across the Hope Fault varies from several metres for single event displacements to a total offset of 20 ± 2 km for displaced stratigraphic markers in the basement rocks (Freund, 1971; McMorran 1991). Displacement of geomorphological features such as river terraces and stream channels present an opportunity for estimating the Late Quaternary slip rate of faults, (Seih and Jahns, 1984; Berryman 1990). A summary of slip rate data for the Hope Fault is presented in Table 1, with methods described in Section 3.1.

Although the errors are often large, due to poor matching of degraded features or imprecise age determination, some significant trends are evident. The Late Quaternary dextral slip rate varies over relatively short distances along the Hope Fault. This variation is due to the effect of changes in fault geometry along its length as discussed above. Cowan, (1989, 1991), discusses the variation of displacement in a single earthquake event (Glynn Wye 1888) and demonstrates how these displacements relate to bends or stepovers in the fault trace. The displacement during that earthquake dropped by approximately 40% across a releasing feature (Lake Glynn Wye Graben) over a distance of only 2 km.

The ratio of horizontal to vertical displacement also varies along the fault. This ratio is also directly related to fault geometry, with a high ratio being indicative of a relatively oblique fault motion. The variations shown in Table 2 are consistent with the structural model of an increasing oblique motion component towards the east coast. The variations in obliquity and rate of displacement along the Hope Fault show that generalisations about fault behaviour, based upon limited data, should be carefully evaluated.

3. EVALUATING SEISMICITY OF THE HOPE FAULT

Evaluation of seismic hazard for a fault or fault segment often involves assessment of the length of fault segment that can rupture to generate an earthquake. This length can be related empirically or mathematically to probable earthquake magnitude (see Section 3.5). The assessment of Late Quaternary slip rate, displacement per event, and time elapsed since the last event on a fault all relate to the seismicity model. Examples from recent studies of the Hope Fault are used in the following sections to summarise the seismic hazard of the Hope Fault.

3.1 1888 Glynn Wye Earthquake

The only earthquake associated with surface rupture of the Hope Fault since European settlement is the 1888 Glynn Wye earthquake. Recorded in some detail by Alexander McKay (1890), this earthquake constituted one of the first detailed descriptions of a surface rupture earthquake and the first report of a strike slip earthquake (Sylvester, 1988).

Recent studies of the historical data and interpretation of the resulting geomorphological expression, suggest that the 1888 event caused a 30 ± 5 km long surface rupture of the Hope River segments (Cowan, 1989, 1991). During the earthquake (M_S7.0 - 7.3) local felt intensities of MMIX were experienced along the ruptured fault. Shaking attenuated rapidly perpendicular to the fault suggesting a shallow focus for the event.

TABLE 1 - SLIP RATES CALCULATED FOR THE HOPE FAULT.

Locality	Source	Slip Rate (mma^{-1})	h/v Ratio	Remarks
1. Harper Pass	Hardy & Wellman (1984)	14	-	28000 yr BP riser? displaced 200 m
2. Glynn Wye	Cowan (1990)	14 ± 3	-	17000 ± 2000 yr BP Moraine displaced 230 ± 20 m
3. Manuka Ck	Cowan (1989)	10.6 ± 0.3	15-17	3482 ± 77 yr BP riser displaced 36 ± 0.5 m
4. Hossack Stn	McMorran (1991)	11 - 26	30-33	2330-3690 yr BP stream channel displaced 40 - 60 m
5. Sawyers Ck	Van Dissen (1989, 1991)	20 - 35	14	2780 ± 560 yr BP riser displaced 78 ± 2 m
6. Goldmine Ck	Van Dissen (1989)	12 - 20		14375 ± 2000 yr BP fan displaced 230 ± 20 m
7. Hapuku R.	Van Dissen (1989)	2.1-7.5	1.5	6290 ± 950 yr BP boulder bar displaced 12.6 m and 8.5 ± 0.3 m

Note that variations in both slip rate and horizontal to vertical displacement ratio occur along the fault. These variations relate to the change in faulting style both locally and regionally. Locality numbers refer to Figure 1.

Severe shaking was also experienced on Hamner Plain during the earthquake, and for more than one month aftershocks were experienced, possibly relating to extension within the basin allowing stress concentration to be re-equilibrated .

Several offsets measured by displaced fencelines at the time of the earthquake showed dextral displacements of up to 2.6 m. Variations in offset were related by Cowan (1989, 1991) to changes in fault geometry as discussed in the preceding sections of this paper.

Recent evidence suggests that the 1888 Glynn Wye earthquake may have been a characteristic event for the Hope River segment and that similar events may occur every 80 - 200 years (Cowan and McGlone, 1991).

3.2 Late Quaternary Slip Rate

The displacement of Quaternary features such as stream channels, river terraces, fans etc., by active faults is a common way to assess slip rate. At Hossack Station, the Conway segment has offset a small stream and created a series of abandoned channels presenting an opportunity for estimation of slip rate. Trenching within two of the abandoned channels revealed a stratigraphy that could be simply divided into coarse grained channel deposits and fine grained flood overbank deposits, the latter presumably accumulating after abandonment of the channel (McMorran, 1991). Radiocarbon dating placed limits on the age of channel abandonment, and slip rates determined at this location are in the range 11 - 26 mma^{-1} for the late Holocene. Large uncertainties associated with timing of channel abandonment are reflected in this range.

A series of post glacial degradational river terraces at Hossack station show a dextral offset of at least 260 m (McMorran, 1991). Downcutting associated with the end of the last glaciation began approximately 13000 years BP suggesting a minimum late Quaternary slip rate of 20 mm per year.

A slip rate at Glynn Wye Station of 14 ± 3 mm per year was determined using offset of a terminal moraine of approximately known age (Cowan, 1990) by glacial chronology. Dating of Late Quaternary geomorphological features has also been carried out by weathering rind methods (Van Dissen, 1989). This technique involves measuring the thickness of weathering rinds on Torlesse sandstone cobbles which weather at a known rate (McSaverney, 1992). Dating of geomorphic features has been carried out with an accuracy of better than ± 10%. Another technique that has been used for the dating of geomorphic surfaces is lichenometry. Yellow rhyzocarpon lichen grow at a known rate such that diameter of lichen can be related to the age of Torlesse sandstone boulders on which it grows (Bull, pers. comm, 1991).

3.3 Displacement Per Event

The estimation of how much displacement will occur on a fault when it next ruptures can be important to the design of engineering projects that are located near to or across that fault. Return period for earthquakes occurring on a fault is often calculated from slip rate and average displacement per event. Also, the magnitude of earthquakes has been empirically related to maximum fault displacement associated with those earthquakes (Bonilla, et al., 1984). Estimating single event displacement can be done by historical review [as was the case with the 1888 Glynn Wye earthquake for the Hope River segment (Cowan, 1991)]. Other techniques include measuring offsets associated with single prehistoric earthquakes (Berryman, 1990; Seih and Jahns, 1984) or estimating offsets based upon rupture of other known faults (Van Dissen, 1991). For the Conway segment, no reliable single event displacements have been recorded. Some offsets of approximately 10 m of dextral displacement have been noted (Pettinga, pers.comm.) and these probably relate to two displacements of about 5 m each. Further mapping is required to evaluate the likely displacement per event for the Conway segment.

3.4 Dating of Previous Earthquakes

Age determination of previous fault rupture events on active faults enables an indication of the timing of the next earthquake generated by that fault. The dating of geomorphological features such as slope failures, depositional events of fault gouge material and tree damage (Cooper & Norris, 1991) can be used to date previous earthquakes. Cowan and McGlone (1991) dated five earthquakes for the Hope River Segment based on silt layers within a peat swamp. It was postulated that silt horizons were associated with abnormally high sediment supply caused by landsliding in the swamp catchment areas following earthquakes. The techniques of weathering rind dating (McSaverney, 1992) and lichenometry discussed earlier have also been used to date paleoseismic events by determining multi modal ages for boulders on or near fault scarps. The last earthquake on the Conway Segment may have been approximately 1838, which coincides with a modal peak for yellow rhizocarpon lichen (Bull et al., 1991). Many potentially datable landslides occur along the Conway Segment including several at Hossack Station. Dating of these features may help to improve the paleoseismicity record for the Hope Fault.

TABLE 2 - ESTIMATED EARTHQUAKE MAGNITUDES

	Length (km)	Surface Wave Magnitude (M_S)	Average Displacement (m)	Moment Magnitude (M_W)
Western Segment	50 ± 5	7.3	3 6	7.0 7.2
Hope River Segment	30 ± 5	7.0 - 7.2	2	6.8-6.9
Conway Segment	70 ± 5	7.4	3 6	7.2 7.4

NOTE: Expected earthquake surface wave magnitudes calculated using empirical formulae from Bonilla et al (1984). Moment magnitudes calculated using formulae from Hanks and Kanamori (1979), with estimated average displacements for western Hope Fault and Conway segments. For discussion and return periods refer Section 3.5.

3.5 Probable Earthquake Magnitude

Studies of active faults have shown that earthquakes can occur at regular intervals (return periods) with similar magnitudes. The Hope Fault may rupture in this way as studies of the Hope River Segment suggest (see Section 3).

For active faults, expected earthquake magnitudes and exceedence probabilities can be empirically determined from statistical analysis of historical earthquakes. Earthquake magnitude can be related to rupture length or maximum fault displacement (Bonilla et al., 1984; Slemmons, 1982). From the fault segment lengths shown in Figure 1, earthquake magnitudes of M_S 7.0 to M_S 7.4 are derived from the relationship of Bonilla et al., (1984), see Table 2. These figures have a 50% exceedence probability, for smaller exceedence probabilities, the distribution of historical earthquake events has a standard deviation of 0.3 M_S units.

Hanks and Kanamori (1979) relate fault rupture area to a scale of moment magnitude (M_W), where moment magnitude approximately equals surface wave magnitude (M_S) for rupture events between M_S 5.0 and M_S 7.5. For the Hope Fault moment magnitudes of between M_W 6.8 and 7.4 are predicted from the above method.

Return periods for earthquake events on the Hope Fault are determined from slip rates and known or estimated single event displacements (Van Dissen 1991; McMorran, 1991), or from indirect dating of prehistoric earthquakes, (Cowan, 1989, 1991; Cowan and McGlone 1991). No single event displacements are documented for the Conway segment and both Van Dissen (1991) and McMorran (1991) calculated return periods of between 90 and 600 years based upon estimated displacement during an earthquake. Single event displacements for the Hope River segment are based upon the historical observations of the 1888 Glynn Wye earthquake (McKay, 1890; Cowan, 1991). The return period calculated by Cowan and McGlone (1991) for the Hope River segments is 81 to 200 years. Few data for the western Hope Fault are recorded and return periods based upon estimated fault displacement of 3 m to 6 m are between 210 and 430 years for earthquakes of magnitude M_S 7.0 to 7.4.

4. CONCLUSIONS

From the above studies many aspects of seismic hazard evaluation, for areas where active faults are present, are discussed.

As a major active dextral strike slip fault, the Hope Fault must be considered a major contributor to the seismic hazard in the northern South Island. The structural model for the Hope Fault includes the subdivision into segments based on geometric and kinematic changes in the structural style of the fault along its length. Variations in both slip rate and obliquity of relative fault motion along the fault relate to proximity to the Alpine Fault and subduction zone to the west and east respectively. Fault segments are likely to rupture independently, and may do so with 'characteristic' earthquakes of relatively uniform magnitude and return period. Rupture of the three major segments are likely to generate earthquakes of M_S 7.0 - 7.4 with recurrence intervals of between 80 and 600 years. Earthquakes of that magnitude may cause local felt intensities of up to MMX along the ruptured fault. It is important to emphasise that evaluation of seismic hazard presented by an active fault must be carried out based on a sound knowledge of the structure and movement history.

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