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An interim classification of New Zealand's active faults for the mitigation of surface rupture hazard

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ABSTRACT: Interim Guidelines for mitigating the impacts of building on, or near, active faults have recently been promulgated in New Zealand. In the Guidelines, the defining fault-avoidance criterion for an active fault is its average recurrence interval of surface rupture. Here we present an interim classification of most of New Zealand's on-land active faults based on the fault-avoidance recurrence interval classes defined in the Guidelines. In assigning faults to specific fault-avoidance classes, we give preference to fault-specific recurrence interval data which, in general, is most complete for the principal faults in New Zealand. For the remainder, and majority, of active faults, where recurrence interval data are generally either less constrained or non-existent, we assign fault-avoidance classes, though with less confidence, based on an iterative combination of available fault-specific data, the use of fault-scaling relationships, and comparisons with similar better studied faults. For each fault we also note the level of confidence with which the fault is assigned to a particular fault-avoidance class. This indicates the precision (or lack thereof) with which active faults can presently be classified according to the fault-avoidance criteria defined in the Guidelines. It also highlights those faults where better constrained recurrence interval data will have the most benefit towards mitigating surface rupture hazard.

1 INTRODUCTION

The Ministry for the Environment, New Zealand, recently circulated Interim Guidelines for mitigating the impacts of building on, or near, active faults (Kerr *at al.* 2002). The aim of the Guidelines is to provide information about active faults, particularly fault rupture hazard, and to promote a risk-based approach when dealing with development in areas subject to fault rupture hazard. In the Guidelines, the defining fault-avoidance criterion for an active fault is its average recurrence interval of surface rupture. The Guidelines also advance a hierarchical relationship between fault-avoidance recurrence interval and building importance (Table 1), such that the greater the importance of a structure, with respect to life safety, the longer the avoidance recurrence interval. For example, only low hazard structures, such as farm sheds and fences (Building Importance Level 1 structures, for more detail see Kerr *at al*. 2002, and King *et al*. 2003), are allowed to be built across active faults with average recurrence intervals less than 2000 years. In contrast, in a "greenfield" setting, more significant structures such as schools, airport terminals, and large hotels (Building Importance Level 3 structures) should not be sited across faults with average recurrence intervals shorter than 10,000 years.

The Interim Guidelines do not, however, contain a listing of New Zealand's active faults grouped according to the fault-avoidance criteria in Table 1. The primary goal of this paper is to provide an interim compilation of such a listing, and, in doing so, hopefully facilitate the use and application of the Guidelines. Towards this end, we first outline the process by which surface rupture recurrence interval is derived, and briefly discuss the potential of using fault-scaling relationships to obtain an approximate estimate of recurrence interval when fault-specific data are less complete, or lacking (Tables 2 & 3; Figs 1 & 2). Then we present an interim listing in Table 4 of most of New Zealand's on-land active faults classified according to the recurrence-interval based fault-avoidance criteria defined in the Guidelines (Table 1).

Table 1. Relationships between fault class, average recurrence interval, and Building Importance Level

<table>
<tr><th rowspan="2">Active Fault Class</th><th rowspan="2">Average Recurrence Interval of Surface Rupture</th><th colspan="2">Building Importance Level* Limitations
(allowable buildings)</th></tr>
<tr><th>Previously subdivided and/or developed sites**</th><th>"Greenfield" sites#</th></tr>
<tr><td>Ia</td><td>≤2000 years</td><td>Building Importance Level 1 –
low hazard structures</td><td rowspan="2">Building Importance Level 1 –
low hazard structures</td></tr>
<tr><td>Ib</td><td>>2000 years to
≤3500 years</td><td>Building Importance Levels 1& 2a –
low hazard & residential timber framed structures</td></tr>
<tr><td>IIa</td><td>>3500 years to
≤5000 years</td><td>Building Importance Levels 1, 2a, & 2b –
low hazard & normal structures</td><td>Building Importance Levels 1& 2a –
low hazard & residential timber framed structures</td></tr>
<tr><td>IIb</td><td>>5000 years to
≤10,000 years</td><td rowspan="2">Building Importance Levels 1, 2a, 2b & 3 –
low hazard, normal & larger structures
(but not essential post-disaster facilities)</td><td>Building Importance Levels 1, 2a, & 2b –
low hazard & normal structures</td></tr>
<tr><td>III</td><td>>10,000 years
≤20,000?[##] years</td><td>Building Importance Levels 1, 2a, 2b & 3 –
low hazard, normal & larger structures
(but not essential post-disaster facilities)</td></tr>
<tr><td>IV</td><td colspan="3">Building Importance Level 4 –
Essential post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000? years[##]</td></tr>
</table>

* The definition of Building Importance Levels, as used here, is found in Kerr *et al*. (2002) and King *et al*. (2003), along with examples of the types of buildings within each level.
** Applies to sites that have been subdivided and/or developed prior to a specified, but as yet undefined, date.
[#] The definition of a "Greenfield" site has yet to be finalised.
[##] The defining recurrence interval for Active Fault Class IV has yet to be agreed on, but will probably be in the order of 20,000 years.

2 ESTIMATION OF RECURRENCE INTERVAL

In the Interim Guidelines, fault-avoidance classes are defined by bounding recurrence intervals of 2000, 3500, 5000, and 10,000 years (Table 1). For many of the principal active faults in New Zealand there are fault-specific recurrence interval data that can be directly used to place these faults into particular fault-avoidance recurrence interval classes (see Section 3 & Table 4). However, for the majority of active faults, recurrence interval data are generally less complete. In these cases, it is often possible to estimate an indicative recurrence interval, using fault-scaling relationships, from other fault rupture parameters for which there is more knowledge. Below, we briefly explore the derivation of average recurrence interval of surface rupture from fault slip rate and rupture length. The fault-scaling relationships we use to do this are listed in Table 2. Other potentially informative ways of viewing recurrence interval are as functions of seismic moment and single-event displacement, or magnitude and displacement; however, page-length restrictions do not permit us to do so here. We relate average recurrence interval of surface rupture (*RI*) to average net single-event displacement (*D*) and net slip rate (*SR*) as follows:

$$RI = D/SR \quad (1)$$

Key input parameters for many scaling relationships are seismogenic thickness, or down-dip rupture width, and style of faulting. Accordingly, our evaluation of recurrence interval based on slip rate and rupture length is subdivided into two regions: a) the Taupo Volcanic Zone (TVZ) typified by thin seismogenic crust, and normal faults, and b) the remainder of New Zealand typified by greater seismogenic widths, and longer strike-slip and reverse faults.

2.1 *Normal faults of the Taupo Volcanic Zone (TVZ)*

The region of most active faulting within the TVZ is defined by Villamor & Berryman (2001). Equation 2 (Table 2) was derived specifically for the TVZ, using seismological data from the TVZ, and we use it exclusively in our estimation of recurrence interval based on slip rate and rupture length. For TVZ normal faults, we adopt a down-dip rupture width of 10 km (Stirling *et al.* 2000; Villamor & Berryman 2001), and because the crust is thin, we do not consider normal fault rupture lengths in excess of 50 km (Table 3). Using Equations 2 & 7, single-event displacement (D) is solved in terms of rupture length, and using Equation 1, D is converted to required slip rate for recurrence intervals of 2000, 3500, 5000, and 10,000 years (Fig. 1).

Table 2. Fault-scaling relationships used to estimate average recurrence interval of surface rupture

Scaling relationship	Eq. No.	Units	Reference
Normal faults of the Taupo Volcanic Zone			
$\log m_o = 23.25 + 2.0 (\log L)$	(2)	m_o, dyne-cm; L, km	Webb *et al*. (2002)
Strike slip & reverse faults			
$\log m_o = 22.33 + \log W + 2 (\log L)$	(3)	m_o, dyne-cm; W, km; L, km; *	Webb *et al*. (2002)
$M_w = \log A + 3.98$	(4)	A, km^2; $A \leq 540$ km^2	Hanks & Bakun (2002)
$M_w = 1.33 (\log A) + 3.07$	(5)	A, km^2; $A > 540$ km^2	Hanks & Bakun (2002)
$M_w = 5.88 + 0.80 (\log L)$	(6)	L, km; $L > 50$ km	Stirling *et al*. (2002b)
Other equations			
$m_o = mLWD$	(7)	m, 2.7×10^{11} dyne/cm^2; L, cm; W, cm; D, cm	
$M_w = 2/3 (\log m_o) - 10.7$	(8)	m_o, dyne-cm	Hanks & Kanamori (1979)

Definitions:
m_o is seismic moment; L is rupture length; W is down-dip rupture width; M_w is moment magnitude; A is rupture area; m is rigidity
* When the available rupture width is greater than rupture length (L), then W is limited to L, otherwise, W is the total available seismogenic down-dip width.

Table 3. Scaling relationships, weights, and rupture widths used to derive single-event displacement

Displacement (for a given rupture length)	Rupture length	Scaling relationship	Equation (Table 2)	(weight)	Down-dip rupture width
Normal faults of the Taupo Volcanic Zone					
Displacement	≤ 50 km	Webb *et al*. (2002)	Eq. 2	(1.0)	10 km
Strike slip & reverse faults					
Displacement	≤ 25 km	Webb *et al*. (2002)	Eq. 3	(0.7)	20 km
		Hanks & Bakun (2002)	Eq. 4	(0.3)	20 km
	> 25, ≤ 50 km	Webb *et al*. (2002)	Eq. 3	(0.7)	20 km
		Hanks & Bakun (2002)	Eq. 5	(0.3)	20 km
	> 50, ≤ 100 km	Webb *et al*. (2002)	Eq. 3	(0.4)	17.5 km
		Hanks & Bakun (2002)	Eq. 5	(0.3)	17.5 km
		Stirling *et al*. (2002b)	Eq. 6	(0.3)	17.5 km
	> 100, ≤ 200 km	Hanks & Bakun (2002)	Eq. 5	(0.5)	17.5 km
		Stirling *et al*. (2002b)	Eq. 6	(0.5)	17.5 km
	> 200, ≤ 400 km	Hanks & Bakun (2002)	Eq. 5	(0.5)	12.5 km
		Stirling *et al*. (2002b)	Eq. 6	(0.5)	12.5 km

2.2 *Strike slip and reverse faults*

For the active faults outside the TVZ, we use a number of scaling relationships (Eqs 3-6) because no single relationship adequately covers the range of faulting styles, and rupture lengths and widths found throughout the remainder of the country. Table 3 lists the rupture lengths and widths over which we apply each relationship as well as the weightings we give to each relationship. Of the above scaling relationships, only Equation 3 is based specifically on New Zealand data, and we give it the greatest weight. The dataset used to derive Equation 3 does not contain earthquakes with rupture lengths greater than about 100 km, so we only use this relationship when $L \leq 100$ km. Equations 4-6 are based on amended and updated versions of the Wells & Coppersmith (1994) world-wide dataset, and we give these relationships equal weighting. The down-dip rupture widths listed in Table 3 are based primarily on the seismogenic thickness data presented by Stirling *et al*. (2000). Single-event displacement (*D*) is obtained from rupture length (*L*) through these scaling relationships (Eqs 3-6), and Equations 7 and/or 8. We fit a best-fit curve ($D = -4.63 + 4.64 (\log L)$; correlation coefficient R = 0.98) to the derived values of *D*, and the best-fit values of *D* are converted to slip rate, using Equation 1, for the recurrence intervals of 2000, 3500, 5000, and 10,000 years (Fig. 2).

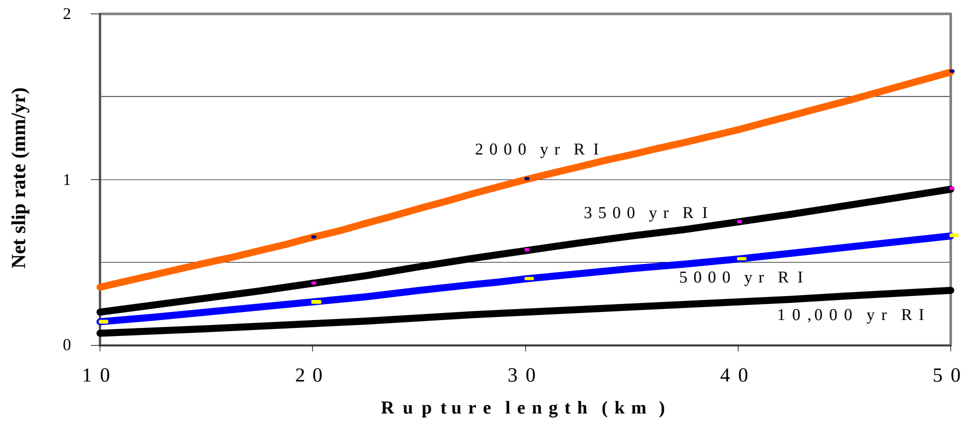
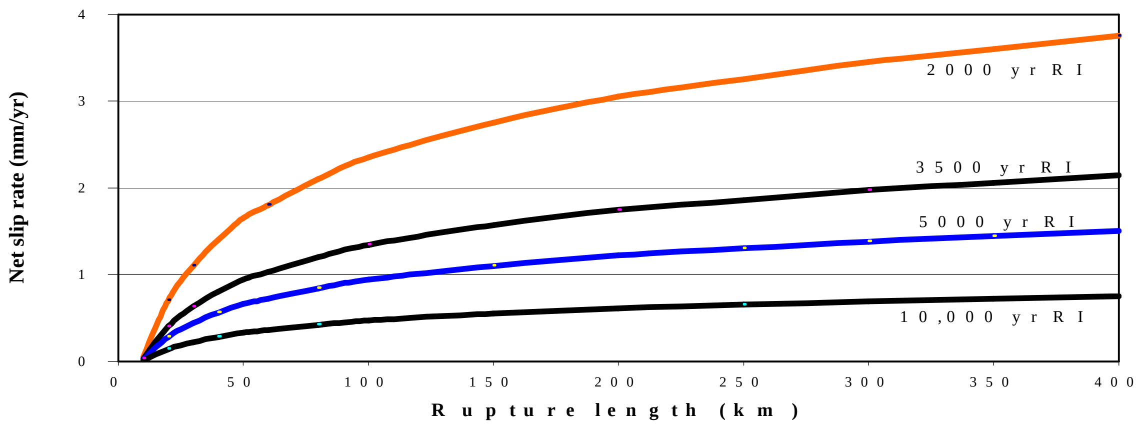


Figure 1. Indicative average recurrence interval (*RI*) of surface rupture as a function of slip rate and rupture length for normal faults in the Taupo Volcanic Zone (TVZ).

Figure 2. Indicative average recurrence interval (*RI*) of surface rupture as a function of slip rate and



rupture length for strike-slip and reverse faults.

3 ACTIVE FAULTS GROUPED ACCORDING TO RECURRENCE INTERVAL

The Interim Guidelines provide a framework for mitigating, in a consistent fashion, the impacts of building on, or near, active faults throughout the country. A necessary next step is to quantify fault rupture hazard, both with respect to location and level of recurrence. Below, we focus on the latter.

In Table 4, we present an interim compilation of most of the known on-land active faults in New Zealand classified according to the recurrence-interval based fault-avoidance criteria defined in the Guidelines (Table 1). In assigning faults to specific fault-avoidance classes, we give preference to well constrained fault-specific recurrence interval data. However, where fault-specific recurrence interval data are either less constrained or non-existent, we assign fault-avoidance classes, though with less confidence, based on an iterative combination of available fault-specific data, the use of fault-scaling relationships (e.g. Figs 1 & 2), and comparisons with similar better studied faults. Table 4 is based largely on: a) the considerable body of both published and unpublished New Zealand active fault research that has amassed over the last several decades (most of the published work is cited in Stirling *et al*. 1998, 2002a, and Pettinga *et al*. 2001, and the reader is referred to these papers for additional detail); and b) the professional judgement of the authors who have over 150 years of combined experience in active faulting research throughout New Zealand.

The fault-avoidance classifications of a significant number of faults listed in Table 4 differ from what would be implied from the fault recurrence intervals previously published in Stirling *et al*. (2000, 2002a). This is largely a consequence of improved slip rate estimates for many faults, the use of different scaling relationships, and our adopted procedure of assigning a fault to the shorter, more restrictive, fault-avoidance class if the "best-estimate" recurrence interval of that fault lies close to the boundary between two classes.

Table 4. Interim classification of most of New Zealand's on-land active faults, based on average recurrence interval of surface rupture, for the purpose of mitigating surface rupture hazard

Fault-avoidance recurrence interval class	Fault name*	Affected Regional Councils**	Confidence of classification[#]	Method of recurrence interval estimation[##]
	Alfredton	Wgtn, M-W	M	1, 2, 3
	Alpine	S, WC, Tas	H	1, 2, 3
	Amberley	C	M	2, 3
	Aorangi - Ngapotiki	Wgtn	M	3
	Aratiatia	W	M	3
	Awatere	WC, C, M	H	1, 2, 3
	Braemar	BP	L	4
	Clarence	WC, C, M	H	1, 2, 3
	Dreyers Rock	Wgtn, M-W	L	4
	Edgecumbe	BP	H	1, 3
	Fyffe	C	L	4
	Hanmer	C	L	3, 4
	Highlands	W, BP	M	3
	Hope	WC, C	H	1, 2, 3
	Jordan Thrust	C	M	1, 4
	Kaiapo	W	M	3
	Kakapo	C	H	3
	Karioi	M-W	M	3, 4
	Kekerengu	C	H	3
£ 2000 years	Kelly	C	L	4
	Kowhia	C	L	4
(Class Ia, Table 1)	Lake Ohakuri	W	L	4
	Maleme (including Rehi fault)	W	H	3
	Matata	BP	M	1, 4
	Mohaka	M-W, HB	M	1, 3
	Mt Grey	C	M	1, 4
	National Park	M-W	L	4
	Ngangiho	W	M	3
	Ohakune	M-W	M	1, 2, 3
	Orakeikorako	W	L	4
	Paeroa	W, BP	H	1, 2, 3
	Patoka	HB	L	4
	Porters Pass	C	M	1, 2, 3
	Poutu	W	M	l, 3, 4
	Puketerata	W	L	4
	Rangiora	HB	H	1, 2
	Rangipo	M-W, W	M	1, 2, 3
	Raurimu	M-W	M	3
	Rotoitipakau	BP	H	1
	Shawcroft Road	M-W	L	3, 4
	Snowgrass	M-W	L	1, 4
	Tumunui	W, BP	L	4
	Waihi	M-W, W	M	3, 4
	Waipukaka	M-W	M	1
	Wairarapa	Wgtn, M-W	H	1, 2, 3
	Wairau	Tas, M	M	1, 2, 3
	Wellington	Wgtn, M-W	H	1, 2, 3

£ 2000 years (Class Ia, Table 1)	West Whangamata	W	L	4
	Whakaipo	W	M	3
	Whakatane (south)	BP	L	3, 4
	Whangamata	W	M	3
	Wharekauhau	W	L	4
	Whirinaki	W	M	3
> **2000 years to £ 3500 years** **(Class Ib, Table 1)**	Akatore	O	M	1, 3
	Ashley - Cust	C	L	1, 4
	Awaiti	BP	L	4
	Barber	W	L	3
	Carterton	Wgtn	M	3
	Cross Creek	Wgtn	L	4
	Elliott	C, M	M	3, 4
	Fidget	C	L	4
	Fowlers	C	L	3, 4
	Fox's Peak	C	L	3
	Hihitahi	M-W	L	4
	Irishman's Creek	C	M	1, 3
	Kerepehi	W	H	1, 2, 3
	Lake Heron	C	M	3
	Little Rough Ridge	O	L	4
	Long Valley	O	M	3
	Makuri	M-W	L	4
	Masterton	Wgtn	L	3, 4
	Mokonui	Wgtn	L	3, 4
	Mt Hutt – Mt Peel	C	L	3
	Northern Ohariu	Wgtn, M-W	L	2, 3, 4
	Ngapouri	M-W, BP	M	3
	Oaonui	T	M	1
	Ohariu	Wgtn	L	1, 2, 3
	Omeheu	BP	L	4
	Onepu	BP	M	1, 4
	Orakonui	W	M	3
	Ostler	C	M	1, 2
	Otakiri	BP	L	4
	Pa Valley	M-W	L	4
	Raetihi	M-W	L	4
	Raggedy Range	O	L	4
	Ranfurly	O	L	4
	Rotohauhau	W, BP	M	1, 3
	Ruahine	M-W, HB	L	3, 4
	Saunders Road	M-W	L	4
	Silver Range	HB	L	4
	Te Teko	BP	L	4
	Te Weta	W	M	3
	Thorpe-Poplar	W	M	3
	Torlesse	C	L	4
	Vernon	M	L	3, 4
	Waikaremoana	HB, BP	L	4
	Waimana	BP	M	3
	Waiohau	BP	M	1, 3
	Waipiata	O	L	4
	Weber	M-W	L	4
> **3500 years to £ 5000 years** **(Class IIa, Table 1)**	Akatarawa	Wgtn	L	3, 4
	Blue Lake	O	L	3
	Cheeseman	C	L	4
	Dry River	Wgtn	M	3, 4
	Gibbs	Wgtn	L	4
	Glendevon	HB	L	4
	Hossack Road	W	L	1, 3
	Huangarua	Wgtn	M	1, 3
	Hundalee	C	L	4
	Inglewood	T	M	1
	Kaiwara	C	L	4
	Kaweka	HB	L	4
	Kidnappers (east)	HB	M	3
	Kidnappers (west)	HB	M	3
	Lees Valley	C	M	1, 4
	Lindis Pass	C, O	L	4
	London Hill	M	L	4
	Martinborough	Wgtn	M	3

> **3500 years** **to** £ **5000 years** **(Class IIa, Table 1)**	Maunga	M-W	L	4
	Moumahaki	T	L	3
	Mt Thomas	C	L	4
	Ngakuru	W	M	1, 3
	Norfolk	T	L	4
	North Rough Ridge	O	L	4
	Omihi	C	L	4
	Oruawharo	HB, M-W	L	4
	Otaraia	Wgtn	L	3, 4
	Poulter	C, WC	L	4
	Pukerua	Wgtn	L	3, 4
	Raukumara (many different faults)	G	L	4?
	Ruataniwha	HB	L	4
	Shepherds Gully	Wgtn	L	2, 3
	Tukituki	HB	L	3
	Waimea - Flaxmere	N, Tas	L	4?
	Waipukurau - Poukawa	HB	M	1, 3
	Waitawhiti	M-W	L	4
	Whakatane (north)	BP	L	1, 4
> **5000 years** **to** £ **10,000 years** **(Class IIb, Table 1)**	Awahokomo	C	L	4
	Bidwill	Wgtn	L	3, 4
	Big River	WC	L	4
	Blackball	WC	L	4
	Cardrona	O	M	1, 3
	Dalgety	C	L	4
	Dunstan	O	M	1, 2, 3
	Esk	C	L	4
	Fern Gully	C	M	1, 2, 3
	Fernside	G	L	3, 4
	Giles Creek	WC	L	4
	Hog Swamp	M	L	4
	Horohoro	W, BP	H	1, 3
	Hyde	O	L	4
	Kirkliston	C	L	1, 3
	Lowry Peak	C	L	4
	Mangaoranga	Wgtn, M-W	L	4
	Mangatete	W	M	3
	Moonlight	S, O	L	4
	Nevis	O	M	1, 3, 4
	Nukumaru	T	L	3
	Paparoa Range	WC	L	3, 4
	Poukawa (north)	HB	M	1
	Punaruku	W, BP	M	1, 3
	Quartz Creek	C	L	4
	Rostreivor	C	L	4
	Rotokohu	WC	L	4
	Rough Creek	WC	L	4
	Southland (several different faults)	S	L	4?
	Springbank	C	L	4
	Waitotara	T	L	3
	West Culverden	C	L	4

* Faults are listed alphabetically within each fault-avoidance recurrence interval class.

** Regional Councils: BP, Bay of Plenty; C, Canterbury; G, Gisborne; HB, Hawke's Bay: M, Marlborough; M-W, Manawatu-Wanganui; N, Nelson; O, Otago; T, Taranaki; Tas, Tasman; S, Southland; W, Waikato; WC, West Coast; Wgtn, Wellington.

[#] Relative confidence that the fault can be assigned to a specific fault-avoidance recurrence interval class.

H, High - fault has a well constrained recurrence interval (usually based on fault-specific data) that is well within a specific fault-avoidance class, or fault has such a high slip rate that it can be confidently placed within the ≤ 2000 year fault-avoidance class.

M, Medium - uncertainty in average recurrence interval embraces a significant portion (> ~25%) of two fault-avoidance classes; the mean of the uncertainty range typically determines into which class the fault is placed.

L, Low - uncertainty in recurrence interval embraces a significant portion of three or more fault-avoidance classes, or there are no fault-specific data (i.e. fault-avoidance recurrence interval class is assigned based only on subjective comparison with other faults).

[##] Method by which recurrence interval was determined/constrained.

1 - fault-specific sequence of dated surface ruptures. The longer the sequence of dated surface ruptures, the more preference we give this method with respect to constraining average recurrence interval, and assigning fault-avoidance recurrence interval class.

2 - fault-specific slip rate and single-event displacement, and the use of Equation 1. The better the constraints on slip rate and single-event displacement, the more preference we give this method with respect to constraining average recurrence interval.

3 – indicative determination of recurrence interval based on fault-specific slip rate constraints, rupture length estimates, and Figures 1 & 2; however, well constrained recurrence interval estimates based on methods 1 & 2 above, take precedence over this method.

4 –based on comparisons with other, similar, faults.

4 CONCLUDING REMARKS

We hope this interim compilation of active faults classified according to the recurrence-interval based fault-avoidance criteria defined in the Interim Guidelines will: a) prove helpful to those who should, in the immediate future, use the Guidelines; and b) direct attention to those faults where better constrained recurrence interval data will most assist in mitigating surface rupture hazard. As with the Interim Guidelines, we encourage, and seek, public feedback on the fault-avoidance classifications presented in Table 4. To facilitate this, it is our desire, in the near future, to convene a series of expert-panel workshops, involving the authors and those working in Universities and private practice, to review Table 4.

We also wish to point out that as better constrained earthquake-geology data become available, we anticipate that a number of faults listed in Table 4 will get re-classified into different fault-avoidance classes. This is especially so for faults with a medium or low confidence of classification. We caution against making significant planning or engineering decisions based on the fault-avoidance class of a fault with a low confidence of classification, without first endeavouring to better constrain the fault's recurrence interval. Further, we wish to note that with continued geological research, additional active faults will be discovered, and these, in due course, will be added to Table 4.

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