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Slip rate variations on major strike-slip faults in central New Zealand and potential impacts on hazard estimation

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ABSTRACT

Geological investigations over the last two decades have demonstrated that major strike-slip faults in central New Zealand (e.g., Awatere, Clarence, Wellington faults) have experienced significant millennial-scale variations in slip rate over the last ~12 kyr (1 kyr = 1000 years). For example, the central Clarence Fault has had a dextral slip rate of ~2 mm/yr over the last ~8 kyr, whereas during the preceding ~4 kyr it had a significantly faster rate of ~9 mm/yr. The southern Wellington Fault provides an even more extreme example: between ~5 and 8 kyr ago, it had a relatively slow slip rate of 1-2 mm/yr, whereas between ~8 and 10 kyr ago its slip rate was nearly 20 mm/yr - approximately an order of magnitude faster.

In probabilistic seismic hazard assessment, the hazard contribution of an active fault (i.e., an active fault earthquake source) is typically a function of its slip rate, and that slip rate is often assumed to be constant. Here we investigate – in a first-order manner – potential impacts of known slip rate variations on probabilistic ground shaking hazard estimation. Specifically, we utilise the most recent published version of the New Zealand National Seismic Hazard Model and track changes in calculated peak ground acceleration and spectral acceleration that result from slip rate variations on the above-cited faults equivalent in magnitude to those experienced in the past, and plausibly anticipated in the future. We report these changes over a range of exceedance probabilities for the central New Zealand urban centres of Wellington, Blenheim and Kaikōura.

1 INTRODUCTION

Fault slip rate is a key parameter in most probabilistic seismic hazard assessments (e.g., Field et al. 2017, Stirling et al. 2012). In these assessments, slip rate is commonly assumed to be constant; however, many recent investigations show that this assumption is not universally applicable, as some faults undergo extended periods (i.e., spanning multiple earthquake cycles) of relatively fast slip rate separated by periods of slower slip rate (e.g., Dolan et al. 2016, Gold & Cowgill 2011, Mason et al. 2006, Ninis et al. 2013, Wallace 1987, Weldon et al. 2004, Zinke et al. 2017, 2019).

In this paper, we summarise slip rate data from three major strike-slip fault in central New Zealand that demonstrates that these faults, or at least parts of them, have undergone significant millennial scale variations in slip rate over the last ~12 kyr (1 kyr = 1000 years). Then, using the New Zealand National Seismic Hazard Model of Stirling et al. (2012), we provide examples of how these slip rate variations may impact hazard estimation at the proximal urban centres of Wellington, Blenheim and Kaikōura.

2 MILLENNIAL SCALE SLIP RATE VARIATIONS ON THE AWATERE, CLARENCE, AND WELLINGTON FAULTS

Building on previous work (e.g., Berryman 1990, Kieckhefer 1979, Knuepfer 1992, Mason et al. 2006, McCalpin 1996), and utilising detailed topographic characterisations and luminescence dating techniques, high-quality incremental slip rate characterisations have been determined for three of the major strike-slip faults in central New Zealand. These being the Awatere Fault at the Saxton River site (Zinke et al. 2017), the Clarence Fault at the Tophouse Road site (Zinke et al. 2019), and the Wellington Fault at the Te Marua site (Ninis et al. 2013) (Figs 1 & 2). Detailed documentation of the incremental slip rates determined at the aforementioned sites, and their attendant uncertainties, is provided by the above authors. Below, we present a summary of these data.

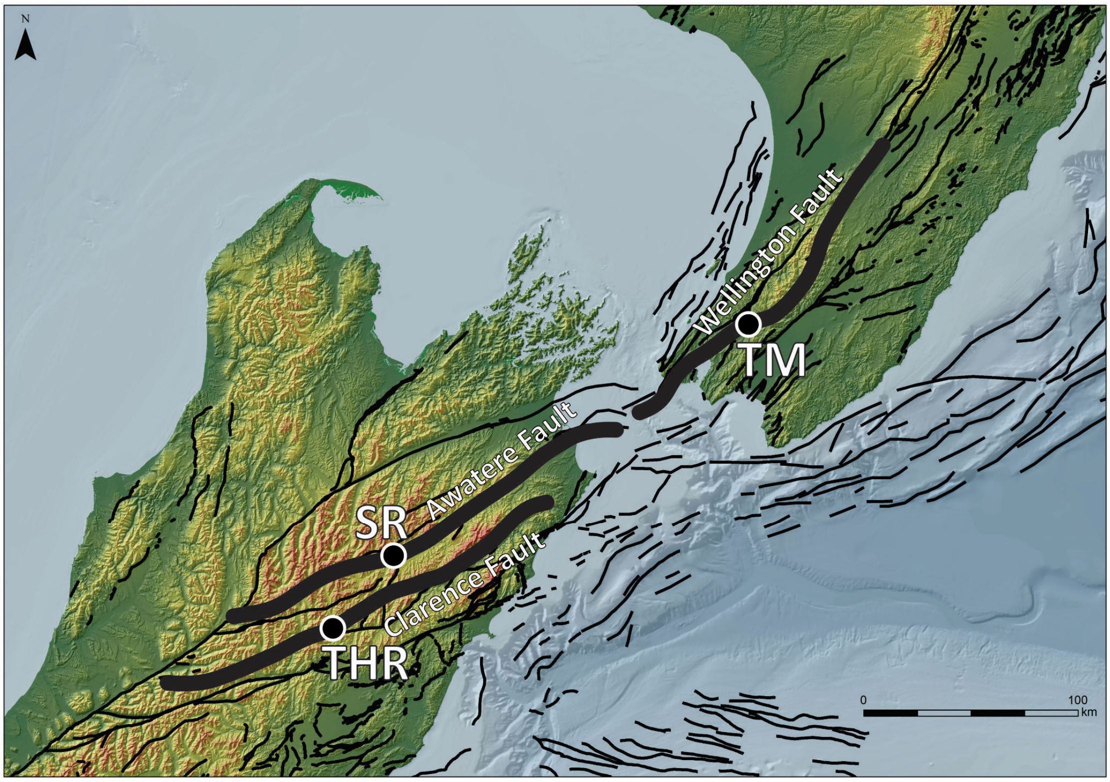

Figure 1: Active faults of central New Zealand with the Awatere, Clarence and Wellington faults highlighted as bold black lines. SR, THR, and TM denote locations, respectively, of the Saxton River site on the Awatere Fault, Tophouse Road site on the Clarence Fault, and Te Marua site on the Wellington Fault. On-land faults from Langridge et al. (2016), and off-shore faults from a number of sources including Barnes (1994), Barnes & Audru (1999), Nodder et al. (2007), Mountjoy et al. (2009), Barnes et al. (2010), Pondard and Barnes (2010), and Mountjoy & Barnes (2011).

The dextral Awatere Fault at the Saxton River site (Fig 1) has undergone at least three differentiable slip rate phases over the last ~14 kyr (Zinke et al. 2017) (Fig 2A). Over the last ~4 kyr, the fault has experienced a relatively slow lateral slip rate of ~3.1 mm/yr, whereas between ~4 and 8 kyr ago it experienced a relatively fast slip rate of ~11.5 mm/yr. Finally, between ~8 and 14 kyr ago, the fault had a relatively slow incremental slip rate of ~3.4 mm/yr. Over the past ~14 kyr, the dextral slip rate of the Awatere Fault at this location has averaged ~5.6 mm/yr.

The dextral Clarence Fault at the Tophouse Road site (Fig 1) exhibits two distinct slip rate intervals over the last ~12 kyr (Zinke et al. 2019) (Fig 2B). Over the last ~9 kyr, it has experienced a relatively slow lateral slip rate of ~2.0 mm/yr, whereas between ~9 and 12 kyr ago it experienced a relatively fast rate of ~9.0 mm/yr. Over the last ~12 kyr, the dextral slip rate of the Clarence Fault at this location has averaged ~4.2 mm/yr.

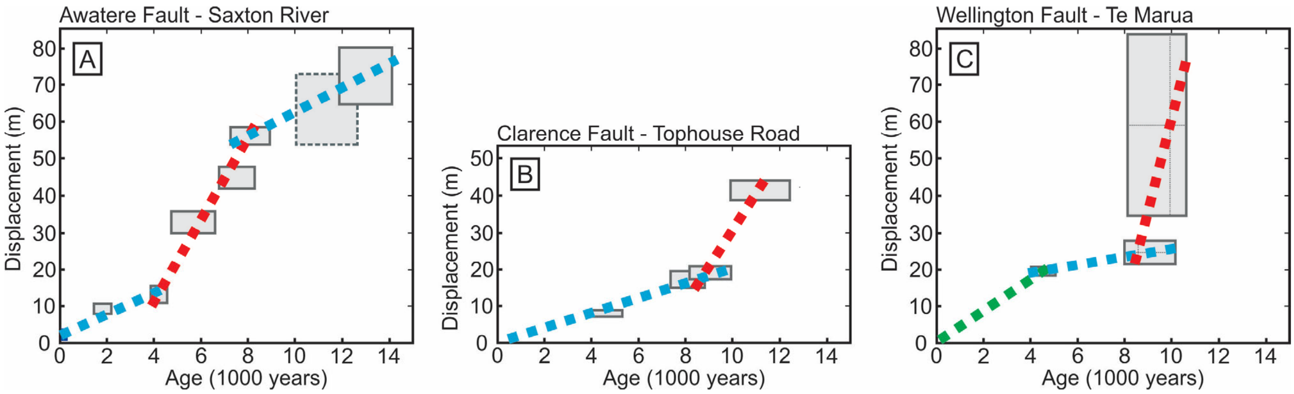

Figure 2: Incremental lateral slip rates for the: (A) Awatere Fault at the Saxton River site (after Figure 4 of Zinke et al. 2017); (B) Clarence Fault at the Tophouse Road site (after Figure 4 of Zinke et al. 2019); (C) Wellington Fault at the Te Marua site (after Figure 10 of Ninis et al. 2013). See Figure 1 for locations. Grey boxes depict displacement and age pairs, including uncertainties, of offset landforms at each site. Bold dashed lines represent best-fit incremental slip rates at the respective sites with blue indicating a relatively slow slip rate interval, green a moderate slip rate interval, and red a fast interval.

The dextral Wellington Fault at the Te Marua site near the Hutt River (Fig 1) has undergone three differing slip rate phases in over the last ~10 kyr (Ninis et al. 2013) (Fig 2C). Over the last ~4.6 kyr it has had a relatively moderately-paced slip rate of ~4.2 mm/yr, whereas between ~4.6 and 8.3 kyr ago it had slow slip rate of only ~1.3 mm/yr. Finally, between ~8.3 and 10 kyr ago, the fault had a relatively fast incremental slip rate of ~19 mm/yr. Over the last ~10 kyr, the lateral slip rate of the fault has averaged ~5.7 mm/yr.

3 SLIP RATE VARIATIONS AND IMPLICATIONS FOR HAZARD ESTIMATION

The considerable millennial scale variations in slip rate for the three faults portrayed in Figure 2 – with a factor of ~15 difference in slip rate between slow phase and fast phase intervals for the Wellington Fault and a factor of ~4 difference for the Awatere and Clarence faults – contradicts the assumption of constant fault slip rate adopted in many probabilistic seismic hazard assessments.

To gain a first-order impression of the potential impacts slip rate variation may have on hazard estimation, we employ the most recent published version of the New Zealand National Seismic Hazard Model (Stirling et al. 2012) and vary the slip rate of the active fault earthquake source most closely related to the slip rate characterisations in Figure 2. That is, we apply the Awatere Fault slip rate characterisation at Saxton River (Fig 2A) to the Awatere Southwest active fault earthquake source of Stirling et al. (2012), the Clarence Fault slip rate characterisation at the Tophouse Road site (Fig 2B) to the Clarence Southwest earthquake source, and the Wellington Fault slip rate characterisation at Te Marua (Fig 2C) to the Wellington Hutt Valley source (Fig 3). Recurrence intervals for each phase are derived for these three active fault earthquake sources by dividing the single event displacement listed for that source in Stirling et al. (2012) by the applicable incremental slip rate (Table 1). Also listed in Table 1 are the earthquake magnitudes, taken directly from Stirling et al. (2012), calculated for those active fault earthquake sources.

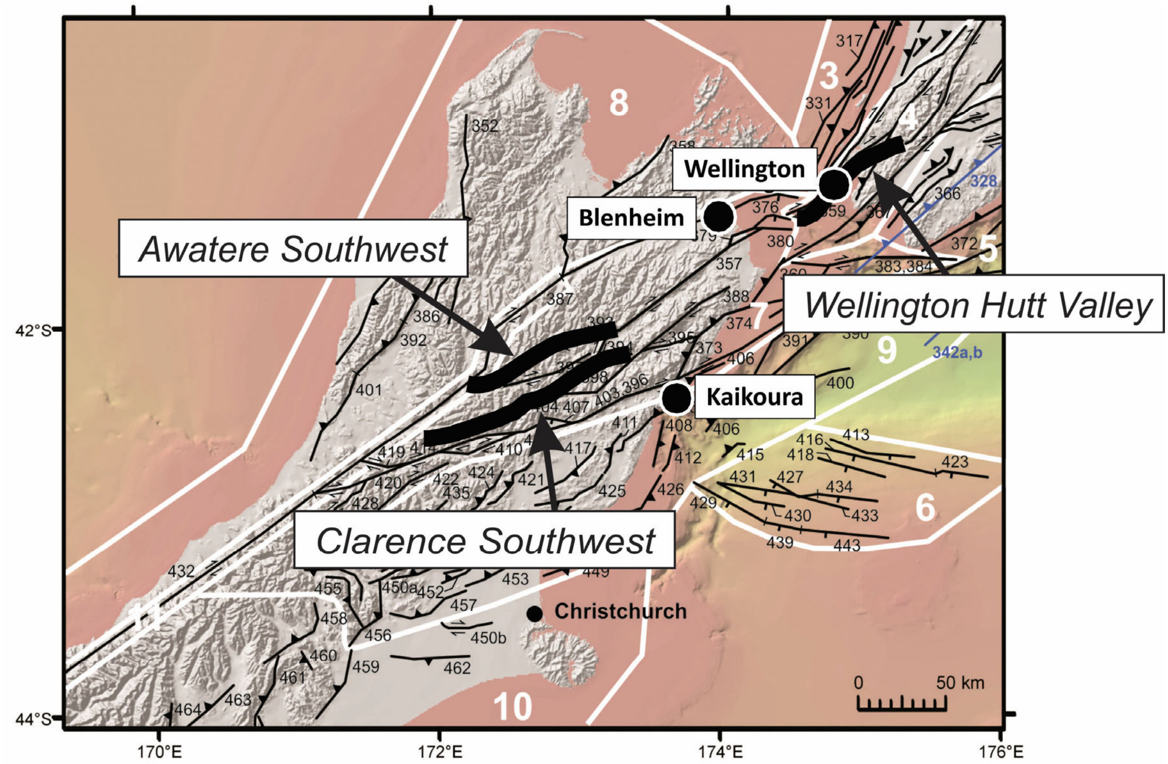

Figure 3: Active fault earthquake sources in central New Zealand (after Figure 3 of Stirling et al. 2012). Highlighted in bold black lines are the three active fault earthquake sources – Awatere Southwest, Clarence Southwest and Wellington Hutt Valley – that most closely relate to the slip rate characterisations depicted in Figure 2.

Table 1: Derived recurrence intervals for the three active fault earthquake sources highlighted in Figure 3 based on the incremental slip rates in Figure 2.

Active fault earthquake source (from Stirling et al. 2012)		M_w (from Stirling et al. 2012)	**Single event displacement* (m)**	**Slip rate** (mm/yr)**		**Recurrence interval*** (years)**
Name	Number			Phase	Rate	
Awatere Southwest	393	7.5	6.5	slow	3.1	2100
				average	5.6	1160
				fast	11.5	570
Clarence Southwest	404	7.4	5.2	slow	2.0	2600
				average	4.2	1240
				fast	9.0	580
Wellington Hutt Valley	359	7.5	5.0	slow	1.3	3760
				moderate	4.2	1200
				average	5.7	880
				fast	19	260

* Scaling relationship-based value taken from Stirling et al. (2012)
** see Figures 2 and 3
*** Derived value calculated by dividing single event displacement by slip rate

Table 2 lists probabilistically-derived horizontal accelerations calculated for Wellington City at selected spectral periods owing to variations in Wellington Fault slip rate and corresponding variations in derived earthquake recurrence interval (Table 1). Results are provided based on two ground motion prediction equation (GMPE) scenarios: one using solely the GMPEs of McVerry et al. (2006), as was done in Stirling et al. (2012), and the other utilising the GMPE logic tree proposed by Van Houtte (2017) which employs a suite of national and international GMPEs including several of those included in the NGA-West2 research project (Bozorgnia et al. 2014). More specifically, for crustal faults the logic tree uses the GMPEs of Abrahamson et al. (2014), Boore et al. (2014), Campbell & Bozorgnia (2014), Chiou & Youngs (2014) and Bradley (2013) with, respectively, the following weights of 0.25, 0.25, 0.25, 0.125 and 0.125.

Two observations are salient from Table 2. The first is that there is an across-the-board increase in estimated hazard using the GMPE logic tree of Van Houtte (2017) compared to the results derived using only the GMPEs of McVerry et al. (2006), except for values obtained at spectral periods close to 0.2 s. The second is that variation in Wellington Fault slip rate potentially has a significant impact on hazard estimation in Wellington City with, for example, a 30-50% difference in calculated peak ground acceleration (PGA) depending on the adoption of slow phase or fast phase slip rate.

Table 2: Horizontal accelerations calculated for Wellington City at selected spectral periods owing to variations in Wellington Fault slip rate and corresponding variations in recurrence interval (see Table 1). Results are probabilistically derived using the National Seismic Hazard Model of Stirling et al. (2012), 5% damping, New Zealand Subsoil Class C ground conditions (i.e., shallow, stiff soil), and are reported in g as the stronger of the two horizontal components. In addition, results are provided utilising the GMPEs of McVerry et al. (2006) and the GMPE logic tree proposed by Van Houtte (2017).

Exceedance probability	**Spectral period (s)**	**Horizontal accelerations (g) at selected spectral periods**					
		Wellington Fault slip rate variation					
		"slow" phase (~1.3 mm/yr)		average (~5.7 mm/yr)		"fast" phase (~19 mm/yr)	
		McVerry et al. (2006)*	GMPE logic tree**	McVerry et al. (2006)*	GMPE logic tree**	McVerry et al. (2006)*	GMPE logic tree**
10% in 50 years	PGA	0.47	0.59	0.53	0.65	0.70	0.81
	0.2	1.58	1.48	1.75	1.61	2.31	1.96
	0.5	0.91	1.05	0.99	1.18	1.21	1.57
	1	0.43	0.57	0.48	0.66	0.62	0.92
	3	0.14	0.15	0.15	0.18	0.20	0.27
2% in 50 years	PGA	0.77	1.13	0.91	1.24	1.16	1.48
	0.2	2.73	2.78	3.27	3.05	4.42	3.63
	0.5	1.42	2.17	1.59	2.49	1.93	3.15
	1	0.74	1.27	0.86	1.50	1.10	1.96
	3	0.26	0.36	0.30	0.44	0.38	0.60

* McVerry, G.H., Zhao, J.X., Abrahamson, N.A., Somerville, P.G. 2006. New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol 39(4): 1-5.

** Van Houtte, C. 2017. Performance of response spectral models against New Zealand data. *Bulletin of New Zealand Society for Earthquake Engineering*, Vol 50(1): 21-38.

Varying the slip rate on the Wellington Hutt Valley active fault earthquake source (Fig 3) in a fashion consistent with Figure 2C has little if any impact on hazard estimation for Blenheim and Kaikōura. Similarly, varying the slip rate on the Awatere Southwest and Clarence Southwest active fault earthquake sources, again in a fashion consistent with Figures 2A and 2B, respectively, had little if any impact on hazard estimation for Blenheim, Kaikōura and Wellington. This is likely because of the relatively large source-to-site distances and because there are closer, more active earthquake sources that dominate the hazard at those centres.

The results presented in Table 2 demonstrate that slip rate variation can have a significant impact on hazard estimation. An unresolved issue, however, is how best to formalize known slip rate variations into probabilistic seismic hazard evaluations. Though not an exhaustive listing, some possible options could include: 1) using an average slip rate with an uncertainty large enough to encompass both slow and fast phases; 2) employing a logic tree where the various slip rate phases are explicitly listed and weighted; and/or 3) adopting the slip rate of the most recent phase as it could be argued that the best representation of near future hazard, say over the next 50-100 years, is the slip rate phase that has most recently occurred in the past. This third option is, in essence, an extreme variant of the second.

To gain an impression of the possible ramifications of the third option, we undertook a series of hazard runs where we applied the moderate phase slip rate to the Wellington Hutt Valley active fault earthquake source (Fig 2C, Table 1), slow phase slip rates to the Awatere Southwest and Clarence Southwest sources, and slow phase slip rates to the adjacent Awatere Fault and Clarence Fault sources immediately to the northeast. The results of these hazard runs for Wellington, Kaikōura and Blenheim, using the GMPE logic tree of Van Houtte (2017), are listed in Table 3. The multi-fault slip rate variation scenario as implemented here has little if any impact on resulting hazard estimation. There is no change to hazard estimated for Kaikōura because hazard there is dominated by the much faster, near-by Hope Fault with a recurrence interval of only a few hundred years (e.g., Stirling et al. 2012, Hatem et al. 2019), and because of the rather large source-to-site distances, exceeding many tens of kilometres, between Kaikōura and the variable slip rate fault sources (e.g., Awatere, Clarence and Wellington) considered in this scenario. There is a slight reduction of hazard for Wellington and Blenheim because the moderate phase slip rate used for the Wellington Hutt Valley active fault earthquake source in our multi-fault slip rate variation scenario is slightly slower than the average rate used for that source in the National Seismic Hazard Model. The significant reduction of slip rate for the Awatere Fault and Clarence Fault sources in our slip rate variation scenario has very little impact on hazard estimation in Wellington and Blenheim because source-to-site distance are in excess of several tens of kilometres.

Table 3: Horizontal accelerations calculated for Wellington, Kaikōura and Blenheim at selected spectral periods owing to slow phase slip rates on the Awatere and Clarence faults, and moderated phase slip rate on the Wellington Fault. Results are derived using the GMPE logic tree of Van Houtte (2017), 5% damping, and New Zealand Subsoil Class C ground conditions.

Exceedance probability	**Spectral period (s)**	**Horizontal accelerations in g at selected spectral periods**					
		Wellington		Kaikōura		Blenheim	
		NSHM regular*	Multi fault slip rate variation scenario**	NSHM regular*	Multi fault slip rate variation scenario**	NSHM regular*	Multi fault slip rate variation scenario**
10% in 50 years	PGA	0.65	0.63	0.67	0.67	0.53	0.52
	0.2	1.61	1.56	1.63	1.63	1.32	1.29
	0.5	1.19	1.13	1.24	1.24	0.88	0.85
	1	0.67	0.63	0.71	0.71	0.48	0.46
	3	0.18	0.17	0.21	0.21	0.13	0.12
2% in 50 years	PGA	1.25	1.21	1.13	1.13	0.92	0.90
	0.2	3.07	2.96	2.80	2.80	2.28	2.24
	0.5	2.51	2.39	2.32	2.32	1.67	1.61
	1	1.51	1.42	1.39	1.39	0.98	0.94
	3	0.44	0.41	0.43	0.43	0.30	0.28

* Using the earthquake source models of Stirling et al. (2012) and the GMPE logic tree of Van Houtte (2017)

** Using GMPE logic tree of Van Houtte (2017), and active fault earthquake sources representing the Awatere and Clarence faults with slow phase slip rates, and Wellington Hutt Valley active fault earthquake source with a moderate phase slip rate.

4 CONCLUSIONS

Major strike-slip faults in central New Zealand have experienced significant millennial scale variations in slip rate over the last ~12 ka. These slip rate variations have the potential to impact hazard calculations, perhaps considerably so. However, the nature and magnitude of the potential impact on hazard is dependent on a number of factors, only one of which is the slip rate (and its variability) of a specific fault source. Additional factors include, for example, source-to-site distance, and the number and activity of other nearby earthquake sources.

From a hazard perspective, and with regards to slip rate variability and its potential impact on hazard estimation, it is most relevant to characterise the slip rate and its variability (or otherwise) of the earthquake source, or sources, that contribute most to the hazard at the specific site of interest.

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