



Slip rate estimation from tilting of marine terraces above an offshore listric thrust fault, Kaikoura, New Zealand

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Abstract: Slip on an offshore fault uplifted and tilted the Kaikoura Peninsula during the 2016 Kaikoura earthquake. Analysis of a 2012, 1m Lidar DEM shows that the uplifted Kaikoura marine terraces have been progressively tilted in the same manner since 120 ka. A Monte-Carlo analysis of tilt-age relationships, based on a model of listric faulting, and using published age data and Papuan and regional sea level curves, implies that slip rates have increased from 2.3 ± 1.3 mm/yr to 4.1 ± 1.2 mm/yr since c.60 ka. Comparison of the elevation of young, uplifted beaches surrounding the peninsula, with a Late Holocene sea level curve, suggests three earthquake events (including 2016) over 3 kyr. The timing of the earthquakes implies lower Late Holocene slip rates, compared with post-60 ka slip rates; comparison of these events with paleoseismic records of the Marlborough Fault System is interpreted to suggest latest Holocene clustering of seismicity.

Key words: Kaikoura Peninsula, marine terrace, slip rates, paleoseismic.

INTRODUCTION

The Kaikoura Peninsula (Fig. 1) lies at the southern terminus of the Hikurangi subduction margin, where plate boundary deformation is progressively transferred to the upper plate faults of the Marlborough Fault System (MFS) (Little and Jones 1998). The peninsula tilted toward the west during the 2016 Kaikoura Earthquake, inferred to be the result of slip on a blind, shallow NW-dipping reverse fault (Clark et al. 2017); similar tilting is recorded by uplifted Pleistocene marine terraces (Campbell et al. 2005, Fig. 2). Furthermore, the peninsula is fringed by Late Holocene beaches that have been interpreted to provide an uplift record over the last three millennia (Barrell 2015, McFadgen 1987). However, the slip rate on the underlying fault, and its variability, is not well known.

The Kaikoura Earthquake was exceedingly complex, involving a diverse range of fault types, with diverse slip rates, and across several tectonic domains (Clark et al. 2017, Hamling et al. 2017). Knuepfer (1992) suggested that the faults of the MFS display episodic variations in activity over 5 ky timescales, and faults such as the Wairau, Awatere, Clarence, Hope, Kekerengu, and Porters Pass Faults had exhibited reduced slip rates over the last 3-5 kyr. To understand how these faults interact over different temporal and spatial scales, it is necessary to understand variability in the slip rates and paleoseismicity of component faults, including the fault that uplifts the Kaikoura Peninsula, and to examine patterns in the regional paleoseismicity of the MFS. Therefore, this study asks (i) what are the Late Quaternary slip rates on the Kaikoura Peninsula Fault; (ii) how do these slip rates compare with slip rates calculated from Holocene beaches using the same geometry; and (iii) how do slip rate variations at the Kaikoura Peninsula relate to slip rate variability across the MFS.

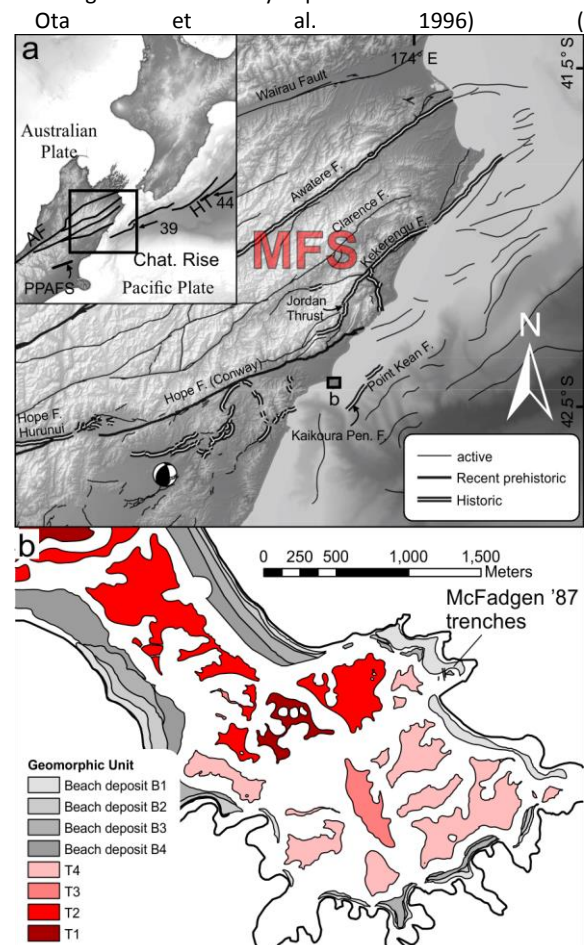


Fig. 1. A) location of Kaikoura Peninsula relative to the Marlborough Fault System; Faults from NZ active faults database, and Stirling et al. (2017); b) Sketch map of the Kaikoura



Peninsula, showing the distribution of Late Pleistocene terraces and Holocene beaches.

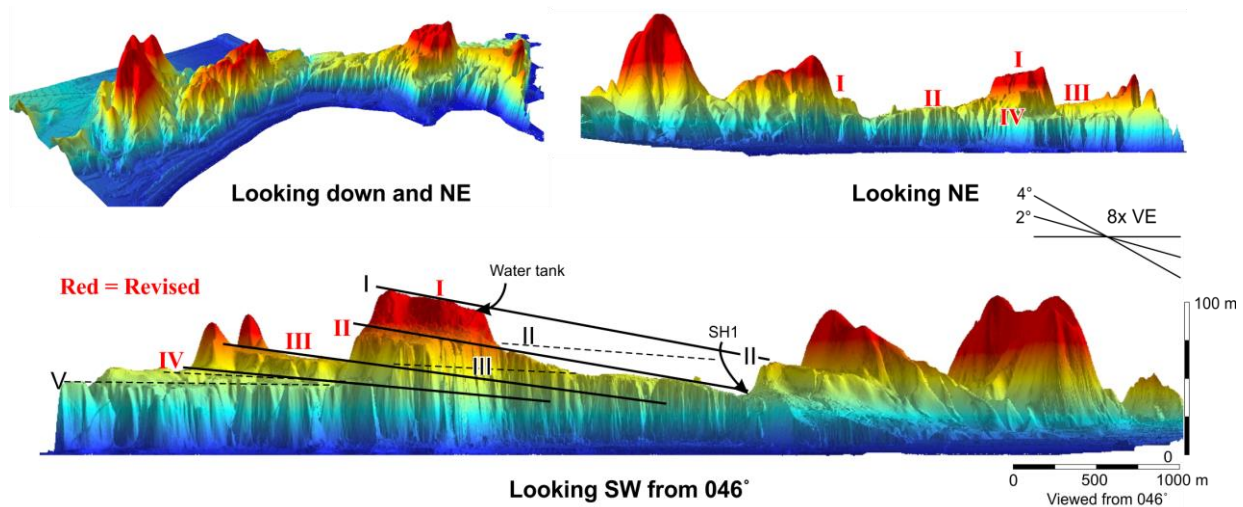


Fig. 2. 1m Lidar DEM showing correlation of terraces with new correlations labelled in **red**, and old correlations labelled in **black**. DEM provided by Environment Canterbury.

METHODS

These questions are addressed here using a 2012 1 m Lidar DEM, based on the interpretation that the progressive tilt at Kaikoura Peninsula records primarily the effects of slip on an underlying listric fault of a constant radius, similar to those that mark the shelf edge further north (Barnes and Audru 1999). The tilt and Lidar elevation at a point of an individual strandline depends on the thickness of cover sediments (taken from Ota et al. 1996), the amount of slip, and the relative sea level (RSL) at which the terrace formed (Fig. 3). This analysis therefore searches for terrace-highstand correlations that produce (i) close agreement of fault radius, and (ii) a close match of elevation at a point using a common fault radius for all terraces. The age of the highest terrace was constrained to 110 ± 20 ka based on the only existing amino-acid-racemization age (Ota et al. 1996).

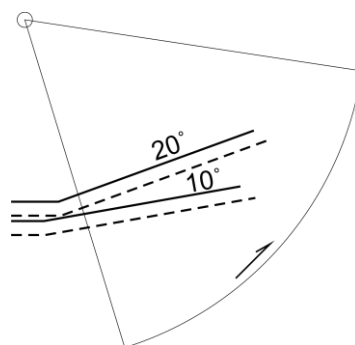


Fig. 3. The elevation-at-a-point of a terrace rotating above a listric fault depends on the RSL at which it formed (compare solid and dashed lines) and the amount of slip on the underlying fault.

The slip rates were determined by relating apparent-strandline tilt and elevation, minus cover thickness, to the Papuan sea level curve (Lambeck and Chappell 2001), and to a regionally-derived sea level curve based on predominantly Southeast Australian data (Blakemore et al. 2014, Hails et al. 1984, Murray-Wallace 2002), with some constraints from Banks Peninsula, south of Kaikoura (Shulmeister et al. 1999). The regional curve provided better results and the Papuan correlations are discussed little here, although the full rationale is presently in review elsewhere. Each of the inputs into this analysis has an associated error; these errors are accounted for in a 10,000 iteration Monte Carlo simulation. All results are presented at 95% confidence interval.

RESULTS

The correlations of terraces along the peninsula are shown in Fig. 2. Four terraces are defined; a previously defined fifth terrace follows the strike of bedrock units that form

resistant topography on the modern shore platform, and is not considered to be a terrace. The slip rates for all



scenarios is shown in Fig. 4. The elevation and rotation of the four terraces is consistent with a 120-60 ka slip rate of 2.31 ± 1.3 mm/yr, based on the preferred regional sea-level history, followed by an increase to 4.1 ± 1.3 mm/yr since 60ka.

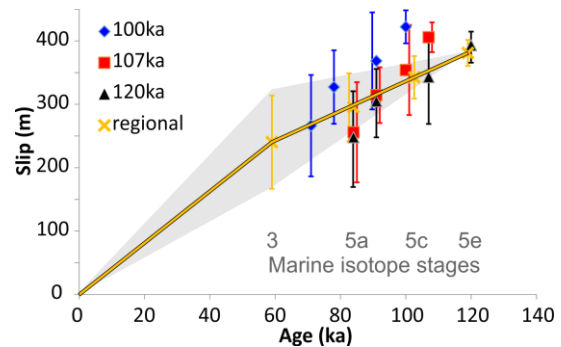


Fig. 4. Summary of slip rates estimated from different scenarios. Grey zone highlights the slip rate history implied by the regional sea level curve.

beaches are consistent in terms of magnitude and timing with Late Holocene sea-level fall. The uplift rate implied by the interval between earthquakes 1 and 2 (Fig. 5) is 0.45 ± 0.16 mm/yr, less than half the Late Pleistocene uplift rate of the peninsula. If the 0.8-1.0 m of uplift during the Kaikoura Earthquake (Clark et al. 2017) is also included, the uplift rate reaches 0.72 ± 0.17 mm/yr, which is still lower than the long-term rates and not consistent with the increased slip rate suggested by Pleistocene terrace uplift.

DISCUSSION

The paleoseismic interpretation in Fig. 5 implies two earthquakes within 500 years on the Kaikoura Peninsula Fault following a relatively quiescent period of ~2 kyr. Comparing this data with records from the rest of the MFS shows that several faults, including the Kekerengu and Hope faults, display similar patterns (Fig. 6), consistent with Knuepfer's (1992) interpretation of a period of Late Holocene quiescence across much of the system. Episodicity or clustering of earthquakes is reported from both stable continental regions (Clark et al. 2012) and other plate boundaries (Dolan et al. 2007); together with similar effects found in numerical models (Ben-Zion et al. 1999), these patterns suggest that fault systems such as the MFS and associated faults may periodically host clusters of seismic events, including the largest events on the system, and otherwise display low moment release during small to moderate earthquakes.

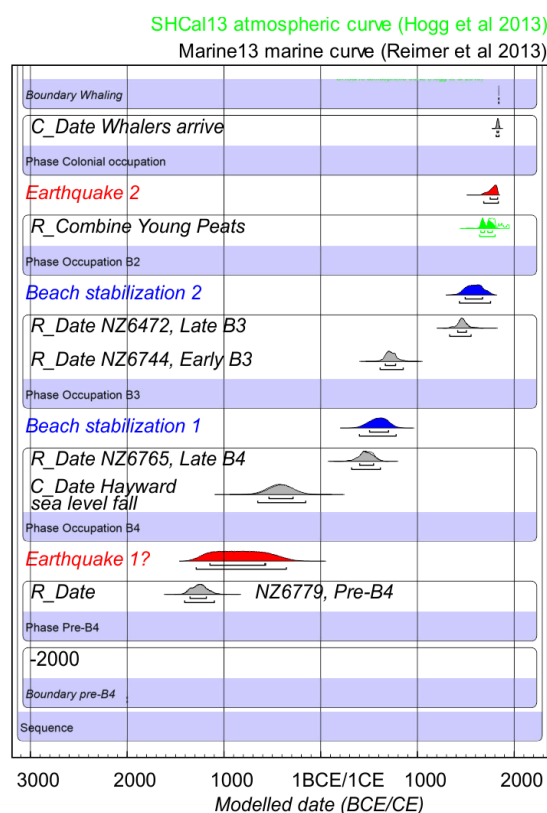


Fig. 5. Oxcal model showing modelled McFadgen (1987) radiocarbon ages, with upper limits constrained by the establishment of whaling at Kaikoura in c.1840 CE. Beach stabilization 1 and 2 (blue) based on comparison of RSL change with Hayward et al.'s (2016) sea-level curve. Earthquake events (red) do not relate to documented sea level falls.

McFadgen (1987) dated several beaches and obtained uplift rates of >2 mm/yr over the latest Holocene. These rates (and Barrell's 2015 review thereof) assumed a constant Late Holocene sea level, but Hayward et al. (2016) showed that sea level has fallen over several stages from a mid-Holocene highstand, and risen markedly over the industrial period. Re-evaluation of McFadgen's (1987) radiocarbon ages within an OxCal model (Fig. 5) and comparison with Hayward et al.'s sea level curve indicate that only the first and last beach forming events (1287 to 356 BCE and 1687 to 1837 CE) are consistent with earthquake uplift, while the other two

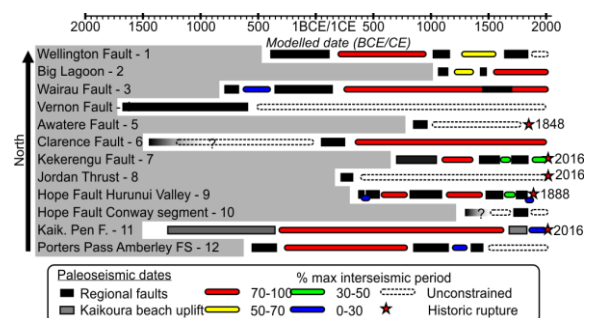


Fig. 6. Compilation of regional paleoseismic ages for MFS faults, ordered from north to South. Greyed out area shows no-data. Interseismic periods are colour coded to highlight short (blue/green) versus longer (yellow/red) interseismic periods.



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Paleoseismic data from: 1 - Langridge et al. (2011); 2 – Clark et al. (2015); 3 – Zachariasen et al. (2006); 4 – Bartholomew et al. (2014); 5 - Mason et al. (2006); 6 - Van Dissen and Nicol (2009); 7 - Little et al. (2016); 8 - Van Dissen et al. (2006); 9 - Khajavi et al. (2016); 10 - Langridge et al. (2003); 11 - This study; 12 - Howard et al. (2005).

CONCLUSION

The Kaikoura Peninsula Fault has been uplifting and rotating the peninsula by slipping at rates that have increased from 2.3 ± 1.5 mm/yr to 4.1 ± 1.3 mm/yr since 60 ka. The age and elevation of beach ridges around the peninsula suggest Late Holocene slip rates are around half of the long term rate. Most of the Late Holocene slip seems to have occurred during two events since ~1800 CE. This period coincides with short recurrence interval ruptures on the Hope and Kekerengu faults in the MFS.

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