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Growth and seismic hazard of the Montserrat anticline in the North Canterbury fold and thrust belt, South Island, New Zealand

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ABSTRACT

Fault-related fold growth is a seismic hazard in North Canterbury, New Zealand. The North Canterbury fold and thrust belt (NCFTB) is located at the southern end of the Hikurangi subduction zone, South Island, New Zealand where the Pacific plate transitions from subduction to transpression along the Alpine fault. Transpression causes shortening beneath the South Island, resulting in basement thrusts generating folds such as the Montserrat anticline. We focus on fault geometry and seismic hazard associated with this structure, exposed along the coast where Pleistocene marine terraces on the backlimb record tectonic uplift. To constrain parameters associated with evolution of this fault-related fold, we model the fold using several trishear kinematic models. A listric fault is most compatible with field and regional geophysical studies. Ages of marine terraces and inner edge elevations constrain uplift rate due to slip on the Glendhu fault to 1.1 ± 0.1 $m(ka)^{-1}$. An ~800 year recurrence interval is calculated for the Glendhu fault. Listric fault geometry lengthens the recurrence interval relative to other fault geometry models. An accurate understanding of subsurface fault geometry and kinematics is important for estimating seismic hazard in regions of fault-related folding such as the NCFTB because it affects recurrence interval estimations.

1. Introduction

Actively growing folds are as important as the recognition of emergent faults for assessing seismic hazard (Stein and King, 1984; Mueller and Suppe, 1997). In fold and thrust belts around the world, many folds overlie blind thrust faults, which are capable of producing large magnitude earthquakes (King et al., 1988; Lin and Stein, 1989; Jackson et al., 1996). Numerous investigations confirm coseismic deformation from fault-related folds, including the 1982–1985 California earthquake sequence (Stein and King, 1984; Stein and Ekstrom, 1992), the 1980 El Asnam (Algeria) earthquake (Yielding et al., 1981), and the 1999 Chichi earthquake in Taiwan (Lin et al., 2007). The North Canterbury region on the South Island, New Zealand is an example of an actively growing fold and thrust belt where thrust faults, sometimes blind, underlie folds, presenting a potential seismic hazard. Onshore faults within North Canterbury are of interest because fault geometry is in many cases poorly known. Onland seismic surveys offer few constraints, and fault surfaces are seldom exposed in outcrop for direct measurement of the dip angle. Understanding fault geometry is important because it affects earthquake magnitude estimates (Stahl et al., 2016) and recurrence interval calculations (Shaw and Suppe, 1996). We focus here on defining the structure of the Glendhu fault, a basement-rooted thrust fault that is deforming a ~1 km thick Cenozoic-Quaternary sedimentary cover to form the Montserrat anticline at Motunau Beach (Yousif, 1987). We use the geometric elements of this structure to evaluate important parameters such as detachment depth and ramp angle based on trishear models.

Previous studies have looked at fault slip rates and recurrence intervals associated with thrusts in North Canterbury (Pettinga et al., 2001; Stirling et al., 2007; Barrell and Townsend, 2012; Barrell, 2015; Barnes et al., 2016). Seismic surveys offshore of North Canterbury demonstrate that thrust faults accommodate slip by folding of Pliocene-Pleistocene sedimentary units (Barnes, 1996; Barnes et al., 2011, 2016). Vertical rates of faulting in the offshore

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region vary from 0.01 to 0.3 $mm(yr)^{-1}$, and the recurrence interval associated with a possible M_w 6.9–7.2 earthquake is 7–15 kyr (Barnes et al., 2016). Nicol et al. (1994) estimated uplift rates of 1.36–2.16 $m(ka)^{-1}$ using marine terraces from the Waipara area of North Canterbury located southwest of Motunau Beach. We aim to quantify the uplift rate associated with the Montserrat anticline and the Glendhu fault at Motunau Beach in North Canterbury to evaluate the rates and kinematics of fold growth and to assess the potential seismic hazard. Assessment of several fault-related fold kinematic models aids in determining fault structure while also providing important constraints for the potential recurrence interval.

A spectacular flight of marine terraces extends along the coastline of Motunau Beach and Happy Valley and parallels the axis of the Montserrat anticline (Yousif, 1987; Forsyth et al., 2008). The Montserrat anticline is a landward-vergent structure, with marine terraces forming on the back limb. Prior studies have used geomorphic relationships to assess the ages of this flight of marine terraces to constrain uplift rates (Yousif, 1987), to examine stratigraphy (Carr, 1970), and to evaluate coastal erosion hazards (Barrell, 1989). Oakley et al. (2017) combined Infrared Stimulated Luminesce (IRSL) and Amino Acid Racemization (AAR) analysis of sediments and shells from these marine terraces to absolutely date the terraces and correlate them to highstands in the eustatic sea level curve. In this paper, we use these ages to calculate uplift rates and combine the uplift rates derived from terraces with a fault-related fold kinematic model to determine the time of the first movement on the Glendhu fault, to evaluate the geometry of this thrust fault that causes folding, and to estimate recurrence interval on this fault. This study has implications not only for the local seismic hazard of the area but also for understanding how fault structure impacts slip-rate-determined earthquake recurrence intervals.

2. Background

2.1. Tectonic setting

The North Canterbury fold and thrust belt (NCFTB) on the South Island of New Zealand is located on the boundary between subduction of the oceanic portion of the Pacific plate beneath the Australian plate and transpressional collision between the Chatham Rise of the Pacific plate with the Challenger plateau of the Australian plate (Fig. 1). The NCFTB is bounded to the northwest by the Hope Fault and to the south by the Canterbury Plains (Fig. 2). The thrust belt extends offshore 20 km onto the continental shelf (Fig. 2) (Barnes, 1996; Pettinga et al., 2001; Barnes et al., 2011, 2016). The valley and ridge topography of this fold and thrust belt is controlled by the geometry of active structures (Nicol et al., 1994). The faults are dominantly thrust and reverse faults striking NE-SW with a SE dip in the study area (Yousif, 1987; Nicol et al., 1994; Barnes, 1996). Folds are NW-vergent with shallow SE-dipping backlimbs, steeply NW-dipping forelimbs, and axes that trend NE-SW (Yousif, 1987; Barnes, 1993, 1996; Nicol et al., 1994). Based

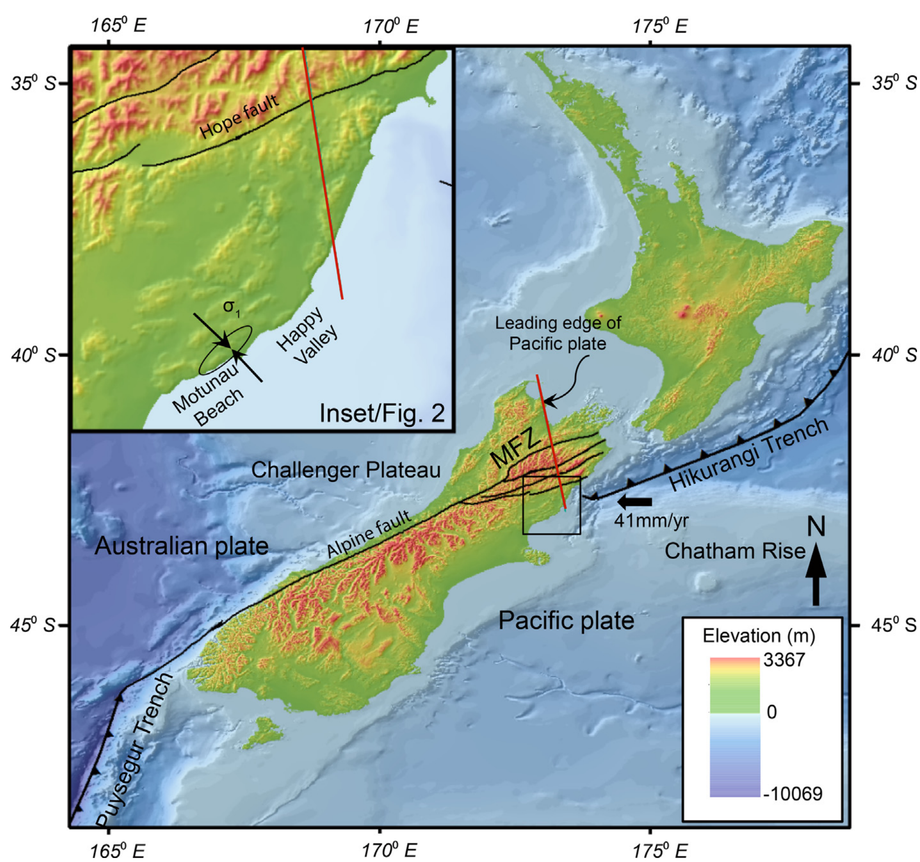

Fig. 1. Digital elevation model (DEM) of the topography and the bathymetry of New Zealand showing tectonic plate boundaries and location of Fig. 2. The Pacific plate subducts beneath the Australian plate at the Hikurangi Trench. The Hikurangi subduction zone transitions onshore to the transpressional right lateral Alpine fault. The Australian plate subducts beneath the Pacific plate at the Puysegur Trench. MFZ = Marlborough Fault Zone. There are four strike slip faults from north to south: Wairau, Awatere, Clarence, and Hope. Pacific plate is subducting at a rate of 41 $m(ka)^{-1}$ relative to the Australian plate (DeMets et al., 2010). Inset: location of the North Canterbury geologic map (Fig. 2). The black oval in the inset outlines the Montserrat anticline. Arrows indicate the orientation of the maximum compressive stress (σ_1) (Nicol and Wise, 1992; Sibson et al., 2011; Ghisetti and Sibson, 2012). Topography and bathymetry are from the National Institute of Water and Atmospheric Research (NIWA) in New Zealand. Projection WGS1984 Mercator.