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An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago

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ABSTRACT

Holocene relative sea-level (RSL) changes have been reconstructed for four regions within the New Zealand archipelago: the northern North Island (including Northland, Auckland, and the Coromandel Peninsula); the southwest coast of the North Island; the Canterbury coast (South Island); and the Otago coast (South Island). In the North Island the RSL highstand commenced c. 8100–7240 cal yr BP when present mean sea-level (PMSL) was first attained. This is c. 600–1400 years earlier than has been previously indicated for the New Zealand region as a whole, and is consistent with recent Holocene RSL reconstructions from Australia. In North Island locations the early-Holocene sea-level highstand was quite pronounced, with RSL up to 2.75 m higher than present. In the South Island the onset of highstand conditions was later, with the first attainment of PMSL being between 7000–6400 cal yr BP. In the mid-Holocene the northern North Island experienced the largest sea-level highstand, with RSL up to 3.00 m higher than present. This is demonstrably higher than the highstand recorded for the southwest North Island and Otago regions. A number of different drivers operating at a range of scales may be responsible for the spatial and temporal variation in the timing and magnitude of RSL changes within the New Zealand archipelago. One possible mechanism is the north-south gradient in RSL that would arise in the intermediate field around Antarctica in response to the reduced gravitational attraction of the Antarctic Ice Sheet (AIS) as it lost mass during the Holocene. This gradient would be enhanced by the predicted deformation of the lithosphere in the intermediate field of the Southern Ocean around Antarctica due to hydro-isostatic loading and mass loss of the AIS. However, no such long-wavelength signals in sea-surface height or solid Earth deformation are evident in glacial isostatic adjustment (GIA) model predictions for the New Zealand region, while research from Australia has suggested that north-south variations in Holocene RSL changes due to hydro-isostatic influences are limited or non-existent. At the regional-to local-scale, post-glacial meltwater loading on the continental shelf around New Zealand is predicted by GIA modelling to have a significant effect on the timing and magnitude of RSL changes through the phenomenon of continental levering. The spatial variation in continental levering is controlled by the configuration of the coast and the width of the adjacent continental shelf, with continental levering providing a robust explanation for the observed spatial and temporal variations in RSL changes. Further research is required to characterise the regional and local effects of different tectonic regimes, wave climates, and sediment regimes. These are potentially very significant drivers of RSL variability at the regional-to local-scale. However, the magnitude of their potential effects remains equivocal.

1. Introduction and background

Over the past 30 years studies of coastal environments in New Zealand have drawn heavily on the Holocene sea-level reconstruction presented by Gibb (1986). This work revised and refined earlier studies (Gibb, 1979, 1983), and found that present mean sea

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level (PMSL) in New Zealand was attained approximately 6500 years BP, with sea levels thereafter remaining largely static.

Gibb (1986) was highly significant at the time it was published, being the first systematic attempt to reconstruct the Holocene sea-level history of New Zealand. As a result Gibb (1986) has been widely utilised, to such an extent that it has been described as the "de facto" Holocene sea-level reconstruction for New Zealand (Hesp et al., 1999; Kennedy, 2008; Clement, 2011).

A number of studies have since investigated the evolution of Holocene coastal environments within the context of the sea-level history presented by Gibb (1986), and have recovered new palaeo sea-level indicators (e.g., Davis and Healy, 1993; Brown, 1995; Heap and Nichol, 1997; Wilson et al., 2007a, b; Abrahim et al., 2008; Kennedy, 2008; Nichol et al., 2009). However, these studies were undertaken almost entirely in isolation of each other, and little consideration has been made of the coherent Holocene sea-level history of New Zealand beyond that presented by Gibb (1986). No attempt has been made to draw the results of these separate investigations together. As a result, Hayward et al. (2010a, c) have rightly described the state of knowledge of Holocene sea-level change in New Zealand as highly fragmented, and in its infancy.

The advancement of the state of knowledge of Holocene sea-level change in New Zealand therefore requires that the findings of these individual investigations be brought together to resolve this fragmentation. The wide utilisation of the Holocene sea-level reconstruction presented by Gibb (1986) has occurred in a vacuum devoid of a robust review of that study. Only Pirazzoli (1991) and Clement (2011) have presented any critical analysis of Gibb (1986). As a result, there are a number of largely unrecognised assumptions and limitations present in the study by Gibb (1986), as well as those subsequent investigations that have adopted that sea-level reconstruction, which should be considered:

No mid-Holocene sea-level highstand or late-Holocene sea-level change. Gibb (1986) attempted to separate the effects of tectonics and eustasy on the elevations of palaeo sea-level indicators used to reconstruct past sea levels. To achieve this, indicators from two sites assessed to be tectonically stable (Blueskin Bay and Weiti River Estuary) were adopted as a 'zero datum', predicated on the assumption that sea level in the New Zealand region had been stable about the present level for the past 6500 years (c. 6700 cal yr BP, Clement, 2011). Gibb (1986) fitted the elevations of relative sea-level (RSL) index points from tectonically unstable locations to the zero datum, and suggested that this allowed rates of long-term tectonic deformation (uplift or subsidence) to be estimated for these tectonically unstable sites. These deformation rates were then used to adjust the observed elevations of these same indicators for tectonic movement, supposedly yielding a RSL signal unaffected by tectonic deformation. This is a circular argument, and the base assumption of stable Late Holocene sea level no longer holds, as a mid-Holocene sea-level highstand is indicated by a large number of studies of Holocene RSL change in New Zealand, including glacial-isostatic adjustment (GIA) models of Holocene sea-level change in New Zealand (e.g., Peltier, 1988; Nakada and Lambeck, 1989; Gehrels et al., 2012), geomorphic studies from a number of New Zealand locations (e.g., Hull, 1985; Hicks and Nichol, 2007; Kennedy, 2008; Schallenberg et al., 2012), and other New Zealand Holocene sea-level reconstructions (e.g., Hayward et al., 2010a, b, c; Clement et al., 2010; Clement, 2011). In the wider context of the southwest Pacific a large number of studies show a mid-Holocene sea-level highstand (e.g., Nunn, 1995, 1998; Woodroffe et al., 1995; Baker and Haworth, 1997, 2000a, b; Baker et al., 2001a, b; Woodroffe, 2009; Lewis et al., 2013). Studies from the east coast of Australia, at similar latitudes to the northern North Island, also show a highstand, and indicate an earlier culmination of the Holocene marine transgression at c. 7700 cal yr BP (e.g., Sloss et al., 2007; Horton et al., 2007; Lewis et al., 2013). These findings are significant in a New Zealand context as both New Zealand and Australia lie within the same regional sea-level zone (e.g., Clark et al., 1978; Clark and Lingle, 1979; Pirazzoli, 1991), in which it is predicted that RSL reconstructions will have a similar form (in the case of New Zealand and Australia in zone V: a sea-level highstand of up to +2 m initiated in the early Holocene, followed by a late-Holocene fall in RSL), though they may differ slightly in magnitude. The Holocene sea-level record presented by Gibb (1986) therefore likely reflects the base assumption of stable sea level after 6500 years BP, rather than an accurate reconstruction of Holocene sea-level changes in the New Zealand region. Gibb (1986) may have misidentified a mid-Holocene highstand as tectonic uplift, thereby removing the indication of a highstand from the sea-level history.

No spatial variation in sea-level change. The reconstruction presented by Gibb (1986) brought together sea-level index points from around New Zealand. This reflected contemporary practice (e.g., Thom and Chappell, 1975; Thom and Roy, 1983). Also, at that time, age control existed for only a limited number of palaeo sea-level indicators; assembling a sufficient number of index points to reconstruct a sea-level history therefore required drawing them from a wide geographic area. The possibility of regional differences in the timing and amplitude of Holocene sea-level changes has been explored in Australia (e.g., Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck et al., 2010; Lewis et al., 2013), but has not been considered in New Zealand. GIA models of Holocene sea-level changes in the New Zealand region indicate that RSL varied both temporally and spatially during the Holocene (e.g., Peltier, 1988; Nakada and Lambeck, 1989). As it groups together index points from across New Zealand, the reconstruction of Holocene RSL presented by Gibb (1986) is therefore a composite of sea-level fluctuations from around the country, and it is unlikely to reliably reconstruct a RSL history that is truly representative of any New Zealand location.

Refinements of earlier studies. Gibb (1986) revised and refined earlier, similar reconstructions of the Holocene sea-level history of New Zealand (cf. Gibb, 1979, 1983). The final reconstruction (Gibb, 1986) features a number of differences in the timing and occurrence of sea-level stillstands and regressions when compared with the two earlier iterations, with no reason or justification given for these changes. As Pirazzoli (1991) observed, the unstated changes between the iterations leaves the impression that the range of vertical uncertainty in the final reconstruction may be much larger than Gibb (1986) inferred. While Gibb (1986) presented indicator points with vertical error bars, the interpreted sea-level history was represented by a single line, seemingly ignoring the inherent uncertainty. A number of subsequent studies have also ignored the uncertainty inherent in Gibb (1986), by presenting only the single line interpreted to represent the sea-level history (e.g., Heap, 1995; Heap and Nichol, 1997; Carter et al., 2002; Thomas, 2000; Ota et al., 1995).

Unconventional dating methods. Recently, a number of studies have attempted to transform the sea-level history presented by Gibb (1986) into sidereal years by calibrating the ages of the index points in order to utilise the sea-level reconstruction in concert with modern radiocarbon age determinations (e.g., Clement et al., 2010; Wilson et al., 2007a; Clark et al., 2011). However, Clement (2011) has noted that the vast majority of the radiocarbon ages presented by Gibb (1986) are not conventional radiocarbon ages (CRAs, cf. Stuiver and Polach, 1977), and therefore cannot be calibrated to sidereal years. As a result the calibrated sea-level reconstructions presented by these recent studies are inaccurate