Response to Comments by Prof. Tim Naish (Referee) to "The last interglacial sea-level record of New Zealand (Aotearoa)"

Deirdre D. Ryan[1*], Alastair J.H. Clement[2], Nathan R. Jankowski[3,4], Paolo Stocchi[5]

[1]MARUM – Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany
[2]School of Agriculture and Environment, Massey University, Palmerston North, New Zealand
[3] Centre for Archeological Science, School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, Australia
[4]Australian Research Council (ARC) Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, Wollongong, Australia
[5]NIOZ, Royal Netherlands Institute for Sea Research, Coastal Systems Department, and Utrecht University, PO Box 59 1790 AB Den Burg (Texel), The Netherlands

26 January 2021

1. Summary

We thank Prof. Naish for his review of our manuscript. Within this response we address each comment individually and detail any changes made to the original manuscript. Comments by Prof. Naish are provided in italic, with our response in standard font, and changes to manuscript are in blue.

2. Overview Comment

The paper by Ryan et al on "The Last Interglacial Sea-Level Record of New Zealand" is a very comprehensive and robust review/evaluation of the previous studies and the literature. It will be an important review for anyone considering further work and it makes some clear recommendations for future work. I commend the authors on this paper, but I do have some concerns about the way in which it assesses some of the previous work. I declare up front that I may be a little defensive having spent most of my career working on sea-level records in New Zealand, and I have worked closely with many of the researchers cited and assessed in this paper.

I think its very important that the authors show they understand the history and context of sea-level studies in New Zealand. Within the Quaternary community New Zealand has held a special place because of its wide range of terrestrial and marine deposits – owing to its convergent plate boundary setting. As I outline below, many of these studies were pioneering and well ahead of the thinking in the Northern Hemisphere that up until the 1980s was influenced by a "Pleistocene" containing 4 glacials and intervening interglacials. While I realise that this paper primarily focusses on the LIG sea-level records and deposits, the introduction and the discussion do refer to the earlier work on older deposits and the LIG is discussed in this context, but I believe a bit inappropriately in the context of the broader work.

Its all very well to say that the LIG deposits are poorly dated, measured and described for sea-level indicators, compared to modern standards, but New Zealand geologists have known that they have always been of limited value for global sea-level reconstructions, because of extensive and widespread tectonic deformation. As the authors quite rightly point out, the dated sea-level indicators where used for understanding long term rates of VLM, not global sea-level change. The paper shows quite clearly that after a robust re-analysis that there is only one site in Northland that has the potential to contribute to global sea-level studies. There is considerable uncertainty about the tectonic stability of Otago coastline based on recent reconstructions using salt marsh cores, GPS and INSAR and geodynamical studies. Also, the latest geodetic work actually shows that Auckland is not stable and is subsiding, slowly.

I initially thought this paper, rather than being a review, was going to contribute some new site elevation data or information on shoreline indicators or geochronology, but realised that that is not really the case. It concludes that New Zealand still has the potential to be an important South Pacific site, based on the one Northland site. I was slightly surprised by the GIA discussion that suggested there could be significant deviations from eustatic during interglacials, when the paper cited, for which Stocchi did the GIA modelling, showed this not be case, especially for the plausible range of LIG ice sheet configurations and meltwater contributions.

My overall recommendation is that this is an important and useful review, but that the authors should relook at the context in which they introduce and discuss the review and adjust the text accordingly.

Responses to the below specific comments address the issues summarized within this overview comment. Although Prof. Naish seems to feel that we are judging the New Zealand record harshly, the intention of this review was to provide readers an understanding of the current state of knowledge of last interglacial sea level within New Zealand. The conclusion that the record is lacking in some areas necessary for sea-level interpretations is not due to a lack of quality research in New Zealand, but rather that it has not been the focus of most research. This conclusion is hardly new as it is an echo of the conclusions made by Gage (1953) and Pillans (1990a) in earlier reviews of shoreline studies within New Zealand as noted within the Introduction.

3. Specific Comments

Comment 1: *Introduction – I was surprised to see the Introduction treat previous work a little dismissively. There are many challenges to identifying, mapping, dating and correlating paleoshorelines, inferred strandlines and wave cut marine terraces in such a tectonically active setting. Given that much of this work occurred in the pre-1980s, with some outstanding geomorphic and geological descriptions and interpretations ahead of their time (e.g. Fleming, Chappell, Gage, Suggate and Pillans), a more generous approach could be taken recognising this early pioneering work. The work of Brad Pillans on the South Taranaki-Whanganui marine terrace sequences remains one of the classic examples in the world today of a suite of wave cut platforms and associated strandlines recording every interglacial from MIS 3-13. The authors should also appreciate more generously, the difficulty in dating these deposits, which also hampers many recent studies (e.g. Hearty et al. 2020 South Africa), and has long been acknowledged by people such as Brad Pillans and Kelvin Berryman as a challenge in NZ. Its only really in the last decade that new approaches for identifying shoreline indicators and the influence of post-depositional processes such as GIA and dynamic topography have been appreciated. However, the authors of this paper have done a nice job of recognising the need for modern approaches of analysing shoreline indicators in their reassessment of the NZ record.*

It is unfortunate that Prof. Naish feels we have treated previous work in New Zealand a little dismissively as this was certainly not our intention. We have added language throughout the Abstract and Introduction (Section 1) to ‘soften’ our approach and provide greater context to the amount and quality of previous research and to highlight the difficulties confronting sea-level studies in New Zealand. We recognize that NZ has a rich record of paleo-shoreline studies and it is for this reason that we chose to write a succinct overview of previous work, directly related to the topic of the manuscript – sea-level records of the last interglacial. Section 4 (the bulk of the manuscript) has a very detailed review of previous studies concerning MIS 5 records. This section is quite long, reflecting the development and wealth of research completed in New Zealand. Section 5 provides a detailed discussion of difficulties in establishing geochronology, and Section 6 touches upon (albeit briefly) on the length of the record beyond the LIG. We are mindful that given the length of the manuscript already and the extensive work that has been done a more detailed review would expand the manuscript beyond its scope. We hope that our softening of the abstract and introduction is sufficient. Rewritten or added sentences are:

Abstract

> Extensive coastal deformation around New Zealand has prompted research focused on active tectonics, which requires less precision than sea-level reconstruction. The range of paleo-shoreline elevations are significant on both the North Island (276.8 to -94.2 m msl) and South Island (173.1 to -70.0 m msl) and have been used to estimate rates of vertical land movement; however, in many instances lack adequate description and age constraint for high-quality RSL indicators.

Introduction

> This latter characteristic has facilitated the preservation of marine terrace sequences spanning the Pleistocene and into the Holocene that have been the target of much research and discussion of New Zealand geomorphology and geology since the late 19th Century. Importantly, the terraces also serve as the primary source of last interglacial paleo-sea level records.

> Resolving a sea-level record from New Zealand marine terraces (and other sea-level indicators) has historically been complicated by the long-term and ongoing coastal deformation (Section 5.2) and difficulties in geochronology (Section 5.3).

> This review of the LIG sea-level indicators in New Zealand, like the preceding reviews by Gage (1953) and Pillans (1990a), found considerable lack of necessary detail in the published literature for the identification of robust sea-level indicators defined by the WALIS framework; including that published post-1990.
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> It must be stressed that the lack of detail for last interglacial sea-level studies in New Zealand reflects the active landscape and that the focus of many studies has not been sea-level at all, but rather understanding the active tectonics and vertical land movements of the archipelago, which require less precision than sea-level reconstruction. Furthermore, until late into the 20th Century studies had to contend with difficulties in correlating distant sequences due to limited geochronological methods and still must grapple with the tectonically active nature of the islands and difficult topography.

Comment 2: *Quaternary oxygen isotope records were published in the late 1970s and early 1980s, which provided a revolutionary tool to understand and date the NZ marine terraces mapped by earlier workers and interpreted within the existing paradigm of 4 NH glaciations. As the authors highlight, absolute age determination of strandlines was limited to the intermittent tephra, biostratigraphic inferences, thermoluminescence and amino acid racemisation dating which have many assumptions and problems. Notwithstanding these challenges, it became clear that some strand lines and terraces could be correlated with specific interglacials identified in the benthic oxygen isotope record, and that based on this, particularly in coastal Taranaki and Whanganui, each interglacial shoreline could be matched to successively older orbitally-paced interglacials. This allowed two things to be established: 1) That there was far field physical evidence that confirmed interpretations of the newly developed benthic isotope sea-level proxy records, and that they really were measuring global ice volume and sea-level (older than the Huon Peninsula coral terraces) [I had this conversation several times with the late Sir Nicholas Shackleton, who always recognised this significance], and 2) based on this relationship, an orbital chronology could be established that allowed uplift rates to be estimated for western North Island*.

Sentences were added to highlight the implementation of marine oxygen-isotope records in the interpretation of New Zealand sea-level and geomorphology. Specifically,

> Following the publication of marine oxygen-isotope records, age determination moved beyond the constraints of the Mediterranean and Huon Peninsula sequences and New Zealand marine terraces were correlated with specific sea-level intervals reflecting global sea-level and ice-volume (e.g. Beu and Edwards, 1984; Ward, 1988a; Pillans, 1980a; 1994; Suggate, 1992; Berryman, 1993; Ota et al., 1996). These correlations not only provided greater certainty in the interpretation of New Zealand geomorphology, but also lent strength to the newly developed marine oxygen-isotope sea-level proxy records.

Comment 3: *It should be noted that pre-GPS surface elevations were largely achieved by handheld altimetry. Moreover, the focus was never really on reconstructing the absolute magnitude of RSL because of the tectonic complication. Although, paleo shorelines were identified, dated and correlated to the benthic oxygen isotope stack the main outcome was constraining vertical land movements thought to be primarily driven by the active plate boundary setting.*

The prevalent use of altimetry is noted in Section 3 "Location and elevation measurements" (Line 178), which the reader is referred to in Lines 54-55, "how geographic location, elevation, and associated uncertainty were assigned to each indicator (Section 3)". We are also not sure at which point of the introduction this comment was written, but at line 79, we expressly note that due to regional tectonics the research focus was the determining VLM and not sea level.

Comment 4: *Line 90 – Written negatively. This was not "an unfortunate outcome" that there were many different names for terraces around NZ, it was the correct stratigraphic approach at the time. Back when they were first described and named the relationship between marine terraces and their deposits in different parts of NZ could not be established, and in some cases are still difficult to establish. The recognition, through improved age control, the development and application of the benthic isotopic proxy of global sea-level then allowed different terrace sequences from different parts of New Zealand to be compared within a unifying chronostratigraphic framework. Pillans 1990 made a big step forward in this regard. Likewise the New Zealand Neogene sedimentary stratigraphy went through the same evolution, of initially being subdivided at regional scale and then national scale on the basis of endemic biostratigraphic criteria, and then meaningless correlations were established the type sections in the Mediterranean. With the advent of magnetostratigraphy calibrated by radiometric dating of tephra, it became possible to correlate orbital sequences with benthic oxygen isotope curve (global climate) and astronomically calibrate age models.*

The interpretation of our phrasing was not as intended and is adjusted as follows:

> Due to the difficulty in relating spatially distant marine terraces, in part due to difficulties in determining a numerical age, nomenclature for the terraces and their associated sediments is regionally specific and has evolved through time with better age constraint (Table 1; Section 4).

Comment 5: *Table -1 For completeness you should cite Fleming 1953. For example he was the first to identify the Brunswick terrace, which Pillans subsequently dated as MIS 9 and adopted Fleming's nomenclature. Previously it had been incorrectly associated with the MIS 7 Ngarino Terrace*.

Since submission of the manuscript we have obtained a copy of Fleming 1953 and agree it should be cited it in this work. Fleming 1953 has been added to Table 1 and in addition to further citations, the following was added to Section 4.1.2:

> Fleming (1953) provided early, detailed descriptions of the Brunswick and Rapanui Terraces, recognizing both as having formed over multiple cycles of sea-level transgression and regression (Table 1). The Rapanui Terrace was later divided into the older Ngarino Terrace and younger Rapanui Terrace (Dickson, 1974).

Comment 6: *Line 199 – I understand that this is a generalistaion but eastern North Island vertical land movements (VLMs) both short and long-term are complex, partly because of the TVZ and mostly because of the Hikurangi margin, with subsidence in the Hawkes Bay Basin and near Mahia Peninsula and in the Bay of Plenty near Whakatane.*

We agree that eastern North Island is tectonically complex and that our brief overview could be expanded. As suggested, we have added remarks to explain the subsidence in the east. This paragraph has been expanded to include the following:

> The entire eastern North Island constitutes the Hikurangi Margin forearc that is being compressed by the collision of the Pacific and Australian Plates (Nicol et al., 2017). The forearc structure from east to west is composed of an accretionary wedge (outer forearc, mostly located offshore), a forearc basin (inner forearc), and the Axial Ranges (frontal ridge) bisected by the North Island Dextral Fault Belt (NIDFB) (Berryman, 1988). The majority of the eastern North Island is being uplifted as the forearc is compressed with the exception of parts of Hawke's Bay: the Heretaunga Plains, a subsiding tectonic depression on the margin of the convergent plate boundary (Lee et al., 2011), and the coast near Wairoa, which experienced late Quaternary co-seismic subsidence (Ota et al., 1989a; Litchfield, 2008). The oblique subduction of the Pacific Plate is rotating the eastern North Island clockwise producing a backarc rift system and volcanic arc: the Taupo Volcanic Zone (TVZ). The Whakatane Graben, at the northern end of the TVZ, is a subsiding tectonic depression bounded by normal faults and infilled with up to 2 km of late Quaternary sediments (Wright, 1990; Beanland and Berryman, 1992).

Comment 7: *Figure 3. Why did you not use the NT1 wave cut surface of Alloway et al. 2005 as a site?*

Alloway et al. (2005) refers to NT1 and NT2 (wave cut surfaces correlated with MIS 5a and 5e, respectively), describing their stratigraphic relationship to debris-avalanche deposits. However, stratigraphic sections are drawn cm below surface and no heights above a sea-level datum are provided, precluding entry into WALIS.

Comment 8: *Also there is a lot of work on the Southern Wellington-Wairarapa coastline in Dee Ninnis' PhD thesis, that the authors had access to and the potential to include and collaborate with. Some figures below that were made available to the authors. Was there a reason for excluding this data?*

There are two reasons for this. First, the intention was only to include published peer-reviewed data, which precludes Masters and PhD theses. We did include some theses (e.g. Goldie, 1975; Hicks, 1975, etc.) that had been referenced by multiple later authors and that seemed likely would not be published independently given the time elapsed since completion. DDR and AC did discuss the inclusion of Dr. Ninnis's recently (2018) completed PhD work. However, we are aware that Dr. Ninnis is working towards publication of that work and did not want to 'scoop' what will be a valuable contribution to New Zealand geology and geomorphology and deserving of initial recognition under Dr. Ninnis's authorship. We would be very happy to have Dr. Ninnis archive her work in WALIS – indeed it is the purpose of WALIS and we encourage her to do so.

Comment 9: *GIA. It's a bit unclear what the message from this section really is. A number of studies (Pliocene and Recent) have shown that New Zealand is largely unaffected by GIA and sits close to the GMSL in most reconstructions where polar meltwater contributions and viscosity models are varied. While a local signal due to water loading of the shelf has been implied for the Holocene, resolving the fingerprint and any flexural wave along NZ is extremely unlikely for the last interglacial given there is really only one site in Northland that is likely to be unaffected by tectonics, and considering the uncertainties the* *authors discuss. It has been implied the effect of GIA could be 5% deviation from North to South. One of the co-authors did a range of GIA experiments for the Pliocene and showed that under a reasonable range of ice histories, NZ lay on the eustatic. For NZ to have a significant GIA deviation during the LIG most of the meltwater would need to come from NH (Greenland) which seems precluded by most geological and ice core reconstructions.*

We agree, this can be written more clearly. For clarity, the entire section content is shown below with significantly altered or new sentences shown in blue font. We have also added a figure to help clarify the GIA discussion.

> Excessive and prevalent coastal deformation will preclude the development of a sea-level reconstruction that can be registered to present day, regardless of the quality of sea-level indicators. The position of the New Zealand archipelago straddling the active boundary of the Australian and Pacific plates has produced a coastline subject to variable rates of vertical land movement (VLM) due to complex tectonics and displacement associated with earthquakes. Although displacement by an earthquake can have dramatic effect, interseismic deformation (deformation between earthquake events) is more likely to influence long-term trends in VLM (Beavan and Litchfield, 2012). As has been shown above, the New Zealand paleo-shorelines and marine terraces (and below-surface marine deposits) have been essential for determining estimates of long-term (beyond Holocene) rates of uplift or subsidence (e.g. Chappell, 1975; Pillans, 1983; Bishop, 1985; Suggate, 1992; Berryman, 1993; Begg et al., 2004; Wilson et al., 2007; Beavan and Litchfield, 2012; Oakley et al., 2018). However, because the research focus has been on determining long-term VLM rates, and due to a lack of adequate geochronological methods for many studies, potential sea-level indicators have been described in less detail than desired for such use. Although any sea-level reconstruction derived from these indicators may not be useful for a relative sea-level curve with relation to present sea level, more precise descriptions and age constraint can improve estimates of VLM rates, especially where there is uncertainty in correlation to the appropriate MIS 5 highstand.
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> GIA encompasses all deformational, as well as gravitational, and rotational-induced changes to relative sea level in response to the buildup and retreat of ice sheets with residual and variable affect along coastal sections depending upon their proximity to former glaciers, ice caps and sheets (Arctic and Antarctic, Simms et al., 2016). In other words, the magnitude and wavelength of the solid Earth response to ice-and water-load history varies with time (in relation to glacial maxima) and geographical location producing a gradient in relative sea level that is modulated by mantle rheology. Neglecting GIA on active coastlines when determining rates of VLM has been shown to lead to overestimated uplift rates at an overage of 40%, but also up to 72% (Simms et al., 2016; Stocchi et al., 2018).
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> New Zealand sits on a ‘sweet spot’ with respect to Antarctica, such that when the northern hemisphere ice sheets are neglected, the local RSL response to either growth or retreat of the Antarctic ice Sheet (AIS) is nearly eustatic. However, deviations from eustatic may increase dependent upon ice mass fluctuations within specific sectors of the AIS. In particular, melting from the east AIS, which is closer to New Zealand, would shift the eustatic band crossing the North and South Islands northward, above the North Island and cause a lower-than-eustatic local sea-level rise. Various scenarios of Antarctic ice geometries indicate New Zealand RSL approximates eustatic sea level with GIA having little effect (~2-3 m deviations from eustatic) on New Zealand (Grant et al., 2019), thus making it useful for constraining global ice-volumes during MIS 5e. The predicted deviations of RSL from the eustatic during MIS 5e are partly due to ocean syphoning and continental levering. The former causes local (New Zealand) sea-level drop in response to water flow towards the subsiding peripheral forebulges that surround the glaciated areas. The latter causes relative sea-level drop in response to local crustal uplift as a consequence of water-loading-induced crustal tilt. Hence, both processes result in a New Zealand highstand 1-3 kyr earlier that eustatic, which is then followed by a RSL drop (Figure 5). The combined effect of ocean syphoning and continental levering may explain the variability of Holocene sea-level change around New Zealand. For example, the Holocene highstand peaked in the North Island at ~2.65 m apsl between 8.1 to 7.2 cal ka BP, whereas in the South Island, the highstand peaked later, between 7.0 and 6.4 cal ka BP, at no more than ~2 m apsl (Clement et al., 2016).
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> The significance of New Zealand glacier ice-volume change on coastal deformation and sea-level reconstructions has not been quantified for New Zealand (King et al., 2020). Resolving any flexure within New Zealand beyond the Holocene, due to regional glacier ice-volume change or any other regional drivers, is unlikely due to the extensive coastal deformation. The gravitational effect of local glaciers would be hard to detect, and similarly with solid Earth deformations. Given the short wavelength of glaciers, their deformations would be most likely elastic and would therefore be compensated by space-limited upper lithosphere flexure/deformation.

The only last interglacial site identified so far that is most likely to have been unaffected by deformation is One Tree Point in Northland (Section 4.1.1), highlighting the importance of this region for additional study.

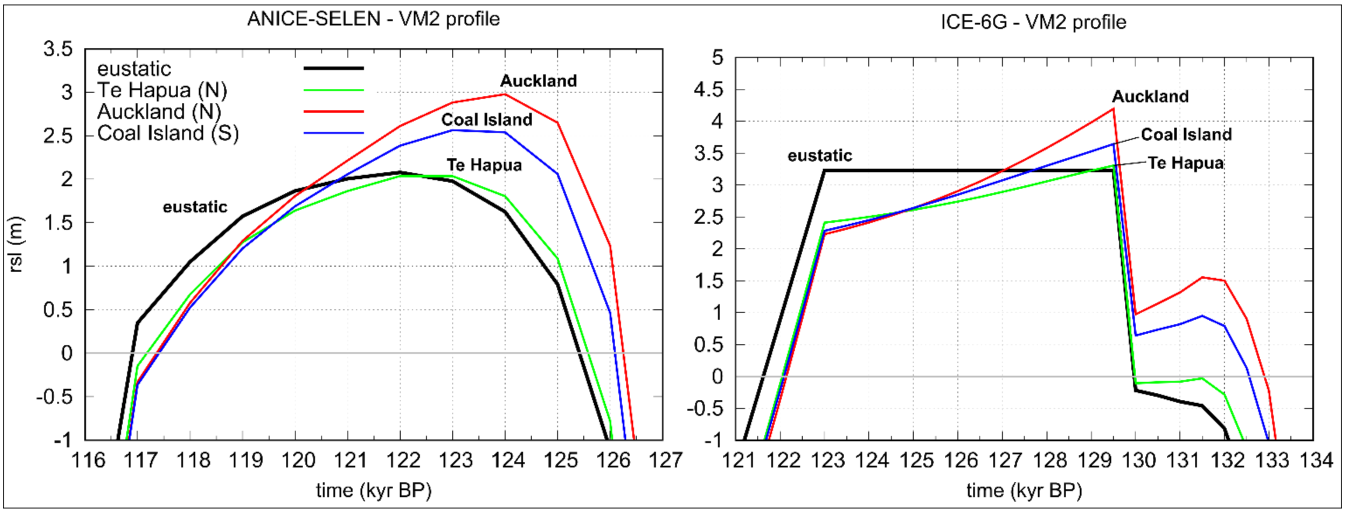

Figure 5: Local RSL curves for MIS 5e sea level at the northernmost tip of North Island (Te Hapua; latitude -34.39, longitude 173.02), Auckland (latitude -36.85, longitude 174.76), and the southernmost tip of South Island (Coal Island; latitude -46.21, longitude 166.66) generated from ANICE-SELEN and ICE-6G models. Similar to the Holocene, sea level peaks earliest and higher in the North Island. The Northland region (Te Hapua) RSL curve is near to eustatic. Deviations of the RSL curves from eustatic is driven by ocean syphoning, suggesting it serves as a primary driver of variability in the timing and height of peak sea level across New Zealand. Note the different scale to x- and y- axes between model outputs.

Comment 10: *Line – 1134 - It wouldn't hurt the authors to cite Naish et al 1998 (QSR) or Pillans et al (2005) here, if they are going refer to these older sequences*.

We thank Prof. Naish for bringing these publications to our attention. They are added as references.

Comment 11: *Line – 1150 – I would suggest the authors also read Grant et al 2019 (Nature), and some of the other Whanganui-based Pleistocene literature. This statement is misleading and shows a lack of understanding as to how the older sea-level reconstructions are established using the shallow-marine record. They are not absolute sea-level indicators like wave cut platforms and strandlines. They cannot be compared to MIS 5 sea-level indicators around NZ. They do however fundamentally record many transgressions and regressions of the shoreline in response to orbitally-paced global sea-level and associated water depth changes. But reconstructed water depth changes are also affected by local tectonic subsidence, compaction, and loading that all have to be accounted for when deriving the amplitude glacial-interglacial global sea-level change. The sea-level cycles reconstructed from the Whanganui sequences cannot be registered directly to present day sea-level because of late Quaternary uplift of western North island, which is the reason the marine terraces are preserved post MIS 15*.

We regret that our writing here was not clear, and we have rewritten material accordingly. We did not say, nor intend for it to be interpreted, that the Whanganui Basin sequence provides absolute sea-level indicators. Nor were we trying to compare them to other MIS 5 sea-level indicators around NZ. Rather, our reference to the record of sea-level fluctuations is to the transgressive and regressive sequences preserved within the basin. With this in mind, the first paragraph of this section (Section 6) was rewritten to better reflect the character of the Whanganui Basin sequence.

The Whanganui Basin, in addition to the Rapanui (MIS 5e), Inaha (MIS 5c), and Hauriri (MIS 5a) terraces (Section 4.1.2), retains a sequence of shallow marine transgressive, highstand, and regressive sediments correlated with each high sea-level marine oxygen isotope stage of the past 2.6 Ma, reflecting cyclic, orbitally-paced eustatic sea-level fluctuation (Pillans, 1991; Beu et al., 2004; Pillans et al., 2005; 2017; Naish et al., 1998; Grant et al., 2019). This record is extremely well-preserved and has been subject to an extensive variety of geochronological and stratigraphical methods. Not only does it offer a detailed paleoenvironmental record from an isolated part of the South Pacific, it serves as a paleo-proxy for the amplitude of interglacial-glacial relative sea-level change and constrains polar ice-volume variability within the Pliocene (3.30 to 2.50 Ma) when atmospheric carbon dioxide concentration was last ~400 parts per million – a climatic condition recently met. It retains a long record of tephra (to c. 2.17 Ma) and loess (to c. 0.50 Ma) deposition, which provides a framework for regional stratigraphic correlation in the North Island. The stratotype sections and points of the four stages representing Quaternary New Zealand are defined by the fossiliferous marine sediments within the Whanganui Basin. A paleovegetation and paleoclimatic record spanning much of the Haweran Stage (0.340 Ma to present) has been developed from the marine and terrestrial sequence. Unfortunately, the ongoing and complex tectonics of the North Island preclude any sea-level reconstruction registered to present day – indeed it is the relatively recent uplift of the basin margins which has allowed preservation of marine terraces formed over the past 0.7 Ma, including the Rapanui, Inaha, and Hauriri terraces.