Clim. Past Discuss.,
https://doi.org/10.5194/cp-2019-29-AC1, 2019

Climate of the Past
Discussions

Interactive comment on "Late Pliocene Cordilleran Ice Sheet development with warm Northeast Pacific sea surface temperatures" *by* Maria Luisa Sánchez-Montes et al.

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Received and published: 22 June 2019

We would like to thank Anders Carlson for the comments provided to encourage discussion of how our manuscript could be improved. Please find below our responses to these comments and the changes in the manuscript.

1-Comment from the referee

Sánchez-Montes et al. present new and exciting SST and IRD data from IODP Site U1417 in the Gulf of Alaska spanning 4 to 1.7 Ma. This occurs during the Pliocene to Pleistocene transition when the world shifted into the modern ice age period. By mea-

suring IRD and SST records in the same core, the authors can provide a one-to- one comparison between local temperature and the behavior of tidewater glaciers. While this data is exciting, the paper needs some substantial revisions and consideration of other data not referenced. I'll leave my comments at a more general level at present to guide revision prior to more specific comments.

First, don't call it the mid-Pliocene warm period. The MPWP is actually the mid- Piacenzian warm period. The Piacenzian used to be in the mid Pliocene but as of 2009, it is now the late Pliocene. See Gibbards et al.'s revision of the Cenozoic timescale.

2-Author's response

Thank you for spotting this, we agree this should be changed.

3-Author's changes in the manuscript

The MPWP will be amended in a revised manuscript to be the acronym of the Mid-Piacenzian Warm Period.

1-Comment from the referee

Second, the authors should skip this comparison with modern SST in their discussion and rather focus on comparing with the alkenone record of Praetorius et al. (2015 Nature) that is from 17 ka-0 ka at what is now Site U1419 (core is EW0408-85JC taken on the site survey cruise for the IODP leg). The core top temp is the same as at U1417, supporting the comparison. And more importantly, the glacial interglacial absolute and relative change at U1419 from 17 to 0 ka is the same as the Pliocene and early Pleistocene range and absolute temps at U1417. I think this rules out a major change in CO2 average composition as a driver of a Pliocene to Pleistocene to last deglaciation SST pattern.

2-Author's response

We could acknowledge the similarity in the range of glacial-interglacial SST changes between the two sites in the manuscript, but with the strong caveat that we would not be comparing like with like. We would like to highlight that U1417 and U1419 are 400 km apart and have around 4 km difference in water depth (Fig. 1). As we show on Figure 1 in our original manuscript, presently these sites are under the influence of different oceanic currents: U1417 is influenced by the Alaskan Current and U1419 is influenced by the Alaskan Coastal Current. If we choose to compare U1417 during the 4 to 1.7 Ma time period with U1419 covering the 17 Ka to 0 Ka interval, we would be comparing the behaviour change over time of two different currents (and we do not have LGM-Holocene data from U1417 to make a direct comparison to U1419). We do not see the benefit of this comparison as an alternative to our current comparison between the modern SSTs at our core site with those of the Pliocene and early Pleistocene. In our manuscript, we prefer to compare Site U1417 with modern SST at the same location (Site U1417), to give information about the degree of change of that particular current under different past climates.

3-Author's changes in the manuscript

Reflecting on the reviewers comments, a sentence in the manuscript has been amended (Page 11, line 31) to make the benefit of the Pliocene and Pleistocene-present comparison clear: "To understand the evolution of the ocean currents governing the North Pacific at the present core sites (Fig. 1) and to find possible explanations of the observed SST distributions during the Pliocene and Pleistocene climate evolution, the modern climate system is used here as an analogue."

1-Comment from the referee

Third, quit saying this is the Cordilleran ice sheet. IRD only means you have a marine terminating ice margin. There is no Cordilleran ice sheet today and the Gulf of Alaska has a lot of marine terminating ice margins and icebergs floating around. For instance, both Bering and Malaspina glaciers could quickly become marine terminating if a big storm came through and blew away their morainal banks that happen to right now be

above sea level. Both glaciers have beds below sea level except for that little bank. The evidence for an ice sheet comes from the dated proglacial gravels to the northeast in Hidy et al. (QSR 2013) that date the first Cordilleran ice sheet to about 2.6 Ma. This paper should be discussed. Likewise, the authors should use the proximal mag sus. record from ODP Site 887 rather than the far removed to western Pacific records of 882 that Haug et al. produced. I would also include comparison of the U1419 mag sun record to 887 to support the authors suggestions/conclusions. The mag sus record could also help in improving the IRD resolution/interpretation. Surprised it isn't included. In summary, the authors should just refer to tidewater glaciation of the mountains, leaving out the word ice sheet or Cordilleran ice sheet. As far as the record they have in U1419, the conclusion is that some icebergs survived to U1419 once at 2.7 Ma and then again after 2.6 Ma. This is important findings but by no means says anything about an ice sheet or its size. The authors could compare IRD abundance to the IRD record from Addison et al. (2012 Paleoc) on 85JC. Now, 85JC is much closer to the ice margin and coast but could provide some kind of context.

2-Author's response

As we noted in the previous comment, Site U1417 is located at present ∼450 km away from the coast (Figure 1). At present, tidewater glaciers have retreated far inland from their advance during the Little Ice Age (Molnia, 2007; 2008). Although icebergs calve into fjords and bays today, they do not survive to reach the Gulf of Alaska. We have found literature on the heavy influence of glacier runoff on the characteristics of the ACC that flows along the NW Alaskan coast (Weingartner et al., 2005; Royer and Grosch, 2006), which today acts as a barrier to icebergs reaching central GOA. Thus, the enhanced iceberg delivery into the GOA during the early Pleistocene requires a more extensive and/or productive calving margin in ice from the Cordillera, than is observed today.

In our multi-proxy data set from Site U1417 we observe notable changes, in addition to peaks in IRD between 3 to 2.5 Ma that support the establishment of the Cordilleran

Ice Sheet (CIS). These include a step-wise increase in sedimentation rates, increase meltwater discharge and increase in the delivery of terrestrial leaf-wax lipids. We assert that the observations recorded at U1417 from 3-2.5 Ma indicate widespread glaciation along the Alaskan margin resulting from an expanding CIS with marine-ending outlet glaciers, and not an advance of a singular mountain glacier to tidewater. A previous study (St John and Krissek, 1999) also identified IRD increasing in Site 887 (Fig 2 right), which is located 200 km southwest of U1417. In Figure 2 (right), IRD from both Site 887 and U1417 are plotted (we can include this in a revised manuscript). Site U1417 records a higher abundance of IRD than Site 887, which we infer could be due to its proximity to the ice in coastal Alaska (Fig. 2 left). Mindful of the differences in the age models of the two sites, the IRD peaks show similar increases and decreases during the 4 to 1.7 Ma interval, suggesting a wider distribution of enhanced iceberg delivery to the GOA than might be expected from a single outlet glacier.

Our study advances the understanding of ice rafting in the North Pacific (as discussed in St. John and Krissek, 1999) by considering SSTs as a significant factor in the survivability of icebergs transiting the Pacific Ocean (page 10, line 6-7 in the firstly submitted manuscript). For example, a reduction in SSTs occurs in association with an IRD peak at 2.9 Ma, and several high frequency peaks in IRD from 2.7 to 2.4 Ma are associated with higher and more variable SSTs. The reviewer notes the work of Hidy et al. (2013) and their chronology for the Klondike gravel, which marks the 'earliest and most extensive Cordilleran ice sheet' on its eastern margins. Hidy et al. (2013) use independent cosmogenic nuclide dating to identify the maximum advance of the CIS at 2.64 Ma (+0.20/-0.18 Ma). A large ice advance on land in the eastern Cordillera, at the same time as enhanced IRD delivery to two sites in the North Pacific (U1417, ODP 887) suggest that widespread glaciation had developed in the interval 2.7-2.4 Ma.

Icebergs were calved from the CIS marine-terminating outlet glaciers, which cut troughs across the continental shelf (e.g. shown for the Last Glacial Maximum (LGM) in Fig 1 of Gulick et al., 2015). As noted during the original IODP expedition, the dom-

inance of low-grade metamorphic lithologies suggest that the Chugach metamorphic complex (Jaeger et al., 2014) was a primary source of IRD for Lithological Unit I (Jaeger et al., 2014). Due to the spatial extent of this formation (Fig. 3) and without further detailed investigation of clast lithologies (and their geochemistry) it is not possible for us to test whether the IRD being deposited at Site U1417 is from one tidewater glacier system or not, although it is not clear why one glacier would advance and generate sufficient IRD in isolation, especially in the context of the eastward advance onshore detailed by Hidy et al. (2013) discussed above. It is beyond the scope of this study to test this question. However, the TAR, CPI and IRD Rc data we also generated for Site U1417 sediments suggest a mix of sediment sources being eroded, transported and deposited to Site U1417. This further supports an influence of widespread glaciation influencing Site U1417 during the Cordilleran Ice Sheet expansion. Connecting this comment with a comment from Reviewer 2, we propose that including the CPI (carbon preference index) might help in visualising the diversity of material (indicated by the maturity of the sediments) reaching Site U1417 and thus, the diverse provenance of material eroded and transported to Site U1417 (Fig. 4). The distance of U1417 from the present coastline (Fig. 2) and the diversity of material arriving to Site U1417 from the terrain (Fig. 4) strongly suggests a mixed source of organic matter to the Site.

We have cited Gulick et al., 2015 in order to link Site U1417 to the other sites (including U1419) drilled along a transect by IODP Expedition 341 (Fig. 1). This transect extends from the deep sea to the Alaskan Margin. It is important to note that the high sedimentation rates in this temperate glacimarine setting preclude the direct comparison of the oNHG described in our paper with any other sites drilled closer to the continent (including U1419 and 85JC mentioned by the referee, which do not extend beyond the most recent glacial stage) (see Figs. 1 & 2). The response of CIS deglaciation after the LGM has been documented at 85JC on the continental rise by sudden reductions in sedimentation rate, IRD delivery, and bulk density (Davies et al., 2011) but the record does not extend to the onset of glaciation during the last marine isotope stage. In response to the reviewer's concerns, we can include additional comparison of our data for the Pliocene/early Pleistocene at Site U1417 with the late Pleistocene data of Sites U1419 / 85JC, but with the caveat that these are quite different sedimentary environments and timescales (as evident by the different range of sedimentary N/C vs δ13C (‰) signature at 85JC and U1417, Table 1).

3-Author's changes in the manuscript

We will include Hidy et al. (2013)'s reference in our revised manuscript to support the attribution of our IRD advance to the Cordilleran Ice Sheet expansion: " The timing of the increase in IRD at Site U1417 coincides with the increase in IRD at Site 887 (St John and Krissek, 1999) and the maximum extent of the CIS as recorded onshore in the eastern Cordillera by the extensive Klondike gravels at 2.64 Ma (+0.20/-0.18 Ma) (Hidy et al., 2013)." (page 10, line 20 in the firstly submitted manuscript).

We will include the CPI (carbon preference index) to help in visualising the diversity of material (indicated by the maturity of the sediments) reaching Site U1417 and thus, the diverse provenance of material eroded and transported to Site U1417 (Fig. 4).

1-Comment from the referee

Fourth, I would greatly reduce to just cut the discussion of the PDO or analogues to modern SST patterns from the paper. The whole section is very confusing and hard to follow. Likewise, this depends highly on the age models of all the cores and these are not discussed. To make such comparisons/conclusions, common age models and uncertainties need to be applied which I think is beyond the scope of this paper. Rather, the authors should smooth down to âĞă0.1 Ma their records in Fig. 3 and support the idea that the North Pacific warmed over the Plio-Pleisto transition while the North Atlantic cooled. At the multi-0.1 Ma timescale, such a conclusion should be robust without delving into age models too far.

2-Author's response

Both reviewers have commented on the complexity of this section and we agree that

smoothing the data in Figure 3 of the manuscript and trim the text significantly would result in a clearer description of the North Pacific Plio-Pleistocene climate patterns. Fig. 5 below will be included in the revised manuscript.

3-Author's changes in the manuscript

We will smooth the data in Figure 3 of the manuscript to highlight more clearly the North Pacific Plio-Pleistocene climate patterns (see Fig. 6 attached).

The text in section 4.4, will be edited (shortened and clarified) to read as follows: "The overall cooling trend during the Neogene, briefly interrupted by the MPWP and intense cooling events such as the M2, is believed to be a dominant pattern in the global climate. This notion is largely based on the global increase in ice volume (e.g. LR04 Benthic ïĄď18O Stack (Lisiecki and Raymo, 2005) and from studies in the North Atlantic SST (i.e. ODP Site 982, Lawrence et al., 2009). In contrast, the contribution of the North Pacific into our understanding of the global climate evolution from the Pliocene to the Pleistocene is limited. Our study at Site U1417 adds valuable regional climate information during the evolution of the Cordilleran Ice Sheet. Unlike the LR04 stack, average Pliocene SST values (4.0 to 2.8 Ma) at Site U1417 are 1 °C colder than the average early Pleistocene values (2.7 to 1.7 Ma) (the Pliocene-Pleistocene SST difference of 1°C has an standard deviation of 0.5°C). In the wider North Pacific, a warming trend from the late Pliocene to early Pleistocene has also been observed at ODP Site 882 in the subarctic Pacific (Martínez-García et al., 2010), at Site 1010 and potentially at Site 1021 (mid-latitude east Pacific) (Fig. 3). Beyond the North Pacific, warmer SST during the early Pleistocene compared to the Pliocene have also been recorded i.e. DSDP Site 593 in the Tasman Sea (McClymont et al., 2016) and Site 1090 (Martínez-García et al., 2010) in the South Atlantic. In contrast, long-term cooling trends mark the early Pleistocene for the mid-latitude west Pacific (Site 1208) and tropical east Pacific (Site 846), more consistent with the development of a cooler and/or more glaciated climate (Fig. 3).

The North Pacific warming occurs despite an atmospheric CO2 drop from 280-450 ppmv to 250-300 ppmv (similar to pre-industrial levels) from 3.2 to 2.8 Ma (Pagani et al., 2010; Seki et al., 2010) and an associated reduction in global radiative forcing (Foster et al., 2017). The early Pleistocene warming signal in the GOA (and the north Pacific more generally) thus implies an important role for local or regional processes. We have discussed above the potential role played by ocean stratification in the North Pacific, and a possible link to the evolving Cordilleran Ice Sheet in the GOA through evaporation/precipitation feedbacks. The synchrony of these changes with observed tectonic uplift (e.g. Enkelmann et al. 2015) makes it difficult to disentangle the potential climatic and tectonic mechanisms behind ice sheet expansion.

To understand the evolution of the ocean currents governing the North Pacific at the present core sites (Fig. 1) and to find possible explanations of the observed SST distributions during the Pliocene and Pleistocene climate evolution, the modern climate system is used here as an analogue. Modern monthly mean SSTs at ODP 882 SSTs are colder than Sites U1417 and 1021 all year around. During the late Pliocene and early Pleistocene, ODP 882 SSTs are 3-4 °C warmer than in the east (Fig. 3f and g). Modern seasonal climate analogues cannot be used to explain to Pliocene and Pleistocene subarctic SST distribution. However, on longer timescales, the strength of the AL is currently linked to the wider Pacific Ocean circulation by the Pacific Decadal Oscillation (PDO) over periods of 20-30 years (Furtado et al., 2011). The Pliocene-Pleistocene North Pacific SST gradients show similarities with the negative phase of the PDO (-PDO), which is characterized by positive SST anomalies in the central North Pacific surrounded by negative SST anomalies along the North American coast and in the east equatorial Pacific. The -PDO associated route of winds might have increased the precipitation in the Gulf of Alaska and represent a key factor for the fast building of ice in the Alaskan mountains."

1-Comment from the referee

In general, the paper needs some heavy editing on the writing side for clarity and

grammar. For instance, conjunctions, such as "aren't", are used at points.

2-Author's response

Thank you.

3-Author's changes in the manuscript

We will carefully review the manuscript to remove typos and improve clarity of writing

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References cited in our reply:

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Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2019-29, 2019.

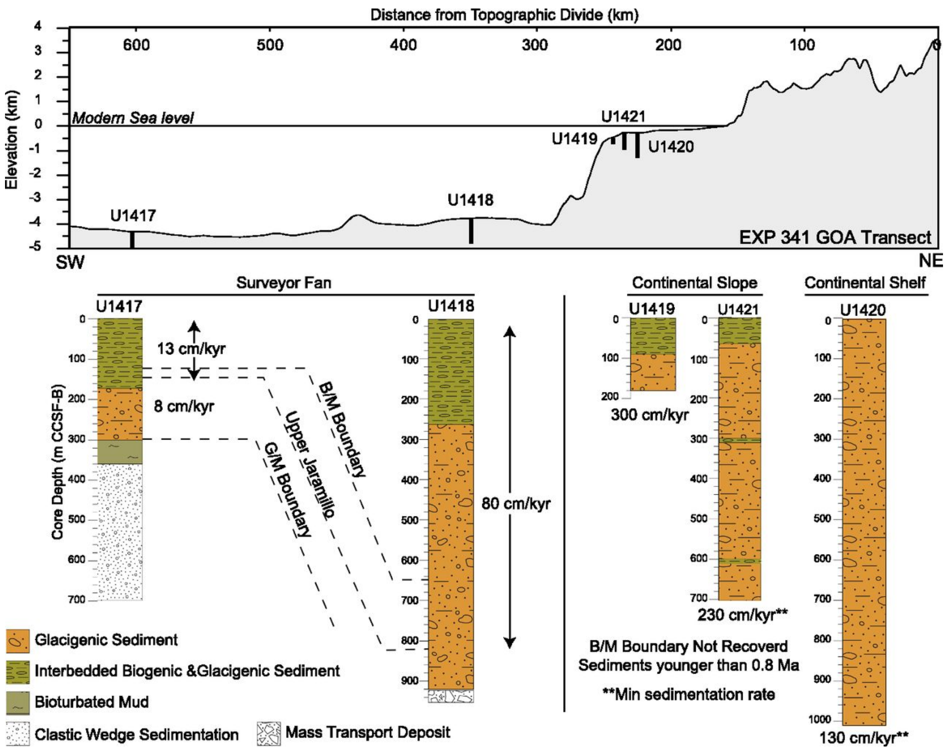

Fig. 1. Figure 1: Profile of IODP Expedition 341 drill sites in the Gulf of Alaska (Gulick et al., 2015).

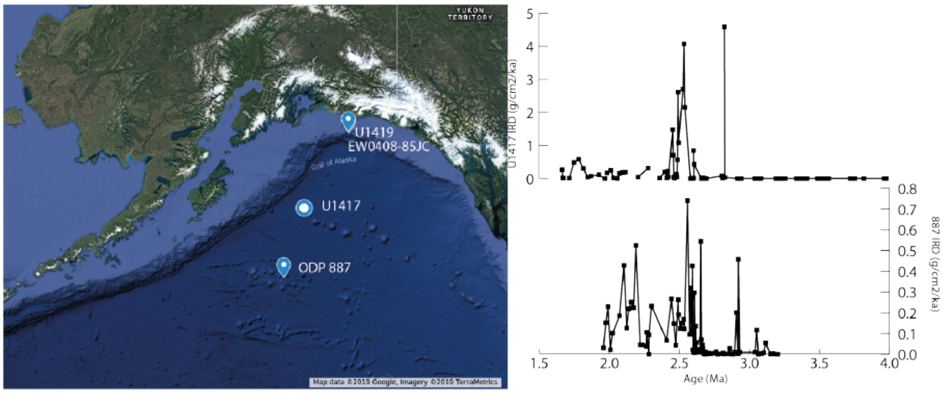

Fig. 2. Figure 2: (left) Locations of Site U1419, EW0408-85JC, Site U1417 and ODP Site 887 and (right) IRD mass accumulation rates at ODP 887 (above) (Prueher and Rea, 2001) and Site U1417 (below).

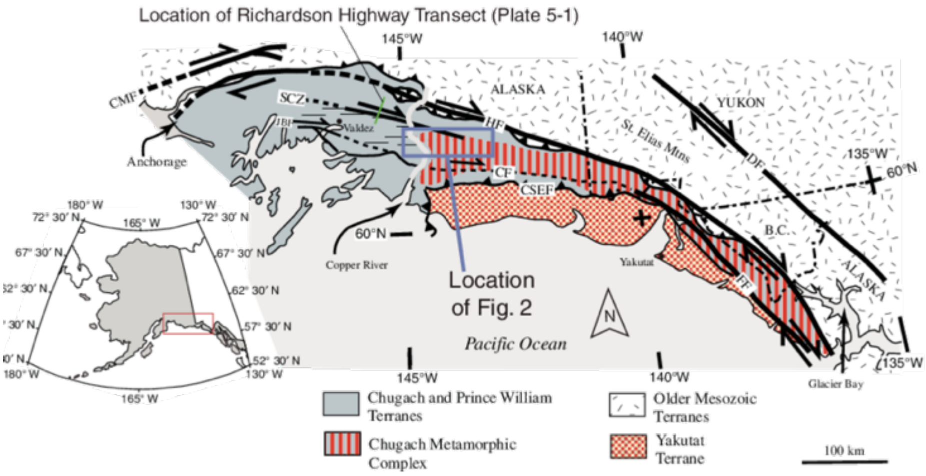

Fig. 3. Figure 3: Map of the Chugach Metamorphic Complex in Scharman et al., (2011).

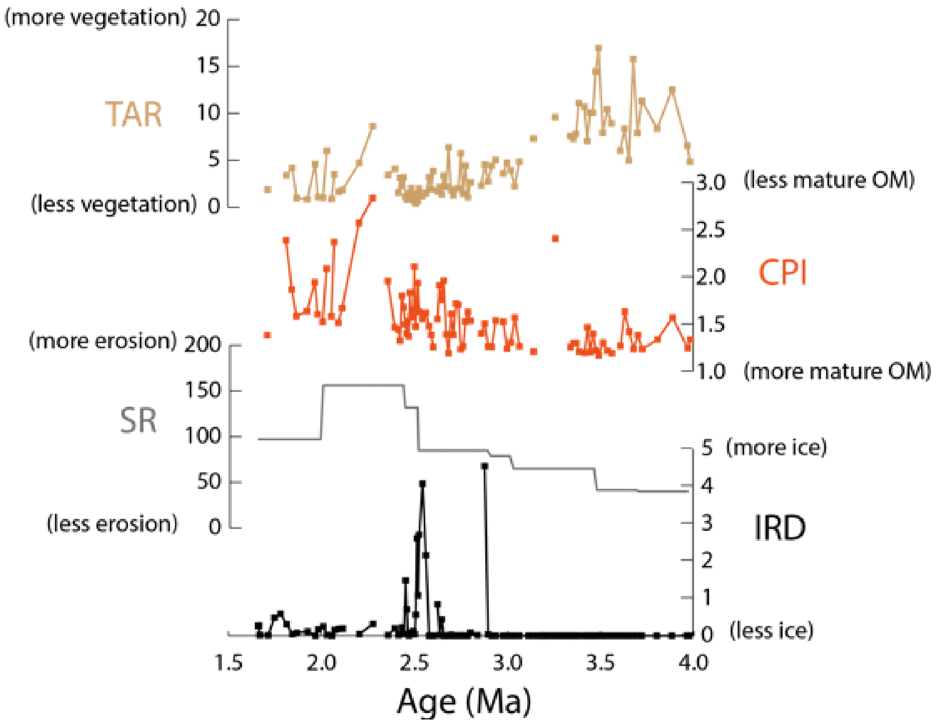

Fig. 4. Figure 4: TAR, CPI, SR and IRD at Site U1417. Missing data points are either a result of samples analysed for SSTs at the early stages of the project which were not subsequently analysed for n-alkane

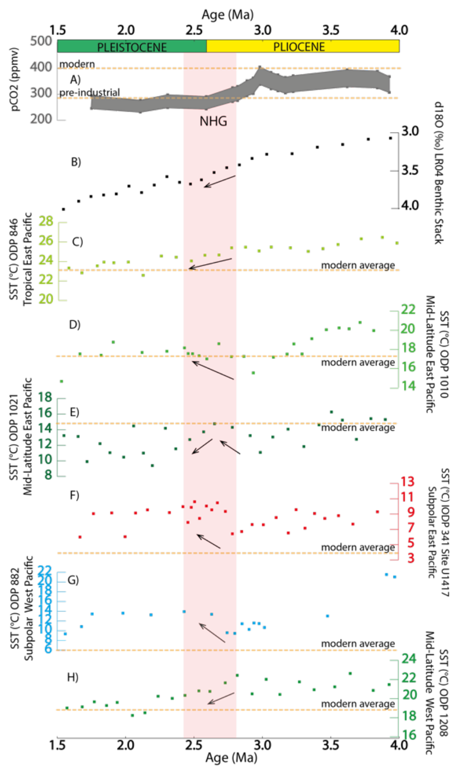

Fig. 5. Figure 5: ∼100 Kyr smoothed North Pacific sites (adapted from Fig. 3 in original manuscript).

		Site U1417		
	EW0408–85JC	Pliocene	NHG	Early Pleistocene
N/C	0.035 to 0.12	0.06 to0.26	0.05 to 0.23	0.04 to0.13
$\delta^{13}C$ (‰)	-26.5 to -22	-26.0 to -21.8	-25.9 to -23	-25.35 to -23.9

Fig. 6. Table 1: Table 1: N/C vs δ13C (‰ at Site U1417 vs range of data at EW0408–85JC (Addison et al., 2012). Data from the Pliocene (4 to 3 Ma), NHG (2.9 to 2.4 Ma) and the early Pleistocene (2.3-1.7 Ma).