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Reply to comments by Bourgois et al. (2019) on: "Glacial lake evolution and Atlantic-Pacific drainage reversals during deglaciation of the Patagonia Ice Sheet"

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Introduction

We welcome the comments of Bourgois et al. (2019) and the opportunity to debate geomorphology, geochronology and palaeoclimate during the Late Glacial Interglacial Transition (LGIT, ~18.0-8.0 ka) in the region of the Río Baker, central Patagonia. Bourgois et al. (2019) conclude that we have propagated inconsistencies in our proposed reconstruction of palaeolake evolution due to geomorphic analytical bias. However, in our view the empirical geomorphological data we have compiled over many field seasons has resulted in a data-rich (though still incomplete) relative chronology that enables us to evaluate inconsistencies in landscape interpretations from previously published geochronological datasets. We would argue that a geochronological bias, over any geomorphological bias, has represented the main reason for multiple landscape interpretations in this region. Indeed, the conflicting palaeolake evolution models published for the Río Baker basin (Turner et al. 2005; Bell, 2008; Hein et al., 2010; Bourgois et al., 2016; Glasser et al., 2016; Martinod et al., 2016) was a major impetus for our paper. These contrasting models were in part a result of the coincident publication of two separate geochronological datasets in 2016, one focused on optically stimulated luminescence (OSL) dating of palaeolake landforms (Glasser et al., 2016), the other cosmogenic nuclide exposure ages (Bourgois et al., 2016). Both datasets provided updates on what we termed the Turner/Hein model in Thorndycraft et al. (2019), but as they did not have access to each other's datasets they ended up with different landscape interpretations.

Missing from both of these papers was detailed geomorphological mapping of the Río Baker valley, a fundamental zone in the overall story of landscape evolution because: firstly, it is in this area where glacier dynamics control the blocking and opening of Pacific drainage pathways from the Lago General Carrera/Buenos Aires (LGC/BA) basin; and secondly, the palaeohydrological record provides insights into lake drainage processes and the relative chronology of regional glacier and ice-dammed lake evolution. Herein, we first consider the specific issues raised by Bourgois et al. (2019) point by point, before outlining what we consider to be the key questions and approaches required to improve our understanding of the complex relationships between the atmosphere, cryosphere, hydrosphere and geosphere in Patagonia.

Geochronology dataset

Bourgois et al. (2019) have argued that we should not have eliminated any dates in our Bayesian age model of regional glacier and lake evolution. However, as clearly illustrated in Figure 1 of their comment, it is challenging to arrive at a consensus using that approach. Thorndycraft et al. (2019) presented a series of geomorphological datasets, including local-scale and regional mapping from field excursions and remotely sensed imagery, a GIS-based palaeoshoreline analysis, and a subsequent altitudinal-based review of available geochronology. These datasets necessitated a re-evaluation of the geomorphic contexts of some dated samples. As an illustrative example, we showed that some morainic boulders sampled for cosmogenic nuclide exposure dating of former ice limits were likely shielded by lake water (Fig. 12 in Thorndycraft et al., 2019). There may be analytical subjectivity in our approach, but the Bayesian age model was developed based on analysis of our empirical geomorphological datasets, that we believe comprise the most comprehensive landform mapping in the region (Bendle et al., 2017a; Bendle et al., 2017b; Davies et al., 2018; Thorndycraft et al., 2019; Martin et al., 2019). The geomorphology therefore provides the relative chronology, and thus *prior* information within the Bayesian age model (Bronk-Ramsey, 2008). We concur it would have been helpful to explain more fully in the Supplementary Materials why some dates were omitted from our model, so we take this opportunity to explain here:

- The Río Fenix date of 15.2 ± 0.5 cal ka (Kaplan et al., 2004; Douglass et al., 2006) is a single radiocarbon date derived from carbonate-cemented concretions sampled from varved sediments that have subsequently been dated to 17–18 ka ago based on the *in situ* preservation of the Ho tephra of Hudson volcano (17,378 ± 118 cal yr BP) within the lake sediments (Bendle et al., 2017b). Therefore, the data was not appropriate to constrain the early phase of our Bayesian model; i.e. the onset of glacial lake formation. The provenance of the carbonate-cemented concretion is uncertain, as presumably concretions were formed post-depositionally. We note, however, that the 15.2 ± 0.5 cal ka age does fit with Stages 3 and 4 of our palaoelake evolution model where the Deseado lake level was in existence and therefore inundating the Fenix Chico valley.
- The single OSL date of 9.7 ± 0.7 ka from the Bayo valley (Glasser et al., 2006) did not fit our empirical geomorphological evidence for the relative chronology of lake level and drainage events, therefore was not included in the age model. We referred to this age in the discussion section of Thorndycraft et al. (2019; p.121). Based on the currently available evidence, this age neither fits the timing of Bayo level lake drainage, based on basal radiocarbon dates from small peat infilled basins (Turner et al., 2005), nor our interpretation of cosmogenic nuclide exposure ages from lake shielded boulders (Fig. 12 in Thorndycraft et al., 2019).
- The Fachinal moraine dates were not relevant for our age model because the readvances, dated to ca. 8.5 and 6.2 ka (Douglass et al., 2005), or the re-calculated ages of 10.9 ± 1.3 ka and 7.9 ± 1.1 ka (Bourgois et al., 2016a), bear no influence on ice-damming in LGC/BA. This palaeoglacier would have only dammed the lake when confluent with the main ice-lobe sourced from the North Pataognian Icefield further west, but once the two ice masses had separated the dynamics of the Fachinal glacier had no bearing on the water level or drainage of LGC/BA. Furthermore, the Douglass et al. (2005) interpretation of these readvances post-dating the Bayo lake level further supports the exclusion of these dates from our age model.
- The ages from Bourgois et al. (2016a) were excluded from the age model because they were not considered sufficiently robust in terms of either provenance or dating uncertainty. The samples listed by Bourgois et al. (2019) were interpreted as dropstones. There are two problems with this: first, there is no evidence to suggest these samples could not have originated from other sources (e.g. valley side, glacier surface lowering); and second, a dropstone does not provide unequivocal provenance. For example, how deep was the lake when the dropstones were deposited? In addition, some landform interpretations were not consistent with our geomorphological mapping. We found no evidence, for example, for a regional LGC/BA lake level from 451-528 m asl. As noted in Thorndycraft et al. (2019), the

detailed mapping and sedimentology from Fenix Chico (Bendle et al., 2017a) demonstrates the lake formed at the Deseado level and that there was no subsequent lake transgression, as argued by Bourgois et al. (2016). We concur with Martinod et al.'s (2016) interpretation in their comment on the Bourgois et al. (2016) paper; i.e. that these levels were older, higher elevation ice-marginal lakes dammed by the LGC/BA ice lobe as it thinned while remaining in the main trunk valley. This point also bears out in regional shoreline dataset, as these levels are all local features that lay well above regionally expressed shoreline traces (Thorndycraft et al., 2019). In fact, four of the Bourgois et al. (2019) cosmogenic ages would fit our interpretation (e.g. 18.5 ± 3.7, 18.8 ± 4.0, 15.2 ± 3.7, 16.5 ± 4.1 ka). However, the high dating uncertainties highlight another issue with this chronological dataset, in that these four examples date boulder exposure to within a time window of 7.4-8.2 ka, which is too great to make meaningful inferences on palaeolake evolution. This is because we date the onset of Deseado drainage to ~18.0 ka and the drainage of the Bayo lake level to >12.0 ka (also see Turner et al., 2005). In other words, the age uncertainties on some of the Bourgois samples are longer in duration than the existence of the Deseado and Bayo lake levels combined. We do note that the single age of 15.0 ± 1.8 ka (sample 59 in Bourgois et al., 2016), albeit from a dropstone (at 443-452 m asl), given the caveats outlined above, does likely fit with an extant Deseado lake level in our palaeolake evolution model.

To conclude this section on geochronology, we note that the youngest age in our Bayesian age model uses a single OSL date. However, this age is consistent with our geomorphological evidence. The sample, dated to 7.8 ± 0.5 ka was taken from a loess deposit post-dating outburst flood sediments. The geomorphology, however, suggests the flood likely occurred prior to stabilisation of the Lago Plomo moraines, dated by Glasser et al. (2012) to ca. 10.5 ka, as there is no evidence of flood erosion on the moraine; i.e. the Soler glacier was positioned at the Lago Bertrand outflow, the source of the Río Baker. We are therefore confident the age of 7.8 ± 0.5 ka can be a considered a minimum age for the event.

Ho tephra age

Bourgois et al. (2019) state that there is no absolute age for the Ho tephra that anchors the Fenix Chico Master Varve Chronology (FCMC17) record (Bendle et al., 2017b). However, this tephra layer has been independently dated at other sites (Weller et al., 2014) and has now been used as a chronological marker for several palaeoenvironmental sequences (Van Daele et al., 2016; Bendle et al., 2017b). We applied standard tephrochronological techniques for the identification of a source eruption, as have been widely applied in Patagonia (Wastegard et al., 2013), and by our research team investigating LGIT palaeoclimate in the British Isles (Matthews, et al. 2011). Bourgois et al. (2019), however, do not comment on the large major- and trace-element chemical dataset presented in Bendle et al. (2017b), which strongly suggests that the Ho eruption of Hudson volcano is the source of the tephra layer found in the FCMC17 varves. Bendle et al. (2017b) used a simple age modelling technique, and eight radiocarbon ages from other sites (Miranda et al., 2013; Weller et al., 2014), to constrain the Ho tephra age and anchor the FCMC17 chronology to the calendar-year timescale. It is also worth noting that the detection of the Ho tephra (17,378 ± 118 cal yr BP) in Fenix Chico is consistent with the 10Be ages of moraine boulders from the Menucos and Fenix moraine complexes to the east. We acknowledge that should the age of the Ho eruption be refined through new dating, the absolute age range covered by the FCMC17 record would also change, as would the timing of lake formation.

Stating that the tephra distribution presented in Weller et al. (2014) did not extend to Fenix Chico (Bourgois et al., 2019) misses the point that the site was previously unstudied in relation to tephra presence. One implication of identifying the Ho tephra at Fenix Chico is that the geographic distribution of visible eruptive products from this event has now been extended, increasing its potential as a chronological marker layer in other palaeoenvironmental archives.

Deseado and Bayo palaeolake levels

Bourgois et al. (2019) are correct to point out that different methods applied to quantifying the palaeoshoreline elevations will produce different results. The approach taken by Bourgois et al. (2019), using differential GPS, will be more accurate than using ASTER gDEM elevation data. However, the key aim of our methodological approach was to evaluate whether palaeoshoreline elevation data could be used to test the timing of lake unification between the LGC/BA and Lago Cochrane/Puerreydon (LC/P) basins (Fig. 1a). To achieve this, we applied the methodology adopted by Breckenridge (2015, 2016) in reconstructing the history of palaeolake Aggasiz of the Laurentide Ice Sheet, with the caveat we did not have access to high-resolution LiDAR terrain data (Thorndycraft et al., 2019). Using the Breckenridge (2015, 2016) approach enabled us to objectively investigate shoreline elevations, in a systematic way, across large spatial areas in both the LGC/BA and LC/P basins. We do not claim that the peaks in the histograms (Fig. 10a in Thorndycraft et al., 2019) provide a more accurate elevation for the lake levels than dGPS. However, the data do show that the peaks between lake basins neatly coincide at the Bayo level, whereas the data is more equivocal at the Deseado level, suggesting that the lakes may not have been unified at that point. However, this needs to be tested further using higher resolution DEMs, such as LiDAR.

Bourgois et al. (2019) note that the different preservation of lake shoreline evidence along the LGC/BA basin is due to morphotectonic landscape control. We concur with this and, like Bourgois et al. (2016), we are interested in the role of tectonics on Quaternary glacial landscape evolution. We have considered morphotectonic structure, and take this opportunity to present some of our regional digital terrain analysis (Fig. 1b), which shows the morphotectonic structure referred to by Bourgois et al. (2019), and also the presence of regional reverse topography. We hypothesise that these retrograde slopes in the southern basin (LC/P) could have led to more rapid glacier recession, accounting for the earlier (15.5 ka) abandonment of Atlantic drainage at the Caracoles outflow (Fig. 1a) than at the Deseado in LGC/BA. Guillaume et al. (2013) model greater rates of dynamic uplift associated with slab window formation associated with the Chile Triple Junction centred around the Monte San Lorenzo massif. Therefore, the interplay between post-Miocene neotectonics (Guillaume et al., 2013) and glaciations (Rebassa et al., 2011) is an important one to consider in the interpretation of Late Quaternary deglaciation in central Patagonia.

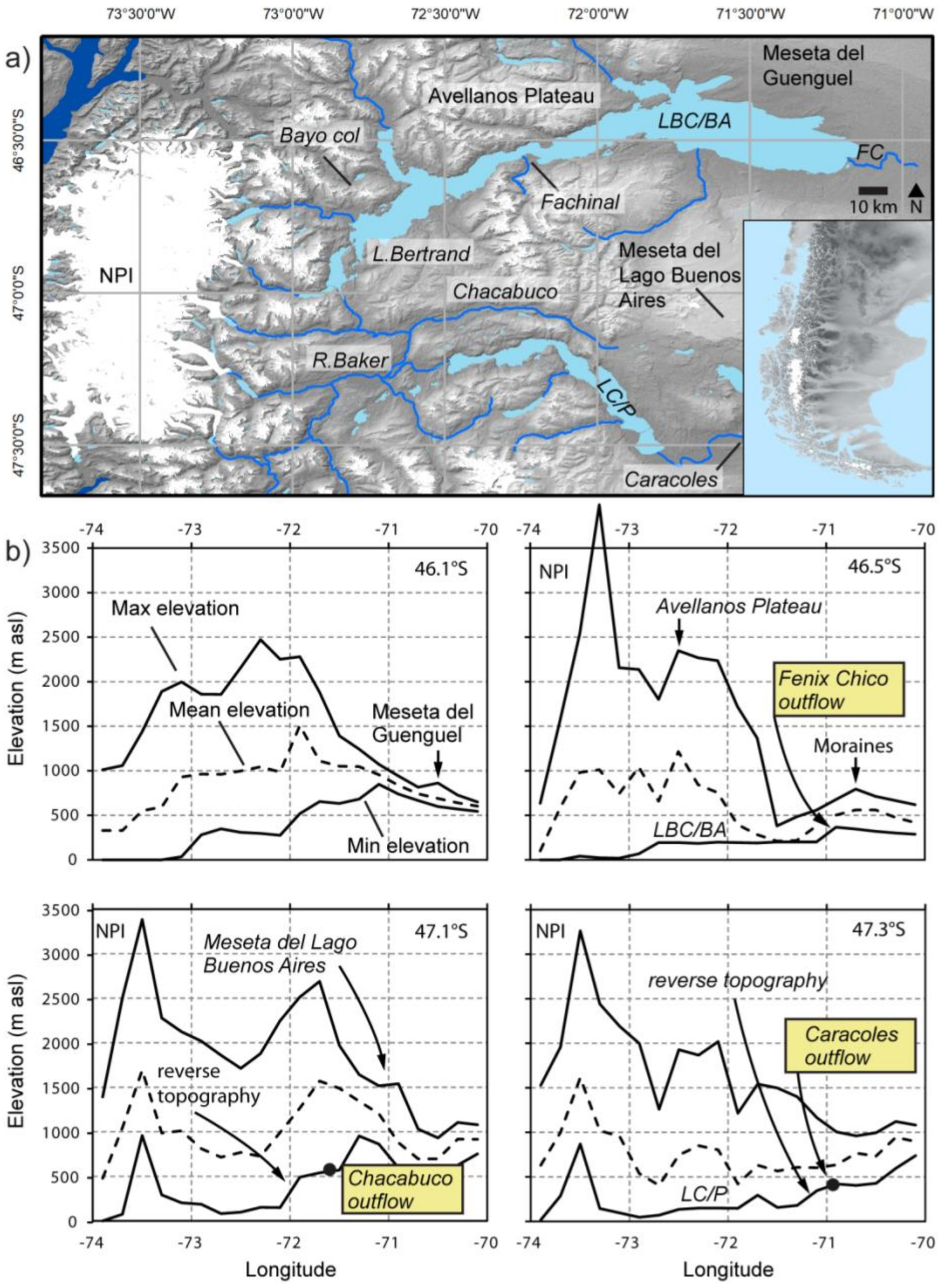

Figure 1. a) Map of the study area showing the Lago General Carrera/Buenos Aires (LGC/BA) and Lago Cochrane/Puerreydon (LC/P) basins and locations named in the text. Inset: southernmost South America. b) Selected digital terrain profiles (extracted from the SRTM DEM) showing the maximum, mean and minimum elevations for 0.2 x 0.2 digital degree cells – 46.1°S, 46.5°S, 47.1°S and 47.3°S (mid-point latitudes). Note, by comparing the 46.1°S data to 46.5°S, the influence of glacial erosion (LGC/BA basin) and moraine deposition of the LGC/BA ice lobe can be seen. To the South, the steepest reverse bed gradient occurs in the Chacabuco valley (47.1°S), which has the smallest outlet ice lobe, in comparison to the LGC-BA and LC-P basins, and therefore lower rates of Quaternary glacial erosion. In our palaeolake evolution model (Fig. 15, Thorndycraft et al., 2019) we hypothesise rapid ice recession from the Chacabuco valley allowing meltwater drainage into the lower Baker.

Bayo spillway

The timing of the opening of the Bayo spillway is one of the uncertainties discussed in our model and, indeed, we leave open alternative hypotheses for the opening of the Bayo valley (Fig. 15e and 15f in Thorndycraft et al. et al., 2019). Both our scenarios, however, predate the Early Holocene date of Glasser et al. (2016) and Bourgois et al. (2019). Bourgois et al. (2019) argue that the Bayo valley was blocked by ice from 9.0-13.0 ka. This argument, however, does not take into consideration the geomorphology and analysis presented in Thorndycraft et al. (2019). We demonstrated that the two cosmogenic nuclide exposure ages cited by Bourgois et al. (2016), samples LTE1 and LTE2 at Lago Tranquilo (Glasser et al., 2006), were likely shielded by lake water as they are located on the lake-proximal side of the drainage col (Fig. 12 in Thorndycraft et al., 2019), so they cannot be used to robustly date ice blocking the valley. This, therefore, leaves the one OSL sample (9.7 ± 0.7 ka) dated by Glasser et al. (2006), and discussed above, as the sole chronological constraint on the timing of ice extent at the Bayo col into the Early Holocene. Given evidence elsewhere for drainage of the Bayo lake level prior to the Holocene, for example, the radiocarbon dates of Turner et al. (2005) and our own reinterpretation of lake shielded boulder ages (Thorndycraft et al., 2019), we consider this age unreliable for underpinning the lake evolution model, which is why the date was not included in our age model.

Fachinal Cold Events

The timing of Fachinal glacier readvances, as current data allows, are irrelevant to the LGC/BA lake evolution story. This is because first, the readvances were not sufficient to dam the lake so have no bearing on drainage through the Río Baker valley. Secondly, according to Douglass et al. (2005), in their morphostratigraphic interpretation the readvances post-date the Bayo lake level. Both their interpretations for readvances at ca. 8.5 and 6.2 ka (Douglass et al., 2005) or the re-calculated ages of 10.9 ± 1.3 ka and 7.9 ± 1.1 ka (Bourgois et al., 2016a) post-date our interpretation of drainage from the Bayo lake level.

Bourgois et al. (2019) state that the Fachinal dates counter our statement that there is no significant (Northern Hemisphere) Younger Dryas readvance in the region. However, the evidence from other glaciers in the Río Baker basin demonstrate that the most significant post-LGM readvance occurred during the Antarctic Cold Reversal (14.5-12.8 ka), for example, at Monte San Lorenzo (Davies et al., 2018; Sagredo et al., 2018) and the Colonia valley (Nimick et al., 2016). For the Monte San Lorenzo ice cap, which is most analogous to the Fachinal palaeoglacier being a separate ice cap located to the east of the Andean Cordillera and North Patagonian Icefield, both Sagredo et al. (2018) and Davies et al. (2018) demonstrate large ACR moraine systems, with recessional moraine ages coinciding with the Northern Hemisphere (Younger Dryas). To infer, from the Fachinal data alone, that cold periods in the Early Holocene were sufficient to block drainage through the Baker valley to dam Lago General Carrera/Buenos Aires will likely lead to misinterpretation of landscape evolution in the basin. As stated earlier, in our detailed morphostratigraphic work from Fenix Chico (Bendle et al., 2017b) there is no geomorphological evidence for a lake level in LGC/BA that is higher than the Deseado level, which is the inference Bourgois et al. (2016a) arrive at.

Fig. 2 a)-d) Photos of high magnitude outburst flood landforms of the Rio Simpson downstream of Coyhaique. a) Two elevations of boulder bars inset within an incised fluviglacial terrace. b) and c) Flow-aligned and Imbricated boulders on the higher boulder bar level. d) Large conical depression, which features boulders at its base, likely formed by eddy scour in a zone of flow separation. e)-f) Sampling of annually laminated lake sediments from the southern side of contemporary LGC/BA. e) Palmer counting macroscale varves. f) Sampling microscale laminations for micromorphology and varve counting under the microscope.

Key research questions and future approaches

The interactions between atmosphere, cryosphere, hydrosphere and geosphere during the LGIT in Patagonia are interesting to elucidate for the following reasons:

1) The cryosphere is sensitive to Southern Hemisphere climate reorganisation and, in particular, the latitudinal position and/or intensity of flow within the Southern Westerly Wind Belt, which controls spatial variations in precipitation (Boex et al., 2013; Moreno et al., 2015; Van Daele et al., 2016) and temperature through radiative forcing (Bendle et al., in press). Indeed, as Bendle et al. (in press) demonstrate, using the high-resolution FCMC17 varve record, at ~46°S the Patagonian Ice Sheet may have responded to an initial atmospheric control (westerly wind shift) at *ca.* 18.0 ka before sustained faster recession began at *ca.* 17.8 ka, following a lagged oceanic warming and associated ambient temperature increase across the South Pacific.
2) The LGIT includes a major cooling episode at 14.5-12.8 ka, broadly equivalent in timing with the Antarctic Cold Reversal as identified in isotopic data from Antarctic ice cores (WAIS Divide Project Members, 2013), the influence of which likely extended northwards to 40°S (Pedro et al., 2016). This period featured a major glacier readvance in Patagonia (Moreno et al., 2009; Garcia et al., 2014; Nimick et al., 2016; Sagredo et al., 2018; Davies et al., 2018) preceding a phase of rapid warming into the Early Holocene. This warming could provide a valuable analogue for valley glacier response to contemporary climate warming (Martin et al., in press) because the main outlet glaciers of the waning Patagonian Ice Sheet and satellite mountain ice caps had separated by this point (Davies et al., 2018).
3) Large palaeolake systems formed as ice receded during the LGIT (Turner et al., 2005; Stern et al., 2011; Solari et al., 2012; Garcia et al., 2014; Glasser et al., 2016; Van Daele et al., 2016; Garcia et al., 2018), the drainage of which may have forced regional climate changes (Glasser et al., 2016). As Thorndycraft et al. (2019) demonstrate, lake drainage in central Patagonia involved multiple high-magnitude glacial lake outburst floods. The Baker valley geomorphic setting is unlikely to be unique in Patagonia, and indeed we have mapped evidence of outburst flood processes in other formerly glaciated valleys, for example, in the Simpson valley (Fig. 1c).
4) We hypothesise that topography, such as the retrograde slopes illustrated in Fig. 1, may have played a role in spatially variable glacier recession through the LGIT. This may be one reason for the earlier (ca. 15.5 ka) lake drainage in the LC/P (Thorndycraft et al., 2019).
5) Evidence of early human occupation in Patagonia dates to before the Antarctic Cold Reversal in northern Patagonia (Dillehay et al., 2015), with timing post-dating the Antarctic Cold Reversal in central Patagonia (e.g. Mendez et al., 2018). Thus, there are interesting research questions concerning the glacier response to climate warming and associated glacial lake drainage events for opening valley landscapes for human occupation (Borrero et al., 2019).

To address these issues, integrated multidisciplinary approaches, without so-called geomorphological (Bourgois et al., 2019), or geochronological, bias are required to overcome the current uncertainties in relative and absolute chronologies. It is challenging to undertake geomorphological mapping in the field in Patagonia yet, as our research has shown, it is essential to provide a more robust framework for evaluating geochronology. In terms of geochronological methods, the radiocarbon dating of infilled basins to date lake level falls has shown promise (Turner et al., 2005; Villa Martinez et al., 2014; Garcia et al., 2018) and should be used to test glacial lake transgression hypotheses, such as proposed by Bourgois et al. (2016). However, this approach needs to be more widely applied. The FCMC17 varve record has demonstrated the great potential offered by varve chronologies to reconstruct ice sheet dynamics through the LGIT, test palaeoclimate hypotheses (Bendle et al., in press), and better constrain moraine ages through Bayesian age modelling applied in tandem with cosmogenic nuclide exposure ages (Bendle et al., 2017b). Work led by Palmer and Pike (Fig. 1d) is currently extending the Lago Buenos Aires varve chronology to elucidate, at centennial to decadal resolution, glacier dynamics and palaeoclimate, and indeed test our own palaeolake evolution model. We look forward to seeing our model refuted in the future with high quality geomorphological and geochronological datasets.

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