Dynamics of former ice lobes of the southernmost Patagonian Ice Sheet based on a glacial landsystems approach

CHRISTOPHER M. DARVILL,[1]* CHRIS R. STOKES,[1] MICHAEL J. BENTLEY,[1] DAVID J. A. EVANS[1] and HAROLD LOVELL[2]
[1]Department of Geography, Durham University, South Road, Durham DH1 3LE, UK
[2]Department of Geography, University of Portsmouth, Portsmouth, UK

ABSTRACT: Reconstructions of former ice masses from glacial geomorphology help to constrain the nature and timing of glaciation in relation to climatic forcing. This paper presents a new reconstruction of the glacial history of five ice lobes in southernmost South America: the Bahía Inútil – San Sebastián, Magellan, Otway, Skyring and Río Gallegos ice lobes. We use previous geomorphological mapping of glacial landforms to reconstruct former glacial limits and proglacial lakes, demarcate flow-sets from the distribution of glacial lineations, and evaluate glacial landsystem signatures and their palaeoglaciological implications. Evidence suggests that the ice lobes predominantly reflect active temperate glacial landsystems, which may have switched to polythermal systems when periods of cold-based ice developed ephemerally. This complex landsystem signature implies that the ice lobes were sensitive to regional climate variability, with active re-advances during overall retreat of the ice margins. There is also evidence for periods of fast ice flow and possible surge-like activity in the region, followed by the rapid retreat or even collapse of some of the ice lobes in association with proglacial lakes. Constraining our new reconstruction with published chronological information suggests that at least some of the ice lobes advanced before the global Last Glacial Maximum (gLGM: ca. 26.5–19 ka) during the last glacial cycle. Our new reconstruction demonstrates a more complex picture of ice dynamics than has previously been portrayed, and one in which the advance and retreat of the ice lobes was likely to have been primarily driven by changes in climate. As such, ice advances before the gLGM in the southernmost part of the Patagonian Ice Sheet are likely to indicate a wider climatic forcing at this time. Copyright © 2016 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: Patagonian Ice Sheet; Active temperate landsystem; Glacial geomorphology; Southern South America; Ice dynamics.

Introduction

Well-preserved glacial geomorphology relating to the former Patagonian Ice Sheet provides a record of the fluctuations of its margins throughout the Quaternary (Clapperton, 1993; Glasser et al., 2008; Glasser and Jansson, 2008). This record can also be used to reconstruct ice-sheet dynamics (Glasser et al., 2005; Glasser and Jansson, 2005; Lovell et al., 2012) and may be supplemented with chronological information to constrain how the ice sheet changed over time because of climatic forcing (e.g. McCulloch et al., 2005b; Douglass et al., 2006; Kaplan et al., 2008a,b; Hein et al., 2010). For example, the southernmost part of the ice sheet was heavily influenced by changes in temperature and precipitation linked to the atmospheric Southern Westerly Winds and oceanic frontal positions (Lamy et al., 2007; Kaplan et al., 2008a; Kilian and Lamy, 2012). Climate reconstructions before the Holocene are uncertain, but temperatures at the global Last Glacial Maximum (gLGM: ca. 26.5–19 ka, Clark et al., 2009) may have been as much as 7–8 °C lower than present (Benn and Clapperton, 2000a; Caniupán et al., 2011). Consequently, reconstruction of the southernmost ice lobes can help to establish likely changes in these climatic systems over time, but this process requires a robust understanding of the glacial history and ice dynamics (Sugden et al., 2005; Kilian and Lamy, 2012).

Previous studies of the southernmost ice lobes of the Patagonian Ice Sheet have tended to focus on dating glacial limits, with a particular emphasis on constraining the local Last Glacial Maximum in relation to the gLGM and younger glacial limits. However, there has been a lack of consistent, detailed mapping across the region (Darvill et al., 2014), and there remains uncertainty about the timing and nature of pre-gLGM glacial advances (Kaplan et al., 2007). Indeed, it has been shown that glacial limits of the Bahía Inútil – San Sebastián (BI-SSb) ice lobe that were previously thought to be pre-last glacial cycle were actually deposited more recently (Darvill et al., 2015b). This suggests that significant glacier advances during Marine Isotope Stage (MIS) 3 (and possibly MIS 4) are represented in the area, perhaps linked to wider glacial activity in the southern mid-latitudes at this time (Putnam et al., 2013; Kelley et al., 2014; Darvill et al., 2015b; Doughty et al., 2015; Schaefer et al., 2015; Darvill et al., 2016; Eaves et al., 2016). In this paper, we use a previously published map of the region, largely based on relatively high-resolution satellite imagery (~30-m resolution; Darvill et al., 2014), and apply glacial inversion methods to produce a new palaeoglaciological reconstruction of the dynamics of the ice sheet that is further constrained through analysis of published chronological data.

Study area

The study area lies between 51–55°S and 68–73°W, and encompasses the area occupied by five former piedmont ice lobes of the Patagonian Ice Sheet (Fig. 1). From south to north, these are the BI-SSb, Magellan, Otway, Skyring and Río Gallegos lobes. The topography of the area changes dramatically from south-west to north-east, with the southern Andes (dominated by the Cordillera Darwin) marking the southern and western boundaries and casting a strong rain

*Correspondence to: C. M. Darvill. Present address: Geography Program and Natural Resources and Environmental Studies Institute, University of Northern British Columbia, 3333 University Way, Prince George, BC, V2N 4Z9, Canada.
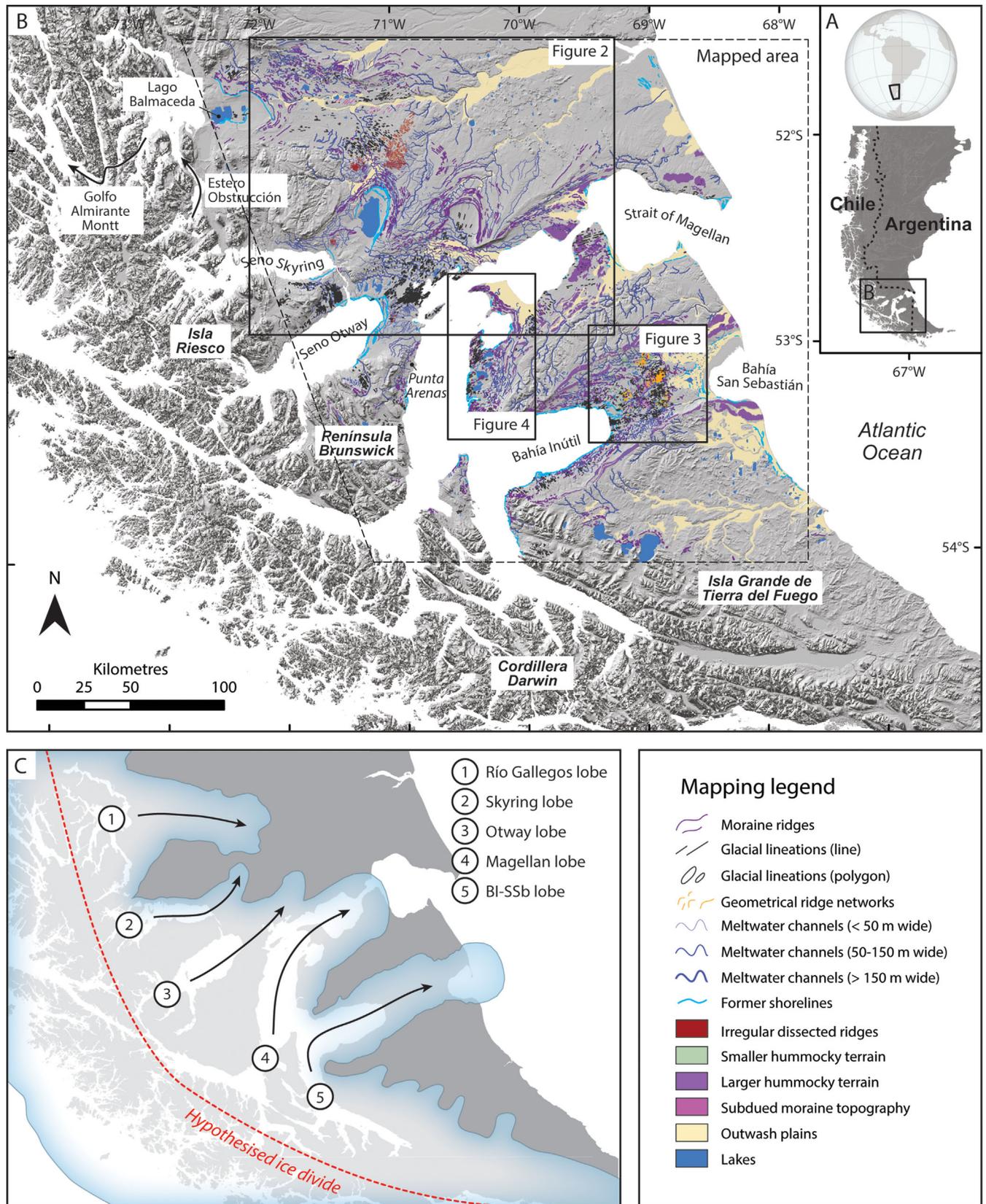E-mail: christopher.darvill@unbc.ca

Figure 1. (A) Location of the study area in southern South America. (B) Overview of the geomorphological map from Darvill *et al.* (2014) showing the locations of figures and locations mentioned in the text. (C) Stylized representation of the southernmost part of the former Patagonian Ice Sheet, highlighting the five former ice lobes discussed in this paper. The approximate position of the ice divide is based on Hulton *et al.* (2002), but is shown for illustrative purposes only.

shadow over the low, flat pampas and coastal areas to the north and east (Coronato *et al.*, 2008). The locations of the former ice lobes are marked by prominent straits and sounds, which were established by one or more major glacial events during the Quaternary (Rabassa, 2008; Kaplan *et al.*, 2009).

Glacial geomorphology relating to the former ice lobes was first described in detail by Caldenius (1932) and has since been updated, and sometimes reinterpreted, by numerous workers (Meglioli, 1992; Clapperton *et al.*, 1995; Benn and Clapperton, 2000a,b; Rabassa *et al.*, 2000; Bentley *et al.*,

2005; McCulloch *et al.*, 2005b; Lovell *et al.*, 2011, 2012; Darvill *et al.*, 2014, 2015a).

Meglioli (1992) used weathering indices to establish an age model for the region, whereby nested moraine limits were deposited during successive glacial episodes from MIS 12 to 2 (Coronato *et al.*, 2004). Subsequently, a range of dating techniques have been used to constrain the ages of some moraine limits deposited during or after the gLGM (Rutter *et al.*, 1989; Porter, 1990; Meglioli, 1992; Clapperton *et al.*, 1995; McCulloch *et al.*, 2005b; Sagredo *et al.*, 2011; Blomdin *et al.*, 2012; Hall *et al.*, 2013). Age constraints before the gLGM are limited (Kaplan *et al.*, 2007; Evenson *et al.*, 2009; Darvill *et al.*, 2015a,b), although ^{40}Ar/^{39}Ar dates suggest that the outermost limits of the Río Gallegos, Skyring, Otway and Magellan lobes date to 1070–450 ka (Meglioli, 1992; Singer *et al.*, 2004). By contrast, Darvill *et al.* (2015b) recently demonstrated that one of two outer limits of the BI-SSb lobe was deposited much more recently, at *ca.* 30 ka. Beyond this, the Magellan and Río Gallegos lobes have only a few scattered cosmogenic nuclide exposure ages (Kaplan *et al.*, 2007; Evenson *et al.*, 2009; Sagredo *et al.*, 2011) and the Skyring and Otway lobes have no age controls before around 15 ka (Kilian *et al.*, 2007, 2013).

Relatively little attention has been given to the nature of ice dynamics recorded by the glacial geomorphology, with the exception of localized studies on the gLGM or post-gLGM limits. Previous work has highlighted factors affecting ice-lobe dynamics and rates of advance and retreat, such as the influence of pro-glacial lakes (Porter *et al.*, 1992; Lovell *et al.*, 2012), subglacial thermal regime (Benn and Clapperton, 2000a,b; Bentley *et al.*, 2005) and evidence for rapid ice flow over a soft-sediment bed (Clapperton *et al.*, 1995; Lovell *et al.*, 2012). As such, there is a need for a regional glacial history that incorporates geomorphological evidence for ice dynamics and reassesses previously published chronological data.

Methods

Geomorphological mapping

This paper uses a previously published glacial geomorphological map of the region (Darvill *et al.*, 2014) to build a new palaeoglaciological reconstruction. Glacial landforms were mapped from Landsat and ASTER satellite images, aerial photographs, Google Earth imagery, and SRTM digital elevation data, and much of the area was also cross-checked in the field, with an emphasis on verifying mapped landforms and identifying cross-cutting relationships of features (Darvill *et al.*, 2014).

Glacial flow-sets, ice margins and landsystems

Glacial landforms can yield information on the extent of former ice advances and ice sheet dynamics using glacial inversion methods (Kleman *et al.*, 2006). Glacial lineation flow-sets reveal coherent patterns of former ice flow trajectories and a landsystem approach links assemblages of glacial geomorphological features to particular styles of glaciation (Evans, 2003a), many of which have modern analogues that aid the interpretation of former glacial and climatic conditions. Following Clark (1999), glacial lineations were grouped into flow-sets according to parallel concordance, close proximity and similar morphometry, as well as relationship to ice-marginal features such as moraines and meltwater channels. By mapping glacial landforms systematically and comprehensively, we were able to both reconstruct glacial limits and assess landsystem types and their palaeoglaciological implications based on landform suites.

Proglacial lake reconstruction

The reconstruction of former proglacial lakes can yield information on the relative position of ice lobes and their dynamics. Following Stokes and Clark (2004) and Lovell *et al.* (2012), we modelled proglacial lake formation using a Digital Elevation Model (DEM), constructed from *ca.* 90-m resolution SRTM data for areas of land, and *ca.* 900-m resolution ETOPO data for submarine areas that may have been previously exposed. The DEM was filled in 10-m increments to examine where lakes developed and over-spilled in relation to former shorelines and ice margins. The DEM data are sufficient for a regional-scale assessment of where lakes were likely to have developed (cf. Lovell *et al.*, 2012), but the coarser resolution of the ETOPO data means that over-spill channels beneath present sea-level may have been missed, and a lack of bathymetric data for present-day lakes means that their exact depths are unknown. Additionally, the DEM provides present-day land elevation and not that during glaciation, when the mass of the Patagonian Ice Sheet would have depressed the mountain range. This should be corrected for glacio-isostatic adjustment, but the resolution of global model output, such as ICE-5G (Peltier, 2004), is too coarse to be of use for this purpose. Consequently, we reconstructed palaeolakes based on a contemporary DEM, but with the caution that they are likely to be minimum estimates of lake depth because the regional pattern of ice loading would have been to over-deepen slopes towards the west. The presence of lakes predicted by the DEM analysis was cross-checked and, although the field evidence is inherently fragmentary, we did not identify any obvious conflict between predicted lake levels and the presence of raised shorelines in the glacial geomorphological mapping.

Glacial landform Assemblages

This section summarizes the nature of the glacial landform assemblages in the study area. The results are in the form of a map published by Darvill *et al.* (2014) and we now describe and interpret the landform assemblages before discussing their palaeoglaciological significance.

Ice-marginal landforms

Moraine ridges

The clearest moraine ridges in the study area are those of the Skyring and Otway lobes, where numerous arcuate ridges are nested around the main depressions (Fig. 2), marking the point at which the lobes were flowing up the adverse slopes of overdeepenings onto higher relief areas (Barr and Lovell, 2014). Similar moraines are found on the northern side of the Magellan lobe, particularly across Primera Angostura (Fig. 2), within *ca.* 10 km of Bahía Inútil in the BI-SSb lobe (Fig. 3), and in the Río Gallegos lobe depression. Smaller, less distinctive ridges aligned perpendicular to former ice flow are often draped over other glacial features within the central Magellan and BI-SSb lobes, such as on Punta Gente, where ridges are draped over drumlinized terrain north of Porvenir (Bentley *et al.*, 2005; Fig. 4). Likewise, in the centre of the BI-SSb depression, ridges can be seen draped over both lineations and subdued moraine topography (Fig. 3).

The ridges include terminal moraines (sharp-crested, arcuate ridges around the main depressions) and recessional moraines or recessional push moraines (smaller, less distinctive ridges perpendicular to ice flow and draping other features), although it is difficult to distinguish their form based on morphology alone. Two exceptions are where we have
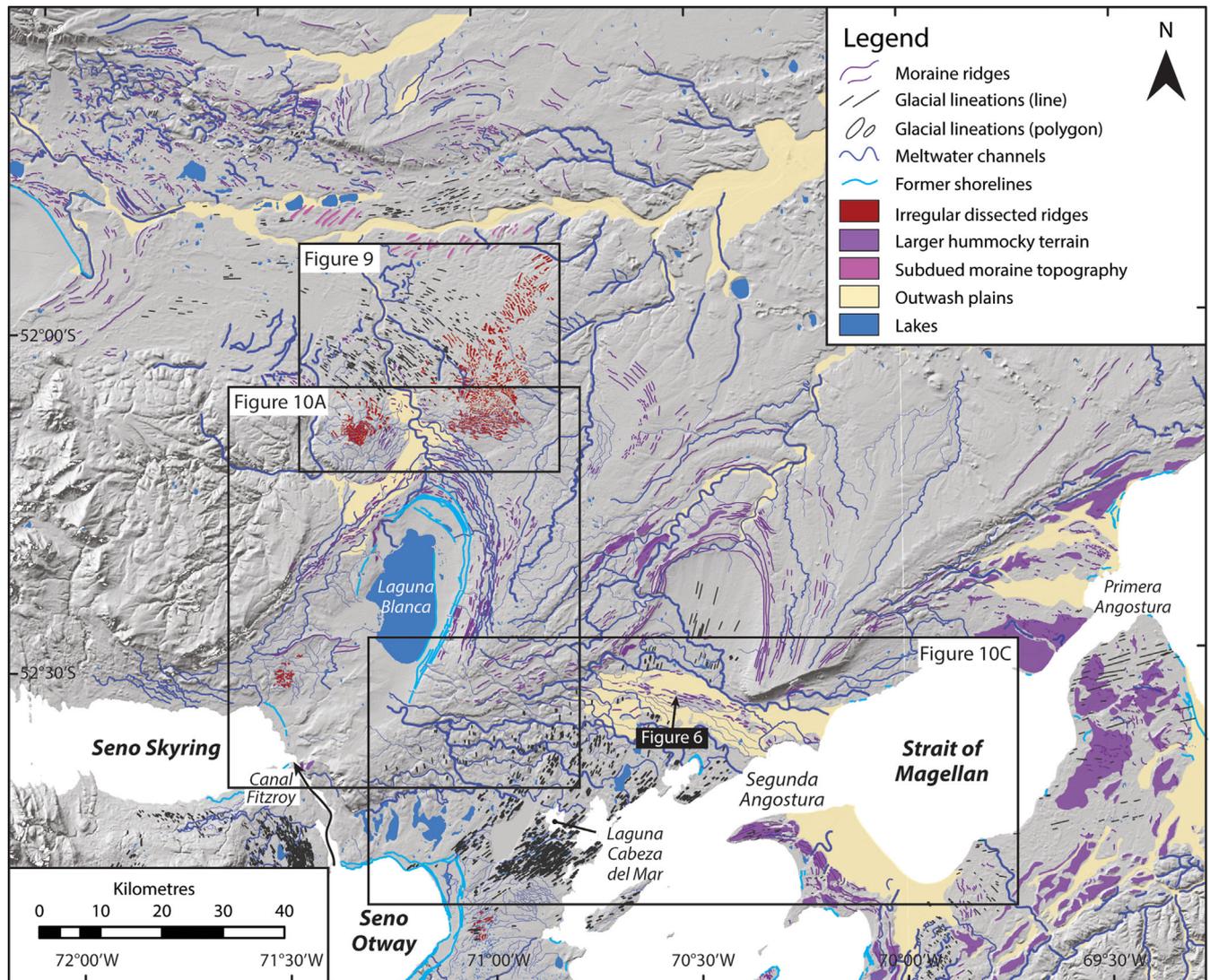
Figure 2. An overview of the glacial geomorphology relating to the Río Gallegos, Skyring, Otway and Magellan lobes, including key locations mentioned in the text (location shown in Fig. 1).

supplementary sedimentological evidence to support the landform data. A section through a moraine in the BI-SSb lobe shows silts and sands that have been strongly faulted and folded (Fig. 5). Similarly, sediments within one of the moraine ridges in the Otway lobe show faulted sands and gravels (Fig. 6). The deformation of moraine sediments in this way indicates proglacial glaciotectonism (Rotnicki, 1976; Aber, 1985; Aber *et al.*, 1989; Van der Wateren, 1995), and we interpret the deformation to represent thrusting and folding during active re-advances of the ice lobes (Oldale and O'Hara, 1984; Harris *et al.*, 1997; Williams *et al.*, 2001; Evans and Twigg, 2002; Phillips *et al.*, 2002, 2008a,b), at least in these two locations. The BI-SSb moraine contains deformed lacustrine silts, indicating that the timing and extent of retreat and re-advance was sufficient to allow a proglacial lake to accumulate. Our interpretation suggests that some of the moraine ridges may be part of composite thrust complexes, similar to those reported around the Strait of Magellan (Clapperton *et al.*, 1995; Benn and Clapperton, 2000a,b).

Hummocky terrain

Hummocky terrain is abundant within the BI-SSb lobe (Fig. 3), but is also found in association with the Magellan lobe (Fig. 4). It consists of semi-rounded hills and hollows at both smaller (e.g. ≤5 m relief) and larger (>5 m relief) scales,

with the smaller hummocky terrain forming arcuate bands running parallel to moraine ridges. The hummocks are predominantly irregular and chaotic and were classified as 'irregular hummocky terrain' (smaller hummocky terrain) and 'kettle-kame topography' (larger hummocky terrain) by Darvill *et al.* (2014).

Hummocky terrain is typically associated with deposition of supraglacial debris (Boulton, 1972; Benn, 1992; Kjaer and Kruger, 2001; Johnson and Clayton, 2003; Schomacker, 2008), although the transport pathway of debris resulting in this terrain is often conjectural (Evans, 2009, and references therein). We infer that the disorganized nature of the landform indicates periods of ice stagnation and down-wasting during overall recession of the ice lobes, leaving behind buried ice and resulting in topographic inversion of the terrain (Clayton, 1964; Boulton, 1972; Etzelmüller *et al.*, 1996; Kjaer and Kruger, 2001; Schomacker, 2008). More specifically, the organization of hummocky terrain in arcuate bands has been interpreted as the product of incremental stagnation (*sensu* Eyles, 1979; Bennett and Evans, 2012) in other lowland settings (e.g. Attig *et al.*, 1989; Ham and Attig, 1996; Clayton *et al.*, 2001; Dyke and Evans, 2003; Evans *et al.*, 2014), a process-form regime that could also apply to the settings described here if the glacier lobes were episodically carrying large englacial and supra-glacial debris loads.
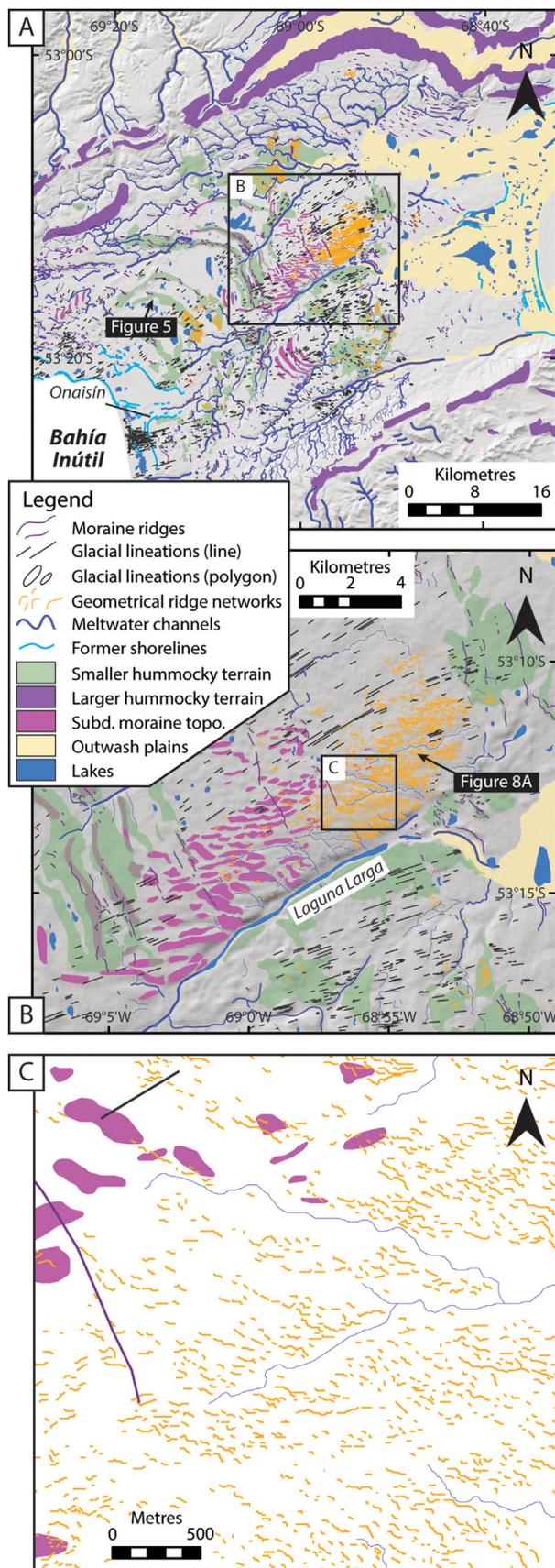
Figure 3. (A) Overview of the glacial geomorphology associated with the centre of the BI-SSb lobe (location shown in Fig. 1). Note the spillway marked by former shorelines associated with a proglacial lake that drained at Onaisín through Laguna Larga. (B) Enlargement of the central part of (A) showing cross-cutting relationships between subdued moraine topography and moraine ridges, glacial lineations and smaller hummocky terrain. (C) Enlargement of (B) showing the ordered nature of the regular hummocky terrain mini-ridges and the cross-cutting relationships more clearly.

Bands of larger hummocky terrain mark the Primera Angostura and Segunda Angostura limits of the Magellan lobe (Meglioli, 1992; Benn and Clapperton, 2000a,b; Rabassa, 2008; Fig. 2), but are seen most clearly as a double band on both the north and the south sides of the BI-SSb depression (Figs 1, 3 and 7). This landform was described as 'kettle and kame topography' by Darvill *et al.* (2014), but the nomenclature is problematic given that there is no sedimentary evidence for kames and similar features in North America have an ambiguous origin (*sensu* Evans, 2009). Rather, we tentatively group the landform with hummocky terrain and suggest that further sedimentary work is required to establish the full nature of this geomorphology. The topography consists of chaotic hills surrounding rounded hollows, and delimited by broad outwash plains. Darvill *et al.* (2015a) mapped a series of erratic boulder trains along the southern edge of the BI-SSb lobe, two of which drape over the larger hummocky terrain. A deep section through the inner band of the BI-SSb lobe (the San Sebastián drift) shows two basal diamict units separated by outwash sands and gravels (Fig. 7). This implies that the ice lobe advanced to form the outer (Río Cullen) band first before retreating into the BI-SSb depression and subsequently re-advancing.

Geometric ridges

A large swathe of strikingly linear cross-cutting ridges occurs north of Laguna Larga in the central BI-SSb depression. These are regularly orientated geometric ridge networks (*sensu* Bennett *et al.*, 1996), described as 'regular hummocky terrain' by Darvill *et al.* (2014; Figs 3B and 8). They comprise discontinuous, cross-cutting, conjugate paired ridges, generally orientated perpendicular to former ice flow. Although long-regarded as the remnants of crevasse-squeeze ridges, and diagnostic of glacier surges in a landsystems sense (Raedecke, 1978; Sharp, 1985; Bennett *et al.*, 1996), such landforms have since also been related to: (i) active temperate glacier lobes, where they occur in narrow concentric arcs in association with sawtooth-style push moraines (Evans and Twigg, 2002; Evans *et al.*, 2015); and (ii) ice stream shutdown, where they occur in narrow corridors on palaeo-ice stream trunks (Evans *et al.*, 2016). The spatial arrangement of the BI-SSb geometric ridge networks is identical to the wide arcuate zones of surge-related crevasse-squeeze ridges found on modern glacier forelands, suggesting they may record a phase of glacier surging by the BI-SSb lobe (see Discussion).

Subglacial landforms

Glacial lineations

Lineations occur in association with all five ice lobes, but vary in morphology from low-relief flutings to prominent oval drumlins. For example, clusters of subdued flutings occur around Bahía Inútil (Raedecke, 1978; Fig. 3), while large swathes of rounded drumlins are found in the Río Gallegos, Skyring, Otway and Magellan lobes. Of particular note are the fields consisting of hundreds of elongate drumlins that occur in the outermost part of the Río Gallegos lobe (Ercolano *et al.*, 2004; Fig. 9), around Laguna Cabeza del Mar in the Otway lobe (Clapperton, 1989; Benn and Clapperton, 2000b; Fig. 10C) and on the eastern side of the Magellan Strait (Bentley *et al.*, 2005; Lovell *et al.*, 2012; Fig. 4).

The precise genesis of glacial lineations is contentious, but it is generally agreed that they are subglacially streamlined landforms related to the deformation and/or erosion of a soft substrate by fast flowing glacier ice (Stokes *et al.*, 2011). Hence, the lineations in our study area were probably formed
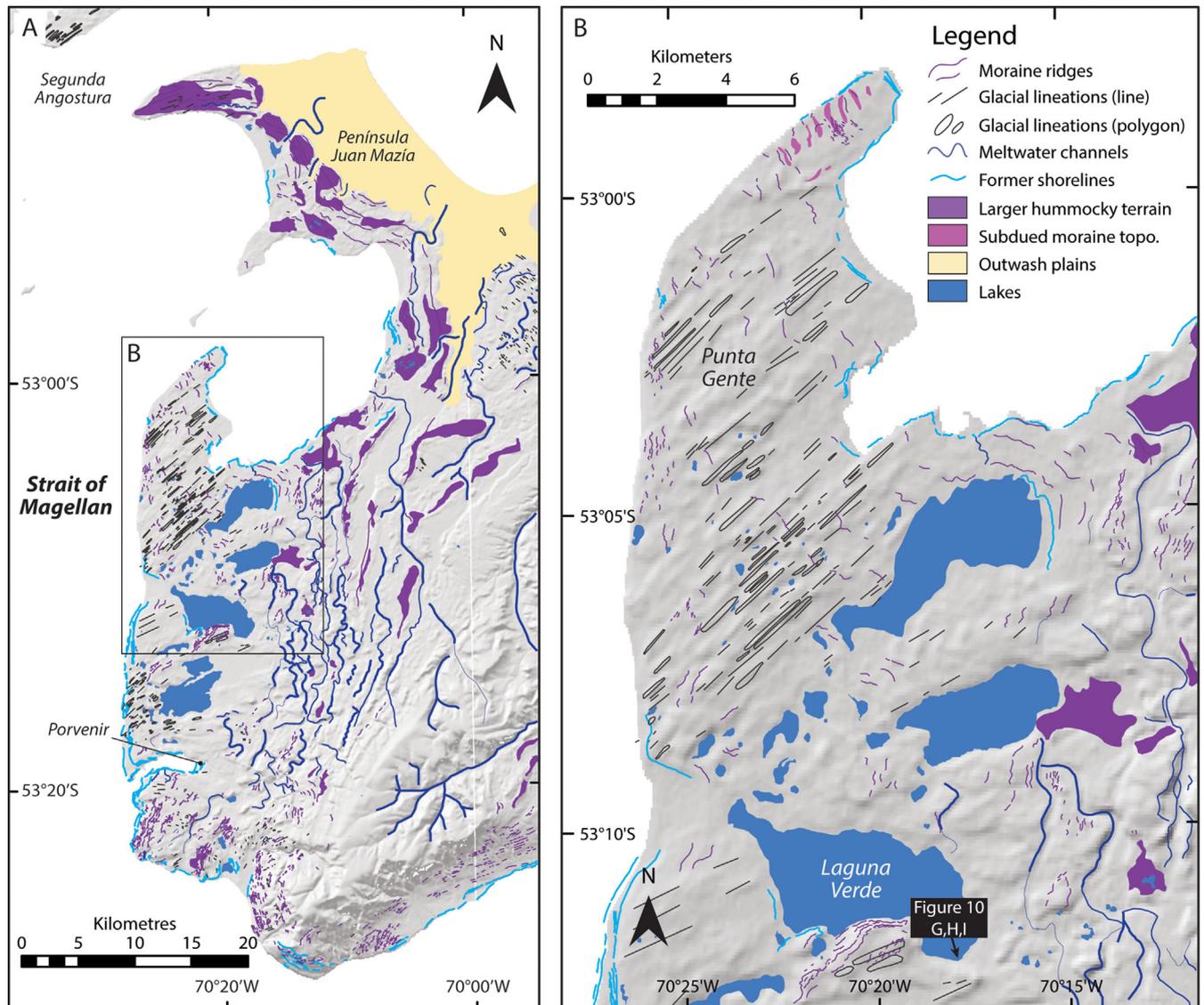
Figure 4. (A) Overview of the glacial geomorphology associated with the Magellan lobe (location shown in Fig. 1). Península Juan Mazía may have been the terminus of a surge-like advance (see text). (B) Enlargement of Punta Gente and the large field of elongate drumlins, in places draped by small moraine ridges.

by subglacial deformation of glaciofluvial deposits during advances of warm, wet-based ice (Clapperton, 1989; Benn and Clapperton, 2000b). Generally, the lineations are associated with ice-marginal features, but a few dense swathes of drumlins occur in isolation from any apparent ice margin and show elements of convergence and divergence, most clearly in the area around Laguna Cabeza del Mar in the Otway lobe (Fig. 2). Here, we suggest that the attenuated bedforms, parallel concordance and abrupt lateral margins of the lineation patterns are similar to those in areas of former rapidly flowing ice (Stokes and Clark, 1999, 2001; Evans et al., 2008; Lovell et al., 2012).

Subdued moraine topography

Subdued moraine topography consists of low, arcuate changes in relief (>1 km wide), often overprinted by other moraine ridges or bands of smaller hummocky terrain. The features are difficult to observe clearly on the ground and are best picked-out as positive relief in SRTM imagery or changes in vegetation in Landsat imagery. Subdued moraine topography is predominantly found in the centre of the BI-SSb lobe and is fragmented in a regular pattern north of Laguna Larga (Raedecke, 1978; Fig. 3B).

The regular fracturing of subdued moraine topography north of Laguna Larga could represent linear en echelon deposits linked to crevassing (Raedecke, 1978). However, this is unlikely because the topography is draped by younger features such as moraine ridges, glacial lineations and smaller hummocky terrain. Another possibility is that the subdued moraine topography is similar to the 'traction ribs' inferred beneath modern ice masses (Sergienko and Hindmarsh, 2013) and palaeo-ice stream tracks in the south-western Laurentide Ice Sheet (Stokes et al., 2016). Given the similarity in orientation to moraine ridges, however, the most likely explanation is that this subdued topography resulted from ice-marginal moraines that were subsequently overridden and moulded subglacially, similar to landforms (overridden moraines) observed in Iceland (Krüger, 1994; Evans et al., 1999, 2015; Evans and Twigg, 2002; Evans, 2009; Evans and Orton, 2015).

Irregular dissected ridges

A series of disorganized ridges, in places intersected by meltwater channels, are found in association with the Skyring and Río Gallegos lobes, most prominently to the south-east of the large swathe of drumlins orientated south-eastward in the
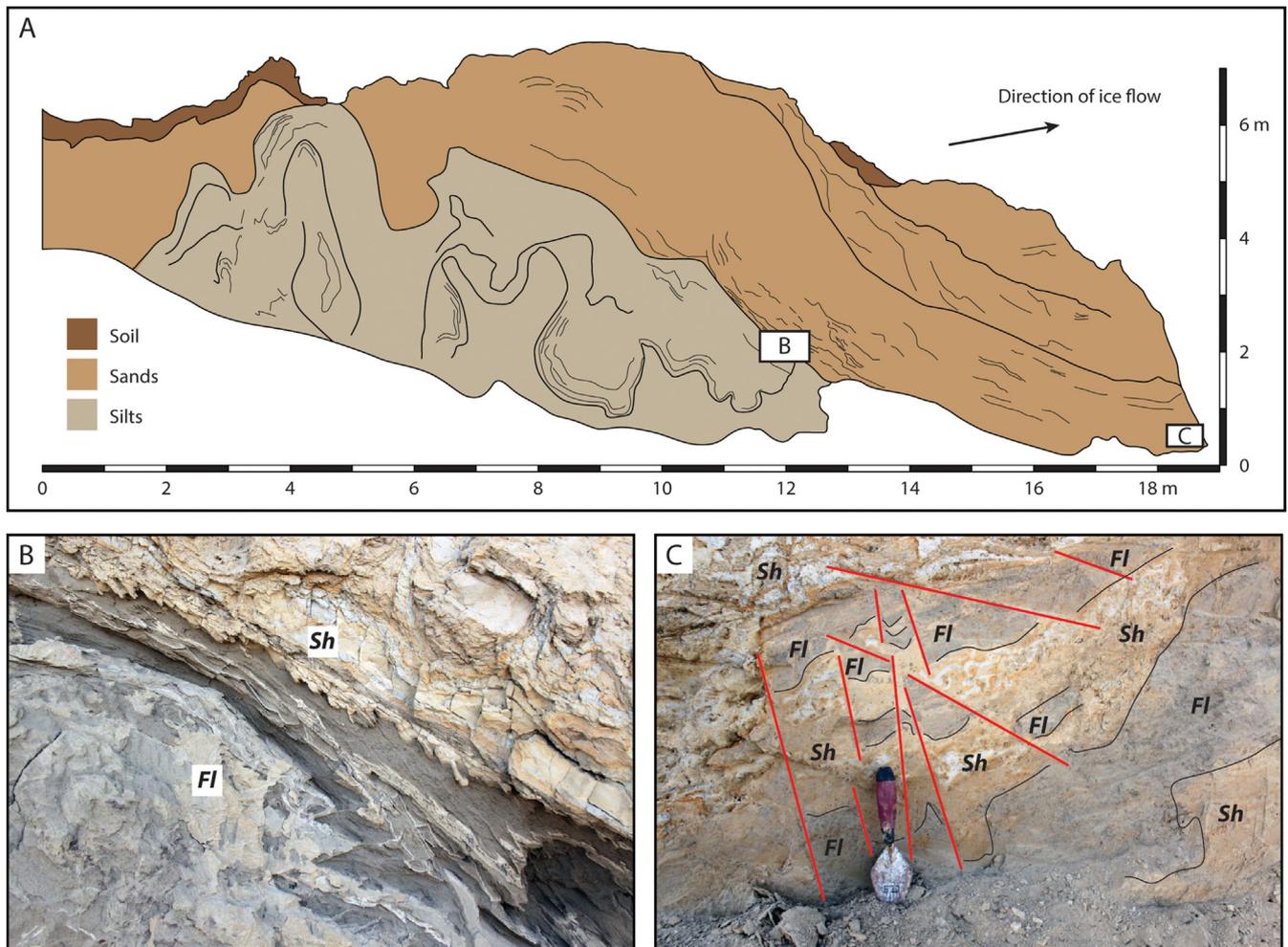
Figure 5. Sketch log (A) and accompanying photographs (B,C) of proglacially tectonized lacustrine silts and sands within an end moraine of the BI-SSb lobe (location shown in Fig. 3A). There is a high degree of folding and faulting. The large section suggests that the ice lobe retreated sufficiently for a sizeable proglacial lake to develop, before re-advance.

Río Gallegos lobe (Flow-set 1: FS 1; Fig. 9). The origin of the features is unclear, although the largest group appears to be situated at the intersection between the former Río Gallegos and Skyring ice lobes.

We suggest that the Río Gallegos lobe advanced first into the area, creating a drumlin field and moraine ridges. Subsequently, the Río Gallegos lobe retreated and the Skyring lobe advanced over the drumlins and moraines, causing subglacial deformation that resulted in an irregular pattern of hills and meltwater channels. The stratigraphic order is indicated by meltwater from the Skyring lobe draining into the Río Gallegos depression.

Glaciofluvial landforms

Meltwater channels

The study area is dominated by meltwater features, including hundreds of sinuous channels. In places, such as the outer moraines of the Skyring, Otway and Magellan lobes, the channels flow between moraine ridges (Fig. 2), but elsewhere, such as the BI-SSb depression and inner parts of the Río Gallegos, Skyring, Otway and Magellan lobes, meltwater channels are clearer than the associated moraines (Bentley et al., 2005). The channels vary in size, from less than 50 m wide to more than 150 m wide, and are sometimes associated with channels of outwash where ice overtopped topographic constraints (e.g. north-east of the Skyring and Otway lobes or north of the BI-SSb lobe).

Outwash plains

Outwash plains were identified based on their relatively smooth, featureless appearance, whose surfaces gently grade downslope from former ice margins. The plains are associated with moraines and hummocky terrain in all the ice lobes, and (where they are unconstrained by topography) wide, open sandur plains grade eastward. A prominent exception is the outwash plain originating from Laguna Blanca in the Skyring lobe (Figs 2 and 10), which trends south-eastward into the Strait of Magellan and surrounds a former moraine belt associated with the Otway lobe (Lovell et al., 2012).

The extensive nature of the glaciofluvial features implies that all the ice lobes produced large quantities of meltwater during stillstands and retreat. While meltwater channels and outwash plains are abundant within the study area, features such as ice contact fans, pitted outwash plains and eskers are not. Indeed, there is a notable absence of eskers associated with the ice lobes, which might imply that meltwater was rarely routed into conduits at the bed (perhaps draining into the substrate or as a result of cold-based ice) or that there was insufficient time for conduits to form (Storrar et al., 2014a,b). Alternatively, ice-walled deposition may have been restricted to englacial settings, in a similar fashion to the receding lowland lobes of Iceland, where drainage bypasses over-deepenings and hence eskers emerge on the surface of downwasting snouts (Spedding and Evans, 2002; Bennett et al., 2010; Bennett and Evans, 2012). Such a scenario would result in tunnel fills being significantly reworked
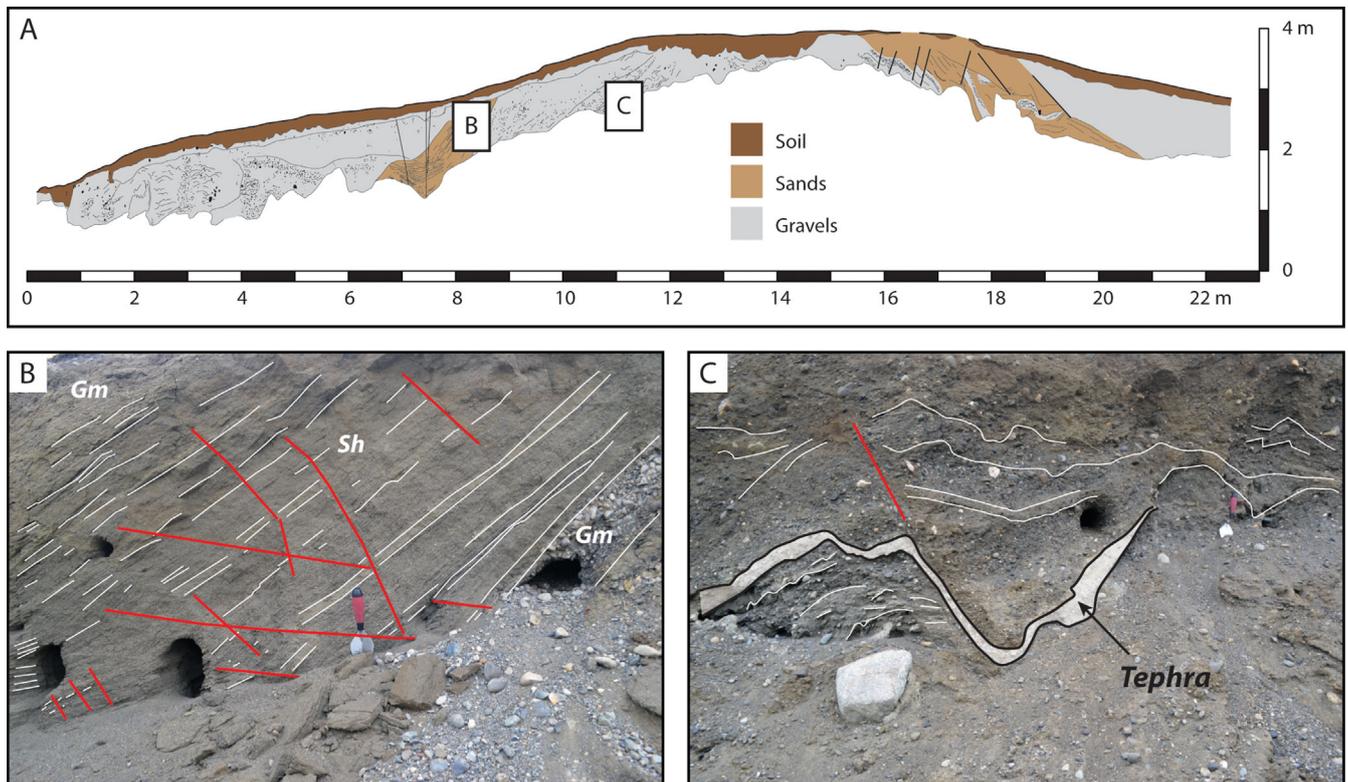
Figure 6. Sketch log (A) and accompanying photographs (B,C) of a glaciotectonized moraine associated with re-advance of the Otway lobe (location shown in Fig. 2). The normal thrust faults are particularly highlighted by a deformed tephra layer in (C). The sediments are characteristic of outwash material that was probably deposited during retreat of the ice before re-advance and proglacial thrusting.

during deglaciation and consequently difficult to identify in the landform record.

Proglacial lake landforms

Former shorelines

Numerous fragmentary shorelines are found within *ca.* 10 m elevation of contemporary coastal areas. In addition, continuous shorelines are found above 10 m and, further inland, around Lago Balmaceda in the Río Gallegos lobe (Fig. 1); Seno Skyring; Seno Otway (Fig. 2); Laguna Blanca in the Skyring lobe (Fig. 10A); south of Primera Angostura in the Strait of Magellan (Fig. 4); and Bahía Inútil (Fig. 3A). While the Skyring, Otway, Magellan and Bahía Inútil shorelines are generally within 30 m of present-day sea-level, those around Lago Balmaceda and Laguna Blanca are substantially higher.

Our glacial reconstruction, combined with DEM modelling, and the occurrence of localized palaeolacustrine sedimentary evidence, leads us to infer that these shorelines relate to a total of six large proglacial lakes that existed at various times in the overdeepenings in front of the former ice lobes. This reconstruction supports previous work on proglacial lake reconstruction in the area (Porter *et al.*, 1992; Clapperton *et al.*, 1995; McCulloch *et al.*, 2005a; Kilian *et al.*, 2007, 2013; Sagredo *et al.*, 2011; Stern *et al.*, 2011; Lovell *et al.*, 2012). The ice-marginal truncation of these shorelines suggests that they formed in front of the ice lobes, probably during recession into their respective topographic basins/overdeepenings.

Style and dynamics of Quaternary glaciation

Active temperate glacial landsystem

Most of the glacial geomorphology in the study area can broadly be divided into three landform assemblages:

morainic, subglacial and glaciofluvial (Fig. 11). The components of each assemblage as well as their inter-relationships are consistent with an active temperate glacial landsystem developed during the advance and retreat of the ice lobes (Evans and Twigg, 2002). The warm-based active recession of this landsystem produces three characteristic landform–sediment associations. Firstly, dump, push and squeeze moraines composed of proglacial sediments mark the ice limit, sometimes displaying annual signatures or evidence for still-stands that create stacked features (Price, 1970; Evans *et al.*, 1999; Evans and Twigg, 2002; Evans *et al.*, 2015). Low-amplitude ridges formed from overridden push moraines may also be found, draped by glacial lineations and moraines. Secondly, subglacially streamlined flutings and drumlins occur between these moraines. Thirdly, extensive glaciofluvial landforms occur where meltwater flows away from the warm-based ice front. These features include ice-contact and spillway-fed outwash fans; ice-marginal outwash tracts; kame terraces; pitted outwash and eskers (Evans and Twigg, 2002; Evans, 2003b). Active temperate glaciers are also capable of constructing arcuate bands of hummocky moraine during recession because of incremental stagnation, driven by pulses of supraglacial debris (Eyles, 1979; Bennett and Evans, 2012). The geomorphology in the central part of the BI-SSb lobe (Fig. 11) displays many of the landforms associated with an active temperate landsystem: moraines containing proglacially thrusted and folded sediments; possible recessional push moraines; overridden moraines; flutings and drumlins; and glaciofluvial meltwater channels and outwash plains.

The similarity between the landform assemblages in our study area and those associated with active temperate glaciers supports the assertion that the ice lobes dominantly operated under an active temperate glacial landsystem. This is especially clear in the geomorphology of the central BI-SSb lobe. The other ice lobes show the characteristics
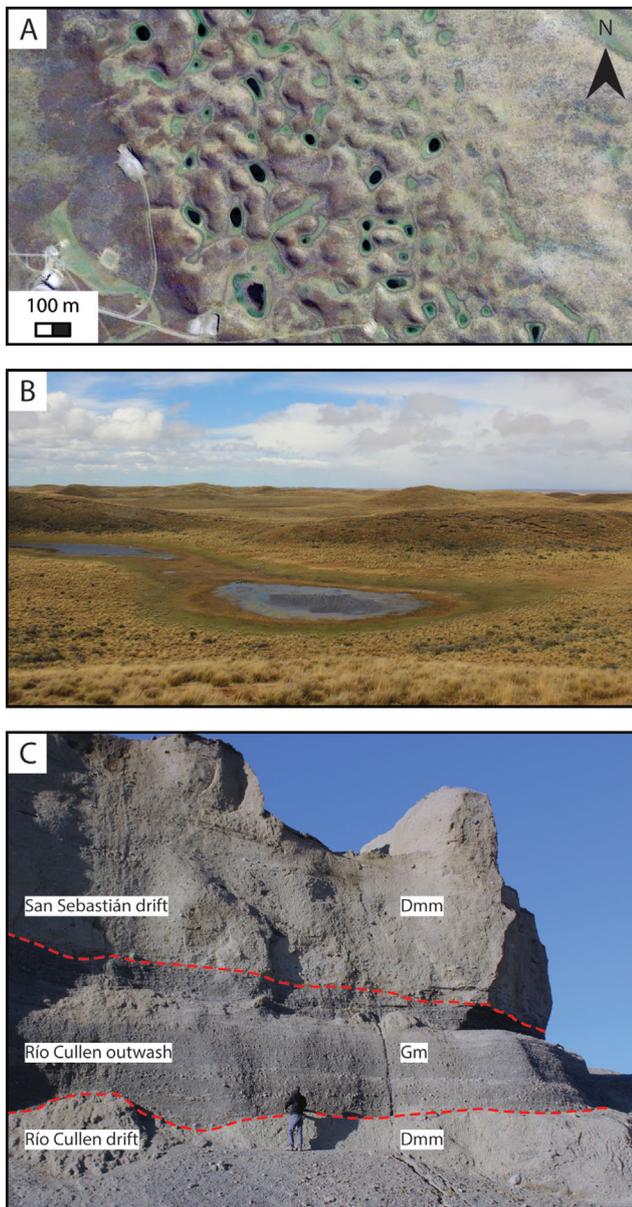
Figure 7. (A) A Google Earth image of larger irregular hummocky terrain from the south side of the BI-SSb lobe. (B) Field photograph of the hummocky topography on the north side of the BI-SSb lobe, illustrating the rounded hills and lakes. (C) A section through the inner band of larger hummocky terrain on the north side of the BI-SSb lobe. The top unit relates to this inner glacial limit (the San Sebastián drift), but overlies an earlier diamict unit and associated outwash (the Río Cullen drift), indicating that the ice lobe re-advanced (person for scale).

Figure 8. (A) A Google Earth image of regular hummocky terrain from the centre of the BI-SSb lobe (location shown in Fig. 3B). This terrain resembles geometric ridge networks and could be preserved crevasse-squeeze ridges. To illustrate this, (B) shows a Microsoft Bing Maps image of crevasse-squeeze ridges in front of the surging Brúarjökull glacier in Iceland. Note that although the glaciers in question are markedly different in size, the images are at the same scale.

associated with active temperate glaciers, but the geomorphology is either not as well preserved (as in the Río Gallegos and Magellan lobes) or the moraines are more tightly nested (as in the Skyring and Otway lobes) so the assemblages are not as clear. Tightly nested moraine sequences may indicate that the Skyring and Otway lobes retreated more slowly than the other ice lobes, although there are no chronological constraints on the rate of this recession (see Chronological framework). Similar patterns of tightly nested features have been observed in Iceland (Bradwell et al., 2013), but, in our study, the cause may be related to topographic constraints, rather than annual cycles in retreat (Kaplan et al., 2009; Anderson et al., 2012; Barr and Lovell, 2014). Hence, the landform assemblages of the Skyring and Otway lobes may indicate an active temperate
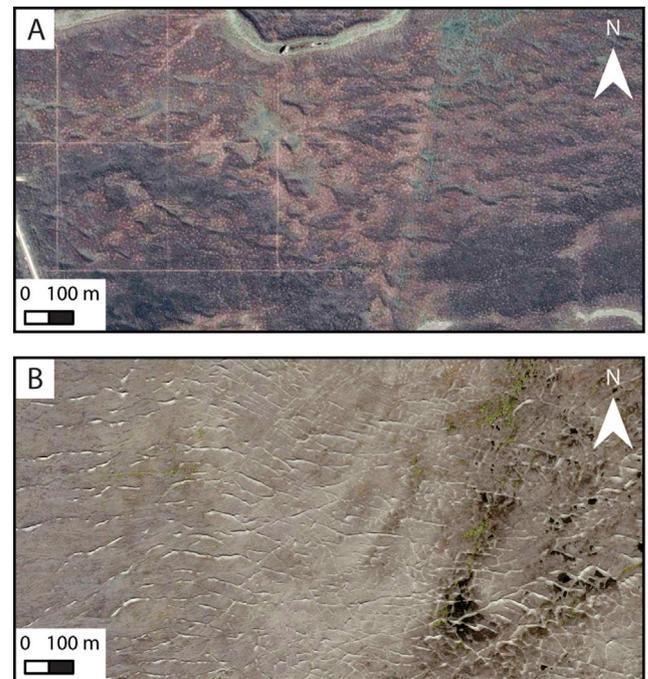
landsystem, but they are not as clear as the BI-SSb lobe due to slower glacier recession.

External forcing of glacier behaviour

There are a number of implications associated with our interpretation of an active temperate glacial landsystem. Principally, Benn & Clapperton (2000a,b) suggested that the Magellan lobe operated under subpolar conditions, with a cold-based margin, during the gLGM. By contrast, Bentley et al. (2005) advocated warm-based conditions extending to the ice margin based on different glacier limits that implied steeper ice surface gradients. The presence of proglacially thrust moraines and arcuate bands of hummocky terrain, if they originated as controlled ridges (sensu Evans, 2009), are consistent with cold-based ice or at least a polythermal basal regime (Benn and Clapperton, 2000b; Evans, 2009). Evidence for glacial lineations extending to individual moraine ridges is a landform association indicative of warm-based ice throughout the snout (Evans and Twigg, 2002; Evans, 2003b), and arcuate hummocky terrain bands set within recessional push moraines are consistent with phases of incremental stagnation by temperate glaciers. However, glacial thermal regimes form a continuum upon which the landsystem signatures of polythermal glaciers, with frozen snouts (e.g. Svalbard valley glaciers and Icelandic upland icefields), and active temperate glaciers, with winter frozen toe zones and pulsed supraglacial debris transfer, would be difficult to differentiate (Evans, 2009). Particularly significant for southernmost Patagonia is the independent evidence for permafrost conditions at the gLGM (Benn and Clapperton, 2000a,b; Bockheim et al., 2009). Therefore, we suggest that the former ice lobes were predominantly active temperate in nature, but were subject
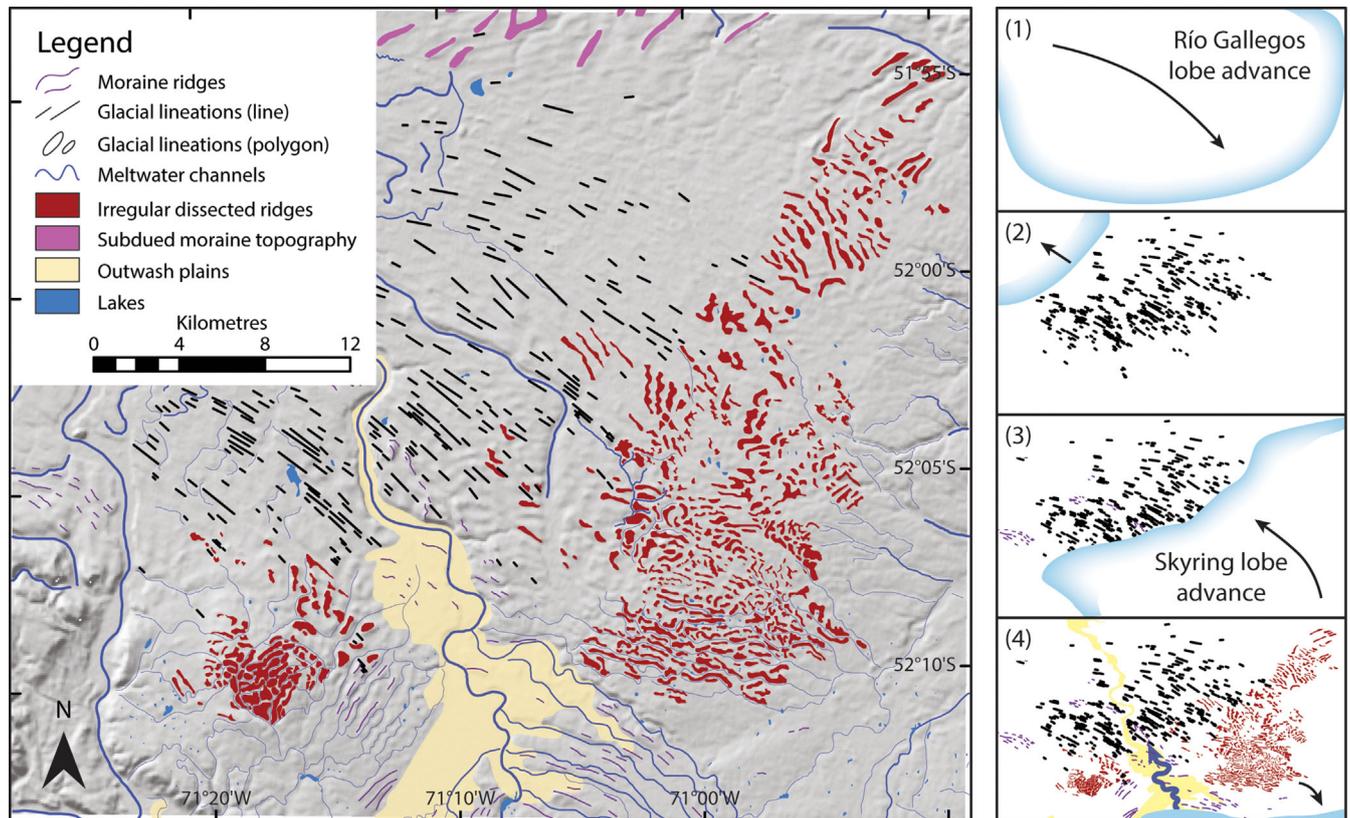
Figure 9. Glacial geomorphology found at the intersection between the Río Gallegos and Skyring lobes (location shown in Fig. 2). (1) to (4) show a stylized formation mechanism for the irregular dissected ridge features. (1) The Río Gallegos advances first, creating a swathe of drumlins (2), and possibly moraines, that are later overridden by an advance of the Skyring lobe (3). The order is dictated by the flow of meltwater from the Skyring lobe into the Río Gallegos basin (4).

to periods of polythermal conditions, thereby giving rise to phases of controlled moraine construction. A similar scenario has been proposed for the southern limits of the Laurentide Ice Sheet in the interior plains of North America (Clayton *et al.*, 2001; Colgan *et al.*, 2003; Bauder *et al.*, 2005; Evans *et al.*, 2006, 2014). This further illustrates the importance of recognizing what Evans (2013) identifies as landsystem superimposition and spatiotemporal change, whereby changes in the climatic environment occupied by a glacier will inevitably be reflected in its geomorphic signature. The incremental stagnation versus controlled origin of the hummocky terrain arcs is important to the palaeoglaciological reconstruction and its palaeoclimatic inferences made above, and therefore needs to be vigorously tested by future sedimentological investigations.

The complex landform–sediment signatures of the southernmost Patagonian outlet lobes indicate active temperate glaciers. Such glaciers are characterized by active advance during periods of overall recession, primarily controlled by regional climatic variability (Colgan *et al.*, 2003; Evans, 2003b, 2011; Evans and Orton, 2015; Evans *et al.*, 2015). Modern examples include Breiðamerkurjökull, Fjallsjökull, Heinabergsjökull, Skalafellsjökull and Fláajökull in Iceland (Evans and Twigg, 2002; Evans, 2003b; Evans *et al.*, 2015; Evans and Orton, 2015). Both topographic control (Kaplan *et al.*, 2009; Anderson *et al.*, 2012; Barr and Lovell, 2014) and internal ice dynamics (Benn and Clapperton, 2000a,b; Lovell *et al.*, 2012) have also been proposed as factors controlling glacial activity within this region. Our geomorphological evidence implies that, for the majority of ice fluctuations, these internal forcing factors may have been of secondary importance to climatic variability.

Internal forcing of glacier behaviour

While the landform evidence suggests that the ice lobes predominantly advanced and retreated according to an externally forced active temperate landsystem, there is also evidence for periods of rapid ice flow and proglacial lake development. Both of these situations may have temporarily interrupted the primary climatic driver of glacial activity.

Transient rapid ice flow

A large swathe of elongated, closely spaced drumlins in the inner part of the Otway lobe around Laguna Cabeza del Mar (FS 8 in Fig. 12) has previously been hypothesized to represent rapid ice flow (Benn and Clapperton, 2000b; Lovell *et al.*, 2012). Unlike other glacial lineations in the study area, this drumlin field resembles a terrestrial palaeo-ice stream, with convergent flowlines, attenuated bedforms and abrupt lateral margins (Stokes and Clark, 1999; Clark and Stokes, 2003; Lovell *et al.*, 2012). Additionally, Lovell *et al.* (2012) raised the possibility for surge-like behaviour of the Otway lobe based partly on this landform evidence. Our study confirms that many of the landforms associated with surging activity are exhibited in the study area, including thrust moraines, highly elongate flutings, hummocky terrain and crevasse-squeeze ridges, which are often viewed as diagnostic of surge activity (Evans and Rea, 1999, 2003; Schomacker *et al.*, 2014; Lovell *et al.*, 2015). As such, we suggest the ice lobes may have periodically displayed rapid ice-flow and possible surge-like behaviour.

Our reconstruction of fast-flowing ice would have affected ice dynamics in parts of the ice lobes. Similar fast-flowing systems in northern Patagonia during the gLGM are
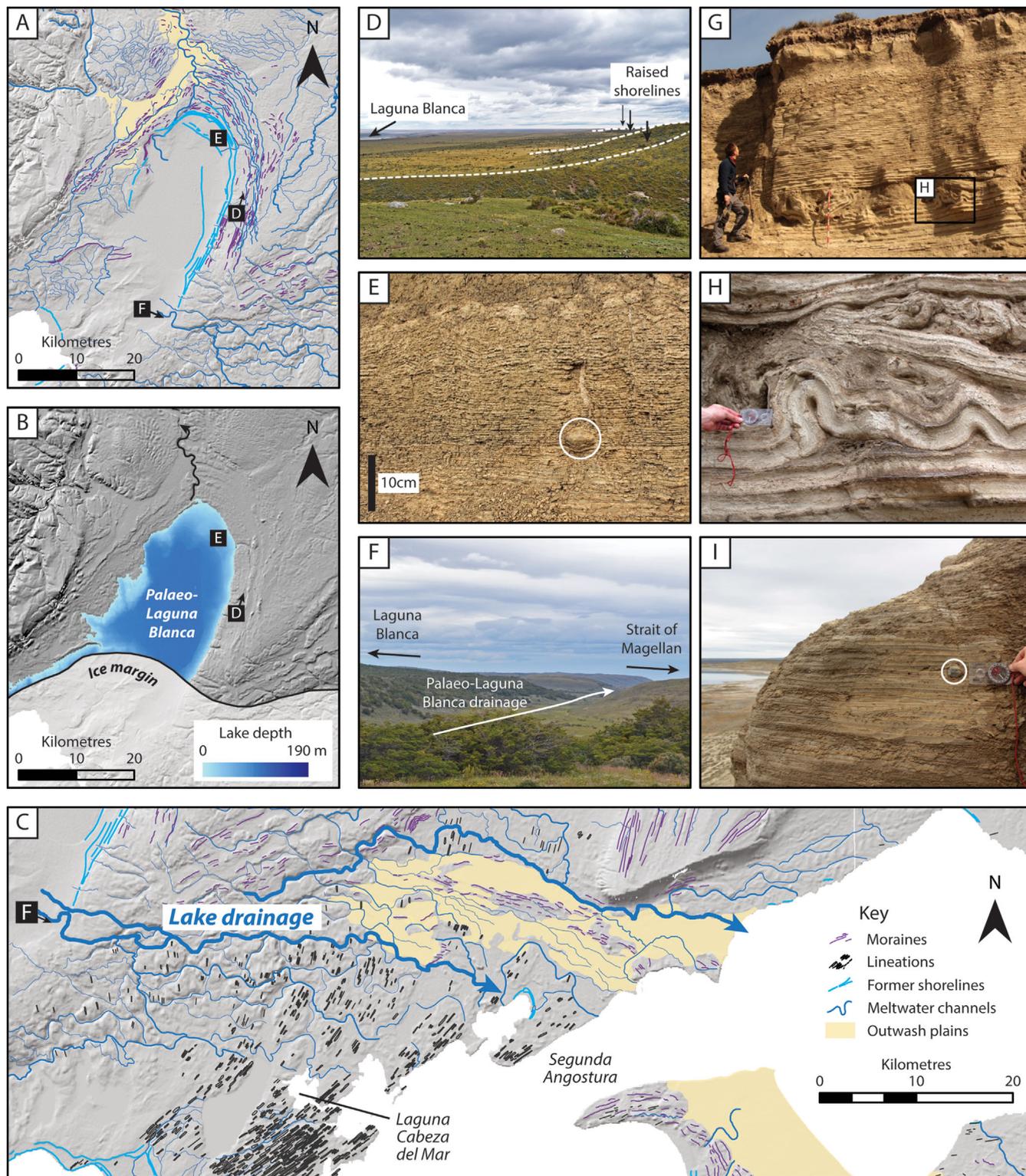
Figure 10. Evidence for proglacial lakes within the study area. (A) The geomorphology and (B) the reconstructed ice limit and palaeo-Laguna Blanca proglacial lake just before drainage, when discharge flowed northwards. (C) The geomorphological evidence for lake drainage eastward into the Strait of Magellan once the Skyring lobe retreated beyond the bluff separating it from the Otway lobe (locations shown in Fig. 2). (D) Raised shorelines, (E) laminated lake sediments with a dropstone circled, and (F) a drainage channel associated with palaeo-Laguna Blanca (locations shown in A and B). (G) Rhythmically laminated sediments from Laguna Verde (see Fig. 4 for location). (H) Enlarged part of (H) showing several heavily deformed layers, possibly due to earthquake-induced tectonization. (I) Dropstones are found within the Laguna Verde sequence (circled).

hypothesized to have resulted in greater ice discharge rates (Glasser and Jansson, 2005), and rapid ice flow across much of the eastern portion of the Patagonian Ice Sheet may help to explain mismatches between model outputs and landform reconstructions (Hulton *et al.*, 2002; Glasser and Jansson, 2005). The presence of landforms linked to possible surge-like

advances further implies that, at times, the ice lobes may have briefly advanced in response to non-climatic forcing. The possible evidence for palaeo-surges warrants further research, particularly given the paucity of examples of surging systems in the palaeo-record and the fact that some contemporary active temperate glaciers, such as Breiðamerkurjökull, have
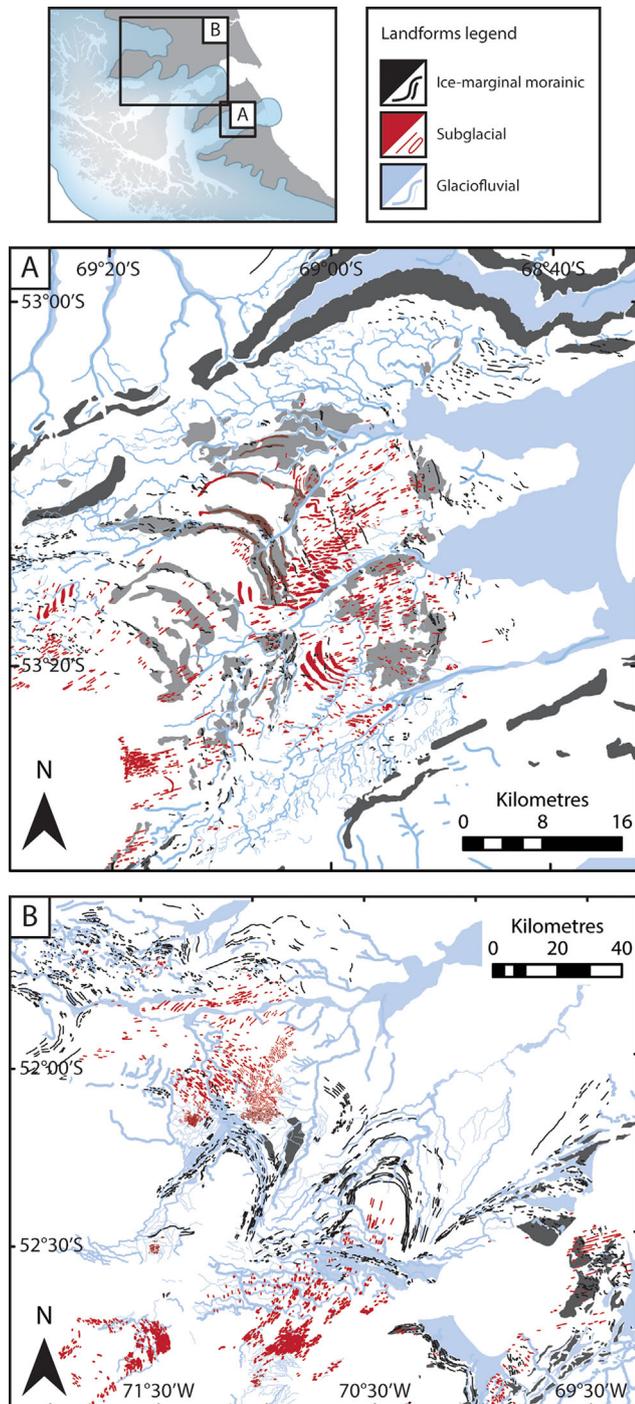
Figure 11. Glacial geomorphology of (A) the BI-SSb lobe and (B) the Río Gallegos, Skyring, Otway and Magellan lobes. The geomorphology has been grouped and re-coloured according to the three dominant landform suites indicative of an active temperate glacial landsystem.

also displayed surging activity and this is recorded in landsystem overprinting (Evans and Twigg, 2002).

Proglacial lake development

The clearest proglacial lake landforms are within the Skyring lobe, where meltwater accumulated above the present-day Laguna Blanca. Shorelines and DEM modelling indicate a maximum lake surface elevation of *ca.* 190 m a.s.l., which drained northward into the basin previously occupied by the Río Gallegos lobe (Lovell *et al.*, 2012; Fig. 10A,B). This reconstruction is supported by sedimentological evidence

north-east of Laguna Blanca consisting of rhythmically laminated silt and clay sediments, containing dropstones (Fig. 10E). Our ice limit for the Otway lobe differs from Lovell *et al.* (2012), such that a similar proglacial lake did not form in front of the Otway lobe because meltwater could drain south-eastward in front of the Magellan lobe. Once the Skyring lobe retreated beyond the topographic bluff separating it from the Otway lobe, drainage of the palaeo-Laguna Blanca proglacial lake switched from a northward to a south-eastward direction, in front of the Otway and Magellan lobes and into the Strait of Magellan (Fig. 10C,F). The drainage resulted in the formation of large meltwater channels and an associated outwash plain that surrounded a moraine belt associated with the Otway lobe.

Proglacial lakes are also reconstructed in front of the BI-SSb and Magellan lobes (Fig. 13), consistent with the presence of lacustrine sediments (McCulloch *et al.*, 2005a). The BI-SSb lake reached approximately 20 m a.s.l. before draining at Onaisín, eastward towards the Atlantic through a channel now marked by Laguna Larga (Fig. 3A,B). Likewise the Magellan lake drained eastward towards the Atlantic, but the height of the lake is less clear as the drainage channel is below present-day sea-level (Porter *et al.*, 1992; Clapperton *et al.*, 1995; McCulloch *et al.*, 2005a). Our reconstruction suggests that at its peak the lake extended onto the low plain in front of the Otway lobe. Small lakes also formed at 10–20 m a.s.l. on the eastern flank of the Magellan lobe, north of Porvenir (Fig. 4B). One of these lakes deposited a large section of rhythmically laminated silt and clay sediments at Laguna Verde (Figs 4 and 10G–I).

A proglacial lake formed in front of the Otway lobe once ice had retreated into the present-day Seno Otway, and there is evidence for a channel initially draining north-eastward into the Strait of Magellan (Mercer, 1976; McCulloch *et al.*, 2005a). However, once the lake level dropped to around 20 m a.s.l., drainage would have switched to the north-west through Canal Fitzroy into a similar lake at 10–20 m a.s.l. within present-day Seno Skyring (Fig. 2). The Skyring proglacial lake drained northward through Estero Obstrucción (Fig. 1) into a large lake in front of the Río Gallegos lobe, the extent of which is unclear (Sagredo *et al.*, 2011; Stern *et al.*, 2011), although final drainage of the Otway, Skyring and Río Gallegos lakes would have been westward through Golfo Almirante Montt (Fig. 1) once ice had receded into the mountains (McCulloch *et al.*, 2005a; Stern *et al.*, 2011).

Former proglacial lakes would also have affected glacial dynamics by promoting increased rates of ice retreat (Porter *et al.*, 1992; Teller, 2003; Lovell *et al.*, 2012; Carrivick and Tweed, 2013). The presence of a proglacial lake at the margin of a glacier can trigger positive feedbacks such as increased englacial water pressure and temperature; increased subglacial pressure; and increased ice surface gradients, which can result in calving, ice-margin flotation and the flushing of sediment from beneath the ice (Carrivick and Tweed, 2013). This results in greater ice mass loss and glacial draw-down (Lovell *et al.*, 2012). Porter *et al.* (1992) also suggested that calving of the Magellan and BI-SSb lobes could have resulted in a rapid loss of ice. Given the potential importance of proglacial lakes in controlling ice dynamics within this region, future work should aim to better constrain their evolution over time.

Glacial reconstruction and timing

Glacial limits and flow-sets

Three sets of ice-marginal landforms were used to demarcate former glacial limits: morainic landforms (including hummocky
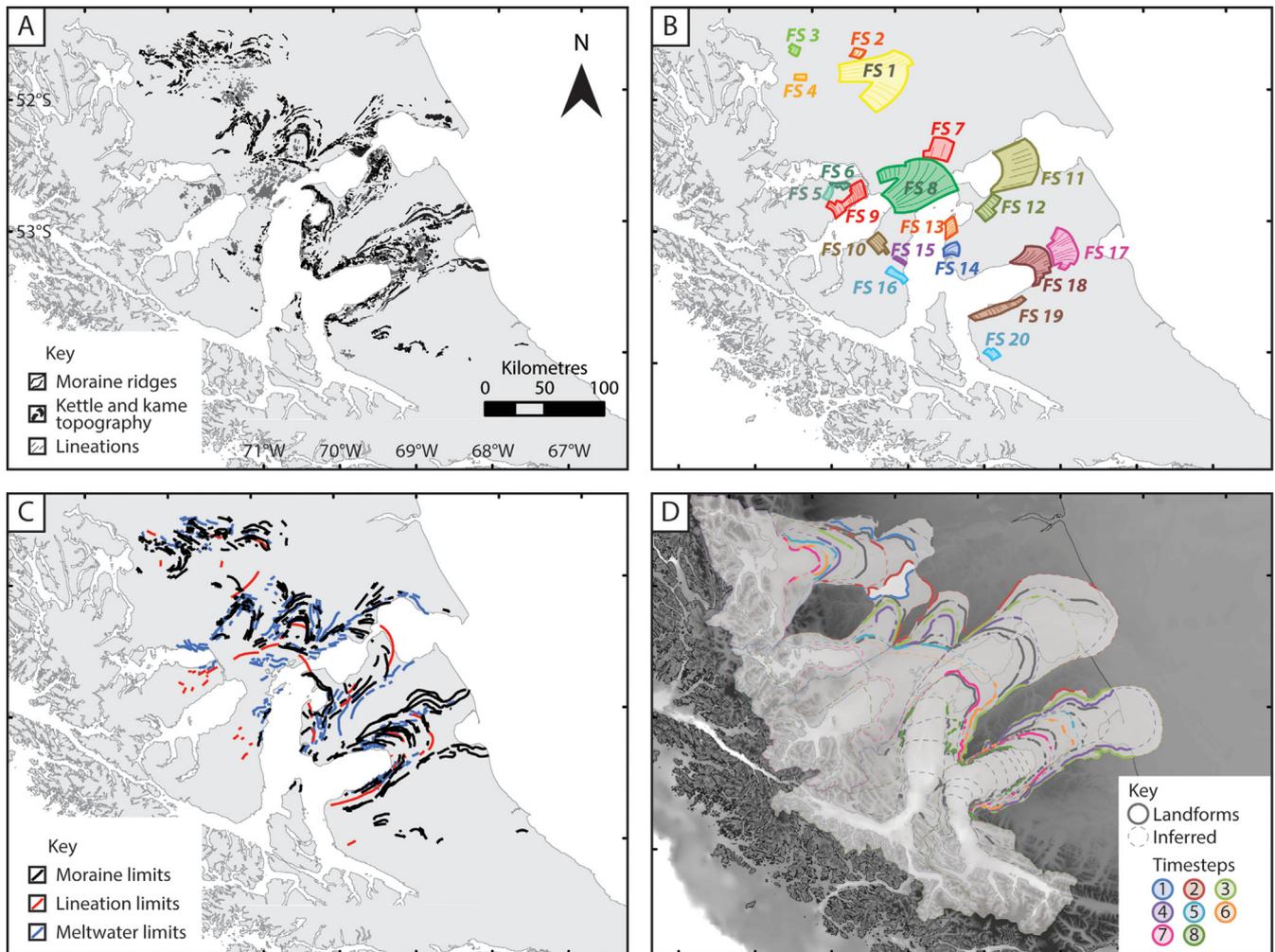
Figure 12. (A) Simplified version of the glacial geomorphology in the study area to show the dominant ice flow and ice-marginal features. (B) The flow-sets defined in this study (FS 1–20). (C) The dominant limits associated with four different sets of ice-marginal features. These were synthesized into glacial limits, shown in (D). The two innermost limits of the Skyring lobe are from Kilian *et al.* (2007). Eight of these limits are used in our glacial reconstruction time steps, coloured according to Fig. 14.

terrain), glacial lineation flow-sets (see below) and meltwater channels. The different lines of evidence yielded a consistent pattern and the data were synthesized to create a map of prominent limits for each ice lobe (Fig. 12). Many of these limits corroborate previous work defining glacial limits in the region (Meglioli, 1992; Clapperton *et al.*, 1995; Coronato *et al.*, 2004; Bentley *et al.*, 2005; Lovell *et al.*, 2012), but the wider scope of our mapping reveals a more detailed pattern than has been previously reported. For comparison, we also included less extensive limits from Kilian *et al.* (2007) for the Skyring lobe (Fig. 12D).

A total of 20 flow-sets (FS) were identified within the study area (Fig. 12B), with those of the Skyring and Otway lobes similar to Lovell *et al.* (2012). An exception is the separation of FS 7 and 8 based on differing morphology: the drumlins around Laguna Cabeza del Mar are noticeably longer, wider, and higher than the long flutings further to the north-east. This division is important because FS 8 corresponds to moraines dissecting the Otway depression. Some flow-sets within the inner parts of the Río Gallegos, Skyring, Magellan and BI-SSb lobes have been discussed in previous studies (Benn and Clapperton, 2000b; Ercolano *et al.*, 2004; Bentley *et al.*, 2005; Lovell *et al.*, 2012), but the outer flow-sets of the Río Gallegos and BI-SSb lobes have not been reported previously.

The glacial limits that we have defined can be used to reconstruct a relative sequence of events in the glacial history, enhanced by information about ice dynamics from our landsystems approach. Correlating between the limits of adjacent ice lobes can be problematic because they are generally reconstructed from fragmentary records, and joining-up limits can over-emphasize correlation without robust chronological controls. However, in places, our approach informs the relative timing of advance and retreat between lobes based on cross-cutting landform assemblages. Using cross-cutting relationships between flow-sets and ice-marginal landform assemblages, we identify eight separate relative time steps in our reconstruction (Fig. 13). These time steps are shown in relation to present-day basal topography and the height of former proglacial lakes in Fig. 14. We now briefly discuss key aspects of the nature and timing of this glacial history in relation to the eight time steps and a compilation of recalibrated chronological information (Fig. 15).

Chronological framework

This study is principally engaged with reconstructing the dynamics of former ice lobes without considering time-dependent variation. However, it is possible and informative
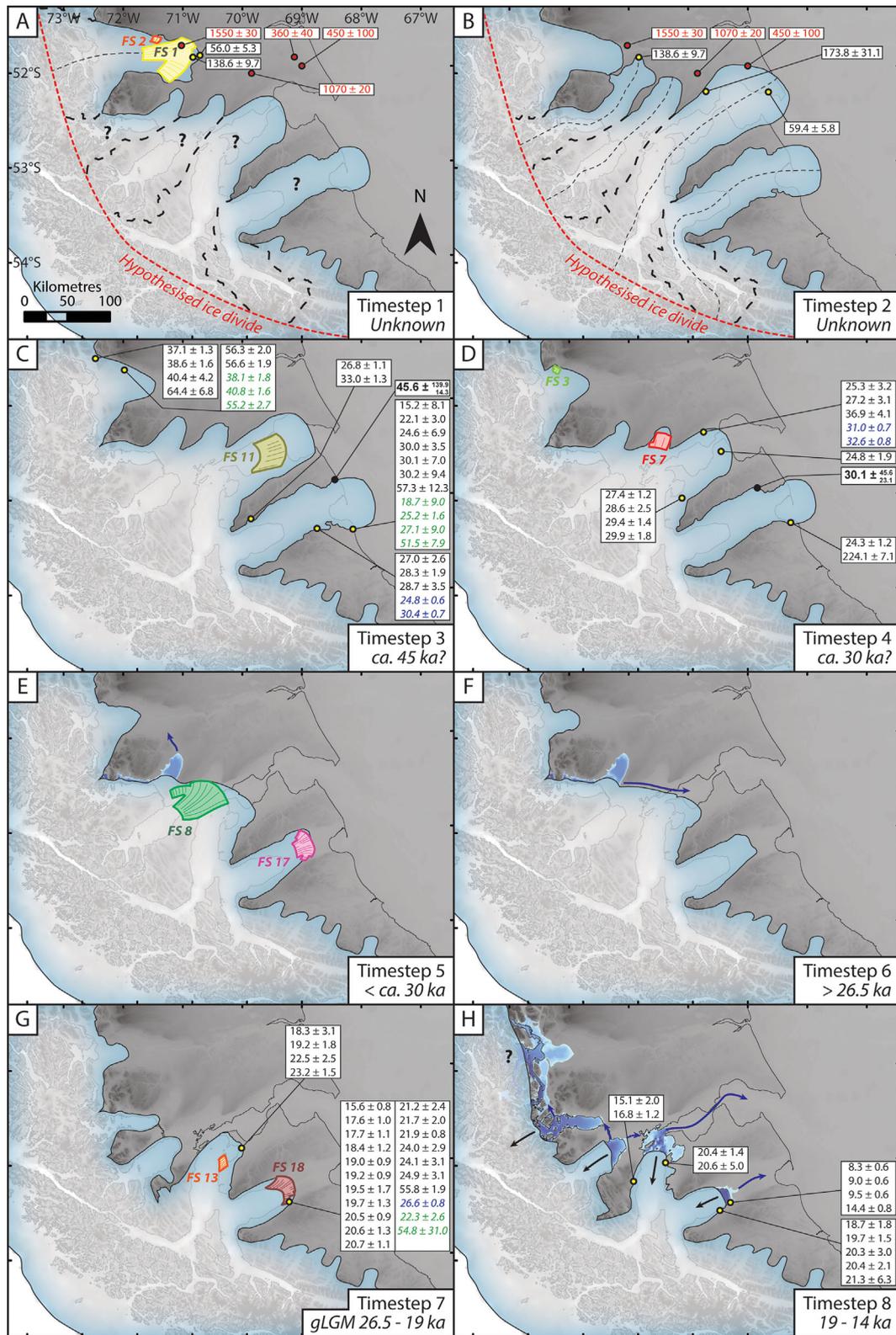
Figure 13. Reconstructed glacial history for the five ice lobes studied, with eight time steps shown in (A) to (H). The hypothesized ice divide based on Hulton *et al.* (2002) is shown in (A) and (B) for reference. We show the rest of the ice sheet for completeness, with hypothesized gLGM limits based on Coronato *et al.* (2004). The rest of the ice sheet would have retreated over time, but that was not part of our study. Also shown in (A) and (B) are hypothesized drainage divides between the five ice lobes (bold dashed black lines) and the lines of topographic profiles for each ice lobe shown in Fig. 14 (fine dashed black lines). Key flow-sets are shown and blue arrows show the direction of lake drainage routes. Question marks show where the ice configuration is unknown and black arrows in (H) show final retreat during time step 8. Published chronological data are shown where appropriate (see text for discussion). These are: argon dates (red text/circles); cosmogenic nuclide exposure dates (yellow circles) consisting of recalibrated ^{10}Be dates (black text), recalibrated ^{26}Al dates (italic blue text) and ^{36}Cl dates (italic green text); and cosmogenic nuclide depth profiles (bold black text/circles).
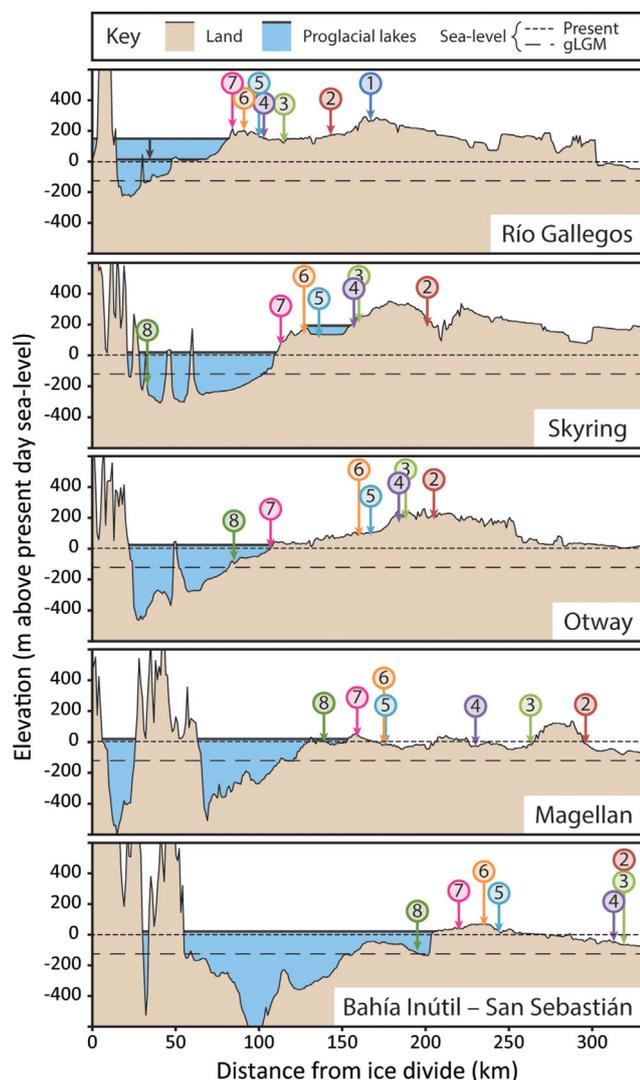
Figure 14. Topographic profiles for each ice lobe, shown as changes in elevation relating to present-day sea-level against distance from the hypothesized ice sheet divide. Ice flowed from left to right. The profiles from the ice divide to the outermost time step are shown in Fig. 13A and B. The coloured numbers relate to the time steps shown in Fig. 13D. Present-day sea-level is shown (short dashes), as well as the approximate sea-level at the gLGM (long dashes). Hence, the outermost limits of the BI-SSb lobe were in the Atlantic Ocean but would have formed on the exposed continental shelf. Also shown are the approximate heights of former proglacial lakes. The Río Gallegos lake would have dropped progressively over time, but the timing is not well constrained.

to place our time steps within a framework of previously published chronological data (Figs 13 and 15). Full details of this chronological compilation, including calibration and recalculation methods, are given in the Supplementary Material and Tables S1–S4.

Time steps 1–4: pre-gLGM advances

There is uncertainty regarding the ages of pre-gLGM glacial limits within the study area (time steps 1–4 in our reconstruction). Cosmogenic nuclide exposure dating of boulders from moraines of the BI-SSb, Magellan and Río Gallegos lobes (Kaplan et al., 2007; Evenson et al., 2009) has yielded ages that are substantially younger than associated $^{40}Ar/^{39}Ar$ dates from nearby volcanic flows (Fig. 13A–C; Meglioli, 1992; Singer et al., 2004), the cause of which is contentious (Kaplan et al., 2007; Darvill et al., 2015a). Darvill et al. (2015b) used

$^{10}Be/^{26}Al$ depth profiles through outwash sediments to show that two limits previously assigned to older glacial stages were deposited during the last glacial cycle. Overall, the large spread of boulder ages associated with time steps 1–4 may result from post-depositional processes such as boulder erosion (Kaplan et al., 2007) and the gradual melt-out of dead ice in hummocky terrain (Schomacker, 2008; Darvill et al., 2015a).

In time step 4, the BI-SSb lobe re-advanced to close to the limit of time step 3 (Fig. 14), with ^{10}Be dates from boulders of 24.3 and 224.1 ka (Fig. 13D; Kaplan et al., 2007). A depth profile through associated outwash yielded a more robust age of 30.1 ka (Darvill et al., 2015b). For the Magellan lobe, eight ^{10}Be ages between 24.8 and 36.9 ka and two ^{26}Al ages of 31.0 and 32.6 ka (Kaplan et al., 2007) imply that the limit may have been deposited at a similar time to that of the BI-SSb lobe (Fig. 15).

Time steps 5–6: re-advances, rapid flow and lake drainage

The Otway lobe re-advanced significantly during time step 5 (Fig. 13E), forming FS 8 around Laguna Cabeza del Mar and shifting the ice divide between the Otway and Magellan lobes south-eastward into the present-day Strait of Magellan. The BI-SSb lobe also re-advanced to a limit close to Bahía San Sebastián, depositing a large terminal moraine that is still preserved east of Laguna Larga (Fig. 3) and forming FS 17 (Fig. 13E). The re-advances of these two ice lobes may have been in response to rapid ice flow (and possible surge-like activity based on the presence of thrust moraines, highly elongate flutings, hummocky terrain and crevasse-squeeze ridges). The Río Gallegos, Magellan and Skyring lobes retreated during time step 5, with the Skyring lobe developing a proglacial lake – palaeo-Laguna Blanca – that may have further facilitated ice loss through calving (Figs 13E and 14). However, there are no direct age constraints for this time step. Recession continued during time step 6, allowing the potentially catastrophic drainage of palaeo-Laguna Blanca from in front of the Skyring lobe east to south-easterly in front of the Otway and Magellan lobes (Fig. 13F). The drainage event is important because it acts as a stratigraphic tie-point for all three ice lobes (Fig. 15). As mentioned for times steps 1–4, ages of 24.8 and 36.9 ka for the Magellan lobe at Primera Angostura (Fig. 2) suggest that it advanced before the gLGM during the last glacial cycle. The lake drainage is constrained by these ages and four more ^{10}Be ages of 27.4–29.9 ka on Península Juan Mazía (McCulloch et al., 2005b; Kaplan et al., 2008a). The implication is that the Skyring, Otway and Magellan lobes were all retreating from more extensive positions before the gLGM (Fig. 15).

Time step 7: the gLGM

During time step 7, the ice lobes reached positions that have been broadly correlated with the gLGM (Figs 13G and 15). Based upon our landform evidence (e.g. highly elongate flutings and hummocky terrain), the Magellan lobe readvance may have been surge-like, and has been ^{10}Be dated to between 18.3 and 23.2 ka. The BI-SSb lobe readvance has also been ^{10}Be, ^{26}Al and ^{36}Cl dated to between 15.6 and 55.8 ka (although 16 ^{10}Be dates were between 17.6 and 24.9 ka; McCulloch et al., 2005b; Kaplan et al., 2007, 2008a; Evenson et al., 2009). The reason for the scatter in ages is unclear, although the ^{10}Be date of 55.8 ka may be due to inheritance, given that most of the dates are from a large erratic boulder train on the south-eastern side of Bahía Inútil
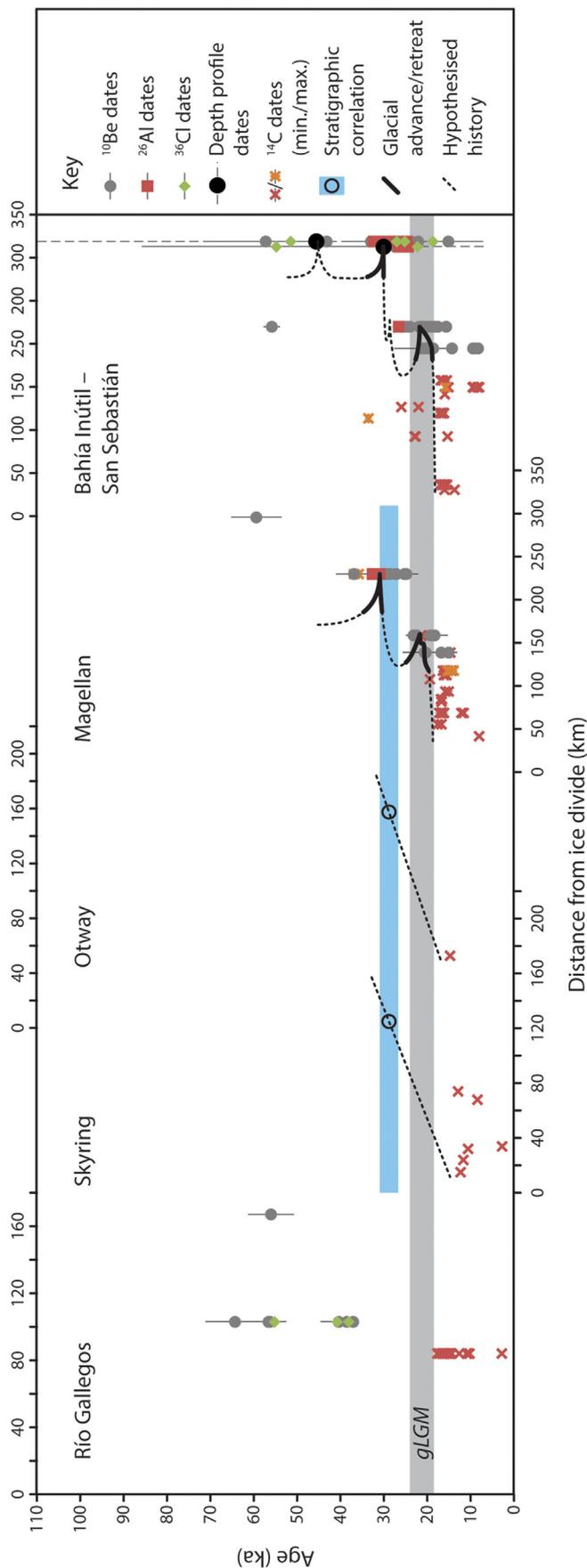
Figure 15. (Continued).

(Darvill *et al.*, 2015a). There are no supporting ages for the Río Gallegos, Skyring and Otway lobes but they were probably situated within the present-day fjords.

Time step 8: rapid retreat

All the ice lobes were in post-gLGM retreat during time step 8 (Fig. 13H), developing proglacial lakes in front of their receding margins that probably increased the rate of ice loss through calving (Fig. 14; Porter *et al.*, 1992; Kilian *et al.*, 2007; Carrivick and Tweed, 2013). The Magellan and BI-SSb proglacial lakes drained eastward towards the Atlantic, although their extent is uncertain. Drainage of the Otway proglacial lake initially occurred east to north-eastward into the Magellan lake, but as lake levels dropped during ice retreat, drainage switched to north-westward into the Skyring proglacial lake, cutting the Fitzroy channel (McCulloch *et al.*, 2005a; Kilian *et al.*, 2013). In turn, the Skyring proglacial lake drained into the Río Gallegos proglacial lake that, by this time, may have drained westward into the Pacific Ocean through ice-free fjords dissecting the Andes (McCulloch *et al.*, 2005a; Kilian *et al.*, 2013). It is possible that Río Gallegos ice was still extensive, such that drainage occurred in a south-wards direction, reaching the Pacific through Seno Otway (Stern *et al.*, 2011). Ultimately, uncertainty in the configuration of the Río Gallegos lobe makes it difficult to assess drainage routes.

Ice-free conditions in Seno Skyring and Seno Otway have been dated to at least 14.8 and 14.7 ka, respectively, based on radiocarbon dating and tephrostratigraphy of sediment cores (Kilian *et al.*, 2013). The Skyring lobe may have been undergoing rapid retreat linked in part to calving (Kilian *et al.*, 2007). Numerous radiocarbon dates suggest that retreat of the Magellan and BI-SSb ice lobes was also under way by at least 14–15 ka (Porter *et al.*, 1992; Clapperton *et al.*, 1995; McCulloch and Bentley, 1998; Anderson and Archer, 1999; McCulloch *et al.*, 2005b), although the presence of the Reclús tephra within lake sediments implies that full retreat and final proglacial lake drainage cannot have been before *ca.* 14.3 ka (McCulloch *et al.*, 2005a). The rapid retreat, and possible collapse, of the BI-SSb lobe is supported by radiocarbon dates as early as 16.8 ka in central Cordillera Darwin (Hall *et al.*, 2013; Fig. 15). A similarly rapid retreat is reconstructed for the Magellan

Figure 15. A distance–time graph for the five ice lobes over the last glacial cycle, based on cosmogenic nuclide and radiocarbon dating discussed in the text. Dated lava flows suggest that most of the ice lobes would have advanced during earlier glacial cycles (Meglioli, 1992; Singer *et al.*, 2004; Kaplan *et al.*, 2007). The BI-SSb lobe contains a large number of dates, but with scattered ages and large associated errors. It is not possible to reconcile the cosmogenic nuclide ages and some of the radiocarbon dates during deglaciation. The Magellan lobe contains fewer dates, but a more consistent ice-retreat history. The Otway and Skyring lobes contain few dates, but must have been retreating from a limit before *ca.* 30 ka because of the lake drainage from palaeo-Laguna Blanca in front of the Skyring, Otway and Magellan lobes (the blue stratigraphic correlation bar). Note the similarities in the glacial histories of these four ice lobes, including retreating from extensive positions before 30 ka and the gLGM, and rapid late-stage retreat. The timing of advance and retreat of the Río Gallegos lobe is not well constrained, partly because many of the cosmogenic nuclide and radiocarbon dates are from lateral positions that cannot be robustly linked to the former ice terminus. A large number of radiocarbon dates are shown from Sagredo *et al.* (2011), but these cannot be tied to the ice terminus and are simply shown against the approximate ice distance in time step 7.

lobe (Fig. 15), probably linked to the broad calving termini of these ice lobes (Porter *et al.*, 1992).

Conclusions

This study presents a reconstruction of the relative history of five former ice lobes in southernmost South America. We reconstruct eight time steps, which highlight the dynamic nature of this part of the ice sheet margin, and use a landsystem approach to show that the ice lobes dominantly displayed behaviour similar to active temperate glaciers. This involved warm-based ice actively re-advancing during overall retreat of the ice margin and questions previous hypotheses that the ice lobes displayed sub-polar characteristics with cold-based margins. The implication is that active temperate ice lobes would have been primarily controlled by regional climate variability. Superimposed on these active temperate landsystems are areas where swathes of elongated, closely spaced drumlins and suites of landforms including possible crevasse-squeeze ridges suggest periodically rapid ice flow, perhaps indicative of some readvances linked to surge-like activity. Additionally, our reconstruction highlights the importance of the palaeo-Laguna Blanca proglacial lake, which developed in front of the Skyring lobe, and drained, potentially catastrophically, before the gLGM. The development of other proglacial lakes in front of all the ice lobes following the gLGM would have promoted calving and rapid retreat, or collapse, of the ice margins.

For the Río Gallegos, Skyring and Otway lobes, existing age constraints are scarce and contradictory, but our recalculation of dates for older positions of the Magellan lobe suggests that at least one limit of greater extent than the gLGM limit was deposited around 30 ka. This suggests that the BI-SSb and Magellan lobes advanced in a similar manner and at similar times. Similarity in the timing of ice advances from the available chronological information implies that, broadly speaking, ice lobe response was primarily controlled by climate variability, supporting a model of active temperate glaciation. However, additional chronological controls are needed to test this model further, particularly for the Río Gallegos, Skyring and Otway lobes.

Supplementary Material

Table S1. Compilation of [10]Be and [26]Al cosmogenic nuclide exposure ages from the study area. Ages have been recalculated.

Table S2. Compilation of [36]Cl cosmogenic nuclide exposure ages from the study area. Ages have not been recalculated.

Table S3. Ages from two depth profiles through outwash associated with glacial limits in the study area. Ages are taken directly from Darvill *et al.* (2015b).

Table S4. Compilation of radiocarbon dates relating to glacier activity within the study area. Ages have been recalculated.

Abbreviations. BI-SSb, Bahía Inútil – San Sebastián; DEM, Digital Elevation Model; gLGM, global Last Glacial Maximum; MIS, Marine Isotope Stage.

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