A glacial geomorphological map of the Seno Skyring-Seno Otway-Strait of Magellan region, southernmost Patagonia

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Abstract:

This paper presents a detailed glacial geomorphological map covering over 16,000 km^2 of the Seno Skyring-Seno Otway-Strait of Magellan region in southernmost Patagonia. It builds on previously published maps produced at a variety of scales and is re-mapped in detail for the purposes of reconstructing the pre-Last Glacial Maximum (LGM) glacial dynamics of the region, with particular focus on deciphering the glacial landsystem north east of Seno Otway, which has been postulated as a zone of ice streaming. Additional areas of interest include the reconstruction of proglacial lakes dammed by the Skyring and Otway lobes; their drainage during various stages of retreat; and a landsystems approach to the overall reconstruction of the combined Skyring-Otway-Magellan ice lobes. Mapping was conducted using a combination of Landsat and ASTER satellite imagery and oblique and vertical aerial photographs, and is centred on approximately 53°S, 71°W. Seven main landform types have been mapped: glacial lineations, moraines, meltwater channels, irregular dissected ridges, eskers, outwash plains and former shorelines. The map records several episodes of ice flow, as revealed by glacial lineations, with the area around

Laguna Cabeza del Mar exhibiting spectacular elongate drumlins. Drumlin fields are associated with three major ice lobes whose extent is marked by a series of moraine ridges and lateral meltwater channels. Large parts of the area were also subjected to proglacial meltwater erosion and deposition, as recorded by large tracts of outwash and associated channels.

1. Introduction and Rationale

The landscape of Patagonia contains an important terrestrial record of glaciation in the Southern Hemisphere, making it an ideal location for assessing the extent to which inter-hemispheric climate fluctuations were synchronous (Singer *et al.*, 2004; Sugden *et al.*, 2005; Douglass *et al.*, 2006). Contemporary glaciation in Patagonia is largely restricted to two large ice caps, the North and South Patagonian Icefields (Glasser *et al.*, 2008; Figure 1a). However, during a succession of earlier and more extensive glaciations these ice caps coalesced with several smaller mountain icefields to form an extended ice sheet along the southern Andes, known as the Patagonian Ice Sheet (Caldenius, 1932; Glasser *et al*., 2008). The most laterally extensive of these glaciations is known as the Greatest Patagonian Glaciation (GPG) and this has been dated to around 1.1 Ma (Mercer, 1976, 1983; Ton-That *et al.*, 1999; Singer *et al*., 2004; Hein *et al.*, 2011). During the GPG valley and piedmont glaciers extended eastwards from the Andes up to several hundred kilometres (Rabassa, 2008). Deposits from this major advance and a series of more recent but increasingly less extensive advances record a glacial history stretching from the Quaternary through to the Holocene (Mercer, 1976; Clapperton, 1993; Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Coronato *et al.*, 2004; Glasser *et al.*, 2008; Rabassa, 2008; Hein *et al.*, 2009, 2011; Kaplan *et al.*, 2009). Outlet glaciers formed large lobes that advanced and retreated along major valleys and embayments, stretching from ca. 36°S to ca. 56°S, including Lago General Carrera/ Buenos Aires, Lago Cochrane/Pueyrredón, Lago O'Higgins/San Martín, Lago Viedma, Lago Argentino, Seno Skyring, Seno Otway and the Strait of Magellan (Mercer, 1976; Clapperton, 1993; Coronato *et al.*, 2004; Singer *et al.*, 2004; Glasser *et al.*, 2008;

Hein *et al.*, 2009). Evidence for these fluctuations is recorded by well-preserved landform assemblages comprised of nested terminal moraine sequences, extensive drift sheets, glacial lineations, meltwater channels and outwash plains (Caldenius, 1932; Mercer, 1976; Clapperton, 1993; Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Singer *et al*., 2004; Bentley *et al.*, 2005; Douglass *et al.*, 2006; Kaplan *et al.*, 2007; Hein *et al.*, 2009, 2011).

In southernmost Patagonia, glaciers periodically occupied the embayments of Seno Skyring, Seno Otway, Bahía Inútil and the Strait of Magellan throughout the Pleistocene (Coronato *et al.*, 2004). Since the GPG, when the Strait of Magellan lobe reached the Atlantic Ocean, successive glaciations have been less extensive (Clapperton, 1993; Kaplan *et al.*, 2009; Figure 1b). Previous work in this area has largely underpinned glacial chronology studies which have helped to constrain the timings of the GPG, Last Glacial Maximum (LGM) and late-glacial advances (e.g. Mercer, 1976; Meglioli, 1992; Clapperton *et al*., 1995; Singer *et al.*, 2004; McCulloch *et al.*, 2005; Kaplan *et al.*, 2007). The GPG is thought to have occurred between 1.168 and 1.016 Ma, based on K-Ar and $^{40}Ar/^{39}Ar$ dating of basaltic lava flows interbedded with glacigenic and glaciofluvial deposits (Mercer, 1976; Meglioli, 1992; Singer *et al.*, 2004; Kaplan *et al.*, 2007). Radiocarbon (^{14}C) dating of moraines, peat bogs and lacustrine deposits, and cosmogenic exposure dating of boulders on moraines has helped to constrain the Segunda Angostura advance (LGM; Advance B of Clapperton *et al.*, 1995; Figure 1b) in the Strait of Magellan to between 25.3 and 23.1 ka (Clapperton *et al.*, 1995; McCulloch *et al.*, 2005). Three subsequent late-glacial advances in the Strait of Magellan (C to E of Clapperton *et al.*, 1995) have also been identified and dated (Clapperton *et al.*, 1995; Bentley *et al.*, 2005;

McCulloch *et al.*, 2005). We aim to augment this chronological work with detailed geomorphological mapping from remotely sensed images in order to improve understanding of the glacial history and dynamics of the region.

The focus of this geomorphological map is the area situated to the west of the Strait of Magellan, between the Advance A and Advance B (LGM) limits of Clapperton *et al.* (1995; Figures 1a and 1b). This area is of particular interest because several authors have noted a spectacular field of highly elongate drumlins towards the axis of the Magellan Strait (cf. Clapperton, 1989; Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Glasser *et al.*, 2008). It has been speculated that these drumlins were "probably associated with a zone of ice streaming within the Magellan-Otway lobe" (Benn and Clapperton, 2000: p. 595). Ice streams are thought to have played an important role in the dynamics and stability of former ice sheets (Stokes and Clark, 1999; Bennett, 2003; De Angelis and Kleman, 2005). Therefore, in order to accurately reconstruct former ice sheets we need to know where and when palaeo-ice streams operated (Stokes and Clark, 2001; De Angelis and Kleman, 2005). The bedforms associated with palaeo-ice streams also provide a unique opportunity to investigate the subglacial processes that facilitate fast ice flow because contemporary ice stream beds are largely inaccessible (Stokes and Clark, 1999; Ó Cofaigh *et al.*, 2005). Several geomorphological criteria have been identified as key indicators of former ice stream activity (Stokes and Clark, 1999; Clark and Stokes, 2005; De Angelis and Kleman, 2005) and these characteristics include the presence of highly attenuated glacial lineations and abrupt lateral variations in the elongation ratio (length to width ratio) of lineations (Stokes and Clark, 1999, 2002; Ó Cofaigh *et al.*, 2005). Together with a number of other features (e.g. characteristic shape and dimensions of the flow pattern and abrupt lateral margins) these criteria have been used to construct a conceptual landsystem model (cf. Evans, 2005) for the beds of palaeo-ice streams (Stokes and Clark, 1999; Clark and Stokes, 2005). A key aim of the new mapping presented here is to test the hypothesis that the landform assemblage in the vicinity of the Strait of Magellan is a palaeo-ice stream landsystem. That analysis will be presented elsewhere but an important justification for the new mapping is that previous maps (e.g. Clapperton, 1989; Benn and Clapperton, 2000; Glasser and Jansson, 2008) have represented the aforementioned zone of elongate glacial lineations as generalised linear features, from which it is not possible to glean more detailed information regarding bedform morphometry (e.g. elongation ratios).

2. Previous mapping

Since the pioneering work of Caldenius (1932), a number of studies have presented mapping of the glacial geomorphology in and around the Strait of Magellan (e.g. Clapperton, 1989; Clapperton *et al.*, 1995; McCulloch and Bentley, 1998; Benn and Clapperton, 2000; Bentley *et al.*, 2005; Glasser and Jansson, 2008). These maps display a landform record comprised of glacial lineations, moraines, meltwater channels, outwash plains, eskers and former shorelines. This section will briefly describe some of the key aspects of this landform record as represented in previous mapping.

Glacial lineations feature heavily in previous maps of the study area. Clapperton (1989) focused on the distinct zone of drumlinised features on the western side of the Strait of Magellan, 10 to 15 km north east of Seno Otway (Figure 2). His mapping was based on a combination of vertical aerial photographs and fieldwork over a 20 km transect (see Fig. 6 in Clapperton, 1989). In this transect, drumlins were represented as single line features along their crests. Detailed sketches of individual drumlins are also included (see Fig. 4 in Clapperton, 1989). Benn and Clapperton (2000) also presented a detailed map of this zone of drumlins (again symbolised as lines). This mapping was conducted from Landsat TM imagery and aerial photographs supplemented by field observations (Benn and Clapperton, 2000).

Glacial lineations also feature in The Glacial Map of southern South America (Glasser and Jansson, 2008), a compilation of the glacial geomorphology of the former Patagonian Ice Sheet on both sides of the Andes between 38°S and 56°S. A map of such a large area creates issues of data reduction and, to an extent, necessitates that some features are generalised. This is particularly apparent in this same area of lineations around Laguna Cabeza del Mar (Figure 2 for location). In their mapping, Glasser and Jansson (2008) also depicted this zone of elongate drumlin features as line symbols.

Moraines have been mapped in the Strait of Magellan region by Caldenius (1932), Clapperton (1989), Clapperton *et al.* (1995), Benn and Clapperton (2000), Bentley *et al.* (2005) and Glasser and Jansson (2008). Caldenius (1932) mapped a large terminal moraine system to the north of Laguna Blanca and Laguna Cabeza del Mar (Figure 2), from which he distinguished three separate moraine belts. The accuracy of this pioneering work has been supported by subsequent maps based on a variety of remotely sensed images and field observations (Benn and Clapperton, 2000;

Glasser and Jansson, 2008). This moraine system is comprised of large arcuate moraine ridges, some of which are tens of kilometres long and over a kilometre wide (Benn and Clapperton, 2000; Glasser and Jansson, 2008). Individual moraine ridges have also been mapped elsewhere in the study area, including to the south west of Laguna Blanca, at the north eastern end of Seno Otway, and on Península Juan Mazia (Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Bentley *et al.*, 2005; Glasser and Jansson, 2008; Figure 2 for locations).

Meltwater channels have been recorded across the study area and are often found in close association with the moraine systems to the north of Laguna Blanca and the zone of glacial lineations around Laguna Cabeza del Mar (Clapperton, 1989; Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Glasser and Jansson, 2008; Figure 2 for locations). The channels immediately north of Laguna Cabeza del Mar, as mapped by Benn and Clapperton (2000) and Glasser and Jansson (2008), record a roughly west to east drainage system which grades into a large sandur or outwash plain. Meltwater channels have also been mapped in a number of other locations, including along both sides of the Strait of Magellan (Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Bentley *et al.*, 2005; Glasser and Jansson, 2008).

Outwash plains, *eskers* and *former shorelines* (also termed fossil shorelines) all feature in previous mapping of the Strait of Magellan region. Outwash plains or sandar have been mapped to the north of Laguna Cabeza del Mar (Benn and Clapperton, 2000; Glasser and Jansson, 2008) and on Península Juan Mazia (Benn and Clapperton, 2000; Bentley *et al.*, 2005; Glasser and Jansson, 2008; Figure 2 for locations). Glasser and Jansson (2008) also mapped a number of former shorelines, particularly at the north eastern end of Seno Otway and to the west of Laguna Blanca (Figure 2 for locations). Eskers only feature in the mapping of Clapperton (1989), who identified two at the northern end of Laguna Cabeza del Mar (Figure 2 for location).

3. Methods

3.1 Imagery

Our new map was produced from a combination of satellite imagery and both oblique and vertical aerial photographs. The majority of the regional-scale mapping was carried out using four Landsat scenes downloaded from the Global Land Cover Facility (GLFC) site (www.landcover.org). Three of these were Landsat Enhanced Thematic Mapper Plus (ETM+) images (path and rows 229/096, 228/096 and 228/097; all acquired in the 2000s) and one was a Landsat Thematic Mapper (TM) image (path and row 229/097; acquired in 1986). Five overlapping ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) scenes covering the study area were also downloaded from the NASA Land Processes Distributed Active Archive Center (LPDAAC) site (http://LPDAAC.usgs.gov/; all acquired in the 2000s). Landsat scenes cover an area of 185 x 185 km and have a spatial resolution of 30 m (15 m in the panchromatic band 8 for ETM+). ASTER scenes cover an area of 60 x 60 km and have a spatial resolution of 15 m. Various band combinations of the Landsat images were used to detect landforms, with Red-Green-Blue false colour composites of bands 4, 3, 2 and 7, 5, 2 (30 m spatial resolution) proving most useful. For the ASTER scenes, band combinations of 1, 2, 3N and 3N, 2, 1 (15 m spatial resolution) were used.

All satellite images were imported into ERDAS Imagine 9.3. The ASTER scenes were geo-rectified to the Landsat scenes using the image geometric correction tool within ERDAS and projected to Universal Transverse Mercator (UTM) Zone 19S (datum: WGS 84). In addition to the Landsat and ASTER imagery, high resolution QuickBird imagery from Google Earth© was used as a reference to guide mapping in a small section on the southern edge of Seno Skyring. QuickBird images have a spatial resolution of approximately 3 m (0.7 m for panchromatic scenes).

Hard copies of 39 vertical aerial photographs covering some of the southern section of the study area around Seno Otway were acquired from the Servicio Aerofotogrametrico de la Fuerza Aerea de Chile (SAF; Chilean Air Force Aerial Photogrammetric Service; taken in 1983-85). Approximate flight lines are shown on Figure 2 as white dashed lines. All photographs were black and white and had an approximate scale of 1:60,000. Along with oblique aerial photographs from a flight over the area, these were used to check the mapping of individual features within the study area and their relationship to each other (e.g. superimposition and cross-cutting relationships).

We used 3 arcsec (90 m spatial resolution) Shuttle Radar Topographic Mission (SRTM) data acquired from the GLFC site (www.landcover.org) to show the topography of the area. This provides a greyscale background to the map (Figure 2).

3.2 Geomorphological mapping

The map was created by on-screen digitisation of features on satellite images within ERDAS Imagine 9.3 (cf. Clark, 1997 for review of methodology; see also Stokes and Clark, 2002; De Angelis and Kleman, 2005; Jansson and Glasser, 2005; Smith *et al.*, 2006). The mapped landforms include glacial lineations, moraines, meltwater channels, irregular dissected ridges, eskers, outwash plains, former shorelines, lakes and scarp lines. These were mapped as polygon symbols (glacial lineations, irregular dissected ridges, outwash plains, lakes) and lines (glacial lineations, moraines, meltwater channels, eskers, former shorelines, scarp lines) depending on their scale relative to image resolution. The different features were digitised on separate vector layers after visual interpretation (e.g. Clark, 1997; De Angelis and Kleman, 2005) and stored as shapefiles (.shp). Landforms were identified and mapped at a variety of different scales to avoid any scale-bias in their detection. The mapping criteria and optimal satellite image band combinations used for detecting each type of feature will be described in section 4, along with possible identification errors. The previous mapping work in the area by Clapperton (1989), Benn and Clapperton (2000), Bentley *et al.* (2005) and Glasser and Jansson (2008) provided a very useful cross-reference and check of our mapping in areas common to both maps. This work was found to be largely in agreement with our mapping, apart from some small areas which we discuss in the next section.

4. Glacial geomorphology

4.1 Glacial lineations

Streamlined subglacial bedforms aligned in the direction of former ice flow are termed glacial lineations. These features can take a variety of forms, ranging from 'classic' egg-shaped drumlins typically on the order of 100s to 1000s of metres in length (Clark *et al.*, 2009) through to mega-scale glacial lineations (MSGLs), particularly long and elongate lineations up to 70 km long (Clark, 1993). The glacial lineations mapped in the Strait of Magellan area are predominantly drumlins between 0.1 and 3 km long, exhibiting a range of forms. These include elongate elliptical, spindle-shaped and barchan-type drumlins (Greenwood and Clark, 2008; Clark *et al.*, 2009; Figure 3) through to highly attenuated drumlins. The latter are particularly spectacular in the zone immediately surrounding Laguna Cabeza del Mar (Figure 2 for location) where approximately up to 50% exhibit elongation ratios ≥10:1.

Glacial lineations occur over large parts of the study area but the majority of the highly attenuated drumlins are located in this zone, and they diverge from this main trunk towards the moraine systems to the north. Streamlined lineations are also present on the northern and southern flanks of Seno Otway, on Isla Isabel, and on the eastern side of the Strait of Magellan (Figure 2 for locations). These landforms were best identified on ASTER images (bands 1, 2, 3N and 3N, 2, 1) as lighter features against the surrounding terrain, often bordered by shadowing on one side due to the change in height (Figure 3). Possible identification errors include the under-estimation of individual features in dense zones and the misinterpretation of bedrock structures as glacial lineations.

In contrast to previous mapping which depicted these features as lines (e.g. Benn and Clapperton, 2000; Glasser and Jansson, 2008), the majority of glacial lineations have been mapped as polygon outlines along their lower break-of-slope in order to show their plan form (Figure 3). On the few occasions where the entire form could not be identified, they have been mapped as lines. As noted above, it is important to map the plan form of these features because it more accurately reflects their morphometry and allows calculation of bedform elongation, which is an important proxy for ice velocity (cf. Stokes and Clark, 2002; King et al., 2009) . Furthermore, the plan form morphometry has traditionally been seen as an important parameter for constraining drumlin formation theories (Spagnolo *et al.*, 2010).

4.2 Moraines

Two distinct lateral-terminal moraine systems with a lobate form have been mapped to the north of Laguna Blanca and north east of Laguna Cabeza del Mar. These were identified on Landsat TM and ETM+ false colour composites (bands 7, 5, 2) as multiple prominent arcuate ridges with positive relief, commonly several kilometres long and 10s of metres wide. They occur as both individual features and as multiple ridges forming part of the larger moraine systems and stand out as features of a lighter colour than the surrounding terrain. These landforms have been mapped as linear features along individual moraine crests, as it is often difficult to detect the entire form of the ridges. Figure 4 shows the moraines that delineate the Otway/eastern lobe to the north east of Laguna Cabeza del Mar. Evidence associated with the Skyring/western lobe to the north of Laguna Blanca (Figure 2 for location) is more fragmentary, with discontinuous moraine crests situated between the more continuous meltwater channels that help delineate the lobate form. The innermost moraine ridges of both lobes are located on the edge of higher ground, and can be clearly seen on the greyscale SRTM that forms the background to the map (Figure 2). Moraines have been mapped within the main zone of streamlined features near Laguna Cabeza del Mar by others (e.g. Clapperton, 1989; Benn and Clapperton, 2000; Glasser and Jansson, 2008) but these were not obvious from the satellite imagery used in this study. In a few cases, the origin of some features is equivocal. For example, Glasser and Jansson (2008) map terminal moraines running sub-parallel to Fitz Roy Channel but we prefer to represent them as non-genetic scarp lines (Figure 5). Moraines have also been mapped at the northern end of Laguna Cabeza del Mar (Glasser and Jansson, 2008) which we could not detect and/or have mapped as meltwater channels. It is possible that identification errors could arise through confusion between moraines and other similar linear features, particularly former shorelines and meltwater channels. Detailed field investigation is required to fully resolve such ambiguities.

4.3 Meltwater channels

A complex system of former meltwater channels and modern drainage routes exists across the mapped area. We have attempted to map only the palaeo-glacial meltwater channels and these include the largest channels and their smaller tributaries (Figure 6). Distinguishing meltwater channels from contemporary drainage routes can be problematic, particularly as many channels cut by meltwater may be occupied by present-day runoff and many contemporary channels may be ephemeral. To reduce the risk of mapping channels that are solely due to post-glacial incision, meltwater channels have been mapped on the basis of a number of criteria (cf. Greenwood et al., 2007; Glasser and Jansson, 2008). These include large (some over 500 m wide and 50 km long) channels that start and end abruptly and have sharply defined edges and/or contain no contemporary drainage (Greenwood *et al.*, 2007; Glasser and Jansson, 2008). A series of channels aligned parallel to each other (Greenwood *et al.*, 2007) and channels that flow obliquely across local slopes are also considered to be of meltwater origin. Landsat TM and ETM+ images (bands 4, 3, 2) were found to be best for detecting such channels because they often stand out as sinuous, meandering features of a lighter colour than surrounding terrain and with shadowing at their edges. Despite attempting to only map channels that fit these criteria, it is possible that some contemporary drainage routes may also have been mapped.

All meltwater channels have been mapped as linear features plotted along their centre line, with three different line thicknesses representing a hierarchy of channel sizes (approximate widths: small <50 m; medium = 50 to 150 m; large >150 m; black arrows heads indicate the inferred direction of drainage). In the centre of the study area, to the north of Laguna Cabeza del Mar, a clear west to east trend in the direction of meltwater flow can be seen extending from the south east margin of Laguna Blanca across to the Strait of Magellan (Figure 6). Meltwater channels often occur between moraines and these help to distinguish the distinct limits of the two lobes, particularly the Skyring/western lobe.

4.4 Irregular dissected ridges

A small group of features located to the north west of Laguna Blanca (Figure 2 for location) appear to have been cross-cut by a number of small meltwater channels and these have been mapped as irregular dissected ridges. These were best identified on ASTER images (bands 1, 2, 3N) as dense groups of small (100s of metres long, 10s of metres wide) ripple-like ridges that stand out as darker features against the surrounding terrain (Figure 7). They have been mapped as polygon outlines along their lower break-of-slope because the entire form of individual ridges can be clearly identified. The orientation of the ridges to the north west of Laguna Blanca is fairly uniform, whilst similar areas of ridges located at the ends of both Seno Skyring and Seno Otway are more irregular. In previous work they were mapped as moraine ridges (Benn and Clapperton, 2000; Glasser and Jansson, 2008), but they have a markedly different morphology to the individual moraine ridges that delineate the lobate forms. To make this distinction clear, we do not genetically classify these landforms but we note similar features that have been mapped in the Canadian Arctic (Storrar and Stokes, 2007) and Ireland (Greenwood and Clark, 2008).

4.5 Eskers

A ridge to the north east of Laguna Cabeza del Mar has been mapped as an esker on the basis of its sinuous plan form and orientation, and relationship to glacial lineations (sub-parallel) and moraines (transverse). It was identified and mapped on an ASTER image (bands 1, 2, 3N) on the basis of its lighter colour against the surrounding terrain and the shadowing caused by the change in relief. The esker is approximately 5 km long and up to 50 m wide and has been captured as a linear feature along its crestline (Figure 8). This esker was also mapped by Clapperton (1989), but did not feature in the mapping of Benn and Clapperton (2000) or Glasser and Jansson (2008). This is unsurprising considering the small scale of the feature. It is possible, although unlikely considering their different morphologies, that eskers could be confused with meltwater channels.

4.6 Outwash plains

Three large outwash plains are located within the mapped area. These are to the north of Laguna Blanca, north east of Laguna Cabeza del Mar (Figure 9) and on Península Juan Mazia (Figure 2 for locations). They were identified on Landsat TM and ETM+ false colour composites (bands 7, 5, 2) as extensive (up to approximately 240 km^2) smooth surfaces and have been mapped as complete polygons, where possible. Meltwater channels that can be detected on the outwash plain surfaces have also been mapped.

4.7 Former shorelines

Distinct continuous or near-continuous linear features that closely parallel the current active shorelines of embayments and lakes have been mapped as former shorelines. These were best detected on Landsat TM and ETM+ false colour composites (bands 4, 3, 2) as darker linear features against the surrounding terrain and, where possible, have been mapped as continuous lines. The clearest examples are located around the north eastern end of Seno Otway (Figure 10) and to the east of Laguna Blanca, where they are often characterised by a series of shorelines closely nested within each other. Other examples of shorelines can be found on the south eastern side of Seno Otway. Some are located as much as 6 km from the active shorelines and up to 40 m above present lake or sea-level. It is possible, although very unlikely, that moraines, meltwater channels and roads/tracks close to marine or lake margins could have been misidentified as shorelines.

4.8 Other features

Lakes (size >500 m^2) have been mapped as polygons. Distinct linear features located at either end of the Fitz Roy channel have been mapped here as scarp lines, rather than terminal moraines (Figure 5). Some large-scale non-glacial geomorphological features, such as the very prominent scarp east of the Otway lobe, have not been mapped but are shown clearly by the SRTM data (Figure 2).

5. Conclusions

This glacial geomorphological map builds on previous mapping (e.g. Clapperton, 1989; Clapperton *et al.*, 1995; Benn and Clapperton, 2000; Bentley *et al.*, 2005; Glasser and Jansson, 2008) of the Strait of Magellan area. A variety of landforms have been mapped including glacial lineations, moraines, meltwater channels, irregular dissected ridges, eskers, outwash plains and former shorelines. We have mapped the complex meltwater channel system in detail, as well as the morphology of individual features in the main zones of highly attenuated glacial lineations. The purpose of this map is to enable a detailed palaeoglaciological reconstruction of ice dynamics in the region, with a particular focus on testing the hypothesis for ice streaming in this location (cf. Benn and Clapperton, 2000) by comparing the geomorphological record with the conceptual landsystem model for the bed of a former ice stream (cf. Clark and Stokes, 2005). An additional area of interest is the evolution of proglacial lakes in the study area, as indicated by the locations of former shorelines and meltwater channels. The map presented in this paper provides the foundation and the key ingredients for assessing the glacial history and dynamics of this sector of the former Patagonian Ice Sheet.

Software

All image processing and mapping was carried out using ERDAS Imagine 9.3. The final geomorphological map was produced using ESRI ArcMap version 9.3 and Adobe Illustrator CS4.

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Map Design

Lineations captured as polygons have been left unfilled, which aids visualisation of individual features. The irregular dissected ridges, captured as polygons, have been filled because they are often separated by meltwater channels, and so are easier to identify as individual ridges. The different meltwater channel line thicknesses have been used to represent a hierarchy of channel widths (small <50 m; medium = 50 to 150 m; large >150 m), rather than symbolising different sized channels identically. The darker shade of blue used for the lakes is to ensure they are visible against the lighter background. Laguna Cabeza del Mar is open to the sea through a narrow channel and so has been represented in the same shade of blue as the sea. The greyscale SRTM image that forms the background to the map has been reversed so that lower relief is lighter. This is to ensure that the mapped detail, which mostly occurs at lower elevations, stands out better. The inclusion of the legend within the map itself rather than at the side is to save space in the marginalia, the area covered beneath it is not part of the study area.

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Figure 1 – (a) Location of the mapped area in the Strait of Magellan region, southernmost Patagonia. Present-day icefields shown in white: (1) North Patagonian Icefield, (2) South Patagonian Icefield, (3) Cordillera Darwin. Orange dashed-line is national border. (b) Location and chronology of major drift limits in southernmost Patagonia (Meglioli, 1992; Rabassa *et al.*, 2000; Bentley *et al.*, 2005). Red rectangle shows mapped area. Segunda Angostura age from McCulloch *et al.* (2005). Figure adapted from Kaplan *et al*. (2007).

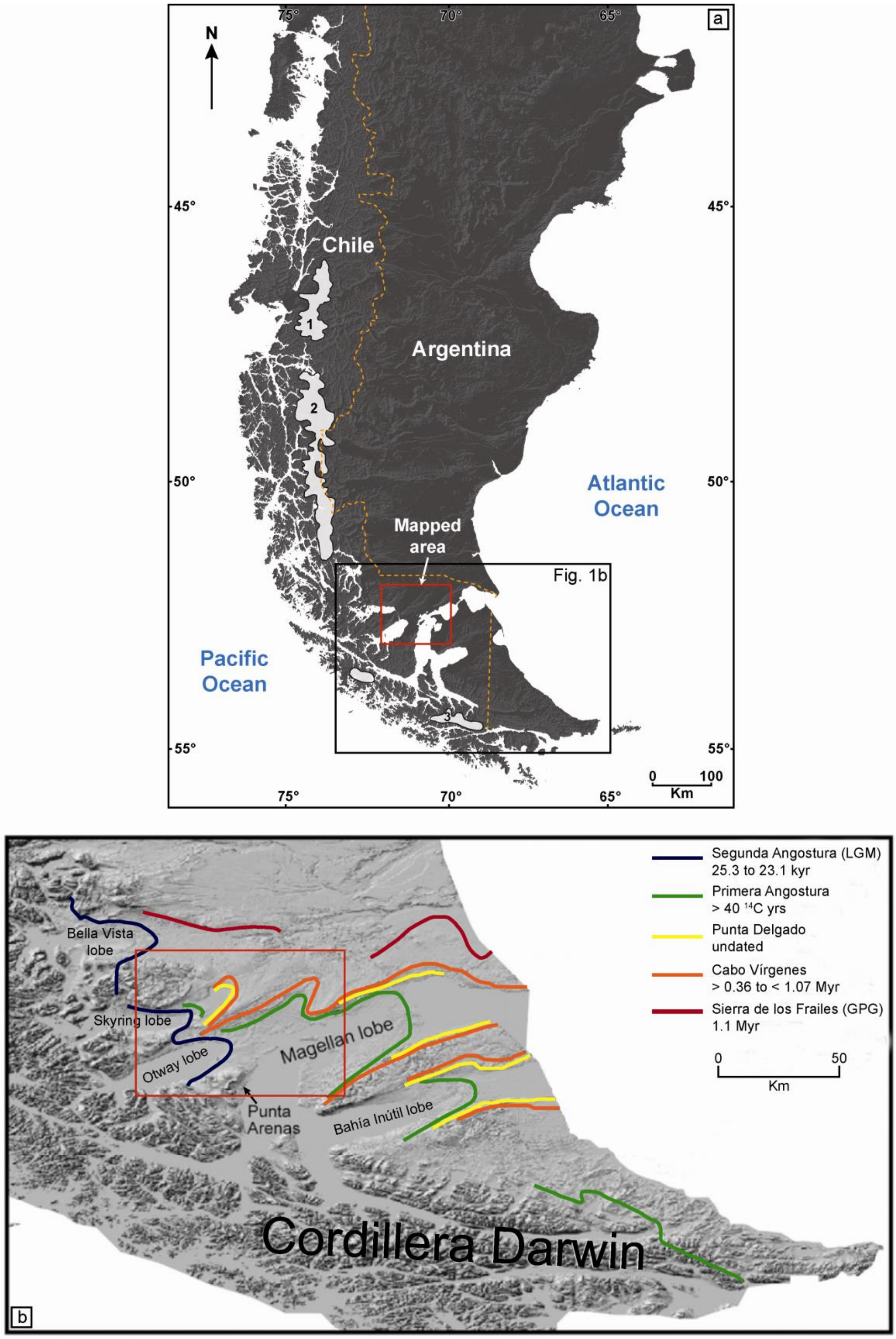

Figure 2 – Map showing extent of the study area. Topography is shown by greyscale SRTM data. Locations of figures shown by boxes. White dashed lines show approximate flight paths covered by the vertical aerial photographs.

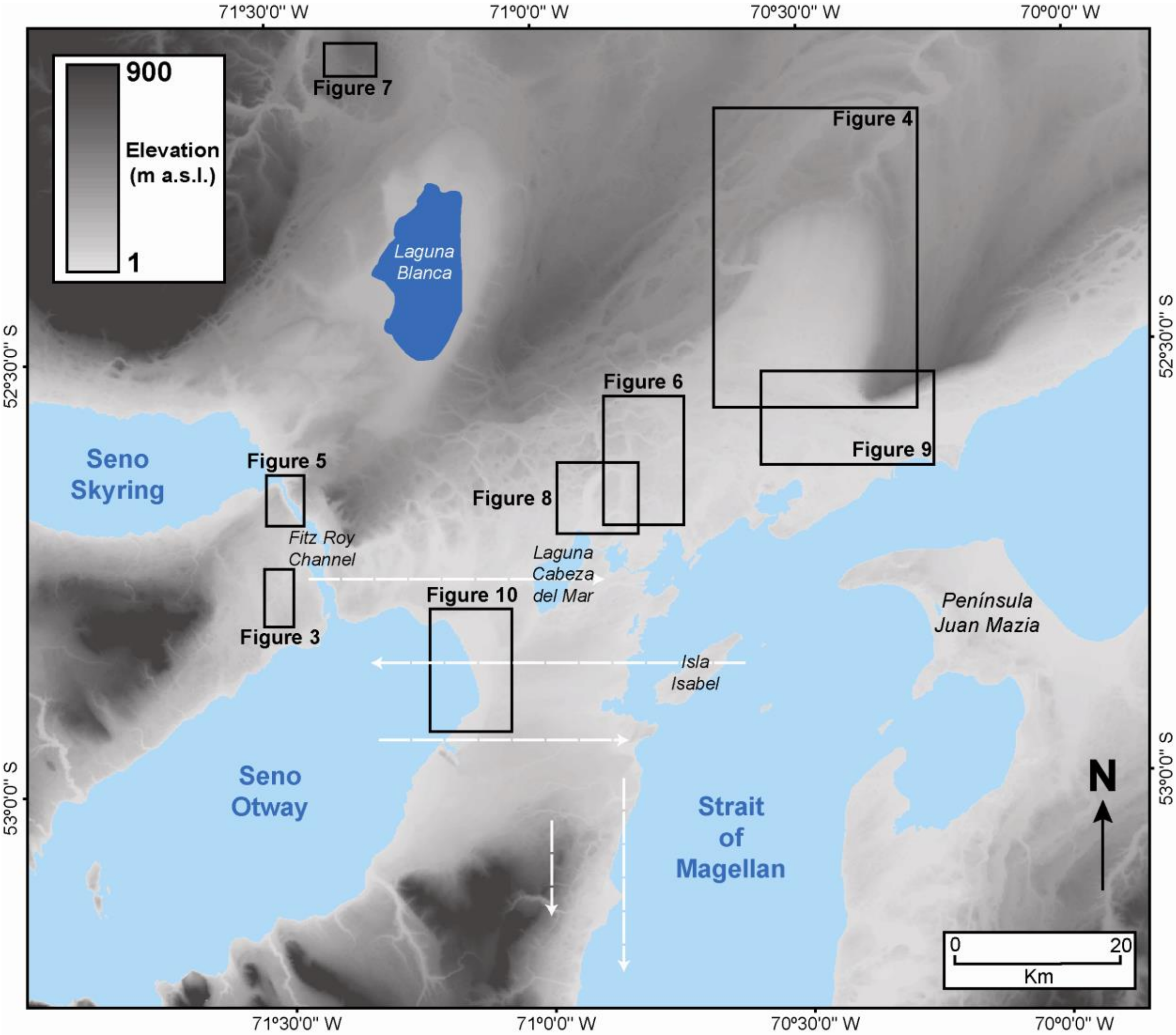

Figure 3 – Glacial lineations between Seno Skyring and Seno Otway. (a) ASTER subscene (bands 1, 2, 3N). Note the range of morphologies, including elliptical, spindle-shaped, barchan-type and highly attenuated features. (b) Lineations (in red; mapped as both polygons and lines) in association with meltwater channels and lakes (in blue). Location shown on Figure 2.

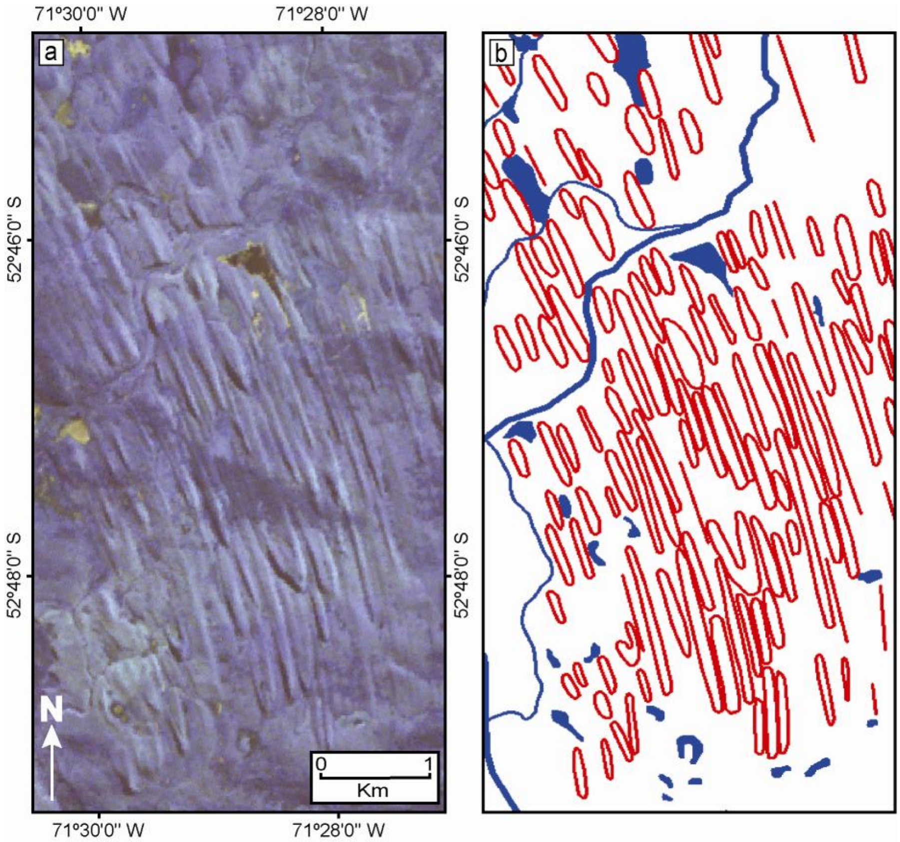

Figure 4 – Lobe north east of Laguna Cabeza del Mar (Otway/eastern lobe). (a) Mosaiced Landsat TM and ETM+ subscenes of false colour composites (bands 7, 5, 2 for both). (b) Mapped moraines (in green) and meltwater channels (in blue). The regularly spaced north-south orientated lines obvious in (a) are thought to be non-glacial features, most likely dirt tracks. Location shown on Figure 2.

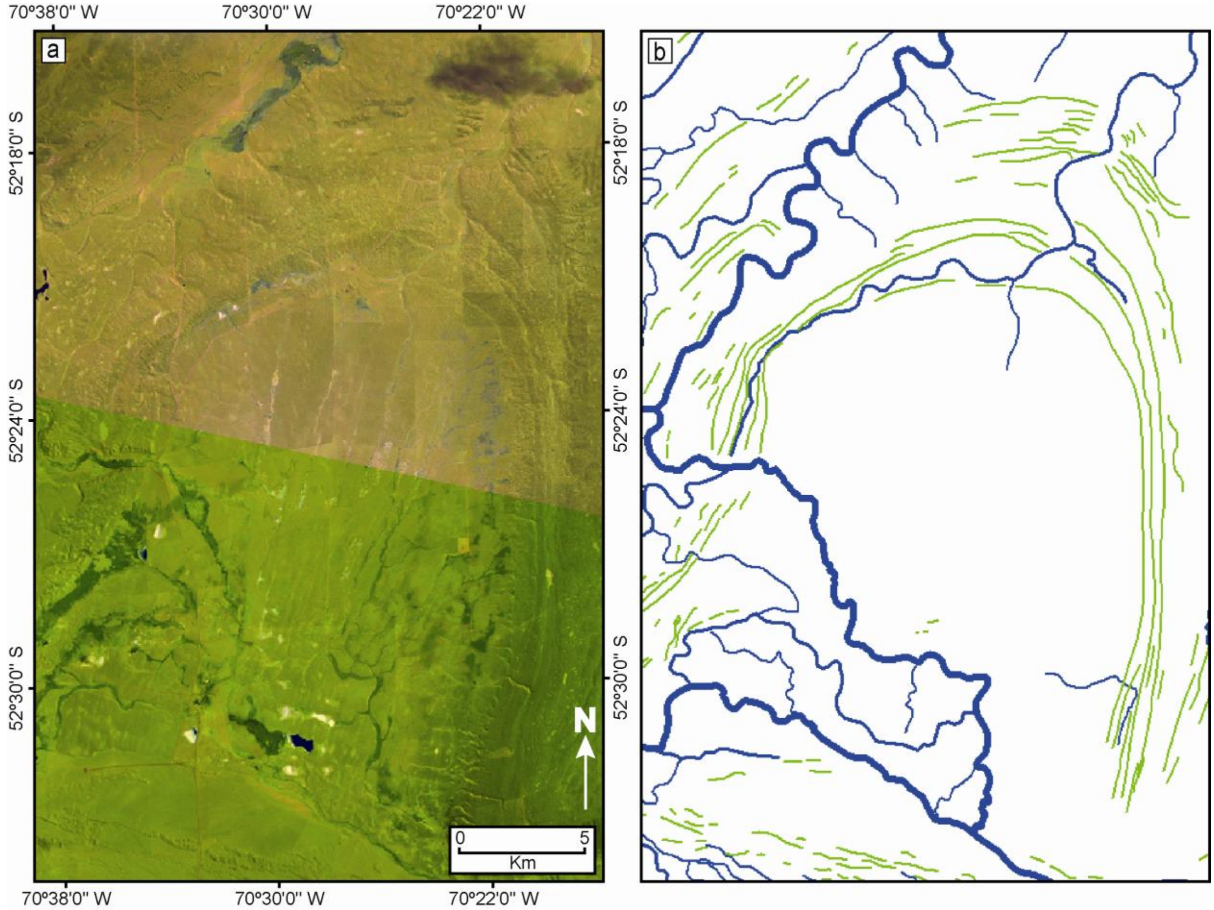

Figure 5 – ASTER subscene (bands 1, 2, 3N) showing two of the distinct linear features located at the northern end of Fitz Roy Channel mapped as scarp lines. Location shown on Figure 2.

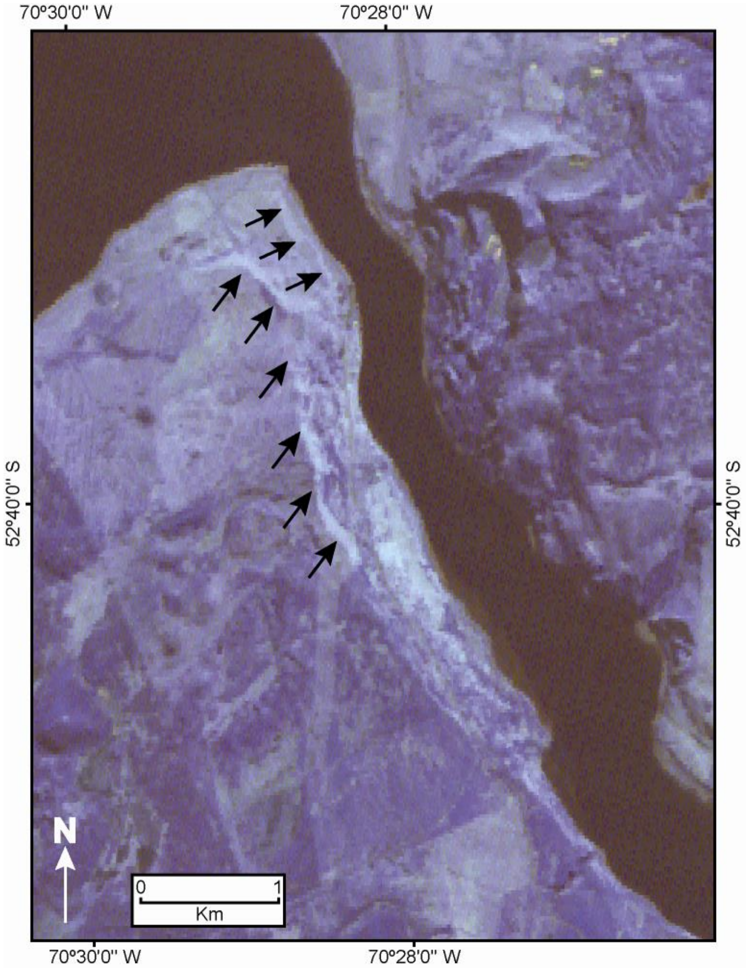

Figure 6 – Meltwater channels north of Laguna Cabeza del Mar. (a) Landsat TM subscene of a false colour composite (bands 4, 3, 2). (b) Mapped meltwater channels, glacial lineations (in red) and lakes. Location shown on Figure 2.

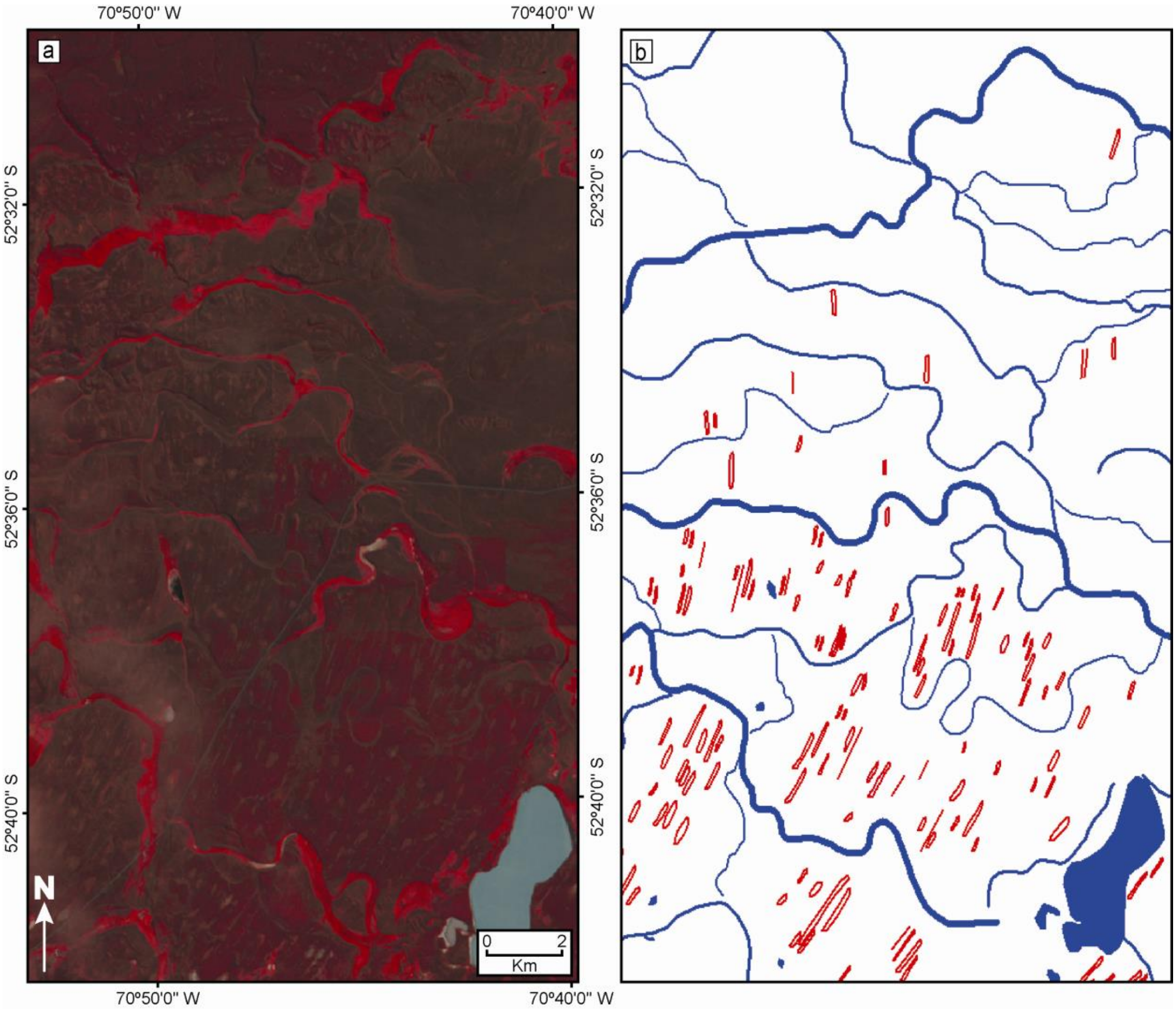

Figure 7 – Area mapped as irregular dissected ridges to the north west of Laguna Blanca. (a) ASTER subscene (bands 1, 2, 3N). (b) Mapped ridges and meltwater channels. Location shown on Figure 2.

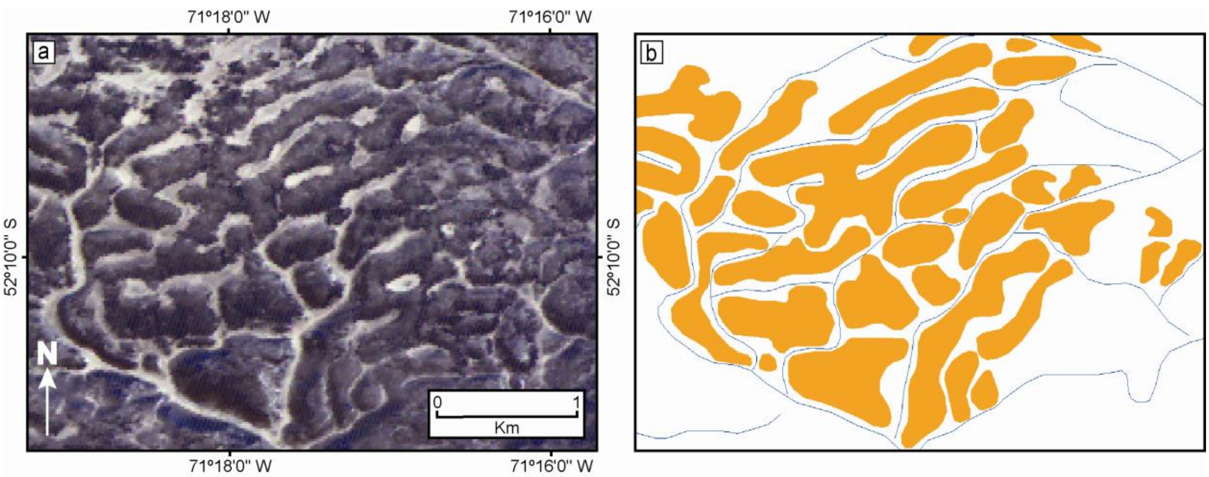

Figure 8 – (a) ASTER subscene (bands 1, 2, 3N) showing esker to the north east of Laguna Cabeza del Mar (see inset for detail). (b) Mapped esker (in yellow), glacial lineations (in red), meltwater channels and lakes (in blue).

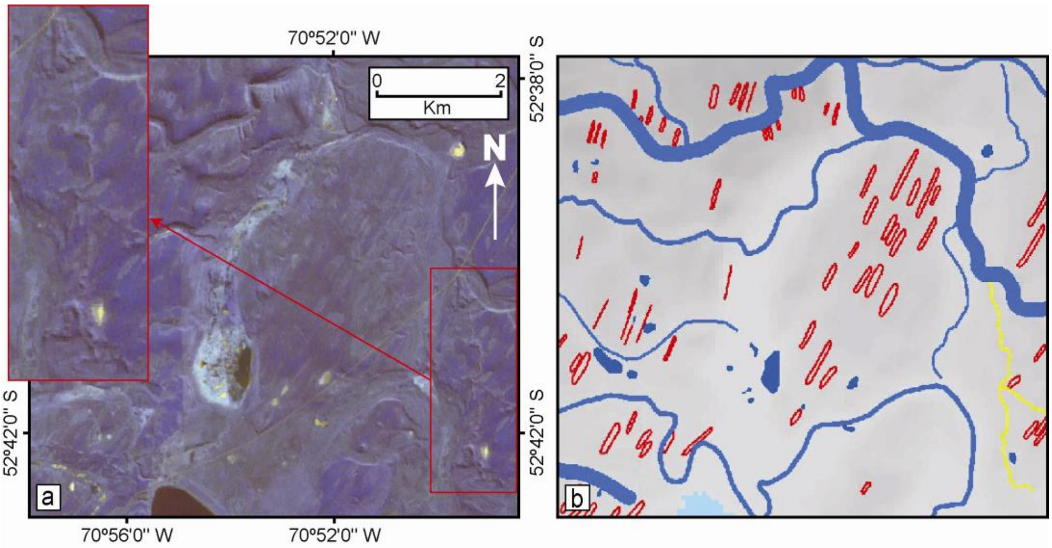

Figure 9 – Outwash plain north east of Laguna Cabeza del Mar. (a) Landsat TM subscene of a false colour composite (bands 7, 5, 2). (b) Mapped outwash plain (light brown colour). Location shown on Figure 2.

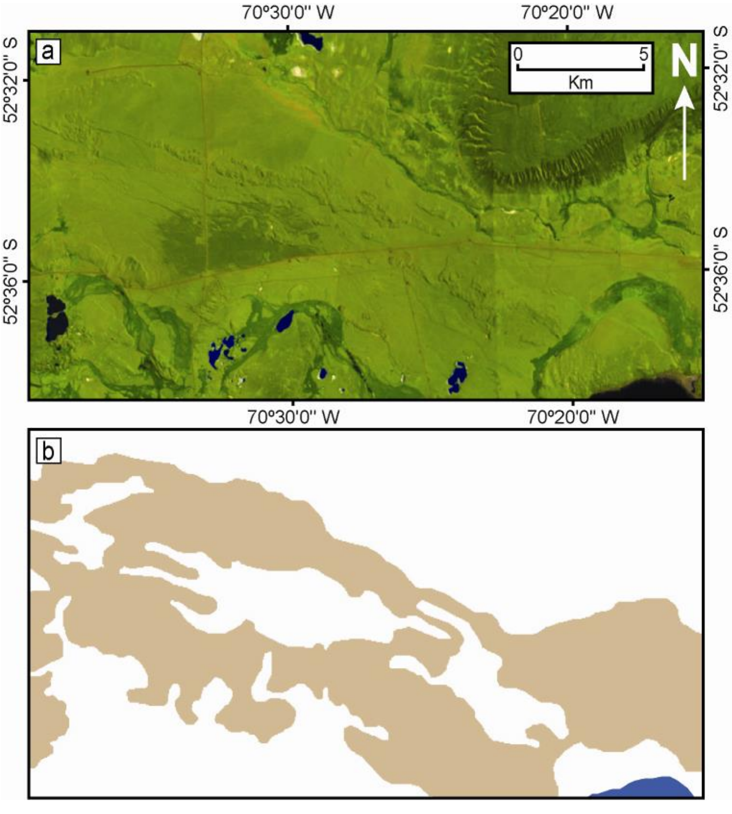

Figure 10 – Former shorelines at the north eastern end of Seno Otway. (a) Landsat TM subscene of a false colour composite (bands 4, 3, 2). (b) Mapped shorelines. Location shown on Figure 2.