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Late quaternary glaciation history of Isla de los Estados, southeasternmost South America

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ABSTRACT

Isla de los Estados is a mountainous island southeast of Tierra del Fuego, in southernmost South America. Its central and eastern parts have an alpine topography, transected by U-shaped valleys, small, partly over-deepened fjords, and a multitude of abandoned cirques, all associated with extensive former local glaciations. Traces of glacial erosion generally reach 400–450 m a.s.l., and above that trimline a distinct sharp-edged nunatak derived landscape is present. The westernmost part of the island has a lower, more subdued topography, reflecting its "softer" geology but possibly also over-running and erosion by mainland-derived ice streams. The present study concentrated on glacigenic sediment sequences exposed along coastal erosional cliffs. A combination of OSL and ^{14}C datings show that these sediments mostly date from the latest (Wisconsinan/Weichselian) glacial cycle, i.e. from the last ca. 100 ka with the oldest (glaciolacustrine) deposits possibly as old as 90–80 ka. The upper parts of overlying tills, with associated lateral and terminal moraines from glaciers that expanded onto an eustatically exposed dry shelf north of the island, date from the last global glacial maximum (LGM). Radiocarbon ages of peat and lake sediments indicate that deglaciation began 17–16 cal ka BP.

Introduction

Isla de los Estados (Staaten Eylandt/Staten Island; position roughly 54°45′S, 64°30′W) is the southeasternmost part of South America and a mountainous extension of the Andes into the South Atlantic Ocean (Fig. 1). It is separated from the mainland (Isla Grande de Tierra del Fuego) by a 30-km-wide sound, the Estrecho de Le Maire. The size of the island is approximately 65 × 35 km and its highest peaks reach ~800 meters above sea level (m a.s.l.).

The island consists of three geologic categories of rocks and unconsolidated sediments (Dalziel et al., 1974; Caminos and Nullo, 1979). The volcanic main part (>75%) of the island is formed by the Jurassic Lemaire Formation, with tuffs, lavas and ignimbrites. Post-volcanic sediments, including shales, mudstones, greywackes and limestones of the Jurassic/Cretaceous Beavoir Formation, are mainly found on the westernmost part of the island and along its northern rim and the outlying Islas Año Nuevo (the New Year Islands). All the above-mentioned rocks have been deformed and/or dislocated in late Cretaceous to early Tertiary times in connection with orogenic developments along the northern flank of the Scotia Arch (Dalziel and Eliott, 1973). Quaternary glacial sediments lie on top of the Mesozoic volcanic and sedimentary rocks (Caminos and Nullo, 1979), superposed by a succession of lake sediments, peat and aeolian deposits (Johns, 1981; Unkel et al., 2008).

The westerlies peak between 45° and 55°S. Positioned in the southern center of this west-wind belt, Isla de los Estados was a notorious shipwreck locality during the era of Cape Horn sailings. Winds are strongest in austral summer, while precipitation reaches a maximum in March–May (Garreaud et al., 2009). The island also faces the Drake Passage between southernmost South America and the Antarctic Peninsula. Its position in a region where the westerly storm tracks change their latitudinal position and strength, both seasonally and over longer time scales, and cold Antarctic air masses may have a highly variable influence on temperature conditions, makes Isla de los Estados very sensitive for changes in effective moisture and temperature and therefore suitable for palaeoclimatic studies (Pendall et al., 2001). Such changes, including meridional changes of Antarctic sea ice extent, must have played a major role for the waxing and waning of ice caps in the Tierra del Fuego region during the last glacial period.

Presented results are from a joint Argentine–Swedish expedition to Isla de los Estados carried out in November–December 2005 (Björck et al., 2007). The glacial morphology and sediments of the island have hitherto only been briefly described by Caminos and Nullo (1979) in descriptive text associated with a geological map of the island.

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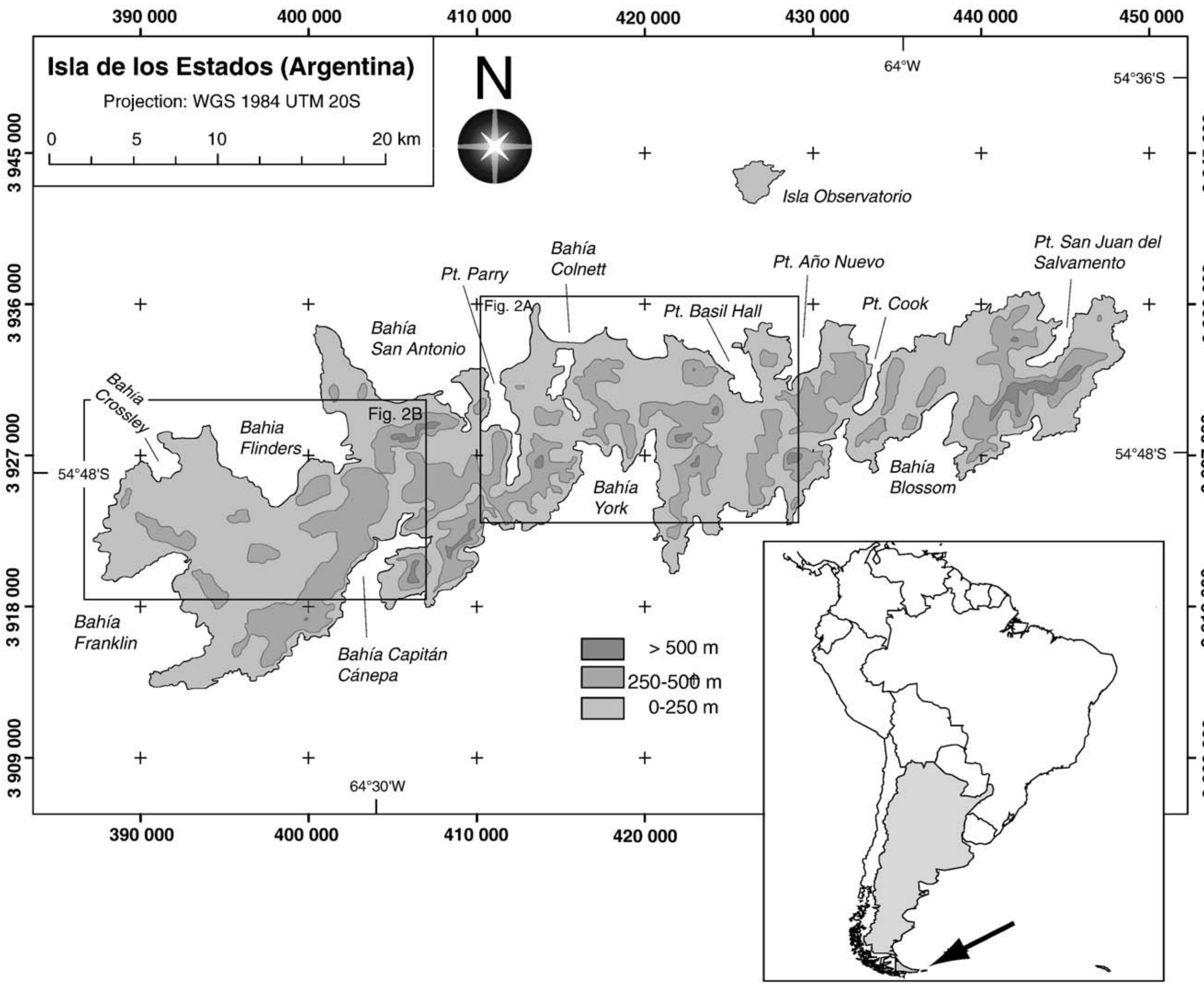

Figure 1. Overview map of Isla de los Estados. Inserts indicate position in South America and the location of Figures 2A and B.

This, however, contained no chronological or detailed stratigraphical information.

Earlier studies

Earlier studies on Tierra del Fuego and in Patagonia have shown that former glaciers originating in the southernmost Andes reached eastward beyond the present Atlantic coastline (e.g., Nordenskjöld, 1898; Caldenius, 1932; Auer, 1956; Malagnino and Olivero, 1999; Rabassa et al., 2000; Sugden et al., 2005). On the first glaciation map ever published for southern South America, Otto Nordenskjöld (1898) envisaged an ice cap that covered the Andes and much of the aerially exposed dry shelf areas southeast of Tierra del Fuego, including Isla de los Estados. Glaciers probably reached that far east about 1 million years ago. During the last glacial maximum (LGM), which in southern South America seems to have culminated roughly between 28 and 16 ka ago (i.e., during MIS 2) (e.g., Denton et al., 1999; Bennett et al., 2000; Rabassa et al., 2000; Hulton et al., 2002; Sugden et al., 2005; Kaplan et al., 2008; Clark et al., 2009), the mainland ice fronts probably reached neither the present coastline of the Atlantic Ocean nor Isla de los Estados (Caminos and Nullo, 1979; Rabassa et al., 2000; Heusser, 2003; Sugden et al., 2005; Rabassa, 2008).

Besides the work of Caminos and Nullo (1979) on the Quaternary, there exist some recently published studies of periglacial features on the island (Ljung and Ponce, 2006), dune geomorphology at Caleta Lacroix (Ponce, 2008) and the geomorphology of the fjords (Ponce et al., 2009).

Methods

Air-photo interpretation, combined with field reconnaissances, sedimentological assessments, glaciotectonic analyses and geochronological investigations were mainly conducted in November and December 2005. Aerial photographs were used to identify glacial cirques, trough valleys, trim lines and ice-marginal moraines, and sites for stratigraphic observations. Stratigraphic and geochronologic investigations were focussed on laterally extensive sections. High vertical sections were dug out in a stair-case manner and logged, mostly at 1:10 scale using standardized lithofacies codes (Table 1). Fabric analyses in diamict beds were based on 25 clasts with the longest axis 3–10 cm and a/b-axis ratios >1.5. All structural data were statistically evaluated, the fabric data according to the eigenvalues method (Mark, 1973) and graphically manipulated in StereoNet for Windows©.

Age control was based on single-stage accelerator mass spectrometer (SSAMS) radiocarbon dating of organic remains and optically stimulated luminescence (OSL) dating of clastic sediments. A total of 7 AMS ^{14}C ages were determined at the Lund University Radiocarbon Dating Laboratory (Table 2). Dated organics were associated with terrestrial or lacustrine depositional settings (peat, twigs, and clay gyttja) and thus no marine reservoir correction

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Table 1
Lithofacies codes (1st, 2nd and 3rd order code system) as used in this work, notably in Figures 6 and 8. Basic system according to Eyles et al. (1983).

Lithofacies code:	Lithofacies type description: grain size, grain support system, internal structures
D(G/S/Si/C)	Diamict, gravelly, sandy, silty or clayey. One or more grain-size code letters within brackets
D( )mm	Diamict, matrix-supported, massive
D( )ms	Diamict, matrix-supported, stratified
D( )mm/ms(s)	Diamict, …., sheared
D( )ms(a)	Diamict, …., attenuated
BP	Boulder pavement in diamict
Co–	Cobbles, as below
D( )mm(ng)	Diamict, matrix-supported, massive, normally graded
D( )mm(ig)	Diamict, matrix-supported, massive, inversely graded
D( )mm (ing)	Diamict, matrix-supported, massive, inverse to normally graded
Gmm	Gravel, matrix-supported, massive
Gcm	Gravel, clast-supported, massive
Gcm(ng); –(cng), –(mng)	Gravel, clast-supported, massive, normally graded; clast normal grading, matrix normal grading
Gcm(ig)	Gravel, clast-supported, massive, inversely graded
Bo/Glg	Boulder/Gravel lag
Sm	Sand, massive
Sm(b)	Sand, massive (burrows, bioturbated)
Sm(ng)	Sand, massive, normally graded
Sm(ig)	Sand, massive, inversely graded
Spp	Sand, planar parallel-laminated
Spc	Sand, planar cross-laminated
Stc	Sand, trough cross-laminated
Sr	Sand, ripple-laminated
Sl(def)	Sand, laminated, deformed
S–sf	Sand –, shallow scour fill
Sim	Silt, massive
Sil	Silt, laminated
Cl	Clay, laminated
Cm	Clay, massive
Cm(dr)	Clay, massive (dropstones)

was necessary. All ^{14}C yr BP were calibrated into calendar years (cal yr BP) with OxCal v3.10 (Bronk Ramsey, 1995, 2001) and southern hemisphere atmospheric data from McCormac et al. (2004) up to ages of 10,000 ^{14}C yr BP, and for older ages with atmospheric data from Reimer et al. (2004). Six OSL ages (Table 3) were determined at the Nordic Laboratory for Luminescence Dating at Aarhus University, Denmark. The single-aliquot regenerative dose protocol applied to quartz grains was used to estimate the equivalent dose (Murray and Wintle, 2000), with blue (470 ± 30 nm) light stimulation, 260°C preheat for 10 s, and a cut heat of 220°C. Photon detection was through a U-340 glass filter. The samples were analyzed for natural series radionuclide concentrations in the laboratory, using high-resolution gamma spectrometry (Murray et al., 1987). These concentrations were converted into dose rates using conventional factors listed by Olley et al. (1996).

The glacial geomorphology of Isla de los Estados — an overview

Satellite images and aerial photos of Isla de los Estados show that this island has been extensively glaciated (e.g., Fig. 2). Much of the island has distinct mountainous, often alpine topography, transected by U-shaped through valleys many of which form small fjords (Figs. 3A–B; Ponce et al., 2009). North-facing fjords in particular, notably Pt. Parry and Pt. Basil Hall, show clear over-deepening relative to the shallow shelf areas to the north. The large-scale geomorphology of Isla de los Estados indicates former extensive glaciation and glacial erosion reaching 400–450 m a.s.l. (Fig. 3E), above which the landscape is characterized by a distinct sharp-edged, tor-rich nunatak topography (Fig. 3C). This topographic boundary suggests that former ice cover(s) on the island did not reach higher than ~450 m a.s.l. The alternative, that ice covers above that altitude were cold-based and non-erosive, we do not hold to be very probable (e.g., for topographic reasons, very narrow interfjord ridges, etc.).

The lower elevation sectors of the island are often characterized by moraine ridges, tills and other glacial or related sediments (Caminos and Nullo, 1979). In many places the stratigraphy of these deposits is exposed in coastal erosive cliffs. Our work on Isla de los Estados was concentrated on Bahía Colnett on the north-central part of the island in an area of high-relief topography related to glaciated valley systems, and at Bahía Crossly in the western part of the island where more gentle topography prevails.

Glacial geomorphology and stratigraphy, Bahía Colnett

The Bahía Colnett ice-marginal moraines

We find traces of at least four moraines in Bahía Colnett that can be connected to glacier expansion and retreat within the valley basin inside Bahía Colnett (moraines A–D, Fig. 4). Moraine C (Fig. 3G) forms a highly arched ridge, 5–15 m high, damming Lago Lovisato to an altitude of ~2 m above present sea level (m a.s.l. is here defined as altitude above mean tide level). The Lago Lovisato basin behind ridge C is shallow, ~2 m, whereas the basin behind ridge D is ~20 m deep. The small Lago Galvarne to the northwest is, however, not dammed by a moraine ridge, but by a pronounced beach ridge complex. This complex is currently being eroded by the sea, as indicated by a small erosional cliff (~1.5 m high) cut into beach gravel, covered by peat. Moraines A and B (Fig. 4) are eroded by the sea at the recent shoreline at more or less right angles to their crest lines, and their tentative former continuation into Bahía Colnett is evident. The ridge marked X in Figure 4 is located along the eastern shore of Bahía San Antonio, separated from moraines A–C by a bedrock ridge extending northwards into the Cabo Colnett peninsula (Fig. 4). This ridge is thus interpreted as a lateral moraine from an outlet glacier once flowing out from Puerto Parry into Bahía San Antonio, therefore not

Table 2
SSAMS-measured ^{14}C ages from investigated sites. For locations, see Figures 4 and 8D. Sample from Caleta Lacroix (marked *, Lab no. AA62509) is from Ponce (2008). Altitude in m a.s.l. is measured in relation to high tide level.

Sites	Sample no.	Dated material	Sed. unit	Sample m a.s.l.	Lab no.	^{14}C yr Bp 1 σ error	Cal yr BP (1 σ)
San Juan del Salvamento 2	SJS 2:1	Peat	–	9.0	LuS 7056	5780 ± 50	6660–6400
Bahia Colnett 2	BCo 2:1a	Peat	4	7.3	LuS 7057	7505 ± 50	8380–8170
Bahia Colnett 2	BCo 2:1c	Small twigs	3	7.0	LuS 8162	8515 ± 60	9550–9300
Lago Galvarne Bog	LGB/749	Peat	–	−6.44	LuS 6510	13,515 ± 60	16,260–15,860
Laguna Cascada	CAS/495	Gyttja clay	–	4.01	LuS 6507	13,285 ± 80	15,949–15,545
Bahia Crossley 1	BCr 1:1	Peat	5	8.0	LuS 7055	8520 ± 55	9550–9390
Teniente Palet Bog	TPB-8.2	Peat	–	−0.2	LuS 6514	8225 ± 50	9290–9000
Caleta Lacroix*	IDE2-65	Clay gyttja	–	23.5	AA62509	10,670 ± 39	12,820–12,660

Table 3
Optically Stimulated Luminescence (OSL) ages from investigated sites. For locations, see Figures 4 and 8D. Sample 071006 is not used, due to poor reproducibility. Altitude in m a.s.l. is measured in relation to high tide level.

Site	Sample no.	Rise lab no.	Sed. unit	m a.s.l.	n	w.c. %	Equivalent dose (Gy)	Dose Rate (Gy)	OSL age (Ka) (1 σ)
Bahia Crossley 1	Bcr 1:3	071001	3	5.7	21	35	26 ± 2	1.34 ± 0.05	19 ± 2
Bahia Crossley 1	Bcr 1:5	071003	2	4.3	23	34	33 ± 3	1.36 ± 0.06	24 ± 3
Bahia Crossley 1	Bcr 1:4	071002	2	3.3	21	30	30 ± 4	1.36 ± 0.06	22 ± 3
Bahia Crossley 2	Bcr 2:1	071005	2	7.3	23	31	36 ± 4	1.37 ± 0.06	27 ± 3
Bahia Crossley 2	Bcr 2:2	071006	2	3.4	27	26	27 ± 6	1.52 ± 0.06	(18 ± 4)
Bahia Colnett 1	Bco 1:1	071004	1	1.6	23	19	299 ± 17	3.47 ± 0.14	86 ± 6

belonging to the moraine ridge complex associated with the valley behind Bahía Colnett.

The internal composition of these moraine ridges is revealed only at site 6 (Fig. 4). Here a wave-cut cliff shows a very irregular but gradual contact from weathered bedrock to a gravelly–sandy, massive and hard diamict with a high content of very angular local rock clasts at the base (Fig. 5B). The sequence extends upward into a more sandy–silty diamict. This diamict is distinctly stratified with frequent occurrences of thin intrabeds of sand, usually in a subhorizontal to slightly inclined position, but some also showing intraformational isoclinal folds (Fig. 5A). The cliff was inaccessible for direct measurements, but the approximately perpendicular position of the cliff to the moraine ridge indicates a stress direction during till deposition from east towards the west (towards the right in Fig. 5A). The lower portion equates with comminution till of Elson (1988), a genetic sub-group of glacitectonite according to Evans et al. (2006). The upper part of the till sequence shows episodes of intrastratification with fluvial deposition by very thin, sorted sediment beds. Deposited during decoupling they were subsequently deformed during bed recoupling in discrete horizons, and the upper till sequence as a whole is interpreted as subglacial traction till (Evans et al., 2006).

A 7.5-m core (Unkel et al., 2008) from a bog between moraines B and C, bordering Lago Galvarne (Fig. 4, coring site 1), displays a basal, very low humified peat overlying impenetrable clastic sediments. Radiocarbon datings indicate that deglaciation occurred before 16,000 cal yr BP (LuS 6510; Table 2). The basal peat shows that deglaciation took place in a terrestrial environment. Furthermore, the extremely well-preserved peat structure and its geochemical proxies imply that deglaciation was followed by permafrost conditions in a fairly dry, cool and windy environment, which lasted ca. 1000 yr (Unkel et al., 2008). At ca. 8000 cal yr BP, limnic and later brackish-marine gyttja beds started forming on top of the peat in association with rising sea and base level. The oldest radiocarbon age inside moraines C and D is from a basin below an abandoned glacier cirque, the so-called Laguna Cascada (Fig. 4, coring site 2), ~4 km south of moraine C. Here the bottom sediments consist of a 22-cm-thick finely laminated unit of at least 30 clay/silt couplets. Gyttja clay, 2 cm above the rhythmically bedded couplets, is dated to ca. 15,700 cal yr BP (LuS 6507; Table 2), which is ca. 300 yr younger than the age of the former ice-front position at moraine C. Considering the depth of the southern part of the Lago Lovisato basin, deglaciation from moraine D (Fig. 4) may have taken place with a subaquatic ice-front margin. The silt/clay couplets in Lago Cascada imply presence of melting ice in the vicinity of the lake, probably in the upstream glacier cirque on the mountain south of the lake, and are interpreted as glaciolacustrine, annually deposited varves (Unkel et al., 2008).

It is not possible to conclude if moraine A marks the terminal position of LGM ice over Isla de los Estados in this area as no detailed bathymetric data are at hand. However, we speculate that ice most probably extended farther out on the shelf. Further, we propose that moraine A, together with moraine X (Fig. 4), mark the split-up into individual outlet glaciers from an ice cap to the south during general ice-front retreat, which from then on was characterized by periods of still-stands or small-scale oscillations, as indicated from the recessional moraines B–D.

Glacial stratigraphy predating the moraines of Bahía Colnett

Towards the east, the shoreline of Bahía Colnett ends at the rocky Pt. Roncagli (Figs. 3G and 4). Here, wave erosion has formed 10–25 m high cliffs (Fig. 3D) that more or less continuously expose a thick diamict, partly observed to be underlain by rhythmically laminated silt and overlain by alluvial sediments and/or peat. Five localities along the cliff were chosen for documentation of the discerned stratigraphy (triangles 1–5 in Fig. 4), from base to top divided into four units, 1–4. Logged sediment sequences for these localities are shown in Figure 6, and it should be noted that the unit 2 diamict could be followed along the cliff between each documented site.

Unit 1: description

Clayey silt is continuously exposed for a few hundred meters in the lower part of the shore cliff around the Bahía Colnett 1 locality (Fig. 6). The clayey silt is blue-gray when fresh but gray-white when oxidized. The unit is rhythmically intrabedded with 0.5–2 cm thick dark clay and 2–10 cm thick silt beds, the latter internally micro-laminated whereas the clay beds are massive (Figs. 7B, C). Dispersed in the silt/clay couplets are clasts, 2–15 cm in diameter. Also, occasionally present are 0.5–2 cm thick sand intrabeds, some including dispersed, 1–5 cm large gravel clasts. One of these sand intrabeds, 18 cm thick, also carries dispersed cohesive silt intraclasts, 2–5 cm in diameter. A sample from this sand bed produced an OSL age of 86 ± 6 ka (lab no. 071004, Table 3). The uppermost part of unit 1 often shows dislocations and deformation (Fig. 7B), grading into diamictized sediment (clayey–silty diamict) below the contact to the above-lying sandy–silty diamict (unit 2). The sediment was scanned for diatoms, dinoflagellates and foraminifera, but was barren.

Unit 1: interpretation

The unit 1 clayey silt is interpreted as lake sediment. The distinct rhythmical bedding with alternating silt/clay beds suggests sharp changes in sediment input and energy level in the water column. This is typical for glaciolacustrine environments with melt-induced summer deposition of silt while clay is deposited out of suspension during winter at low sediment input. The glacial setting is further indicated by dispersed gravel to cobble-sized clasts, interpreted as ice-rafted/dropped debris. Unit 1 is thus interpreted as a glaciolacustrine, annually varved sediment sequence. Traction-load structures like ripples are absent and thus suggest deposition of summer beds by fallout from suspension, while sporadically occurring thin sand intrabeds and the thicker sand bed with floating silt intraclasts suggest deposition from slump-generated turbidity currents. As inter/overflow sediment distribution usually produce varve thicknesses of <1 cm (e.g., Smith and Ashley, 1985) the silt beds were most probably deposited by fallout from density underflows and the unit as such

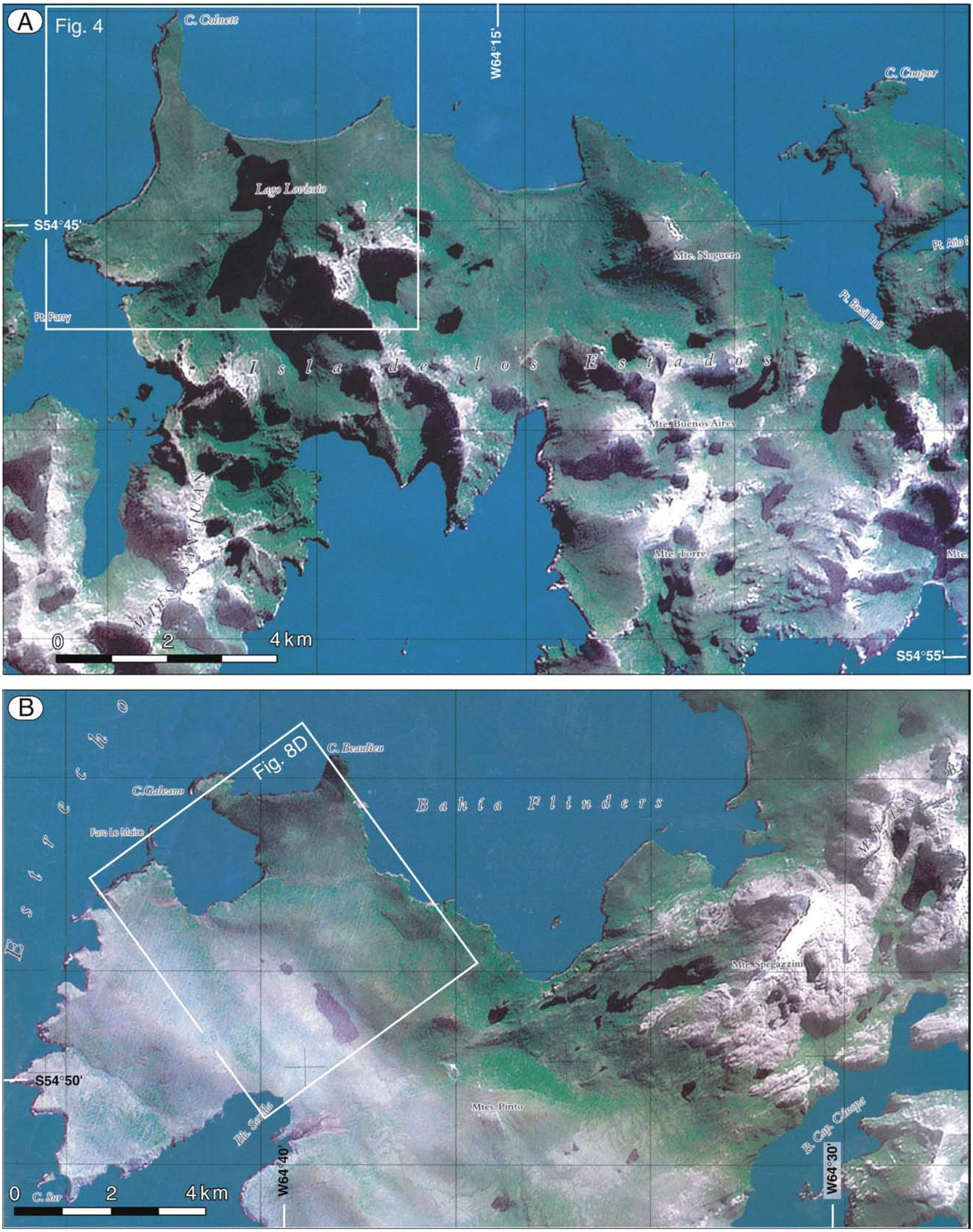

Figure 2. Satellite image map, showing the pronounced glacial relief of the central part of Isla de los Estados with nunatak, cirque and trough-valley morphology, in contrast to the western part of the island with its more subdued topography. Extracts from the map "Carta de imagen satelitaria de la República Argentina, Isla de los Estados 5563-13, 14, 7 y 5566-18". The locations of these two extracts are shown in Figure 1.

could be classified as an intermediate glaciolacustrine facies sequence (see Ashley, 1988).

The only age control for deposition of unit 1 is the OSL age of 86 ± 6 ka, suggesting an early Wisconsinan/Weichselian age (MIS 5). The dated sand bed is interpreted as resulting from a turbidity current, which during transport into the lacustrine basin was erosional and incorporated rip-up clasts of lacustrine silt. Such an environment is not optimal for bleaching and age zeroing of the sediment (e.g., Fuchs

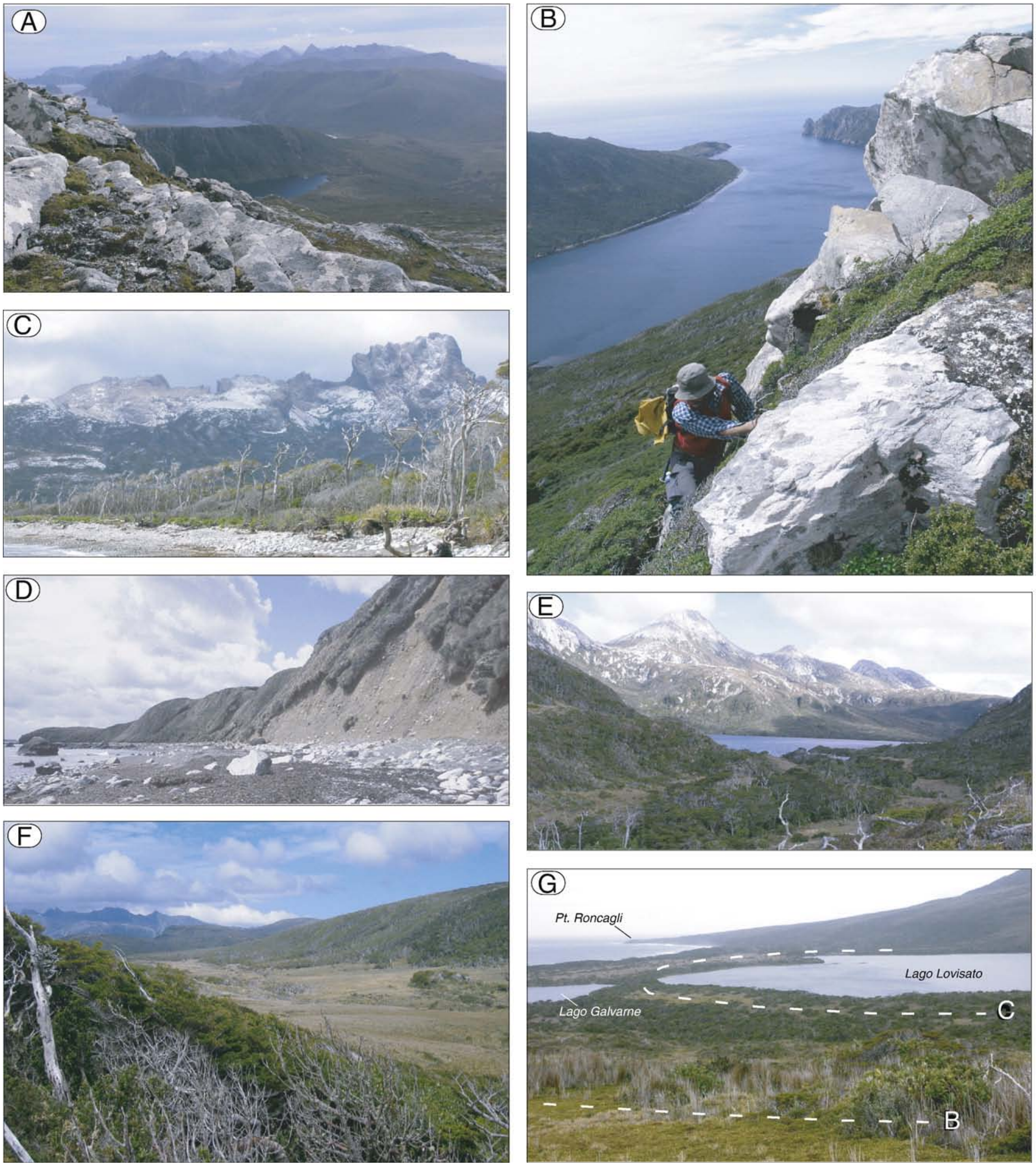

Figure 3. (A.) View towards the west from Pt. San Juan del Salvamento (Fig. 1), showing the alpine relief over the high parts of Isla de los Estados. (B). The presently submerged trough valley (mini-fjord) of Pt. San Juan del Salvamento (Fig. 1). (C). The Bahía Colnett coast with its rugged nunatak topography in the background, starting above a glacial trim line at ~400–450 m a.s.l. (D). The Bahía Colnett coast with shore bluffs; Pt. Roncagli (Fig. 4) seen in the far left background. (E). South of Pt. Basil Hall (Fig. 1) with glacially scoured terrain and over-deepened rock basin(s). Only the highest mountain peaks reach above the glacial trim line at ~400–450 m a.s.l. (F). The subdued morphology inside Bahía Crossley (Figs. 1 and 8D), facing east. The valley (Taniente Palet, Fig. 8D) is occupied by aeolian dunes and peat accumulations. (G). Moraine morphology inside Bahía Colnett. Moraine ridges B and C in Figure 4 are indicated with stippled lines.

and Owen, 2008), so the age should only be treated as a maximum one.

Unit 1 is presently exposed close to sea level. Despite glacial loading and deflection of the crust in connection with glaciation of Isla de los Estados, eustatic sea level must have been lower than the glaciolacustrine basin at the time of deposition of unit 1. Eustatic sea levels at 80–90 ka (MIS 5a–5b) varied significantly and would have been in the order of 20 to 50 m lower than present (Lambeck and Chappell, 2001; Cutler et al., 2003), and even lower if the retrieved OSL age is too old, suggesting a mainly dry shelf between Isla de los Estados and the South American mainland during time of unit 1 deposition.

Unit 2: description

Bedrock (black schist) or glaciolacustrine sediment (unit 1) are overlain by unit 2, which is predominantly diamict sediments

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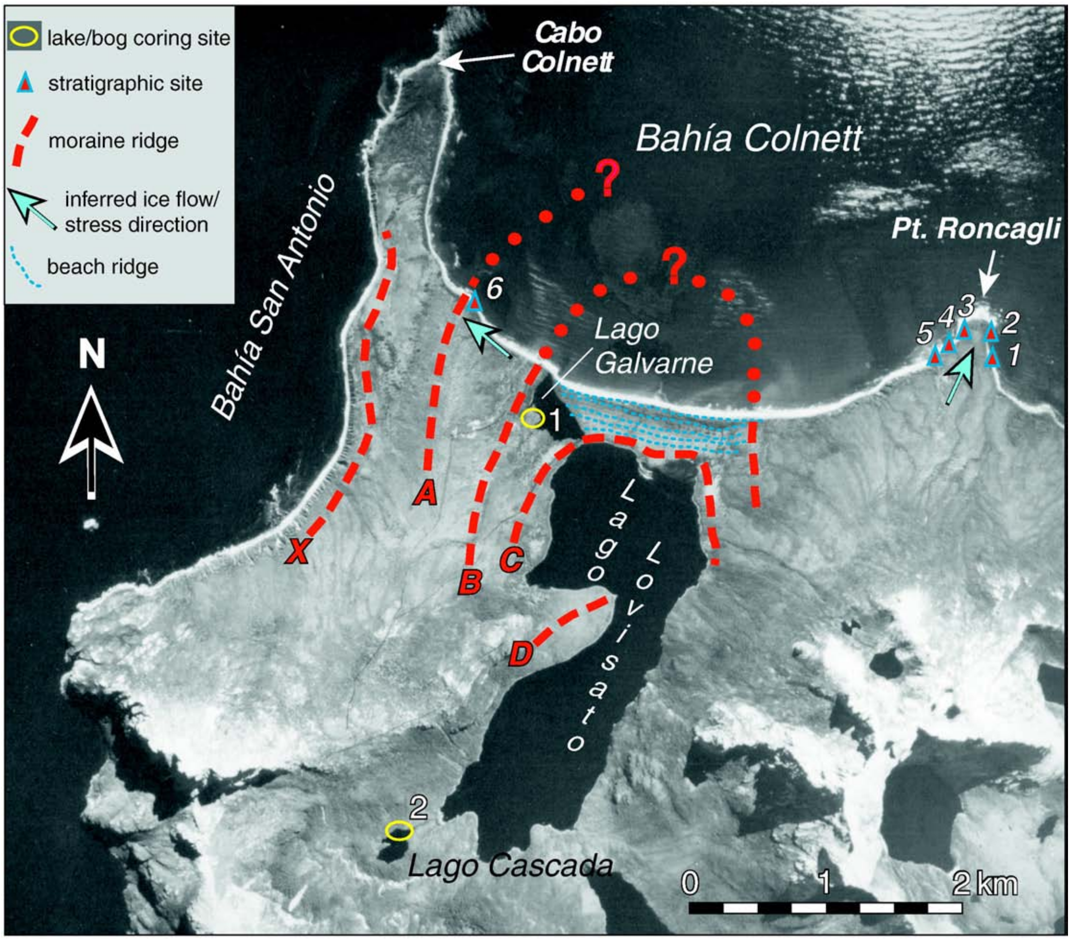

Figure 4. Aerial photo image of the Bahía Colnett area. The position of ice-marginal moraines, investigated glacigenic stratigraphic sites and bog/lake coring sites are indicated.

intercalated with both fine-grained and coarse-grained beds of sorted sediments. Unit 2 at the Bahía Colnett sections ranges from 2 to 18 m in thickness (logs 2–5, Fig. 6). The lower part (unit 2-a) is a sandy silty, very hard, matrix-supported clast-rich diamict. The matrix is yellow-grayish, resembling the silt of unit 1. Predominant clast size is 5–15 cm, but boulders up to 4 m in diameter occur and clasts are often glacially striated. The diamict is commonly massive, but in some horizons becomes distinctly stratified. Stratification is expressed as very thin silt and/or sand laminations that are planar to somewhat folded (Fig. 7E) and sometimes expressed as partings in the diamict. The stratification dips ~5–10° southwards (e.g., Fig. 7F). One excavated parting shows slicken-sides on the lower surface in N–S direction. The diamict at places shows a well-developed fissility. Apart from a more random clast distribution, a number of clast/boulder pavements occur. These can be traced for more than 15–20 m in the coastal section. Associated clasts are typically 15–25 cm in diameter and the spacing between them is 15–40 cm. The diamict is intrabedded with massive to laminated silt beds, some being folded, and also massive gravelly sand beds, the latter often contorted, quite short (0.5–1 m) and at places forming lenses lining up "en echelon" (boudinage).

A fabric analysis at the Bahía Colnett 5 section showed a statistically significant long-axis preferred orientation (S_1 eigenvalue 0.838; Fig. 6). The V_1-axis orientation with azimuth towards 197°/5° suggests a stress transfer direction from the SSW, i.e. from the Lago Lovisato basin.

A sequence of fluvially sorted sediment (~1.2 m) occurs at Bahía Colnett section 5 (Fig. 6). The sorted sediment beds could be traced ~15 m along the cliff on either side of the logged section but then fades out. It consists of a stacked sequence of clast-supported, normally graded cobble gravel to sandy gravel beds, intercalated with planar laminated sand. Boulders with diameters between 0.25 and 1 m are dispersed in the sequence, often with deformational load structures at their contact with laminated sand.

Lens-shaped bodies (0.5–2 m in diameter) of grayish silt, resembling the basal unit 1 silt, occur dispersed in the diamict along the cliff, although not in the logged sections. These silt bodies are generally massive but may include folded internal laminations. A stratified diamict at one observation point indicates a complex three-dimensional folding history, resembling a sheath fold.

At Bahía Colnett 4 (Fig. 6), the diamict becomes sandy gravelly and very rich in clasts (unit 2-b). It is preferentially massive but at places is distinctly laminated with thin, drawn-out gray laminae or thicker reddish banding (e.g., Figs. 7D and G). Cobble/boulder pavements also occur (e.g., Fig. 7D at arrow) and they are laterally traceable for at least 15–20 m.

Unit 2: interpretation

The exposed parts of the high bluffs do not suggest more than one depositional sequence. There is no evidence of interrupted sedimentation such as weathering or soil horizons, laterally continuing erosional surfaces, or laterally consistent sorted sediment beds. On the other hand, it is obvious from the logged sections that deposition of diamict at the ice/bed interface were temporally and spatially interrupted due to decoupling and the formation of subglacial drainage systems. For example, there is sedimentological evidence for former occurrences of shallow channels into which massive to laminated silt (low-energy environment) and sand (higher-energy

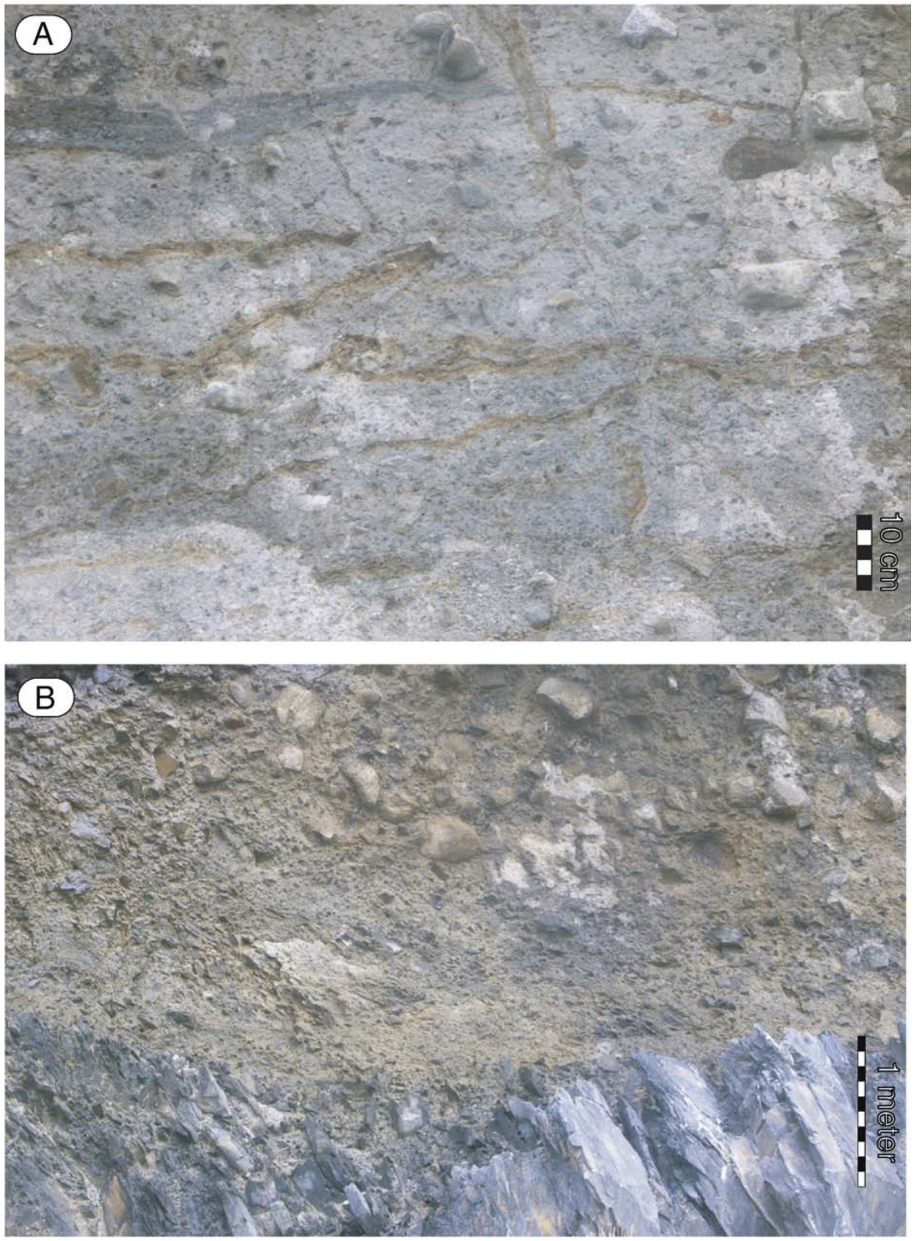

Figure 5. Stratigraphic site 6 in Bahía Colnett, with a shore platform cutting into bedrock and moraine ridge A (Fig. 4). (A) Sandy silty diamict with thin sand intrabeds, revealing syn-sedimentary isoclinal folding towards the west (right). (B) The contact to underlying bedrock, showing a massive diamict with a high content of very angular clasts of the local bedrock.

environment) was deposited. The thick, sorted sediment sequence 6.4–8.0 m a.s.l. in the Colnett 5 section (Fig. 6) shows three cycles of upward-fining sequences, each overlying scoured erosional bases. Large boulders with load-deformation structures occur at contacts with enclosing sediment. These fluvially sorted beds indicate erosion and deposition during initially high energy to later waning flow within subglacially formed channels with large depths and width. Boulders apparently fell from a cavity roof and were incorporated in the fluvial sediment.

The absence or presence of deformational structures (folds) within sorted sediment intrabeds, and contacts between sorted sediment and diamict, suggest that regained ice/bed coupling could develop either as sliding bed or deforming bed conditions. At places, sorted sediments are totally incorporated into the diamict, showing intricate fold patterns (e.g. Fig. 7E). This suggests development of thicker deforming bed zones with pervasive but not penetrative deformation. Isolated smaller clasts of sand and silt, massive or with deformed primary lamination, are interpreted as splitting-up of previously deposited intrabeds in varying stages of boudinage formation in a deforming bed before bed stabilization. Larger intraclasts of silt, whose texture and structure resemble the unit 1 silt, are interpreted as rafts eroded from beneath (unit 1) and transported within a deforming bed under more or less pervasive deformation before deposition within the enclosing diamict.

The massive to distinctly laminated parts of the diamict, which include a distinct fissile structure and occasional partings with slicken-sides, suggest a ductile to brittle deformation history with formation of shear lamina or shear surfaces Also evident is a more penetrative deformation with a massive diamict as an end member in the lower part of a deforming bed zone where sediment is transferred from a plastic to a more semi-solid state (the transitional A/B and the B horizon of a deforming bed, e.g. Benn (1995), Benn and Evans (1996, 1998)). Such deformation style is also compatible with the measured high strength fabric with *a*-axes paralleling the main stress direction.

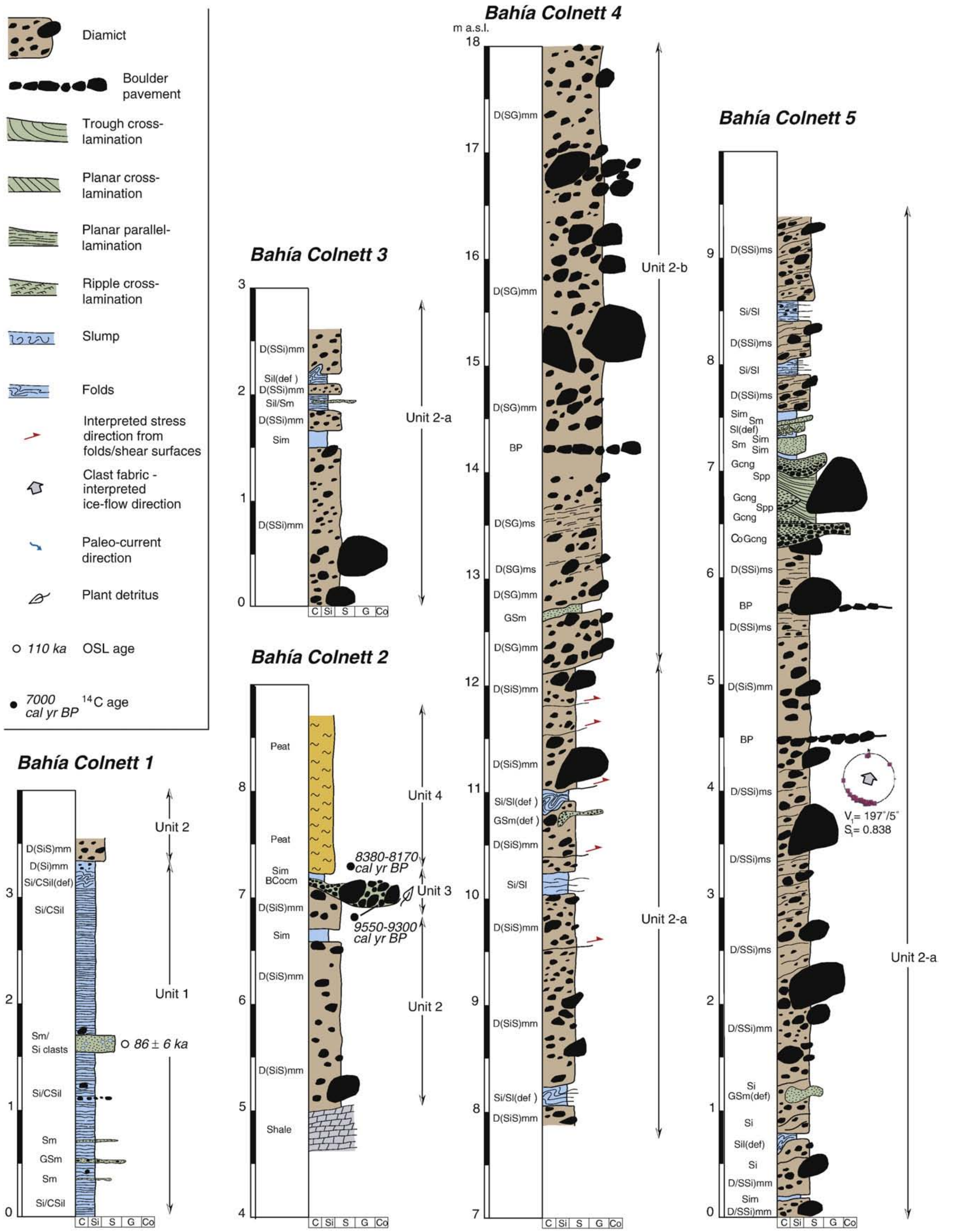

Figure 6. Stratigraphic logs for the Bahía Colnett 1–5 sites (locations in Fig. 4). Lithofacies codes in Table 1 and details on ^{14}C and OSL ages in Tables 2 and 3.

The frequently occurring cobble to boulder pavements also indicate more or less thick deforming bed zones beneath the ice/bed interface; Boulton (1996) proposed that thickening and thinning of a deforming layer will eventually create a concentration of larger clasts at the interface between a more viscous A horizon and a more semi-solid B horizon when the A horizon during erosion "cannibalizes" the B

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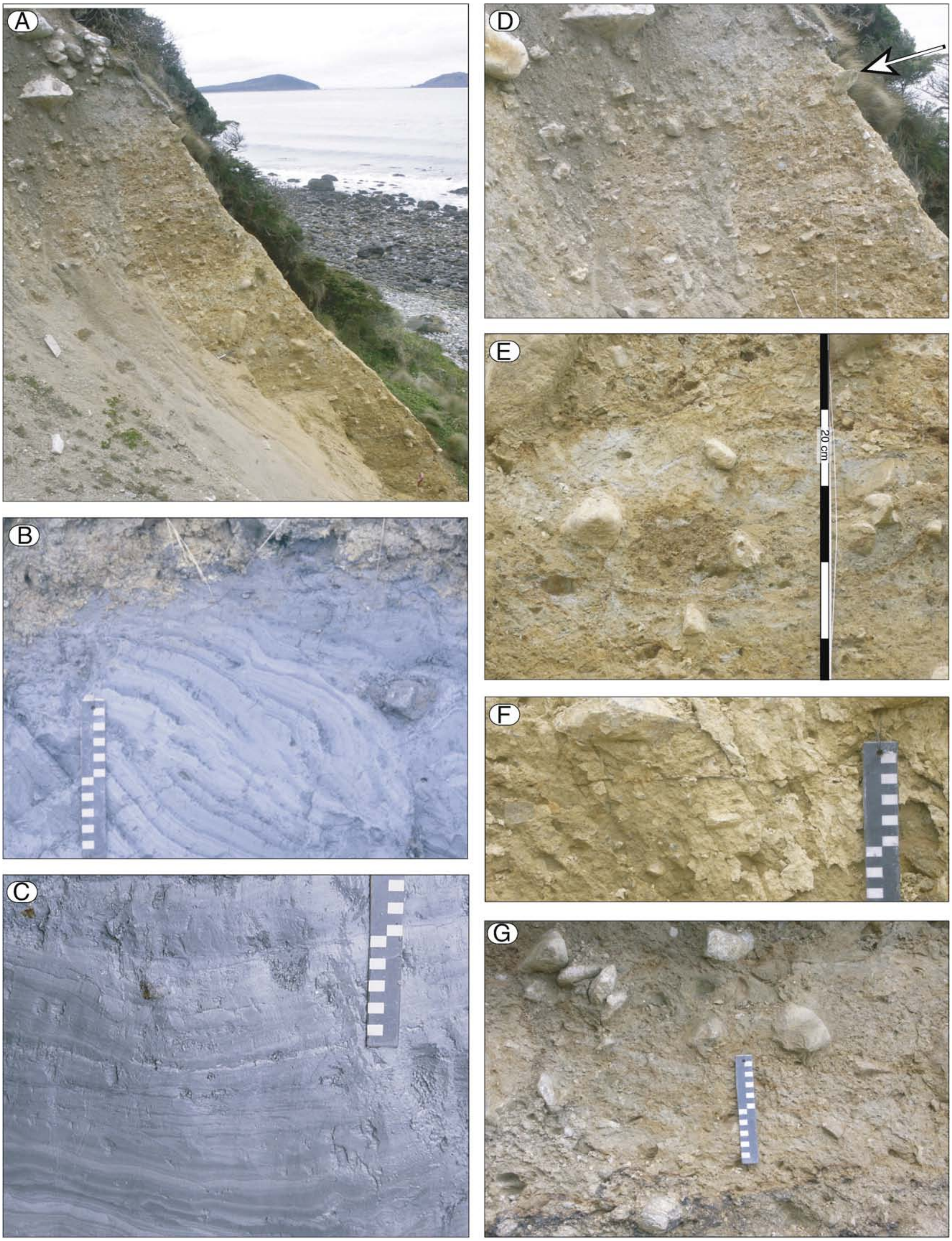

Figure 7. (A) Overview of the unit 2 diamict sequence in log Colnett 4 (~ between 8 and 15 m a.s.l.). (B) Unit 1 rhythmically laminated silt and clay. Note the thicker summer silt beds (light gray) and thinner winter clay beds (dark gray) and ice-rafted pebble clast to the right. The photo shows the upper part of the unit, deformed by glacial tectonics below the contact to the unit 2 diamict. (C) Unit 1 rhythmically laminated silt and clay with ice-rafted drop clasts in the upper part. (D) Upper part of the unit 2 diamict in the Colnett 4 section. Note the crude stratified appearance and distinct clast pavement in the upper part (marked by arrow). (E) Intricately folded silt beds in the unit 2 diamict. (F) Massive, fissile unit 2 diamict with shear planes. The pronounced *a*-axis clast fabric ($S_1 = 0.83$, see log Colnett 5) is macroscopically visible. (G) Red/gray-banded unit 2 diamict (~ at 6 m a.s.l. in log Colnett 5), interpreted as a shear lamination.

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horizon diamict. Another possible explanation for the formation of clast pavements is sinking of clasts to the base of a deforming layer (e.g., Clark, 1991).

The sedimentary structures, sediment facies and architecture of the unit 2 diamicts and their intercalated sorted sediments, are indicative of very complex processes expected beneath a wet-based active glacier, where subglacial traction till deposition is common (Evans et al., 2006). These complex sedimentologies are consistent with the views of Piotrowski and Kraus (1997) and Piotrowski et al. (2004), who suggested deposition of subglacial beds that represents a mosaic of regimes that change temporally and spatially with variations in deformation, sliding, warm-based and cold-based conditions. The thick successions of glacigenic sediments in the Bahía Colnett shore cliffs might indicate (e.g., Boulton, 1996) a gradual thickening of the sediment accumulation towards a sub-marginal/terminal zone, suggesting that the front of the outlet glacier from the Lago Lovisato trough at this time stood not much farther north than indicated by moraine A in Figure 4.

Unit 3: description and interpretation

An erosional boundary to the unit 2 diamict is expressed as a boulder lag (boulder diameter 20–60 cm) (Bahía Colnett 2, Fig. 6). This lag grades laterally into clast-supported gravel, intercalated with beds of sand and silt, with a total thickness of 0.5 m. Organic detritus, but also small twigs occur both in the gravel and silt beds. Radiocarbon dating of a twig gave an age of c. 9470 cal yr BP (LuS 8162; Table 2). Unit 3 has a lateral continuity of ~20 m and probably represents infill in a fluvial down-cut channel that was abandoned prior to deposition of unit 4.

Unit 4: description and interpretation

Unit 4 is a peat, in the section ~3 m thick. Radiocarbon dating of the base suggests that peat growth started ca. 8300 cal yr BP (LuS 7057; Table 2). All documented sections along Bahía Colnett end in a draping peat. Absence of capping peat in some logs is explained by the inaccessibility or covered nature of the uppermost parts of some sections. At another locality, Pt. San Juan del Salvamento (Fig. 1), peat growth overlying a till section, not presented here, started at ca. 6500 cal yr BP (LuS 7056; Table 2).

Glacial geomorphology and stratigraphy, Bahía Crossley

The area inside Bahía Crossley (Figs. 2B and 8D) has a much more gentle topography than at Bahía Colnett. Two drainage basins lead in WNW/W directions towards the bay, with a smooth bedrock ridge in between rising to an altitude of ~150 m a.s.l. The low-lying areas behind the shore are occupied by aeolian dunes and peat deposits which are being eroded by two fluvial drainage systems. Two outcrops of Quaternary deposits on top of shale were located, lying well above a wave-cut bedrock platform (Fig. 8D). Five stratigraphic units were identified here (units 1–5; Fig. 8A). A peat sequence was cored in the eastern drainage basin, called Taniente Palet Bog (Fig. 8D).

Units 1–3: description

At the two Crossley stratigraphic sections shown in Figure 8, lying ~250 m apart, sandy deposits (units 1–3) lie below a diamict (unit 4). At Crossley 2 the sequence above shale starts with bedsets of planar parallel-laminated medium to coarse sand (unit 1), with erosional scour and gravel stringers between some beds. Four beds, between 30 and 75 cm thick, consist of massive, very well sorted sand (unit 2). Three of these show normal grading from coarse medium sand at the base to fine medium sand at the top. At Crossley 1, unit 2 is characterized by a >2.4 m thick bed of weakly parallel-laminated, very well sorted medium sand. The sand sequence is capped by unit 3, which at Crossley 2 is represented by interbedded couplets of clayey silt and massive gravelly sand and at Crossley 1 by scour troughs filled with planar parallel-laminated sand and stringers of gravel.

Five OSL samples were taken from units 1–3; all gave ages consistent with a range of 27 to 18 ka (Table 3). All samples gave weak OSL signals, and measurement uncertainties were correspondingly large. This is reflected in the relative standard deviations of the dose estimates, which all lie between 30 and 60%. The exception to this is sample 071006 (18 ± 4 ka; Table 3) for which the RSD was 115%; although the derived age is not inconsistent with the other four, this result is nevertheless considered less reliable than the others.

Units 1–3: interpretation

Units 1 and 3 are interpreted as deposited in fluvial environments, particularly indicated by the frequent occurrence of scoured contacts and gravel stringers. The genetic interpretation of the unit 2 sediment is, however, not straightforward; it could represent fluvial deposits, but the very small variation in structures and the small variation in grain size, combined with the very high sorting, could also indicate vertical accretion of wind-blown sand. A comparison with recently deposited nearby aeolian dune sand reveals the same grain size and lack of structures, supporting the latter interpretation. The three OSL dates from the Crossley 1 site (Fig. 8A) give a consistent, quite narrow time frame (24–19 ka). The slight age reversal is in this context unproblematic. The 27 ka age in the upper part of unit 2 sand at the Crossley 2 site suggest a slightly older sedimentation age than at nearby Crossley 1 and thus extends the age frame of the documented depositional environment. Unfortunately the OSL-dated unit 1 produced an unreliable age estimate (Table 3).

Unit 4: description

Unit 4 is a matrix-supported, massive, and clast-rich silty diamict, ~2.2 m thick in both sections. The predominant clast size is 5–20 cm, with a very high frequency of flat-shaped, sometimes striated shale clasts, visibly arranged in an imbricated and ordered manner (Fig. 8C). Clast fabric analysis in the Crossley 1 section showed the occurrence of very strong long-axis preferred orientation (S_1 eigenvalue 0.902; Fig. 8A) and a pronounced *a*-axis dip. The V_1-axis orientation with azimuth towards 107°/9° suggests a stress transfer direction from the east, that is out of the valley and more or less parallel to the bedrock ridge dividing the drainage basins inside Bahía Crossley (Fig. 8D). The contact with underlying sediment is sharp and erosional. A 15-cm clast protruding from the diamict into unit 2 at the Crossley 1 site reveals deformation of sand at the contact with the overlying diamict.

Unit 4: interpretation

The predominance of local bedrock clasts and the absence of boulders in the sections suggest the diamict may represent local colluvium. However, the very strong preferred long-axis clast orientation and striated clasts indicate an origin as glacial till. This is further implied by the depositional direction indicated by the azimuth of the fabric, also suggesting deposition parallel to the long axis of the valley (i.e., from the east) and not along the valley side slope. Further evidence for a glacial origin is deformation around clasts at the contact between diamict and underlying sand, suggesting clast ploughing during a lodgment process. Consequently, the diamict is interpreted as a subglacial traction till in accordance with the terminology of Evans et al. (2006).

Unit 5: description and interpretation

Unit 5 is a peat, in both sections >1 m thick. A basal radiocarbon age indicates that peat growth started at ca. 9500 cal yr BP (LuS 7055;

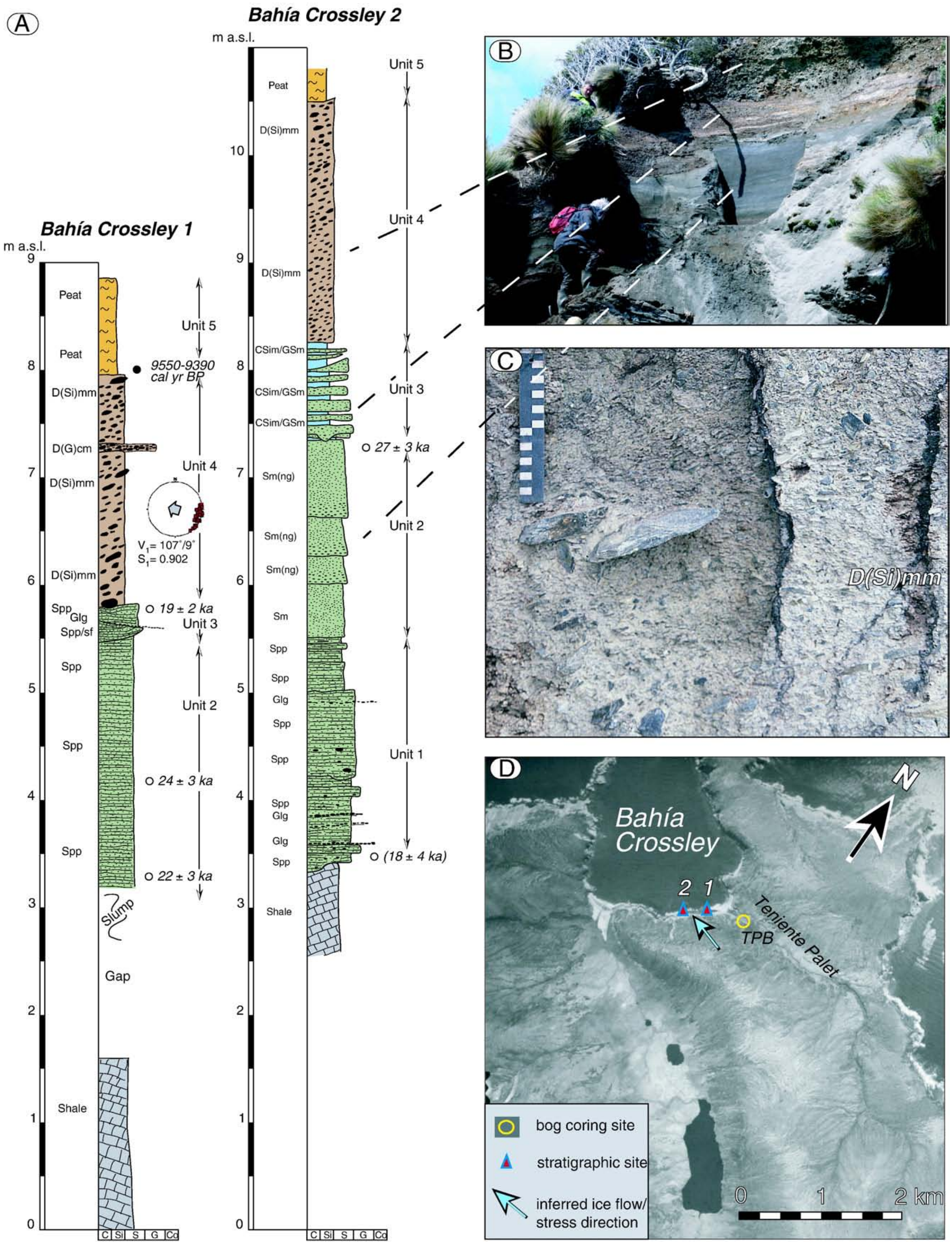

Figure 8. (A) Stratigraphic logs for the Bahía Crossly sites 1–2 (location in panel D). Color codes for sedimentary units are the same as for Figure 6. For lithofacies codes see Table 1, for details on ^{14}C and OSL ages Tables 2 and 3. (B) Upper part of section Crossley 2. Units 4 (diamict), 3 (interbedded silt and sand) and 2 (normally graded beds of sand) are marked in the log with stippled lines. (C) The unit 4 massive silty diamict with a very pronounced clast a-axis preferred orientation. (D) Aerial photo image of the Bahía Crossley area. Positions of the investigated stratigraphical sites are shown as well as the peat bog coring site in the Taniente Palet valley.

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Table 2) at this locality. The area inland from the coast of Bahía Crossley is also to a large extent draped in peat deposits. The oldest age for inland peat came from a 10.9-m-deep core retrieved ~400 m east of the coastal sections where an age of ca. 9150 cal yr BP (LuS 6514; Table 2) was determined (TPB, Fig. 8D). This represents a young age with respect to the known deglaciation age of the island (e.g., Unkel et al., 2008). The oldest age retrieved from this western portion of Isla de los Estados is ca. 12,750 cal yr BP (AA62509, Table 2; Ponce (2008)), and is associated with a ^{14}C-dated basal clay gyttja at the bottom of a bog at Caleta Lacroix by Bahía Sevilla (Fig. 2B). This site is located ~4 km SSE of Bahía Crossley.

Discussion, conclusions and suggestions for future research

Isla de los Estados's alpine topography, with common abandoned cirques, glacially eroded valleys and presently marine-inundated fjords, gives an impression of a long glacial history, but results presented herein support the idea that these landforms developed since MIS 5. The island's landscape displays evidence of strong glacial abrasion to an altitude of ~450 m a.s.l. Sharp-crested mountain ridges with tors occur above ~450 m a.s.l., and we interpret these landforms as former nunataks. The earliest age of glaciation is unknown, but our present dating of existing glacial deposits yield ages that mainly associate with the latest glaciation cycle. Glaciations older than 1 Ma, identified both in Tierra del Fuego and the Magellan Strait areas (e.g., Rabassa et al., 2000; Sugden et al., 2005; Rabassa, 2008), probably also occurred on Isla de los Estados. However, this remains to be documented.

The present study suggests that most of the glacigenic sediments exposed along the coastal cliffs relate to the latest (Wisconsinan/Weichselian) glacial cycle (MIS 2), with ages younger than about 27 ka. However, a sequence of glaciolacustrine sediments, unit 1, at Bahía Colnett, is OSL-dated to 80–90 ka. This age is problematic, however, because it involves dating of sediment associated with a turbidity current. As such, sediment exposure may have been insufficient to reset the cosmogenic clock.

Glacial till that overlies these OSL-dated sediments dates from the last glacial maximum of the island. Peat and lacustrine sediments in the Lagos Galvarne/Lovisato/Cascada basins (Fig. 4), dated to between 16,300 and 15,500 cal yr BP (Unkel et al., 2008), approximate the deglaciation age. These ages are in accordance with initial deglaciation ages from other parts of southern South America (e.g., Denton et al., 1999; Rabassa, 2008). The OSL-dated fluvial and aeolian sediments (27–19 ka) below the till in Bahía Crossley also suggest ice expansion over this area that is in accordance with the regional LGM (e.g., Sugden et al., 2005; Kaplan et al., 2008; Clark et al., 2009). The build-up of ice sheets here is most likely related to the coincident occurrence of a minimum in austral summer insolation and northwards expansion of Antarctic sea ice and cold fronts.

We conclude that most of the glacial relief and the glacial sedimentary sequences on Isla de los Estados are products from local glaciations, where more or less interconnected ice caps have sent outlet glaciers towards the north, terminating on a dry shelf. Towards the south, outlet glaciers probably were closer to the continental shelf break and probably in contact with the sea, forming tidewater-glacier termini. That Isla de los Estados was not completely covered by an ice sheet that could coalesce with any Isla Grande de Tierra del Fuego ice sheet probably is explained by northwards displacement of the humid westerlies and the subsequent invasion of Antarctic sea ice with cold, dry Antarctic air masses. Although temperatures might have fallen drastically, under these conditions the necessary precipitation for ice-sheet building would be heavily reduced, hampering build-up of any large ice sheet.

The rapid deglaciation and disintegration of the Isla de los Estados ice caps may be related to the simultaneous and steep rises in south and tropical Pacific SSTs, Pacific deep water temperatures, increased austral summer insolation and Antarctic temperatures between 19,000 and 17,000 cal yr BP (Stott et al., 2007). These changes imply major reorganizations of the circulation pattern in the southern hemisphere, which in our study area might have resulted in reduced Antarctic influence and a southern displacement of the westerlies. The former should have meant less cold conditions and an ocean without extensive sea ice, while the consequence of the latter would have been an increased influence from the more humid, but much milder westerlies. Such a change probably resulted in a rapid decay of the island's low-altitude ice caps and deglaciation around 16,000 cal yr BP. This was followed by peat formation in a subaerially exposed glacial landscape, initially characterized by a millennium of permafrost (Unkel et al., 2008), indicating that the apparent climatic impact from Antarctica did not cease until 15,000 cal yr BP, when organic sedimentation started in local fresh-water basins. The peat covering most surfaces at higher altitudes (e.g., unit 4 at the Bahía Colnett and unit 5 at the Bahía Crossley sites, respectively) began later at around 9500 cal yr BP, coinciding with a considerable humidification of the climate in the early Holocene (Unkel et al., 2008).

An interesting geomorphological question concerns explanation of the distinctly non-alpine, relatively flat and undulating westernmost part of Isla de los Estados (Fig. 2B). The low-relief terrain could simply be the presence of softer, easier erodable rocks from the Beauvoir and Lemaire Formations (Caminos and Nullo, 1979), or, it could also be a consequence of maximum glaciation erosion related to mainland-derived ice streams originating in the Andes of eastern Tierra del Fuego. Such an ice sheet could have crossed a dry Le Maire strait and eroded the westernmost parts of Isla de los Estados. This latter hypothesis is similar to what Otto Nordenskjöld (1898) and Caldenius (1932) suggested on their pioneer glaciation maps of southernmost South America and Tierra del Fuego, respectively. This topic remains as an interesting subject for future investigations. Evidence for the age of the earliest Quaternary glaciation is not presently available on Isla de los Estados, but glaciation dated to greater than 1 Ma for southern mainland South America possibly also produced glaciation here. Future cosmogenic nuclide dating of the bedrock landforms above the ~450 m a.s.l. level of the apparent maximum vertical extent of glaciation reported herein is needed to help clarify the Quaternary history of Isla de los Estados.

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References

Ashley, G.M., 1988. Classification of glaciolacustrine sediments. In: Goldthwait, R.P., Matsch, C.L. (Eds.), Genetic Classification of Glacigenic Sediments. Balkema, Rotterdam, pp. 243–260.

Auer, V., 1956. The Pleistocene of Fuego-Patagonia. Part I: The Ice and Interglacial Ages. Annales Academia Scientiarum Fennicae, Series A III 45, 1–22.

Benn, D.I., 1995. Fabric signature of subglacial till deformation, Breidamerkurjökull, Iceland. Sedimentology 42, 735–747.

Benn, D.I., Evans, D.J.A., 1996. The interpretation and classification of subglacially-deformed materials. Quaternary Science Reviews 15, 23–52.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London.

Bennett, K.D., Haberle, S.G., Lumley, S.H., 2000. The Last Glacial–Holocene transition in southern Chile. Science 290, 325–328.
Björck, S., Hjort, C., Ljung, K., Möller, P., Wohlfarth, B., 2007. Isla de los Estados — Quaternary geology and palaeoclimatology at the end of the world. In: Rickberg, S. (Ed.), Swedish Polar Research Secretariat, Year book 2006. Swedish Polar Research Secretariat, Stockholm, pp. 44–49.
Boulton, G.S., 1996. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. Journal of Glaciology 42, 43–62.
Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal Program. Radiocarbon 37, 425–430.
Bronk Ramsey, C., 2001. Development of the Radiocarbon Program OxCal. Radiocarbon 43, 355–363.
Caldenius, C., 1932. Las glaciaciones cuaternarias de la Patagonia y Tierra del Fuego. Geografiska Annaler 14, 1–164.
Caminos, R., Nullo, F., 1979. Descriptión Geológica de la Hoja 67 e, Isla de los Estados. Servicio Geológico Nacional, Buenos Aires.
Clark, P.U., 1991. Striated clast pavements, products of deforming subglacial sediments? Geology 19, 530–533.
Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710–714.
Cutler, K.B., Edwards, R.L., Taylor, F.W., Cheng, H., Adkins, J., Gallup, C.D., Cutler, P.M., Burr, G.S., Bloom, A.L., 2003. Rapid sea-level fall and deep-ocean temperature change since the last glacial period. Earth and Planetary Science Letters 206, 253–271.
Dalziel, I.W.D., Eliott, D., 1973. Evolution of the Scotia. Nature 233, 246–252.
Dalziel, I.W.D., Caminos, R., Palmer, K.F., Nullo, F., Casanova, R., 1974. South extremity of Andes: geology of Isla de los Estados, Argentine Tierra del Fuego. American Association of Petroleum Geologists Bulletin 58 (12), 2502–2512.
Denton, G.H., Heusser, C.J., Lowell, T.V., Moreno, P.I., Andersen, B.G., Heusser, L.E., Schlüchter, C., Marchant, D.R., 1999. Inter-hemisphere linkage of palaeoclimate during the last glaciation. Geografiska Annaler 81A, 107–153.
Elson, J.A., 1988. Comments on glacitectonite, deformation till and comminution till. In: Goldthwait, R.P., Matsch, C.L. (Eds.), Genetic Classification of Glacigenic Sediments, 85–88. Balkema, Rotterdam.
Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. Earth-Science Reviews 78, 115–176.
Eyles, N., Eyles, C.H., Miall, A.D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamicton and diamictite sequences. Sedimentology 30, 393–410.
Fuchs, M., Owen, L.A., 2008. Luminiscence dating of glacial and associated sediments: review, recommendations and future directions. Boreas 37, 636–659.
Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. Palaeogeography, Palaeoclimatology, Palaeoecology 281, 180–195.
Heusser, C.J., 2003. Ice Age Southern Andes — A Chronicle Of Palaeoecological Events. : Developments in Quaternary Science, vol. 3. Elsevier, Amsterdam.
Hulton, N.R.J., Purves, R.S., McCulloch, R.D., Sugden, D.E., Bentley, M.J., 2002. The Last Glacial Maximum and deglaciation in southern South America. Quaternary Science Reviews 21, 233–241.
Johns, W.H., 1981. The vegetation history and paleoclimatology for the Late Quaternary of Isla de los Estados, Argentina. Michigan State University, Dept. of Geology, MSc thesis.
Kaplan, M.R., Fogwall, C.J., Sugden, D.E., Hulton, N.J.R., Kubik, P.W., Freeman, S.P.H.T., 2008. Southern Patagonian glacial chronology for the Last Glacial period and implications for Southern Ocean climate. Quaternary Science Reviews 27, 284–294.
Lambeck, K., Chappell, J., 2001. Sea level change trough the last glacial cycle. Science 292, 679–686.
Ljung, K., Ponce, J.F., 2006. Periglacial features on Isla de los Estados, Tierra del Fuego, Argentina. : III Congreso Argentino de Cuaternario y Geomorfología, vol. 1. Córdoba, Argentina, pp. 85–90.
Malagnino, E.C., Olivero, E.B., 1999. New evidence of the total glaciation of the Isla Grande de Tierra Del Fuego. Journal of South American Earth Sciences 12, 343–348.
Mark, D.M., 1973. Analysis of axial orientation data, including till fabrics. Geological Society of America Bulletin 84, 1369–1374.
McCormac, G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere calibration, 0–11.0 cal kyr BP. Radiocarbon 46, 1087–1092.
Murray, A.S., Wintle, A.G., 2000. Luminiscence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.
Murray, A.S., Marten, R., Johnston, P., Martin, A.J., 1987. Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry. Journal of Radioanalytical and Nuclear Chemistry 115, 263–288.
Nordenskjöld, O., 1898. Geologie, Geographie und Anthropologie. Wissenschaftliche Ergebnisse der schwedischen Expedition nach den Magellansländern 1895–1897, unter Leitung von Otto Nordenskjöld. Norstedt and Söner, Stockholm.
Olley, J.M., Murray, A.S., Roberst, R.G., 1996. The effects of disequilibria in uranium and thorium decay chains on burial dose rates in fluvial sediments. Quaternary Geochronology 15, 751–760.
Pendall, E., Markgraf, V., White, J.W.C., Dreier, M., 2001. Multiproxy record of Late Pleistocene–Holocene climate and vegetation changes from a peat bog in Patagonia. Quaternary Research 55, 168–178.
Piotrowski, J.A., Kraus, A.M., 1997. Response of sediment to ice sheet loading in northwestern Germany: effective stresses and glacier-bed stability. Journal of Glaciology 43, 495–502.
Piotrowski, J.A., Larsen, N.J., Junge, F.W., 2004. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. Quaternary Science Reviews 23, 993–1000.
Ponce, J.F., 2008. Palinología y Geomorfología del Cenozoico tardío de Isla de los Estados. Unpublished PhD. Thesis, Departamento de Geología, Universidad Nacional del Sur, Argentina.
Ponce, J.F., Rabassa, J., Martínez, O.A., 2009. Morfometría y génesis de los fordos de Isla de los Estados, Tierra del Fuego. Revistita de la Asociación Geológia Argentina 65, 638–647.
Rabassa, J., 2008. Late Cenozoic glaciations in Patagonia and Tierra del Fuego. In: Rabassa, J. (Ed.), The Late Cenozoic af Patagonia and Tierra del Fuego. Developments in Quaternary Science, vol. 11. Elsevier, pp. 151–204.
Rabassa, J., Coronato, A., Bujalesky, G., Salemme, M., Roig, C., Meglioli, A., Heusser, C., Gordillo, S., Roig, F., Borromei, A., Quattrocchio, M., 2000. Quaternary of Tierra del Fuego, southernmost South America: an updated review. Quaternary International 68–71, 217–240.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guildersson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S.W., Ramsey, C.B., Raimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, C.B., Plicht, J.V.D., Weyhenmayer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal ky BP. Radiocarbon 46, 1029–1058.
Smith, N.D., Ashley, G., 1985. Proglacial lacustrine environment. In: Ashley, G.M., Shaw, J. and Smith, N.D. (Eds.), Glacial sedimentary environments. SEPM Short Course 16, 135–216.
Stott, L., Timmermann, A., Thunell, R., 2007. Southern Hemisphere and deep-sea warming led deglacial CO_2 rise and tropical warming. Science 318, 435–438.
Sugden, D.E., Bentley, M.J., Fogwill, C.J., Hulton, N.R.J., McCulloch, R.D., Purves, R.S., 2005. Late-glacial glacier events in southernmost South America: a blend of "northern" and "southern" hemispheric climatic signals? Geografiska Annaler 87A, 273–288.
Unkel, I., Björck, S., Wohlfarth, B., 2008. Deglacial environmental changes on Isla de los Estados (54.5°S), southeastern Tierra del Fuego. Quaternary Science Reviews 27, 1541–1554.

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