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Relict sea-floor ploughmarks record deep-keeled Antarctic icebergs to 45°S on the Argentine margin

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ABSTRACT

This paper reports ploughmarks on the Argentine continental margin up to 44° 50′S, the most northerly morphological evidence of giant icebergs in the southern Atlantic. More than 2500 ploughmarks up to 32 km long, 685 m wide and more than 20 m deep have been observed at modern water depths up to 646 m. Taking into account these iceberg sizes, and ocean current directions which appear to have remained similar from the last full-glacial to the present interglacial, the icebergs that produced the ploughmarks are interpreted to be calved from fast-flowing ice streams draining huge basins of the West Antarctic Ice Sheet and the western Antarctic Peninsula during the Last Glacial Maximum (LGM) about 20,000 years ago. Ploughmarks at the deepest water depths correspond to icebergs more than 500 m thick and at least 2 km wide, given a sea-level rise of 120 m since the LGM. The icebergs, after having drifted northeast in the Antarctic Circumpolar Current, were transported northward by the Falklands/Malvinas Current; a total distance of 2000 to 4000 km. The waters north of the Falkland Islands in particular were probably several degrees colder than today to prevent rapid iceberg melting and deterioration.

1. Introduction

Icebergs are produced where glacier ice and ice sheets, sometimes including attendant ice shelves, reach the sea. The highest flux of modern icebergs is from fast-flowing ice streams and outlet glaciers draining huge interior basins of the Antarctic and Greenland ice sheets (e.g. Bentley, 1987; Rignot and Kanagaratnam, 2006), and from collapse of major ice shelves (e.g. Silva et al., 2006). Evidence of iceberg occurrence in the marine-geological record is an important indicator of the former presence of extensive ice sheets that reached to sea level (e.g. Dowdeswell et al., 2007). Ploughmarks form when the submarine keels of icebergs ground on the sea floor (Woodworth-Lynas et al., 1991). The resistance of the soft, sedimentary bed is often insufficient to halt drifting icebergs, and iceberg keels cut through the sea floor to form ploughmarks that are often linear to curvilinear and sometimes exhibit abrupt changes in direction (Dowdeswell et al., 2007; Rebesco et al., 2010). The continental shelves surrounding Antarctica and Greenland are heavily disturbed by icebergs to a depth of about 400 to 500 m, with evidence of well-preserved streamlined subglacial landforms indicative of past ice flow found mainly at greater shelf depths because few icebergs have keels deeper than this (e.g. Canals et al., 2000; Anderson et al., 2002; Ó Cofaigh et al., 2002; Evans et al., 2006). However, Dowdeswell and Bamber (2007) suggested that Antarctic icebergs disturb the sea floor to water depths of 500 to 600 m, and in the Amundsen Sea sector there are scours to depths of 720 m (Larter et al., 2009). In the Northern Hemisphere, ploughmarks have been observed to almost 1000 m offshore West Greenland (Kuijpers et al., 2007) and to between 650 and 700 m on the Canadian margin (Piper and Pereira, 1992).

Today, few icebergs are found in the relatively warm waters north of the Antarctic Polar Front at about 60°S, and have been observed only rarely north of the Falkland Islands (e.g. Long et al., 2002; Silva et al., 2006). Here we present sea-floor morphological evidence to demonstrate, for the first time, that icebergs up to about 500 m in submarine keel-depth drifted and grounded as far north as 45°S on the Argentine continental slope of eastern South America (Fig. 1).

Marine-geophysical data were acquired from the continental shelf and upper slope off Argentina during cruises of the Spanish research vessel *Miguel Oliver* in 2007 and 2008 between approximately 44°40′S to 47°50′S and 59°W to 60°30′W (Fig. 1). The area is part of the terraced slope that developed in the middle Miocene between Rio de la Plata and the Falkland Islands (Hernández-Molina et al., 2009). Navigation data were acquired using differential GPS and a Seapath inertial navigation system. A Kongsberg-Simrad EM 302 multibeam swath-bathymetry system was used to acquire about

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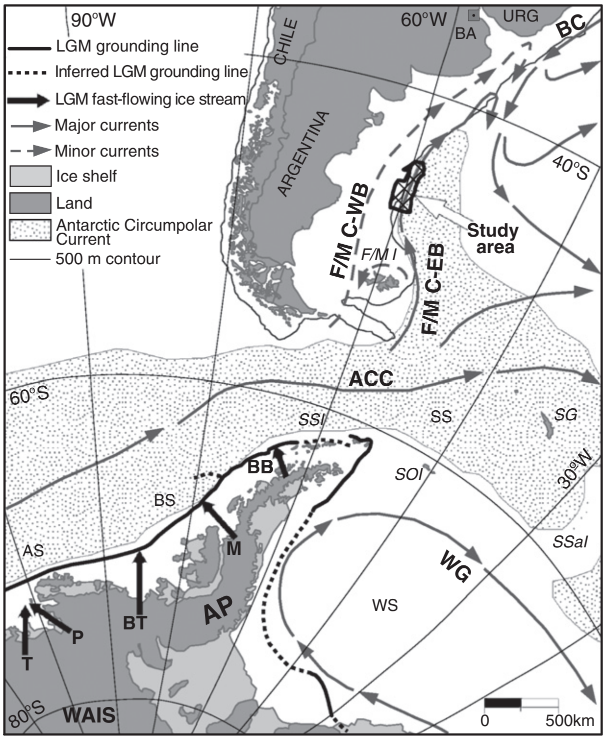

Fig. 1. Location and setting of the study area. Currents in the Southern Ocean and South Atlantic and iceberg sources on Antarctica, with the study area off Argentina shown. AP = Antarctic Peninsula, AS = Amundsen Sea; BA = Buenos Aires, BS = Bellingshausen Sea, SS = Scotia Sea, WS = Weddell Sea, WAIS = West Antarctic Ice Sheet, URG = Uruguay. Islands are: FI = Falkland Islands, SG = South Georgia, SSI = South Shetland Islands, SOI = South Orkney Islands, SSal = South Sandwich Islands. LGM ice streams are: T = Thwaites Glacier, P = Pine Island Glacier, BT = Belgica Trough Ice Stream, M = Marguerite Bay Ice Stream, BB = Bransfield Basin Ice Stream. Ocean currents are: BC = Brazil Current, F/MC-EB = Falklands/Malvinas Current Eastern Branch, F/MC-WB = Falklands/Malvinas Current Western Branch, ACC = Antarctic Circumpolar Current, WG = Weddell Gyre. Oceanographic information adapted from Orsi et al. (1995), Piola and Rivas (1997), Piola and Matano (2001) and Carter et al. (2009). Glaciological information adapted from Anderson (1999), Canals et al. (2000), Ó Cofaigh et al. (2005) and Evans et al. (2006).

34,000 km^2 of sea-floor bathymetric and morphological data, which were subsequently gridded at a horizontal resolution of 25 m and a vertical accuracy of about 0.4 to 1.5 m depending on the depth. Shallow sea-bed stratigraphy was obtained from a TOpographic PArametric Sonar (TOPAS) PS18 sub-bottom profiler operating at a centre frequency of 3.5 kHz.

2. Location, morphology and orientation of iceberg ploughmarks

The study area comprises a relatively flat continental shelf (<0.5°), with a well-defined shelf edge at about 150 m in water depth (Fig. 2A). To the east, the uppermost slope is relatively steep at between about 2° and 5°, with lower gradients of <1° beyond this. The sediments on the slope are part of a contourite depositional system built up since the Eocene (Hernández-Molina et al., 2009). The slope is dissected by seven large, branching and steep-sided (>10°) canyon systems up to about 500 m deep (Fig. 2A). Pockmarks up to 800 m in diameter are also present on the slope (Fig. 3D); this suggests the seepage of gas, as demonstrated in several TOPAS profiles that show acoustic tails associated with pockmarks.

The areas of the continental slope between the canyons contain over 2500 individual linear to curvilinear sea-floor landforms (Fig. 2). The landforms occur at modern water depths from 135 to 646 m (Fig. 2A, Table 1); about 85% are found between 250 and 550 m and 5% occur between 550 and 646 m (see histogram in Fig. 2A). Although many of the landforms have several segments with slightly varying orientations (we measured 2518 features, with 3407 segments of varying orientation), they have a very strong overall directionality from south to north (see rose diagrams in Fig. 2A). The length of individual linear landforms ranges from about 0.3 km to 32 km, with a mean of almost 2 km. Widths are between 73 and 685 m, with a negative relief range of 10–25 m and an average of about 15 m (Table 1).

Examination of shallow acoustic stratigraphy shows that the features are erosional (Fig. 3B–D) and some also have berms at their lateral margins that rise slightly above the general level of the sea floor (Fig. 3B, C). Some cross-cutting relationships are apparent (Fig. 3B, C), and there may be a thin veneer of subsequent hemipelagic sedimentation in some areas (Fig. 3D). Similar landforms do not occur on the shelf itself, which shows evidence of bedforms indicative of current activity (Fig. 2A).

The sea-floor landforms on the continental slope to 646 m water depth are interpreted as iceberg ploughmarks, formed by the grounding of submarine keels of icebergs that drifted northwards across the study area. They are similar in morphology and dimensions to both modern and relict iceberg ploughmarks observed in sea-floor sediments offshore of the Antarctic and Arctic (e.g. Stoker and Long, 1984; Barnes and Lien, 1988; Dowdeswell et al., 1992; Piper and Pereira, 1992; Dowdeswell et al., 1993; O'Brien et al., 1997; Syvitski et al., 2001; Kuijpers et al., 2007). Note that the recorded water depths in which ploughmarks occur are relative to modern sea level (Table 1), and that global sea level was about 120 m lower at the Last Glacial Maximum (e.g. Bard et al., 1990; Clark and Mix, 2002).

Individual ploughmarks on the Argentine margin show a variety of different forms when viewed in detail (Fig. 3). In some areas there are sets of linear grooves that are exactly parallel (Fig. 3C). These are interpreted as ploughmarks produced by a single iceberg with a multi-keeled base. The largest of these sets has three keels which have formed grooves totalling about 2 km wide (including inter-groove spacing) and up to 16 m deep in a water depth of 465 m (marked with a * in Fig. 3C). This implies a minimum width of 2 km for the iceberg base, suggesting that the mega-bergs were probably tabular. Some ploughmarks also display a "chevron-shaped" form, implying abrupt changes in drift direction of individual bergs that may be linked to grounding and ungrounding events (Fig. 3B–D). In most cases the new orientation is into deeper waters; an appropriate way to liberate a grounded iceberg. Two of the deepest ploughmarks in the study area, at 575 m water depth, are also chevron-shaped with grounding pits about 10 m deep at their shallowest points (Fig. 3D). We also show some of the most northerly observed ploughmarks in Fig. 3A. Sub-bottom profiles associated with several of these features show lateral berms above the general level of the sea floor and erosion of the acoustic stratification (Fig. 3B, C).

3. Timing of iceberg occurrence

There are no dates on sediment cores from the study area. Our many TOPAS profiles, with a resolution of 0.3 m and recorded simultaneously with multibean data, demonstrate that there has been very little or no sedimentation since the formation of the ploughmarks. The landforms are also well-preserved and clearly defined on sea-floor imagery (Figs. 2 and 3). We infer, therefore, that the ploughmarks were produced the last time relatively cold currents allowed icebergs to drift northwards to the southern Argentine margin; that is, at the last full-glacial period about 20,000 years ago in Marine Isotope Stage 2 (MIS2).

Dated sediment cores from between the Falkland Islands and South Georgia indicate the presence of limited numbers of relatively coarse-grained particles, inferred to be iceberg-rafted debris (IRD), during MIS2 (Ó Cofaigh et al., 2001). Unfortunately, other deep-drilling sites from the South Atlantic have low resolution for the latest Quaternary. There is also some evidence of IRD delivery to the deep south-east Atlantic Ocean at this time (Kanfoush et al., 2000). These