Marine Geology 386 (2017) 140–152

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Iceberg scours, pits, and pockmarks in the North Falkland Basin

Christopher S. Brown [a,d,*], Andrew M.W. Newton [a,b], Mads Huuse [a,b], Francis Buckley [c]

[a] School of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK
[b] Cryosphere Research at Manchester, University of Manchester, M13 9PL, UK
[c] Lloyd's Register Survey and Geoengineering Ltd., UK
[d] Department of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form 25 February 2017
Accepted 9 March 2017
Available online 10 March 2017

Keywords:
Icebergs
Scours
Antarctic Peninsula
North Falkland Basin
Pits
Pockmarks

ABSTRACT

Glaciation in the Southern Hemisphere is limited by the availability of land from which to seed ice sheets. The extents of the Antarctic, Patagonian, and New Zealand Ice Sheets at the Last Glacial Maximum (LGM) are relatively well known, although the rates and styles of their retreat after the LGM are poorly constrained, particularly in Antarctica. Offshore records of glaciation are relatively sparse in the Southern Hemisphere despite the potential ocean-climate insights that can be gained from records of glaciation that are preserved offshore. In this study, we document the occurrence of iceberg scours and accompanying pits within the North Falkland Basin (c. 50° S) and discuss their origin. The cross-sectional shapes of scours are u- to v-shaped and occur in present-day water depths of 280 to 460 m. Individual scours are up to 38 km long, 1 km wide, and up to ~10 m deep. The scours are observed as erosional linear to curvilinear depressions, showing only one point of contact between the iceberg and seafloor, often with raised berms, composed of excavated material, identified either side of the main depression. Undulating width of scours is interpreted as an effect of rotation of the iceberg keel during scour excavation. The elongate morphology of the scours differentiates them from asymmetrical pits, interpreted to represent iceberg impact pits, and symmetrical pockmarks, interpreted to form due to fluid expulsion. In cross-section the differentiation is highly interpretative, but the 3D bathymetric expression is unequivocal. The sinusoidal character of the scours suggests the interaction between local tidal currents and the East Falkland/Malvinas Currents in the North Falkland Basin at the time of formation. Offshore and onshore landscape analysis is used to determine potential sources of icebergs and suggests that they were most likely sourced from the Antarctic Peninsula. These results inform our understanding of Southern Hemisphere ocean-climate interactions during the last glacial cycle and suggest that the East Falklands/Malvinas Current, a key current in the Southern Hemisphere bringing cold, low-salinity Antarctic-derived waters into the South Atlantic, was in operation during the last glacial cycle. The accumulation of icebergs west of the Falkland Islands would also result in further cooling from fresh, meltwater perturbations, enhancing the development of a potential ice-bridge along the Argentinian coast.

1. Introduction

Iceberg scours are a common feature on many high-latitude margins and are formed when a floating iceberg becomes partially- or fully-grounded on the seafloor. Subsequent ocean currents, tidal changes, storms, subglacial drainage, and calving events can then drive the iceberg forward, scouring the seafloor, leaving a record of its trajectory behind (Bass and Lever, 1989; Woodworth-Lynas, 1996; Carlson et al., 2005; Goff and Austin, 2009; Newton et al., 2016). When iceberg scouring events occur, they provide insight into oceanic and glaciological conditions that can be indicative of past climate-ocean interactions on a range of spatial scales (Todd et al., 1988; Dowdeswell and Bamber, 2007; Newton et al., 2016). Their preservation within the geological record is thus significant for palaeo-environmental reconstructions from local to hemispheric scales.

In the Northern Hemisphere, a large number of studies have documented the occurrence of iceberg scours across multiple glaciated margins (Barnes and Lien, 1988; Syvitski et al., 2001; Goff and Austin, 2009; Sacchetti et al., 2012; Batchelor et al., 2013). Iceberg scours have also been found buried at several levels within the Pleistocene (Goff and Austin, 2009; Buckley, 2012, 2014; Dowdeswell and Ottesen, 2013), whilst some scour marks have been identified great distances from their prospective sources, reaching low- to mid-latitudes along the

* Corresponding author at: Department of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
E-mail address: CSB600@student.bham.ac.uk (C.S. Brown).

http://dx.doi.org/10.1016/j.margeo.2017.03.001

Southern US Atlantic margin (Duncan and Goff, 2001; Hill et al., 2008; Hill and Condron, 2014). In the Southern Hemisphere, comparatively few iceberg scour studies have been documented outside of Antarctica, with even fewer being documented at mid-latitudes (López-Martínez et al., 2011). At present, icebergs have rarely been recorded north of the Falkland Islands, with only giant icebergs capable of reaching warmer waters (Silva et al., 2006). In this paper, we document iceberg scour morphology, location, and potential sources for icebergs affecting the North Falkland Basin (NFB). The landform record is finally used to inform the palaeo-oceanography of the South Atlantic during the last glacial cycle.

Pockmarks and iceberg pits are circular features that share similar characteristics and are recorded around the world. Pockmarks are circular to elongate crater-like depressions that have been found in a range of marine settings, generally ranging from 10 to 250 m diameter (Pilcher and Argent, 2007). Pockmarks are related to fluid flow and form when fluid is expelled from the seabed in fine-grained sediment (Hovland and Judd, 1988; Dando et al., 1991). Iceberg pits are observed as circular to semi-circular depressions, created when an iceberg re-adjusts its hydrostatic equilibrium when melting, impacting the sea floor (Syvitski et al., 1996, 2001), or through the temporary grounding of an iceberg during low tidal conditions. Pits and pockmarks are distinguished on the basis of morphology, stratal relations and the association, or not, with subsurface fluid flow indicators (e.g. Cartwright et al., 2007; Løseth et al., 2009). In most cases this set of criteria allows the circular depressions to be related to either fluid flow or the movement of icebergs, but in some cases a clear distinction cannot be made on fully objective grounds.

2. Regional setting

The NFB is located on the Falkland Plateau, an extension to the Argentinian continental shelf, in water depths reaching up to 2500 m (Arhan et al., 2002), deepening northward and eastward (Fig. 1). The Falkland Islands represent a small proportion of the Falkland microplate (Mitchell et al., 1986). The earliest glacial sediment encountered on the Falkland Islands was deposited in the Carboniferous, when Gondwana was situated in southern polar latitudes and covered by ice sheets, with tillites and erratic boulders found (Stone, 2010). The NFB developed in the late Jurassic to early Cretaceous, during the disintegration of Pangea and extension of the South Atlantic, leading to lacustrine-fluvial conditions and the more recent marine setting (Richards and Hillier, 2000). Recently, during the Pleistocene, low sedimentation rates have been recorded on the Falkland Plateau (Barker et al., 1977), and along the Argentinian shelf (López-Martínez et al., 2011). It is therefore assumed in this study that sediment accumulation has been low throughout the Pleistocene.

Ocean currents in the South Atlantic are a crucial component of the global thermohaline circulation. In addition to the North Atlantic, deep-water production is also found in the Weddell and Ross Seas off of Antarctica. In the western side of the South Atlantic, deep- and bottom-water flows between the North Atlantic and the Antarctic Circumpolar Current (ACC) result in large fluxes of heat between different latitudes and the different hemispheres (Rahmstorf, 2002). The ACC is a major current in the South Atlantic, due to its high influence in sub-Antarctic waters (Fig. 1). It is an eastward-flowing current, connecting all of the Earth's major oceans and is driven by westerly winds at latitudes of 45°–55° S (Trenberth et al., 1990; Orsi et al., 1995). The ACC circulates the Antarctic Peninsula and represents an important region of transition between Antarctic and sub-Antarctic waters (Meinardus, 1923; Nowlin and Klinck, 1986).

3. Data and methods

Five high-quality 3D seismic datasets, covering an area of 1550 km^2 (Fig. 1) were used, focusing on a geomorphological analysis of the seafloor and the shallow subsurface, in water depths of 300–500 m. The 3D datasets were acquired during an exploration campaign between 2010 and 2011, by Desire Petroleum and Rockhopper Exploration (MacAulay, 2015; Subsea IQ, 2017). The Polarcus Nadia; a 12 streamer 3D seismic vessel, that uses dual sources and a multi-streamer Sercel Seal Marine Data Acquisition system, was used to obtain the data (Polarcus, 2017; Subsea IQ, 2017). In the near seabed sediment, using a velocity of 1800 m/s, the 3D seismic data have a frequency of 30 to 50 Hz, a vertical resolution of ~15 to 9 m and horizontal resolution of 30 to 18 m respectively. Supplementary 2D seismic lines were also used, which cover several different parts of the margin (Fig. 1b). This is legacy data with a typical resolution of ~20 to 40 m and is provided through the British Geological Survey and the Falkland Islands' Department of Mineral Resources.

Data were analysed using Petrel software, ArcGIS, and Microsoft Excel. Curvilinear and sinuous features interpreted as iceberg scours, and pitted features interpreted as pockmarks and iceberg pits, were identified on the seafloor using surface attributes such as depth, amplitude, dip and dip-azimuth, and a variable light source in order to highlight the more subtle morphologies on the gridded surfaces. These features were then digitised and exported to ArcMap where their geometries were analysed. In order to consider prospective source locations for the icebergs, satellite imagery and topographical analysis in Google Earth were used in combination with published literature to assess the most likely location of the parent ice sheet.

We infer that the freshness and lack of reworking of the scours suggests that they are a relatively recent formation and that they probably formed during the Last Glacial Maximum (LGM) and the ensuing deglaciation, when large ice sheets were available to seed deep-keeled icebergs in such quantity. However, given the low sedimentation rates, it is possible that some scours are relicts from prior glaciations.

4. Characterisation of seabed erosion features and their origin

All the seabed depressions found in this study share a cross-sectional morphology ranging from u- to v-shaped. Iceberg scours are easily distinguished based on 3D seismic or multibeam bathymetry and sidescan data or 3D seismic timeslices due to their curvilinear to sinusoidal planform, whereas iceberg pits and pockmarks are more difficult to distinguish, given both are largely circular in plan view. Though pockmarks and iceberg pits have a similar morphology, they form through different means; pockmarks are related to fluid expulsion, whilst pits are related to the movement of icebergs in the water column. The depressions can be distinguished by their relationship (or not) with fluid-flow indicators, location, stratigraphic and palaeo-environmental context, symmetry, diameter, and seismic distortion. These characteristics are mostly not unequivocal so the full suite of characteristics is used to distinguish the two types of features and even then may result in an ambiguous partitioning.

Iceberg pits are only found in sediment exposed during glacial or post glacial conditions, forming when icebergs periodically impact the seafloor due to instabilities caused by buoyancy or changes in water depth. In this study, iceberg pits are generally found on the seafloor or just below it. Pitted features are usually concentrated in proximity to iceberg scours, due to instabilities created by buoyancy (Dowdeswell et al., 1993; Syvitski et al., 2001). Pits can also be identified in linear arrays, typically referred to as crater- chains, forming as an iceberg repeatedly hits the seafloor (Bass and Woodworth-Lynas, 1988). Iceberg pits are often surrounded by a berm consisting of ejected material (Fader et al., 1988; Mortensen and Buhl-Mortensen, 2004). As an iceberg becomes grounded, sediment is excavated in an upward and outward motion caused by the iceberg keel ploughing the seafloor (Eden and Eyles, 2001; Van Landeghem et al., 2009). Sediment is then deposited on the far side of the pit as a berm or rim, causing asymmetry. Pits can vary in diameter and have been found ranging in diameter between 10 and 700 m (Geirsdóttir et al., 2008; McKenzie et al., 2013). They are usually