EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 84 NUMBER 11 18 MARCH 2003

Uncovering the Footprint of Former Ice Streams off Antarctica

Antarctic ice sheets and ice caps have been expanding and contracting following global climatic cycles. The last time the Antarctic ice cover peaked, at least in Western Antarctica, was ca. 21 ky ago during the Last Glacial Maximum (LGM). The strong warming (nearly 2.8°C) over the past 50 years, and the yearly recent collapse of limited portions (hundreds to a few thousands of square miles per event) of ice shelves around the Antarctic Peninsula have brought to the headlines the debate about the potential collapse of the West Antarctic Ice Sheet (WAIS) in the near future under the influence of global warming.

> Ice streams are a key element to solve the puzzle linking ice sheet stability, sea level rise, and climate change at a global scale.

Such a catastrophe would substantially contribute to global sea level rise (a resulting 5 m increase is expected); alter water mass conditions, circulation, and productivity around Antarctica and in the world ocean; and modify the Earth's climate. The economic, social, and ecological impacts of these changes would depend greatly on the rate at which they might take place [*Bindschadler*, 1998]. A detailed knowledge of the past extent of ice sheets and the timing of their advances and retreats thus becomes essential to quantify the rates of change and to properly assess the future stability of the WAIS and nearby ice caps. The stability of ice sheets is largely dependent on ice drainage, which mostly occurs via ice streaming along glacial troughs. Ice streams are thus a key element to solve the puzzle linking ice sheet stability, sea level rise, and climate change at a global scale.

Because of its low latitude and maritime climatic setting, the northern Antarctic Peninsula (NAP) is the warmest region in West Antarctica, and overall, has lost two thirds of its ice mass since the LGM [*Bindschadler*, 1998]. As a consequence of the ice retreat, large, formerly ice-covered areas are now exposed on the post-glacial sea floor. Ice streams—parts of an ice sheet where ice flows more rapidly than in surrounding regions—played a key role in sub-glacial erosion and transport carrying huge amounts of sediment from continental and inner shelf source areas to the outer continental margin around Antarctica. Sub-sea floor sedimentary sequences in the same region hold the record of repeated episodes of ice streaming. A sound combination of techniques able to image the sea floor and the sub-sea floor at various resolutions and penetrations is required to understand how these glacial systems worked. This implies undertaking full coverage surveys at a scale of thousands of km^2, larger than those attempted in previous surveys of the Antarctic margin.

Sea Floor Evidence of Ice Streaming

The first unequivocal evidence of mega-scale (10^3-10^5 m in length) sea floor structures formed under ice streams on the continental margin came with a multi-beam reconnaissance of the outlet of the Gerlache Strait, in the Western Bransfield Basin (BB). A >100-km-long, 14-to-21-km-wide flow-set of streamlined bedforms (bundles) indicated that ice flow excavated the continental shelf to depths over 1000 m before spreading toward the outer shelf [*Canals et al.*, 2000]. Mega-scale, sub-glacial bedforms indicate flow direction and basal ice flow conditions. Minimum ice thickness and volume can be estimated from the depth of the bedforms on the modern sea floor, minus the sea level lowering at the time of their formation. Sea floor streamlined bedforms can show parallel, convergent, divergent, and crossing patterns, and allow estimations of their relative age.

Glacial systems and ice stream dynamics are driven by a number of factors, including sub-glacial geology and topography, ice surface slope, climatic setting, and the marine or continental character of the terminus of the system. Sub-glacial geology controls ice-base

Ice Streams cont. on page 102

BY THE COHIMAR/SEDANO SCIENTIFIC PARTY

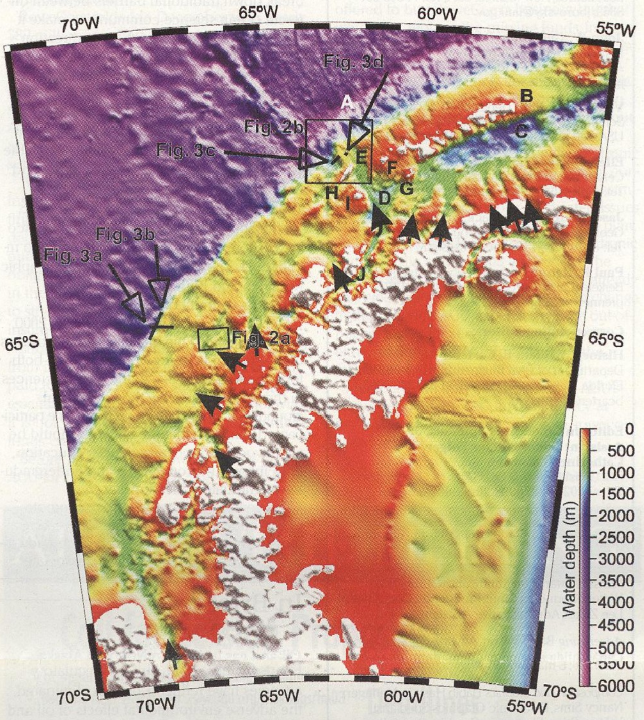

Fig. 1. Shaded relief image of the northern Antarctic Peninsula region. Black arrows point to the main glacial troughs. A: South Shetland Trench. B: South Shetland Islands (Is.). C: Central Bransfield Basin. D: Western Bransfield Basin. E: Boyd Strait. F: Snow Is. G: Deception Is. H: Smith Is. I: Low Is. J: Gerlache Strait. Black boxes show location of Figures 2a and 2b. Location of Figures 3a to 3d is also shown.

Does the Mesozoic Dipole Low Really Exist?

Documenting variations in the virtual dipole moment (VDM) of the geomagnetic field through geologic time has recently been the subject of considerable interest, not the least because a detailed and reliable VDM record would provide a key constraint for geodynamo modeling. Such a record would also inform the debate concerning issues related to Earth's geodynamic evolution, such as how the geomagnetic field responds to stages in supercontinent cycling. The relationship between variations in geomagnetic polarity and field intensity with lowermost mantle (LMM) processes is fundamental, but the paucity of the VDM record has focused research on the links between polarity and LMM processes. Nonetheless, authors agree on the crucial need to produce a detailed VDM record in which we can place sufficient confidence to allow these major issues to be addressed [e.g., *Biggin and Thomas*, 2003; *Heller et al.*, 2002; *Riisager et al.*, 2002; *Tarduno et al.*, 2001; *Selkin and Tauxe*, 2000].

One proposed major feature in the VDM record is the so-called Mesozoic Dipole Low (MDL), during which the VDM appeared to be about one-third of its present value for a period of at least 50 m.y. [*Prévot et al.*, 1990]. The validity of this feature has recently been questioned by *Goguitchaichvili et al.* [2002a,b], who concluded that the MDL hypothesis is probably untenable. This conclusion was reached following an analysis of the 160–5 Ma part of the VDM record and the recognition that the Early Cretaceous VDM may have been similar to, or possibly much higher than, the current value (Figure 1). *Goguitchaichvili et al.* [2002a,b] present valuable new data and an addition to the general debate, but unfortunately, they reach their conclusion by using potentially flawed reasoning. In this article, we present an alternative argument, concluding that a temporally significant period of low VDM did exist during the Mesozoic.

The MDL Debate: A Brief Summary

Prévot et al. [1990] suggested the existence of a 'Mesozoic Dipole Low,' although their analysis was unable to identify the precise age of the MDL extremities. They suggested that its onset may have followed a high field period during the Early Jurassic, and its termination may have been linked to a major dissociation of D" at around 100 Ma. *Perrin and Shcherbakov* [1997] were unable to distinguish, statistically, between two lows (separated by a brief return to high values) or a single low in

BY D. N. THOMAS AND A. J. BIGGIN

Mesozoic Dipole Low cont. on page 103

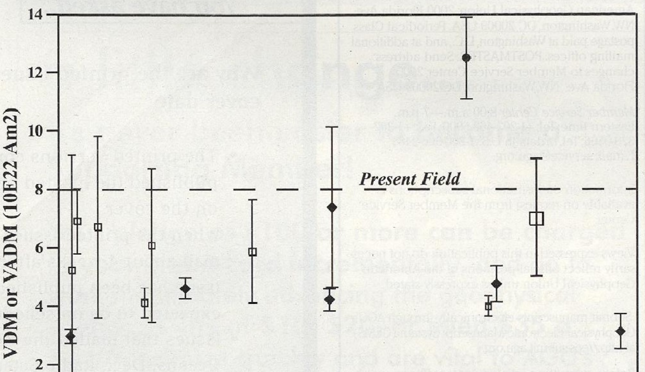

Fig. 1. The mean Virtual Dipole Moment (VDM) and Virtual Axial Dipole Moment (VADM) from 160–5 Ma (from Goguitchaichvili et al., 2002b, with permission). Open squares represent mean VDMs from continental lava flows, diamonds represent mean VADMs from submarine basaltic glass, and closed circles represent a Mean VDM from single plagioclase crystals. The 160–5 Ma portion of the Geomagnetic Polarity Timescale is shown at the base of the figure.

Ice Streams

cont. from page 97

topography and roughness, and the production of debris that could be incorporated into basal tills. Basal ice-flow conditions change substantially if ice is grounded on bedrock or on sediment. The slope angle both of the ice base and the ice surface determines the gravitational effect on flow speed and the generation of frictional heat. The climatic setting influences meltwater production at the ice boundaries and inside the ice mass. It also determines precipitation rates, thus governing losses and gains of the ice mass. In the long term, climate determines the stability of glacial systems. Marine terminating ice streams and glaciers are particularly sensitive to sea level fluctuations, causing them grounding and degrounding on the sea floor.

The Long-term Record

The extension and transport efficiency of sub-glacial depositional systems must be directly related to the waxing and waning of grounded ice sheets. In parallel, mega-scale streamlining must have occurred repeatedly since the onset of glaciation in Western Antarctica, sometime before 10 MY ago.

To elucidate the long-term history of glaciation, it is necessary to investigate the sedimentary sequences that hold the record of ice volume fluctuations. Dip-oriented, penetrative, multi-channel seismic reflection profiles have shown large erosional surfaces on the continental shelf at depths far below the range of eustatic sea level fluctuations.

The association of an over-deepened, landward sloping continental shelf with an over-steepened continental slope were considered univocally as indicators of sedimentation under the influence of an ice shelf grounded on the continental shelf edge. However, identification of these morphometric characters in the deep seismic record becomes more difficult.

Earlier interpretations of deep penetration seismic reflection profiles were questioned by single-channel, higher-resolution profiles parallel to the margin. These revealed a previously unknown depositional and erosional lateral variability on the glaciated continental shelf, suggesting dramatic spatial shifts of glacial erosion within ice troughs through geological time [*Bart and Anderson*, 1995]. In addition, huge sedimentary mounds on the upper continental rise separated by deep turbidity channels were found to be systematically associated to glacial lobes and interlobe segments on the shelf edge. This gave support to the view that shelf-grounded ice sheets also had a profound influence on deep-sea sedimentation [*Rebesco et al.*, 1996].

Strategic and Technical Approach

An offshore survey onboard the R/V *Hesperides* was carried out (November 2001 to January 2002) on areas where large ice streams developed off major glacial troughs (65 to 500 km long, up to 70 km wide, and 1 km deep) on the NAP Pacific margin (Figure 1). Because of the large size of the glacial systems to be investigated, the research effort focused on the southern Biscoe and Gerlache-Boyd Trough systems (Figures 1, 2a-b). Southern troughs differ from those opening to the Central BB because they shallow toward a 400–500-m-deep lobate shelf edge, while the Central BB ones progressively deepen down to an 800–900-m-deep shelf edge [*Canals et al.*, 2002].

During the survey, a battery of nested techniques was used to image the imprint of the LGM ice streams on the modern sea floor and to unveil the internal structure, extent, and distribution of older glacial and pre-glacial deposits. Simrad EM12S swath bathymetry and parametric profiles imaged with excellent resolution the sea floor and the uppermost sedimentary units recording the deglaciation and post-glacial history. Sub-sea floor imaging was achieved by an intermediate-resolution, 96-channel seismic reflection system. One or two tuned GI guns provided a narrower seismic signature than those traditionally employed in multichannel surveys on the Antarctic margin. The reflected signal was collected with an ITI solid state streamer with a nominal horizontal resolution of 3 m. Both source and streamer were towed to preserve the highest recordable frequencies.

A SIG-120 single-channel streamer collected the highest frequencies produced by the GI guns, thus covering the gap in between parametric records and multichannel seismics. As a general strategy, in order to obtain the best representation of the buried geological structures with respect to recent ones, seismic profiles run along lines planned on the onboard processed multi-beam bathymetry.

From Bedrock to Shelf Edge Sediment Lobes

The Biscoe Trough system (170 km long, 23–70 km wide) runs ESE-WNW slightly south of the 65°S parallel (Figure 2a). It consists of three branches with up to 800-m-deep axial overdeepenings. A structurally controlled prominent "mid-shelf high" (MSH) crosses the main branch in a SW-NE direction. MSH fault displacement at the sea floor is about 300 m in this sector. Upper and mid-course trough boundaries are steep and straight, with local elevations in excess of 600 m with respect to < 200-m-deep side banks. Topography becomes progressively smoother toward the shelf edge, at 450–500 m depth.

Spectacular, fan-shaped streamlining floors the upper and mid-trough course, thus revealing past ice flow (Figure 2a). An innermost segment displays poorly organized lineations on hummocky sea floor bedrock. The smoother downstream segment until the MSH shows more organized lineations and a step-like pattern attributed to abraded stratified formations resembling roches moutonnees. We do not interpret these bedforms as drumlins because of the rocky nature of the sea floor, as seen on seismic reflection profiles. West of the MSH, glacial lineations form a bundle that smoothens till subduing toward the shelf edge. While lineations exiting from the SE branch are cut by those from the more efficient main central trough, kilometer-long iceberg plough marks point to the SE branch as the main iceberg source area during deglaciation.

The 5–20-km-wide Gerlache-Boyd Trough system extends for 340 km. Compared with the Biscoe system, it is larger, deeper, much more topographically constrained, and experiences marked direction shifts (Figure 1). The Gerlache-Boyd system first follows a NE-NNE direction, then turns northward, and finally takes a NNW direction toward the Boyd Strait and the shelf edge over the 4600-m-deep South Shetland Trench (Figures 1, 2b). Whereas the upper NE-NNE-oriented reach is strongly constrained between the mountainous Palmer Archipelago and the NAP, the middle-lower N to NNW reach is constrained between the shallower shelves of Smith-Low islands and Deception-Snow islands [*Canals et al.*, 2000].

Seaward of topographic constrictions, a large outer continental shelf lobe north of Smith Island has been imaged (Figure 2b). Its location downstream of the bundle structure described by *Canals et al.* [2000] and its flat-topped character suggest that streamlining is somehow controlled by lateral topographic constrictions of the ice flow. On the outer shelf, unconstrained ice can spread and shift laterally, probably in association with a lowering of its profile and till sheet deposition. Lobe progradation (>40 km for the Boyd shelf edge lobe) results in steep upper continental slopes (Figure 2b). Three depositional terraces on the western flank of the Boyd lobe probably represent major till sheet units with an overall minimum thickness of about 600 m. The lower continental slope off the Boyd lobe displays a smoothened topography that strongly contrasts with the uneven slope behind Smith Island, where glacial sediment cover is absent. The lack of lobe development northwest of Smith Island proves that such an island acted as a barrier to ice flow, which prevented basal till deposition.

Windows to the Distant Past

Many advantages result from locating seismic lines over a detailed bathymetry. Profiles along glacial trough axis yield the longest seismic records before arrival of secondary returns (multiples) and penetrate into the oldest sedimentary sequences favored by ice stream trough axis erosion. This is crucial near the shelf break where a window to the pre-glacial margin may open. Contrary to the typical progradational nature of the glacial continental slope, a buried aggradational paleo-slope appears in obvious geometric discordance with the overlying inferred glacial till units (Figure 3a). By following the 1000-m isobath along the upper continental slope, we obtained a cross-section of this deeply incised paleo-slope (Figure 3b). This suggests that prior to the Plio-Pleistocene main phase of margin progradation, there was a high-energy sedimentary system that dissected a pre-glacial or incipient glacial margin. Because there is no evidence of a drastic change of sedimentary regime in the deep sea in the 10 MY glacial record of the NAP Pacific margin, we suggest

Ice Streams cont. on next page

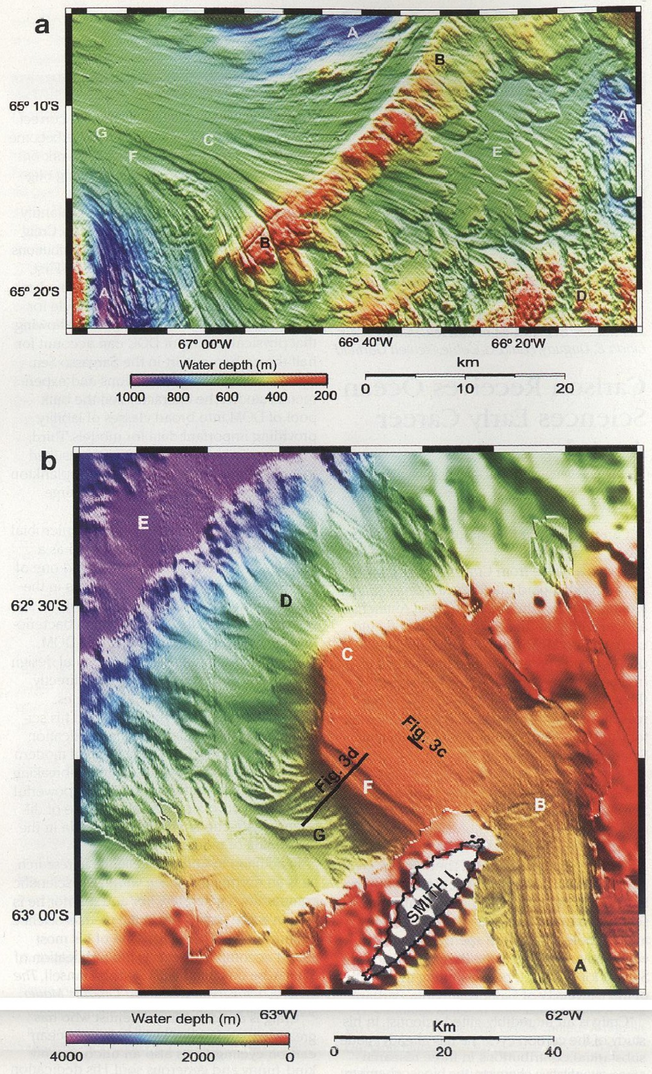

Fig. 2. a: Shaded relief image of the Biscoe Trough system. Main ice flow was from ESW (right) to WNW (left). A: axial overdeepenings. B: Mid-shelf high. C: subglacial, fan-shaped streamlining (bundle structure). D: Poorly organized lineations on hummocky sea floor bedrock. E: roches moutonnees on abraded stratified bedrock. F: NNW-oriented streamlines from the SE branch (violet and blue colors) cut by WNW-oriented streamlines from the main central branch. G: kilometer-long iceberg plough marks made by icebergs exiting from the SE Biscoe branch during deglaciation. b: Shaded relief image of the outer shelf lobe seaward of the Gerlache-Boyd Trough made from swath data (higher resolution main central area) combined with Smith and Sandwell *(1997) data (lower resolution areas). Main ice flow was from S to N up to the latitude of Smith Is. and then turned northwestward to the shelf edge. Note the lack of glacial sedimentation on the continental slope northwest of Smith Is., which behaved as a barrier against ice flow. A: Mega-scale streamlining (bundle structure). B: Boyd Strait. C: Prominent outer shelf till lobe. D: Continental slope off C. E: South Shetland Trench. F: Glacial depositional terraces on the western flank of the Boyd lobe. G: Uneven slope behind Smith Is. Solid lines show location of seismic reflection profiles on Figures 3c and 3d. SE-NW parallel stripes on top of the Boyd lobe are artifacts.*

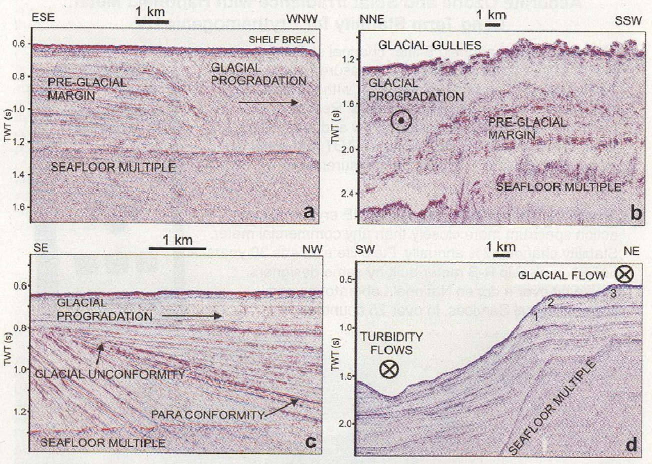

Fig. 3. Selected segments from multichannel seismic reflection profiles acquired during the COHIMAR-SEDANO cruise. a: Buried aggradational Biscoe paleo-slope, interpreted as pre-glacial, separated from overlying glacial units by a prominent discordance. b: Along slope section illustrating the deeply incised nature of the older Biscoe continental margin, interpreted as pre-glacial. c: Pre-glacial tilted strata over the Boyd lobe. d: Southwestern lateral termination of the Boyd outer shelf lobe showing three depositional terraces (numbered 1, 2 and 3) resulting from ice sheet advances and retreats.

Mesozoic Dipole Low

cont. from page 97

260–120 Ma period. They also addressed the issue of MDL reliability, recognizing that many authors were skeptical of its existence. Their analysis of cooling unit data from 260–120 Ma confirmed the dipolar nature of the field during this time, and concluded that the MDL could not have resulted from insufficient sampling of a Neogene-type field. This reinforced the credibility of the MDL as a true long-term feature of the field.

In a subsequent study, *Selkin and Tauxe* [2000] only accepted paleo-intensity data derived using the Thellier method, with pTRM checks for laboratory-induced thermal alteration (so-called T+ estimates). They concluded that there was, in fact, no long-term variation in dipole moment from 300 Ma–0.3 Ma, and that the dipole field intensity averaged about 63% of its present value during this time period. They regard the dipole field during the Mesozoic to be of "average" rather than "low" strength. However, both *Heller et al.* [2002] and *Biggin and Thomas* [2003] reject the Selkin and Tauxe model for reasons discussed later.

Paleo-intensity studies of southern hemisphere Mesozoic intrusions and rocks from the Permo-Carboniferous reversed superchron [e.g., *Thomas et al.*, 1998; 2000] support the idea that the 'MDL' may be part of a generally weak, pre-Tertiary field (the Pre-Cenozoic Dipole Low). Subsequent analysis of an enhanced version of the data base by *Heller et al.* [2002] concludes that the existence of a MDL cannot be discounted on statistical grounds. The study of *Biggin and Thomas* [2003] confirms that a low VDM did exist for at least 50 m.y. during the period 250–50 Ma, with a minimum value at ~170 Ma, but that the extremity ages cannot be precisely constrained by the currently available data. It appears, then, that the only major statistical study to claim the absence of a Mesozoic Dipole Low is that of *Selkin and Tauxe* [2000].

Criteria for Data Selection

The identification and interpretation of long-term features in the VDM record relies heavily on the criteria used for accepting data. While it is essential to eliminate poor quality and unreliable data, it is also important to use the remaining available data to their full potential. It is generally agreed that any credible data set, in order to be used for the above purpose, must contain data satisfying certain basic criteria related to dating, paleomagnetic inclination, identified polarity, and paleo-intensity technique. The details of these criteria are well documented in the major statistical analyses of the record.

Satisfaction of these basic criteria will eliminate obviously unreliable data, but it is at the next stage of filtering that various studies differ in approach. Many recent investigations e.g., *Goguitchaichvili et al.*, 2002a; *Riisager et al.*, 2002; *Selkin and Tauxe*, 2000 do not consider paleo-intensity estimates produced using non-T+ methods. This blanket exclusion alone eliminates ~80% of potentially suitable data in the period 400–10 Ma and may well lead to aliasing of the record. Furthermore, it does not ensure that the remaining data are reliable, which increases the potential for biasing the record. The use of pTRM checks offers an extra safeguard against alteration occurring in the laboratory and should, therefore, be standard procedure in paleo-intensity experiments. However, such checks do nothing to warn against adverse effects resulting from non-single-domain grain size [e.g., *Calvo et al.*, 2002], non-thermal origin of remanence [e.g., *Heller et al.*, 2002; *Goguitchaichvili et al.*, 1999], or faster cooling rates in the laboratory than in nature [e.g., *Thomas et al.*, 2000]. Therefore, paleo-intensity estimates acquired using the T+ method are not guaranteed to be reliable.

Equally, estimates produced without the use of pTRM checks are certainly not guaranteed to be unreliable. In fact, laboratory-induced alteration is often (though not always) associated with a curvature of the NRM-TRM (Arai) plot, and hence may be observed in samples regardless of whether pTRM checks are used. Therefore, it seems totally unreasonable to reject over three-quarters of the available data solely due to the absence of pTRM checks. Indeed, doing so makes the data selection process dangerously counter-productive in the context of identifying long-term VDM evolution.

An Alternative Approach to Data Acceptance

Biggin and Thomas [2003], like *Perrin and Shcherbakov* [1997], use a self-consistency criterion instead of a T+ filter to produce

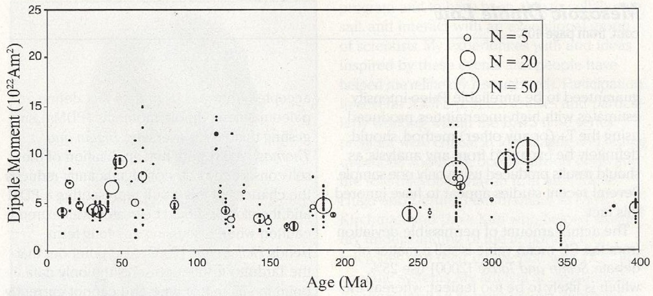

Fig. 2. Plots of cooling unit (CU; black) and rock suite (RS; clear) data for the three groups of data described fully in Biggin and Thomas [2003]. The size of each RS point is proportional to the amount of CU data it comprises and a representative scale is provided for each plot (from Biggin and Thomas, 2003, with permission).

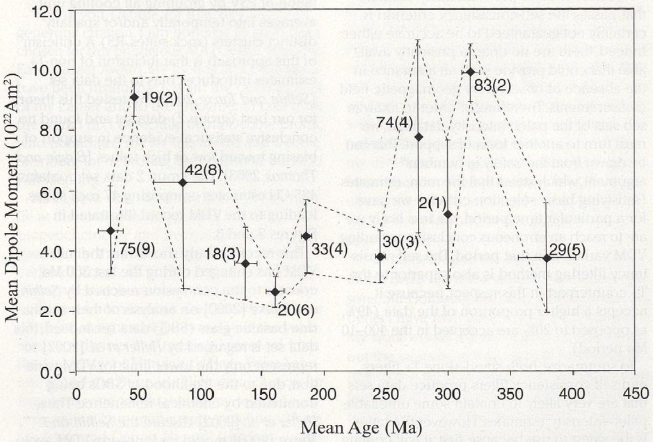

Fig. 3. Plots of the mean ages and dipole moments of all segments from the group 2 data set of Biggin and Thomas [2003]. The error bars indicate the standard deviation of each value and are representative of variation rather than uncertainty. The number of cooling unit estimates that comprise each segment and its corresponding number of rock suites (in brackets) are shown next to each segment mean. Dashed lines join the limits of segment means ± standard deviations to highlight the patterns of variation currently shown by the data set (from Biggin and Thomas, 2003, with permission).

their selected data set. The justification for this is simple; there is no geomagnetic reason for paleo-intensity estimates derived from 'ideal' samples in, for example, the same lava flow or baked sediment, to yield widely varying results. However, non-ideal sample behavior resulting from one or more of the adverse processes outlined above may well lead to widely differing results. Cooling units that fail the self-consistency criterion are therefore

Mesozoic Dipole Low cont. on page 104

Ice Streams

cont. from page 102

that this buried continental margin is pre-Late Miocene, most likely pre-glacial.

The Boyd glacial wedge is underlain by a tectonic discordance produced by tilting of inner shelf strata that vanishes seaward (Figure 3c). This implies continuous sedimentation on the outer shelf over a long time span. Likely pre-glacial terrigenous deposition in the South Shetland fore arc basin has gradually changed into pro-glacial sedimentation under the influence of the prograding Gerlache-Boyd ice stream. Seismic imaging (Figure 3d) of the three morphological terraces (see above) reveal that the latest glacial advances originated by the Gerlache-Boyd ice stream carried a lower sediment volume than the previous ones. This is in accordance with the general steadily decreasing sedimentation rate observed in the deep sea all around the Antarctic margin [*Barker et al.*, 1999]. Our data refute the hypothesis of increased sediment trapping on the continental shelf to explain lower provision of sediments to the outer continental margin during glacial advances.

Implications and Future Developments

The difficulty in understanding the past glacial record of Antarctica does not reside only in the remoteness and hostile environmental conditions researchers have to cope with. There is also a lack of an actualistic model for glacial stages shaping and outbuilding Antarctic margins. With the exception of local innermost continental shelf settings, interglacial stages are widely recognized to represent periods of sediment starvation. As a consequence, preservation of the relict glacial topography after lift-off of the grounded ice sheet is favored on most of the margin.

Present Antarctic margin morphology is largely inherited from the LGM, with glacial bedforms eventually capped only by thin veneers of post-glacial sediment. The understanding of the LGM glacial marine processes at the ice-sediment interface, as well as beyond the grounding line down to the deep sea, is essential to the reconstruction of the Antarctic glacial history.

The scale of the glacial bedforms identified on the NAP margin suggests that ice streaming on the continental shelf is, per se, a mega-scale process. Therefore, its study has to be addressed through full bathymetric coverage of very large sectors of the margin from the inner shelf to the deep sea. Nested seismic reflection profiling makes an ideal complement to elucidate the record of past glaciations. Paleo-ice stream research around Antarctica is still in its infancy. Crude general bathymetric maps such as *Smith and Sandwell's* [1997] make it obvious that large glacial troughs, where old ice streams were located, are common on most Antarctic continental shelves. Ice streaming has had a profound impac,t both on modern continental shelf morphology and on margin construction.

Massive iceberg releases probably related to ice streaming correspond to some of the most important paleoceanographic events (e.g., Heinrich events) in the North Atlantic [*Stokes and Clark*, 2001]. Our data strongly suggest that widespread, repeated events of that nature must have occurred all around Antarctica, although their record in Southern Ocean deep sea sediments remains to be unveiled. Incorporating the ice stream concept on climatic and ice cover numerical models is of enormous importance in that challenge too.

Acknowledgments

The authors thank the Commandant, crew, and technicians onboard the R/V *Hesperides*. Supported by the Spanish (ref. REN2000-0896/ANT), Italian, and Belgian Antarctic programs, Fulbright Commission GEMARANT project, and Generalitat de Catalunya GRC grant 2001SGR-00076.

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