Margin architecture reveals the transition to the modern Antarctic ice sheet ca. 3 Ma: COMMENT AND REPLY

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Rebesco et al. (2006) present multichannel seismic (MCS) reflection profiles showing a regional change in the style of margin accretion on the Pacific margin of the Antarctic Peninsula (PMAP), and estimate an age of ca. 3 Ma for this change by correlation with Ocean Drilling Program (ODP) Site 1101. They also review seismic stratigraphy and drilling results from other Antarctic margins and suggest that changes in several places were associated with a transition from wet- to dry-based ice regimes that affected the whole ice sheet synchronously. The prominent shelf-slope unconformity on the PMAP highlighted by Rebesco et al., however, is significantly older than they estimate, and glaciological considerations make a synchronous, continent-wide change in basal ice conditions unlikely.

By tracing seismic reflections more than 100 km beneath the upper continental rise and slope, Rebesco et al. correlate sediments at ODP Site 1101 (aged 2.9 ± 0.2 Ma) with a continental shelf and slope unconformity that marks a regional change in the style of margin accretion. They interpret this unconformity as the boundary between sequence groups S1 and S2 in the stratigraphic scheme of Larter and Barker (1989, 1991). Regionally, however, the main change in stratal geometry on the PMAP occurred earlier, at the S2-S3 boundary (Larter et al., 1997; Hernández-Molina et al., 2006). Moreover, the change in stratal geometry at the unconformity highlighted by Rebesco et al. is typical of the S2-S3 boundary: aggrading sequences with paleo-shelf breaks that are gently curved in profile exist immediately below the unconformity, while above it, the sequences prograde, have sharp paleo-shelf breaks, and have forset reflections that downlap onto the unconformity. S1 to S3 were originally defined on a network of MCS profiles centered ~150 km northeast of the profiles presented by Rebesco et al. S1 pinches out at the seafloor when traced along shelf seismic profiles running southwest from that area; so it may be thin or absent on the shelf in the area in question. Indeed, the sequence boundary with a paleo-shelf edge 1 km landward of the modern shelf break on Line 281 of Rebesco et al. exhibits characteristics typical of S1-S2.

If the unconformity Rebesco et al. highlight is indeed the S2-S3 boundary, results from continental shelf ODP sites 1097 and 1103 indicate a late Miocene age. At Site 1097, ~200 km southwest of the MCS lines presented by Rebesco et al., the change in stratal geometry Larter et al. (1997) interpreted as corresponding to S2-S3 (unconformity 3.13 of Bart and Anderson, 1995) was drilled at 310 mbsf (Bart et al., 2005). Diatom zones identified at Site 1097 (Iwai and Winter, 2002) constrain the age of this boundary to be between 6.12 and 7.94 Ma. At Site 1103, in the area where S1 to S3 were originally defined, diatom zones (Iwai and Winter, 2002) and Sr isotope dating of barnacle fragments (Lavelle et al., 2002) constrain the youngest S3 sediments to be within the same age range, although S2 is absent at this site. The discrepancy between these ages and the age derived by Rebesco et al. through seismic correlation to Site 1101 may in part be due to the inescapable ambiguity in seismic correlation through the slope, resulting from extensive downlap of reflectors onto the unconformity in question. The discrepancy may also partly reflect the difficulty in tracing sequence boundaries through the zone of major facies changes at the base of the continental slope and beneath the erosionally dissected upper rise.

The occurrence of melting at the base of an ice sheet depends on basal temperature and pressure, which in turn are affected by a range of parameters including ice thickness, surface temperature, accumulation rate, geothermal heat flow, and amount of heating from internal strain and basal sliding. The variations in these parameters across Antarctica make it unlikely that there was ever a synchronous, continent-wide change in basal ice conditions. Thus, while climatic changes were probably the ultimate cause of changes in patterns and rates of sedimentation around Antarctica in the late Miocene and late Pliocene, a continent-wide change in basal ice conditions is an improbable mechanism. Observations of the modern ice sheet show much heterogeneity in flow (e.g., Bamber et al., 2000) and therefore in basal regimes. Thus, the past ice sheet was probably similarly heterogeneous. The discovery of a large number of paleo-ice streams on Antarctic margins in recent years supports this view.

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In his Comment, Rob Larter (2007) notes that the main change in stratal geometry within the Pacific margin of the Antarctic Peninsula (PMAP) occurred at the S2-S3 boundary, earlier than we estimated in our 2006 *Geology* article. Moreover, he argues that a synchronous, continent-wide change in basal ice conditions on Antarctica is unlikely.

We agree with Larter that a change in stratal geometry on the continental shelf of the PMAP occurred between 6.12 and 7.94 Ma at the S2-S3 boundary, which separates aggrading sequences with gently curved paleo-shelf breaks (below) from prograding sequences with sharp paleo-shelf breaks (above). This change, identified and defined by Larter and Barker (1989, 1991), was interpreted by Larter et al. (1997) as the transition from "pre-glacial" to glacial-marine deposition (the so-called onset of glacial sedimentation on the PMAP). This interpretation, however, was later discounted by the results of Ocean Drilling Program (ODP) Leg 178 drilling (Barker et al., 2002), which showed the glacio-marine nature of both S2 and S3 sequences.

Conversely, the architectural change we considered on the continental shelf is a major unconformity between sequences of similar geometry (sequences with sharp paleo-shelf breaks above and below). Therefore, we cannot share Larter's inference that the change in stratal geometry at the unconformity that we highlighted is typical of the S2-S3 boundary, or that the actual S1-S2 boundary, identified in Fig. 2 of our article, is to be in a higher stratigraphic position. In fact, not to argue the assumption that gently curved paleo-shelf breaks are limited to S3, we note that gentler "transitional" paleo-shelf breaks identical to those ascribed in our article to S2 were already ascribed to S2 by Larter et al. (1997) and Larter and Barker (1991). Therefore, the interpretation of the S1-S2 and S2-S3 boundaries in Fig. 2 of our article is consistent with that of seismic Line AMG845–03 of Larter et al. (1997; see their fold-out Fig. 5)

The relevance of the S1-S2 unconformity becomes much more evident in front of glacial troughs, where the erosion cuts into the base of the two underlying sequences, S2 and S3 (see Figure 1 of our article). One of the points made in support of our interpretation is that, unlike the S2-S3 boundary, the S1-S2 boundary is of margin-wide significance on the PMAP as it correlates with other pronounced changes in the continental slope (regional downlap surface) and rise (decrease in accumulation rate).

We are confident that the unconformity we highlighted is indeed the S1-S2 boundary. This interpretation is supported by careful correlation within the available seismic grid across the entire margin. This boundary is recognized in most profiles crossing the outer shelf, where the four seismic sequences S1 to S4 established by Larter and Barker (1989, 1991) are preserved. Larter et al. (1997) defined S1 to S4 ~150 km northeast of the profiles that we presented, and named A1 to A4 the comparable (but not directly correlatable) sequences identified over 300 km southward. The results of the ODP Leg 178 drilling and the seismic profiles that we discussed permit us to tie the S1-S2 boundary to ODP Site 1101 and the A1-A2 boundary to ODP Site 1096. The two unconformities are indeed coeval.

In regard to less specific considerations, we agree with Larter's Comment that the past ice sheet was probably heterogeneous in ice flow and basal regime. This is what we suggested in distinguishing the conditions "at the bases of a few large ice streams" from those on the adjacent banks. Moreover, we did not explicitly define as synchronous the inferred continent-wide change in basal ice conditions. What we suggested is that similar changes in the architecture of the margin—beneath the continental shelf, slope, and rise—are observable in the Pliocene in the key sectors of the West and East Antarctic margin, and dated to nearly 3 Ma in the PMAP. A recent stratigraphic review by Volpi et al. (2007) based on seismic-aided log-to-log correlations following the drilling of ODP Leg 188 in Prydz Bay (Cooper et al., 2004) refines the constraints for the change we observed on the Prydz Bay margin, suggesting that it may well have an age comparable to that on the PMAP. We suggested that the changes in the architecture of the margin occurred at about the same time as the climatic change that generated the Northern Hemisphere glaciation. Such climatic change is not particularly abrupt, as it results from the stable isotope curves (e.g., Zachos et al., 2001) or from the pre-dating of the Northern Hemisphere ice sheet proposed by Moran et al. (2006) following IODP drilling in the Arctic Ocean.

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