Geological record of Ice Stream Collapse, Pine Island Bay, West Antarctica

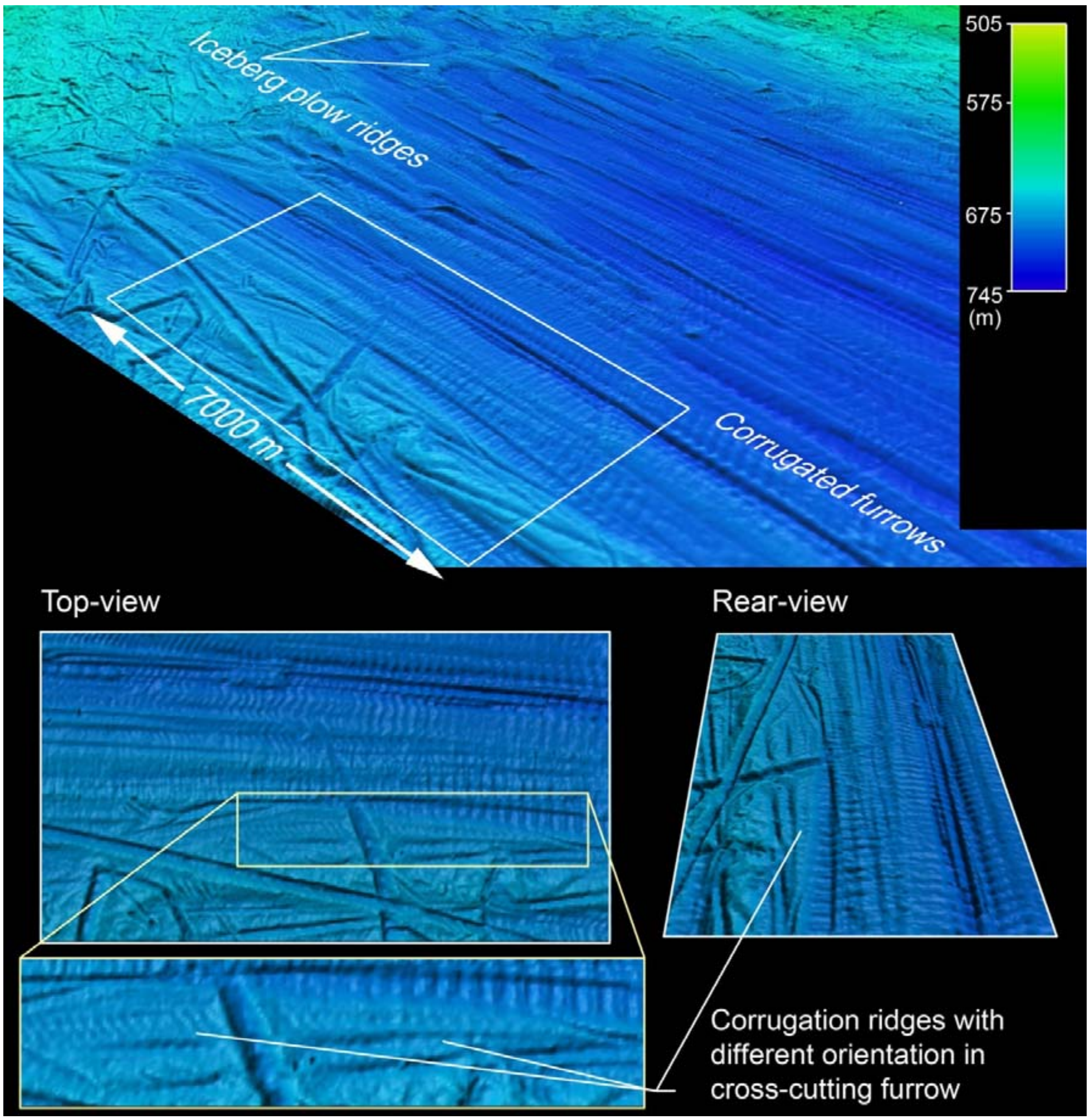

Figure DR1. The corrugated furrows in central Pine Island Bay Trough and the iceberg plow ridges viewed from different directions.

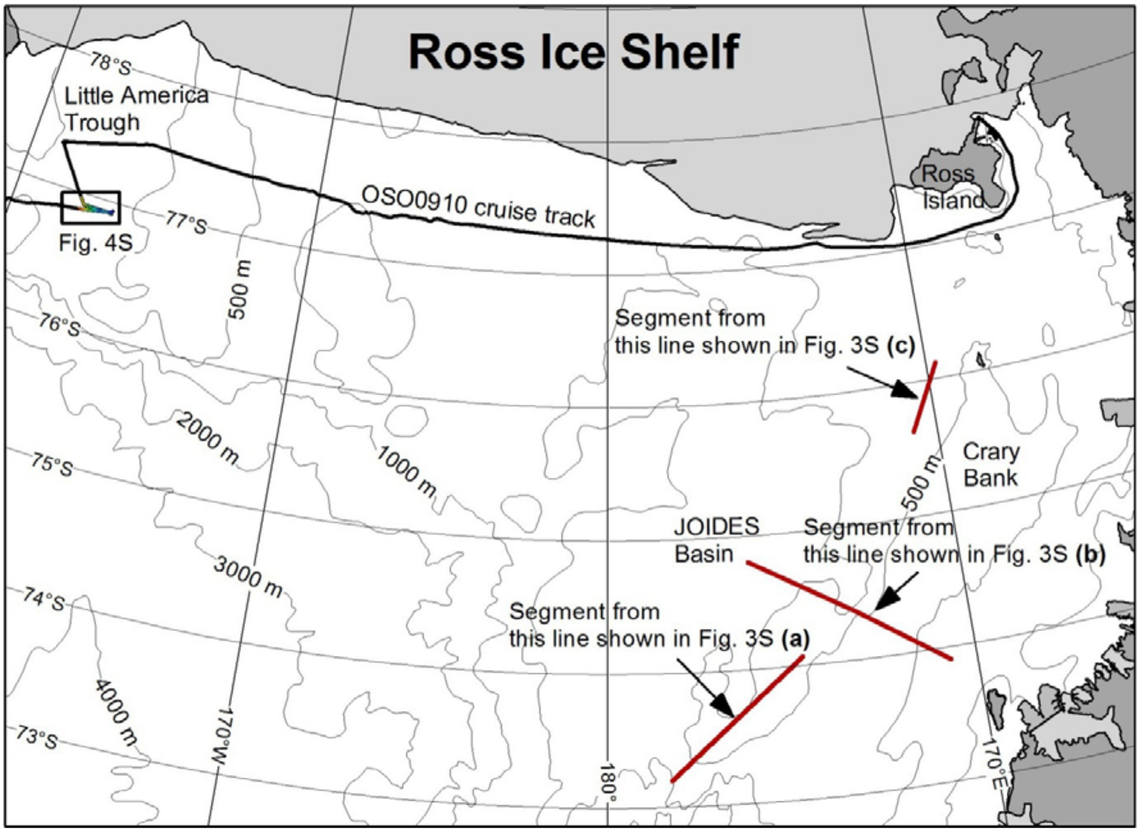

Figure DR2. Map showing locations of the side-scan sonar tracks with representative line segments shown in Figure 3S and the multibeam image shown in Figure 4S.

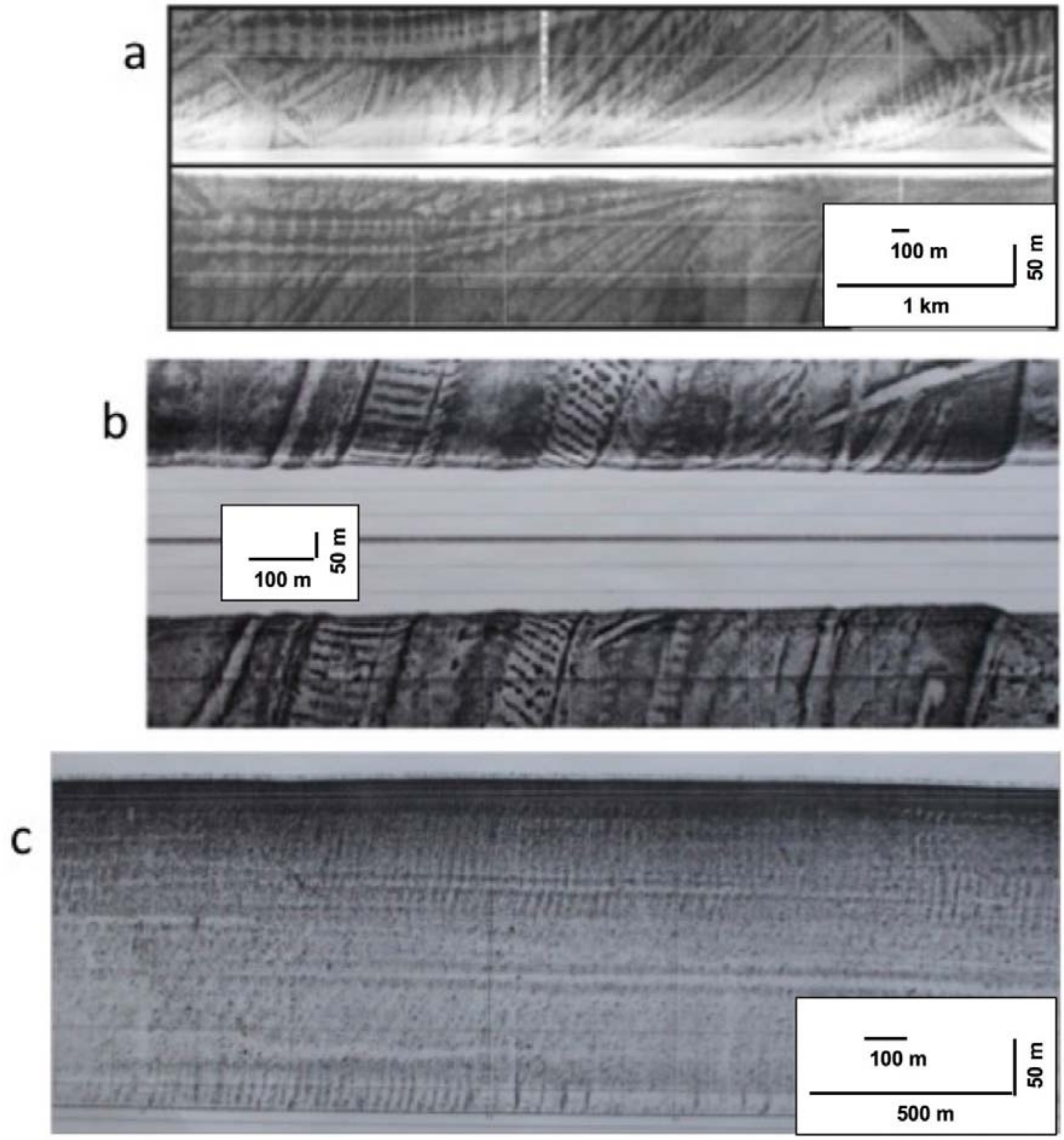

Figure DR3. Side-scan sonar records from the JOIDES Basin in western Ross Sea showing cross cutting iceberg furrows with corrugation ridges on the outer shelf (**a**), near parallel corrugated furrows on the mid-shelf (**b**), and corrugation ridges similar to those in Pine Island Bay further proximal to the ice margin (**c**). Figure 2S shows the locations of the segments in **a-c**. This sequence of side-scan images illustrate how an armada of grounded, tightly clustered mega-bergs eventually further disintegrate to individual icebergs on the outer margin that form corrugation ridges in their trails due to tidal movement.

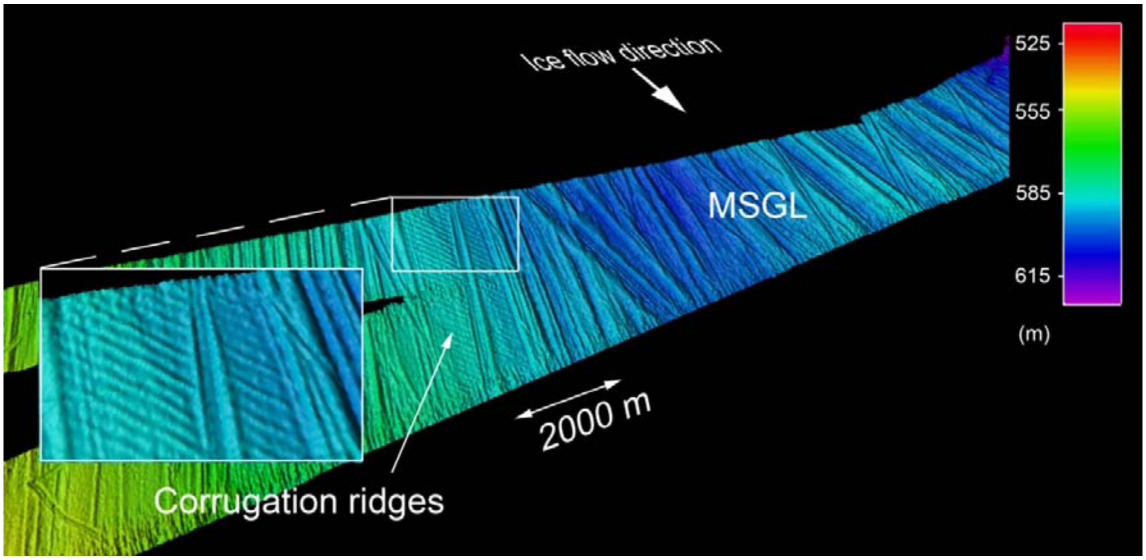

Figure DR4. Corrugated furrows in the eastern Ross Sea imaged with the multibeam system on icebreaker *Oden* during the OSO0910 expedition. These features have similar dimensions to those mapped in Pine Island Trough, although ridges are oriented close to 45° relative to the MSGL.

Table DR1. Considered Landforms and formation models for corrugation ridges.

Considered Landform	Morphological description	Formation model	Key References	Comment in relation to corrugation ridges (CR)
De Geer moraines	Ridges transverse to glacial flow, typically c. 30 m wide, 1-3 m (up to 7 m) high, crests 50-200 m apart.	Subglacial sediment advection at the ice margin during annual to sub-annual halts in grounding line retreat.	Todd et al (2007); Lindén & Möller (2005)	Similar ridge height and spacing as CR, but not nearly as regular. De Geer moraines are clearly separated, pseudo-linear or gently sinusoidal from above, while CR are characterized by sharp kinks. De Geer moraines are not confined to furrows or iceberg plowmarks, instead they are depositional features overprinting landforms indicating ice flow.
Rogen moraines	Continuous ("wavy") ridges transverse to glacial flow , typically c. 150-300 m wide, 10-30 m high, crests 300-1200 m apart.	No consensus. Model ("BRIE"): naturally arising instability in coupled ice and till flow.	Stokes et al. (2008); Dunlop et al., (2008); Hättestrand and Kleman (1999)	Are often associated with MSGL. Generally much larger, and much less regular in pattern than CR.
Current induced bedforms (sand waves, mega ripples)	Sub-parallel, sharp-crested wavy ridges, typically c. 1-500 m wide, 0.1-10 m high, crests 1-500 m apart.	Sediment remobilization by current activity, often tidal	van Dijk et al. (2008); Amos and King (1984); McCave (1971)	Requires medium-fine grained relatively well sorted bed material, which is entirely lacking in the CR areas that, on the contrary, are characterized by unsorted diamicton and poorly sorted glacimarine sediments. Can be highly regular in transect, but are not as continuous as CR along ridges. Always pseudo-linear or gently sinusoidal from above, while CR are characterized by sharp kinks.
Small transverse ridges	Network of sub-parallel ridges, transverse to glacial flow, typically c. 100-200 m wide, 2-5 m high, and crests 100- 250 m apart.	Annual ice push during minor winter re-advance of grounded ice margin	Dowdeswell et al., (2008a); Ottesen et al. (2008); Boulton et al. (1996)	Much more irregular than CR, which do not form networks. AUV-swath data suggests that marine glacier undersides are highly irregular (Dowdeswell et al., 2008b).
Corrugation moraines	Regularly spaced ridges, 2-5 m high, crests 0.7 to 1 1 km apart	Annual features.	Shipp et al. (1999)	Much larger wave length and occur on sloping sea floor (200 m depth range).

Table DR1 References:

Amos, C.L. and King, E.L., 1984. Bedforms of the Canadian eastern seaboard: A comparison with global occurrences. Marine Geology 57, 167-208.

Boulton G.S., van der Meer J.J.M., Harts J., Beets D., Ruegg G.H.J., van der Wateren F.M., Jarvis J., 1996. Till and moraine emplacement in a deforming bed surge: an example from a marine environment. Quaternary Science Reviews 15, 961-987.

van Dijk, T. A. G. P., Lindenbergh, R. C. and Egberts, P. J. P., 2008. Separating bathymetric data representing multiscale rhythmic bed forms: A geostatistical and spectral method compared, Journal of Geophysical Research 113, F04017, doi:10.1029/2007JF000950.

Dowdeswell, J.A., Ottesen, D., Evans, J., Ó Cofaigh, C., and Anderson, J.B., 2008a, Submarine glacial landforms and rates of ice-stream collapse: Geology, v. 36, p. 819-822.

Dowdeswell, J.A., Evans, J., Mugford, R., Griffiths, G., McPhail, S., Millard, N., Stevenson, P., Brandon, M.A., Banks, C., Heywood, K.J., Price, M.R., Dodd, P.A., Jenkins, A., Nicholls, K.W., Hayes, D., Abrahamsen, E.P., Tyler, P., Bett, B., Jones, D., Wadhams, P., Wilkinson, J.P., Stansfield, K., Ackley, S., 2008b. Autonomous underwater vehicles (AUVs) and investigations of the ice–ocean interface in Antarctic and Arctic waters. Journal of Glaciology 54, 661-672.

Dunlop, P., C. D. Clark, and R. C. A. Hindmarsh (2008), Bed Ribbing Instability Explanation: Testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment, J. Geophys. Res., 113, F03005, doi:10.1029/2007JF000954.

Hättestrand C, Kleman J. 1999. Ribbed moraine formation. Quaternary Science Reviews 18: 43–61.

Lindén, M. and Möller, P. 2005. Marginal formation of De Geer moraines and their implications to the dynamics of grounding-line recession. Journal of Quaternary Science, Vol. 20, 113–133.

McCave, I. N., 1971. Sand waves in the North Sea off the coast of Holland. Marine Geology 10, 199-225.

Ottesen D., Dowdeswell J.A., Benn D.I., Kristensen L., Christiansen H.H., Christensen O., Hansen L., Lebesbye E., Forwick M., Vorren T.O., 2008. Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. Quaternary Science Reviews 27, 1583-1599.

Shipp, S., Anderson, J.B., Domack, E.W., 1999. Late Pleistocene-Holocene retreat of the West Antarctic ice-sheet system in the Ross Sea; Part 1, Geophysical results Geological Society of America Bulletin 111, 1468-1516.

Stokes, C.R., Lian, O.B., Tulaczyk, S., Clark, C.D., 2008. Superimposition of ribbed moraines on a palaeo-ice-stream bed: implications for ice stream dynamics and shutdown. Earth Surface Processes and Landforms 33, 593–609. DOI: 10.1002/esp.1671

Todd, B. J., Valentine, P. C., Longva, O. & Shaw, J. 2007 (April): Glacial landforms on German Bank, Scotian Shelf: evidence for Late Wisconsinan ice-sheet dynamics and implications for the formation of De Geer moraines. Boreas, Vol. 36, pp. 148169. Oslo. ISSN 0300-9483.

C-14 dating from Pine Island Bay

Table DR2. Radiocarbon constraints on West Antarctic Ice Sheet retreat following the Last Glacial Maximum (LGM) in Pine Island Bay. Compiled uncorrected and calibrated radiocarbon ages representing minimum estimates of glacial retreat.

Expedition[a]	Core ID[b]	Lab ID	Material Dated[c]	Water Depth (m)	Latitude	Longitude	Sample Depth Interval (cm)		Conventional ^{14}C age (yr PB)	+/− (yr)	*R*[d] (yr)	Calibrated[e] age (cal yr BP)	2σ[f]
							From	**To**					
OSO0910	KC19	LuS9037	Foraminifera	782	-73.1285	-106.9688	90	92	11775	100	*1297*	12296.5	327.5
OSO0910	KC23	LuS9038	Foraminifera	660	-72.8923	-106.9243	20	22	11170	110	*1297*	11411	355

Notes: [a] OSO0910: Oden Southern Ocean 2009-2010; [b] KC: Kasten Core; [c] *N. Pachyderma*; [d] Reservoir age for Antarctic marine carbonates estimated as 1297 ± 70 (Berkman and Forman, 1996). Delta R=897+-70. This reservoir correction is based on closest possible calibration point; [e] Calibrated using CALIB program v. 6.0 (Stuiver et al. 1998) with Marine09 curve. Ages reported in calendar years before present (cal yr BP). [f] Calibrated sigma age range using CALIB v 6.0

Table S2 Reference:

Berkman, P.A. and Forman, S.L., 1996, Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean, *Geophysical Research Letters 23,* p. 633–63.