Composition and microstructure of marine ice at the Southern McMurdo Ice Shelf, Antarctica

I. Koch [1], S. Fitzsimons [1], N. Cullen [1], M. Hambrey [2], D. Samyn [3], and J.-L. Tison [4]

(1) Department of Geography, University of Otago, Dunedin, New Zealand (inka.koch@geography.otago.ac.nz), (2) Centre for Glaciology, Department of Earth and Atmospheric Sciences, Aberystwyth University, Wales, United Kingdom, (3) Department of Mechanical Engineering, Nagaoka University of Technology, Nagaoka, Niigata, Japan, (4) Laboratoire de Glaciologie (DSTE), Université Libre de Bruxelles, Brussels, Belgium

(1) Introduction

Marine ice forms from a mixture of sea water and glacial melt water at the base of ice shelves and is thought to enhance ice shelf stability by adding layers of dense ice mass and/or infilling structural weaknesses such as bottom crevasses or rifts. Marine ice is widespread in Antarctic ice shelves, which fringe 44% of the Antarctic continent and buffer glaciers and ice streams draining into the ocean. The physical and chemical properties of marine ice, however, remain poorly understood. The aim of this project is to understand processes of marine ice formation at Southern McMurdo Ice Shelf (SMIS) through the geochemical and crystallographic investigation of marine ice cores extracted from the ice shelf surface. The SMIS is a small ice shelf (~ 5000 km²) adjacent to the western margin of the Ross Ice Shelf (Fig. 1). It flows southwest toward shore at velocities between 4 and 7 m a^{-1} (Fig. 1). As the ice becomes grounded in the south it slows to 1 to 2 m a^{-1} and a broad zone of dark ice crops out on the surface of the ice shelf (Fig. 2). This ice contains marine debris and macrofossils and has a negative surface mass balance of -0.16 m a^{-1}. Several types of marine ice have been described previously.

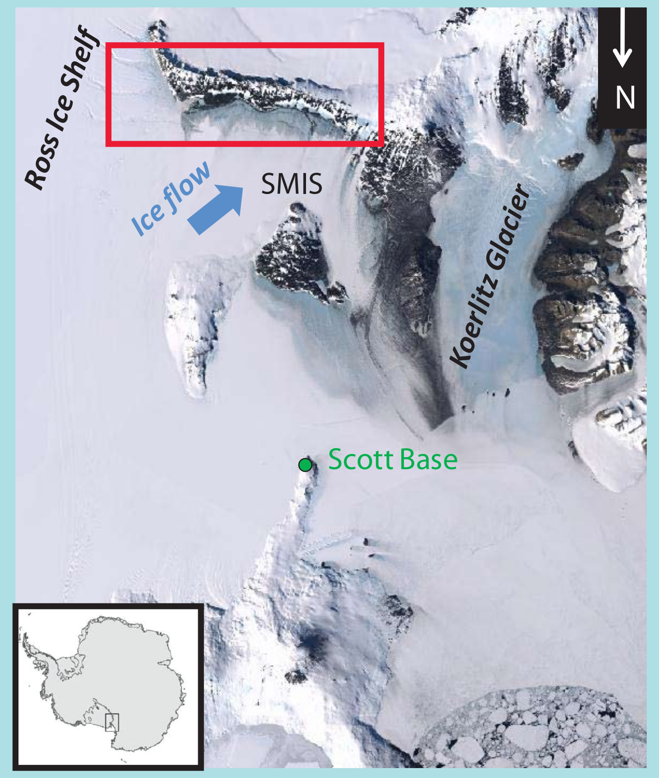

Figure 1: The Southern McMurdo Ice Shelf (SMIS) adjacent to the Ross Ice Shelf, Antarctica.

(2) Marine ice formation

- **Congelation ice**: a freezing front advances slowly into sea water forming thin layers of congelation ice of small equigranular ice crystals (e.g. below the Ross Ice Shelf (Zotikov et al., 1980).
- **Frazil ice**: due to changes in ice shelf thickness and hence a change in the pressure melting point, supercooled water can be present below ice shelves. Often this supercooled water is formed from a mix of sea water and more buoyant glacial water. Marine ice that forms from supercooled water forms fast from primarily frazil ice crystals (suspended crystals in the water column) (Craven et al., 2009; Morgan, 1972; Oerter et al., 1992). Frequently, these often elongated frazil ice crystals (platelet ice) align parallel to the ice-ocean interface (Souchez et al., 1991; Tison et al., 1993) and can form a marine ice layer of up to several hundred metres in thickness.
- **Anchor ice**: when supercooled water extends to the ocean floor in shallower waters, frazil ice crystals attach to objects on the seabed forming clusters of anchor ice (Kempema et al., 2001). As the anchor ice grows, clusters of randomly oriented frazil ice crystals, which are less saline than the surrounding water, become more and more buoyant and eventually float up to accrete at the bottom of the ice shelf.

(3) Methods

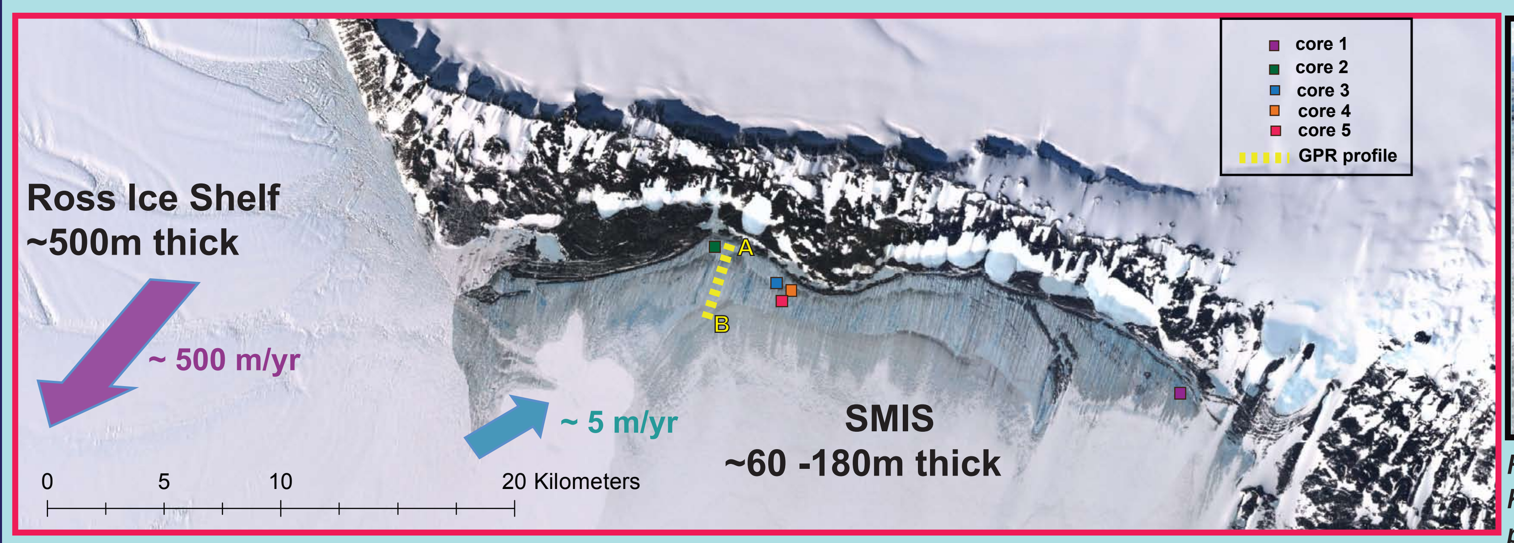

Figure 2: Ice core locations on SMIS.

Figure 3: barrel of the Kovacs Ice corer and a piece of ice core on SMIS.

- Four ice cores between 2.5 and 10 m in length were extracted from the ice shelf surface from the band of dark bare ice (Fig. 2) using a Kovacs ice corer.
- Vertical thin sections were prepared every 7-9cms covering the whole length of the ice cores using a microtome at -25 °C. The thin sections were photographed in cross-polarized light and the ice crystals were classified into 3 different main ice facies (platelet, banded and granular) (Table 2). Thin section ice fabric was determined automatically using a G50 ice fabric analyzer developed by Russell-Head Instruments.
- The ice was melted and analyzed every 10 cms for major cations (Na, Mg, K, Ca) and anions (Cl, Br, SO_4, NO_3, CO_3) using an ion chromatograph with a precision less than ± 3% for all ions.
- Water isotopes (δD and $\delta^{18}O$) were measured every 10 cms with an isotope laser spectrometer (Picarro). The precision for the measurements are ± 0.06 ‰ for $\delta^{18}O$ and ± 0.18 ‰ for δD.
- To determine changes in ice structure/composition, Ground Penetrating Radar (GPR) profiles were run perpendicular to the shore with a PulseEkko Pro with 50MHz antannae in a broadside configuration towed at about 4.6 km/hr.

(4) Ice chemistry

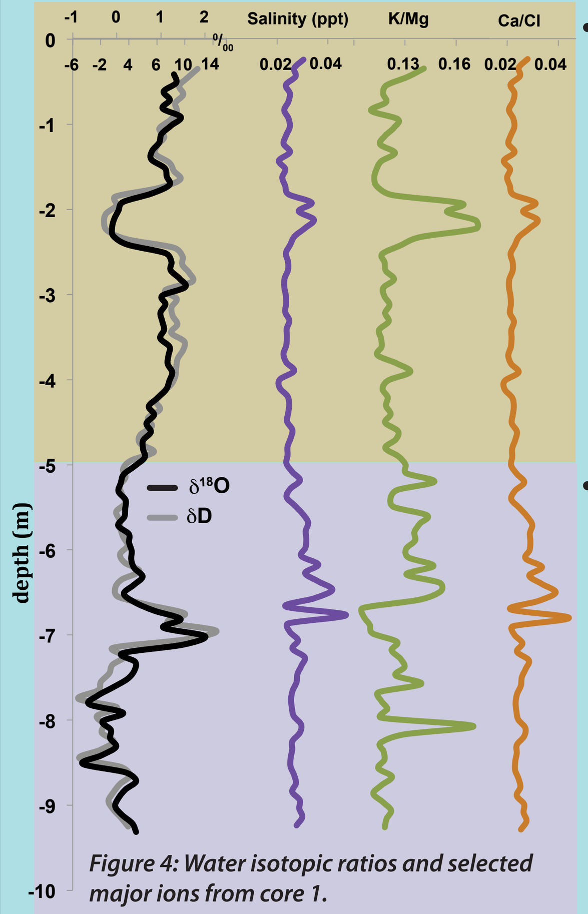

Figure 4: Water isotopic ratios and selected major ions from core 1.

- Table 1 shows the average solute and isotopic composition of marine and meteoric ice from SMIS. Marine ice is mostly relatively enriched in water isotopes with respect to sea water and has a salinity of one order of magnitude lower than sea water. The solute concentration is about one order of magnitude higher than in meteoric ice.
- An increase in salinity and the K/Mg ratio, together with depleted isotopic ratios, point toward an increase in freezing speed around 2m depth (Fig. 4) in core 1. The increase of the Ca/Cl ratio is consistent with increased influx of meteoric water which may be sourced from bottom melting.

Table 1: Major ion and water isotopic composition of ice samples from SMIS. Sea water as a reference.

	Na (ppm)	Mg (ppm)	K (ppm)	Ca (ppm)	Cl (ppm)	Br (ppm)	SO4 (ppm)	NO3 (ppm)	Ca/Cl (ppm)	TDS (ppt)	d18O	dD
C1 (top 5m)	97.88	9.78	3.81	4.01	166.13	0.57	26.34	0.08	0.024	0.34	0.97	6.94
C1 (lower 5m)	61.81	6.58	2.56	2.82	99.67	0.36	14.83	0.28	0.028	0.21	0.23	0.61
C2	11.16	0.49	0.37	0.49	14.04	0.06	5.89	0.03	0.034	0.04	0.43	4.93
C3	14.43	0.98	0.47	0.68	22.03	0.07	3.88	0.08	0.031	0.05	-4.82	-37.28
C4	55.00	6.13	2.28	2.28	98.33	0.36	8.98	0.10	0.023	0.18	0.94	8.67
C5	71.24	7.71	2.95	3.41	114.18	0.45	25.80	0.03	0.030	0.24	1.83	15.48
meteoric ice	0.99	0.16	0.20	0.4	1.58	< 0.01	0.39	0.09	0.253	<0.01	-29.99	-238.26
sea water	10556	1262	380	400	18980	65	2649	<1	0.021	34	-0.67	-5.70

(5) Ice shelf structure

Marine ice crops out in a dark band in the south of SMIS, with large scale structures visible in satellite images (Fig. 2). These bands are internal ice layers of the ice shelf as visible in Figure 5. The GPR profile also shows internal planar reflectors that increase in dip toward shore (Fig.6). An angular unconformity of a strong reflector possibly distinguishes marine ice from meteoric ice (Fig 6).

The strong reflector at the ice shelf bottom delineates a thinning of the ice shelf toward shore from 110m to ~50m thickness.

Figure 5: Marine ice on SMIS showing dipping layers.

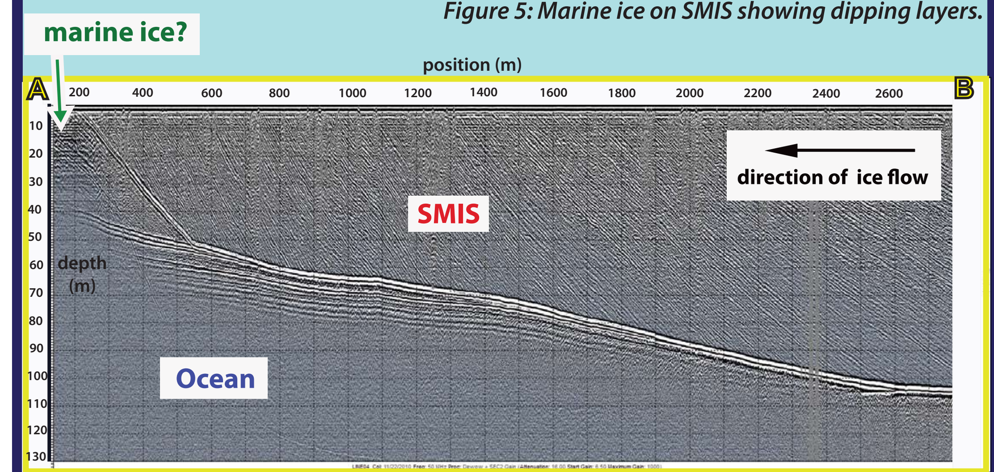

Figure 6: GPR profile run perpendicular to shore with a PulseEkko Pro with 50MHz antannae.

(6) Ice crystallography

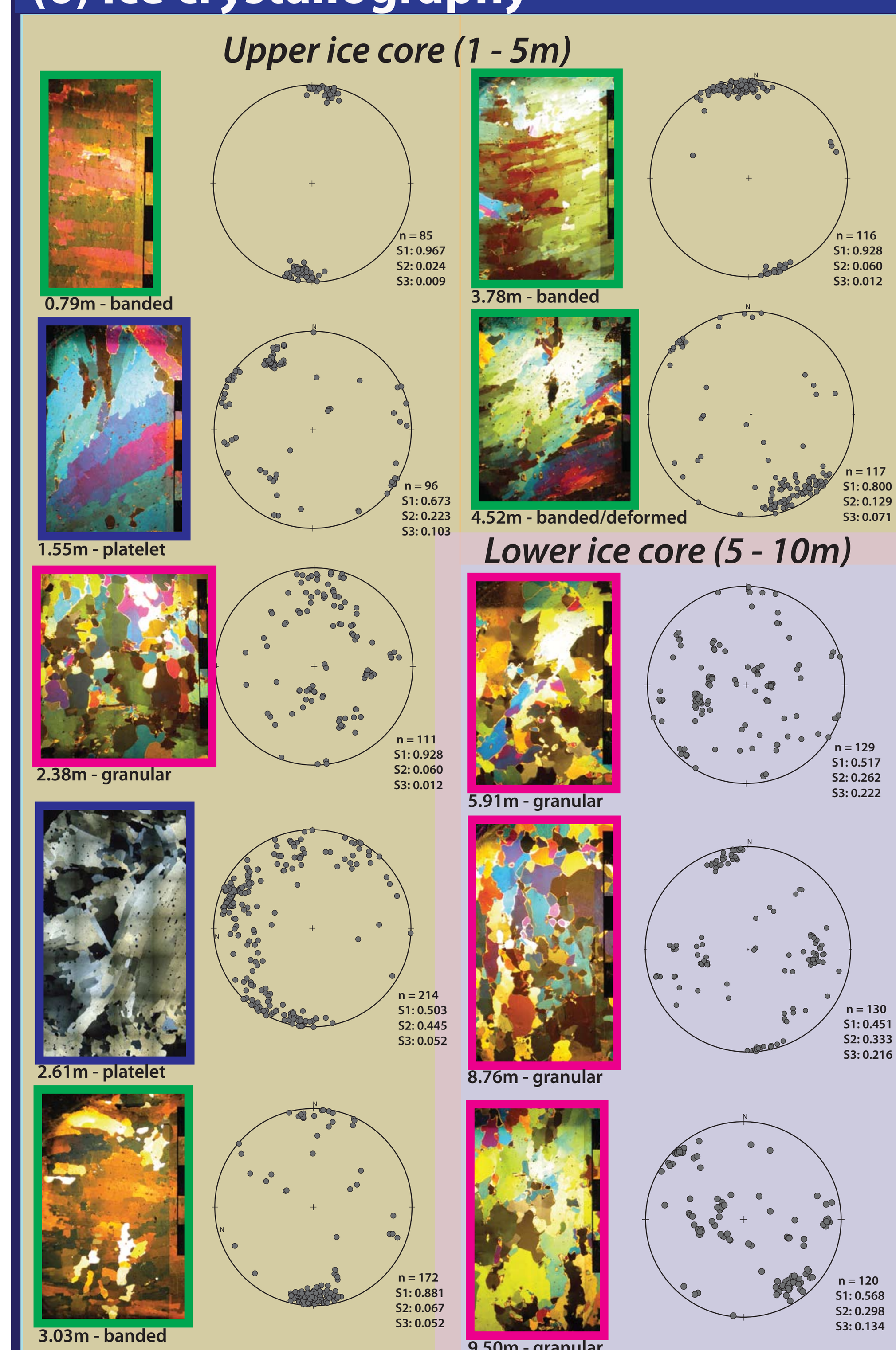

Figure 7: Pictures of thin sections in cross-polarized light (scale is 1cm) from selected depths of core1 and corresponding ice fabric diagrams.

Table 2: Ice facies observed in SMIS.

Name	crystal shape	crystal edges	crystal size	crystal orientation (visual in thin section)	formation
Platelet	elongated (often wide in middle, thinner toward edges)	irregular edges, can be frayed	~1cm - several cms	several directions	frazil ice (anchor ice?)
Banded	elongated (middle and ends have equal thickness)	sharp, often square corners	~0.5 - ~5cms	crystals are aligned and all point into the same direction	frazil ice
Granular	equigranular, orbicular	irregular, sharp	~0.1 - 1cm	not visible in thin-section photograph	frazil / congelation ice / (anchor ice?)

- Marine ice thin sections have been classified into three facies: platelet, banded and granular (described in Table 2). Platelet ice only occurs in cores 1 and 5, whereas banded and granular facies exist in all marine ice cores even though granular ice facies are even more abundant (Table 3). Core 3 and 4 are mostly composed of granular ice facies (Table 3).
- Figure 7 shows typical thin section facies for certain depths in core 1. Platelet and banded ice faciers are more abundant in the upper part of the ice core, whereas granular ice facies are predominant in the lower half of the ice core.
- **Banded ice facies** generally have a strong anisotropic fabric (Fig. 7), a **point fabric** in the ternary diagram of eigenvalues (Fig. 8).
- The fabric of **platelet ice facies** is less strong (Fig. 7) and plots as a **girdle fabric** in the ternary diagram (Fig. 8).
- **Granular ice facies** are more isentropic (Fig. 7) or **random** in the ternary diagram (Fig. 8).

Table 3: Percentage of ice facies in ice cores

	platelet	banded	granular
C1 (top 5m)	23 %	32 %	45 %
C1 (lower 5m)	8%	20%	72%
C2	n/a	n/a	n/a
C3	---	8%	92%
C4	---	17 %	83 %
C5	1 %	58 %	41 %

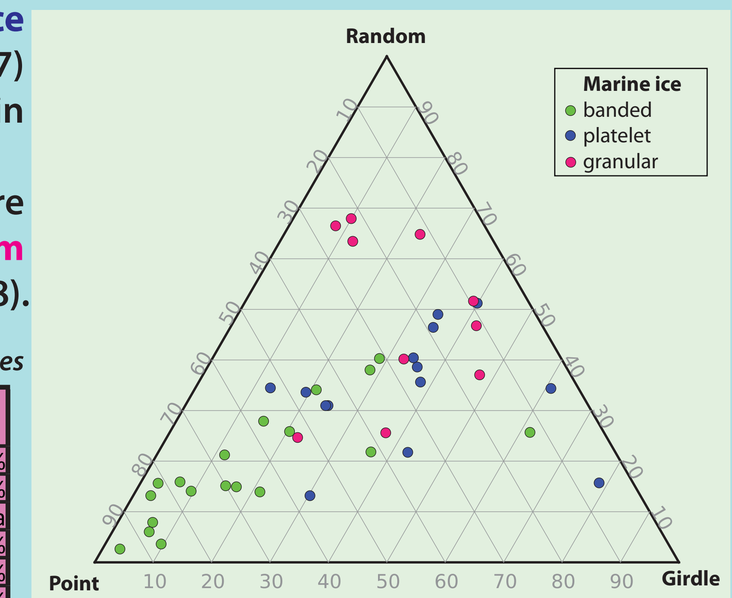

Figure 8: Ternary diagram of eigenvalues for thin sections sorted by ice facies

(7) Source water

The isotopic composition of marine ice can be used to determine the orign of the source water since sea and glacial water have very different isotopic signatures. Co-isotopic diagrams can help to establish the mode of freezing. Figure 9 shows that most of the marine ice from SMIS could theoretically originate from pure sea water (here with a concentration measured in McMurdo Sound of -0.67 $\delta^{18}O$ and -5.7 δD) using Jouzel and Souchez's (1982) fractionation model from a liquid to a solid in a closed system. The isotopic data plots along the modelled freezing slope of Jouzel and Souchez (1982)(Fig. 9). During freezing of sea water, heavy isotopes become preferentially included in the ice. This means that ice formed initially from sea water is enriched with respect to the parent material. In an open system the ice always stays enriched with respect to the parent water whereas in a closed-system the ice becomes depleted with respect to the parent water when a fraction of 0.67 or more of the initial water is frozen. The freezing slopes in an open and a closed system are however not easy to distinguish (expected to be 7.38 and 7.16 respectively with pure sea water as a parent material). Since closed-system freezing at SMIS is unlikely and the slope of the data is 7.74 (Fig. 9), the marine ice has likely formed in an open system. However, a change in the source water composition as a result of the addition of glacial water can also explain some of the range in the isotopic data. The green triangles in Figure 9 show the isotopic composition of the initial frozen fraction of sea water mixed with varing fractions of glacial water (0 -0.25). Hence, the more isotopically depleted marine ice at SMIS could have mixed origin source water.

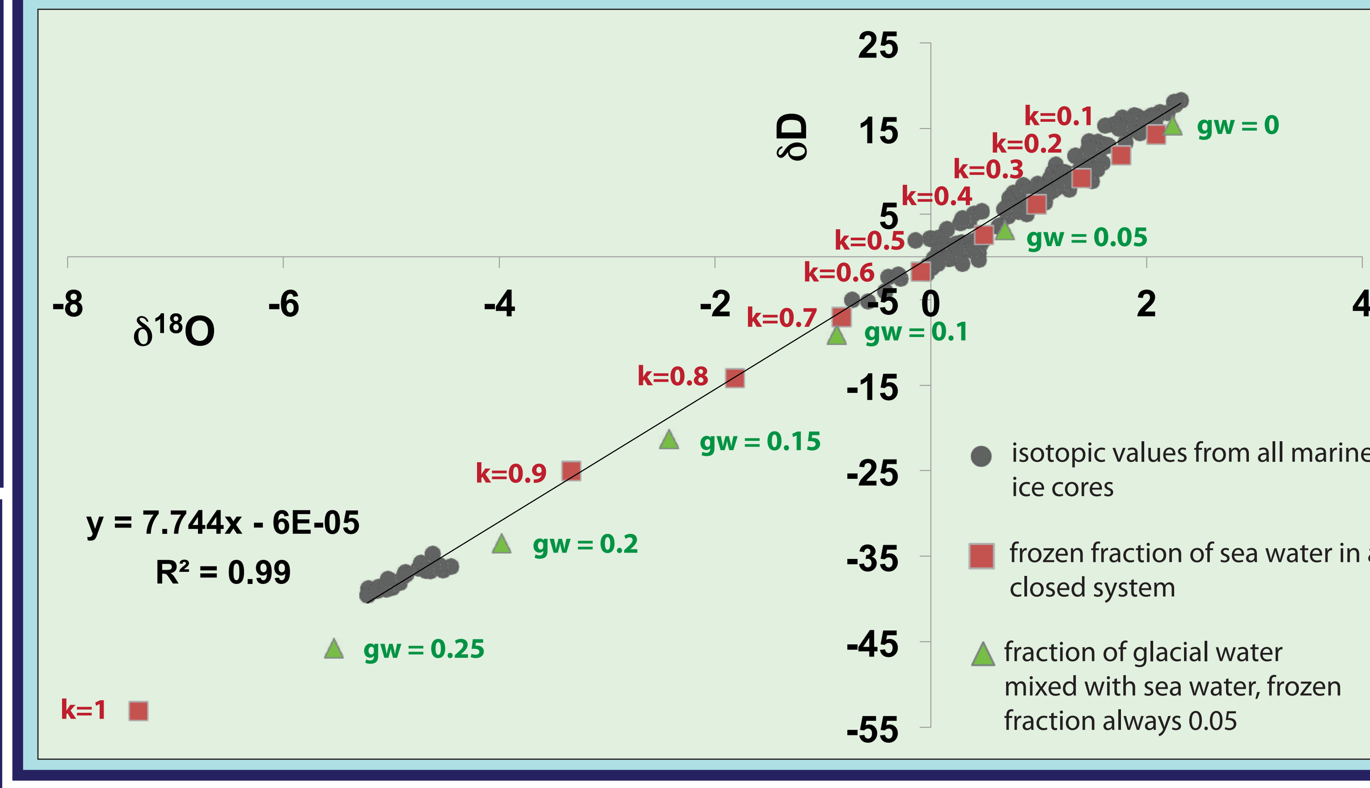

Figure 9: Co-isotopic diagram of data from the marine ice cores. Also plotted are the theoretical co-isotopic values of ice formed in a closed system from varing fractions of sea water (e.g. k = 0.1, where 10% of the reservoir is frozen) after Jouzel and Souchez (1982) using the fractionation coefficients of Lehmann and Siegenthaler, 1991). The Figure also shows co-isotopic values of ice formed from mixing sea water with varing proportions of glacial water (gw) (0 - 25%) plotted for the frozen fraction of 0.05.

(8) Conclusions

- GPR and ice composition data show that a broad band of marine ice exists at the ice margin of SMIS that has been accreted to the ice shelf bottom/ice shelf margin.
- Marine ice, especially platelet and banded ice, is primarily more isotopically enriched than sea water and the isotopic data plots on a freezing slope suggesting that most marine ice at SMIS was formed without a large contribution of glacial water
- Marine ice with predominantly granular ice crystals (e.g. the lower 5m of core 1 and core 3) is frequently isotopically more depleted. When coinciding with a higher salinity and K/Mg ratio (e.g. at depth 2m in core 1) this could be a result of an increased freezing rate. However, an increase in the fraction of meltwater, as indicated by an increase in the Ca/Cl ratio in the lower 5m of core 1, could also lead to an isotopic change .
- The presence of platelet and banded ice in all marine ice cores suggests that marine ice frequently forms from frazil ice crystals at SMIS. It remains unclear whether girdle type platelet ice facies were formed as anchor ice on the ocean floor or accreted as suspended frazil ice crystals. However, the presence of intact marine organisms on the ice shelf surface suggests that at least some of the marine ice is anchor ice that formed on the sea floor.

Acknowledgements & References

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