

CONCLUSION

There are no true glaciers in the Picos de Europa Massif but perennial snowpatches with firm where the presence of small fossil ice bodies is possible. In the Jou Negro depression, one of these snowpatches contains periglacial ice and, also, there could be ice inherited from the Little Ice Age. However, these are examples of dead, not moving, ice and they serve to establish the presence of sporadic permafrost in the Picos de Europa periglacial belt.

ACKNOWLEDGEMENT

The authors are greatly indebted to N. Martin, who checked the English text.

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28 October 1994

REFERENCES

González Suárez, J. J. and V. Alonso. 1994. Correspondence. Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain. *J. Glaciol.*, **40**(134), 198–199.
 Martínez de Pisón, E. and M. Arenillas Parra. 1988. Los glaciares actuales del Pirineo español. In *La nieve en el Pirineo español*. Madrid, Ministerio de Obras Públicas y Urbanismo, 29–98.
 Obermaier, H. 1914. *Estudio de los glaciares de los Picos de Europa*. Madrid, Establecimiento Tipográfico Fortanet. (Trabajos del Museo de Ciencias Naturales. Serie Geológica 9.)
 Penck, A. 1897. Die Picos de Europa und das kantabrische Gebirge. *Jahresberichte des Vereins von Freunden der Erdkunde zu Leipzig*, **3**, 278–281.
 Prado, C. de. 1860. Valdeón, Caín, la Canal de Trea: ascensión a los Picos de Europa en la Cordillera Cantábrica. *Revista Minera*, **11**, 62–72 and 92–101.
 Saint Saud, C. and P. Labrousche. 1893. Les Picos de Europa (Monts Cantabriques): étude orographique. *Ann. Club Alpine Français*, **38**.
 Serrat, D. 1980. Catálogo de los glaciares de la Península Ibérica. *Notes de Geografía Física*, **3**, 35–55.

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Glacial-ice fragments in Antarctic sea ice

Sea ice, as the result of freezing of sea water, can have various textures determined by the prevailing thermal and hydrodynamic conditions during ice formation and subsequent growth (Weeks and Ackley, 1982; Eicken and Lange, 1989). In the Antarctic, flooding of surface snow also often leads to snow-ice formation, giving rise to a meteoric component in the sea ice (Lange and others, 1990; Eicken and others, 1994), which has a granular texture with grains of several millimeters up to some centimeters in size. Snow-ice is believed to form up to 4%

of the total sea-ice volume in the Weddell Sea (Eicken and others, 1994) and perhaps more than twice as much in the Ross, Amundsen and Bellingshausen Seas (Jeffries and others, 1994).

Here, we report a novel finding of glacial-ice fragments (up to several centimeters in diameter) in a sea-ice core obtained in the Bellingshausen Sea north of Alexander Island, Antarctica. To our knowledge, glacial ice has not previously been described as an important component of sea ice, although in this core it amounted to 20% of the core volume. The features of the core, including texture, salinity and $\delta^{18}\text{O}$ measurements, are reported and the relevance of glacial ice fragments as a component of the sea ice in this region of the Antarctic is discussed.

GENERAL ICE-CORE PROPERTIES

Ice coring was part of a larger sea-ice program during an expedition of RV *Polarstern* to the Bellingshausen and Amundsen Seas in the late austral summer of 1994 (Fig. 1; Miller and Grobe, 1995). The ice core was obtained on 29 January 1994 during an ice station at 68°40.2'S, 72°37.3'W, approximately 11 nautical miles (n.m.) south of the sea-ice edge and 20 n.m. from the coast. The ice concentration was 10/10 and the ice floes were mostly 10–100 m in diameter with piled-up brash in between. There was hardly any evidence of ice deformation (see Haas and Viehoff (1994) for a detailed description of ice conditions). The floe sampled was approximately 30 m × 40 m in size and had a mean ice thickness of 3.1 ± 1.1 m, covered with 0.51 ± 0.13 m of snow. A thickness profile

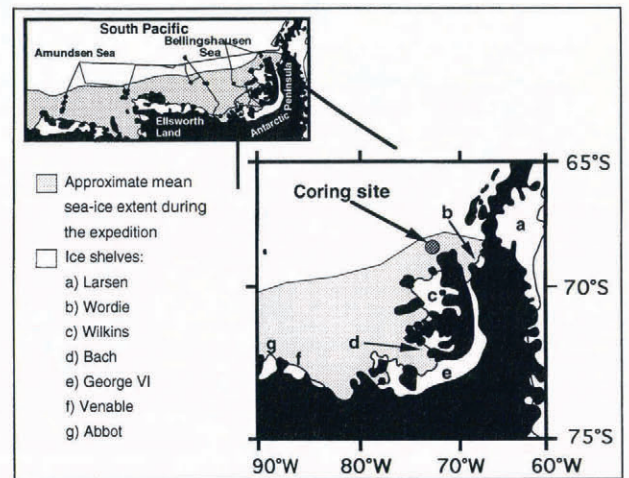


Fig. 1. Map of the cruise track. The site where the glacial-ice fragments were found is marked by an arrow. All other coring sites during the expedition are indicated by black circles.

derived from drilling (Fig. 2) revealed that, although the surface was rather flat, the underside of the ice was highly irregular. During drilling, many gaps or voids several centimeters thick were penetrated. These were mainly in the uppermost ice and may be characteristic of summer sea ice in this region (Jeffries and others, 1994). Some

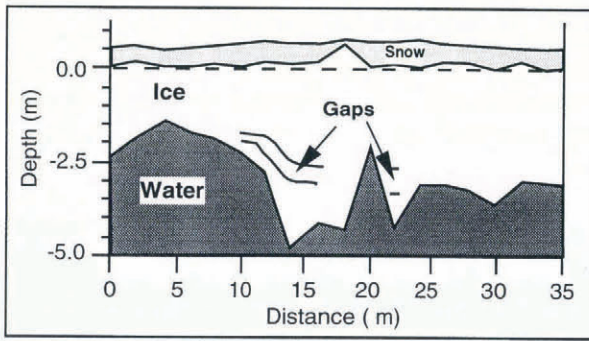


Fig. 2. Ice-thickness profile of the floe derived from drilling. The ice core was obtained at position 0.

larger voids were measured as indicated in Figure 2.

A 2.12 m long ice core (10 cm diameter) was obtained at position 0 of the thickness profile (Fig. 2). The mean bulk salinity of the core was only 1.52 ± 0.83 psu, the lowest value of the 30 cores drilled during the expedition (Fig. 1), which had a mean salinity of 2.55 psu. The ice was of orbicular granular texture throughout, with a small section of columnar ice between 1.34 and 1.47 m (see Eicken and Lange (1989) for nomenclature). The glacial-ice pieces were distributed mainly within the lower two-thirds of the core (Fig. 3).

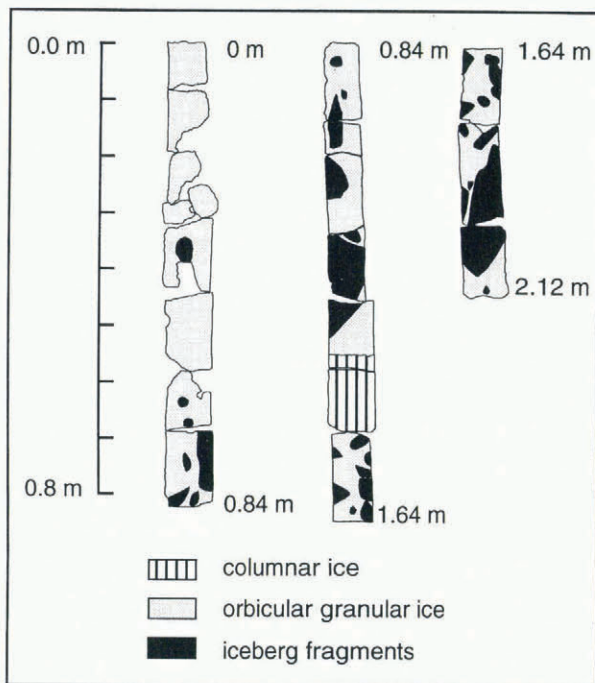


Fig. 3. Schematic drawing of ice-texture classes and distribution of glacier-ice fragments as seen from ice thick sections. The irregular shape of the thick sections is a result of damage caused by drilling and sawing.

PROPERTIES OF GLACIAL-ICE FRAGMENTS

Image analysis of Figure 3 showed that the fraction of glacial-ice pieces within the total area of the ice thick sections was 20.7%. This can be considered the volume

fraction of glacial ice in the whole core. The fragments varied in size, ranging from sub-centimeter to a maximum of 15 cm in diameter, although the majority were less than 5 cm. The edges and corners of the pieces were generally rounded.

Glacier-ice pieces could mainly be distinguished from sea ice by their characteristic pore structure in the ice thick sections (Fig. 4a, c): they had a high density of equally distributed small pores (less than 1 mm in diameter) and in many pieces the pores were elongated and appeared to be aligned linearly along layers of some millimeters width. Generally, no pores surrounded the fragments to indicate the boundary between glacial and sea ice. Fine cracks, some centimeters in length, which crossed each other at various angles were often visible (Fig. 4a, c). Ice thin sections, viewed between crossed polarizers, yielded information about crystal structure

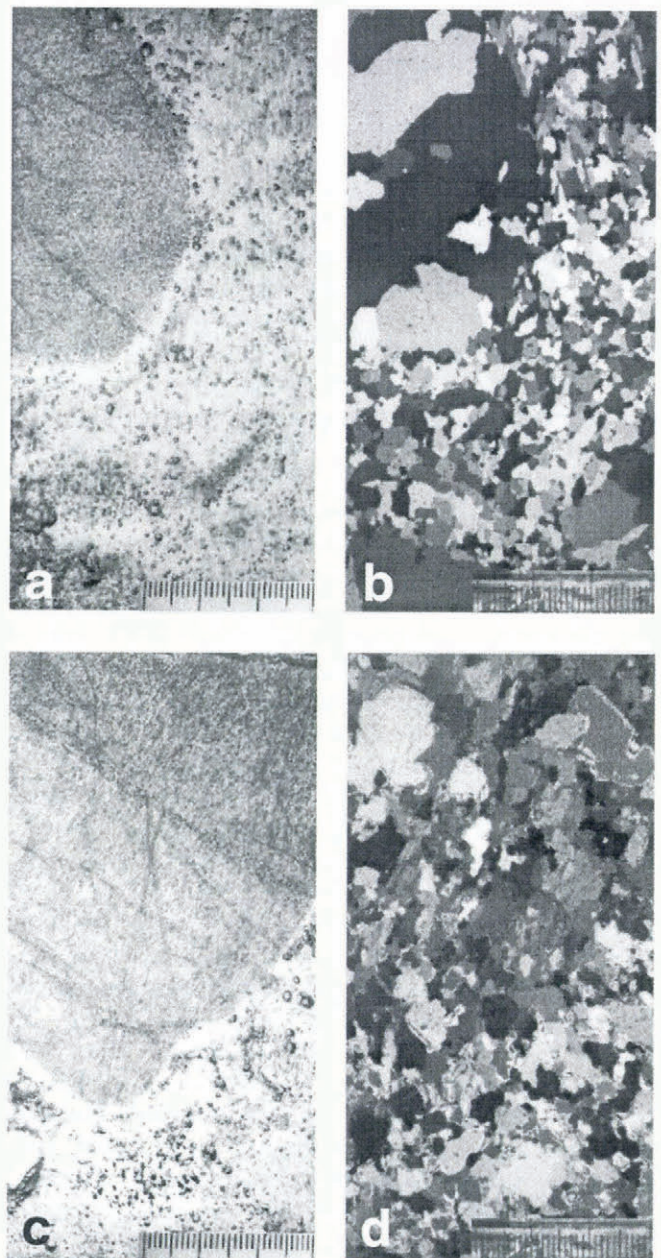


Fig. 4. Vertical ice thick (a, c) and thin (b, d) sections at depths of 1.04–1.14 (a, b) and 1.93–2.03 m (c, d), photographed in normal light and between crossed polarizers, respectively. Scale bars are in mm.

(Fig. 4b, d). The texture of the pieces was typical of glacier ice (e.g. interlocking grains) and different from the polygonal granular structure of snow or sea ice (Eicken and Lange, 1989). However, because grain-sizes ranged from some millimeters to some centimeters (Fig. 4d), it was difficult to distinguish between sea ice and iceberg ice from thin-section analysis.

Some of the larger fragments were cut from the ice and the salinity and the ratio of oxygen isotopes $^{18}\text{O}/^{16}\text{O}$ measured. Salinities were zero or slightly above zero. $\delta^{18}\text{O}$, the difference between the ratio $^{18}\text{O}/^{16}\text{O}$ in the sample and in a standard (VSMOW: Vienna Standard Mean Ocean Water), ranged from -14.4 to -10.8‰ (mean -11.9‰). These values are probably small overestimates, because of a possible contamination with sea salt during sample preparation, indicated by the slightly elevated salinities.

DISCUSSION

From the properties described above, it is evident that the fragments contained within the sea ice were of glacial origin: salinity and $\delta^{18}\text{O}$ values, together with shape and pore structure, made it possible to differentiate between the sea ice and the glacial ice. Texture, as determined from thin-section analysis, was the main aid in distinguishing between fragments of snow-ice and glacial ice. This underlines the importance of careful inspection of sea-ice cores to avoid misinterpretation of glacial fragments, especially since $\delta^{18}\text{O}$ of snow-ice can be very close to the values for glacial ice measured here (Jeffries and others (1994) measured $\delta^{18}\text{O}$ as low as -18‰ in the western Bellingshausen Sea). Since glacial-ice fragments could also have sizes in the range of some meters, they could also contribute to larger ice-floe features such as surface roughness being misinterpreted as a pressure ridge.

It is most likely that the glacial fragments were incorporated in autumn or winter during sea-ice formation in an area with glacial brash or in the vicinity of icebergs. The glacial fragments were distributed mainly over the lower two-thirds of the core (Fig. 3) down to 2.12 m depth. Since the glacial fragments were bouyant, there must have been turbulent conditions during initial ice formation or later rafting and deformation. Probably both processes were involved. Ice growth, as in "the pancake-cycle" (Lange and others, 1989), influenced by strong wave action would explain the orbicular granular texture. Although the surface of the floe was rather flat, the undulations and gaps along the thickness profile indicate that deformational processes acted during the history of the floe (Fig. 2). Additionally, the section of columnar ice at 1.34 m depth may demarcate the former underside of the floe, where congelation of ice commenced after a closed ice cover had formed. Later rafting may have contributed to further thickening of the floe, including iceberg pieces that were originally incorporated further above.

Crocker (1993) described an inverse exponential relationship in the size distributions of particles calved per calving event from Arctic icebergs. Due to his methodology, the distribution ends at a lower limit of 0.5 m, but he stated that below this limit numbers of

pieces decrease towards zero for very small fragments. For the pieces described here, this seems not to be the case, since no larger fragments were found and no growlers were observed along the thickness profile (Fig. 2). We speculate that this iceberg brash had already been in the water for a considerable time, and was close to complete melting. Therefore, the bits found in the core are the last remnants of that brash but, although smaller, they may still resemble the size distribution after calving.

The fact that this is the first recording of glacial-ice fragments within sea ice raises the question of how widespread this phenomenon is and whether or not it is peculiar to the Bellingshausen Sea? During the expedition, a large number of icebergs (mostly less than 1 km in size) were observed, especially around Alexander Island and in Ronne Entrance where more than 100 icebergs were counted in many of the regular 2 h ice observations (Haas and Viehoff, 1994). Within the pack ice they were mainly tabular, while in the open sea they were smaller and of no particular shape. In the open sea, the icebergs were often surrounded by areas (up to several square kilometers) of iceberg brash, including growlers and very small ice pieces less than a few meters in diameter. Thus, the Bellingshausen Sea is evidently a region in which a high degree of iceberg disintegration will occur. This would suggest that glacial ice is likely to contribute to sea-ice thickness over a wider area.

The $\delta^{18}\text{O}$ data do not allow the determination of the region or ice shelf from which the ice fragments originated. Clearly, it is most likely that they came from the nearby Wordie, George VI, Wilkins or Bach Ice Shelves. This is supported by $\delta^{18}\text{O}$ values from the Alexander Island region, given by Peel and Clausen (1982), who measured a range with a mean of 15‰ , similar to our values, especially considering the probable contamination of our samples with sea water.

Speculating about the consequences of atmospheric warming, it is possible that glacier fragments may become a more important component to overall sea-ice thickness. A scenario similar to the recent rapid disintegration of the Wordie Ice Shelf (Doake and Vaughan, 1991) could also occur within the ice shelves west of Alexander Island. This would result in even higher numbers of icebergs, although at least for the Wilkins Ice Shelf, Vaughan and others (1993) have predicted a melting of the ice shelf rather than it breaking off. Considering the huge volume of ice contained within the ice shelves and icebergs, glacially derived brash, either floating or incorporated into the sea ice, could even partially compensate for the sea-ice retreat in this region observed by Jakobs and Comiso (1993). This could also apply to the Weddell Sea, if the Larsen Ice Shelf, located near the climatic limit of viability, starts to disintegrate. However, general ice-drift patterns may result in a significant difference between the Bellingshausen Sea and the Weddell Sea: calving from, and deterioration of icebergs, mainly results from wave action, and is therefore mostly limited to open water (Wadhams, 1988). For iceberg fragments to occur within sea ice, it is therefore necessary that the sea around the iceberg brash freezes shortly after the event. Little is known about drift patterns in the Bellingshausen Sea but, if they are oriented toward the continent (Talbot, 1988), this ice could be preserved within the pack-ice region. In

the western Weddell Sea, the Weddell Gyre is known to transport icebergs away from the sea-ice zone, so making the incorporation of glacial ice into sea ice a less probable event.

ACKNOWLEDGEMENTS

We are grateful to the crew of RV *Polarstern* for their assistance in the field and to H. Eicken for his help during the preparation of this manuscript. This is publication No. 891 of the Alfred-Wegener-Institut für Polar- und Meeresforschung.

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20 January 1995

REFERENCES

- Crocker, G.B. 1993. Size distribution of bergy bits and growlers calved from deteriorating icebergs. *Cold Reg. Sci. Technol.*, **22**(1), 113–119.
- Doake, C. S. M and D. G. Vaughan. 1991. Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. *Nature*, **350**(6316), 328–330.
- Eicken, H. and M. A. Lange. 1989. Development and properties of sea ice in the coastal regime of the southeastern Weddell Sea. *J. Geophys. Res.*, **94**(C6), 8193–8206.
- Eicken, H., M. A. Lange, H.-W. Hubberten and P. Wadhams. 1994. Characteristics and distribution patterns of snow and meteoric ice in the Weddell Sea and their contribution to the mass balance of sea ice. *Annales Geophysicae*, **12**(1), 80–93.
- Haas, C. and T. Viehoff. 1994. *Sea ice conditions in the Bellingshausen/Amundsen Sea: shipboard observations and satellite imagery during ANT XI/3*. Bremerhaven, Alfred-Wegener-Institut für Polar- und Meeresforschung. (Technical Report 51.)
- Jakobs, S. S. and J. C. Comiso. 1993. A recent sea-ice retreat west of the Antarctic Peninsula. *Geophys. Res. Lett.*, **20**(12), 1171–1174.
- Jeffries, M. O., R. A. Shaw, K. Morris, A. L. Veazey and H. R. Krouse. 1994. Crystal structure, stable isotopes ($\delta^{18}\text{O}$), and development of sea ice in the Ross, Amundsen, and Bellingshausen seas, Antarctica. *J. Geophys. Res.*, **99**(C1), 985–995.
- Lange, M. A., S. F. Ackley, P. Wadhams, G. S. Dieckmann and H. Eicken. 1989. Development of sea ice in the Weddell Sea. *Ann. Glaciol.*, **12**, 92–96.
- Lange, M. A., P. Schlosser, S. F. Ackley, P. Wadhams and G. S. Dieckmann. 1990. ^{18}O concentrations in sea ice of the Weddell Sea, Antarctica. *J. Glaciol.*, **36**(124), 315–323.
- Miller, H. and H. Grobe. In press. The expedition ANTARKTIS-XI/3 of RV "Polarstern" in 1994. *Ber. Polarforsch.*
- Peel, D. A. and H. B. Clausen. 1982. Oxygen-isotope and total beta-radioactivity measurements on 10 m ice cores from the Antarctic Peninsula. *J. Glaciol.*, **28**(98), 43–55.
- Talbot, M. H. 1988. Oceanic environment of George VI Ice Shelf, Antarctic Peninsula. *Ann. Glaciol.*, **11**, 161–164.
- Vaughan, D. G., D. R. Mantripp, J. Sievers and C. S. M. Doake. 1993. A synthesis of remote sensing data on Wilkins Ice Shelf, Antarctica. *Ann. Glaciol.*, **17**, 211–218.
- Wadhams, P. 1988. Winter observations of iceberg frequencies and sizes in the South Atlantic Ocean. *J. Geophys. Res.*, **93**(C4), 3583–3590.
- Weeks, W. F. and S. F. Ackley. 1982. The growth, structure and properties of sea ice. *CRREL Monogr.* 82-1.