NMR Studies on Antarctic Sea Ice

Paul Callaghan and Craig Eccles

Department of Physics, Massey University
Palmerston North, New Zealand

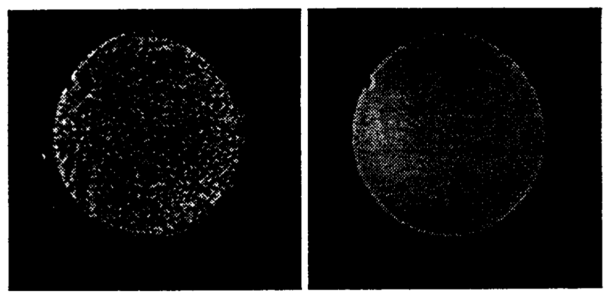
INTRODUCTION

With a seasonal variation in surface area of almost 20 million square km and an albedo of 95% the sea ice surrounding the Antarctic continent has a significant impact on global climate. Consisting of frozen sea water, the ice is formed gradually over a period of several months during the Antarctic winter. Far from being a homogenous material, sea ice has a complex structure. As the sea water freezes, concentrated salt water accumulates in small cavities called "brine pockets". Generally less than 0.5 mm in diameter they can extend for many mm vertically. During the winter, gravity causes much of the entrapped brine to move down through the ice resulting in a non-uniform salinity profile.

The presence of the brine pockets gives the sea ice unusual mechanical properties. An understanding of these properties and their implications for annual sea ice formation and break up can be gained by macroscopic stress measurements1, or by inference from microscopic analysis of sea ice morphology. Until now, microscopic studies have been practically non-existent, apart from some laboratory studies on home-grown sea ice2. However given the unusual conditions of Antarctic sea ice formation, such as variable temperature gradients, long growth periods and wave action, an on-site analysis would seem to be preferable.

NMR AS A PROBE OF SEA ICE

NMR provides a non-invasive technique for studying sea ice morphology using imaging or bulk measurement techniques. Not surprisingly, previous work has been done with high field instruments[3] (fig l), however the possibility of taking such a facility to the Antarctic is remote. Given the low level of electromagnetic interference in Antarctica, NMR studies which use the Earths magnetic field would seem to provide an attractive alternative. Although an imaging system based on the Earth's field has been demonstrated4 the resolution is too coarse to allow detailed studies of the microscopic sea ice structure. The alternative is to use NMR to provide bulk measurements of liquid water content and relaxation times. More ambitious experiments using pulsed-gradient spin-echo NMR can be used to obtain information on restricted self diffusion5, from which average brine pocket dimensions can be inferred.



sea ice (-5°C) horizontal slice　　reference seawater (1 0°C)

Fig 1. *3OOMHz proton NMR image of a cross section through some home-grown sea ice. A sea water image is provided for comparison*

NMR IN ANTARCTICA

In the spring of 1994 we spent several days on the sea ice, 25 km from Scott Base, in Antarctica's McMurdo Sound. An Earth's field NMR apparatus, based on a 3rd year student laboratory experiment at Massey University, was assembled in a polar tent and measurements were made on ice cores extracted from the sea ice.

The ice core samples, 120 mm long and 75 mm in diameter, were cut from 2 m long cores, the thickness of the sea ice in this area. Each sample was placed inside the NMR probe which was housed in a snow cave to reduce the effects of generator and computer interference. The probe consisted of a large solenoidal polarizing coil, capable of producing a field of approximately 0.03 Tesla, an excitation coil and 2 receiver coils (fig. 2). The polarizing coil was isolated from the sample by a glass dewer so as to minimise heating effects.

Note that unlike a conventional NMR system the uniformity of the polarizing field is not especially critical since the FID is acquired in the Earths field, which in isolated areas such as this, is uniform to better than 1 part in 10^6. This and the fact that we were working at such low frequencies made for a compact and relatively inexpensive spectrometer.

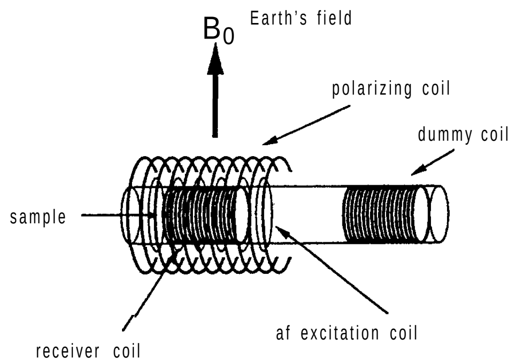


Fig 2. *The orientation of the various coils in the NMR probe head with respect to the Earth's magnetic field*

Free induction decays were acquired as indicated in figure 3. The polarizing coil was energised for approximately 5 seconds to produce a bulk magnetization in the sample. The polarizing current pulse was then switched off, but sufficiently slowly so that the magnetization had time to redirect itself along the Earth's magnetic field - almost vertical and of strength 65 μT in this location. A 2 ms, 90" pulse at the Larmor frequency of 2.76 kHz, was then applied to the sample via the excitation coil so as to tip the magnetization back into the horizontal plane where it could be subsequently detected as an induced emf in one of the receiver coils. T_2 relaxation data was obtained using a standard spin-echo pulse sequence.

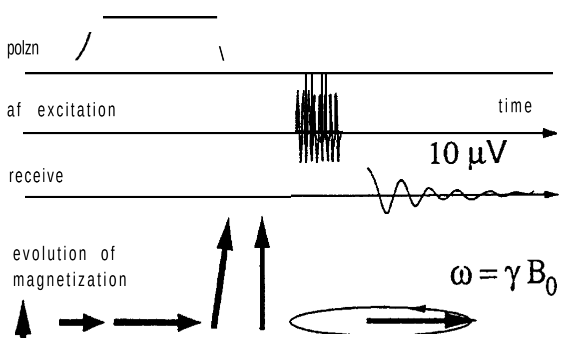


Fig 3. *The pulse sequence used to observe a free induction decay in the Earth's magnetic field.*

EQUIPMENT

All the necessary switching pulses, including the audio-frequency pulse applied to the excitation coil, were generated by a Tecmag-Aries system6 and Macintosh IIci computer. The induced signal (~10μV) was amplified by a home built, low-noise, differential amplifier and bandpass filter. External, common-mode interference was minimised through the use of a second receiver coil. The resultant signal was digitized and accumulated by the Tecmag system in the usual way (see below).

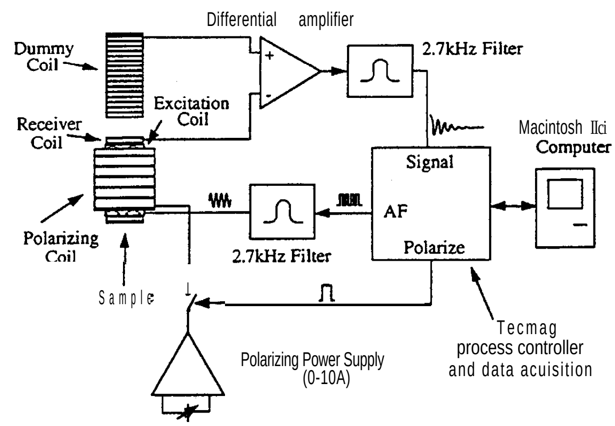


Fig 4. *A block diagram of the Earth's field NMR apparatus.*

RESULTS

An example of the quality of the NMR data which can be obtained with this equipment can be seen in figure 5 which shows free induction decays from a 500ml water sample and a typical ice core.

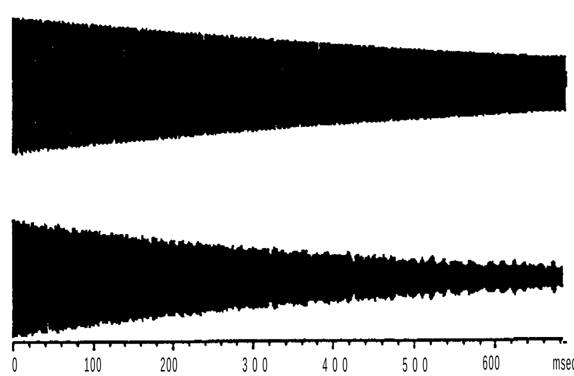


Fig 5. *Example free induction decays for water (top trace, 4 accumulations), and sea ice (bottom trace, 64 accumulations, waterfraction -6%).*

T_2 experiments were performed on 8 sea ice samples taken at depths ranging from 60 to 1810 mm (just above sea level). For each sample a new core was extracted to minimise temperature changes. Even so, a temperature change of 1-2° C was typical during each 20 minute experiment. A reference measurement using (warm) water was made before each T_2 experiment to check on the stability of the apparatus and to provide a reference signal from which the water content in each sample could be determined (fig 6).

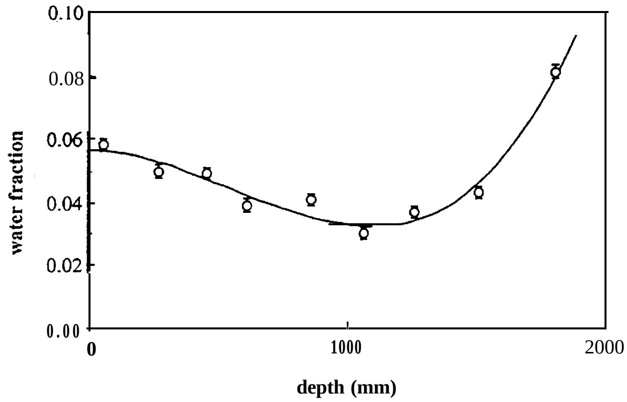


Fig *6. Water fraction in sea ice as a function of depth (the curve is simply a best fit polynomial).*

Water fraction data was found to be in qualitative agreement with salinity which had been determined from conductivity measurements made on each sample (fig 7).

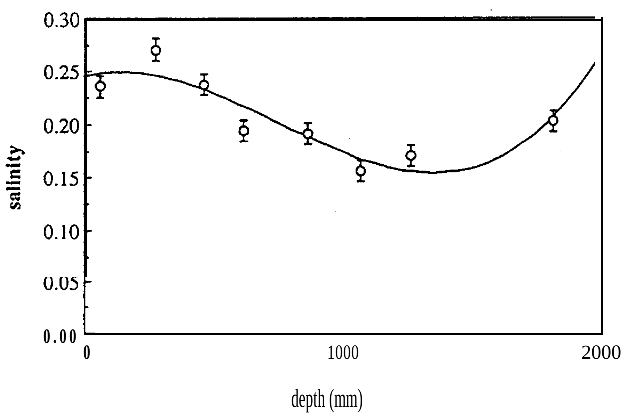


Fig *7. Sea ice salinity as a function of depth (the curve is simply a best fit polynomial).*

As expected, the temperature was observed to increase with depth, reflecting the temperature gradient between the air (-10 °C to -15 °C) and the sea water (-1.7 °C).

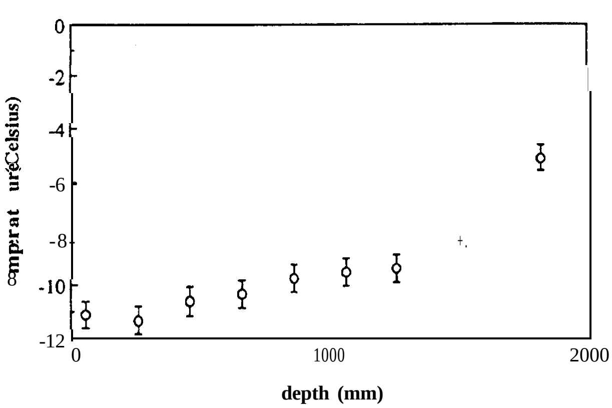


Fig *8. Sea ice temperature as a function of depth*

The transverse relaxation time, T_2, will clearly depend on a number of factors, including brine content, temperature and pore size. One might expect T_2 to increase with depth since temperature does as well, however a downward trend is observed (fig 9). This could be due to chemical exchange at the solid-liquid interface in the brine-pockets. This would explain the observed trend since the exchange rate will increase with temperature.

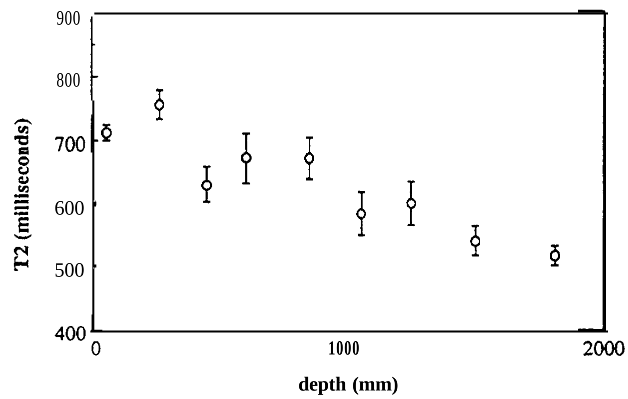


Fig 9. *Transverse relaxation in sea ice as a function depth.*

FUTURE EXPERIMENTS

In October 1995 we will return to the Antarctic with improved equipment. In addition to repeating the aforementioned experiments we plan to make restricted diffusion measurements to determine the dimensions of the brine pockets at various depths. With this additional data we hope to be able to provide some insight into the observed macroscopic properties of sea ice.

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