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Hot water drilling on the Amery Ice Shelf —the AMISOR project—

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Abstract: The hot water drilling component of the AMISOR (Amery Ice Shelf Oceanographic Research) project is designed to produce a series of access holes through the Amery Ice Shelf to allow measurements within the shelf and in the ocean water below. The data will be used to investigate the interaction of the ice shelf (and in particular melting and freezing on its base) with the ocean. Fieldwork commenced in 1999/2000 with drill testing and over the 2000/2001 season a hole was successfully drilled through 380 m of ice. Measurements were made in the sea water and a sediment core was obtained from the sea bed. Permanent instrumentation was installed to provide continuous data.

1. Introduction

A large part of the outflow of ice from the Antarctic Ice Sheet occurs through the glacier streams and floating ice shelves that fringe the continent. Loss of ice from the ice shelves is predominantly by iceberg calving, however for some ice shelves, *e.g.* the Filchner-Ronne and Amery up to 50% is now thought to be from basal melting. The distribution and rates of the melting is complicated and there are also known areas where ice is freezing-on below both the Amery Ice Shelf (Morgan, 1972) and the Ronne Ice Shelf (Engelhardt and Determann, 1987). The modification of the ocean water by the ice shelves melting and freezing may be important in the formation of Antarctic Bottom Water and hence critical in global ocean circulation. The AMISOR (Amery Ice Shelf Oceanographic Research) hot water drilling on the Amery Ice Shelf is one part of a larger program that aims to quantify the interaction between the Amery Ice Shelf and the ocean and determine the implications of the interaction for the discharge of grounded ice and the formation of bottom water. Other parts of the project include sediment and ice coring (to derive a long-term record of the time variability of the interaction) and mass balance studies on the inland ice sheet. The project builds on previous glaciological studies of the Amery Ice Shelf/Lambert Glacier system, on oceanography and sediments data from Prydz Bay and adds to remote sensing studies of the Amery (Fricker *et al*., 2001). The aim of the hot water drilling is to produce a series of access holes through the ice shelf to allow measurement within and below the floating ice. Figure 1 shows locations on the Amery Ice Shelf.

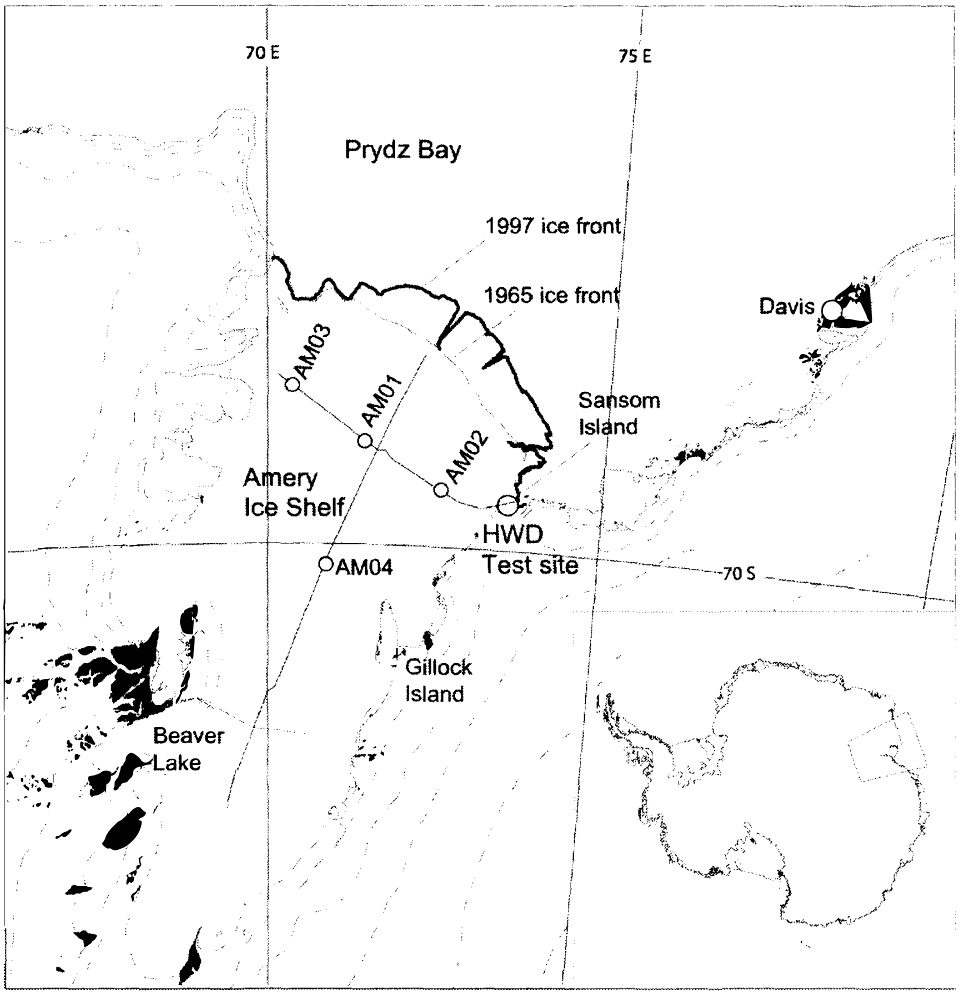

Fig. 1. Hot water drilling locations on the Amery Ice Shelf.

2. Program

The fieldwork is planned to run over three or four summer seasons:

1999/2000	Tests of the new HW drill and support equipment at a site (69°42.8′S, 73°35.0′E) at the NE corner of the ice shelf.
2000/2001	Further trials, completion of one borehole completely through the northeast Amery Ice Shelf at AM02 (−69°42.8′S, 72°38.4′E, ice thickness 380 m). Measurements and sampling through the borehole and in the water below the ice shelf and installation of instrumentation.
2001-2004	Further borehole drilling, in-hole measurement and sampling and instrument deployment at: AM01: −69°27.0′S, 71°29.8′E, a zone which has a marine ice layer, but which currently is close to a balance between freezing and melting. AM03: −69°11.1′S, 70°22.1′E; a location where there is rapid

basal freezing.
AM04: −70°10.2′S, 70°51.9′E, southern site near boundary of melting.

The ice thickness is approximately 500 m at the first 2 sites, and about 630 m at AM04.

3. The hot water drill

The HW drilling system was designed to be capable of drilling at least a 250 mm diameter hole through up to 1000 m of ice. The design draws on established drill technology (see Makinson, 1984 and references therein). A large amount of information made available by Prof. Keith Echelmyer (Geophysical Institute, Alaska), Dr. Keith Nichols (BAS) and Josef (Sepp) Luthiger VAW, ETHZ, Switzerland) greatly facilitated the construction of the operational system.

Hot water is supplied by a Hatz 2G40 motor driving a CAT 1051 high pressure pump which draws cold water from an 8000 *l* reservoir and delivers water at up to 45 *l*/min to the heater manifold. Five 80 kW Lavor Volcano portable car-wash heaters are plumbed in parallel via inlet and outlet manifolds to heat the water up to 80°C. Initially only three heaters were used but it was found in tests that, in Antarctica, the heaters only produced about 50 kW. The hot water output from the manifold is connected to the main winch hose via a Dueblin rotary union. The downhole section uses 1″ (25 mm) internal diameter 580N-16-SL thermoplastic hose in 600 feet lengths (183 m) to deliver hot water to a 90 kg stainless steel drill stem. The drill hose is raised and lowered by a capstan winch while the bulk hose is stored on a separate drum. The hose and capstan winches are individually driven by 4.7 kW Baldor servo motors and controllers driving a Brevini 50 : 1 reduction gearbox. This system allows very fine control (better than 1 cm/s at full torque) of drilling feed rates, and hauling rates of greater than 1 m/s. A sensor block provides continuous readout of water temperature, pressure and flow rate to an operator. A load cell fitted to one of the hose pulleys provides feedback on hose tension. A set of "Spraying Systems" nozzles, covering a range of outlet diameters, deliver either a solid stream or full cone spray to the borehole, depending on whether drilling is underway in a water filled ice cavity or in the upper air filled porous firn section of the hole.

The water recovery system uses water recirculation from an auxiliary borehole drilled next to the main hole down to impermeable ice below sea level and hydraulically connected to the main borehole. Circulation is provided by a Grundfos SP5A-38, 4 kW submersible pump in the auxiliary borehole which pumps the water back to the main water tank. A submersible pressure sensor connected to the pump provides indication of water level above the pump. The signal from this sensor also detects when the main hole connects with the seawater as the water level in the borehole rises to above sea level on connection with the sea. A small amount of the hot water is bled back to the bottom of the auxiliary borehole to prevent freezing around the submersible pump. The 8000 *l* reservoir serves as ballast in the system when drilling in ice but when drilling either the main or auxiliary holes in the upper firn part of the shelf, water from the nozzle is lost and therefore the supply must come from the reservoir. Drilling in firn is estimated to consume about 80 *l*/m so the reservoir gives a capability of 100 m without replenishment. During drilling in solid ice there is only about 10% effective water loss due to the difference

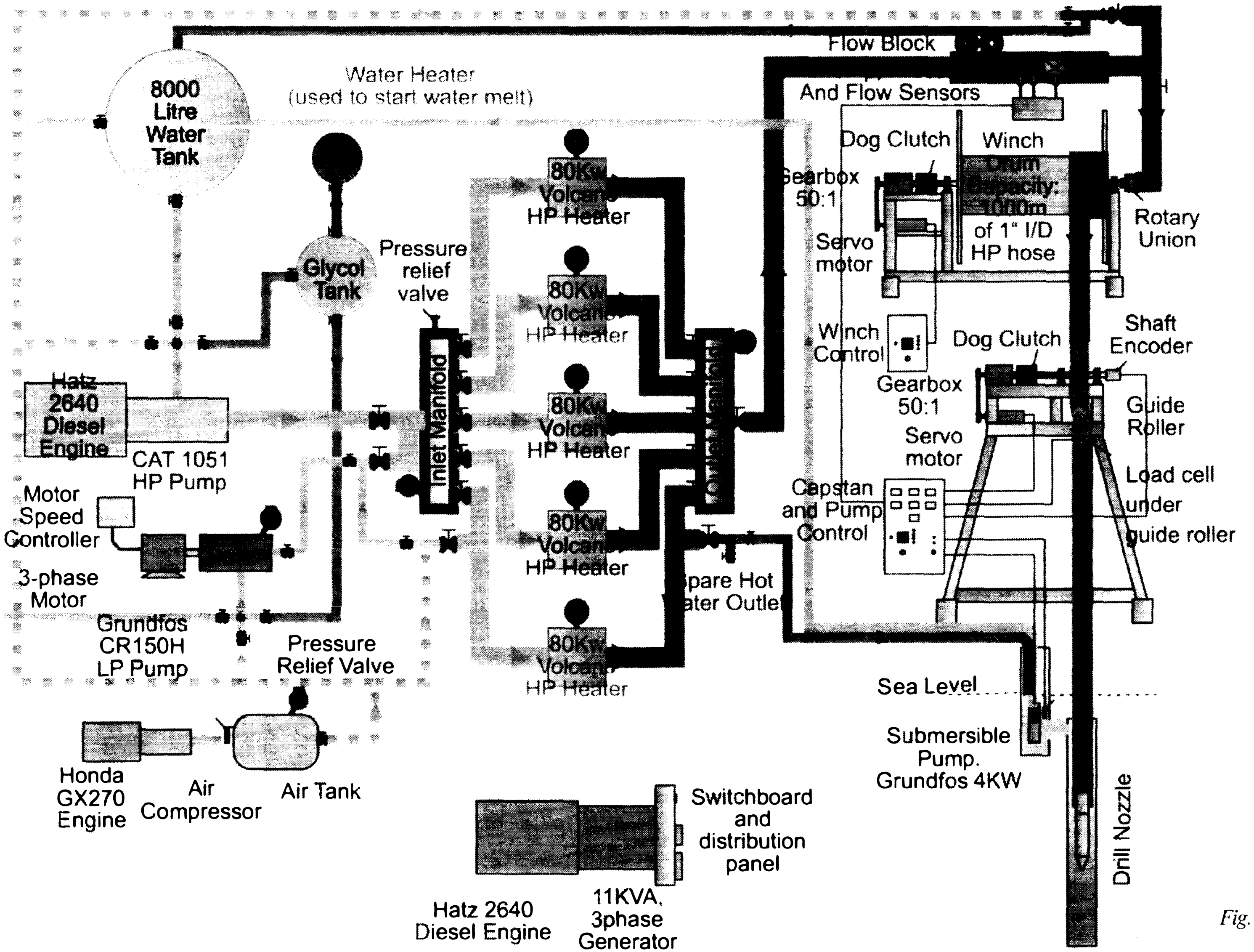

Fig. 2. *The hot water drill system.*

Table 1. Principal components of the hot water drill.

Item	Part No.	Specifications
High Pressure Hose	Parker Parflex 580N	1" I/D, 2000PSI working pressure. Uses Parker 58 series fittings
Motors	Baldor BSM 90A-3	3 Ph, 4.5 KW, 13.3 Nm torque Servo Motor. 50 Nm peak torque
Motor Controller	Baldor SD23H4A08E	4.5 KW flux vector motor controller
Gearbox	Brevini ET3010MR1	50.15:1 ratio, 1000 Nm continuos torque, 1800 Nm max. torque,
		thermal rating 3.5 KW continuous at 40 C, 5 KW at 10C.
Diesel Generator	Hatz 2G40	2 cylinder, air cooled diesel, 16 KW with 3 phase, 12KVA altenator
High Pressure Pump	CAT 1051	45 litre/min, at 1800 PSI, 3 plunger pump driven by
		Hatz 2G40 engine
Heaters	Lavor Volcano S	80 KW high pressure (2900PSI working) water heaters,
		1800 litres/ hour flow rate.
Submersible pump	Grundfos SP5A-30	155 cubic metres/ hour at no head, 60 L/m at 150m head
		driven by 4 KW, 3 phase motor
Borehole pump hose	1.5" Wellmaster layflat	
Flubber	Structure Flex	Self supporting 8000 litre Polyurethane material. Rated at -30 C
		folding temp., +70 C before fabric hardens and shortens life.
Low Pressure Pump	Grundfos CR2150	65 litres/ min flow at no head
Air Compressor		200 PSI unit driven by a 9 HP Honda petrol engine
Low pressure ball valves		1000 PSI rated stainless steel valves.
		Note: The valves used in the test season were made of brass and
		proved inadequate as water trapped between the wall
		and the ball froze and cracked the valve wall
High pressure ball valves		Stauff High pressure ball valves
Drill stems		3 stems of 1.5m length each which can be as a single 1.5m drill stem
		or joined together to form a stem of 4.5m length and 90 Kg in weight
Reaming stem		A 1.8m length, 127mm Dia. Stem with a backward spray
		for hole reaming.
Hose winch		Designed and built inhouse to accommodate 1000m of 1" I/D hose
Capstan tower		Designed and built inhouse with a clearance of 2m from the hole,
		and the capacity to drive a 1" hose with a 120Kg load up and down
		at speeds ranging from 1mm/ sec to 1.5m/ sec.
Nozzles	Spraying Systems Company	Range from 2.7mm to 6.4mm solid stream and 3.2mm to 7.2mm
		cone spray
		Cone spray used in fim, solid stream used in ice.
Rotary union	Dueblin 1.25"	4000 PSI rated, 20 RPM constant rotation at max. pressure rating.
Flowmeter	Hoffer	1" I/D, magnetic pickup coil. Linear range 15-227 litres/ min.
	HD1X1-4-60-UB-1M-BSP-SP	Repeatable range 7.6-284 litres/ min.
Shaft encoder	Hengstler RI41-0/3600ER.11KB	3600 pulses/ rev. dual phase shaft encoder
Water pressure sensor	Sensit M6420-200G1-50	0-200 Bar, 4-20 mA, 10-32 V supply
Water Temp. sensor	Amalgamated Instruments	PT100, 3 wire temperature sensor with adaptor for installation into
		high pressure thermal well
Load cell	Precision transducers LS	50 Kg, 2mV/V, 5-15V low profile shear beam load cell
Borehole pressure sensor	Amalgamated Instruments	Downhole 0-10Bar pressure sensor
	A6420-10.0G100M	with 100m vented cable, 4- 20mA output
Speed/ Depth Display	Hengstler	7 segment, 5 digit, up/ down counter with rate, 240V supply,
	tico 0 735 P 51300	10 KHz max. frequency
Flow display	Amalgamated Instruments	
	PM4-TR-240-6E-AR	6 digit display, selectable input, 100 KHz max count rate,
		0-10 V output retransmission, alarm output, 240V power input
Pressure/ temp./	PM4-IV-240-5E-AR	5 digit display, selectable input, 4 samples/ sec,
borehole pressure display		0-10V retransmission, alarm output, 240V power input
Load cell display	PM4-WT-240-5E-AR	5 digit display, 4 wire ratiometric input, 0.5-100 mV input sensitivity,
		output excitation, 5 to 100 samples/ sec. Selectable, 0-10 V
		retransmission, alarm output, 240V input

between the density of water and ice. This system of hot water drilling has been successfully employed elsewhere (*e.g.*, on the Ronne Ice Shelf (Makinson, 1994). Electric power is produced by a Hatz 12 kVA 3-phase diesel generator.

A schematic of the drilling system is shown in Fig. 2 and a list of the main components in Table 1.

4. Season 1999/2000-testing

During the 1999/2000 season the hot water drilling system was tested at a site at the NE corner of the Amery Ice Shelf. This site minimised flight time from the ship while providing surface conditions similar to those expected to be encountered in the following years. Some 12 t of drilling and field camp equipment was transported from the ship using Sikorsky S76 helicopters. The field camp comprised a drilling shelter (Weatherhaven), a kitchen/dining shelter (Weatherhaven mobile work shelter), polar pyramid tents, which together with one A-frame tent and a small dome tent accommodated the four person drill team. The drilling shelter housed the hose capstan and winch but all other drilling equipment, including the diesel pump, diesel generator, heaters, manifolds and water tanks were set up in the open. Near the front of the Amery the annual accumulation rate is quite high—more than a metre of snow per year—and this, combined with large amounts of blown snow, showed the camp and drilling arrangements to be inadequate. It was clear that for serious drilling, when stoppages due to snow clogging intakes would be unacceptable, shelters would be required for the diesel engines and the water heaters. General work efficiency would also be improved by better living facilities. Despite these difficulties, the drill was set up, but before any drilling could be started the original 6000 *l* reservoir (the flubber) came apart at one of the welded seams and deposited the water it contained into the snow. Further testing with an improvised reservoir was limited by its 2000 *l* capacity but did result in a hole down to solid ice at 47 m and demonstrated that the system worked.

5. Season 2000/2001-first drilling

For the 2000/01 season the field station was considerably modified. The original Weatherhaven shelter was again used to house the winch and capstan and another shelter was fitted with exhaust ducts and air inlets and used for the engines and water heaters (Fig. 3). Another insulated Weatherhaven shelter was used as a kitchen/mess and three mobile work shelters used for accommodation. Work output was also considerably enhanced by the provision of a full-time cook for the field station. The modified set-up turned out to be very effective (the better weather experienced by working earlier in the season also helped) and overcame all the problems experienced in 1999/2000. A view of the 2000/2001 field camp is shown in Fig. 4.

On the 31st of December 2000 a 300 mm diameter hole was completed through the ice shelf (which is 380 m thick in this location) in 24 hours. During the next 24 hours a rotating roster of 6–8 hours reaming (heating) the hole and 6–8 hours for sampling gave, after several reaming runs, a hole nearly 500 mm in diameter over the full depth. Caliper and inclinometer measurements were made in the borehole and multiple CTD (conductiv-

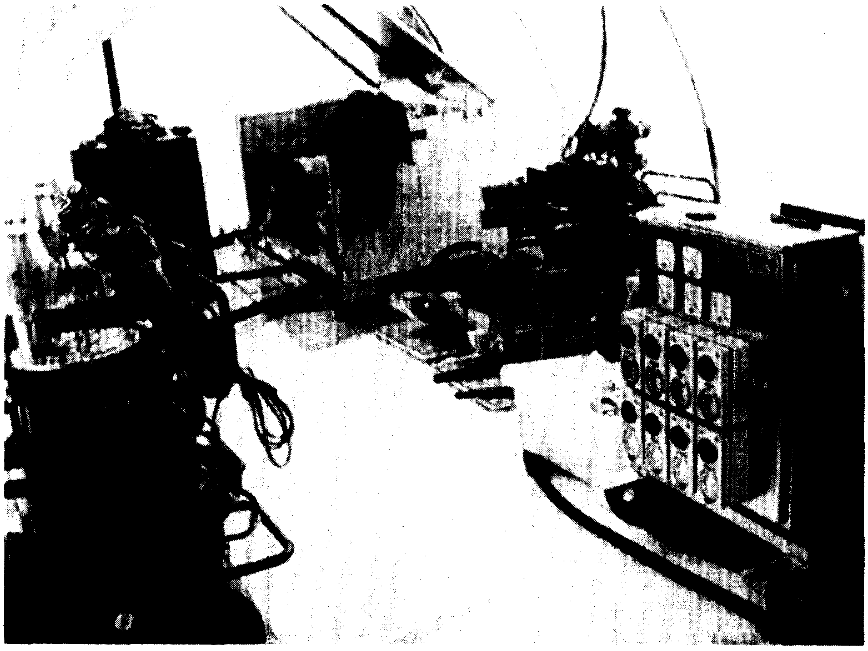

Fig. 3. Engines and water heaters in shelter (2000/01 season).

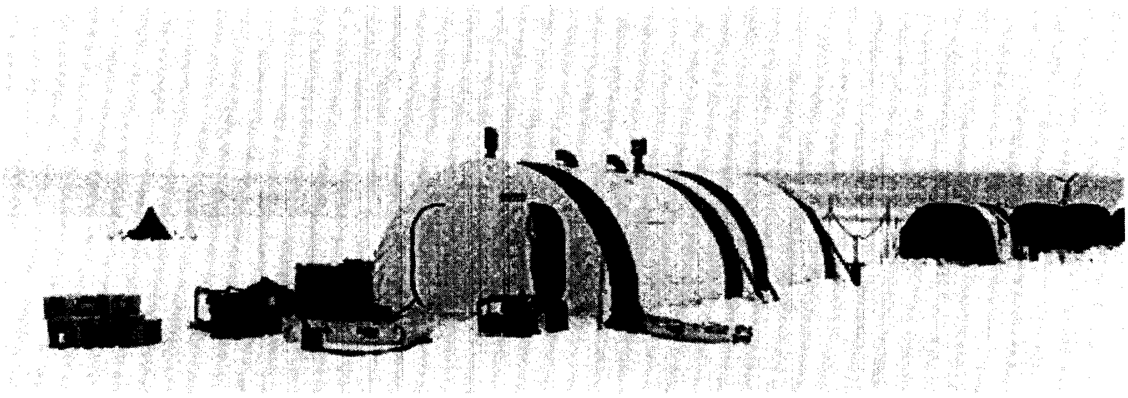

Fig. 4. View of the field camp 2000/01.

ity, temperature, density) profiles in the water cavity below the base of the shelf. The seabed is around 842 m below the surface, giving a cavity some 469 m deep. Water sampling runs were attempted, but the timer release mechanisms proved unreliable, and the Niskin bottles themselves appeared to have leaked. A 1.5 m long sediment core was taken from the sea floor using a gravity corer. The floor was composed of 'SMO' (siliceous muddy ooze) soft and light grey at the top and darker toward the bottom.

Permanent instrumentation was then installed in the hole. This consists of:

Seabird "Microcat" CTD's. Three of these are anchored to a mooring cable to collect conductivity, temperature and pressure data over an annual cycle. The data collected is stored internally and the plan is to interrogate the units and upload the data next season via the mooring cable, which forms a conductive loop with the sea water to provide a modem link to the units.

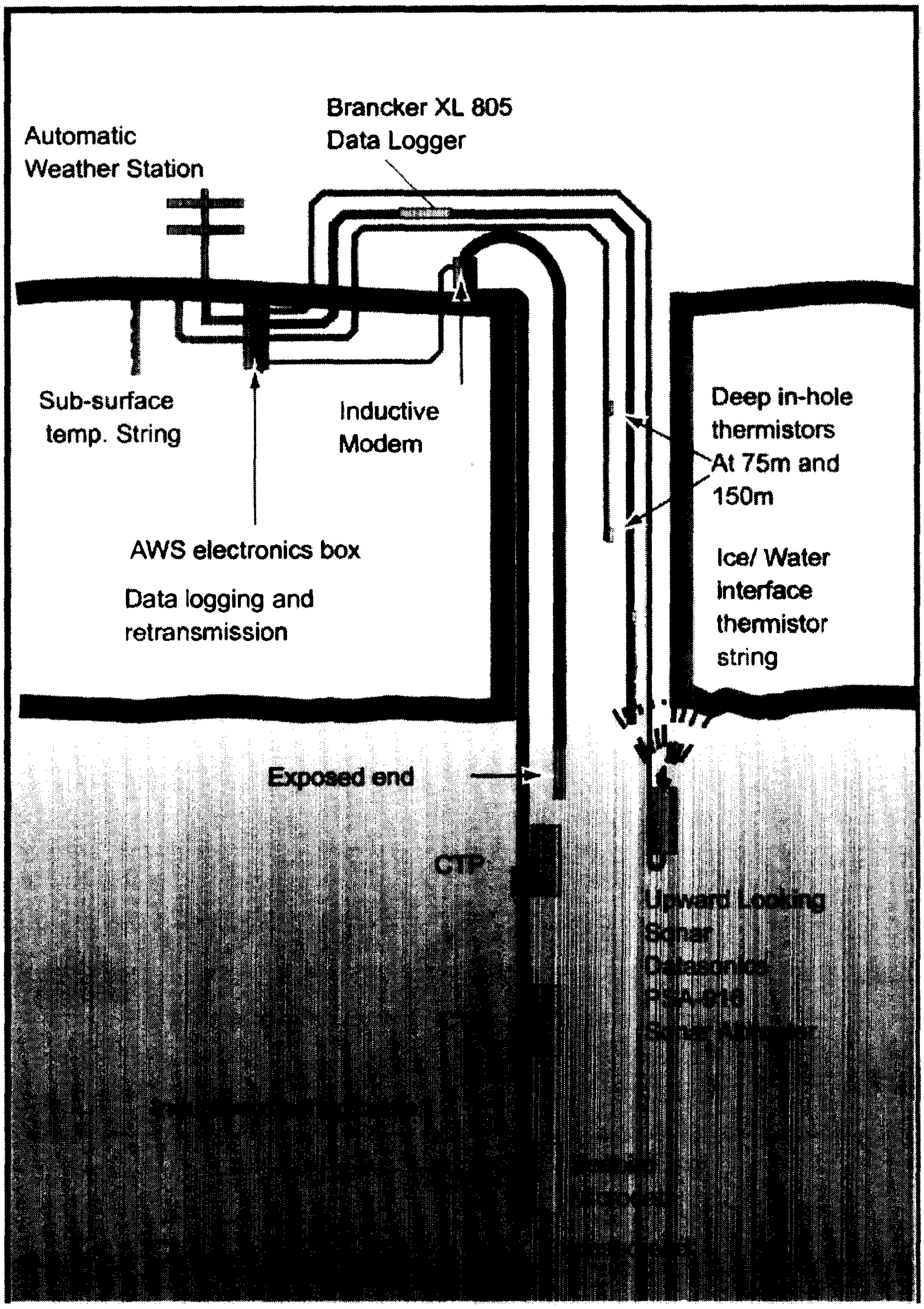

Fig. 5. *Downhole instrumentation.*

1: Seabird Microcats. 3 units measuring temperature, conductivity and pressure.

2: Upward Looking Sonar. 10 m below ice shelf. Measures melt rate beneath the shelf.

3: Thermistor String at Interface. 8 units at 1 m below and 0.5 m, 1 m, 2 m, 4 m, 8 m and 16 m above ice/water interface. Measuring melt rates.

4: Deep in Hole Thermistors. Located at 75 m and 150 m within the hole. Data for ice shelf temperature profile modelling.

5: Automatic Weather Station.

A thermistor string deployed just above the ice water interface (with one thermistor protruding through to the water). The thermistor string is an integral part of the data cable and connects to a data logger at the surface. The data will be used to deduce melt rates beneath the shelf from the temperature gradient at the base of the ice shelf.

An automatic weather station measuring surface temperature, wind speed and direction, surface pressure, snow accumulation and temperatures at 0 m, 1 m, 3 m, 10 m 80 m and 150 m was set up near the borehole. Data from the subsurface temperatures will be used for modelling the temperature profile of the ice shelf.

It was intended to install an upward looking sonar beneath the ice shelf (to provide a direct indication of melt rates beneath the shelf) but the equipment was not ready in time to be taken to Antarctica.

The intention is to eventually interface the CTD's, thermistor string and upward looking sonar to the AWS for retransmission of data via the ARGOS satellite system. Because of time constraints, this is planned for the following field season.

About two weeks worth of data was retrieved from the downhole instruments prior to the completion of the field season. A schematic of the downhole instrumentation is shown in Fig. 5.

References

Engelhardt, H. and Determann, J. (1987): Borehole evidence for a thick layer of basal ice in the central Ronne Ice Shelf. Nature, **327**, 318-319.

Fricker, H.A., Hyland, G., Coleman, R. and Young, N.W. (2001): Digital elevation models for the Lambert Glacier—Amery Ice Shelf System, East Antarctica, from ERS-1 satellite radar altimetry. J. Glaciol., **46**, 553-560.

Makinson, K. (1994): BAS hot water drilling on Ronne Ice Shelf, Antarctica. Proceedings of The Fourth International Workshop on Ice Drilling Technology. Tokyo, April 20-23, 1993. 192-202.

Morgan, V.I. (1972): Oxygen isotope evidence for bottom freezing on the Amery Ice Shelf. Nature, **238**, 393-394.

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