The investigation and experience of using ESTISOL™ 240 and COASOL™ for ice-core drilling

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ABSTRACT. Continuous good-quality deep ice cores provide excellent scientific data with which to reconstruct a past climate record for >800 ka. At depths starting from ~100 m using an electro-mechanical drill, a drilling liquid is essential for successful recovery of the very high-quality ice cores demanded by modern scientific analysis techniques (e.g. continuous flow analysis). Finding a suitable drill fluid for use at deep ice-coring drill sites is not an easy task. Temperatures vary greatly not just from site to site, but also at a site where the average mean temperature from surface to bedrock can vary from –55°C to –2.75°C. In the past 60 years, many fluids have been used, with varying degrees of success, but for various reasons are either unavailable, are now considered unsafe and dangerous or are too environmentally damaging to be permitted. Here we report on our pre-season investigation into possible candidate drill fluids, with specific information concerning ESTISOL™ 240 and COASOL™, the rationale behind the redesign of our drill successfully used at NorthGRIP, Greenland, and EPICA DML, Antarctica, the knock-on effect of those changes, and our field experience in Greenland at Flade Isblink in 2006 and at NEEM in 2009–10.

KEYWORDS: glaciological instruments and methods, ice core, ice coring, ice engineering

INTRODUCTION

The 1987 Montréal Protocol on Substances that Deplete the Ozone Layer prescribed an initial phased reduction followed by elimination of nearly 100 chemicals responsible for ozone depletion. The most aggressive Class I substances are chemicals, such as chlorofluorocarbons (CFCs), production of new stocks of which ceased by 1994 and which by 2010 had been virtually phased out worldwide. Class II substances, chemicals of a less aggressive ozone-depleting nature, including the hydrochlorofluorocarbons (HCFCs), were initially given a longer phase-out period. This period changed when the 1993 Accelerated Phase-out of Class II Controlled Substances was established to phase out earlier chemicals such as HCFC-22, HCFC-141b and HCFC-142b. Specifically for the US, this action banned the production and consumption of HCFC-141b as of 1 January 2003 (Final Rule, 10 December 1993; 58 FR 65018). Similar accelerated phase-out actions were taken by European Union and other countries.

Up until this point, several deep ice-core drilling operations (e.g. NorthGRIP in Greenland, EPICA Dome C and EPICA DML in the Antarctic) had been using HCFC-141b as an essential additive with Exxsol™ D series de-aromatized hydrocarbon fluids to fine-tune the density. With the accelerated phase-out plan of HCFC-141b, several teams started to investigate suitable replacement drill fluid candidates for future deep ice-core drilling projects (e.g. Talalay and Gundestrup, 2002; M. Gerasimoff, unpublished information; Steffensen and others, unpublished information).

In 2004 our investigations included a wide variety of possible substances as singular fluids and as combination fluids, including densifying additive replacements for HCFC-141b. We initially reinvestigated previous candidate fluids, then investigated 'new' possible candidate fluids, and eventually focused our investigations on a group of fatty acid esters produced by EstiChem A/S in Denmark and DOW Chemical Company in Germany.

In laboratory tests ESTISOL™ 240 and COASOL™ showed desirable properties, including the ability to fine-tune the density to 920–950 kg m^{-3}, have a far lower environmental impact, contribute to overall better health and safety, and simplify logistical transport (i.e. non-hazardous classification). We found that what was initially considered an undesirable property, the relatively high level of viscosity, is now considered an advantage in 'warm' areas of the ice sheet. There are some undesirable properties, such as the physically degrading effects on softened synthetic rubbers and certain soft plastics.

ESTISOL™ 240 was field-tested within an ice-coring project at Flade Isblink, northeast Greenland, in 2006. The drilling was found to perform well, with good production rates and excellent ice-core quality. It was noted that these fluids have an undesirably slippery nature and special precautions would be required during their use (Steffensen and others, unpublished information).

After careful consideration, in 2009 a deep drilling ice-core operation was started at NEEM (North Greenland Eemian Ice Drilling) on the Greenlandic ice sheet (77°27′ N, 51°3.6′ W), using this two-fluid combination. This ice-core drilling operation was successfully concluded in 2010 when sediments were recovered at 2537 m depth. In 2011 and 2012, ice and sedimentary cores were successfully recovered.

DESIRABLE CRITERIA OF ICE-CORE DRILLING FLUIDS

Several quite specific physical, chemical and biological attributes are required for a drill fluid, or drill fluid

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combination, to be suitable for recovering an ice core to several thousand metres and for supporting the borehole over forthcoming decades to allow access to borehole logging instruments.

Fluid density

One of the most essential physical characteristics of the fluid is the density. The density of the fluid, in conjunction with the fluid column height, determines the pressure exerted by the fluid onto the borehole ice surface. This pressure helps to relieve the possible abrupt isostatic pressure release during the drilling process, which in turn minimizes stress-related lateral fractures produced in the ice core, and thus improves ice-core quality. This drilling issue is first apparent at depths of ~100 m where the drill fluid is first used. The fluid density is also essential to produce a balanced, even distribution of pressure against the borehole wall so as to minimize borehole closure.

For a deep drilling operation, there are two options for matching the drill fluid pressure to the ice isostatic pressure. Adjusting the fluid head height is by far the most simple and can give good pressure matching at specific depths, though not necessarily the whole depth. When the fluid column height is used in combination with adjusting the fluid density, the matching of pressure can be set not only more precisely but over a much wider depth and temperature range by adjusting the mixing ratio. For practical purposes a drill fluid density of ~920–950 kg m^{-3} over a temperature range of –10°C to –32°C is desirable (Gundestrup and others, 1994) and preferably with the ability, by mixing, to fine-tune by ±25 kg m^{-3}.

Fluid viscosity

The majority of drill systems used in ice-core drilling operations are wire line types. The drill is lowered down a borehole from the surface using a cable, a core is drilled, the drill and core are hoisted to the surface, the ice core removed, the drill cleaned and the process repeated. This incremental drilling operation directly affects the time a complete drilling operation takes in the very expensive working environment, usually limited to 2 or 3 month long seasons. Thus, the time taken for drill runs has a significant influence on overall project costs. A faster operation might subtract a year or more compared to a slower operation.

A significant contributor to the overall drilling operation time is the time taken for the drill to descend and ascend the borehole, particularly when recovering ice cores at lower depths. From personal experience at EPICA Dome C II, for example, at 3200 m 3 hours were required to recover 40 cm of ice core. The drill travel speed is related to the viscosity of the drill fluid. To allow the drill to quickly descend and ascend, a low kinematic viscosity is a desirable criterion, preferably <5 mm^2 s^{-1} (<5 cSt) at –32°C (Gundestrup and others, 1994).

Compatibility

For ice cores to be scientifically useful the drill fluid should have little or no effect on the ice, or the scientifically interesting chemical species contained within the core. It is essential that the drill fluid be compatible with ice and water, without dissolution of ice core. It should also be compatible with materials used in and around the drill site, the logging process and storage facilities; it should be compatible with substances or techniques used during drill emergency recovery situations; and it should be compatible with modern borehole logging probes.

Further essential properties

Low toxicity is essential for the work environment and to minimize environmental impact.

Availability, both currently and for the foreseeable future.

Easy logistical transport.

Stability in the environmental conditions and over time.

Realistic overall costs.

The choice of fluids that meet these criteria is limited. Table 1 gives a brief list of past and possible new candidate fluids, with clearly undesirable properties highlighted in bold.

LABORATORY TESTS: DENSITY AND VISCOSITY

During the laboratory tests, candidate fluids were initially tested at room temperature then cooled and tested at various temperatures from 0°C down to –45°C in either cold rooms or within refrigerator chest freezers. The fluids were tested in pure form and mixed at several different volumetric ratios. Measurements were made to characterize the density vs temperature and the dynamic viscosity vs temperature. From these measurements the kinematic viscosity vs temperature can be calculated.

Density was measured directly in kg m^{-3} using a calibrated hydrometer (±2 kg m^{-3}) with a built-in thermometer. Temperature measurements were first made approximately with the hydrometer thermometer and then accurately using an ISOTECH TTI-7 calibrated platinum thermometer (±0.004°C). Three to five density measurements were made at specific temperatures. The process was repeated three times.

Dynamic viscosity was measured directly in Pa s, and more specifically within the range of these fluids, in dPa s, using a Thermo Scientific HAAKE Viscotester VT 1 and VT 2 plus viscosity meters (±5% full scale deflection (FSD)). The fluid temperature was measured using the ISOTECH TTI-7 calibrated platinum thermometer (±0.004°C). Five to eight viscosity measurements were made at specific temperatures. The process was repeated three times.

From the dynamic viscosity and density measurements the kinematic viscosity (ν) was determined by the ratio of the dynamic viscosity μ to the density of the fluid ρ.

The SI unit of kinematic viscosity is m^2 s^{-1}. Due to the long history of drilling fluids, a commonly used and familiar physical unit used is the CGS physical unit for kinematic viscosity, the stokes (St), more specifically the centistokes (cSt) (1 cSt = 1 mm^2 s^{-1}). At 20°C, water has a kinematic viscosity of ~1 mm^2 s^{-1} (1 cSt). In the following discussion the SI unit mm^2 s^{-1} is used.

LABORATORY RESULTS: DENSITY AND VISCOSITY

Density

Initially many candidate fluids were tested for suitability and compared. Figure 1 shows the density measurements of ESTISOL™ 240, COASOL™ and three different mixture ratios at various subzero temperatures. The green band on the graph represents a broad desired density range which

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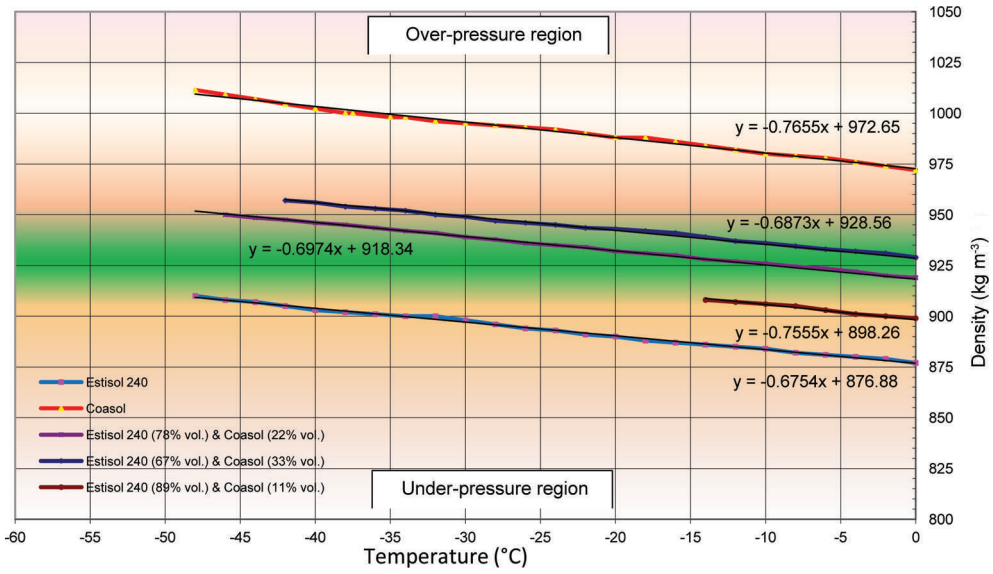

Fig. 1. Density temperature measurements of candidate drill fluids and mixtures. The central green band represents the desirable density, and the upper and lower red areas are undesirable densities. The volumes of mixtures are at 20°C.

can be used in conjunction with fluid column height adjustment for borehole pressure balancing. The lower and upper bands represent undesirable (under and over) density ranges for pressure balancing. For deep drill sites in Greenland, where the ice temperature is from >–9°C down to –34°C (Dahl-Jensen and others, 1998) and has been measured up to –3.4°C at NEEM (Fig. 12, further below), the range of mixture ratios to fit the density requirement to the

Table 1. List and comparison of ice-core drilling fluids. Undesirable attributes are shown in boldface

	n-butyl acetate (also known as butyl ethanoate)*	Exxsol™ D40 (low aromatic hydrocarbon solvent)†	Lusolvan® FBH (dicarbonic acid–di-isobutyl ester)‡	COASOL™ di-isobutyl succinate, di-isobutyl glutarate, di-isobutyl adipate§	ESTISOL™ 240 (distilled ester from coconut oil)§	ESTISOL™ 256 (distilled ester from coconut oil)§	EDGA (ethylene glycol diacetate)¶
Manufacturer	Hangzhou Ruijiang Chemical Co., Ltd.	ExxonMobil	BASF	DOW	EstiChem A/S	EstiChem A/S	DOW
Melting point (°C)	–77.9	<–75(1)	<–60	<–60	<–50	<–40	<–31
Boiling point (°C)	126.5	163–187	>260	274–289	255–290	270–280	190
Flash point (°C)	**22**	**40–45**	131	131	136	>100	82
Explosive limit (% vol.)	1.2–7.5	0.6–7%(1)	0.6–4.7%	0.6–4.7%	None	None	None
Vapour pressure (25°C) (kPa)	**1.1**	0.013(1)	0.001	0.075	0.0012		0.03
Density (20°C),(1) (15°C) (kg m^{-3})	880	771	960	960	863	863	1128
Kinematic viscosity (20°C) (mm^2 s^{-1})	0.8	1.28 at 25°C	**7**	**5.3**	3	4.4	**6.8**
Auto ignition temperature (°C)	425	260	400	400	None	None	482
Biodegradable	Yes	Yes‖	Yes	Yes	Yes	Yes	Yes
Firefighting equipment	CO_2, dry chemical	Water spray, CO_2, dry chemical	Water spray, foam, CO_2	Water spray, foam, CO_2	Water spray, CO_2, foam, dry chemical	Water spray, CO_2, foam, dry chemical	Water spray, CO_2, foam, dry chemical
Special protection	Ventilate, safety glasses, gloves, impervious attire	Ventilate, safety glasses, gloves	Safety glasses	Safety glasses	Safety glasses	Safety glasses	Safety glasses
Hazardous material	**Class 3, UN 1123**	**Class 3, UN 1863**	No	No	No	No	No
Explosive risk	Yes	Yes	None	None	None	None	None
Max. workplace air levels (ppm)	**20–150**	**197**	None	None	None	None	
Price (US$ kg^{-1})	1.5–2.2 (2014)	1.2 (2014)	4.2 (2005)	4.8 (2010)	5.4 (2014)	4.4 (2005)	2.1 (2005)

*Data from manufacturer and Gerasimoff (2003). †Data from ExxonMobil Chemical, unless (1), then from Talalay and Gundestrup (2002).
‡Manufacturer's information. §Data from safety tests according to EU Safety 91/155/EU, article 204020, 203989, 205698 and 204872 respectively.
¶Manufacturer's information. ‖Exxsol™ is expected to biodegrade at a rapid rate and not to persist in the environment – manufacturer's information.

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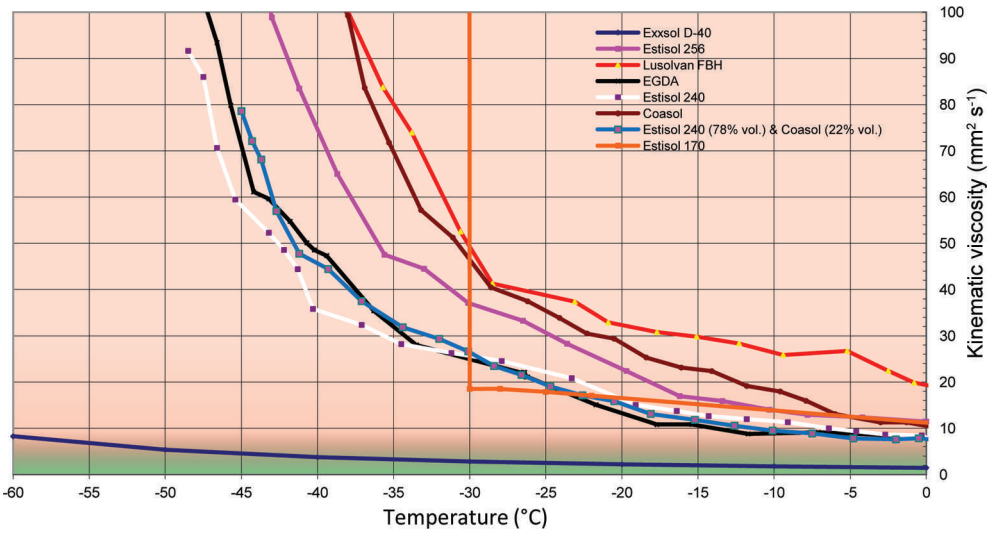

Fig. 2. Kinematic viscosity measurements for several test candidate drill fluids. The lower green area represents desirable attributes according to Gundestrup and others (1994), and the upper red undesirable attributes. ESTISOL 170, Lusolvan FBH, ESTISOL 256 and EDGA were initially considered and tested. They were found to be less suitable. ESTISOL 170 'froze' at –30°C; ESTISOL 256 has similar density characteristics to ESTISOL 240, but with a higher viscosity. EDGA was found to be very aggressive to plastics. Lusolvan FBH has high viscosity. The volumes of mixtures are at 20°C.

anticipated temperature range is approximately 78–66% ESTISOL™ 240 to 22–34% COASOL™ by volume (Fig. 1).

Kinematic viscosity

The kinematic viscosity of ESTISOL™ 240 (78% by vol.) and COASOL™ (22% by vol.) mixture at –30°C is 27 $mm^2 s^{-1}$. The kinematic viscosity of Exxsol™ D60 with HCFC-141b, used at NorthGRIP (1997–2004), is 3 $mm^2 s^{-1}$ at –30°C (Talalay and Gundestrup, 2002). Therefore, the new candidate drill fluid mixture has around nine times higher kinematic viscosity at –30°C than the drill fluid used at the previous deep drilling operation in Greenland (Fig. 2).

LABORATORY TESTS: COMPATIBILITY

Hydrophobic properties

The fluids were tested for hydrophobic properties, initially by mixing with water at room temperature, and then with small granules of ice at –16°C and –25°C. At room temperature the water and candidate fluids were poured into a glass graduated cylinder and mixed thoroughly by sealing the cylinder top and shaking. The mixed components rapidly separated into two distinct layers, the water in the lower layer, and the ESTISOL™ 240 and COASOL™ in the upper layer. The fluids were repeatedly mixed by stirring or shaking. On each occasion there rapidly occurred a well-defined visible separation of ESTISOL™ 240/COASOL™ mixture and water.

In a –16°C freezer, ice granules were then poured into, and mixed by shaking with, cooled ESTISOL™ 240/COASOL™ mixture. Within 10 s they began floating to the upper area of the container. After 1 min the majority of the ice had formed in the upper area, and within 5 min a stable well-defined visible separation of ice chips and drill fluid had occurred. The mixture was then repeatedly shaken to mix the components thoroughly and left to stabilize. The mixture repeatedly separated and stabilized. It was then left for several days without any noticeable change. Subsequently it was left for a total of 7 years without any noticeable change to the separated ice and drill fluid, and any visible dissolution of ice (Fig. 3).

This test procedure was repeated with a second batch in the –25°C freezer. Similar tests and observations were made. This second mixture was left for a total of 7 years without any noticeable change to the separated ice and drill fluid, or any visible dissolution of ice.

Material tests on plastics and other materials

The fluids were tested with many materials and chemicals which were considered likely to be used in a future ice-core drilling project and with which the fluids might have contact (Table 2). The following useful observations and laboratory

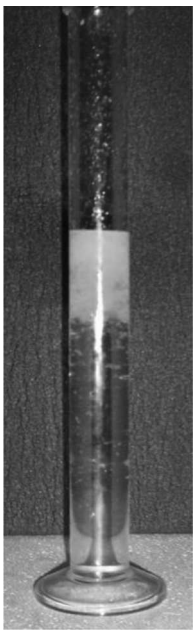

Fig. 3. Ice granules mixed with ESTISOL™ 240/COASOL™ at –25°C.

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tests were carried out with ESTISOL 240™ or COASOL™ concerning usage within an ice-core drilling environment:

ESTISOL™ 240 and COASOL™ are clear optically transparent fluids suitable for video logging the borehole using visible spectrum

No electrical breakdown could be detected at up to 3000 V cm^{-1}

No adverse reaction with glycol or ethanol

The fluid has a wet slippery feel, unlike previous fluids used

Some of the tests were 'very noticeable', such as when the fluids come into contact with expanded polystyrene (EPS) foam, which rapidly dissolves. EPS foam was used as an ice-core packing and thermal insulation material. Other materials, such as nitrile rubber O-rings, showed effects only days later. With prolonged exposure, nitrile rubber O-rings expand by ~17.5% (Fig. 4).

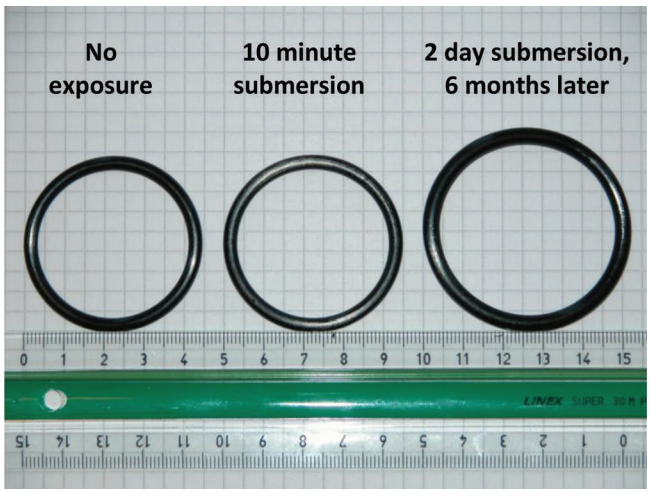

Fig. 4. Nitrile rubber O-rings used within the ice-core drill

VISCOSITY EFFECTS ON THE DRILL

For a new deep drilling project in Greenland with an anticipated temperature range similar to NorthGRIP of –2.5°C to –35°C, the kinematic viscosity of the ESTISOL™/240 COASOL™ mixture is approximately nine times greater than both our previously used drill fluid combination, Exxsol™ D-60 and HCFC-141b, at NorthGRIP, Greenland (1997–2004), and over five times the maximum recommended kinematic viscosity of 5 $mm^2 s^{-1}$ (Gundestrup and others, 1994). The effect of this higher kinematic viscosity on the drilling operation was suspected to be negative, but it was unclear by how much. Therefore we needed to determine what the effect would be and, if necessary, how to minimize any negative effect.

Trip speed

During an ice-core drilling operation the speed at which the drill can ascend and descend has a significant impact on the overall drilling time, and thus the costs associated with the entire project. For instance, from previous literature, lowering/hoisting operations were found to take 50–90% of the total time of the drilling operation (Vasiliev and Kudryashov, 2002).

The speed at which the drill can travel in the borehole is determined by the force applied minus the force resisting its motion. To hoist the drill back to the surface, the winch motor is normally set so the drill travels at a speed considered 'safe', usually similar to the descent speeds of 1.1–1.2 m s^{-1} and where the cable tension does not exceed limits of 5000–7500 N. During the drill descent, the force of gravity is used on the drill mass to 'pull' the drill down the borehole, and the release of cable from the drill winch is used to control the descent speed within 'safe' boundaries. The resisting force to the drill's motion is defined by a number of complex parameters associated with the drill's mechanical design, the borehole diameter and the kinematic viscosity of the drill fluid.

Using the drill velocity calculator developed by P. Journé (unpublished information, 1996), we initially compared

Table 2. Materials with no noticeable effects, and with noticeable effects, after contact with ESTISOL 240™ or COASOL™

Material	Effect
High-density blown film polyethylene (ice-core bags)	None
Polyethylene film (bubble wrap)	None
Polypropylene (PP)	None
Polytetrafluoroethylene (PTFE/Teflon)	None
Polyesters (in fabrics, bottles, screens, etc.)	None
Water and ice – hydrophobic/non-polar	None
Wood	None
Various metals (Al, Fe, Ti, Cr, Au)	None
Nitrile rubber O-rings (NBR, HNBR, HSN)	Expansion during 2 days of immersion. Loss of physical strength. No noticeable return to original dimensions
Polyvinyl chloride (PVC)	Surface dissolves slightly, becoming sticky to the touch
Softened plastics (shoe soles, gloves, aprons)	Would expand, lose physical integrity and easily break with normal operational stresses
Expanded polystyrene (EPS) foam	Dissolves
Paper	Though the physical structure is not detrimentally affected, written or printed text would smudge, quickly becoming illegible. Paper would saturate and not dry
Cardboard and paper packing	Once wet they lose their structural integrity and are easily broken
Rigid polystyrene	Dissolves
Clothing	Though the physical structure is not detrimentally affected, clothing can quickly become saturated and will not dry

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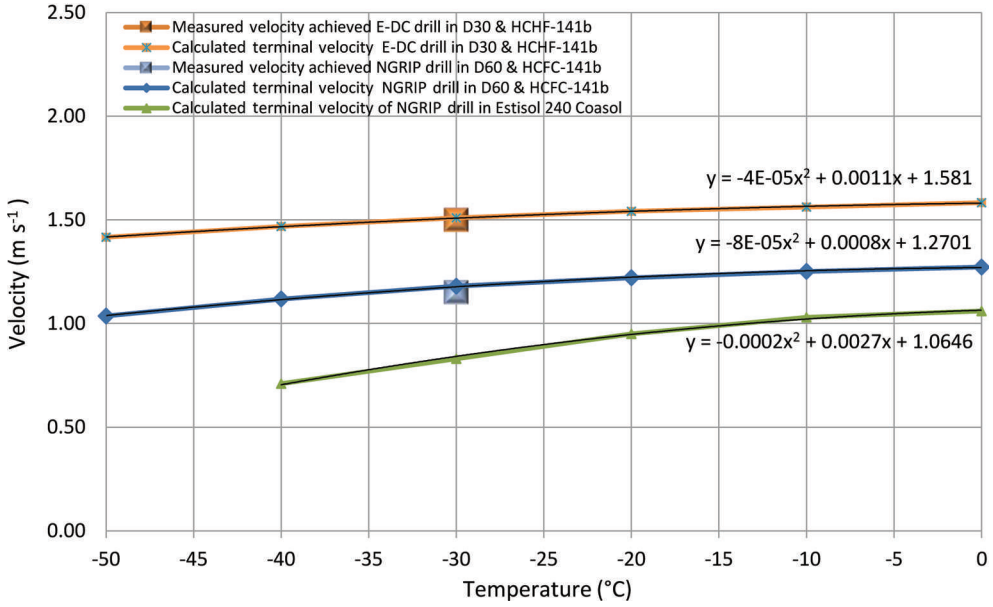

Fig. 5. Measured and calculated maximum descent velocities (terminal velocity) of drills used at EPICA Dome C and NorthGRIP. Terminal velocities were measured at (i) actual velocity achieved at EPICA Dome C in 2004, in Exxsol™ D30 and HCFC-141b with the EPICA Dome C drill at –30°C, depth ~1950 m; (iii) NorthGRIP II in 2003 and 2004 in Exxsol™ D60 and HCFC-141b with the NorthGRIP drill at –30°C, depth ~1850 m. The terminal velocity was calculated for (ii) EPICA Dome C drill in Exxsol™ D30 and HCFC-141b at 0°C to –40°C; (iv) NorthGRIP drill in Exxsol™ D60 and HCFC-141b at 0°C to –40°C; and (v) NorthGRIP drill in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture at 0°C to –40°C.

actually measured maximum descent velocities achieved by drills at NorthGRIP in 2003 and 2004 and at EPICA Dome C II in 2004 with these calculated descent velocities to check the validity of the calculations (see Table 3).

The calculated terminal velocities for the NorthGRIP and EPICA Dome C set-ups appears to be within a few per cent of what was actually measured, thus giving us a degree of confidence in our calculations. After this comparison the effects of the new drill fluids at temperatures from 0°C to –40°C were calculated (see Fig. 5).

From these calculations it was concluded that, for a NorthGRIP-type drilling set-up used in an ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture at –30°C, the terminal velocity would be 0.83 m s^{-1}, or 72% of the descent velocity actually experienced with the NorthGRIP drill in Exxsol™ D-60 and HCFC-141b at –30°C.

Table 3. Comparison of measured and calculated maximum drill descent velocities (terminal velocity) at NorthGRIP and EPICA Dome C

	NorthGRIP drill	EPICA Dome C drill (extra 50 kg 'dead weight')
Borehole diameter (mm)	129.6	129.6
Drill fluid used	Exxsol™ D-60 and HCFC-141b	Exxsol™ D-30 and HCFC-141b
Kinematic viscosity at –30°C ($mm^2 s^{-1}$) (Talalay and Gundestrup, 2002)	2.99	1.72
Calculated descent velocity at –30°C (m s^{-1})	1.18	1.51
Maximum measured descent velocity at –30°C (m s^{-1})	1.16 ± 0.05	1.50 ± 0.05
Calculated ascent velocity at –30°C with 7500 N (m s^{-1})	1.18	1.53
Maximum measured ascent velocity at –30°C with ~7500 N (m s^{-1})	1.16 ± 0.05	1.55 ± 0.05

Note: the calculations, made using unpublished information from P. Journé, do not consider the resistance of the cable on the borehole wall, in the drill fluid or the winch spooling mechanism.

VISCOSITY EFFECTS ON THE DRILLING PROJECT

Before starting a deep drilling project, while considering using a relatively high-viscosity drill fluid, it is desirable to estimate the time the project will take, in this case the number of field seasons. Using the time measurements of previous drilling projects to estimate the surface time, down time, night breaks and drilling time, and summing these times with the calculated drill descent and ascent times, an estimate was made for the total project time. We estimated that using a NorthGRIP configured drill to recover ice core to a similar NorthGRIP depth at similar temperatures would add one more season using the ESTISOL™ 240/COASOL™ mixture compared to the previous lower-viscosity Exxsol™ D-60/HCFC-141b mixture (see Fig. 10, further below).

To try to reduce the detrimental effects caused by the relatively high kinematic viscosity, several possible drill parameter changes were considered to improve the fluid dynamics:

1. Drill weight – increase the drill mass, and thereby increase the force of descent speed
2. Drill length –
   a. Reduce drill length to reduce fluid resistance
   b. Increase drill length to increase ice-core length, reducing the number of drill runs

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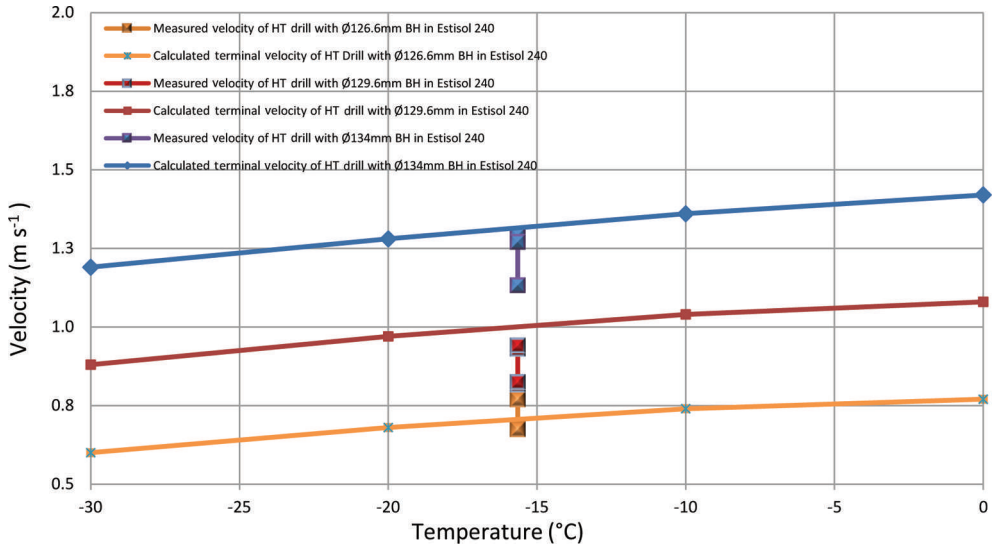

Fig. 6. Comparison of maximum measured and calculated descent velocities (terminal velocities) of the Hans Tausen (HT) drill in borehole diameters 126.0, 129.6 and 134 mm in pure ESTISOL™ 240 at Flade Isblink. (i) Measured terminal velocities of HT drill in 126.0 mm diameter borehole in ESTISOL™ 240 at –15.7°C with a kinematic viscosity of 13.5 $mm^2 s^{-1}$; (ii) calculated terminal velocity of HT drill in 126.0 mm diameter borehole in ESTISOL™ 240 in the range –30°C to 0°C; (iii) measured terminal velocities of HT drill in 129.6 mm diameter borehole in ESTISOL™ 240 at –15.7°C with a kinematic viscosity of 13.5 $mm^2 s^{-1}$; (iv) calculated terminal velocity of HT drill in 129.6 mm diameter borehole in ESTISOL™ 240 in the range –30°C to 0°C; (v) measured terminal velocities of HT drill in 134 mm diameter borehole in ESTISOL™ 240 at –15.7°C with a kinematic viscosity of 13.5 $mm^2 s^{-1}$; and (vi) calculated terminal velocity of HT drill in 134 mm diameter borehole in ESTISOL™ 240 in the range –30°C to 0°C.

3. Borehole diameter – to reduce the resistance of fluid displacement, but with more ice chips, thus requiring a longer chip chamber and thereby increasing fluid resistance
4. Open up the drill to increase internal flow
5. Reduce the diameter of the electronic section

It was initially calculated that to reduce the detrimental effects of using a higher-viscosity drill fluid the most efficient change to the drill configuration should be to increase the borehole diameter from the normal 129.6 mm to 132.0 mm, and possibly as large as 134 mm.

FLADE ISBLINK (2006)

To test this calculation and to test more generally the field suitability of the fluid in May and June 2006 a small camp was established on the independent ice sheet at Flade Isblink, northeast Greenland (81.3° N, 15.7° W; 620 m a.s.l.).

Several different drill cutters were used to make different borehole diameters, and the drill was allowed to free-fall by releasing the winch. The following diameters were tested:

126.0 mm diameter borehole

129.6 mm diameter borehole

134.0 mm diameter borehole

Test results

Using an unmodified Hans Tausen (HT) drill weighing 90 kg in 'wet' mode using the booster pump, average descent speeds of 0.72 ± 0.07 m s^{-1} were measured in pure ESTISOL™ 240 at temperatures of –15.7°C in a 126.0 mm diameter borehole. In these conditions the calculated descent speed was estimated at 0.70 m s^{-1}, a difference of –3%.

By increasing the borehole diameter to 129.6 mm, a 6% increase in borehole area, the average measured descent velocity increased to 0.88 ± 0.06 m s^{-1}, an increase of 22%. In these conditions the calculated descent speed was estimated at 1.00 m s^{-1}, a difference of +12%.

By increasing the borehole diameter further to 134 mm, a further 7% increase in borehole area, the average measured descent velocity increased to 1.20 ± 0.09 m s^{-1}, an increase of 36%. In these conditions the calculated descent speed was estimated at 1.32 m s^{-1}, a difference of +9% (see Fig. 6).

The measurements at Flade Isblink clearly showed that a small increase in borehole diameter caused a significant increase in descent velocity. Roughly, a 1% increase in borehole diameter increased the speed by 10%. The actual measured velocities and calculated velocities do not compare as well in the tests from NorthGRIP and Dome C II, with differences of up to 12%. There are thought to be several possible reasons for this, associated with measuring the descent velocity of the drill. To measure the descent velocity the drill was allowed to go into free fall, the time measured between an upper and lower depth, and the velocity calculated.

The errors could occur

1. Due to the process of time measurement.
2. Due to cautious drillers holding back the free fall of the drill at speeds greater than 'normal', i.e. >1.00 m s^{-1}.
3. Due to resistance to 'free'-fall descent of the drill from the resistance to rotation in the shallow winch drum, which increases with speed and which is not calculated in the equation.

It was considered that even with comparison errors of 12% between the 'real' and calculated descent velocities, the detrimental effects of using a relatively high-viscosity fluid

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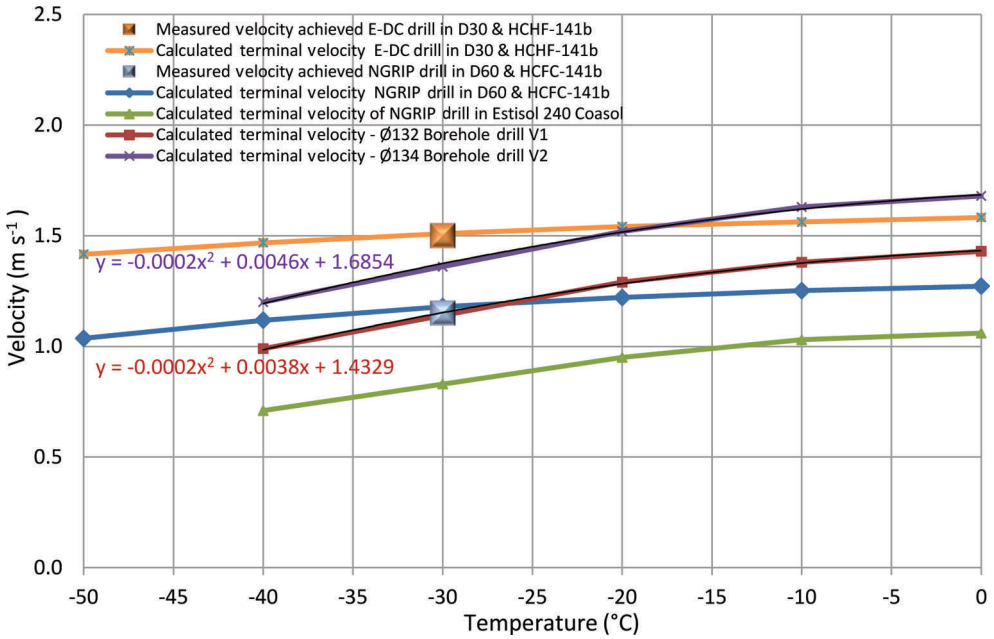

Fig. 7. Comparison of maximum drill descent speeds (terminal velocities) for various measured and calculated drill configurations, types of drill fluid and temperatures. Terminal velocities were measured at (i) EPICA Dome C in Exxsol™ D30 and HCFC-141b with the EPICA Dome C drill at –30°C, depth ~1950 m; (iii) NorthGRIP II in Exxsol™ D60 and HCFC-141b with the NorthGRIP drill at –30°C, depth ~1850 m. The terminal velocity was calculated for (ii) EPICA Dome C drill in Exxsol™ D30 and HCFC-141b at 0°C to –50°C; (iv) NorthGRIP drill in Exxsol™ D60 and HCFC-141b at 0°C to –50°C; (v) NorthGRIP drill in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture at 0°C to –40°C; (vi) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture at 0°C to –40°C; (vii) NorthGRIP drill configured with enlarged cutters for 134 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture at 0°C to –40°C. Due to the larger borehole diameter, extra chips would be produced for the same length of ice core recovered. This required a larger chip chamber volume. This increase in chip volume increased the overall length of the drill by 2 m. This increase in drill length would have a knock-on reduction in the descent velocity.

could be significantly reduced by simply increasing the borehole diameter.

Summary of drilling at Flade Isblink

A complete 98 mm (~4 in) diameter ice core was drilled using the HT drill to a depth of 423.3 m, including 263 m of this core using ESTISOL™ 240 as the drilling fluid. The ice-core quality using ESTISOL™ 240 is excellent. No difficulties were encountered in cleaning and processing the ice core. The mixture has a slippery feel with no discernible odour. Due to the fluids' slippery nature, special flooring was considered necessary for operator safety and drainage of spillage.

NEEM ICE-CORE DRILLING PROJECT

The North Greenland Eemian (NEEM) ice-core drilling project (77.45° N, 51.06° W; 2545 m a.s.l.) was an international research project aimed at retrieving ~2550 m of ice core from northwest Greenland. In 2007 a shallow 80 m ice core was recovered from the NEEM site, and the borehole temperature measured. At 80 m depth the ice temperature was measured at –29°C. Using this value and assuming a temperature profile similar to NorthGRIP, but without basal melting, the temperature of ice to be drilled was estimated to be within the range –3°C to –30°C. This temperature range fits within the density temperature profile of ESTISOL™ 240 and COASOL™ at mixing ratios of 25% to 33% by volume. For an anticipated lowest ice temperature of –30°C, with a density balancing fluid mixture ratio of 25% by volume, the kinematic viscosity would be ~25 $mm^2 s^{-1}$.

Using the HT drill it was first calculated, and then confirmed in 2006 at Flade Isblink, that the most efficient change would be to increase the borehole diameter from 129.6 mm to 132 mm and possibly 134 mm. Similar calculations were applied to the longer, heavier versions of the HT drill, the EPICA Dome C drill and the NorthGRIP drill, and compared to measured descent velocities. Calculations were also made to try to predict the effects of using a higher-viscosity drill fluid with various drill configurations (Figs 7 and 8).

As Figure 8 shows, the calculated terminal velocity of a 2 m longer version of the NorthGRIP drill travelling in a borehole of 132 mm diameter in an ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture would have a similar velocity at –30°C to that found with the NorthGRIP drill travelling in a borehole of 129.6 mm diameter in an Exxsol™ D60/HCFC-141b mixture. At fluid temperatures above –25°C this new configuration was calculated to be faster than the NorthGRIP set-up.

In Figures 8 and 9 we show the differences these drill configurations and drill fluid viscosities make to the predicted drill terminal velocity and the subsequent effects on the drill run time.

Using these run-time predictions, while assuming the full 2008 season is required for drilling 100 m, installing the drill-fluid-roof casing and setting up the deep drilling equipment, the total drilling project time was estimated (Fig. 10). Though configurations (ii) and (iii) have higher transit speeds they take longer to drill the 2550 m compared to configuration (iv). This is because those configurations drill shorter ice cores before the chip chamber is full.

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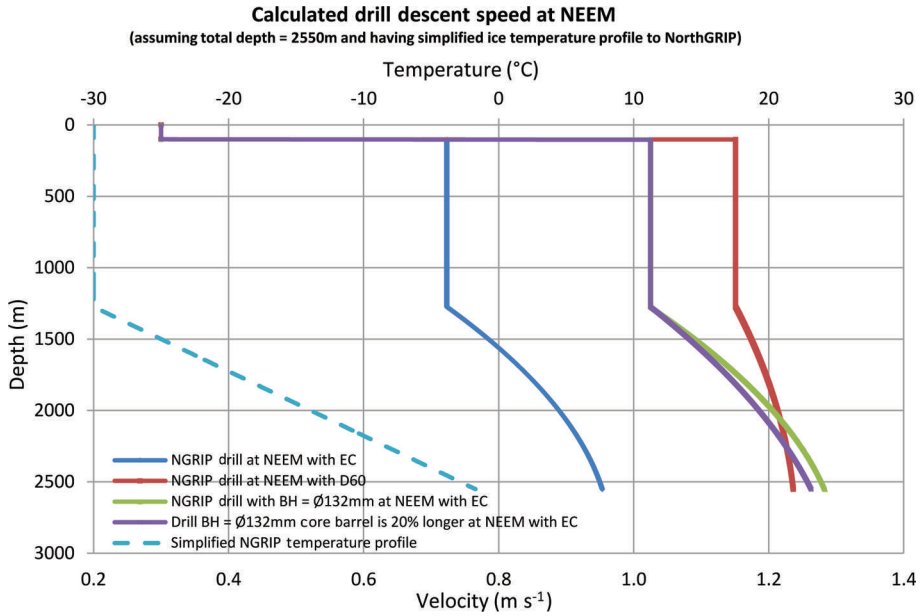

Fig. 8. Assuming the new drill site NEEM has an ice temperature depth profile similar to NorthGRIP and GRIP over the predicted ice depth of 2550 m, we calculated the terminal velocity of the drill for several drill configurations. The terminal velocity was calculated for (i) NorthGRIP drill in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (ii) NorthGRIP drill in Exxsol™ D60 and HCFC-141b; (iii) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (iv) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture. (v) A simplified temperature profile based on NorthGRIP, but assuming 2°C warmer and no basal melting.

Therefore, more transits are required and the accumulated time is greater for a given depth.

From our calculations we could see that drilling a borehole of 132 mm diameter should complete the fluid drilling phase in two seasons. As a precaution at NEEM it was decided to start the fluid drilling phase with 134 mm diameter cutters from 100 m to 160–200 m, where checks would be made of the maximum descent velocity. If the borehole diameter was considered excessively large, we would start using the 132 mm diameter cutters. Therefore,

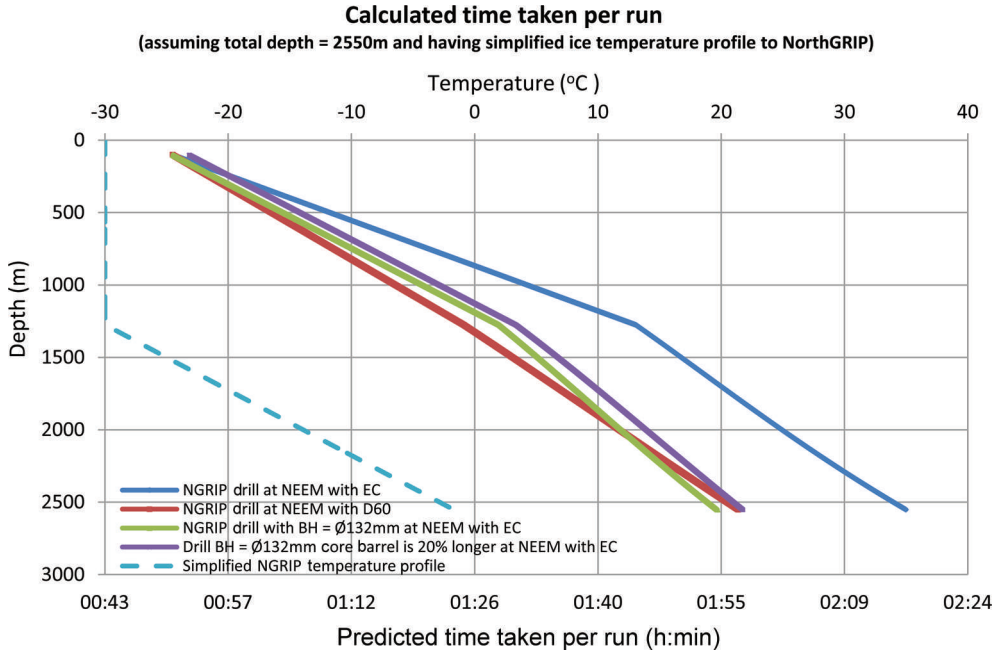

Fig. 9. Assuming the new drill site NEEM has an ice temperature depth profile similar to NorthGRIP and GRIP over the predicted ice depth of 2550 m, we calculated the terminal velocity of the drill for several drill configurations. The predicted time taken per run for (i) NorthGRIP drill in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (ii) NorthGRIP drill in Exxsol™ D60 and HCFC-141b; (iii) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (iv) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture. (v) A simplified temperature profile based on NorthGRIP, but assuming 2°C warmer and no basal melting.

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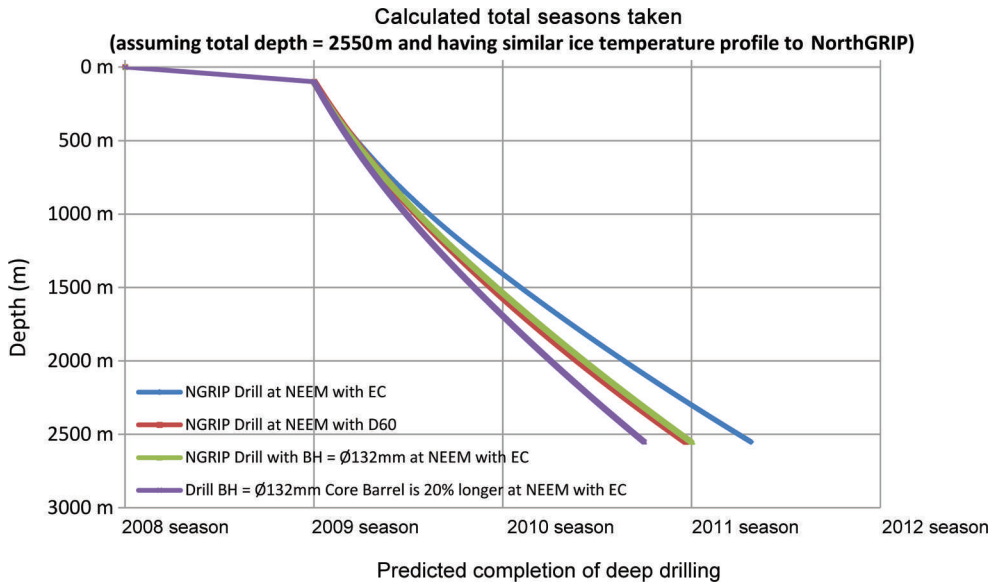

Fig. 10. The estimated effects of the drilling configuration on the number of seasons required to complete the project. The 2008 season is assumed to be consumed by drilling the firn and adding the casing. The fluid phase drilling starts in 2009. The estimated completion at 2550 m is in 2010 or 2011 depending on the configuration. The predicted project time for (i) NorthGRIP drill in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (ii) NorthGRIP drill in Exxsol™ D60 and HCFC-141b; (iii) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture; (iv) NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/COASOL™ (22% vol.) mixture.

before the 2009 season of the NEEM project several ice-core cutters were manufactured to produce these two diameters.

NEEM drill set-up

Based on the extended NorthGRIP version of our HT drill

Core barrel length increased to be able to drill 4 m long core

Chip chamber length increased to 6 m optimized for 4 m core and 134 mm diameter borehole

18 000 holes to chip chamber outer barrel to improve filtering

Outer core barrel coupled (not welded) to chip chamber

Wider cutter selection to drill 132 or 134 mm diameter borehole

Additional dead weights

New integrated load cell

New surface software

Longer tilting tower to accommodate extra 12.5 m drill

Optimized for

4 m high-quality ice core

High production rate at deep depths

Drilling in new higher-viscosity drill fluid

6.1 m longest box, improved flexibility for transportation

Knock-on implications

Using a higher-viscosity drill fluid led to the following knock-on effects:

A larger borehole: 129.6 mm to 132 mm diameter (from 110 m to 170 m: 134 mm diameter)

Requiring more drill fluid: 41 m^3 to 44 m^3 (for 2550 m)

Adding greater cost: US$135,000 to US$150,000

2 m longer drill length: 10.5 m drill to 12.5 m drill

Deeper/longer inclined trench: 7 m to 8.5 m

Longer tilting tower: 2 m longer

Anti-slip flooring: from plywood to plywood and gratings

NEEM ice-core drilling

As predicted, the 2008 season was dedicated to camp set-up, drilling the first 110 m, casing the top 100 m of the borehole and setting up the deep drilling system. At the beginning of 2009 the recovery of ice core using an ESTISOL™ 240/COASOL™ mixture started at a relatively slow pace, mainly due to the need to complete the drill trench set-up and so the drillers could find an optimal working mode. The borehole was initially drilled at 134 mm diameter until 170 m. This produced lots of excess ice chips. Below 170 m the borehole diameter was reduced to 132 mm, reducing the quantity of ice chips, allowing descent speeds in excess of 1.1 m s^{-1} and saving ~US$10,000 in drill fluids (Popp and others, 2014a). Production rapidly increased, averaging 14.9 m d^{-1}, until on 26 July 2010 at 2537.36 m sedimentary basal deposits were found in the ice core and the deep ice-core drilling operation was officially complete.

The new NEEM drill used in the ESTISOL™ 240/COASOL™ mixture produced 2437 m of ice core in 163 drilling days, and followed quite closely the predicted timeline (Fig. 11).

The performance of the drilling set-up was very positive: ice-core production in 2009 set a new record for one season, with 1648 m of ice core recovered and logged (Popp and others, 2014a).

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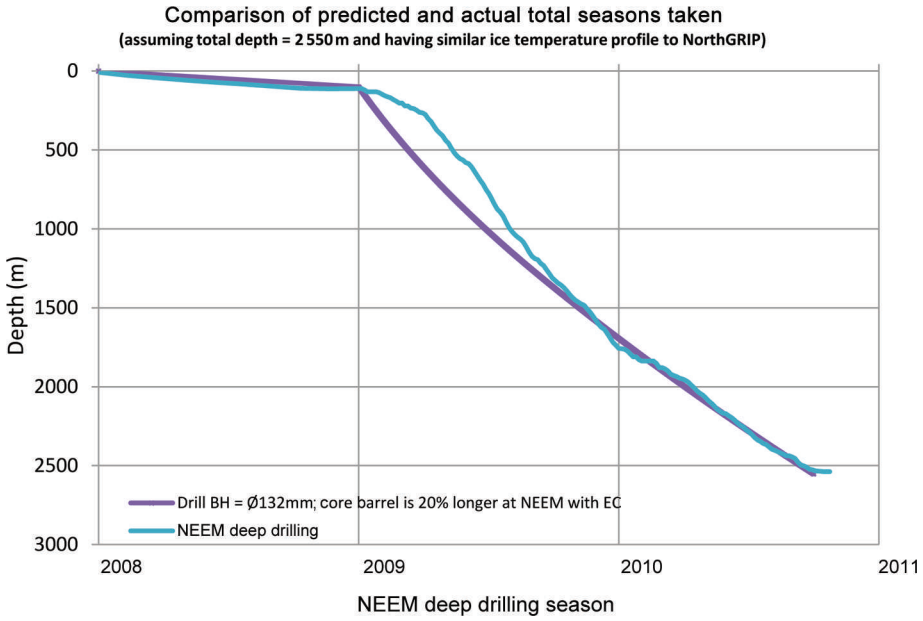

Fig. 11. Comparison of the actual and estimated effects of the drilling configuration with the actual drilling progress. (i) Estimate using NorthGRIP drill configured with enlarged cutters for 132 mm diameter borehole and 2 m longer chip chamber in ESTISOL™ 240 (78% vol.)/ COASOL™ (22% vol.) mixture. (ii) Actual progress during NEEM drilling.

'Special' characteristics

Before the start of the NEEM deep drilling operation the slippery nature of ESTISOL™ 240 and COASOL™ was considered when applied in our previous deep drilling operational set-ups. A specific issue identified was the danger of an accident caused by slipping on drill fluid spilt on the plywood flooring used in the drill trench. To reduce this risk, 1.0 m × 1.0 m × 0.02 m gratings were fixed over the plywood sheets to form a non-slip flooring.

As discussed above in 'Material tests on plastics and other materials', softened plastics were found to absorb, and some very slowly dissolve in, both ESTISOL™ 240 and COASOL™, which over time caused them to lose structural integrity. Specifically affected were the soles of certain types of drillers' boots. While walking on the gratings, mentioned previously, the boots were less exposed to the fluids, but when spilt on or while on the warm metal floor within the drillers' cabin the sole would be affected more. These boots needed to be disposed of after a period of ~6–10 weeks deployment.

Both COASOL™ and ESTISOL™ 240 have relatively low vapour pressures (0.075 and 0.0012 kPa, respectively) and boiling temperatures (274–289°C and 255–290°C respectively). When used in the context of a drilling operation these have both advantages and disadvantages. For instance, evaporation in the drill trench, science trench and storage areas is very low, so health risks associated with inhalation are reduced and air extraction systems are not required. Conversely, removing the excess fluid residue from ice cores and equipment required cleaning with paper towels. Further, drillers' clothing progressively soaked up these fluids and could not be cleaned in a practical manner in the field. Drillers' suites, similar to drillers' boots, required disposal after the deployment period.

Furthermore, unlike with previous drill fluids (e.g. the Exxsol™ D range), exposed skin did not dry out and lead to dry cracked skin, which is also considered an improvement. Nevertheless, from a health perspective, two drillers reported developing skin rashes most probably associated with fluid irritation. In future drilling projects, where drill liquids are used, we intend to give higher priority to procedures to reduce contact between drill fluids and participants, and to survey those participants more closely.

Warm ice

At previous deep drilling sites in Greenland and the Antarctic, 'warm' ice has presented a considerable challenge to the drilling operations. For instance, at NorthGRIP and EPICA Dome C 2, several field seasons were spent drilling the final 250 m of ice. Problems began at depths where the ice temperature was –10°C and above. With each run the amount of core drilled decreased initially below the average, then quickly to small pucks, and finally to no ice core at all. This problem is primarily caused by ice building up around the cutters and on the shoes, initially reducing and then finally preventing penetration of the drill head. It was concluded that the heat generated during the drilling process caused a small amount of ice to melt and then refreeze onto the drill head and shoes. To prevent this, various changes were made to the drill-head configuration and the drilling technique, all without lasting success. Eventually, a mixture of ethanol and water solution (EWS) at NorthGRIP 2003 was deployed in the drill with each run. This EWS stopped the meltwater refreezing onto the drill-head shoes and immediately improved the drilling performance, allowing both NorthGRIP and EPICA Dome C to drill in the warm ice. However, using EWS in an ice-coring operation has detrimental effects on the ice, such as dissolving the top of the ice core which is left in the hole between runs, dissolving the borehole walls, causing the ice core to be stuck and difficult to extract from the core barrel, and producing excessive chips mixed with refrozen EWS.

At NEEM we did not encounter such severe difficulties and completely avoided using EWS even though we drilled within ice at temperatures of –3.4°C at 2537 m, ~6.6°C warmer than both the NorthGRIP and EPICA Dome C sites

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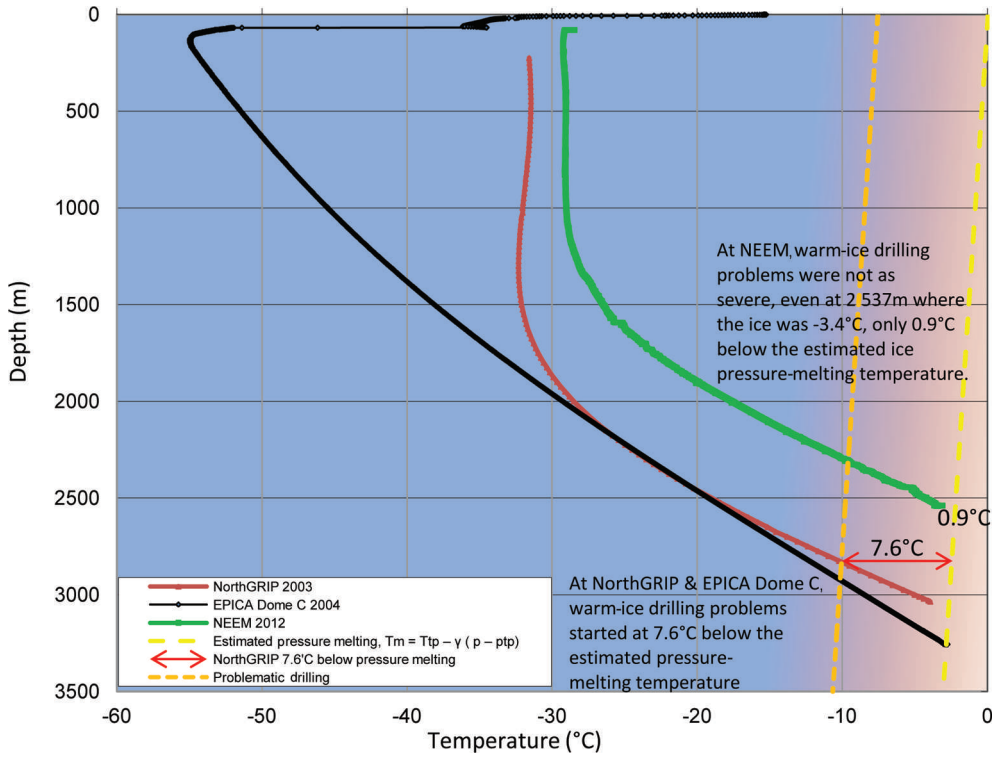

Fig. 12. At both NorthGRIP and Dome C, problems associated with 'warm'-ice drilling were encountered at ~–10°C, ~7.6°C below the pressure-melting temperature. At the NEEM site at 2537 m, where the ice temperature was –3.4°C, no warm-ice problems were encountered even though the ice was only 0.9°C below the estimated ice pressure-melting temperature. We concluded that the differences in depth, and hence the pressure-melting temperature, did not influence the improved drilling performance at NEEM.

with a similar drill-head configuration. Why did we not encounter problems associated with 'warm'-ice drilling?

Ice pressure-melting point

We initially considered whether the pressure-melting point of the ice could be influential. The maximum drilled depth at NEEM was 2537 m, ~548 m less than the 3085 m at NorthGRIP, and ~736 m less than the 3273 m drilled at EPICA Dome C. Within these environments the melting temperature of ice decreases with increased pressure, i.e. increased drilling depth.

For pure ice the melting temperature T_m depends on absolute pressure p by

$$T_m = T_{tp} - \gamma(p - p_{tp})$$

(Harrison and Raymond, 1976), where T_{tp} = 273.16 K and p_{tp} = 611.73 Pa are the triple-point temperature and pressure of water.

The Clausius–Clapeyron constant is $\gamma_p = 7.42 \times 10^5$ K kPa^{-1} for pure water/ice. Since glacier ice contains soluble and insoluble chemicals and air bubbles, the value of γ can be as high as $\gamma_a = 9.8 \times 10^5$ K kPa^{-1} for air-saturated water (Harrison and Raymond, 1976). From this equation the pressure-melting temperatures were calculated for North-GRIP, Dome C and NEEM drill sites and compared (Fig. 12). From this comparison we concluded that the differences in depth, and hence the pressure-melting temperature, did not influence the improved drilling performance at NEEM.

Hydrophobic non-wettable surfaces

A further possible explanation concerns the 'sticky' relatively viscous hydrophobic nature of the drill fluid. During the laboratory tests when a surface was subjected to or coated with the drill fluids it would easily retain a thin surface of the fluids. In both laboratory tests and in the field the drill fluid was quite difficult to remove from surfaces, being very slippery while sticky. When applied to a surface the combination of this slippery sticky nature and hydrophobic property gives the drill fluids a good water-dispersing property. This property could be a good reason why any water generated by the drill-head cutters did not refreeze onto the drill-head shoes, thereby preventing penetration, but was pumped into the drill to refreeze harmlessly in the drill fluid and ice chips.

Borehole stability

The primary scientific goal for the NEEM project was to recover a complete undisturbed ice core using these new fluids, which was successfully completed in July 2010. Further scientific goals involve 'logging' the borehole, such as determining the ice-sheet temperature profile, and the recovery of basal sediments (Popp and others, 2014b). To allow for these further scientific goals to be completed, the borehole needs to be stable over a much longer period than the 2 years taken to complete the ice-core drilling. As mentioned earlier, this long-term stability is determined by carefully balancing the drill fluid pressure against the ice isostatic pressure for the whole borehole length.

To check the stability of the borehole, the Centre for Ice and Climate has the KU Borehole Logger which measures the diameter and can be used to determine whether there is any borehole closure or expansion. The borehole diameter was precisely measured in May 2011 and May 2012 (Fig. 13; Table 4). From these discrete measurements

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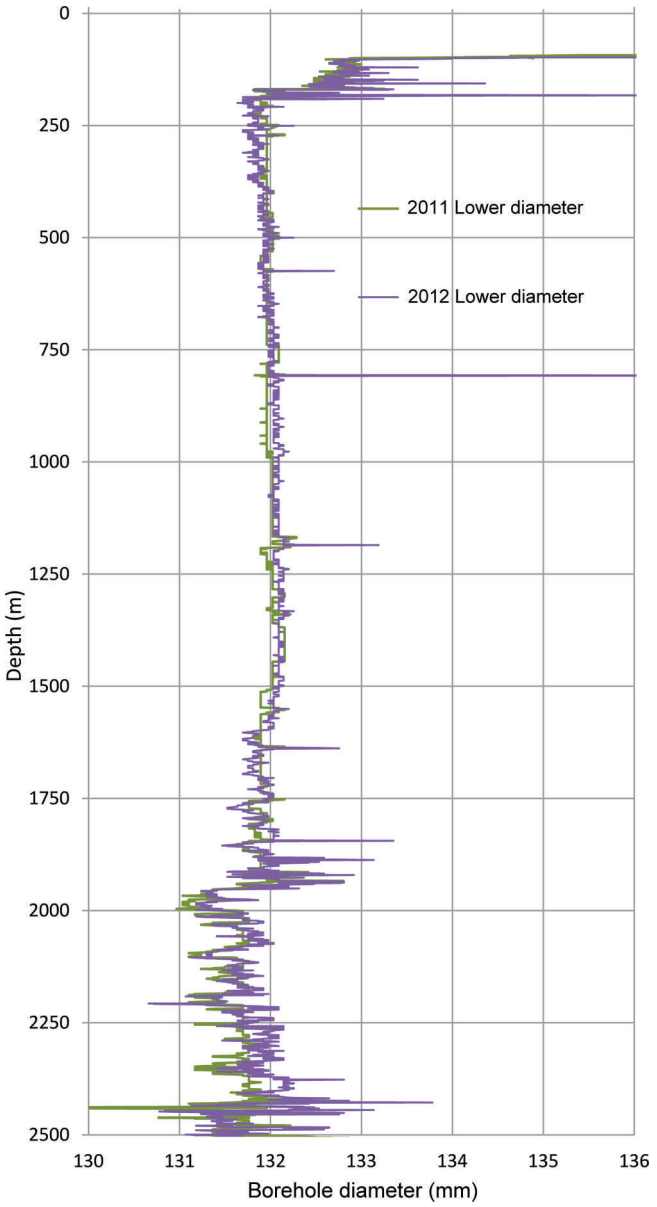

Fig. 13. NEEM borehole diameter vs depth for 2011 and 2012.

the upper section of the borehole appears stable. The central section appears slightly larger, though well within measurement errors. The lower section appears to have a very small increase in borehole diameter between 2011 and 2012. The differences that appear in the measurements from 2011 to 2012 are still too small and could be measurement errors. Future measurements to monitor the stability are planned for 2015.

CONCLUSION

We have reported successfully drilling 263 m of ice core at Flade Isblink in 2006, and 324 m of ice core at NEEM (S2 core) in 2011 using ESTISOL™ 240 as a single fluid, and 2427 m of ice core at NEEM (S1) in 2009 and 2010 using a mixture of ESTISOL™ 240 and COASOL™. The NEEM S1 deep drilling operation was completed in less than two field seasons, setting a new depth record in 2009 for recovering 1647 m of continuous ice core.

The modifications and changes we made to the design of the new NEEM drill system removed the detrimental effects on a deep drilling operation using a higher-viscosity drill fluid. Specifically, (1) increasing the borehole diameter from 129.6 mm to 132 mm, and (2) increasing chip chamber volume by increasing the length by 2 m, allowed the drill to ascend and descend quickly, allowing completion of the ice-core recovery component of the project within the projected time and budget. Before the use of these fluids, for an ice-core drilling project the maximum kinematic viscosity was considered to be 5 $mm^2 s^{-1}$ (Gundestrup and others, 1994). We successfully used fluids with a kinematic viscosity of ~27 $mm^2 s^{-1}$ to drill 1240 m of ice core at NEEM, and a further 1187 m at gradually reducing viscosity (Popp and others, 2014a).

Table 4. The difference in borehole diameter from 2011 to 2012 in several discrete sections

Depth range	Borehole diameter			
	2011	2012	Difference	Precision
m	mm	mm	mm	mm
200–967	131.96	131.96	+0.00	(±0.07)
967–1733	132.00	132.05	+0.05	(±0.07)
1733–2500	131.65	131.79	+0.13	(±0.07)
200–2500	131.87	131.93	+0.06	(±0.07)

This new fluid combination gave beneficial drilling performance within the lowest 250 m section of the ice sheet where ice temperature conditions were previously associated with problem 'warm'-ice drilling. This was attributed to the slightly sticky hydrophobic nature of the fluid combination, reducing the build-up of refrozen ice on the drill head.

To date, the measurable change in borehole diameter is well within the errors of the logging tool. Further investigations will be carried out in the future. For the time being, we conclude that the pressure exerted by the ESTISOL™ 240/COASOL™ drill fluid combination is fairly evenly balancing the ice isostatic pressure, possibly with a slight overburden at the lower depths.

Furthermore, using the ESTISOL™ 240/COASOL™ drill fluid combination in 2011 and 2012, sedimentary basal material was recovered from NEEM (Popp and others, 2014b).

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