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Operations Overview for the ANDRILL Southern McMurdo Sound Project, Antarctica

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Abstract - During the austral spring of 2007-08, a 1138 metre (m)-long rock and sediment core (ANDRILL [AND]-2A) was recovered from beneath the land-fast sea-ice in southern McMurdo Sound (SMS) in 384 m of water. A custom-built drilling system comprising an UDR-1200 rig, jack-up platform, hot water drill, sea riser, and diamond-bit wireline coring string was set up on the sea-ice approximately 32 kilometres (km) from Scott Base (NZ) and McMurdo Station (USA). The drilling system employed technology developed to handle challenging environmental conditions, including drilling from an 8 metre-thick sea-ice 'platform' that moved both laterally and vertically, tidal currents, and high winds. Drill site set up commenced in early September 2007, and the first AND-2A core was recovered on 10 October 2007. Drilling operations continued until 5 December 2007. Science operations were conducted at the drill site, in both the borehole and a purpose-built laboratory complex, and at the Crary Science and Engineering Center (CSEC), McMurdo Station (USA). Drill site science operations involved downhole logging, which was carried out in the borehole casing and in parts of the open hole, fracture studies, and physical properties measurements. Core was transported by helicopter from the drill site to McMurdo Station, where it was split, scanned, described, and sampled for initial characterisation. Once initial studies were completed, the core was packed into crates for shipment to the Antarctic Research Facility (ARF; core repository) at Florida State University in the United States.

DRILLING OPERATIONS OVERVIEW

The ANDRILL SMS Project drilling and science operations occurred at two primary locations: the drill site and Crary Science and Engineering Center (CSEC), McMurdo Station. Table 1 summarises key operational events and data.

Tab. 1 - Summary drilling data for AND-1B.

Drill rig location (9 October 2007)	77.758141 S, 165.276765 E
Sea-ice thickness	~8-8.5 metres (m)
Freeboard	0.74-0.80 m
Ice-shelf lateral movement (from 9 Oct. to 4 Dec. 2007)	~5.47 m @ 024.5°T
Depth to mean seafloor (from platform cellar floor)	383.57 m
Maximum sea ice tidal range (single diurnal cycle)	~1.33 m
Sea riser spud in	9 October 2007
Sea riser shoe set at	8.89 metres below seafloor (mbsf)
PQ coring started	10 October 2007 @ 8.81 mbsf
PQ coring ended	26 October 2007 @ 229.24 mbsf
PQ casing shoe (PQ3 bit) set	26 October 2007 @ 229.24 mbsf
HQ coring (HQTT bit) started	29 October 2007 @ 229.24 mbsf
HQ coring ended	21 November 2007 @ 1011.04 mbsf
HQ casing shoe set	25 November 2007 @ 1011.87 mbsf
NQ coring (NQTT bit) started	26 November 2007 @ 1011.87 mbsf
NQ coring ended	30 November 2007 @ 1138.54 mbsf
Sea riser cut	4 December 2007
Sea riser and float column recovered	5 December 2007

SEA-ICE THICKNESS

Multi-year ice at least seven metres thick was expected at the SMS site based on field reconnaissance in the 2006-07 season and monitoring of satellite imagery during the winter. Inspection of the sea-ice conducted by divers from the United States Antarctic Program on 27 September 2007 indicated that the ice was between 8 and 8.5 metres thick. An additional 5-6 m of dense platelet ice had also formed beneath the sea-ice.

During planning phases for the SMS Project, a sea-ice thickness of 1.75 m at day 250 was established as minimum for safe drilling operations (Falconer & Pyne, 2004). Due to the occurrence of substantially thicker multi-year sea-ice at the site, airbag flotation was not critical for safe operations. As deployment of the airbags would have been difficult for divers due to the substantial amount of platelet ice, it was decided not to deploy the airbag flotation.

SEA-ICE EXTENT

On 30 November 2006, the sea-ice in the vicinity of the SMS drill site was inspected for both thickness and surface conditions. During the austral winter of 2007, sea-ice in the area had been monitored using satellite imagery. Image analysis showed that the edge of the thick multi-year ice had remained at least 7 km from the drill site (Falconer & Pyne, 2007). However, the annual sea-ice in the south central McMurdo Sound (greater than 7 km north of the drill site) did not stabilise, with storms mobilising the new ice throughout the winter period. First year ice in the southern central McMurdo Sound area stabilised in spring but remained thin, generally less than 1 m thick.

In planning, a 5 km stable ice zone between the drill site and the ice edge was considered mandatory and was to be maintained for the duration of drilling operations. Monitoring during the field season (through physical inspection and analysis of satellite imagery) confirmed that breakouts of first year ice did occur but that no breakouts of the 7 km multi-year ice happened during the drilling period.

SEA-ICE TEMPERATURE

Sea-ice temperature at the drill site was monitored using two 10 foot-long thermocouple strings, which recorded a gradual increase in ice temperatures during the season (see Fig. 1). Comparison of baseline temperatures for sea-ice from a location away from the drill site with data from the thermocouple located next to the drill system power pack indicated some 'local' warming of the ice likely due to the proximity of structures and drill site operations.

Temperatures 2-3 m beneath the sea-ice surface remained below -10°C until early December. The thick ice remained cold and strong during the drilling period and freeboard measurements indicated that no significant surface depression due to site loading occurred (Fig. 1). Small changes (0-5 cm) in freeboard are within measurement errors. It is unclear what caused the freeboard changes recorded in early December 2007.

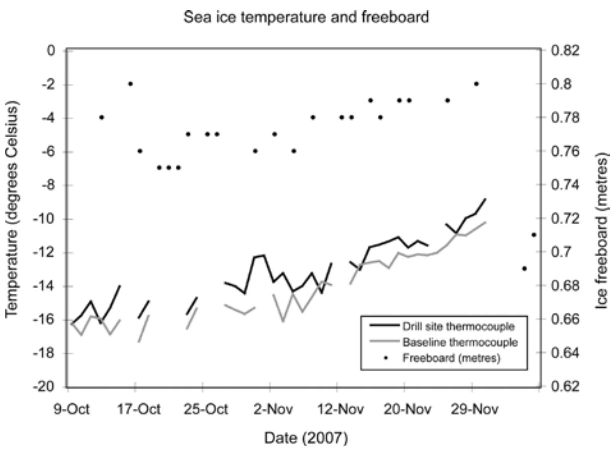

Fig. 1 – Sea-ice temperature and freeboard.

LATERAL MOVEMENT

The sea-ice in the SMS area moves gradually, probably in response to several drivers. One driver is the northward ice shelf movement south of the drill site. A second driver is sea-ice relaxation towards the area of unconfined open water north of the drill site possibly in combination with thermal expansion of the sea-ice as the spring and summer air temperatures increase.

GPS monitoring of lateral movement of the SMS site utilised equipment set up by UNAVCO on the roof of the drill site laboratory building. From sea riser spud in date (9 October 2007) to the sea riser cut off date (4 December 2007) a lateral movement of 5.47 metres @ 24.5°T was measured (Fig. 2).

TIDAL MOVEMENT

Tidal models compiled using data from Scott Base, approximately 40 km away from the drill site, predicted a maximum vertical movement of the sea-ice of approximately 1.4 m (Robinson, 2006; 2007). The drilling rig and platform and the tide compensation equipment was set up in a similar fashion to that employed during the McMurdo Ice Shelf (MIS) Project and was designed to deal with the full predicted range of tidal motion and maintain a constant tension on the sea riser and internal casings.

GPS monitoring at the SMS site was used to record tidal (vertical sea-ice) movement. These measurements generally reflected the tidal cycle model prepared prior to drilling (Fig. 3). Note that GPS-based vertical measurements have not been corrected for barometric pressure change, or other vertical uncertainties.

WATER CURRENTS

Limeburner et al. (2007) utilised data from a site survey conducted in 2006-07 to model the speed

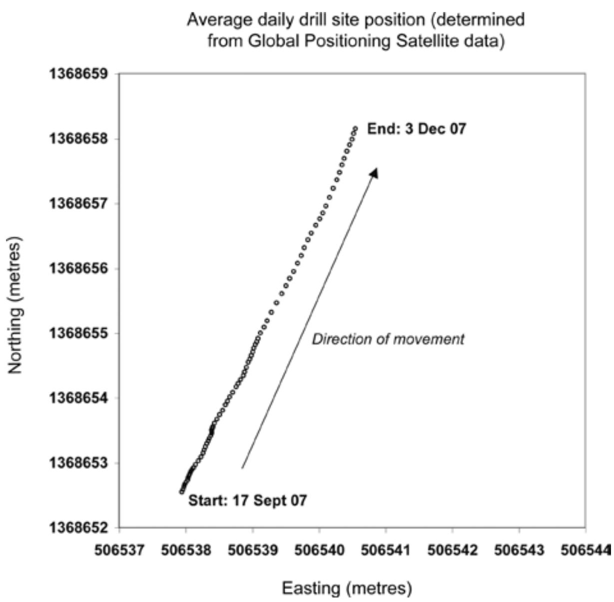

Fig. 2 – Average daily position of SMS drill site from GPS.

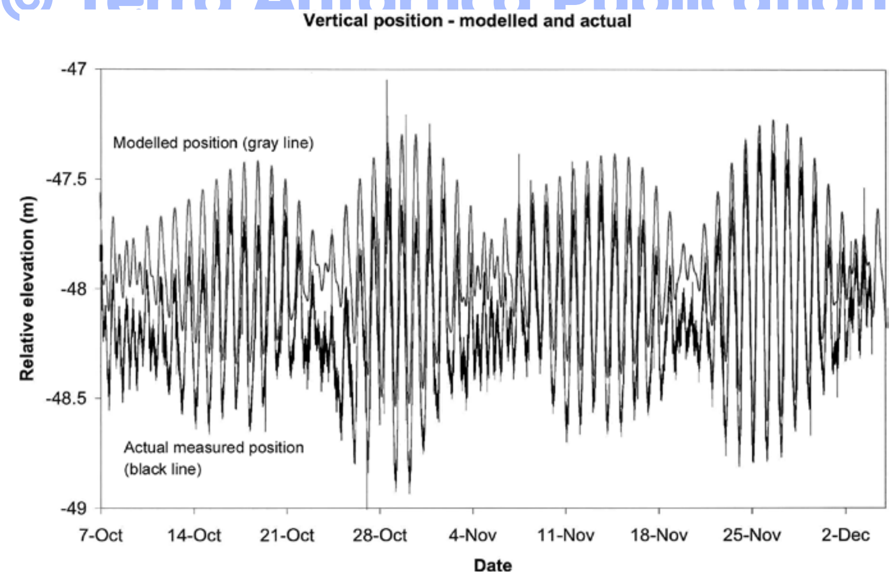

Fig. 3 -Vertical position - modelled and actual.

and direction of currents likely to occur in the water column beneath the sea-ice and at the sea floor. These data were used to model sea riser performance (Freitas et al., 2007), which showed that expected current velocity fell within safe operating parameters for the sea riser.

Water currents were not measured during drilling operations at SMS. In contrast to the MIS Project, where vibrations were thought to be induced by currents (Falconer et al., 2007), no vibration of the sea riser was observed during SMS operations.

WEATHER

A wind speed monitor located in the drill rig dog box was linked to an ultrasonic wind speed sensor that was mounted approximately 6.5 m above the ground surface on top of the UDR power pack near the drilling platform. The wind speed sensor was affected by turbulence due to its location near the drill rig. Measured data reflect wind influence on the shroud enclosure and are not considered representative of the local wind regime. The enclosure has a streamlined shape and the drill rig was aligned to mitigate the impact of the strongest winds, which were expected to come from the south at the SMS site. A new shroud was fitted to the rig at the beginning of the season and a spare shroud (used the previous season) was on site for backup.

During SMS operations sustained winds of more than 40 kts occurred on more than one occasion, with gusts over 65 kts. Small tears and punctures formed in the shroud where it came into contact with attachments to the drill rig mast, but the tears were repaired and no damage was sustained. Drilling was suspended for 4.5 hours on 8 November 2007 due to concern over the unknown maximum capability of the shroud in the face of strong building winds, which caused significant movement of the mast. Fortunately no damage occurred and drilling was able to continue in similar weather conditions over the following two days.

DRILLING OPERATIONS

SETUP

An eight-person Winter Fly-in (Winfly) crew set up the drill system in September. Due to its location on multi-year sea-ice, the surface at the drill site was expected to be rough with subsurface voids and ice hoar. However, when the Winfly team arrived it was determined that the site comprised a smooth surface ice with 'wavy' low relief of up to 20 cm over 10-20 m. These surface conditions required relatively little surface scraping to level the drill rig platform and connected catwalk. The drill site set-up was similar to that employed during the MIS Project operations (see Fig. 4 in Falconer et al., 2007 for details). The mast and shroud enclosure were raised in late September and the drilling system was ready to go when the first members of the drill crew arrived at the site on 3 October 2007.

FLOTATION DEPLOYMENT

An air bag flotation system (Fig. 4) was designed to support and tension the sea riser and casing to reduce loading on the sea ice platform in combination with the PLC controlled Tide Compensation Beam (TCB). This airbag system consisted of two 5 tonne and two 10 tonne enclosed parachute lift bags anchored to a 8 inch casing that allowed the riser to be deployed through it and then locked off.

A second air bag system comprising 10 tonne enclosed cylindrical airbags was planned for deployment directly under the sea-ice to compensate for the loading of the drill system in the vicinity of the ice access hole. This airbag deployment required the services of a United States Antarctic Program (USAP) diver. However, the diver who assessed the platelet ice layer suggested that it may not be possible to deploy the bags. This recommendation was followed as the 8+ m-thick multi-year ice platform was expected to have sufficient buoyancy and strength to support the drill system without an unacceptable loss of freeboard.

The sea riser airbag system was deployed as planned, but attachment complications with one of the 10 tonne bags meant it was non-functional, and the other 10 tonne bag was not fully inflated because it deployed in the platelet ice zone and there was concern that it may become stuck. Approximately 10 tonnes of lift was maintained in the sea riser airbags and the remainder applied through the TCB.

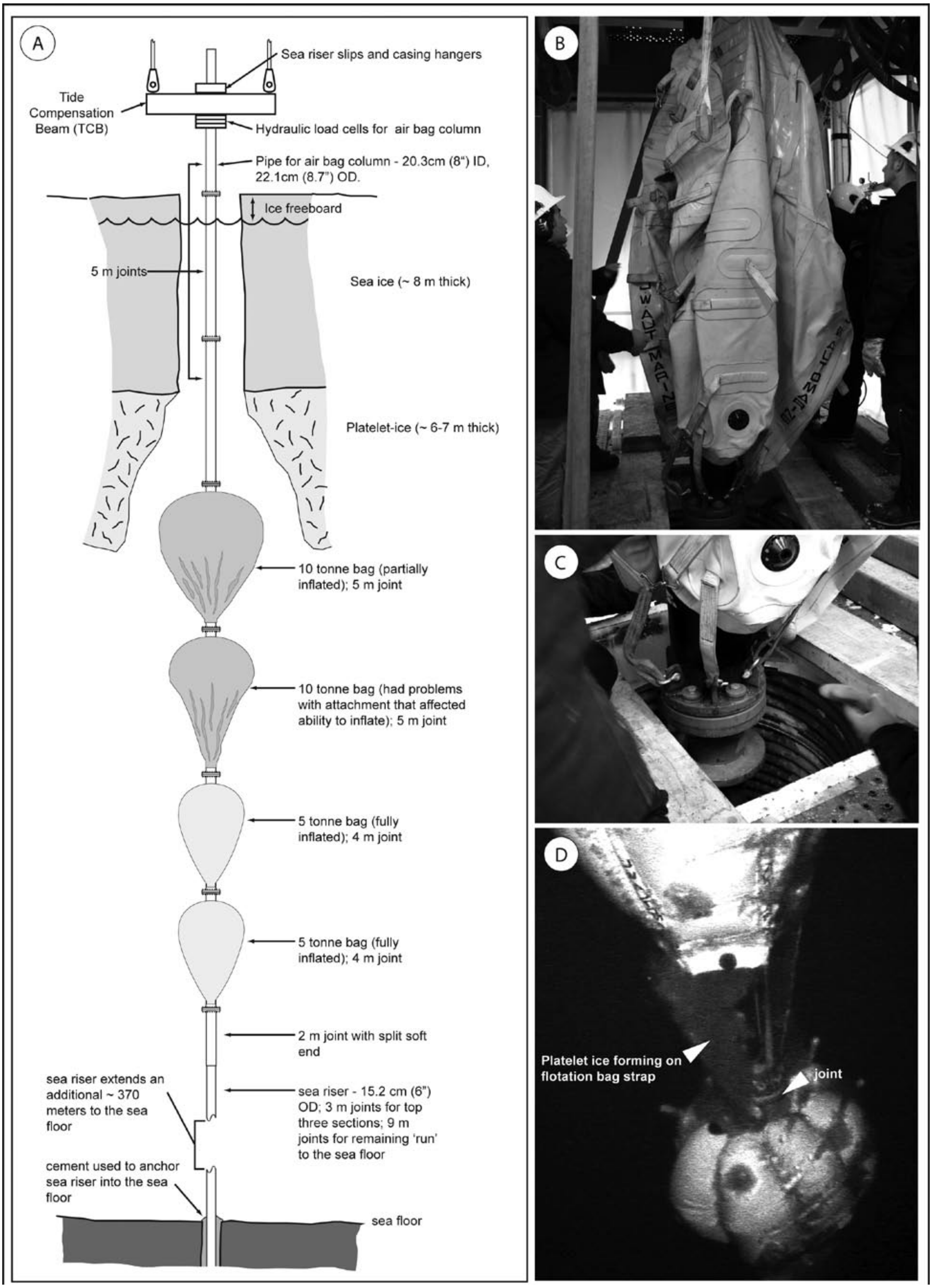

Fig. 4 – Sea-ice riser flotation system. A. Schematic diagram; B. images.

SEA RISER EMBEDMENT AND SEDIMENT CORING

SEA RISER EMBEDMENT

The sea riser shoe and casing was set at 8.89 m below sea floor (mbsf) and cemented back to approximately 0.26 mbsf on 12 October 2007.

The sea riser was spudded into the sea floor on 9 October 2007. The riser embedment process used a rotating sea riser shoe driven by a splined section on the PQ coring barrel on the PHD drill string that was rotated within the sea riser casing, while the riser casing did not rotate. This process allows coring while spudding in the riser. Drawing on MIS Project experience, and acknowledging the shorter time window available for drilling on sea-ice, it was decided that the priority was to embed the riser and forgo attempts to recover sea floor surface sediments during riser advancement, and consequently, specialist soft sediment coring barrel assemblies were not used at SMS.

On 10 October 2007, during the sea riser embedment process, a foreign object became lodged in the PHD drill string and the string had to be tripped out. Unfortunately, this trip out required circulation to be stopped for 6 hours and this probably allowed sea floor material to settle around the riser shoe. Further advancement of the riser became problematic although drill fluid circulation to the sea floor was possible, and little further downward progress was made. The riser appeared anchored and this was confirmed when 10 tonnes of over-pull was applied without any movement from the sea floor. Consequently, the PHD string with the spline drive was used to cement the sea riser in place at 8.89 mbsf using a low-temperature permafrost cement. The PHD drill string was then tripped out and set up for coring. Once the cement set, additional over-tension was applied to the riser (above that required to hold the weight of the riser in the water column) to ensure the riser was well anchored. Note that later, when the PHD casing was cemented in the sea floor, the tension applied to the riser was increased to hold the additional weight of this casing. While the sea riser spud in and cementing provided a secure embedment, the cement did not provide a complete seal around the riser to the sea floor and circulation was lost early in the subsequent PQ coring phase.

SEDIMENT CORING AND DOWNHOLE LOGGING

A drill hole plan was developed prior to drilling to include time for coring and downhole experiments. Actual coring progress against planned progress for the entire SMS hole is shown in figure 5 and summarized in the following discussion.

PQ Coring

PQ3WL coring commenced on 10 October 2007, at a depth of 8.81 mbsf and continued to 26 October to a final depth of 229.24 mbsf.

In the top 50 m of the hole, the formation was very weak and unconsolidated with loose sand layers between harder strata, which were inclined to 'block off'. This necessitated short drilling runs and consequently, slower drilling rates. High fluid losses occurred at the start of the PQ section, which resulted in high usage of drill fluids products (Nye, 2007a). In order to stem fluid losses, a LCM pill was set at 49.5 mbsf on 17 October 2007; unfortunately, fluid losses were back at high levels by 19 October 2007.

On 25 October 2007, while retrieving the inner tube, a piece of core fell from the lifter case, blocking the inner tube from latching back into the barrel. Due to the unconsolidated nature of the formation, it was decided to drill through the blockage and bit with the NRQHP drill string, rather than risk pulling out the PHD string. This decision proved successful and PQ coring was able to continue.

Drill site management personnel decided to stop PQ coring on 26 October 2007 due to relatively slow coring rates and high fluid usage. Because of the occurrence of unconsolidated layers in the cored section the PQ bit and barrel assembly were cemented in place with Permafrost C grout. A casing shoe was not used due to the unacceptable risk associated with tripping out the PHD drill string and related potential for bore hole collapse.

A 3 m PQ3 coring barrel configured with a 2.13 m extension and sub was integrated into the PQ coring procedure from 16 October to allow use of a GyroSmart™ down hole survey tool for core orientation. Total outer tube length was 6.261 m. The tool was used intermittently and gave variable results in the PQ section of the hole (see Paulsen et al., this volume for details).

Note that while downhole logging was carried out in both casing and in parts of the open hole (see Wonik

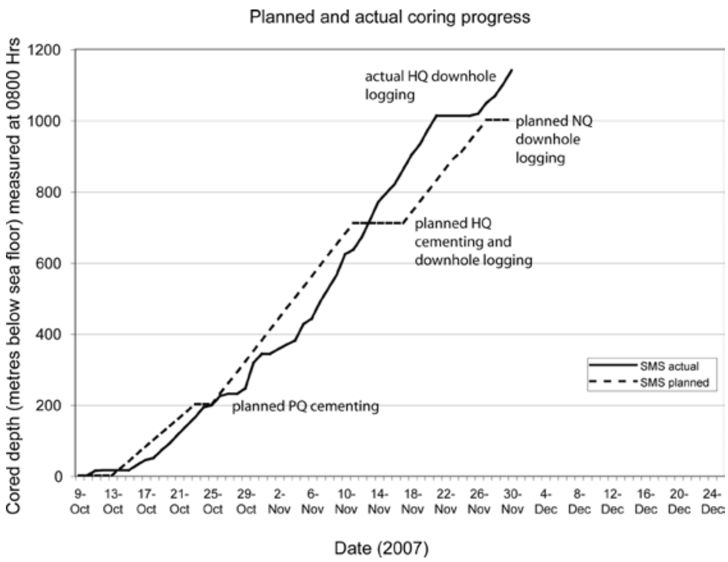

Fig. 5 – Planned and actual coring progress.

et al., this volume) none of the PQ hole was exposed and made available for open hole logging because this part of the hole was considered unstable. The fact that the PHD casing remained stuck in the hole after it was cut (see below for details) supports the view that the hole would have been unstable and therefore unsuitable for logging.

HQ Coring

HQ coring commenced on 29 October 2007 at a depth of 229.24 mbsf and continued to 21 November to a final depth of 1 011.04 mbsf.

After an initial unsuccessful attempt to drill through the PQ bit with a series 2 bit, the HQ drill string was tripped out and tripped back in with a series 4 bit, which successfully drilled through the PQ bit and HQ coring commenced.

Initial coring of the HQ section from 229.24 to 341.71 mbsf was straightforward with excellent recovery and good drill fluid returns. However, on 30 October at 341.71 mbsf the bit entered a zone of unconsolidated sands and gravel pressurised with brine, which migrated 27 metres up inside the barrel and drill pipe. The drill string was tripped out, the sand and gravel was removed, and the string tripped back in using a significantly higher mud weight of 9.1-9.2 ppg (pounds per US gallon) mud density. However, a second influx of sand and gravel migrated 48 metres up the drill string. On the third attempt to redeploy the string and continue coring, the barrel was washed down from approx 100m off bottom, and this approach proved successful. Coring continued with the weighted drill fluid and hole stability gradually increased, particularly below 367.61 mbsf. Drill fluid weight was gradually decreased to reduce drilling induced fracturing and ballooning from the formation. The drilling operations team decided that cementing the HQ drill string at this point would reduce the options available for possible issues deeper in the hole. However, the unconsolidated zone needed to be stabilised to continue coring, particularly as there were limited stocks of drill fluid products. It was decided to plug the unconsolidated zone with a cement pill and this was done on 2 November from 367.59 mbsf to approximately 25 metres from the bottom of the hole. Coring recommenced with improved fluid returns.

At 429 mbsf the drill string was tripped out to change the 6 m HQTT barrel configuration and include a 1.91 m extension and sub to allow the use of a GyroSmart™ internally recording down hole survey tool for core orientation (see Paulsen et al., this volume for run details). The drill string was tripped back in cautiously and did encounter some bridged zones as anticipated, but the hole had not caved in. At 635.17 mbsf, the HQ drill string was tripped out again to change the bit. A section of under gauge core recovered from approximately 795 mbsf to 820 mbsf was attributed to the mudstone formation being drilled, and core quality improved from 820 mbsf to the base of the HQ section at 1011.08 mbsf.

Following completion of HQ coring, the barrel was tripped out and an HQ casing advancer run as a wiper trip to the bottom of the hole. The hole was displaced with a drill fluid made up with fine grade KCl, and the HQ casing pulled back to 410 mbsf (just below a bridging zone). This allowed downhole logging between 410 mbsf and 620 mbsf at which depth another bridging zone was encountered. Once logging was completed, the casing was advanced to 640 mbsf and the remainder of the hole below this depth was logged successfully (see Wonik et al., this volume). Upon completion of downhole logging, an HQ casing shoe was run in on 25 November 2007 and set at 1 011.87 mbsf. The HQ casing was not cemented in place due to time restraints and the fact that only a short section of NQ was to be drilled.

High fluid losses and subsequently high usage of drill fluid products (particularly weighting agents in the influx zone) during HQ coring meant that additional supplies of Barite (to increase density) had to be ordered from New Zealand and were flown south. Obligations under the Comprehensive Environmental Evaluation (CEE) (Huston et al., 2006) stated that drill fluid products to control pressurised formations would always be on site. This minimum quantity of product was maintained at all times, but was a significant driver for the need to fly in additional product. As a comparison, no Barite was used at MIS, whereas 8 tonnes were used in six days at SMS (Nye, 2007a; 2007b).

NQ Coring

NQ coring commenced on 26 November 2007 at a depth of 1 011.87 mbsf and continued to 30 December to a final depth of 1 138.54 mbsf. The NQ hole was continuously cored but the primary objective was to provide open hole for the hydrofracture experiment (see Wonik et al., this volume).

NQ coring was generally successful with good core recovery and high fluid returns. The 6 m NQ barrel was initially configured from two 3 m outer tube sections and full hole joining coupling to stiffen a mid section of the barrel and stop under-gauge core in softer sediments that was believed to result from the very flexible 6 m tube (based on experience gained during the MIS Project). However, high pump pressures necessitated replacing the full hole coupling with a reamer shell and removing the orientation tool extension to shorten the overall barrel length. This successfully reduced pump pressures but the orientation tool was not run below 1057 mbsf.

After the completion of NQ coring, the barrel was tripped back to the HQ casing shoe before tripping back in to the bottom of the hole as a 'wiper trip'. The hole appeared to be stable, with no bridges. Prior to removal of the NRQHP drill string (which requires that all NRQHP pipe is broken down into 3 metre lengths and rebundled) the HQ casing was lifted to ensure it was not stuck in the hole and could be recovered without cutting (which would have required the NRQ drill string). The HQ casing proved to be free and the hole was then displaced with fine-grade KCl in preparation for downhole logging before the barrel was tripped from the hole.

CASING AND SEA RISER CUTTING AND RECOVERY

Upon completion of NQ downhole logging, HQ casing was pulled back to 320 mbsf where a 30 m cement plug was displaced above the influx zone at 341 mbsf. The remaining HQ casing was pulled from the hole to allow logging within the PHD casing.

Once logging was completed, mechanical cutters attached to the HQ/HRQ drill strings were used to cut the PHD casing. A first cut was made at 175 mbsf, but casing remained stuck. A second cut was made at 130 mbsf, but the casing remained stuck. Finally, the casing was successfully cut and freed at 20 mbsf. Considering the type of formation drilled in the PQ section (*i.e.* unconsolidated sands), it is not at all surprising that the majority of PHD casing below sea floor was stuck and abandoned.

A cement plug was placed to seal the hole from 0 to 20 mbsf and the remainder of HWT casing was retrieved.

The sea riser was cut off just above the sea floor with an explosive 'colliding detonation cutter' deployed by the wire line and fired electrically. The first attempt detonated successfully at approximately 4 to 5 metres above sea floor. The sea riser was then recovered to the base of the flotation column where sea riser and flotation column were stripped one over the other to recover both columns. The strip over was necessitated by the fact that the base of the sea riser was cut unevenly and could not be pulled through the flotation column.

CORE MANAGEMENT AND SCIENCE OPERATIONS

Core management and scientific activities occurred at the SMS Project drill site and at McMurdo Station. Procedures and protocols were similar to those utilized during the MIS Project (see Falconer et al., 2007). The method of core transportation from the drill site to McMurdo Station was the major difference between the two seasons. For the SMS Project, core was transported to McMurdo Station via a dedicated helicopter (UH 212) flight that was scheduled to arrive at the drill site once daily at approximately 2200 hrs (weather permitting). Empty core boxes were returned from McMurdo Station to the drill site on the outgoing flight. Full core boxes were transported from the drill site laboratory to the helicopter pad in skidoo trailers and loaded on to the helicopter by drill site staff and the helicopter technician. On average, fourteen aluminium core transport boxes packed with core were collected and transported on each flight. Core-catcher material and all associated paperwork were also transported back to McMurdo at the same time. Time-sensitive whole-round samples were collected at the drillsite for microbiology and porewater geochemistry studies from selected lithologies and transported with the core boxes in frozen and cooled (not freeze) containers, respectively.

Upon arrival at McMurdo Station curatorial staff met the helicopter, loaded the core boxes into USAP F-350 pick up truck and transported the core to the Core Storage Facility. Core processing procedures closely followed those implemented during the MIS Project (see Falconer et al., 2007). Some minor changes to previous procedures include the following: an additional two sections were added to the RAC-Tent Core Scanning Facility (RTCSF) to provide more working space; each core section was imaged in the RTCSF at a resolution of 125 pixels/cm (PQ), 167 pixels/cm (HQ), and 200 pixels/cm (NQ) using a Geoscan III imaging system with a Cosina 50mm lens. The camera was mounted on a GEOTEK multisensor core logger (MSCL). Each 1 m section took approximately 6 minutes to scan. A total of 1120 core sections were scanned.

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