

## Downhole Measurements in the AND-2A Borehole, ANDRILL Southern McMurdo Sound Project, Antarctica

T. WONIK<sup>1\*</sup>, T. GRELLE<sup>1</sup>, D. HANDWERGER<sup>2</sup>, R.D. JARRARD<sup>3</sup>, A. MCKEE<sup>4</sup>, T. PATTERSON<sup>5</sup>,  
 T. PAULSEN<sup>6</sup>, S. PIERDOMINICI<sup>7</sup>, D.R. SCHMITT<sup>8</sup>, H. SCHRÖDER<sup>1</sup>, M. SPEECE<sup>5</sup>, T. WILSON<sup>9</sup>,  
 & THE ANDRILL-SMS SCIENCE TEAM<sup>10</sup>

<sup>1</sup> Leibniz Institute for Applied Geophysics, 30655 Hannover - Germany

<sup>2</sup> TerraTek (Schlumberger), Salt Lake City, UT 84104 - USA

<sup>3</sup> Dept. of Geology and Geophysics, Univ. of Utah, Salt Lake City, UT 84112 - USA

<sup>4</sup> Raytheon Polar Services Corporation, Centennial, CO 80112-3938 - USA

<sup>5</sup> Montana Tech, 1300 West Park Street, Butte, MT 59701 - USA

<sup>6</sup> Dept. of Geology, Univ. of Wisconsin at Oshkosh, Oshkosh, WI 54901-8649 - USA

<sup>7</sup> Ist. Nazionale di Geofisica e Vulcanologia, Rome 00143 - Italy

<sup>8</sup> Inst. for Geophysical Research, Dept. of Physics, Univ. of Alberta, Edmonton, Alberta, T6G 2G7 - Canada

<sup>9</sup> School of Earth Sciences, The Ohio State University, Columbus, OH 43210-1522 - USA

<sup>10</sup> <http://andrill.org/projects/sms/team.html>

\*Corresponding author (thomas.wonik@liag-hannover.de)

**Abstract** – Under the framework of the ANDRILL Southern McMurdo Sound (SMS) Project successful downhole experiments were conducted in the 1138.54 metre (m)-deep AND-2A borehole. Wireline logs successfully recorded were: magnetic susceptibility, spectral gamma ray, sonic velocity, borehole televiewer, neutron porosity, density, calliper, geochemistry, temperature and dipmeter. A resistivity tool and its backup both failed to operate, thus resistivity data were not collected. Due to hole conditions, logs were collected in several passes from the total depth at ~1138 metres below sea floor (mbsf) to ~230 mbsf, except for some intervals that were either inaccessible due to bridging or were shielded by the drill string. Furthermore, a Vertical Seismic Profile (VSP) was created from ~1000 mbsf up to the sea floor. The first hydraulic fracturing stress measurements in Antarctica were conducted in the interval 1000-1138 mbsf. This extensive data set will allow the SMS Science Team to reach some of the ambitious objectives of the SMS Project. Valuable contributions can be expected for the following topics: cyclicity and climate change, heat flux and fluid flow, seismic stratigraphy in the Victoria Land Basin, and structure and state of the modern crustal stress field.

### INTRODUCTION

The main goal of the ANDRILL Southern McMurdo Sound (SMS) Project is to establish the history of Neogene Antarctic ice sheet variation and long-term climate evolution. Harwood et al. (2005) describe the major scientific objective in the following way: "The recovery of middle Miocene Antarctic stratigraphic sequences is required to evaluate the history derived from global proxy records that invoke a change from a warm climatic optimum (~ 14 Ma) and the formation of a quasi-permanent ice sheet on East Antarctica." The 1138.54 m-deep AND-2A drillhole sampled a sequence of strata identified on seismic lines and inferred to represent an early Miocene through middle Miocene sequence of seismic units that expand basinward and are overlain disconformably by Pliocene and Pleistocene strata. This borehole penetrated strata that mostly lie stratigraphically above the lower Miocene section recovered at the top of the sequence drilled by the Cape Roberts Project (CRP) (17 – 34 Ma; Davey et al., 2001). Furthermore, this core overlaps by several hundred metres with the ANDRILL McMurdo Ice Shelf (MIS) Project borehole AND-1B core, which

consists of sediments as old as 14 Ma, providing a composite sequence of strata aged from 34 Ma to Recent for the McMurdo Sound region.

Downhole experiments from Antarctica are still a rarity. Most downhole logging has been performed from drill ships, under the framework of the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). In the McMurdo Sound region, only the CIROS-1 borehole (Cenozoic Investigation of the Western Ross Sea), the two Cape Roberts Project (CRP) boreholes (CRP-2 and CRP-3) and the ANDRILL AND-1B borehole had been previously downhole logged (Harwood et al., 2005). All mentioned drillholes are situated on the south-western margin of the Victoria Land Basin, the westernmost of four north-south trending basins formed by extensional rifting of the Ross Sea region. The CIROS-1 hole (Barrett, 1989) was drilled in 1986 and was located about 15 kilometres (km) away from the AND-2A borehole. It reached a total depth (TD) of c. 700 m and recovered sediments as old as 37 Ma. Only a limited downhole logging program was conducted (White, 1989). More than 100 km north of the SMS drill site, the CRP boreholes were drilled in 1997 - 1999. The age of the drilled

sediments is 17-34 Ma; the downhole logging was reported by Bücker et al. (2001). In 2006, the 1284.86 m deep AND-1B drillhole was logged down to a depth of 1018 mbsf (Morin et al., 2007). Vertical seismic profiles (VSP) could be measured only in the CRP-2 and CRP-3 boreholes and the AND-1B drillhole. The first hydraulic fracturing stress determinations in Antarctica were successfully carried out in the AND-2A borehole. For all of these drillholes, downhole experiments were a powerful tool for obtaining new insight in lithology, (seismic) stratigraphy, chronostratigraphy, palaeoclimate, structure, and state of stress of the drilled sequences. This report combines data from all ANDRILL SMS downhole experiments, including (a) downhole logging, (b) VSP, and (c) hydrofracture experiment for the AND-2A borehole.

## DOWNHOLE EXPERIMENTS EQUIPMENT

### GEOPHYSICAL LOGGING TOOLS

The logging equipment consists of three main components: (1) a surface unit, (2) a 2 000 m-winch and a 4-conductor 4.8 millimetres (mm) cable, and (3) a suite of logging tools. The surface unit controls the measurements, including the movement of the probe in the borehole; it provides the energy supply to the probe and records, displays, and stores the data. The energy is supplied through the cable, which also conveys the electrical signals between the probe and the surface unit. The depth at which a measurement is made is given by a gauge on the winch.

The logging tools lowered into the AND-2A borehole were: spectral gamma-ray, density, neutron porosity, geochemical tool, sonic velocity, borehole televiewer, VSP tool (a single 3-component clamped geophone), focussed laterolog, dipmeter, magnetic susceptibility, mud temperature and conductivity, and a 3-arm calliper. For a detailed description of these tools see the Initial Reports of CRP-2 and 3 (CRP Science Team, 1998; 1999; 2000). The few modifications are compared to Table 2.3 (p. 37 in the CRP-3 Initial Report; CRP Science Team, 2000):

- the 'new' spectral gamma-ray tool has a diameter of 70 mm and runs with a speed of 3 m/min;
- the borehole televiewer (BHTV) runs with a speed of 1.5 m/min, and the susceptibility tool (SUSC) with 7 m/min;
- the VSP receiver spacing was 6 m;
- the Array INDuction tool (AIND) was not used, but a 3-arm calliper (diameter: 55 mm, speed: 15-20 m/min, sample rate: 0.05 m) and a geochemical logging tool (diameter: 55 mm, speed: 1 m/min, sample rate: 0.1 m) were lowered in the AND-2A borehole.

Because the geochemical tool was used for the first time in Antarctica, a short description of its principle is given: the neutron generator in the tool consists of an ion source, a high voltage power supply, and a tritium containing target - all contained

in an evacuated chamber. The ions produced are deuterons (from deuterium), sourced from the target. If these positively-charged ions are accelerated to hit the target with a high enough speed, the nuclear reaction  $3\text{H} (\text{d}, \text{n}) \text{4He}$  takes place, and neutrons with an energy of 14.1 MeV are produced. The neutron outputs are  $10^8$  n/s. Neutrons are produced in bursts, with a burst rate of 20 kHz. Immediately after their production, high energy neutrons hit a nucleus within the wall rock and some of the energy is transferred to it. Most of this energy is almost immediately released again in the form of gamma radiation. The energy spectrum of the gamma rays produced that way is typical for the element which was hit. The tool quantitatively records the relative contents of carbon (C), calcium (Ca), iron (Fe), hydrogen (H), oxygen (O), and silica (Si).

The BHTV and the dipmeter tools were oriented with respect to the Earth's magnetic field using a three-axis fluxgate magnetometer. Since the drill site is less than 1200 km away from the magnetic pole, the magnetic declination can change dramatically and suddenly. Therefore, a magnetic-field survey station at the surface about 30 m away from the drill rig was used to record the natural variations of the Earth's magnetic field during downhole logging. The station's records can be compared with the registrations of the magnetic station at Scott Base, which are available on the internet (<http://www.geomag.bgs.ac.uk/GIN/GINForms>; pers. comm. T. Hurst). Fortunately, the magnetic field was quiet during the logging activities. Therefore, the orientation data deduced from the BHTV and dipmeter tools were not appreciably influenced by variations of the Earth's magnetic field.

### VERTICAL SEISMIC PROFILE EQUIPMENT

A single Generator-Injector (GI) air-gun was used as the seismic source for the VSP experiment. It was deployed through a hole in the sea-ice, which was made with a hot-water drill at a horizontal offset of 80 m up structural dip from the wellhead. The air-gun was lowered to a depth of 18 m below the ice surface to insure it could be fired below the platelet or frazil ice. We used a ski-mounted insulated hut to house recording equipment and the GI air-gun. The interior of the hut was divided into two rooms. The forward room was devoted to the GI air-gun. Data recording instruments and the GI air-gun shot control were located in the hut's rear room. Power for the recording and GI air-gun instrumentation was supplied by batteries that were recharged by solar panels placed on the outer walls of the hut. The GI air-gun was suspended from a motorized winch that was powered by an electrical connection to a Pisten Bully tracked vehicle. The winch arm with the attached GI air-gun was manually moved from a shooting position outside of the vehicle back to a stored position inside the hut. Compressed air was stored in seven cylinders and fed to the GI air-gun

by two hoses.

Two gas-powered Bauer drive air compressors were run during the seismic survey to keep the compressed-air cylinders full. The air compressors were rated at 0.14 m<sup>3</sup>/min at 24 MPa. A kerosene heater was kept in the air-gun room to keep the GI air-gun system from freezing. Additionally, antifreeze was injected periodically into the GI air-gun to keep it from freezing.

Six live channels of a snow streamer located at the ground surface were placed near the source to keep track of recording instrument timing. This was done because we observed erratic timing-trigger errors associated with air-gun freezing and failing seals on the air-gun. Gimballed geophones were attached at each takeout of the streamer at an interval of 25 m and the nearest geophone to the source was at a distance of 25 m. Gimballed geophones were constructed using 30 Hz vertically oriented sensors. The streamer data were recorded using a Geometric Geode system located inside the recording room of the hut. The room was heated by a propane heater fed by external tanks. The 3-component geophone in the VSP tool registered the data for 3 s. with a sampling rate of 1 ms. A receiver interval of 6 m was selected. This system of data generation and recording followed closely the approach described in Betterly et al. (2007) for the seismic survey of lines ATS-05-01 and ATS-05-02, upon which the AND-2A drillhole was situated.

#### HYDRAULIC FRACTURING APPARATUS

The hydraulic fracturing measurements were accomplished using a wireline-transported system developed for ANDRILL by Downhole Systems Inc., NY, consisting, essentially, of two synthetic polymer packers that were inflated to isolate the 1.4 m-long pressurisation interval (Fig. 1) topped off with an instrument package containing two submersible pressure transducers to measure directly the downhole interval and packer pressures. The length of this tool, as measured from the top of the rock catcher to the bottom of the stub, is 6.45 m-long for the NQ configuration.

The tool is supported in the borehole by a 4-conductor, 2 km long wireline. Two high pressure flexible tubing cables (2 km-long) provide fluid to the packers and to the interval. During deployment, these two hoses were taped using high strength electrical tape to the wireline at about 10 m increments as the tool was lowered into the borehole. The pressures were provided by a pump and series of control valves at the surface, which directed pressurisation and release of pressure through the hoses.

The control system provided digital output of the flow rates both in and out (upon release), the uphole pressures for both the packer and the interval, and the downhole pressures for both the packers and the interval. These latter two signals were sensed within the downhole instrument packages and transmitted

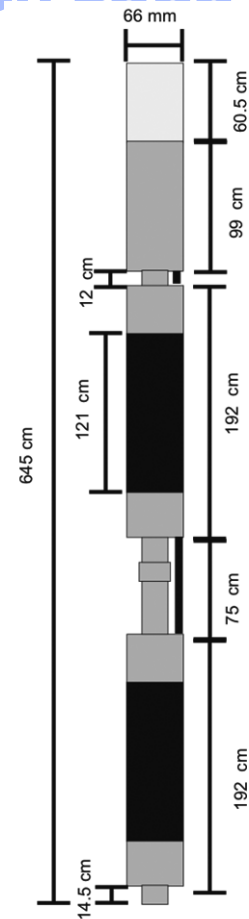


Fig. 1 - Simplified diagram of the downhole hydraulic fracturing tool and straddle packer assembly.

via the wireline to the surface recording system. All six of these signals were sampled at a rate of 0.1 s and recorded in a text file. Unfortunately, this system would crash and require the acquisition program to be restarted, and some data was irretrievably lost.

A typical protocol for carrying out a test at a given depth is given in table 1.

#### DOWNHOLE OPERATIONS

Due to a sand layer at ~340 mbsf, the original plan of an intermediate logging run from the base of PQ at ~200 mbsf to ~700 mbsf (assumed base of HQ) was abandoned to continue drilling in what was considered to be a difficult drillhole condition. We decided to continue HQ coring as long as possible, in hope that we could achieve the scientific objectives of coring without changing to NQ. The revised plan was then to log a long continuous HQ section rather than risk acquiring only 300 m of poor quality data in the middle of the section. This was essentially achieved, but in five phases of runs.

Figure 2 shows schematically the data acquired with the various logging tools in these five phases of logging. In figure 3, the different borehole linings for the five phases are given.

Tab. 1 - Summary of hydrofracture stations measured.

St. <sup>1</sup>	Depth				Data files		Comments
	mWWD <sup>2</sup>	mBHTV <sup>3</sup>	Top interval mbsf <sup>4</sup>	Bottom interval mbsf <sup>4</sup>	Raw	Edited	
1	1420.79	1439.67	1053.41	1054.87	frac1420, frac1420b	NA	Unable to pressurize interval at 1420.79 mWWD initially.
2	1419.03	1437.91	1051.65	1053.11	frac1420b	ed1420.txt	High packer pressures @ 2900 psi, may have fractured formation by packer. 3 cycles plus flow rate test. Initial breakdown may not have been recorded.
3	1415.57	1434.45	1048.19	1049.65	frac1416, frac1416b, 1416c	ed1416.txt	1 <sup>st</sup> crash during initial packer inflation, 2 <sup>nd</sup> crash after cycle 3. 3 cycles plus flow rate test.
4	1412.95	1431.83	1045.57	1047.03	frac1413, frac1413b	ed1413.txt	Crash during interval release period after cycle 1. 6 cycles at variety of pressurization rates.
5	1410.02	1428.90	1042.64	1044.1	frac1410	ed1410.txt	5 cycles
6	1404.77	1423.65	1037.39	1038.85	frac1405	ed1405.txt	4 cycles, program crashed during cycle 4 shut in period.
7	1401.02	1419.90	1033.64	1035.1	frac1401, frac1401b, frac1401c frac1401d	ed1401.txt	4 cycles, 1 <sup>st</sup> crash at end of cycle 2, twice, then during shut in on cycle 3.
8	1397.85	1416.73	1030.47	1031.93	frac1398	ed1398.txt	4 cycles
9	1394.35	1413.23	1026.97	1028.43	frac1394, frac1394b, frac1394c	ed1394.txt	4 cycles, 1 <sup>st</sup> crash during shut in on cycle 1. 2 <sup>nd</sup> crash during shut in on cycle 3.
10	1376.74	1395.74		1054.87	frac1377, frac1377b	d1377.txt	Crash during packer settling period. In HQ drill string. No useful data.
11	1500.08	1518.96	1132.7	1134.16	frac1500, fracc1500	ed1500.txt	Failure to communicate with interval, no data.
12	1490.1	1508.98	1122.72	1124.18	fracc1500 frac1490b	ed1490.txt	Fluid pressure communication re-established with interval. Break-down likely toward the end of the last file which remained running.
13	1484.95	1503.83	1117.57	1119.03	frac1485	ed1485.txt	4 cycles
14	1460.01	1478.89	1092.63	1094.09	frac1460, frac1460b,	ed1460.txt	4 cycles, crash during packer pressurization.
15	1453.95	1472.83	1086.57	1088.03	frac1454, frac1454b, frac1454c, frac1454d	ed1454.txt	4 cycles, 1 <sup>st</sup> crash prior to pressurization(?), 2 <sup>nd</sup> crash during first cycle shut in, 3 <sup>rd</sup> crash during third cycle shut in.
16	1441.97	1460.85	1074.59	1076.05	frac1442, frac1442b, frac1442c	ed1442.txt	4 cycles, 1 <sup>st</sup> crash during first cycle shut in, 2 <sup>nd</sup> crash after first cycle pressure release.
17	1436.99	1455.87	1069.61	1071.07	frac1434	ed1434.txt	Note error in filename to depth. 3 cycles, best fracture of the day.
18	1426.97	1445.85	1059.59	1061.05	frac1427	ed1427.txt	4 cycles, excellent breakdown.
19	1412.49	1431.37	1045.11	1046.57	frac1412, frac1412b	ed1412.txt	4 cycles, crash after 1 <sup>st</sup> cycle pressure release.
20	1408.31	1427.19	1040.93	1042.39	frac1408, frac1408b, frac1408c	E,d1408.txt	3 cycles. PFPAC failed to provide signal during this test. 1 <sup>st</sup> crash after 1 <sup>st</sup> cycle pressure release, 2 <sup>nd</sup> crash after 2 <sup>nd</sup> cycle shut in.

<sup>1</sup> Station<sup>2</sup> mWWD is the direct measurement of the hydraulic fracture winch with no corrections. As noted in the text above the measurement at the bottom of the hole was 1501.17 mWWD. As the tool length is 6.45 m, this means that the bottom of the hole would be at 1507.62 mWWD<sup>3</sup> This is the downhole logging depth of the BHTV detector on the first run.<sup>4</sup> mbsf = depth in meters below sea floor – to be completed once logging information is complete.

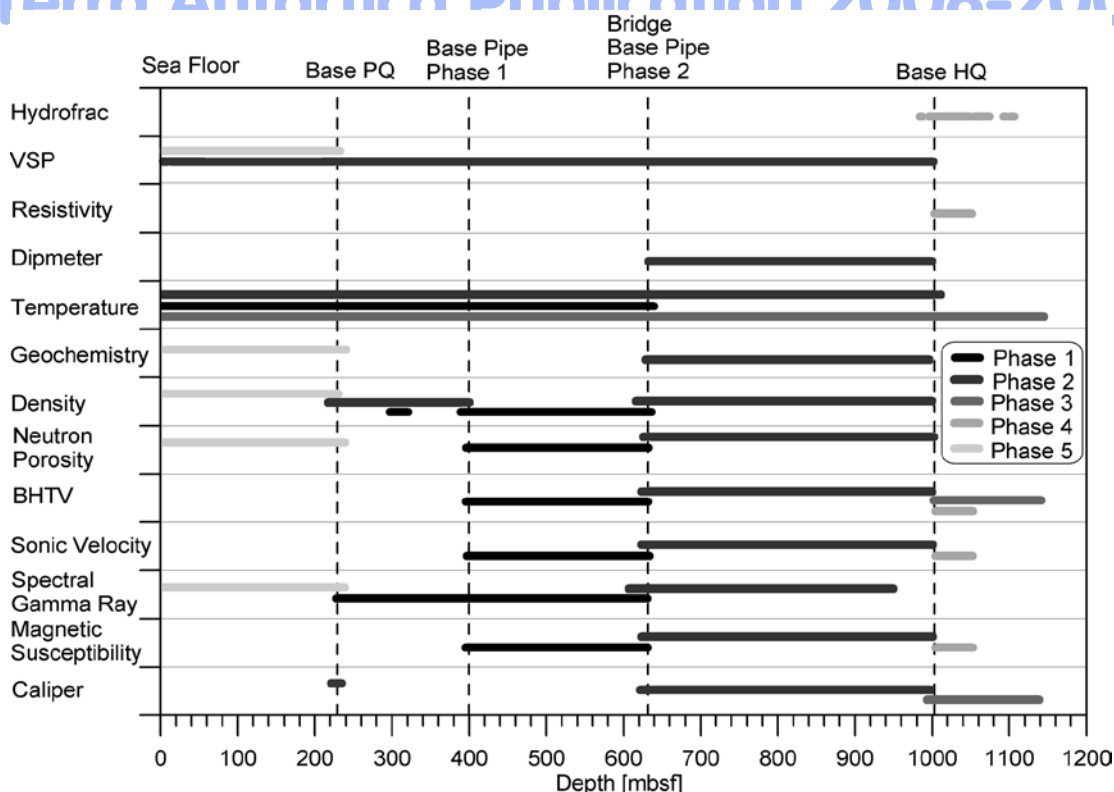


Fig. 2 – Schematic summary of downhole logging experiments in the Southern McMurdo Sound Project, AND-2A borehole.

**PHASE I (22-23 Nov. 2007)**

Initially, the HQ drill string was raised to 410 mbsf to prevent loose sediments above from collapsing into the borehole. We then lowered the calliper tool until we hit a bridge at 635 mbsf. Because we were unable to break through this bridge, we logged from

there to the base of the HQ drill string at 410 mbsf. The calliper arms, however, failed to open and no log was recorded. We then lowered the susceptibility tool and it was also unable to break through the bridge at 635 mbsf, so we logged from the bridge to the bottom of the drill string. Next, we logged with

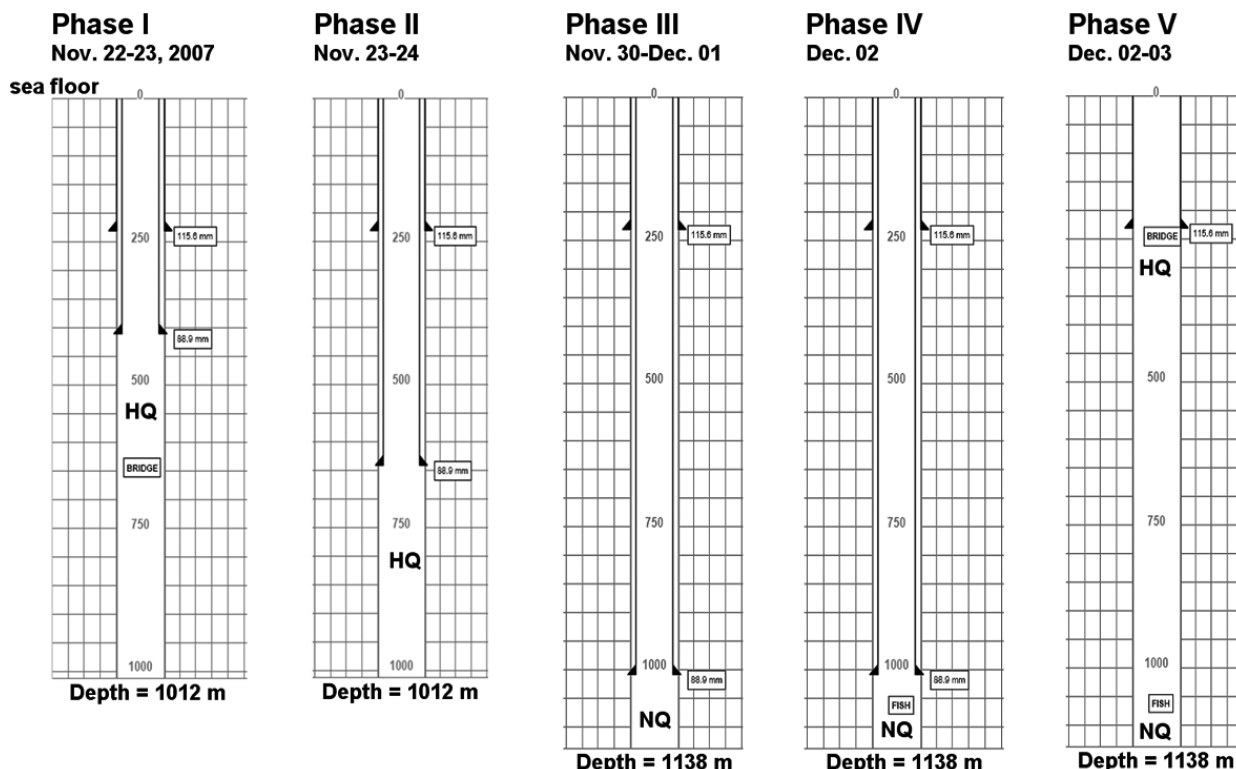


Fig. 3 - The different borehole linings for the five phases of downhole experiments in the Southern McMurdo Sound Project, AND-2A borehole.

the spectral gamma ray, the sonic velocity, and then ran the BHTV. The acoustic calliper from the BHTV tool demonstrated that this interval of the hole we were logging was in very good shape, with only minor borehole rugosity of <5 mm. We then ran the tools sensitive to borehole conditions, the neutron porosity and density logs, followed by a temperature/conductivity log of the mud. The measurement of the resistivity was unsuccessful as the tool and the backup tool refused to work properly. We did not run the geochemical or dipmeter tools because they run slowly and we were under time constraints.

#### PHASE II (23-24 Nov. 2007)

The HQ drill string was lowered through the bridge and held ~7 m below the bridged interval to prevent collapse. All tools were then run from the TD of HQ (~1011.08 mbsf) to the new base of the drill string at 640 mbsf. All runs, except the resistivity tool run, were successful. A vertical seismic profile (VSP) was also run in this section of the hole, with shots taken through casing from ~400 mbsf to the sea floor at 6 metre intervals. From the base of PQ at 229.24 mbsf, however, the shots were taken through dual casing (HQ and PQ). This portion of the VSP was repeated in Phase V, after the hydraulic fracture experiment and logging was completed at the base of the hole, and after the HQ casing was pulled. Details of the VSP experiment are given later in this section.

#### PHASE III (30 Nov. - 01 Dec. 2007)

The scientific objectives of coring for SMS were achieved within the HQ section of the borehole, however ~120 m of NQ coring were done below this to create a sufficient "rat hole" to allow the hydraulic fracture experiment to take place in that space. For details of the hydraulic fracture experiment see the text later in this section. This 120 m section was logged with the calliper, BHTV and temperature logs, primarily in support of the hydraulic fracture experiment. The calliper and BHTV were run to assess the borehole conditions and choose fracture location. The temperature log was run to verify and extend previous temperature logs that suggested an unusually high temperature gradient in the lower portion of the AND-2A drillhole.

The hydraulic fracturing tool was lowered into the NQ hole, and hit a bridge at 1052 mbsf. A number of fracture experiments were performed at multiple intervals in the overlying rock up to the base of HQ temporary casing. Once casing was reached, another attempt was made to break through the bridge at 1052 mbsf, which was successful. The tool was then lowered to TD (1138.54 mbsf) and more fracture experiments were conducted at discrete intervals, identified through the BHTV images and core analyses, up to the aforementioned bridge. Upon completion of hydraulic fracturing the tool was removed, but got stuck in the HQ casing at ~500 mbsf, likely due to

pressure differentials between the wellbore fluid and the closed packer hydraulic lines. Attempts to free the tool ended up causing the shear pins in the tool to fail, separating the transducer section from the packer section. This freed the tool, but unfortunately, the section below the shear pins (packers) fell to the bottom and only the transducer section and cabling were recovered.

#### PHASE IV (02 Dec. 2007)

With the lower two-thirds of the fracture tool now at some unknown depth in the borehole, either still stuck in casing or somewhere in the NQ section, the susceptibility tool was lowered gingerly down the hole in an attempt to identify its final resting place. The tool got stuck at 1052 mbsf, exactly where the hydraulic fracturing tool had difficulties to pass during Phase III. Finally, the BHTV was re-run to record the induced fractures created by the hydraulic fracturing to be compared with the BHTV image collected in virgin rock prior to the fracturing, but only for that 40 m of unobstructed hole. We also ran the sonic velocity tool in those 40 m because core-based physical properties velocity data were unreliable in the NQ core due to the narrow gauge of the core. Furthermore, sonic velocities could prove useful for calculating the dynamic Young's modulus and Poisson's ratio of the rock, which would aid in interpreting the fracture results. The backup resistivity tool was also run because an attempt was made to fix the problem that caused the tool failures in the initial logging runs.

#### PHASE V (02-03 Dec. 2007)

After logging of the NQ hole was completed, the HQ drill string was removed and logging was started again in the PQ casing. The VSP was also completed by re-recording the data in the PQ casing. The original VSP, as mentioned above, was carried out from the base of the HQ coring to the sea floor, except for the upper 230 m, which meant data were recorded through dual casing (HQ and PQ). Due to severe attenuation of the seismic signal in double-casing, the VSP was re-recorded through the single casing of the PQ string only. Once the VSP in PQ was completed, the sonic tool was run in the PQ casing as a cement-bond log to identify the top of the cement holding the PQ casing in place, so that the drillers would know where to cut the PQ casing to retrieve it. Next, we lowered the calliper tool to see how far we could go beyond the base of the PQ string in order to log more open hole. Unfortunately, we hit another impenetrable bridge 7 m below the base of PQ (237 mbsf) and so resigned ourselves to only running logs that could be done in casing. Those consisted of the spectral gamma ray, neutron porosity, density and geochemical logs, all of which were run from the base of PQ to the sea floor. We started the density log several metres above the base of casing, just to insure that there was no chance of

it entering open hole and getting stuck either in a bad condition hole below PQ, or upon re-entry into the PQ string.

## THE DATA

Pre-processing of the downhole logging data comprises the conversion from logging depth to core depth, the elimination of spikes and the compilation of different measuring intervals from one tool into one file, if possible. The difference between core depth and downhole logging depth is constantly 390 m. This value considers 383 m of water depth plus 7 m, the distance between mean sea level and the drillers' reference on the drill rig floor. The most important downhole logging data of AND-2A are plotted in figure 4 at a large scale. This is to give only an overview about the actual available data. Provided that no measurements in open hole for the PQ interval were possible, about 70% of the maximal feasible data could be measured.

During the logging activities we had to diagnose that the neutron porosity and fluid conductivity tools were unexpectedly not calibrated properly. These problems will be fixed off-ice and absolute values of these parameters will be obtained in mid-2008.

Log quality and reliability are judged to be excellent for nearly all of the logging tools. We base this conclusion on (a) a 'smooth' calliper of the borehole without intervals of great breakouts, (b) internal consistency for some tools (e.g., three different types of calliper measurements), (c) repeatability as observed on some repeated runs in short intervals, and (d) the similarity with core logging data (density, sonic velocity, and susceptibility; see Dunbar et al. this volume).

The vertical component VSP results are given in figures 5 and 6. The raw unedited P-wave or vertical component data (Fig. 5) contain several bad traces at the top of the borehole and at the bottom of the PQ casing. An edited version of these data (Fig. 6) shows that the numerous timing errors were corrected using the surface geophones as a reference and the bad traces were zeroed.

The hydraulic fracturing tests were conducted at the end of the drilling and logging in a ~130 m section specially drilled below 1000 mbsf for hydraulic fractures. This zone was drilled primarily through competent, dense, and low permeability diamict lithologies. The core fracture and borehole televiewer logging information was used to site 20 separate measurements. Classic hydraulic fracturing

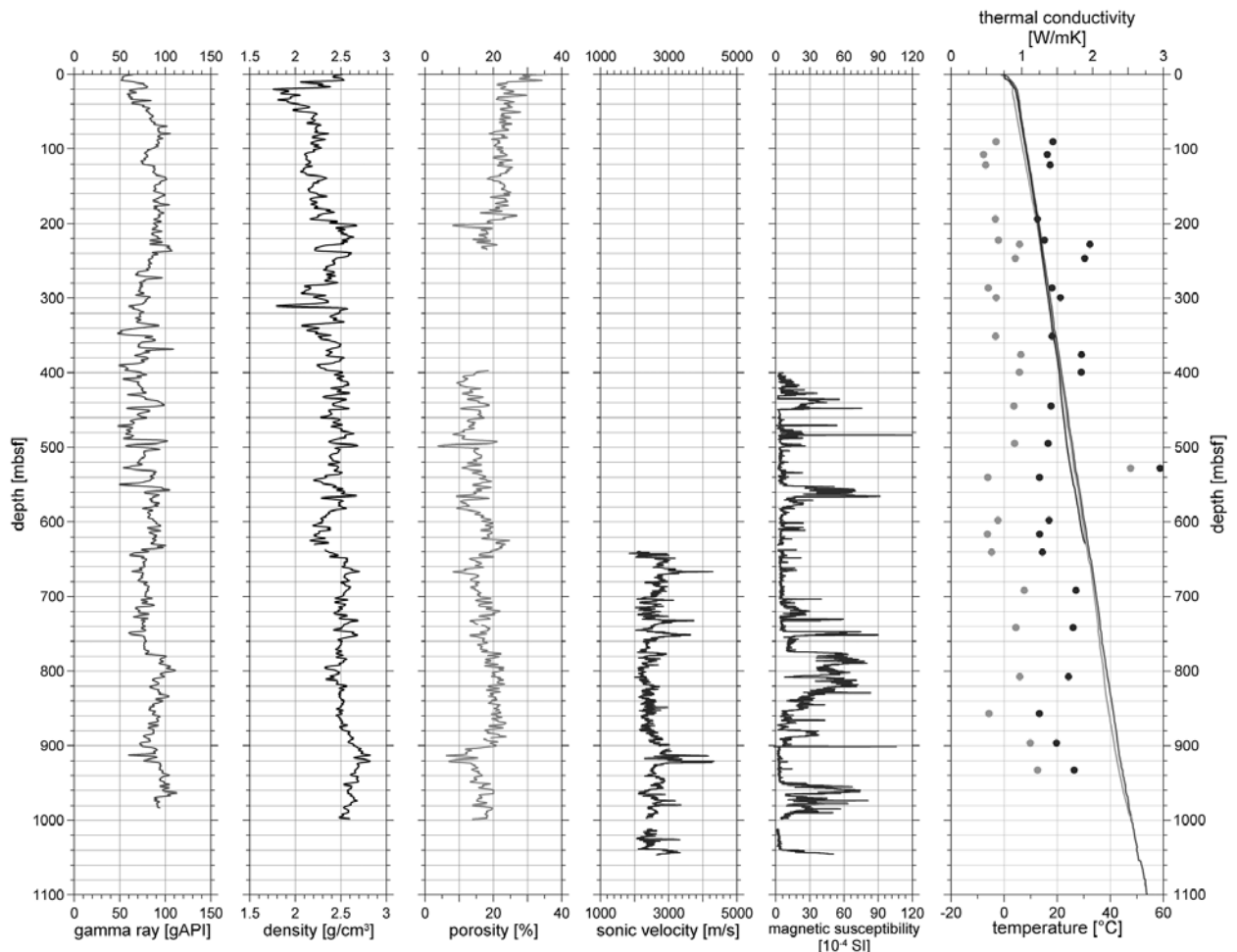


Fig. 4— Most important downhole logging data of the Southern McMurdo Sound Project, AND-2A borehole: gamma-ray, density, neutron porosity, sonic velocity, magnetic susceptibility, and temperature. Some lab-originated thermal conductivity measurements on plugs are added (light dots - dry samples; solid dots - water-saturated samples).

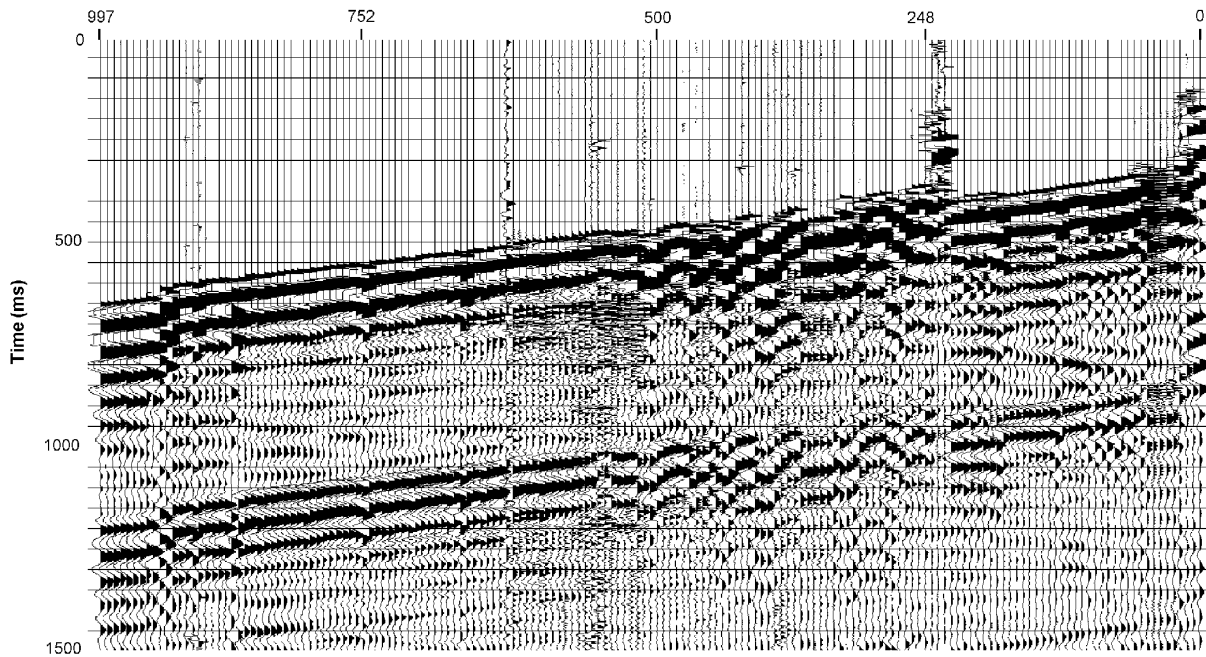


Fig. 5 - Southern McMurdo Sound Project, AND-2A borehole VSP vertical component (P-wave) raw data results. These data show timing error associated with air-gun misfiring and bad traces at the top of the borehole and at the bottom of PQ casing. Data were recorded in casing above 632 mbsf and in open hole below.

pressurisation records with unambiguous breakdown and fracture closure pressures were obtained in about one-half of the measurements. Table 1 presents a summary of the 20 separate stations with 18 successful hydraulic fractures induced over this interval.

A typical pressurisation curve with four cycles is shown in figure 7. Note that this curve is contaminated with a transient noise with a period of approximately 1 min, the source of this noise is not known but it may be inherent to the pressure transducers employed downhole as this noise does not appear on any other

of the recorded channels. That it may be connected to the transducers themselves is further suggested by the observation that the noise waveform appears on the two downhole pressure transducers at different times.

The measurements ceased at Station 20 at which point the downhole transducer measuring the packer pressure failed and this began to cause instability of the data recording system. In addition, the measurements had been proceeding for over 20 hours continuously at this point.

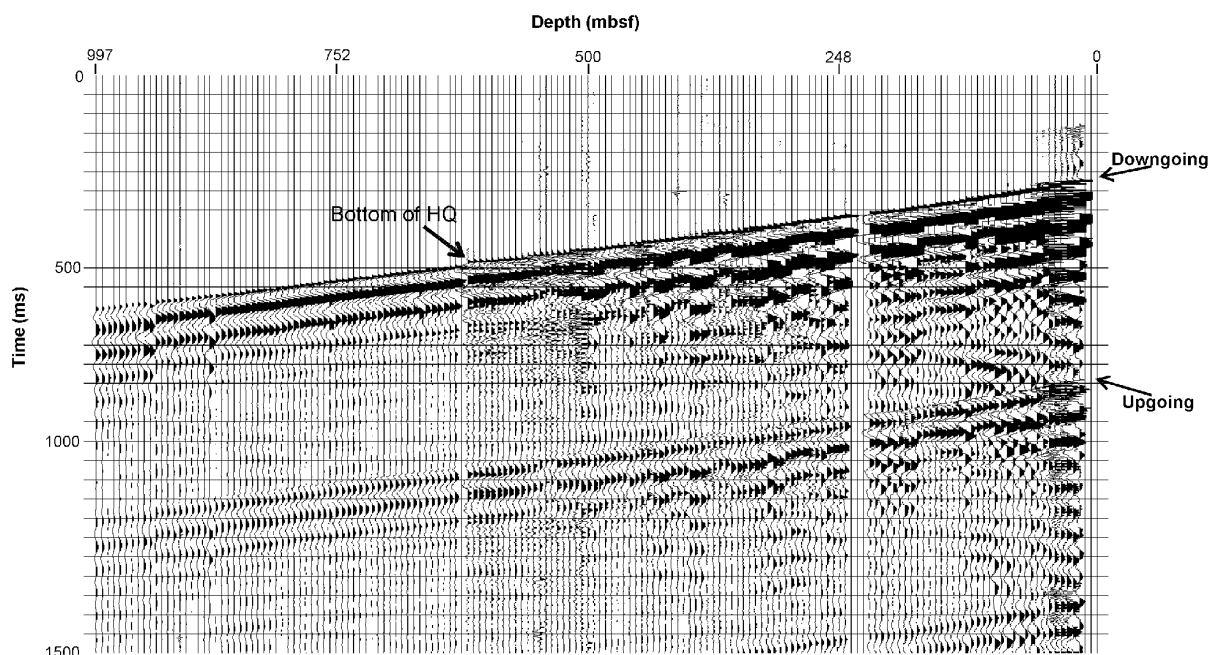


Fig. 6 - Southern McMurdo Sound Project, AND-2A borehole VSP vertical component (P-wave) edited results. Data were recorded in temporary HQ casing above 632 mbsf and in open hole below.



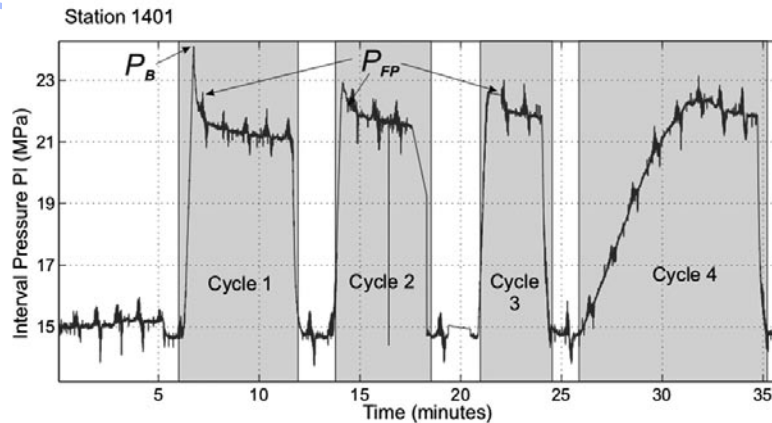


Fig. 7 - Example of hydraulic fracturing record showing four cycles and illustrating the periodic noise (arrows) along the pressure record.

## FIRST DATA ANALYSIS

### CALLIPER

Calliper data indicate that the diameter of the borehole is generally even. Only in the interval from 770 to 815 mbsf were some wash-outs detected. The inclination of the drillhole generally deviates from the vertical by  $2^\circ$  to  $2.5^\circ$  to the SE.

### SPECTRAL GAMMA-RAY

Total gamma-ray values, as well as the individual amounts of potassium (K), thorium (Th), and uranium (U), increase slightly with depth; their variations are relatively small (*e.g.*, the total gamma-ray values vary only between 45 and 100 API). Some prominent U- and Th-anomalies can be found (*e.g.*, at 40 mbsf, 70 mbsf, and 73 mbsf), which probably originate from volcanic clasts. In the interval from 400 to 600 mbsf some fining-upwards and coarsening-upwards sequences are especially evident.

### DENSITY, SONIC VELOCITY, AND SUSCEPTIBILITY

A comparison between core and downhole logged density, sonic velocity, and susceptibility data shows excellent correlation. The downhole density data are slightly higher than the core data, and this discrepancy increases with depth. Some data gaps caused by missing core can be filled with the downhole data – a complete data set for the overall length of the borehole is possible to achieve.

### TEMPERATURE

Although the temperature field had not reached equilibrium after it was disturbed by the drilling process, the temperature logs detected substantial fluid flow at several locations: 340 mbsf (the interval where loose sands were encountered), 465 mbsf, 530 mbsf, 760 mbsf, and 1 152.54 mbsf (where the hydraulic fracturing tool got stuck). Temperatures are exceptional high:  $56.9^\circ\text{C}$  at 1138 mbsf depth. The temperature gradient shows two values: from sea floor to about 1000 mbsf depth it is about  $44^\circ\text{C}/\text{km}$ , in the lower part of the hole it increases to  $65^\circ\text{C}/\text{km}$ .

For comparison: the temperature gradient in CRP-3 is in the order of  $25 \text{ K}/\text{km}$ .

### MAGNETIC FIELD

Vertical intensity of the Earth's magnetic field and the susceptibility are very similar in character. This similarity implies that the overall nature of magnetization in the sediments is induced rather than remnant. No strong anomaly can be observed in the magnetic field.

### POROSITY

Absolute porosity values still have to be checked. A first comparison with the density data show a negative correlation, as expected. Additionally, some strange trends (increasing values with depth) can be observed, which are not visible in the density data, *e.g.*, in the intervals 650 – 750 mbsf and 900 – 1000 mbsf.

### GEOCHEMICAL

Geochemical data in the PQ section had to be measured through casing. Its effect on the data is still unclear. Nevertheless, data of six chemical element concentrations were obtained. Their comparison with the XRF-scanner-based results on the core will provide information about the quality and value of these data.

### BHTV AND DIPMETER

The BHTV and dipmeter tools worked fine; data show a lot of features related to sediment bedding, thin bed laminae, breakout directions, bed boundaries, individual clasts, and fractures.

### VSP

All three borehole geophone components contain strong downgoing P-wave arrivals. The horizontal component data (Figs. 8 & 9) comprise more steeply dipping S-wave downgoing arrivals that are partially masked by the P-waves. The horizontal data show phase rotation caused by the tool twisting in the borehole and will need to be corrected. The upgoing or reflected wavefield is nearly absent in these

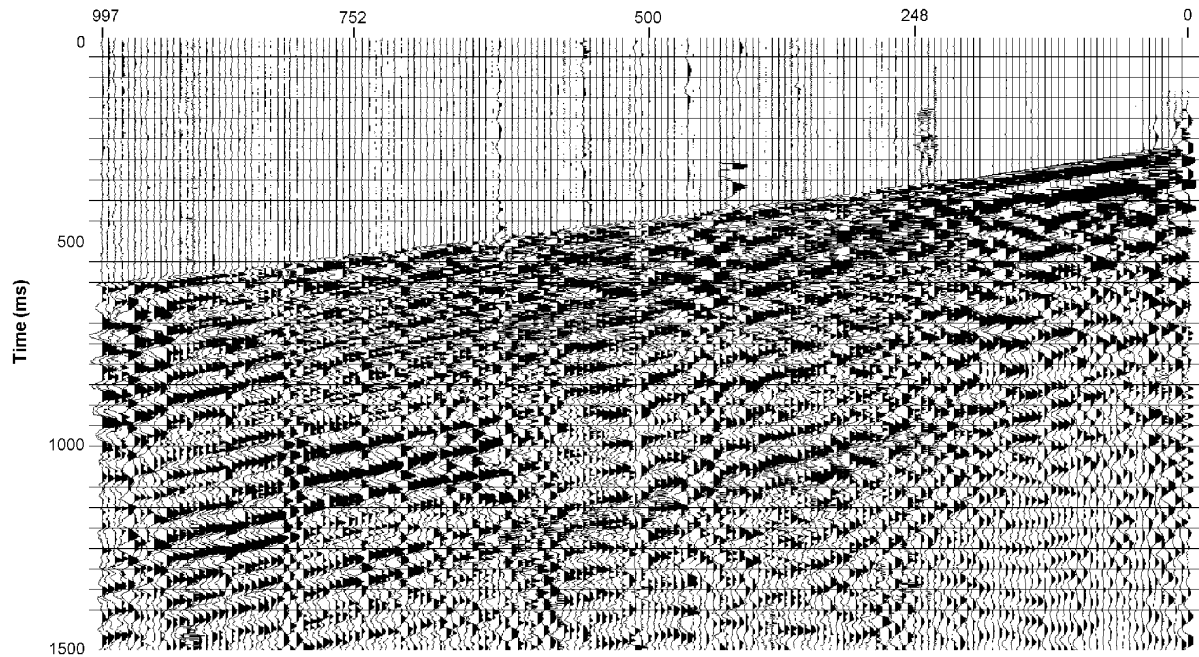


Fig. 8 - Southern McMurdo Sound Project, AND-2A borehole VSP first horizontal component (S-wave) results. Data were recorded in casing above 632 mbsf and in open hole below.

unprocessed data; however, preliminary dip filtering of the downgoing wavefield show that useful reflected arrivals can be obtained.

First-break time picks of the downgoing P-wavefield provide a time-depth curve (Fig. 10) that is not in good agreement with the time-depth curve produced from surface seismic reflection data. These data prove that the actual rock velocities obtained from the VSP are significantly higher than the velocities predicted from surface data.

#### HYDRAULIC FRACTURING

Comparison of the borehole televiwer images obtained before and after the hydraulic fracturing tests highlighted the existence of at least one artificial hydraulic fracture; more could not be obtained because blockage of the borehole did not allow the lowest sections to be logged a second time. Preliminary analysis of the results are in generally good agreement with the stress directions indicated

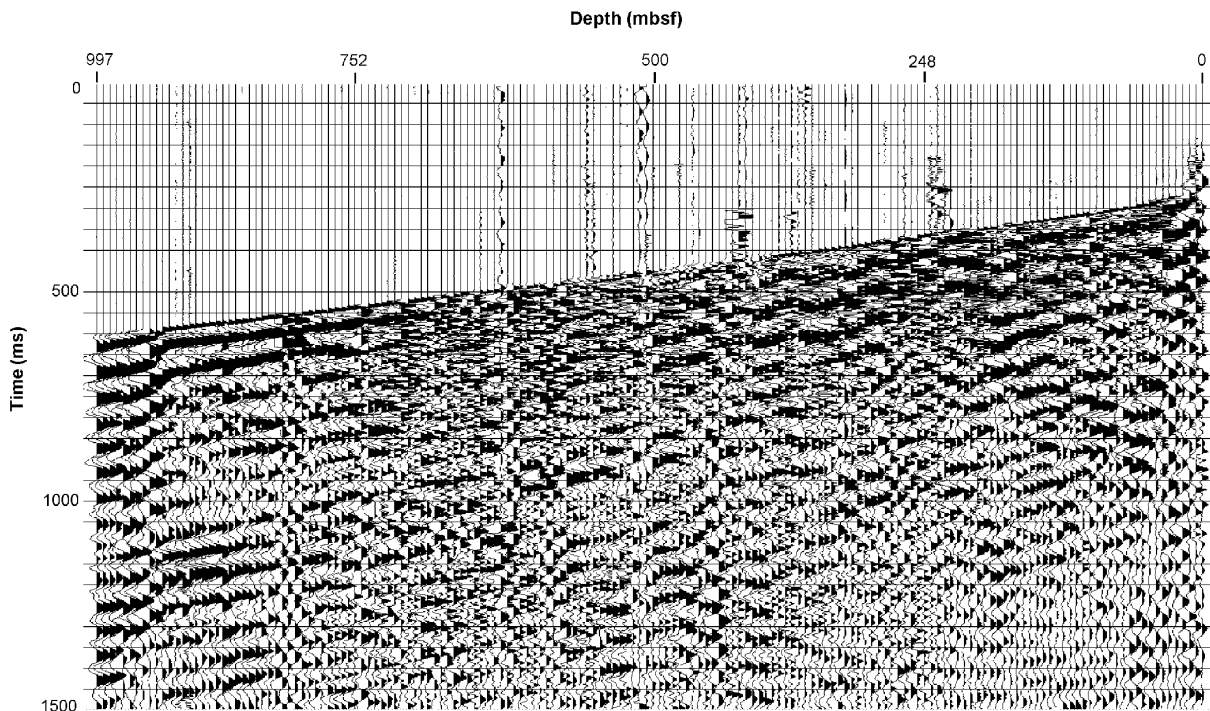


Fig. 9 - Southern McMurdo Sound Project, AND-2A borehole VSP second horizontal component (S-wave) results. Data were recorded in casing above 632 mbsf and in open hole below.

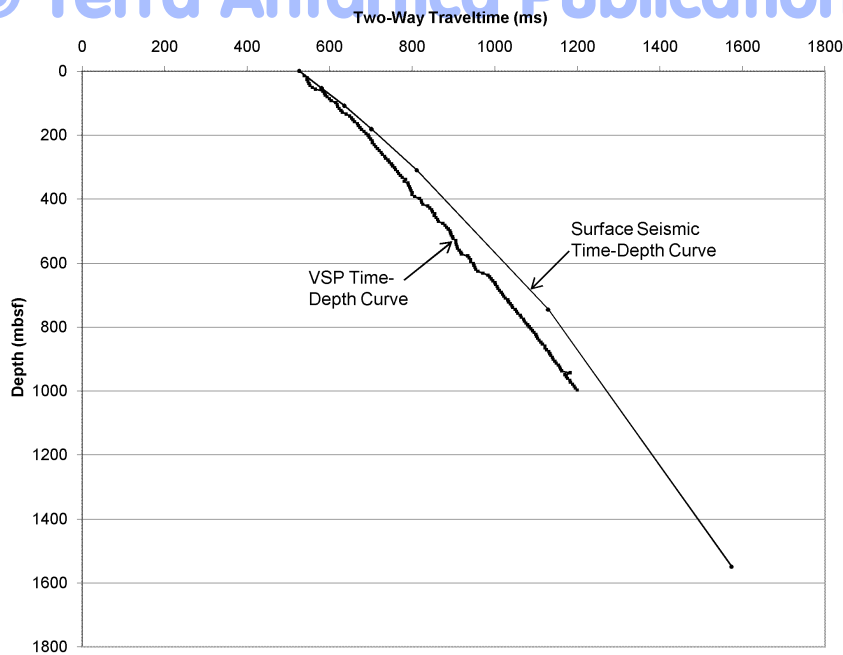


Fig. 10 - Southern McMurdo Sound Project, AND-2A borehole time-depth curves. Surface seismic time-depth curve is calculated from stacking velocities after Betterly et al. (2007). VSP time-depth curve is picked from the P-wave first arrivals (Fig. 6) and converted to two-way travel time.

by the core fracture logging and the stress regime suggested by the character of the drilling- induced core fractures (see Paulsen et al. this volume). Despite the loss of the packers, the authors consider this set of hydraulic fracturing tests to be both a technical and a scientific success. It is not known if so many hydraulic fractures have been induced within a single borehole before. As well, this is the first hydraulic fracturing stress measurement in Antarctica.

Further investigations of all the achieved downhole experiments, and their integration with other data from the AND-2A drillcore, will provide a better understanding of the geological history of the western Ross Sea region.

## OUTLOOK

In order to reach the scientific objectives of downhole experiments in the ANDRILL SMS Project, further work and research is necessary. The most important goals are as follows:

- reconstruction of continuous lithological profiles based on the physical properties of the rocks with a vertical resolution in the order of cm;
- conclusions about sedimentary environments and sedimentation rates;
- characterisation of petrophysical properties of the sedimentary rocks;
- determination of dip and orientation of sedimentary structures (dipmeter measurements);
- combination of the stratigraphic profile with seismic sections (VSP and sonic measurements);
- information on the shape of the borehole as influenced by the regional stress field (BHTV, dipmeter and calliper measurements) and the re-orientation of the cores (BHTV measurements and core orienting tool);
- the comparison between downhole and core logging data, giving precise core depths and corrections of core deformation resulting from the drilling process (*i.e.*, stretching and compressing).
- determination of breakdown and fracture propagation pressures. This will include a variety of analysis strategies that have been developed [*e.g.*, Lee & Haimson, 1989];
- measurement of the tensile strength  $T$  on representative core samples from the intervals. This will likely be carried out using the Brazilian technique;
- constraint of the greatest horizontal principal stress by use of a series of bounding hydraulic fracturing breakdown formulas;
- detailed comparison of borehole televiewer and core fracture logs with the hydraulic fracturing results.

**Acknowledgements** - The wireline hydraulic fracturing system was designed and constructed by Erich Scholz of Downhole Systems Inc. of Piermont, NY. Personnel who directly assisted in the set up and data acquisition for the downhole experiments are Jonathan Leitch, Jeremy Rigden, and Hedley Berge (who assisted with set up and system testing and trouble shooting of the hydraulic fracturing equipment); Bill Nye, Drill Fluids Engineer; Tamsin Falconer, Assistant to the Drilling Science Manager and drill site logistics co-ordinator; and Alex Pyne, Drilling Science Manager; and all of the personnel associated with the ANDRILL SMS Project. The ANDRILL Programme is a multinational collaboration between the Antarctic programmes of Germany, Italy, New Zealand and the United States. Antarctica New Zealand is the project operator and developed the drilling system in collaboration with Alex Pyne at Victoria University of Wellington and Webster Drilling and Exploration Ltd. Antarctica New Zealand supported the drilling team at Scott Base; Raytheon Polar Services Corporation supported the science team at McMurdo Station and the Crary Science and Engineering Laboratory. The

ANDRILL Science Management Office at the University of Nebraska-Lincoln provided science planning and operational support. Scientific studies are jointly supported by the US National Science Foundation (NSF), NZ Foundation for Research, Science and Technology (FRST), the Italian Antarctic Research Programme (PNRA), the German Research Foundation (DFG) and the Alfred Wegener Institute for Polar and Marine Research (AWI).

#### REFERENCES

- Barrett P.J. (ed.), 1989. Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. *DSIR Bulletin*, 245, 254 pp.
- Betterly S.J., Speece M.A., Levy R.H., Harwood D.M. & Henrys S.A., 2007. A novel over-sea-ice seismic reflection survey in McMurdo Sound Antarctica. *Terra Antartica*, **14**(2), 97-106.
- Bücker C.J., Jarrard R.D. & Wonik T., 2001. Downhole temperature, radiogenic heat production, and heat flow from the CRP-3 Drillhole, Victoria Land Basin, Antarctica. *Terra Antartica*, **8**(3), 151-160.
- Davey F. J., Barrett P.J., Cita M.B., van der Meer J.J.M., Tessensohn F., Thomson M.R.A., Webb P.-N. & Woolfe K.J., 2001. Drilling for Antarctic Cenozoic climate and tectonic history at Cape Roberts, southwestern Ross Sea. *EOS, Transactions of the American Geophysical Union*, **82**(48), 585, 589-590.
- Dunbar G.B., Atkins C., Magens D., Niessen F. & the ANDRILL-SMS Science Team, 2008-2009. Physical Properties of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica. *Terra Antartica*, **15**, this volume, 49-56.
- Harwood D.M., Florindo F., Levy R., Fielding C., Pekar S., Speece M. & SMS Science Team, 2005. ANDRILL Southern McMurdo Sound Project Scientific Prospectus. *ANDRILL Contribution*, 5, 28 pp.
- Lee M.Y. & Haimson B.C., 1989. Statistical evaluation of hydraulic fracturing stress measurement parameters. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 26, 447-456.
- Morin R., Williams T., Henrys S., Crosby T., Hansaraj D. & the ANDRILL-MIS Science Team, 2007. Downhole Measurements in the AND-1B Borehole, ANDRILL McMurdo Ice Shelf Project, Antarctica. *Terra Antartica*, **14**, 167-174.
- Paulsen T., Millan C., Pierdominici S., Wilson T., Drew S. & The ANDRILL-SMS Science Team, 2008-2009. Fracture logging of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica. *Terra Antartica*, **15**, this volume, 69-76.
- White P., 1989. Downhole logging. In: Barrett P. (ed.), Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. *DSIR Bulletin*, 245, 7-14.