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Abstract - Whole-core measurements of Wet Bulk Density (WBD), compressional (P)-wave velocity (Vp), and Magnetic Susceptibility were measured at a sampling interval of 1 or 2 centimetres (cm) throughout the AND-2A drill core for initial core characterisation and on-site correlation with seismic modeling to predict target-reflector depth. Measurements were made using a GEOTEK (Multi-Sensor-Core-Logger MSCL). Density and velocity standards were measured together with core runs of 3-6 metres (m) (and occasionally up to 18 m) throughout the entire depth range to monitor data quality. Drift of the magnetic susceptibility sensor was also monitored and corrected where necessary. These physical properties show a large range of values, reflecting the different nature of the various lithologies including extremely high velocity and density values in individual clasts, and the effects of cementation on porosity. A downcore increase in WBD and Vp occurs in the upper 200 m, however, no systematic trend exists at greater depths although large fluctuations on a m-decimetre- (dm) scale occur. Magnetic susceptibility is generally low (<100 x 10^{-5} SI), however, four intervals of high (>600 x 10^{-5} SI) susceptibility occur at 560, 800, 980 and 1 080 mbsf, indicating a relatively greater contribution of volcanic-derived material to the core site in the lower half of the AND-2A core.

INTRODUCTION

Whole-core physical properties provide a means of rapidly and non-destructively characterising geological core at cm-scale resolution (*e.g.* Mayer, 1991; Weaver & Schultheiss, 1990; Weber et al., 1997). During the drilling of AND-2A, on-site core measurements were carried out in a similar manner to those described for the Cape Roberts Project (CRP) (Cape Roberts Science Team, 1998; 1999; 2000) and the McMurdo Ice Shelf (MIS) (Niessen et al., 2007).

Wet Bulk Density (WBD), P-wave velocity (Vp) and Magnetic Susceptibility (MS) can be used to characterise gross lithology, including the effects of diagenesis (*e.g.* Jarrard et al., 2000; Niessen et al., 2000). Importantly, whole core physical logs can be used to correlate between drill sites where downhole logs are absent or incomplete (Henrys et al., 2000).

Furthermore, P-wave data can be processed on-site to yield 'real-time' vertical profiles of cumulative P-wave travel time that allows the stratigraphic depth of target seismic reflectors to be recalculated from the initial geophysical survey interval velocities (*e.g.* Henrys et al., 2000; 2001).

This paper presents (i) data acquisition, calibration and processing of physical properties during the drilling phase on-ice, (ii) analysis of physical-property standards and suggestions for enhancing the data through off-ice processing, and (iii) a preliminary overview of stratigraphic patterns in the physical-property data in the AND-2A core.

METHODS AND MATERIALS

A GEOTEK Multi-Sensor-Core-Logger (MSCL) was used at the drill site to measure core temperature, core diameter, P-wave travel time, gamma-ray attenuation and MS data (Fig. 1; details of the instrument and measurement process can be found at www.geotek.co.uk). In addition to the standard MSCL measurements, as part of the P-wave travel time acquisition process, full waveform transmission seismograms were digitized using the approach of Breitzke et al. (1996). The technical specifications and setup of the MSCL system as used during AND-2 drilling are summarized in table 1.

Each 1 m-long whole-core section was logged by placing it on a plastic carrier (a "split"). This was used to maintain the integrity of fractured or friable sections of core as they passed through the sensor array. The methodology is described in detail in the CRP-2 Initial Report (Cape Roberts Science Team, 1999). Individual 1m-long core sections were butted together to create continuous logging runs between 3 and 18 m (usually 6 m) in length. At the beginning and end of each run, standards made of aluminum, water and PolyOxyMethylene (POM) were logged to calibrate and/or monitor data quality for core diameter, WBD and Vp. The calibration process is described in more detail below. Magnetic susceptibility sensor drift was determined by "zeroing" the sensor in air at the start of the run and by temporarily removing the core from the loop at the end of the run and making another "air" measurement. The difference from zero of this measurement is the sensor drift. Where sensor drift exceeded ~2 (x10^{-5}) SI, a linear correction was applied and negative values removed from the data. The infrared temperature sensor was calibrated daily by placing containers of heated or cooled water under the sensor so the water surface was at the same height that the surface of the core would be under normal logging conditions. The temperature of the water was measured with an Hg thermometer. Prior to logging, cores on carriers were described in detail with respect to occurrence of cracks, fractures, unconsolidated or crumbly materials, missing (foam filled) core sections and undergauge core, all of which influence the quality of physical property data. These notes are available as PDF files (http://sms.andrill.org/Science/Data/MSCL/), and will be available with all on-ice SMS data at the end of the SMS Project moratorium period [Nov. 2009]).

Raw data from individual runs were processed together with data measured on calibration and monitoring standard cylinders logged before and after each core run. Data were assigned the correct depth below sea floor using GEOTEK software (v6.2). WBD and Vp logs were also processed from the raw data using this software, which applies data calibration as described below. From there data were exported to Kaleidagraph™ software where MS data were corrected for sensor drift if necessary and an empirical loop/core diameter correction applied. After run-wise separation of processed calibration data and core data both data sets were accumulated according to depth. Using Kaleidagraph's graphical editor, WBD, Vp and MS core data were cleaned run-wise for outlier points caused by core quality (natural or coring induced, gaps on carriers or between carriers) or obvious MSCL data acquisition problems.

WHOLE-CORE PHYSICAL-PROPERTY DETERMINATION

MAGNETIC SUSCEPTIBILITY (MS)

MS was measured in terms of SI units corrected for loop-sensor internal diameter and core diameter as follows:

$$MS\ (10^{-5}\ SI) = \text{measured value}\ (10^{-5}\ SI)\ /\ K\text{-rel} \quad (i)$$

Where K-rel is a sensor-specific empirical correction calculated from the ratio of the core diameter to the internal diameter of the loop sensor, given in table 1. No external calibration of this sensor is required.

P-WAVE VELOCITY (Vp)

Vp was measured using acoustic rolling contact (ARC) transducers. These oil-filled transducers roll along the top of the core and the underside of the plastic carrier respectively (Fig. 1). The acoustic coupling between the transducers and core is aided by dripping (~1 drop per second) distilled water onto the surface of the core and the upper surface of the lower P-wave transducer. Vp was calculated from the measured core diameter and acoustic travel time after subtraction of the travel time through the core carrier wall and ARC transducers, electronic delay, and detection offset between the first arrival and second zero-crossing of the received waveform (the "P-wave travel-time offset", PTO) where the travel time can be most reliably detected (Cape Roberts Science Team, 1998; 1999; 2000). This travel-time offset was determined using cylindrical POM standards of PQ, NQ and HQ diameter of known velocity. Following previous work, Vp was normalized to 20°C using temperature measurements made by infrared sensor using GEOTEK

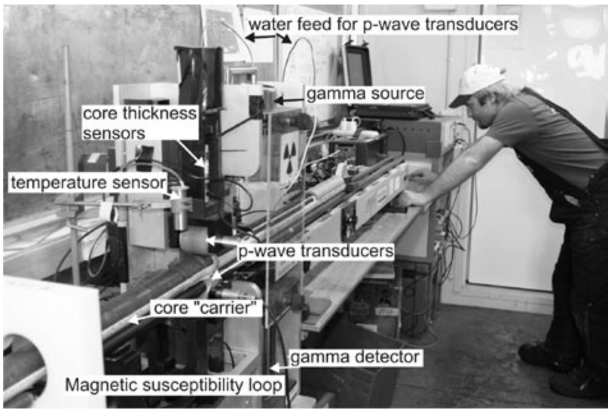

Fig. 1 – The setup and key sensors of the GEOTEK MSCL used to log the AND-2A core.

Tab. 1 - Multi-Sensor-Core Logger (MSCL, Ser. No. 25)

P-wave Velocity and Core Diameter	
Transducer	Acoustic Rolling Contact Transducer (ARC) (GEOTEK Ltd.)
Transmitter pulse frequency	230 kHz (ARC)
Transmitted pulse repetition rate:	100 Hz
Received pulse resolution	50 ns
P-wave Transmission Seismograms	
ADC board	T3012 (National Instruments)
Sampling frequency and resolution	30 Mhz, 12 bit
Sampling interval	50 ns
Length of seismograms	200 ms
Wet Bulk Density	
Gamma ray source	^{137}Cs
Source activity	356 MBq
Source energy	0.662 MeV
Counting time	10 s
Collimator diameter	2.5 mm
Gamma detector	NaI-Scintillation Counter (John Count Scientific Ltd.)
Magnetic Susceptibility	
Loop sensor type	MS-2B (Bartington Ltd.)
Loop sensor diameter	100 mm PQ, 80 mm HQ, NQ
Alternating field frequency	0.565 kHz
Sensitivity	10s (<20 10^{-5} SI), 1s (>20 10^{-5} SI)
Magnetic field intensity	approx. 80 A/m RMS
Loop sensor correction coeff. K-rel	1.487 PQ, 1.1795 HQ, 0.4848 NQ
Temperature	
Sensor types	Infrared

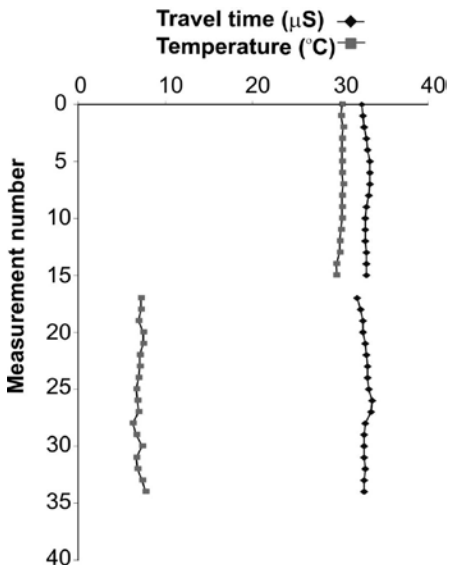

Fig. 2 – Comparison of measured travel time (and hence P-wave velocity) and core temperature for the same section of fine sandstone.

software according to the equation:

$$Vp = Vpm + 3 * (20 - tm) \qquad (ii)$$

where Vpm = measured P-wave velocity;
tm = measured temperature.

Subsequently, test measurements were made on a section of HQ diameter core comprising uniform fine sandstone that had been immersed in water at 7ºC and then 30ºC and allowed to equilibrate for ~30 minutes each time. The results show an identical travel time (and thus P-wave velocity) of 33 µS, apparently independent of core temperature (Fig. 2), suggesting further investigation of the validity of the temperature correction is warranted.

Post-ice investigation of the P-wave data showed a small systematic offset in velocity between PQ and HQ and NQ standard values. For PQ POM and Al velocities were on average 36 and 330 m.s^{-1} higher than for HQ and NQ, suggesting the PTO used for PQ was slightly too long. Accordingly we have applied a linear correction to P-wave data and standards for PQ to realign these values with HQ and NQ values (Fig. 3).

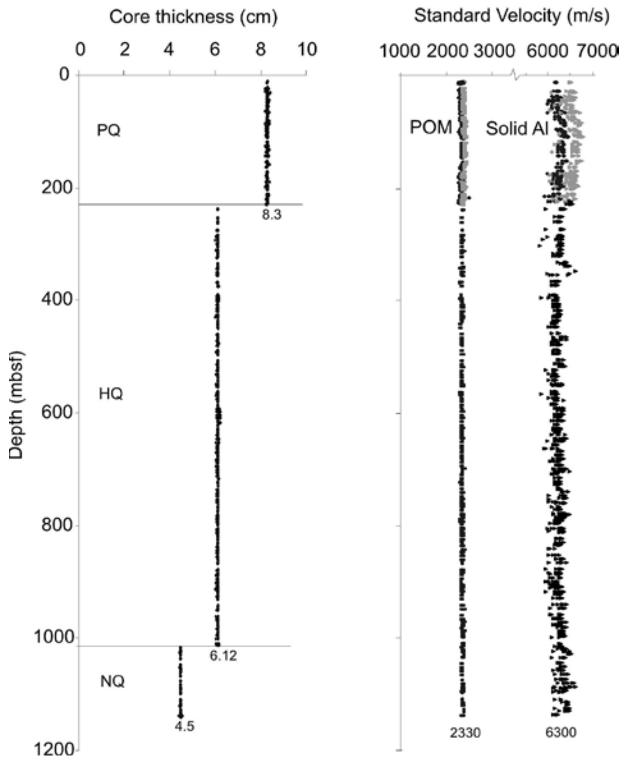

Fig. 3 – Downcore variability of core calibration thickness standards for PQ, HQ and NQ with nominal diameters of 8.3, 6.12 and 4.5 cm respectively and P-wave velocity measured for PolyOxyMethylene (POM) with a nominal velocity of 2 330 ms^{-1} and solid Al (6 300 ms^{-1}). Data points in grey are uncorrected values. See text for explanation.

FULL WAVEFORM TRANSMISSION SEISMOGRAMS

In addition to the standard Vp-detection system of the GEOTEK MSCL, a laboratory-built P-wave digitizer was used to capture the full transmission seismogram associated with each P-wave measurement. We used the same approach and apparatus as described for physical-properties logging of the AND-1B core (Niessen et al., 2007) except the data acquisition system was fully automated, allowing collection of seismograms simultaneously with Vp.

WET BULK DENSITY (WBD)

WBD was determined from attenuation of a gamma-ray beam transmitted from a ^{137}Cs radioactive source (Tab. 1). A 2.5 mm diameter collimated beam was used and the beam aligned through the core-centre into a scintillation-gamma detector. For density calibration and monitoring of PQ, HQ and NQ core-size cylinders consisting of different proportions of aluminum and water and a solid cylinder of POM were logged at the end of each core-logging run (nominally every 3-6 m).

To calibrate WBD from gamma counts, we applied a 2nd order polynomial function to describe the relationship between the natural logarithm of gamma counts per second (ln cps) and the product of density and thickness of the measured material (see www.geotek.co.uk). For calibration, the equations are determined empirically for each core diameter on each run by plotting average data points of 2.71, 1.76, 1.23 g.cm^{-3} standards. For PQ core, a value of 1.41 g.cm^{-3} was used for POM and this was included in the calibration. For HQ and NQ the POM value was omitted from the calibration as it yielded a gamma density closer to 1.46 g.cm^{-3} when compared against the HQ and NQ Al-water standards. More detailed post-ice investigation of the density standards suggests the problem lies with the purity (and thus density) of some of the Al used to fabricate the standards. Unfortunately the actual standards measured with the SMS cores have not been available for re-examination; however, analysis of the original billet used to make the standards gave a density of 2.8 g.cm^{-3} (rather than a value of 2.7 g.cm^{-3} which we assigned to all our "Al" standards) for some pieces. The most likely explanation therefore, is that the Al used to make the PQ and NQ standards was an alloy with a density of 2.8 g.cm^{-3} whilst the HQ standard was pure Al (2.7 g.cm^{-3}). If this is the case, then the density calculated for PQ and NQ core is underestimated by up to 4% at a true density of 2.7 g.cm^{-3}. At this point we have not corrected the on-ice measurements, but anticipate doing so when we are able to confirm the actual density of the standards.

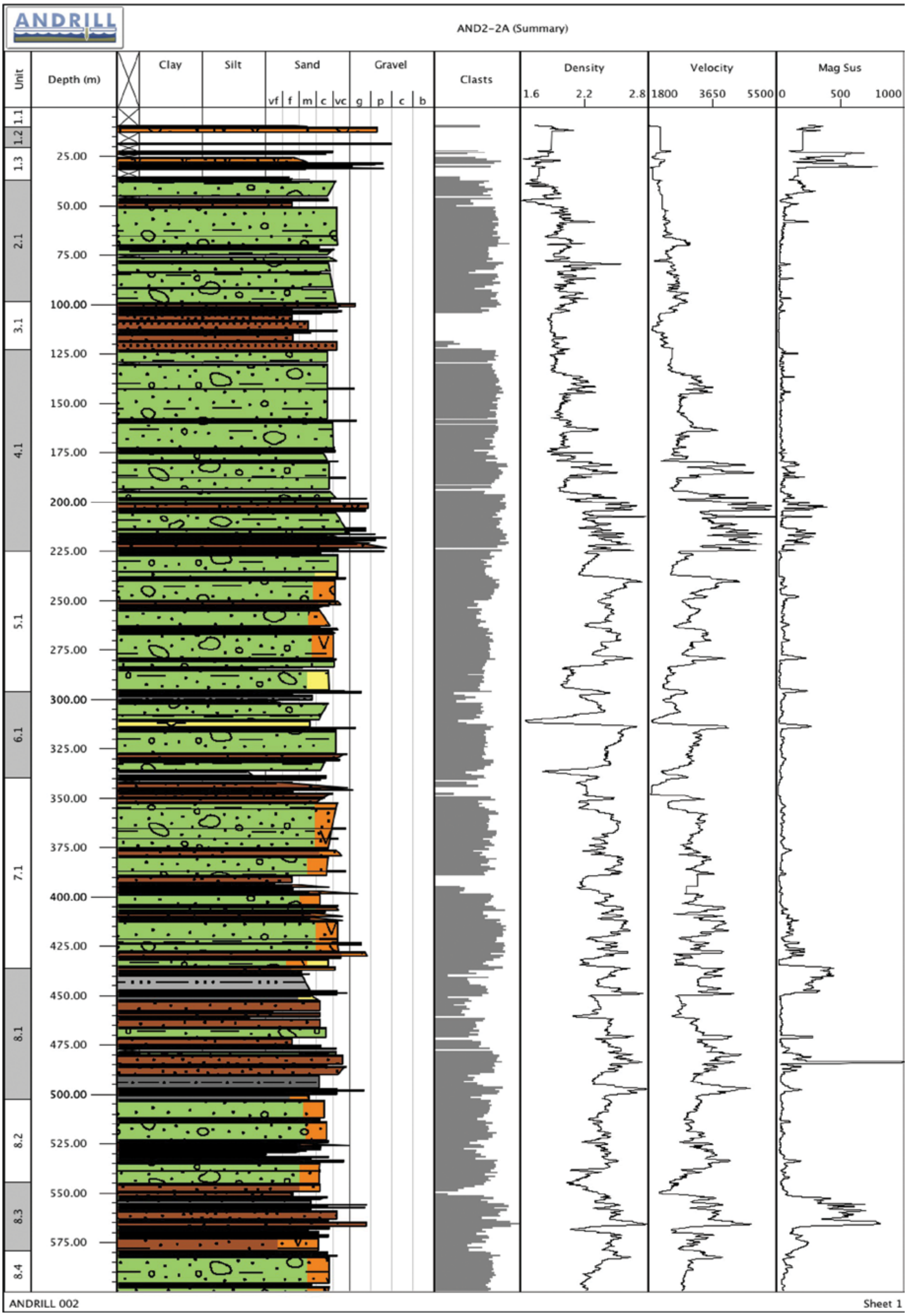

Fig. 4 – Summary logs of Vp, WBD and MS (smoothed over 50 data points) from 0 to 1132 mbsf, compared to lithology. See Fielding et al. (this volume) for key to lithology.

PRELIMINARY RESULTS AND INTERPRETATION

After processing and eliminating unreliable data points, a total of 51 903, 57 066 and 64 526 P-wave, WBD and MS measurements were acquired on the AND-2A core (Fig. 4). These data provide a general characterisation of the core material in terms of gross lithology and diagenetic history (to the extent that this alters primary porosity).

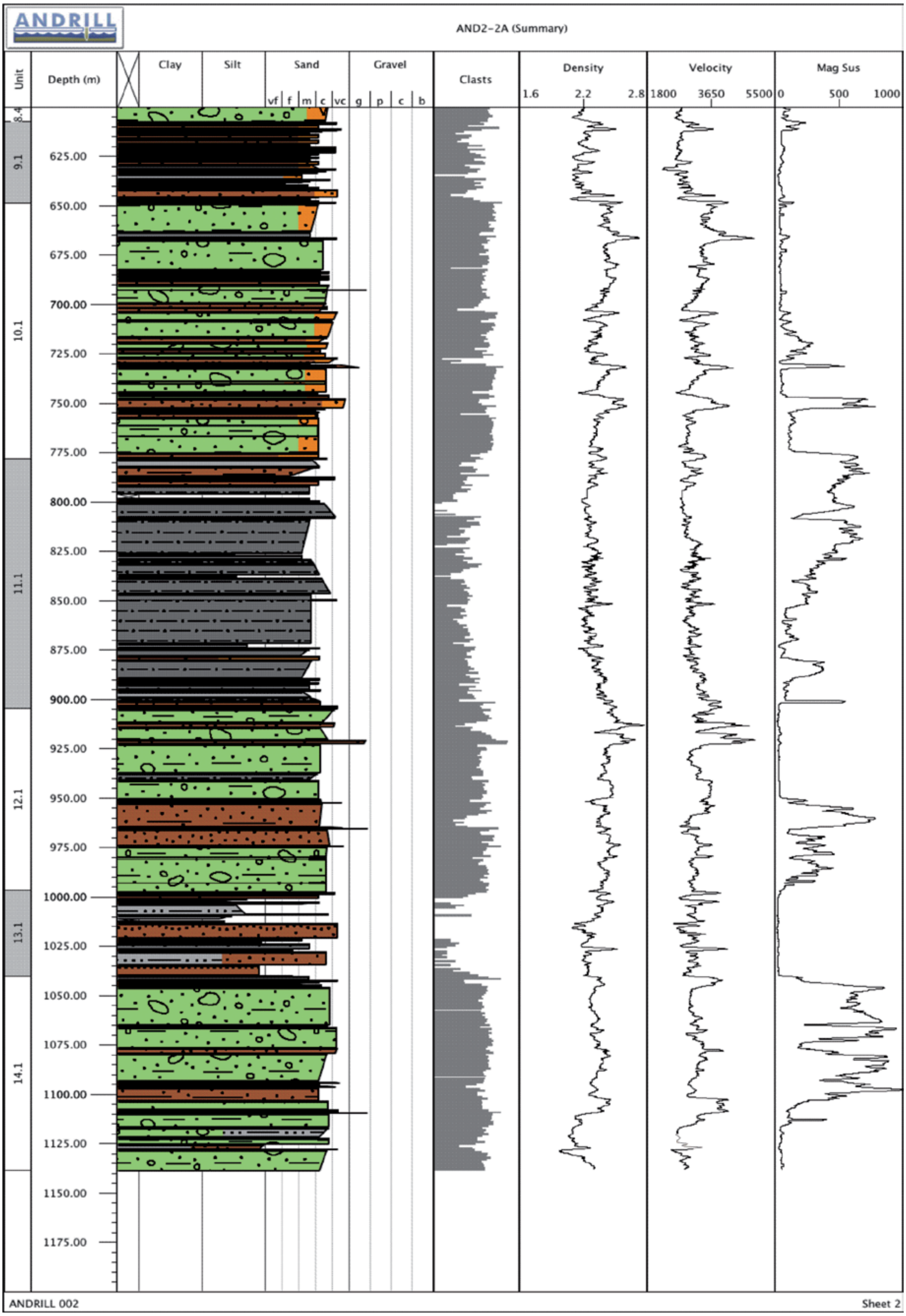

Fig. 4 – Continued.

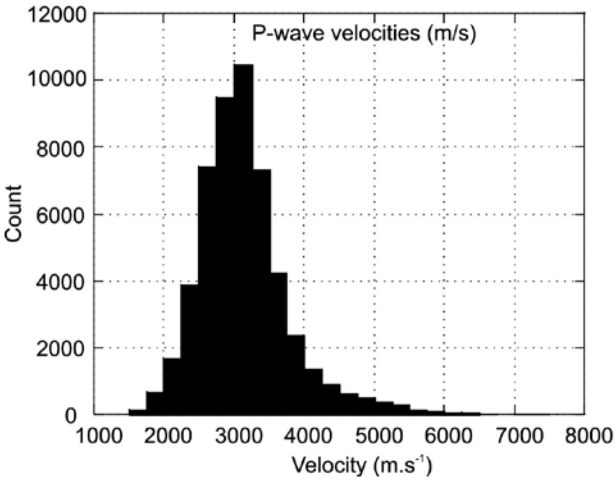

Fig. 5 – Histogram of all valid P-wave data from core AND-2A. See text for explanation.

CORE-DATA RANGES, STATISTICS AND TRENDS

Vp ranges from 1 460 m.s^{-1} in unconsolidated mud at the top of the core to more than 7 000 m.s^{-1} through single clasts. The SMS core is dominated by a single lithology (diamictite) that is relatively uniform in physical properties and the resulting Vp histogram is unimodal with a mean value of 3 140 m.s^{-1} (Fig. 5). The distribution of Vp is slightly positively-skewed, mostly due to very high values measured in clasts of core size or bigger, which occur relatively infrequently in the record, or in intervals with pervasive carbonate cement. An overall increase in velocity with depth is only apparent in the upper 200 m and there is considerable meter-scale variability within this interval. Velocity values below 200 m show no systematic trend with depth although, again, there is considerable decimetre to metre scale variability down core. The data are not corrected for *in situ* conditions.

WBD ranges from about 1.6 g.cm^{-3} in diatomaceous mudstone to about 3.1 g.cm^{-3} in single large clasts. Like Vp, the distribution of density is unimodal, although with a slight negative-skew reflecting the relatively low WBD of some sand and mudstones despite their higher Vp values (Fig. 6).

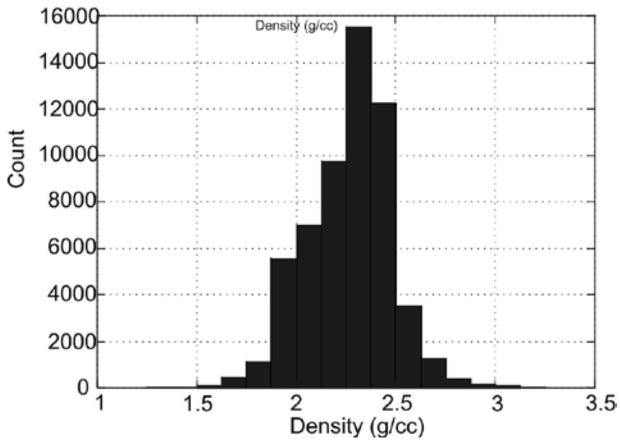

Fig. 6 – Histogram of all valid density data from core AND-2A. See text for explanation.

Similarly, there is an increase in WBD from 1.7 g cm^{-3} at 10 mbsf to 2.4 g.cm^{-3} at 200 mbsf. A slight decrease of 2.4-2.3 g.m^{-3} occurs between 200 mbsf and the bottom of the hole, although there are large m- to dm-scale variations superimposed on top of this trend. As for Vp, the data are not corrected for *in situ* conditions.

MS ranged over four orders of magnitude although most data (80%) lie between 0 and 200 (x 10^{-5}) SI. Very low (<20 x 10^{-5}SI) values are observed in some diamictites and large clasts (Fig. 4). By contrast, MS data from volcanic clasts and diamictite matrix material containing a substantial amount of material derived from volcanic rocks can reach up to 8000 (x 10^{-5} SI). There are large fluctuations in magnetic susceptibility in the core but no significant overall down-core trend in the data. Several broad intervals of high MS are centered on 560, 800, 980 and 1080, indicating relatively greater supply volcanic sediment to the core site in the lower half of the record.

Six examples of transmission seismograms from different lithologies and different depth in core are compared (Fig. 7). Arrival times depend on the velocity in the core and generally decreases with core depth as velocity increases as a function of compaction and degree of cementation. Sound attenuation is inversely proportional to maximum amplitude in the seismograms and highly variable. In the examples (Fig. 7), attenuation is largest in diamictite (±0.1 Volt) and minimal in diatomite (±1 V). The full waveform is also different in the different lithologies (Fig. 7). Whereas differences in waveforms are subtle between diatomite and mudstone with variable degrees of cementation they are clearly visible for diamictite and crystalline rock such as measured on large single clasts. These differences are thought to be related to grain size (Breitzke et al., 1996). Other factors such as grain fabric and degree of cementation may also play a role on the frequency distribution and amplitudes of the seismograms and needs to be analysed further.

DOWNCORE COMPARISON WITH THE AND-1B CORE

Unlike the AND-1B core (Naish et al., 2007), which is characterised by two dominant lithologies (diamictite and diatomite) with strongly contrasting physical properties, the AND-2 core is dominated (~75%) by a single lithology – diamictite. Although there is a strong positive correlation between WBD (inversely proportional to porosity assuming a constant grain density) and Vp, below 200 mbsf, the expected increase in WBD and Vp with increasing depth (and hence compaction) is not observed in AND-2A. Although the reasons for this are speculative, the common occurrence of carbonate cement and diamictite containing large clasts, both of which result in an increase in WBD and Vp at shallow depths, must play a role as well as the

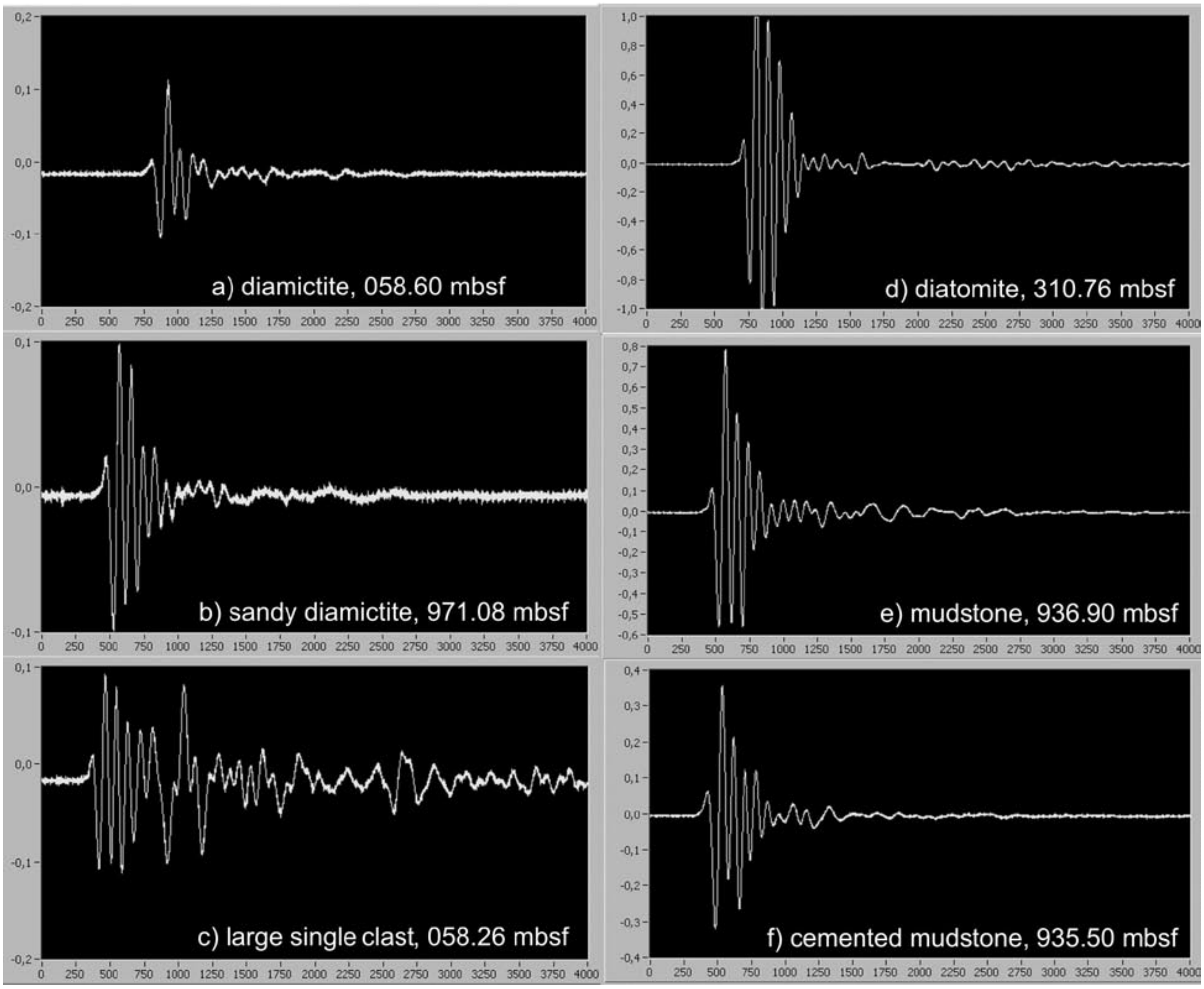

Fig. 7 – Examples of single transmission seismograms measured in different depth intervals and lithologies. Horizontal axis is time in µs, vertical axis is receiver amplitude in Volts (V).

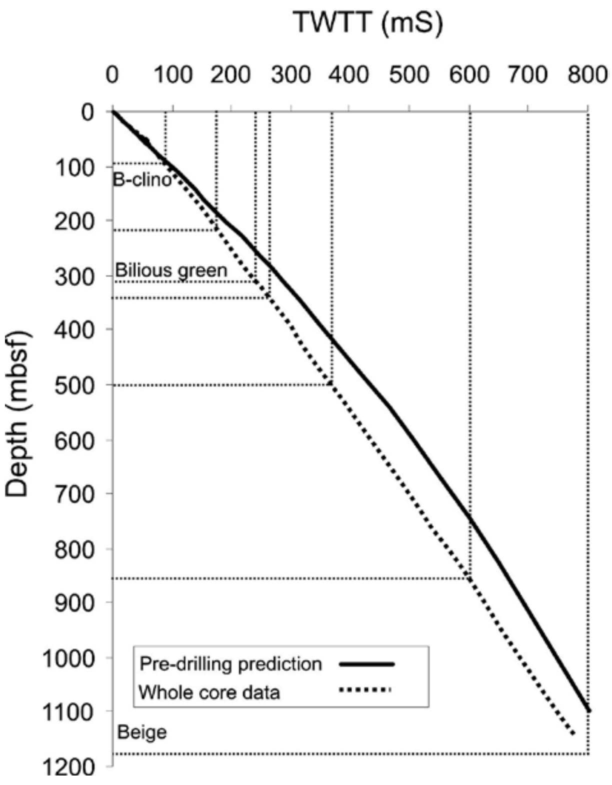

Fig. 8 – Cumulative whole core P-wave two-way travel time (TWTT) *vs.* depth compared with the pre-drilling TWTT *vs.* depth estimate. The depths of key seismic reflectors identified in the pre-drilled seismic workshop are marked.

potential for significant over-consolidation from ice loading during glacial periods.

WHOLE-CORE TWO-WAY TRAVEL-TIME

Vp measured across the core at each depth interval was used to calculate the vertical travel time in the core to the next deeper interval, assuming isotropy of the rock on scales of a few centimeters. These travel times between depth intervals were compiled to a cumulative two-way travel time (TWTT) *vs.* depth profile in order to predict the depths of the target reflectors defined on the seismic profile (Fig. 8). Velocities were not corrected to reflect borehole pressure and temperature conditions. TWTT was computed using a 50 pt running mean over a Vp dataset re-sampled at 2 cm intervals. Compared to the pre-drilling seismic survey data, the whole-core data show a consistently higher interval velocity between 50 and ~650 mbsf, resulting in a significantly steeper

TWTT *vs.* depth curve over this interval. Consequently, the location of seismic reflectors identified as pre-drilling targets actually occurred up to 110 m deeper than predicted (Fig. 8). Vertical seismic profiling (VSP) carried out after drilling was completed, confirms the much steeper TWTT *vs.* depth curve generated on the whole core data.

CONCLUDING REMARKS

Further data processing is necessary with regard to correcting the WBD measurements for the offset between pure Al density (2.7 $g.cm^{-3}$) and Al-alloy (density 2.8 $g.cm^{-3}$) thought to have been inadvertently incorporated in the PQ and NQ WBD standards. If this is the case, then WBD has been underestimated in PQ and NQ sized core by up to 4% at a true density of 2.7 g.cm-3. Further investigation will also be made into the validity of the temperature correction applied to Vp data, although it should be noted that removal of this correction will only make as small change (typically <15 $m.s^{-1}$) to the absolute Vp value. In addition, processing and study of the transmission seismograms may yield a geologically useful relationship between their spectral amplitudes and grain size composition and porosity (*e.g.* Breitzke et al., 1996).

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