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Sedimentology and Stratigraphy of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica

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Abstract - During the 2007 – 2008 austral spring season, the ANDRILL Southern McMurdo Sound Project recovered a core 1138 metres long (AND-2A) from a location in the southern McMurdo Sound near the Dailey Islands. This core contains a range of lithologies, including various types of terrigenous clastic diamictite, conglomerate and breccia, sandstone and mudrocks, volcanic lava, pyroclastic and reworked volcanic sedimentary rocks, and diatomite. The succession is divided into fourteen lithostratigraphic units (LSUs), two of which (LSUs 1 and 8) are further subdivided into three and four sub-units, respectively, based on changes in abundance of lithologies. Thirteen lithofacies are recognized, ranging from diatomite and bioturbated, fossil-bearing mudrocks (representing most ice-distal environments) through interlaminated sandstone-mudrock facies and sandstone with varying dispersed gravel components, to diamictite and conglomerate (representing most ice-proximal environments), and also lava, volcanic breccia and volcanic sedimentary rocks representing extrusion, fragmentation, fallout and reworking of material from basaltic volcanic activity. Three distinct types ('motifs') of vertical facies stacking patterns are recognized, recording glacial advance-retreat-advance cycles with varying degrees of facies preservation. Carbonate, pyrite and zeolites are the principal secondary mineral phases in the core. The pyrite overprint is particularly prominent in the lower half of the core, where it typically obscures stratification and sediment texture. Studies of modern aeolian sediment deposition onto McMurdo Sound sea-ice reveal that between 7600 and 24 000 kg km^{-2} of terrigenous clastic material is being stored on the sea-ice in this region.

INTRODUCTION AND OVERVIEW

This paper presents the results of sedimentological description and interpretation, and lithostratigraphic subdivision of the AND-2A core. The detailed core descriptions at 4 m/page will be available on the ANDRILL drive at http//:sms.andrill.org, following the end of the moratorium period. Summary logs, at a scale of 100 m/page, are included here in 11 images as figure 1 (A-K).

The core is divided into 14 lithostratigraphic units (LSUs) on the basis of major changes in lithology recognized during core description (Tab 1). This division emphasizes the relative importance of diamictite and associated lithologies, relative to other terrigenous clastic and volcanogenic lithologies. Criteria used to define LSUs included diamictite abundance, sandstone/mudstone abundance, volcanogenic component in lithologies, biogenic silica abundance, and abundance of conglomerate within diamictite-dominated intervals. Two of these LSUs were further subdivided, LSU 1 into three sub-units (1.1, 1.2, 1.3) and LSU 8 into four sub-units (8.1, 8.2, 8.3, 8.4).

Thirteen recurring lithofacies are recognized, and interpreted in terms of a spectrum of depositional environments ranging from possibly subglacial, through ice-contact proglacial and glacimarine, to less ice-influenced, shallow marine settings.

A preliminary analysis of stratigraphic stacking patterns reveals three distinct "stratigraphic motifs" or sequence styles, each bounded at the base by a diamictite recording glacial advance, and overlying, better-sorted terrigenous clastic facies recording glacial retreat, transgression and sea-level highstand. Differences between the three motifs are in the character of the diamictites, in each case, and the relative thickness and lithological diversity of overlying,

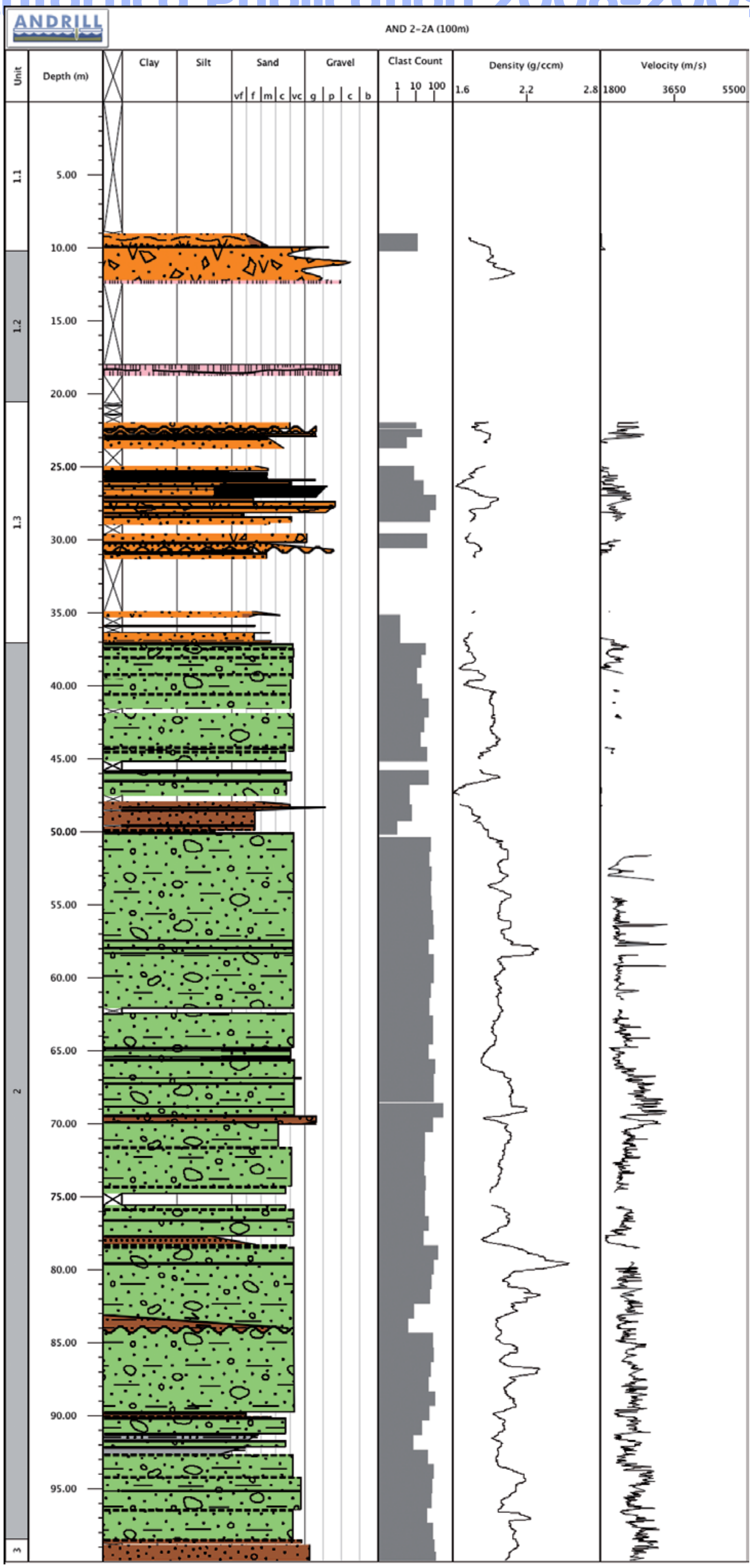
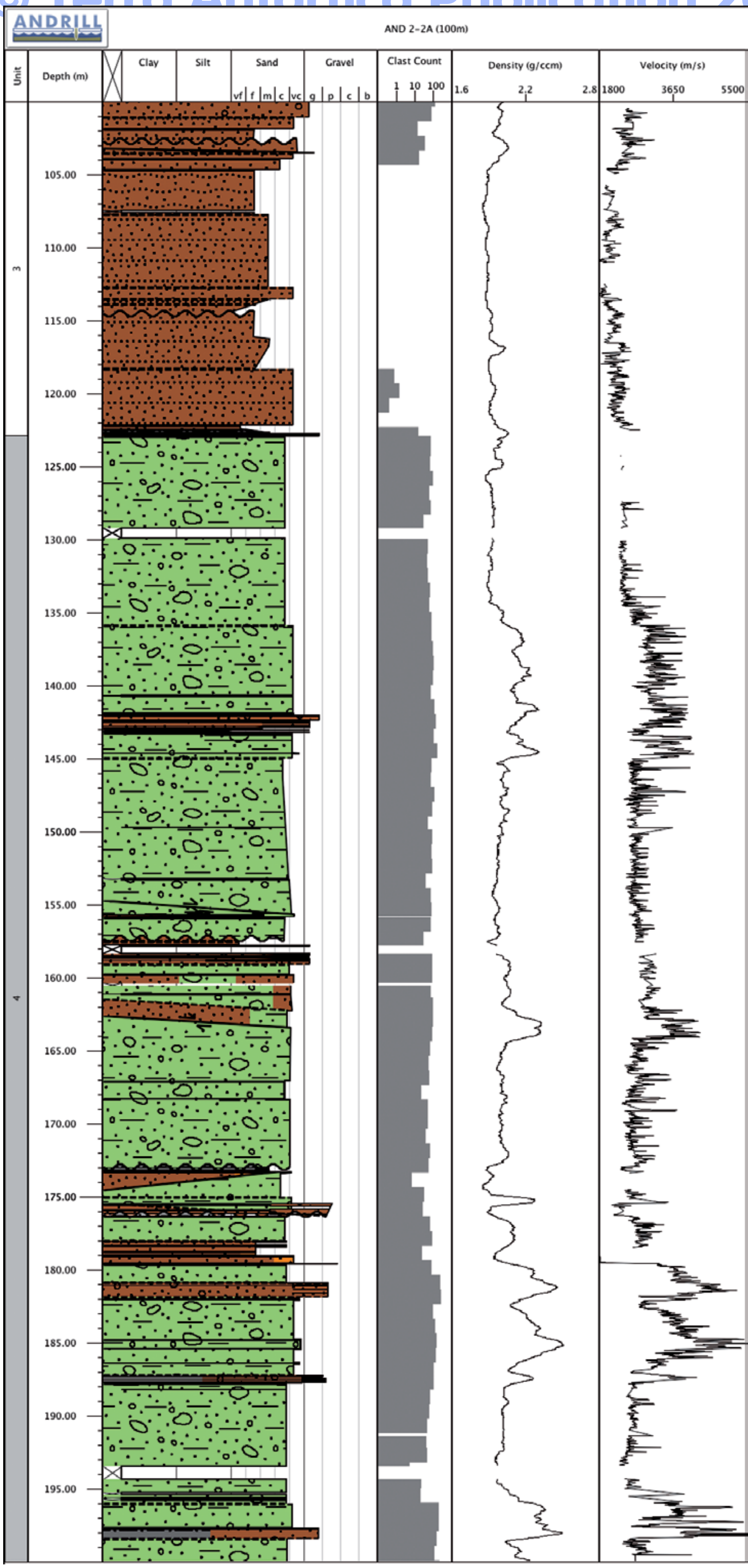


Fig. 1 – Summary logs of AND-2A at 100 m per page, showing lithostratigraphic subdivision and general facies assignment.



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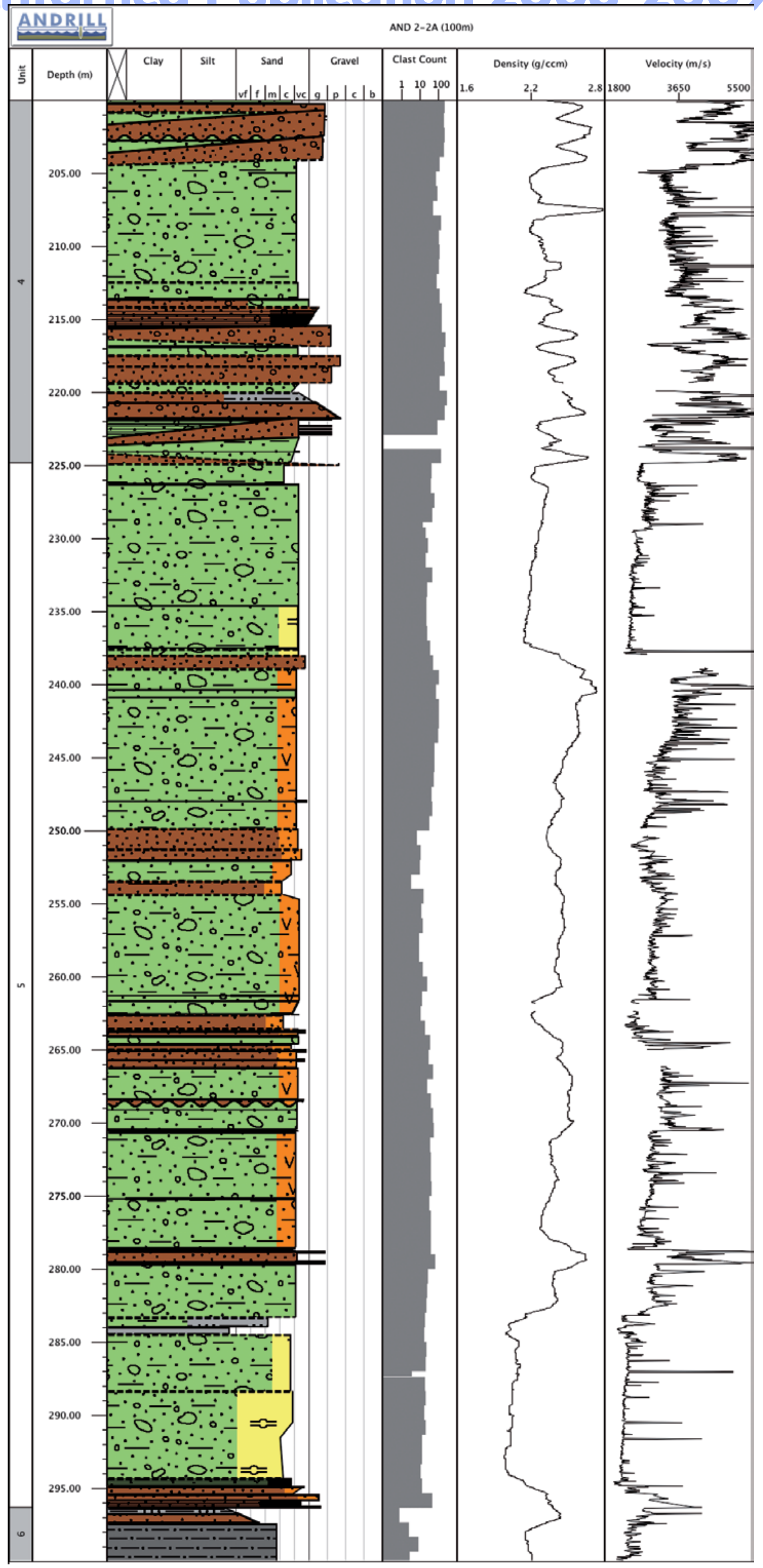

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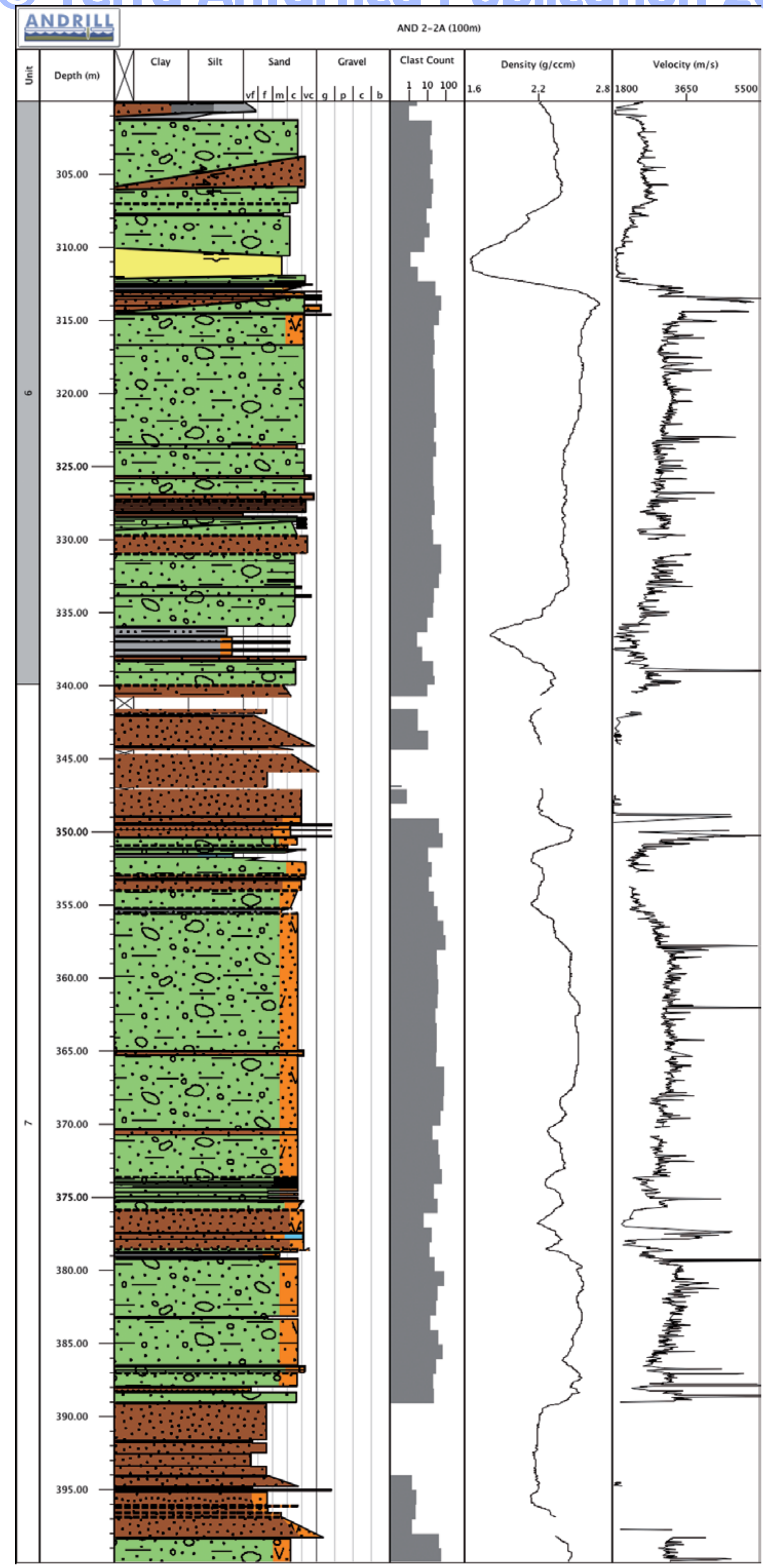

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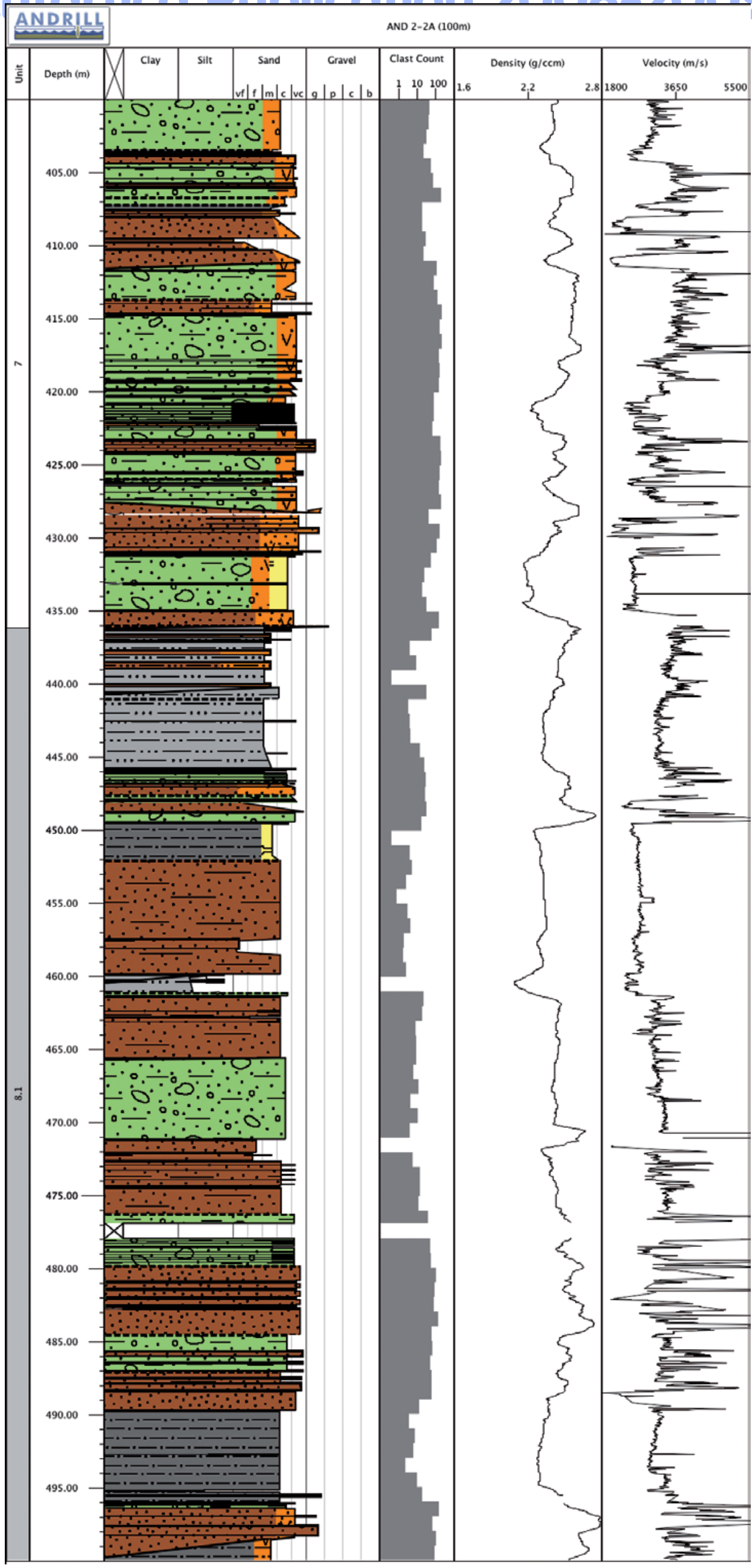

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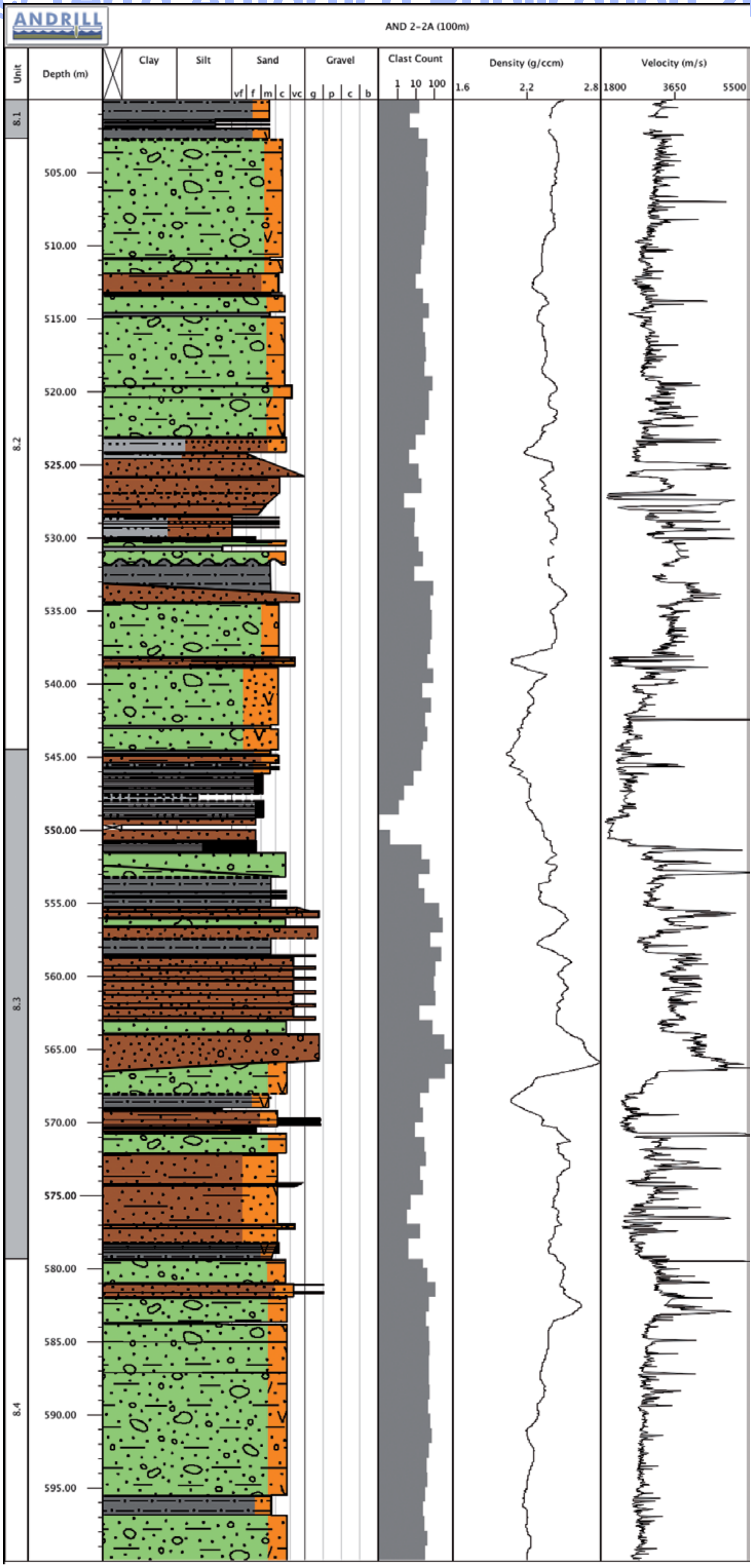

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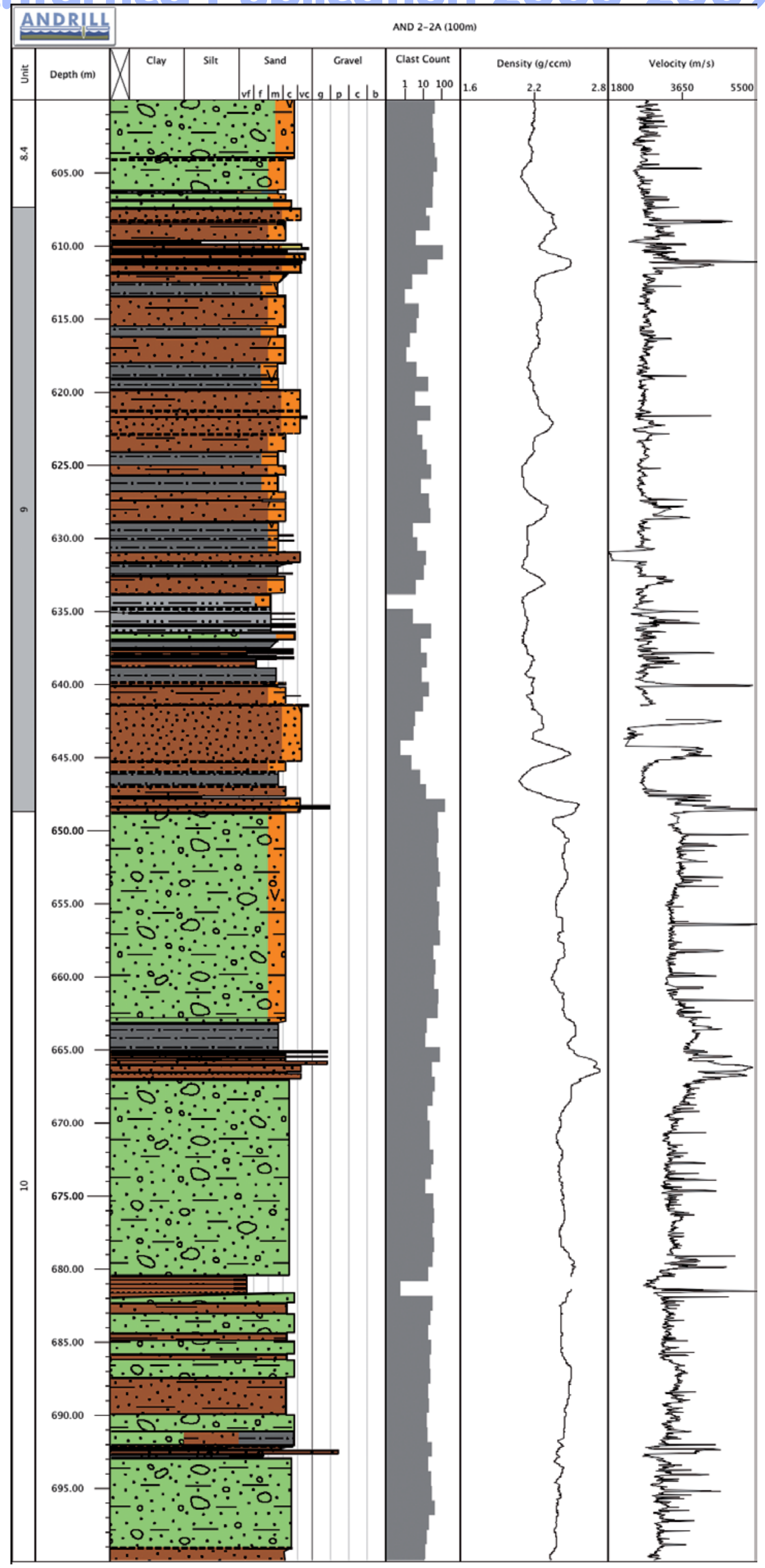

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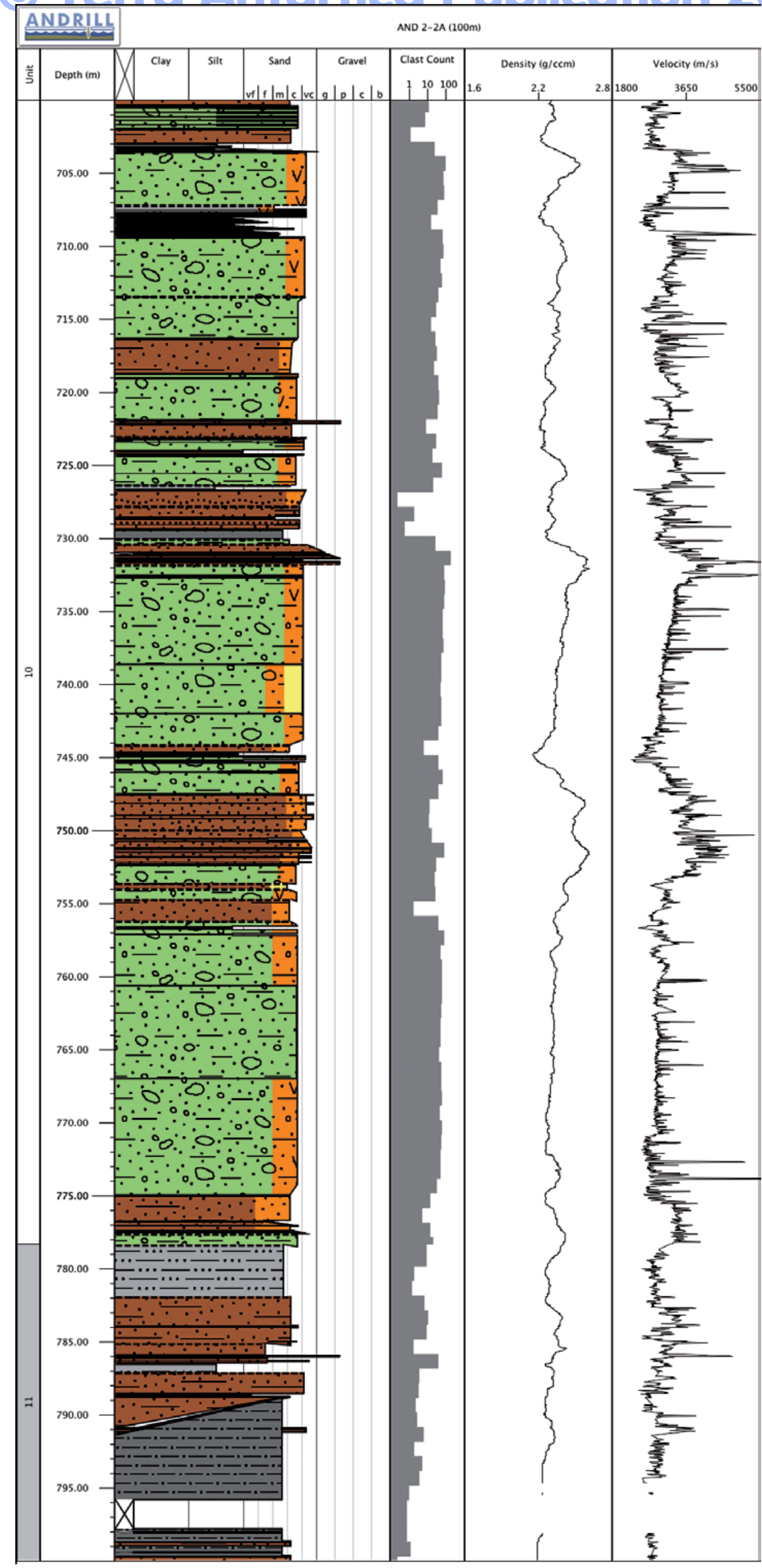

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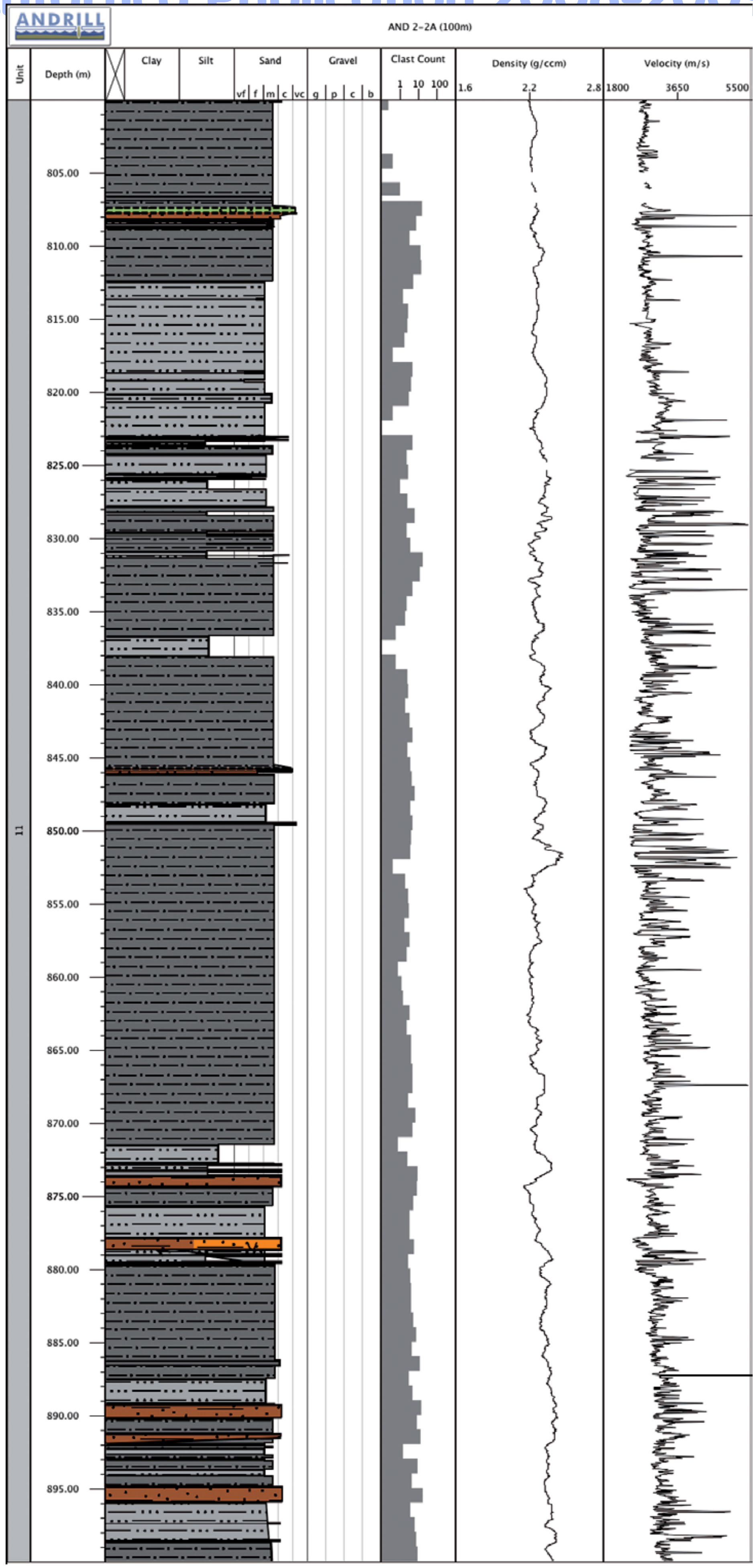

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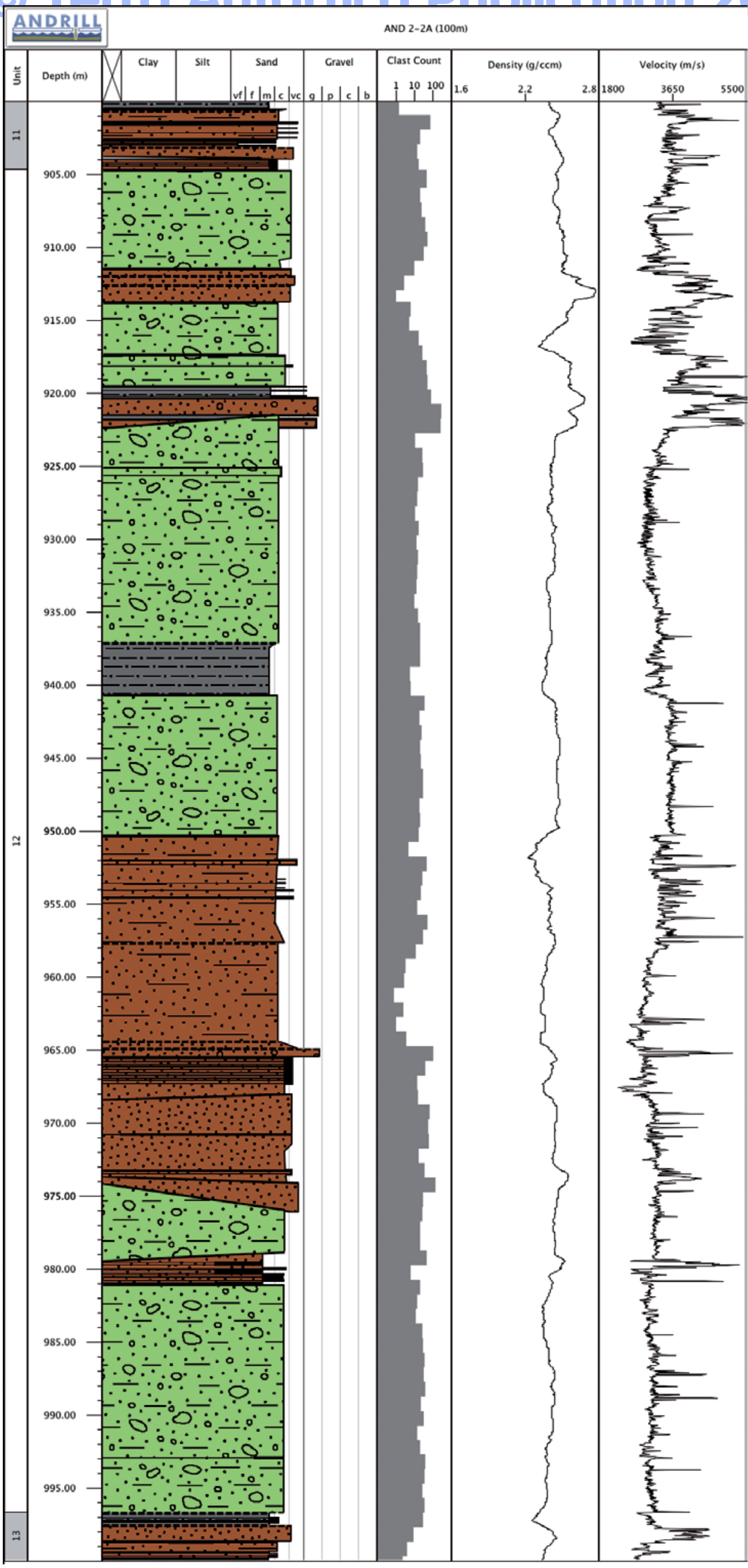

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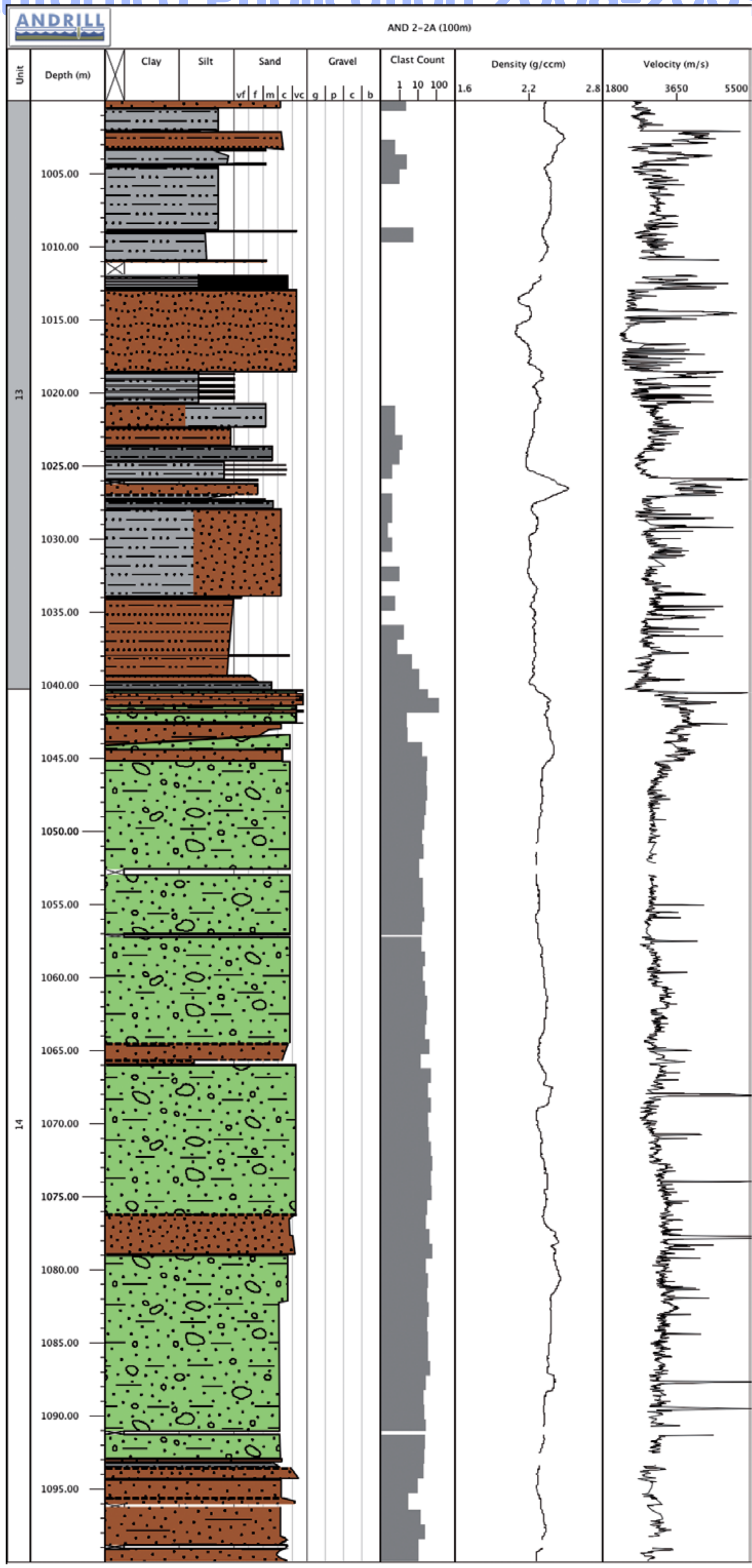

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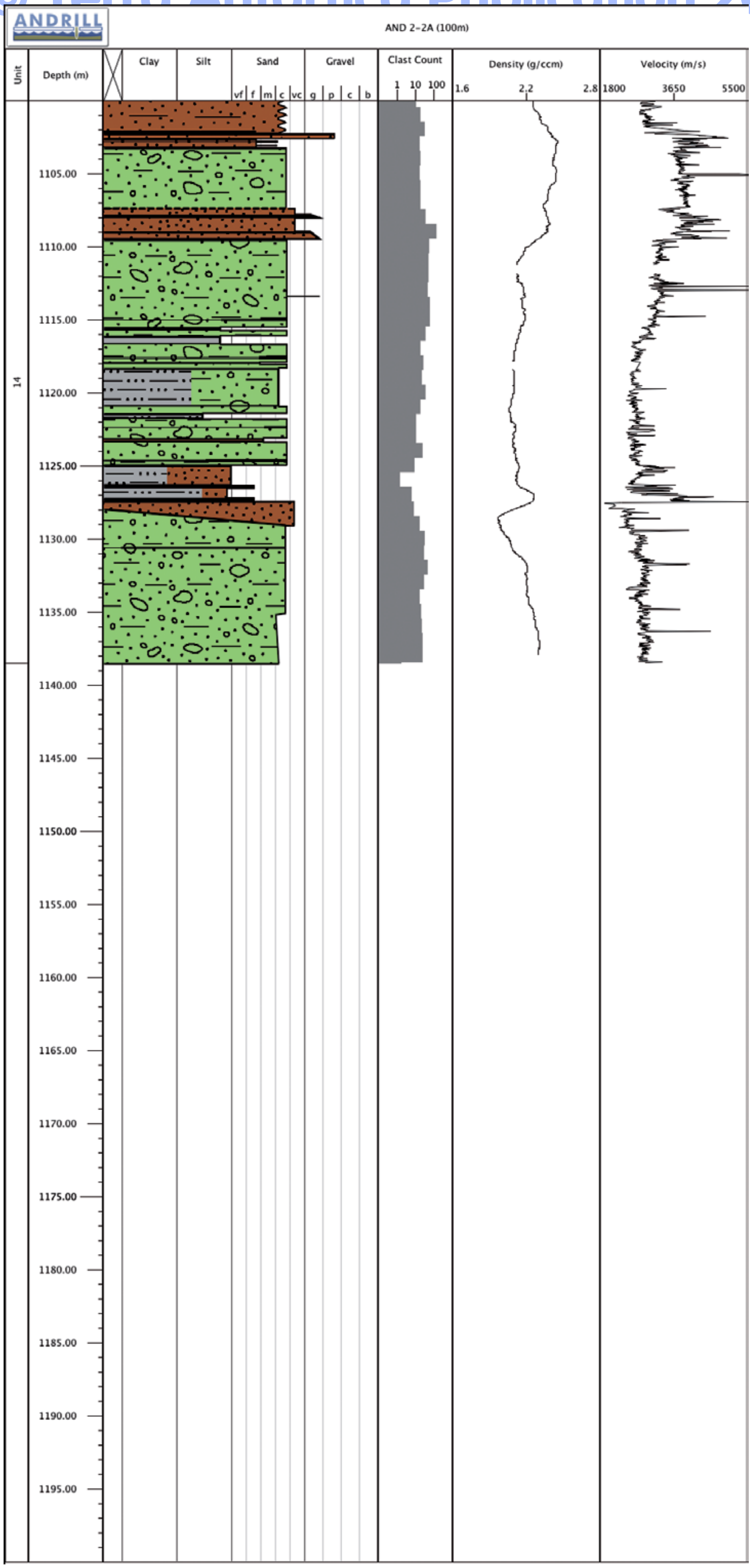

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finer-grained and better-sorted facies.

Investigations of aeolian sediment transport and deposition onto McMurdo Sound sea-ice reveal that between 7 600 and 24 000 kg km^{-2} of sediment is being stored by this mechanism, and ultimately delivered to the sea-floor during seasonal sea-ice melting.

An initial analysis of diagenesis in the core reveals that the principal diagenetic phenomena are carbonate cementation, authigenic pyrite formation, and alteration of volcanic glass (devitrification, hydration and zeolitisation). Several factors have combined to make the AND-2A section highly reactive diagenetically, including the high geothermal gradient, the presence of alkaline formation waters, and the abundance of chemically reactive volcanic constituents throughout the core. Biogenic silica, in the form of sponge spicules and diatoms, persists to near the base of the hole. Preservation to this great depth was likely enhanced by association with the abundant volcanic components.

EXPLANATORY NOTES

The objectives, roles, operations and procedures of the ANDRILL Southern McMurdo Sound (SMS) Project Sedimentology/Stratigraphy Team are described below.

Roles: Because the commitment to core description consumed all the time and effort of the night shift sedimentologists (Brad Field, Chris Fielding, Larry Krissek, Kurt Panter, Sandra Passchier), the day-shift sedimentologists (Kari Bassett, Greg Browne, Stephen Pekar) assumed primary responsibility for the more interpretive and integrative tasks. These tasks included (1) defining and describing Lithostratigraphic Units (LSUs), (2) developing the lithofacies scheme, and (3) gathering information that would be of value in establishing a sequence stratigraphic interpretation. Following completion of the core description phase, the night-shift sedimentologists contributed to these efforts by reviewing the existing classifications and interpretations, and by providing additional descriptions, discussions, and interpretations. At this time, summary graphic logs were developed (with significant input from Josh Reed), general interpretations of glacial proximity and depositional environment developed, and a preliminary sequence stratigraphic interpretation formulated, all as a group effort by the Sedimentology/Stratigraphy Team. During the core description phase, Joanna Hubbard and Rainer Lehmann, ARISE (ANDRILL Research Immersion for Science Educators) participants, worked with the day-shift sedimentologists. Their primary responsibility was the capture of representative digital images of lithofacies, bed and unit contacts, and other features of significance, from the *Corelyzer* system.

Procedures: The night-shift sedimentologists carried out the core description and logging in a series of nightly increments, typically ~30 metres of core per shift. Sandra Passchier and Chris Fielding simultaneously made observations on the core: Passchier compiled a draft version of the official core log on paper forms, while Fielding recorded information separately in a notebook. This methodology was chosen rather than direct transfer of observations to *PSICAT* based on experience from the ANDRILL MIS Project, when it was found useful to have a manual backup of logs and an opportunity to organize observations prior to compiling the logs on *PSICAT*. Once a logging form was completed, it was passed to Larry Krissek to be drafted using *PSICAT* (Paleontological Stratigraphic Interval Construction and Analysis Tool). Concurrent with these operations, Kurt Panter made observations on any components within the core that might be of volcanic origin and potentially suitable for radiogenic isotope dating by the $^{40}Ar/^{39}Ar$ method (see Acton et al., this volume). Also concurrent with these operations, Brad Field prepared and examined smear slides, typically at 1 m spacing throughout the core, and recorded semi-quantitative estimates of composition for each smear slide. Smear slide compositional data are presented in Panter et al. (this volume). Tracy Frank assisted in the preparation of smear slides during the second half of the core description phase. Sonia Sandroni and Franco Talarico logged the occurrence, position, composition, dimensions and other features of gravel-grade clasts throughout the core. Their results are presented in Panter et al. (this volume). Samples for granulometric analysis were acquired at ~1 m spacing from the entire core by Fielding, Passchier and Pekar during the on-ice phase. The sample set was divided among the three investigators with control samples at 10 m intervals to be analysed by all three, and at the time of writing analyses are in progress.

Classification schemes: The classification scheme for granular sediments presented in the Science Logistics Implementation Plan (SLIP) document for the MIS Project (Naish et al., 2006) was used successfully during core description, including the modifications to terminology for volcaniclastic granular sediments proposed by White and Houghton (2006) adopted during the MIS Project. Rather than naming the volcanic-dominated sediments on the basis of grain-size and mode of origin (*i.e.,* volcaniclastic, pyroclastic, or autoclastic), the volcanic-dominated sediments were given a textural name based solely on grain-size (*e.g.*, claystone, siltstone, sandstone, conglomerate, or diamictite), preceded by the modifier "volcanic". Volcanic dominance of a specific interval was recognized by the abundance of volcanic glass or altered volcanic glass, pumice or pumiceous grains, or euhedral mineral grains. The distinction between biogenic and diagenetic carbonate was hindered by the toughness of the core, requiring sampling by scraping that often destroyed the texture of the carbonate. The rarity of recognizable biogenic calcite (*e.g.*, as foraminiferal tests) suggests most of the calcite noted is secondary/diagenetic.

In order to maintain consistency in the *PSICAT* graphic logs, a graphic lithology and a representative grain-size were assigned to each subdivision within Moncrieff's (1989) classification scheme for poorly-sorted terrigenous clastic sediments containing gravel. The assignments used are as for the MIS Project and are tabulated by Krissek et al. (2007). Equivalent assignments were made for the classes of poorly-sorted volcanic sediments containing gravel; the only difference is that the equivalent volcanic lithologies, rather than terrigenous clastic lithologies, were assigned.

LITHOSTRATIGRAPHY

The following is a lithostratigraphic summary of the ANDRILL SMS Project core from McMurdo Sound (AND-2A). It is based on core descriptions by the ANDRILL Sedimentology/Stratigraphy Team. All depths are recorded as metres below sea floor (mbsf) unless otherwise stated, and relate to the depths recorded while drilling. In this summary we have tried to establish an objective description of the rock units, and have subdivided the cored interval into 14 lithostratigraphic units (LSUs) based on significant lithological changes observed downcore. Where appropriate, some of these LSUs are subdivided further into subunits (Fig. 1, Table 1).

Lithostratigraphic Unit 1

(PQ core down to 229.24 mbsf)

LSU 1 (0.0 to 37.07 mbsf) comprises a succession of mixed volcanic rocks ranging from reworked volcanic sand to diamicton and breccia, with basaltic lava.

Lithostratigraphic Unit 1.1

Mixed volcanic and sedimentary rocks; 0-10.22 mbsf; 10.22 metres thick (various bagged samples)

In LSU 1.1, lithologies include 1) lithic-bearing volcanic muddy sandy breccia, comprising subangular to subrounded clasts up to 11 cm in diameter in an olive-grey, poorly sorted fine to medium-grained lithic-bearing volcanic silty sand matrix and, 2) dark olive-yellow quartz-bearing volcanic silty sandstone and olive-yellow volcanic sandy siltstone, in part trough cross-laminated.

Lithostratigraphic Unit 1.2

Volcanic: basaltic lava and monomictic lava breccia; 10.22 to 20.57 mbsf with bagged samples from 10.22-12.41, 17.96-18.73 mbsf (possibly 10.35 meters thick)

LSU 1.2 comprises ~10 m of monomict volcaniclastic breccia and lava. The lavas (bagged samples) are black, vesicular and amygdaloidal basalt. Minerals filling vesicles (amygdules) are

Tab. 1 - Summary of the lithostratigraphic units defined within the AND-2A drillcore.

LSU	***Depth - top (m)***	***Depth - base (m)***	***Unit Thickness (m)***	***Lithology***
1,1	0	10.22	10.22	Mixed volcanic rocks and sedimentary rocks
1,2	12.22	20.57	10.35	Volcanic: basaltic lava & monomictic lava breccia
1,3	20.57	37.07	16.5	Volcanic sedimentary rocks
2	37.07	98.47	61.4	Diamictite with minor sandstone, conglomerate and clayey siltstone
3	98.47	122.86	24.39	Planar bedded sandstone and conglomerate
4	122.86	224.82	101.96	Diamictite with minor sandstone, conglomerate and siltstone
5	224.82	296.34	71.52	Diamictite with biogenic silica, sandstone and minor conglomerate & siltstone
6	296.34	339.92	43.58	Diamictite, diatomite, conglomerate, fine-grained sandstone, siltstone, and claystone
7	339.92	436.18	96.26	Volcanic-bearing diamictite and sandstone
8,1	436.18	502.69	65.51	Volcanic-bearing mudstone, with sandstone and diamictite
8,2	502.69	544.47	41.78	Volcanic-bearing diamictite, mudstone, and sandstone
8,3	544.47	579.33	34.86	Volcanic-bearing sandstone, conglomerate, mudstone, and diamictite
8,4	579.33	607.35	28.02	Volcanic-bearing diamictite, siltstone, sandstone, and conglomerate
9	607.35	648.74	41.39	Volcanic-bearing sandstone, siltstone, and minor diamictite
10	648.74	778.34	129.6	Volcanic-bearing diamictite, sandstone, and sandy mudstone
11	778.34	904.66	126.32	Sandy siltstone with dispersed clasts and sandstone with/without dispersed clasts
12	904.66	996.69	92.03	Clast-rich and clast-poor diamictite, muddy sandstone with dispersed clasts, and minor mudstone with dispersed clasts
13	996,69	1040.28	43.59	Fine siltstone, coarse siltstone, and very fine-grained sandstone with dispersed clasts and rare diamictite
14	1040.28	1138.54	98.26	Diamictite, sandstone, and siltstone

non-calcareous and assumed to be zeolite or clays. Vesicularity varies from minor to more abundant with the spherical vesicles reaching up to 5 mm in diameter. Between 18.50 and 18.69 mbsf, the vesicles are smaller (1-2 mm in diameter) and irregular in shape. Vesicles are less abundant but larger reaching up to 1 cm in diameter in the interval 18.69-18.73 mbsf. Neither the upper nor lower contacts of LSU 1.2 were recovered in the core.

Lithostratigraphic Unit 1.3
Volcanic sedimentary rocks; 20.57-37.07 mbsf; 16.5 metres thick

LSU 1.3 is a series of fining-upward beds ranging from volcanic breccia to cobble-bearing volcanic sandstone at the base, to medium-grained sandstone to sandy siltstone near the top. Sand and gravel grade material dominates this subunit, with thinner intervals of finer-grained sediment. Basal contacts of many of the coarser intervals are sharp and in some cases may be erosional. Brecciated units contain granular to occasional pebbly grains, while the coarsest grained interval contains cobble-sized clasts. These coarser grained intervals are olive-grey to greyish black in colour, and in some cases are faintly stratified. Some of the clasts are rust-stained suggesting subaerial exposure. Tops of these coarser intervals mostly grade into finer units. Intraformational clasts of volcanic sediments or clays are present, and in the case of the former, their abundance results in a mottled appearance. Finer-grained intervals typically consist of light olive-grey to brownish black volcanic fine-grained to occasionally very fine-grained sandstone. Laminae are locally developed, and comprise volcanic siltstone and medium-grained sandstone with dispersed clasts. Sandstone intervals also display ripple cross-lamination with possible hummocky cross-stratification recognised in two intervals.

The contact between LSU 1.3 and the underlying LSU 2 is a sharp boundary at 37.07 mbsf between fine-grained volcanic sandstone and underlying clast-rich, sandy diamictite, which is the uppermost diamictite encountered in the core.

Lithostratigraphic Unit 2
Diamictite, with interbedded sandstone, siltstone, and conglomerate; 37.07-8.47 mbsf; 61.4 metres thick

LSU 2 represents the first downhole occurrence of diamictite, with subordinate non-volcanic sandstone, siltstone, and conglomerate.

Greenish grey to dark olive-grey, clast-rich and clast-poor sandy diamictite is the dominant lithology of LSU 2. Clast abundance varies between 5 and 30%, and clasts are angular to rounded, up to cobble grade (up to 25 cm), and mostly of basement (extrabasinal) lithologies – dolerite, granite, volcanics, quartzite, and gneiss, as well as more locally derived diamictite, basalt, and mudstone. Pumice clasts become common below ~86 mbsf. Much of the diamictite is massive, but some intervals are weakly to strongly stratified by clast concentrations and clast alignment, and by the presence of deformed wispy grey mud laminae and dark yellowish brown sand laminae. Lithologies are locally intermixed by shearing or interbedding.

Intercalated with the diamictite are fine- to coarse-grained sandstone, siltstone (some richly diatomaceous), and conglomerate. Fine-grained sandstone is greenish black, with wispy lamination to ripple cross-lamination. Dispersed clasts up to granule grade are common. Coarse-grained sandstone is dark greenish grey, with diffuse and deformed upper and lower contacts. Siltstone is dark greenish grey, interlaminated with pinstripe laminae of fine-grained sandstone. Microfaulting is common in the finer grained lithologies. A greenish grey to dark greenish grey conglomerate from 69.42 to 69.83 mbsf consists of angular to rounded granules, inversely graded at the base, with planar bedding and crude cross bedding in the middle part of the bed.

The contact between LSU 2 and the underlying LSU 3 is marked by an abrupt change from diamictite downward into sandstone with abundant clasts at 98.47 mbsf.

Lithostratigraphic Unit 3
Planar bedded sandstone and conglomerate; 98.47-122.86 mbsf; 24.39 metres thick

LSU 3 consists of grey sandstone and minor conglomerate. The upper part comprises a stack of decimetre- to metre-thick sandy conglomerate to sandstone intervals with abundant, common, or dispersed clasts. They are olive-grey to greenish grey, moderately sorted, clast-supported, crudely stratified coarse-grained sand to pebble-cobble conglomerate with clasts of crystalline basement, sedimentary, and intraformational lithologies. The sandstone in the upper interval contains variable proportions of clasts.

The bulk of the LSU comprises greenish grey to olive-grey, crudely stratified to ripple cross-laminated, fine to coarse-grained sandstone with clasts of crystalline, sedimentary, and intraformational lithologies up to pebble size. Below 104.62 mbsf, the sandstone is primarily olive-grey to greenish grey in colour, planar laminated in the main, and medium- to fine-grained. Extraformational clasts are absent between 104.62 and 112.69 mbsf. Ripple cross-lamination, trough cross-bedding, and possible hummocky cross-stratification are also present. Light coloured laminae (possibly carbonate-cemented) are common. One 5 cm-thick sandstone interval contains sandstone intraclasts that appear to have been rotated to a near vertical fabric.

The contact between LSU 3 and the underlying LSU 4 is an abrupt change from a sandy mudstone with dispersed clasts downward into a sandy pebble-cobble conglomerate at 122.66 mbsf.

Lithostratigraphic Unit 4
Diamictite with conglomerate, sandstone, and siltstone; 122.86-224.82 mbsf; 101.96 metres thick

LSU 4 represents a return to diamictite, with subordinate conglomerate, sandstone, and siltstone.

The dominant lithology is greenish grey, clast-rich to clast-poor muddy to sandy diamictite. Clast abundance varies up to 30%, the clasts ranging from very angular to well-rounded, and comprising intraformational, crystalline basement, and pumice clasts up to 34 cm in diameter. Some clasts are preserved in clusters. Both stratified and unstratified fabrics occur in the diamictite, with "boxwork" networks of fractures and brecciation developed to varying degrees throughout. Scattered shell fragments are common, especially in the upper and middle portions of the diamictite, and serpulid worm tubes are present in some intervals. In the lower part of the unit, the diamictite contains interbedded fine-grained planar and ripple cross-laminated sandstone, and locally contains sand- to granule-filled clastic dykes.

Conglomerate, sandstone, and siltstone are minor lithologies. Muddy sandy conglomerate typically occurs immediately beneath diamictite intervals. It consists of greenish grey, angular to subrounded, granule to pebble conglomerate, comprising polymictic clasts that make up to 80% of the lithology. Crude stratification is indicated by semi-horizontal alignment of clast long axes. Bioclasts include bivalve and serpulid worm fragments and are dispersed throughout. The bases if many conglomerate beds are loaded. Sandstone and siltstone occur as interstratified lithologies or as discrete beds. The latter comprise greenish-grey, silty very fine to coarse-grained sandstone with or without dispersed granules, shells (serpulid tubes), and bioturbation (*Planolites* and *Chondrites*). Many of the sandstone intervals are volcanic-bearing and many are ripple cross-laminated.

The boundary between LSU 4 and the underlying LSU 5 is marked by a gradational contact between sandy cobble conglomerate and underlying clast-poor, muddy diamictite at 224.82 mbsf.

Lithostratigraphic Unit 5

(HQ Core from 229.24 mbsf)

Diamictite with sandstone and minor siltstone 224.82-296.34 mbsf; 71.52 metres thick

LSU 5 is dominated by diamictite with less abundant sandstone and siltstone, in large part lacking conglomerate. It also contains an appreciable amount of biosiliceous material (including diatoms) based on smear slides. It has an abundance of marble clasts in the upper portion, and correspondingly fewer pumice clasts.

The diamictite consists of greenish-grey to very dark grey, clast-poor to clast-rich, muddy and sandy diamictite, with clast content varying between 1 and 20%. Clasts are angular to subrounded, and up to 15 cm in diameter. Clast types include granitoids, marble, dolerite, and mafic volcanics. Marble clasts are abundant in the interval from 238.75 to 255.5 mbsf. Pumice clasts are less abundant than in LSU 4, but become more abundant below 277.5 mbsf. Poorly-sorted beds of coarse-grained sand and gravel locally impart stratification to the diamictite. Thin sandstone interbeds, where present, are locally disturbed by soft-sediment deformation and shearing. "Boxwork" networks of fractures are common in certain intervals, and clastic intrusions are also common. Possible shear zones with rotated clasts ("comet structures") are present, and in places, ductile deformation occurs around individual clasts. Clastic intrusions are relatively common especially below 247.27 mbsf. Zones with discrete vertical fractures, in part cemented, are also common throughout. Some diamictite intervals contain biogenic silica in the matrix, with abundant diatoms (10 to 60%) identified in smear slides between 284.95 and 294.84 mbsf, as well as serpulid worm tubes, and rare foraminifera and bioturbation.

Thick sandstone beds (up to 180 cm-thick) contain dispersed or common angular to subrounded granules. The sandstone beds vary in colour from greenish grey to dark greenish grey, and below 262.5 mbsf, they are very dark grey to black. They are very fine- to medium-grained, crudely planar stratified, and trough cross-bedded to ripple cross-laminated. Soft-sediment deformation and microfaulting are common. Some intervals contain serpulid worm tubes. Muddy sandy conglomerate beds up to 25 cm-thick occur near the base of the LSU below 278.71 mbsf, and comprise very dark grey, angular to rounded polymictic clasts including crystalline rocks, volcanics, and dolerite up to 9 cm in diameter. Also close to the base of the LSU is very dark grey ripple cross-laminated soft sediment-deformed siltstone, in part intermixed with diamictite.

The boundary between LSU 5 and the underlying LSU 6 is taken at an abrupt, erosional contact between sandy conglomerate and underlying, strongly soft-sediment-deformed interlaminated siltstone and sandstone at 296.34 mbsf.

Lithostratigraphic Unit 6

Diamictite, diatomite, conglomerate, fine-grained sandstone, siltstone, and claystone; 296.34-339.92 mbsf; 43.58 metres thick

LSU 6 marks a major shift to finer-grained lithologies with diatomite. The most abundant lithology is dark and very dark grey to very dark greenish grey, clast-poor muddy and clast-rich to clast-poor sandy diamictite. Clasts are up to 7 cm in diameter, angular to subrounded, and comprise up 1-5% of the rock. Clast abundance and clast size increase below 321 mbsf. Compositionally they are polymictic, including crystalline, volcanic, and intraformational clasts; often concentrated into clusters. Below 314.44 mbsf, diamictite lithologies are volcanic-bearing. Smear slides indicate >10% volcanic material below this depth. Thin beds of sandstone or mudstone are locally intercalated within the diamictite, the mudstone possibly modified by loading and/or bioturbation (possibly *Planolites*). In places, the diamictite includes interstratified and physically intermixed fine-grained sandstone, both lithologies having been modified by soft-sediment deformation. Fossils including fragments of shells and corals, and diatoms (from smear slides) are present locally. Bases of some diamictite beds are loaded into underlying lithologies. Soft-sediment folding and shear fabrics are common, many are cemented, and include "boxwork" networks of fractures.

Diatomite and silt-bearing diatomite occur for the first time in the core between 310.02 and 312.12 mbsf. Olive-grey in colour, the rock is laminated throughout at the mm-scale and contains coarse-grained sand through to granule-sized clasts (up to 7 mm in diameter).

Less abundant intercalated lithologies include olive-grey, dark greenish-grey to very dark grey, volcanic-bearing sandy conglomerate, sandstone, siltstone, and claystone. The conglomerate intervals contain ~30-40% angular to subrounded, granule or larger clasts within a sandy matrix. Sandstone lithologies are very dark greenish grey, and fine- to medium-grained, with or without dispersed clasts. Siltstone comprises very dark greenish grey to very dark grey, calcareous siltstone and volcanic-bearing siltstone, that both locally contain thin, fine-grained sandstone laminae. Bioturbation is locally present in siltstone intervals. Olive-grey, biosiliceous-rich sandy mudstone occurs interbedded with clast-poor muddy diamictite. Claystone is rare, and consists of very dark greenish-grey, bioturbated claystone interlaminated with siltstone and fine-grained sandstone. Many intervals of these finer grained lithologies are pervasively disturbed by soft-sediment deformation and microfaulting. Clastic intrusions filled by medium-grained sandstone occur in siltstone, fine-grained sandstone, and sandy siltstone.

The boundary between LSU 6 and the underlying LSU 7 is taken at a gradational contact between clast-poor, sandy diamictite and underlying muddy very fine-grained sandstone with dispersed clasts at 339.92 mbsf.

Lithostratigraphic Unit 7

Volcanic-bearing diamictite and volcanic-bearing sandstone; 339.92-436.18 mbsf; 96.26 metres thick

LSU 7 is characterised by more abundant sandstone beds relative to diamictite, more volcanic debris, more macrofossils (locally), and stratified, clast-poor diamictite.

The dominant lithology remains diamictite, but is of different character from those in LSU 6. Typically the diamictite is volcanic-bearing and stratified, sand-rich to less commonly muddy, and locally contains an abundance of macrofossil remains (serpulid worm, coral fragments, bivalves, and internal casts of gastropods). The diamictite is dark grey to very dark greenish grey in colour and clast-poor to clast-rich, with angular to subrounded clasts up to 13 cm diameter making up ~1-20% of the lithology. Below 431 mbsf, the diamictite contains 10-15% biosiliceous material (from smear slides). Clasts are polymictic but generally do not include mudstone or diamictite intraclasts. Stratification is caused by variations in matrix grain size, variations in clast abundance, and by wispy mud laminae. In addition, some of the lamination is from sedimentary injection features. In some intervals, the diamictite is stratified locally by the presence of siltstone laminae or thin beds. Soft-sediment deformation, "boxwork" fractures, and high-angle cemented fractures are common. Smear slides commonly contain 10-20% volcanic material, and in places, >10% carbonate.

Volcanic-bearing sandstone is more abundant in this LSU than higher in the core. Sandstone intervals are dark grey, very dark grey, and dark greenish grey in colour, very fine- to coarse-grained, and some contain dispersed to common clasts. Many beds display normal grading, and planar and ripple cross-lamination is present in some sandstones. Fossils (bivalves, gastropods, and serpulid tubes) are locally abundant, and may also be associated with bioturbation. Smear slides indicate between 10-20% volcanic material. Sandstone lithologies are interbedded with very dark grey to dark greenish grey sandy conglomerate with clasts up to 1 cm in diameter. Less common is very dark greenish grey, sandy mudstone with dispersed clasts. Clasts in these beds are up to 3 cm in diameter and are weakly stratified.

The boundary between LSU 7 and the underlying LSU 8.1 is taken at an erosional and soft-sediment-deformed contact between sandy pebble conglomerate and underlying, interlaminated siltstone and fine-grained sandstone at 436.18 mbsf.

Lithostratigraphic Unit 8

LSU 8 (436.18 to 607.35 mbsf) comprises a heterogeneous assemblage of diamictite and other terrigenous clastic lithologies, with variations in the proportions of those lithologies allowing the definition of four sub-units.

Lithostratigraphic Unit 8.1

Volcanic-bearing mudstone with/without dispersed clasts, sandstone and diamictite; 436.18-502.69 mbsf; 65.51 metres thick

LSU 8.1 marks a change to finer-grained lithology dominated by mudstone and very fine to fine-grained sandstone, together with less abundant diamictite. All beds are volcanic-bearing, with varying amounts of authigenic pyrite, either grain replacements or as elongate nodules. Pyrite appears intermittently below 449 mbsf.

Fine-grained material comprises: very dark greenish-grey, sandy or non-sand-bearing mudstone with dispersed to abundant clasts (up to 10%). The matrix is coarse to fine-grained siltstone, the polymict clasts being angular to well-rounded and ranging up to 5 cm in diameter. Clasts (locally in clusters) are polymictic and include pumice clasts. Stratification is present in the form of sandstone laminae, locally disturbed by soft-sediment deformation and microfaulting. Serpulid tubes, shell fragments, moulds of fossils, and possible bioturbation are present. Some high-angle fractures are filled with small pyrite nodules. Smear slides indicate 5-10% volcanic material in the mudstone and ~35% in the sandstone interbeds. The mudstone is interbedded with volcanic-bearing to volcanic-rich sandstone with common clasts. Boundaries between the sandstones and the mudstones are irregular and inclined, and appear to be deformed and/or caused by loading.

Very dark grey to very dark greenish-grey (a) biosiliceous-bearing sandy mudstone with dispersed clasts, and (b) biosiliceous-rich siltstone and very fine-grained sandstone. The matrix is siltstone, with sand dispersed throughout. Polymictic clasts up to 1 cm diameter occur throughout the biosiliceous-bearing sandy mudstone, but are absent from the biosiliceous-rich siltstone and sandstone. Faint mm-scale lamination occurs throughout and contains dark brown to black coloured layers (?pyrite). Laminae are typically disturbed by soft sediment deformation. Smear slides contain ~10% biogenic silica in lithology (a) and up to 25% in lithology (b). Millimetre-wide high-angle fractures filled with light-coloured material are common.

Very dark grey, massive clayey siltstone with dispersed sand grains or rare dispersed granules is a rare lithology.

Very dark grey to very dark greenish grey volcanic-rich sandstones form a subordinate lithology to the fine-grained units. They comprise (a) muddy, very fine to fine-grained sandstone with dispersed clasts, (b) volcanic-rich medium-grained sandstone with dispersed clasts, (c) very fine to medium-grained sandstone with common to abundant clasts, and (d) fine-grained sandstone lacking clasts with planar stratification and possible inclined stratification. Subangular to subrounded clasts are polymictic and up to 23 cm in diameter. Beds often display faint mm-scale lamination, planar stratification, and planar cross-bedding, with grading over the thickness of individual beds. Deformation in the form of loading, folding, and fracturing of the sandstone beds is common. Smear slides contain 5-50% volcanic material. Shell fragments are dispersed throughout.

Diamictite is typically interbedded with sandstone and mudstone. It forms a smaller proportion of the LSU than higher in the core. Diamictite forms <1 m-thick beds of very dark grey to very dark greenish grey, clast-poor (up to 2.5 % clasts), and less commonly clast-rich (5-10% clasts) sandy diamictite. Angular to subrounded polymict clasts are common, up to 42 cm in diameter, and locally occur in clusters. Some intervals are crudely planar stratified, and may include 1-17 cm-thick sandstone beds. Shell fragments, particularly serpulid tubes and locally foraminifera, are present. "Boxwork" fractures are developed locally.

One bed of very dark grey planar stratified, muddy, soft-sediment-deformed conglomerate occurs between 495.43 and 495.63 mbsf. Smear slides indicate >10% carbonate in places in this LSU.

The boundary between LSU 8.1 and the underlying LSU 8.2 is taken at a gradational contact between sandy mudstone with dispersed clasts and underlying clast-poor, sandy diamictite at 502.69 mbsf.

Lithostratigraphic Unit 8.2

Volcanic-bearing diamictite, mudstone with/without dispersed clasts, and sandstone; 502.69-544.47 mbsf; 41.78 metres thick

LSU 8.2 is similar to LSU 8.1, but is more diamictite-rich, contains less finer-grained lithologies, and also lacks any biosiliceous fine-grained sediments. Lithologies other than diamictite are as for LSU 8.1.

Diamictite intervals are clast-poor sandy variants with wispy lamination, with clasts up to 6 cm in diameter, making up to 5% of the rock. Microfaults and boxwork fractures are common. Coaly plant material occurs locally within the diamictite and sandstone. Smear slides indicate 5-20% volcanic material in most lithologies. Biosiliceous material forms a minor component in some smear slides.

The boundary between LSU 8.2 and underlying LSU 8.3 is taken at an abrupt contact between volcanic-rich, clast-poor, muddy diamictite and underlying volcanic-bearing sandy mudstone with dispersed clasts at 544.47 mbsf.

Lithostratigraphic Unit 8.3

Volcanic-bearing sandstone, conglomerate, mudstone with dispersed clasts, and diamictite; 544.47-579.33 mbsf; 34.86 metres thick

LSU 8.3 differs from the overlying LSU 8.2 in containing more abundant conglomerate, and being darker in colour presumably due to pyrite cement. In other respects it contains similar lithologies to the other LSU 8 units, so again the description is not repeated here, but rather exceptions noted.

Sandstone comprises the dominant lithology in this LSU. They are fine-grained with or without dispersed clasts, and many occur interbedded with mudstone. Sandy conglomerate is more common in this LSU than in the other subunits of LSU 8, where it is typically interstratified with medium to coarse-grained sandstone. Clasts make up to 60% of the conglomerate, and are angular to rounded, polymictic, granule to cobble-sized (up to 10 cm in diameter). Rare coal fragments occur within the conglomerate, and shell fragments especially serpulids are common, being scattered throughout the conglomerate lithologies. In rare cases, the conglomerate contains dm-thick greenish grey to dark greenish grey clayey siltstone. Diamictite intervals are clast-poor with clast abundances up to 2.5 % dominated by angular to subrounded clasts up to 11 cm in diameter. Shell fragments, especially serpulid tubes, are common in the diamictite.

Smear slides indicate the LSU generally contains 5-40% volcanic material, particularly in the lower half, and pumice clasts are common.

The boundary between LSU 8.3 and the underlying LSU 8.4 is taken at an abrupt contact between volcanic-bearing sandy mudstone with dispersed clasts and underlying volcanic-bearing, clast-poor, sandy diamictite at 579.33 mbsf.

Lithostratigraphic Unit 8.4

Volcanic-bearing diamictite, siltstone, sandstone, and conglomerate; 579.33-607.35 mbsf; 28.02 metres thick

LSU 8.4 is similar to LSU 8.2, being dominated by diamictite. Two intervals of finer-grained sandstone and siltstone are the only lithological variants. The diamictite beds are clast-poor and sand-rich, greenish-black in colour, with a clast content decreasing from 5 to 2.5% below 580.06 mbsf. Clasts are polymictic, angular to subrounded, and up to 9 cm in diameter. Foraminifer fragments and a varied fossil assemblage of bryozoan, coral, and shell fragments occur throughout. One interval of dark grey sandstone with dispersed to abundant clasts interbedded with conglomerate, occurs between 580.97 and 581.9 mbsf. Greenish black volcanic-bearing siltstone interlaminated with very fine-grained sandstone occurs in a few cm- to dm-thick beds below 583.5 mbsf, and again between 595.45 and 596.86 mbsf. A less common lithology is a dark greenish grey to greenish black, volcanic-bearing, carbonate-bearing, biosiliceous-bearing sandy siltstone with dispersed clasts, and abundant serpulid tubes.

Smear slides indicate between 10-25% volcanic material throughout LSU 8.4, and up to 25% carbonate in some of the siltstone intervals. Pumice clasts are common throughout and many are replaced by pyrite.

The boundary between LSU 8.4 and the underlying LSU 9 is taken at an abrupt contact between volcanic-bearing, clast-poor, sandy diamictite and underlying volcanic-bearing fine-grained sandstone with common clasts at 607.35 mbsf.

Lithostratigraphic Unit 9

Volcanic-bearing sandstone, siltstone, and minor diamictite; 607.35-648.74 mbsf; 41.39 metres thick

LSU 9 marks a distinct change in lithology to richly fossiliferous sandstone and siltstone. Diamictite is less abundant and appears only below 635 mbsf.

Sandstone lithologies comprise very dark grey to greenish black, volcanic-bearing muddy fine to coarse-grained sandstone with dispersed to common polymictic clasts. The coarsest-grained material is angular to rounded clasts, up to 15 cm in diameter, often present in clusters. Small pumice clasts are commonly distributed throughout. In some intervals the lithology is biosiliceous-bearing. Shell fragments including bryozoans, foraminifera, and articulated bivalves are common, but the macrofauna is dominated by serpulid tubes. They occur throughout the lithology and throughout the LSU. Bioturbation is locally present in the upper portion of the LSU, but becomes more common below 632.5 mbsf with a bioturbation index (BI) between 3 and 4. Ichnogenera include *Asterosoma*, *Planolites*, *Teichichnus*, *Ophiomorpha*, and possible *Rhizocorallium*. Smear slides contain up to 25% carbonate.

Finer-grained lithologies include volcanic-bearing clayey siltstone, and more abundant, volcanic-bearing muddy sandstone with dispersed clasts, to volcanic-bearing sandy mudstone with dispersed clasts. These lithologies are very dark grey to very dark greenish grey. The clayey siltstone is laminated at a mm-scale and possibly bioturbated with soft-sediment deformation throughout. The more commonly occurring muddy sandstone to sandy mudstone with dispersed clasts often grades from one lithology to the other. Clasts are predominantly angular to subrounded granules, and range up to 4 cm in diameter. Volcanic clasts are common, with concentrations of volcanic sand, many with loaded bases. Fossil debris is abundant – primarily serpulid, foraminifera, bivalve, and bryozoan fragments - though some intervals are less fossiliferous than others. Bioturbation is moderately common in some of these finer-grained intervals, and includes *Asterosoma* and *Planolites*, and possible *Rhizocorallium Chondrites*. Smear slides indicate >10% carbonate.

Minor lithologies include very dark grey, intercalated siltstone with dispersed clasts, and volcanic-bearing clast-poor diamictite. This unit is stratified at mm- to cm-scales and may possibly be bioturbated. Numerous diamictite intraclasts are present as dropstones or thin interbedded diamictite. Synsedimentary microfaults are common.

Very dark greenish grey, clast-poor sandy diamictite occurs below 635 mbsf, in some cases interbedded with sandstones and mudstones. Clasts are up to 11 cm in diameter, and comprise phonolite, granite, and intraformational mudstone and diamictite clasts.

Two cm-thick intervals of volcanic sand or volcanic clasts (?tephra) occur at 636.18, 636.26, and 636.4 mbsf, and again between 640.04 and 640.15 mbsf.

The boundary between LSU 9 and the underlying LSU 10 is taken at an abrupt, erosional contact between volcanic-bearing coarse-grained sandstone with common to abundant clasts and underlying volcanic-bearing, clast-poor, muddy diamictite at 648.74 mbsf.

Lithostratigraphic Unit 10

Volcanic-bearing diamictite, sandstone, and mudstone, 648.74-778.34 mbsf; 129.6 metres thick

LSU 10 marks a prolonged return to diamictite-dominated lithologies with intercalated, less abundant sandstone and mudstone.

The dominant lithology is very dark greenish grey volcanic-bearing mostly clast-poor muddy diamictite. A few intervals include clast-poor to clast-rich sandy diamictite. Clasts are angular to well-rounded, up to 14 cm in diameter, and form <7.5% of the lithology. Clasts are polymict and many comprise pumice fragments. Both the clast abundance and the matrix sand content are variable, and locally the sand content approaches 90%. In general the diamictite is interbedded with laminated sandstone or mudstone, or wispy laminae, often displaying extensive soft-sediment deformation and shearing. Some fractures are filled with pyrite or are filled with cement. "Boxwork" networks of filled fractures occur at several intervals. Irregular shaped veins are present at various intervals. Foraminifer, serpulid tubes and shell fragments occur sporadically throughout. Smear slides contain >25% carbonate, ~10% biogenic silica (in the interval 738.5 to 742 mbsf), and 10-15% volcanic material, though locally this reaches 30%. In many places, the lithology grades to muddy sandstone with dispersed clasts where the proportion of clasts drops below 1%. Bases of diamictite units are typically gradational into underlying lithologies.

Finer-grained lithologies include sandstone and mudstone. Sandstone lithologies are more common and comprise very dark greenish-grey, muddy, very fine to medium-grained sandstone with dispersed clasts, in part interbedded with muddy sandy conglomerate. Stratification, where present in the sandstone, occurs as mm- to cm-scale planar and inclined bedding, trough cross-lamination, or ripple cross-lamination. Small load casts are present on the base of some sandstone laminae. Possible bioturbation occurs particularly in the lower portion of the LSU, but is somewhat enigmatic (BI = 1-2). Many sandstone beds are disturbed by soft-sediment deformation. Smear slides indicate ~10% carbonate in the upper part, but >30% carbonate below 730.5 mbsf, and up to 30% volcanic glass.

Where not interbedded, conglomerate also occurs as discrete beds. In these cases, the lithology comprises intraformational granule to small pebble clast conglomerate, and is coloured very dark greenish grey. Clasts include rounded mudstone and polymictic clasts up to 1.5 cm in diameter. Serpulid fossils are rare in the sandstone, and the interval 753.55 to 753.96 mbsf is biosiliceous-bearing. Possible coaly fragments occur at 702.6, 702.77, and 727.70 mbsf. Pyrite nodules occur from 776 mbsf, along with the colour change to black, a few metres below this at the base of the LSU.

Sandstone also occurs associated with siltstone beds, and most grade upward into siltstone, though inverse grading also occurs. In this interval, the sandstone comprises greenish black fine-grained sandstone with coarse sand grade clasts of diamictite and/or pumice; the siltstone also greenish black in colour, displays mm-scale laminations, ripple cross-lamination, and soft-sediment deformation. A pumice clast-rich zone occurs between 708.9 and 709.3 mbsf in a ripple cross-laminated sandstone interval.

Mudstones comprise three dominant lithologies:

(a) Serpulid and shell-bearing, very dark greenish grey sandy mudstone with dispersed angular to rounded clasts up to 1 cm in diameter. These are planar laminated at cm-scale by interbedding with fine-grained sandstone, massive sandstone, and siltstone. Soft-sediment deformation is common.

(b) Very dark grey, fine to coarse-grained siltstone, bedded at a mm-scale and locally microloaded at the base of the coarse-grained siltstone units. They form inversely graded beds up to 6 cm thick.

(c) Very dark greenish grey, sandy, crudely-stratified mudstone (siltstone) with dispersed clasts (up to 4 mm in diameter). These are extensively modified by soft-sediment deformation and boudinage (folding and faulting).

One very dark greenish-grey breccia bed from 721.87 to 722.10 mbsf comprises angular to rounded clasts up to 4 cm in diameter. The bed is associated with sandstone and likely represents a slightly more angular variant of the conglomerate described above.

The boundary between LSU 10 and the underlying LSU 11 is taken at a gradational contact between clast-poor, sandy diamictite and the underlying sandy siltstone with dispersed clasts at 778.34 mbsf.

Lithostratigraphic Unit 11

Sandy siltstone with dispersed clasts, and sandstone with/without dispersed clasts 778.34-904.66 mbsf; 126.32 metres thick

LSU 11 is distinguished by an abundance of siltstone and sandstone, with very little diamictite.

The dominant lithology is black to greenish-grey sandy siltstone with dispersed angular to subangular polymictic clasts up to 6 cm in diameter. These clasts make up 1% of the lithology, and often occur in clusters. Pumice clasts and grains occur throughout the LSU, and occasionally form centimetre-thick inversely graded pumice layers. Some clasts have deformed laminae below them and are assumed to be dropstones. Thin, sharp-based, very fine-grained sandstone laminae and sandstone stringers are intercalated with the siltstone. Below 868.6 mbsf, the siltstone is intermittently interstratified with clayey siltstone and sandy siltstone. Soft-sediment deformation is common throughout, especially where interstratified by some of these other lithologies. High-angle cemented fractures and extensive microfaulting are common.

Fossils, especially serpulid tubes, are common along with shell fragments (?pectens, pyritised bryozoa, ?fish vertebrae, and large foraminifera). Mottling is locally present and is interpreted to be due to bioturbation (BI <2-3). *Palaeophycus* was identified in several intervals. Possible *plant* fragments were recognised at 826.89 mbsf. Pyritised nodules and clasts are common. Smear slides contain 10-25% carbonate, increasing to ~40% locally, though there is little in the upper third of the unit. There is locally as much as 5% biogenic silica.

Intermittently, the sandy siltstone is interbedded with black clayey siltstone with dispersed clasts up to 1 cm in diameter. Beds of clayey siltstone are generally internally stratified, with well-developed laminae present in some intervals. *Chondrites* burrows occur throughout the clayey siltstone. Smear slides contain 30% carbonate.

A less abundant lithology is sandstone, which occurs as: black to very dark grey, muddy (silty) medium to coarse-grained sandstone with dispersed angular to subrounded polymictic clasts up to 10 cm, in some cases in clusters. In some intervals these sandstones are interstratified with siltstone. Pumice clasts occur throughout this sandstone facies in the LSU. Laminae or thin beds of medium to coarse-grained sandstone and gravel are common. Changing inclinations of laminations in some intervals are taken to represent cross-bedding or local post-depositional tilting of strata. Coal and/or laminated carbonaceous mudstone dominate the clast assemblage. Vertical stringers of coarse-grained sandstone and gravel are interpreted as clastic dykes. Soft-sediment deformation features are common. Pyritised serpulid tube fragments are abundant in 10-15 cm-thick intervals, or scattered through the lithology, especially below ~845.7 mbsf. Shell fragments are locally abundant and in addition to the serpulids, include bivalves (?scallops), and rare large foraminifera. Bioturbation occurs in this facies throughout the LSU, the ichnogenera recognised including *Chondrites* and possible *Palaeophycus*. Smear slides contain ~20% carbonate.

Massive to ripple- and plane-laminated (possibly hummocky cross-stratified), black silty very fine to fine-grained sandstone lacking clasts.

An interval of very dark grey volcanic silty sandstone with dispersed clasts.

Other rare lithologies include:

(a) Black sandy conglomerate with angular to rounded polymictic clasts, the coarser clasts (<6 cm in diameter) making up to 30-40% of the lithology.

(b) Black, clast-rich sandy diamictite composed of angular to subrounded clasts up to 2.5 cm in diameter, and constituting up to 10% of the lithology.

The boundary between LSU 11 and the underlying LSU 12 is taken at an abrupt contact between muddy sandstone with dispersed clasts and the underlying clast-rich, sandy diamictite at 904.66 mbsf.

Lithostratigraphic Unit 12

Clast-rich and clast-poor diamictite, muddy sandstone with dispersed clasts, and minor mudstone with dispersed clasts; 904.66-996.69 mbsf; 92.03 metres thick

LSU 12 is dominated by diamictite with subordinate sandstone, and minor mudstone. Diamictite, the dominant lithology in this LSU, includes both clast-rich and clast-poor varieties. Both are very dark grey in colour, with clast abundance in the clast-rich variants between 5 - 7.5%, with angular to well-rounded polymictitic clasts up to 4 cm diameter. The clast-poor variants contain 1 to 5%, angular to subrounded polymictic clasts up to 15 cm in diameter, including bluish-green mudstones as clasts, similar to those described in the sandstones below. Clast-poor diamictite in places grades upward into clast-rich diamictite. Crude stratification at cm- to dm-scale is evident in both styles of diamictite, produced from the alignment of elongate clasts, silt-rich laminae, matrix grain-size variations, or alignment of shell fragments. Serpulids are particularly common in some intervals. In some intervals, bioturbation may be present. Possible shear fabrics and "boxwork" fabrics occur in the mid-portion of diamictite intervals or toward the middle and base. Smear slides indicate ~15-20% carbonate in places and, rarely, up to ~10% biosiliceous material. Patchy pyrite cement occurs within the diamictite from the top of the LSU at 911.33 mbsf.

Most of the sandstone beds are very dark grey in colour, muddy (silty) sandstone with angular to well-rounded dispersed clasts. The latter are up to 7 cm in diameter and are polymict in composition. In some instances, these clasts occur in clusters. In two occurrences the sandstone includes blue-green mudstone clasts at its base. Volcanic clasts are locally common. Sandstone ranges from fine- to coarse-grained. Stratification occurs at mm- and cm-scales. The mm-scale stratification appears to be produced from interlaminated coarse-grained and fine-grained sandstone, the cm-scale lamination by interbedded fine-grained sandstone, often with soft-sediment deformation features. Fractures are also common in the sandstone, filled with both carbonate and unidentified cement phases. Bioturbation (BI = 3-4) is present and shells, especially serpulids, are common. Pyrite cement within the sandstone appears in patches from 954.09 mbsf and within burrow fills.

Many sandstone intervals are interbedded with very dark grey sandstone with abundant (<20%) angular to well-rounded clasts <2.5 cm in diameter. Their composition, like the sandstone with dispersed clasts, is polymictic. In some intervals, the sandstone with abundant clasts includes sandy conglomerate. Shell fragments, especially serpulids, are common.

Fine-grained rocks are less common than diamictite and sandstone. They are very dark grey sandy mudstone (siltstone) with dispersed clasts forming beds up to ~2 to 40 cm-thick. Clasts are angular to subangular, polymictic, and up to 7 cm in diameter. The lithology is typically interbedded with ~10 to >100 cm-thick beds of sandstone with dispersed clasts or cm-scale stratification. Millimetre-scale laminae of siltstone and muddy sandstone are present in the lithology below 940 mbsf. Serpulid tubes occur within some intervals, as well as bioturbation (BI = 2-3). Soft-sediment deformation is common. Smear slides contain as much as 5% biosiliceous material.

The boundary between LSU 12 and the underlying LSU 13 is taken at a gradational contact between clast-poor, sandy diamictite and underlying interlaminated sandy siltstone and muddy, fine-grained sandstone at 996.69 mbsf.

Lithostratigraphic Unit 13

(NQ Core from 1011.87 mbsf)

Fine siltstone, coarse siltstone, and very fine-grained sandstone, with very fine to fine-grained sandstone with dispersed clasts, and rare diamictite; 996.69-1040.28 mbsf; 43.59 metres thick

LSU 13 is dominated by interlaminated siltstone and sandstone, with less abundant sandstone and siltstone beds, and is largely devoid of diamictite.

Most of the LSU comprises a heterolithic interlaminated black, fine and coarse siltstone to sandy mudstone, and muddy to very fine-grained sandstone. These lithologies are interlaminated at a mm- and cm-scale, the sandstone being less abundant than the siltstone overall. Dispersed clasts are locally present in all of these lithologies. Mudstone includes angular clasts up to 4 mm in diameter, but are generally rare. The mudstone is bioturbated (BI = 2-3) including identifiable *Teichichnus* and ?*Rhizocorallium* burrows.

The sandstone component of these heterolithic lithologies is light grey to black, muddy, and very fine to fine-grained. Clasts are angular to subrounded, up to 8 cm in diameter, and some occur in clusters. They include angular diamictite clasts up to 1 cm in diameter. Sandstone intervals are planar laminated, and ripple cross-laminated with mud drapes. Pinstripe lamination is prevalent in the most thinly-laminated intervals. Intervals of soft-sediment deformation and microfaulting are common throughout. Millimetre-scale clastic intrusions and soft-sediment deformation are common especially below 1018.54 mbsf. In some intervals, these heterolithic interbeds have been physically intermixed by intensive soft-sediment deformation. Synaeresis cracks are common in some intervals. Sandstone intervals are bioturbated (BI = 2-3), and include serpulid tubes concentrated into clusters. Shell fragments and an articulated bivalve shell occur in this fine-grained sandstone. Nodular pyrite cement is common in certain intervals. Smear slides typically contain ~5 to 30% carbonate.

The other main lithology is cm- to metre-thick sandstone beds, which tend to be less abundant in the lower part of the LSU. These sandstones are very fine to fine-grained, contain dispersed clasts, and are light grey, grey, to black in colour. Dispersed clasts are generally rare, are angular to subrounded in shape, and up to 4 cm in diameter. Clasts are generally polymictic and include intraformational mud clasts and some angular diamictite clasts. Ripple cross-lamination in 1 cm-thick sets is locally common, and some include mud drapes. Possible bidirectional ripples occur locally, and black grains, possibly volcanic, are present on some ripple foresets. Bioturbation is common throughout (BI = 4-5), and includes possible *Planolites*. Locally, serpulid tubes and synaeresis cracks are present. Pyrite cement occurs throughout as <2 mm sized micronodules or in cemented zones. In addition, tan-coloured, noncalcareous cement horizons and micronodules occur below 1008.84 mbsf, and are common below 1014.47 mbsf. Smear slides locally contain ~5 to ~30% carbonate.

A less abundant lithology is grey to dark grey, sandy mudstone (siltstone) with dispersed clasts. Clasts are angular to subangular and up to 3 cm in diameter. They are typically present in clusters, and are mostly associated with an increased sand content. Crude stratification is present in some beds. Bioturbation (BI = 3-4) includes distinct *Palaeophycus*, *Teichichnus*, and *Chondrites*, as well as unidentified burrows. Shell fragments are present. Rare, pumice-bearing clayey siltstone with dispersed clasts is present, as 3-5 mm-thick laminae of diamictite interlaminated with 1-2 mm-thick clayey siltstone laminae. The dispersed clasts are up to 5 mm in diameter, many with dropstone features.

Two beds of cm- to dm-thick black clast-rich sandy diamictite occur, the clasts are predominantly granule-grade, with intraformational clasts becoming more common below 1008.90 mbsf.

The boundary between LSU 13 and the underlying LSU 14 is taken at a gradational contact between sandy mudstone with dispersed clasts and the underlying clast-rich, sandy diamictite at 1040.28 mbsf.

Lithostratigraphic Unit 14

Sandy diamictite and sandstone with dispersed clasts; 1040.28-1138.54 mbsf; 98.26 metres thick

LSU 14 is dominated by diamictite, with <1 m-thick sandstone intervals developed near the top of the unit.

The dominant lithology is black, clast-poor sandy diamictite, and in the lower 6 m of the core, includes clast-poor muddy diamictite. Clasts comprise between 1 and 5% of the lithology, and consist of angular to subrounded clasts up to 14 cm in diameter. Compositionally polymictic clasts are dominant, but intraclasts of volcaniclastic sandstone are dispersed below 1051.25 mbsf. Wispy lamination, interbeds of siltstone with dispersed clasts, ~1 cm-thick siltstone to very fine-grained sandstone, and cm-thick interbedded diamictite and siltstone occur at several intervals, locally soft-sediment-deformed and/or possibly bioturbated. Siltstone becomes more common below 1115 mbsf either as interbeds or mixed with the diamictite. Serpulid tubes and shell fragments occur at several intervals. Veins are common and filled with white calcite and non-calcareous cement. "Boxwork" fractures, low-angle fractures cemented with brown-coloured cement (possibly pyrite), and high-angle fractures filled with calcite occur in some of the diamictite. Smear slides indicate between 10 and 30% carbonate is present.

Intercalated with the diamictite, particularly in the upper portion of the LSU is cm- to m-thick, black, fine to medium-grained sandstone with dispersed clasts, and silty fine-grained sandstone with dispersed to common clasts. The dispersed to common clasts are angular to subangular and up to 10 cm in diameter. Flattened pumice clasts occur in the interval between 1092.75 and 1095.11 mbsf, and are mostly concentrated in cm-thick zones. The sandstone locally contains convolute bedding or planar stratification. Foraminifera and other fossils, such as an articulated bivalve/brachiopod shells and serpulid tubes, occur sporadically throughout. In rare cases, black pebble conglomerate may occur in association with the sandstone lithologies. In these conglomerate intervals, clasts comprise 40-50% of the lithology, and are dominated by angular to well-rounded polymictic clasts up to 5 cm diameter. Smear slides typically contain ~5% carbonate, locally reaching over 10%.

The lower portion of the LSU (below 1125 mbsf) contains dm-thick intervals of black interstratified clayey siltstone, coarse siltstone, and fine-grained sandstone, interlaminated with mm-scale pinstripe lamination. In addition, interlaminated clayey siltstone and diamictite also occurs below this depth, microfaulted throughout, and in part soft-sediment-deformed.

FACIES ANALYSIS

Thirteen lithofacies are identified on the basis of grain-size distribution, bedding relationships, contained sedimentary structures, fossil content and other characteristics. Where possible, facies are labeled using assigned descriptive names, or an association of different lithologies. Terminology refers to lithified forms (suffix "-stone" or "-ite", although some facies in the upper parts of the core are unlithified). General facies assignments for the stratigraphic section in the AND-2A core are indicated in figure 1.

FACIES 1 - DIATOMITE, OPAL-BEARING OR CALCAREOUS FOSSIL-RICH MUDSTONE

This facies consists of siltstone composed of either: a carbonate admixture of carbonate bioclastic debris (shell fragments, serpulid tubes principally), or siliceous microdebris composed of whole or fragmented diatoms and sponge spicules, with or without a fine-grained terrigenous component. This lithofacies is often associated with bioturbated mudstones and fine sandstones, and interstratified fine-grained sediments.

Sediments composed almost entirely of biogenic silica (*i.e.*, diatomite and silt-bearing diatomite) are observed only in LSU 6 and are olive-gray, weakly stratified, and moderately bioturbated, with occasional dispersed coarse sand to granule clasts present. Siliceous biogenic sediments with a significant terrigenous component are typically laminated and often are soft-sediment deformed. Siltstones with common to abundant calcareous shell material most commonly occur in LSU 9 and are dark olive-gray to very dark greenish gray and form beds at the dm-scale that contain common to abundant fossils and fossil fragments (Fig. 2), consisting of either bivalve shell material or serpulid tubes, with rare to occasional foraminifers and bryozoans. Often the fossil material occurs in a preferred horizontal orientation. Dispersed clasts also occur.

Diatomite and silt-bearing diatomite, and mudstones with common to abundant calcareous macrofossils were deposited by pelagic to hemipelagic sedimentation from suspension settling in an open marine environment. Granule to coarse sand grains suggest that episodic periods of iceberg rafting also contributed sediment. This facies represents the most ice-distal lithology identified in the AND-2A core.

FACIES 2 - BIOTURBATED FINE SANDSTONE AND MUDSTONE WITH DISPERSED CLASTS

This facies is composed of greenish gray to very dark greenish gray, moderately to extensively bioturbated siltstone to very fine-grained sandstone and muddy fine sandstone. This facies mainly occurs in LSUs 8-11 and 13, and is rare above 450 mbsf. The most common ichnofossils identified in this facies include *Asterosoma*, *Teichichnus*, *Planolites*, *Ophiomorpha*, *Chondrites*, *Palaeophycus*, and *Rhizocorallium* (Fig. 3). Dispersed clasts occur commonly within this facies, typically <5 mm in size. Fossils are locally observed and include serpulid tubes and shell fragments, as well as siliceous microfossils. This facies can be occasionally interbedded with sandstone and diamictite and can also be locally graded or inversely graded. Deformation features also occur within this facies and include loading structures and fracturing. This facies often occurs in association with lithofacies 1, 3, and 5.

This facies was deposited from hemipelagic suspension settling. Lower sedimentation rates are suggested by the presence of significant bioturbation.

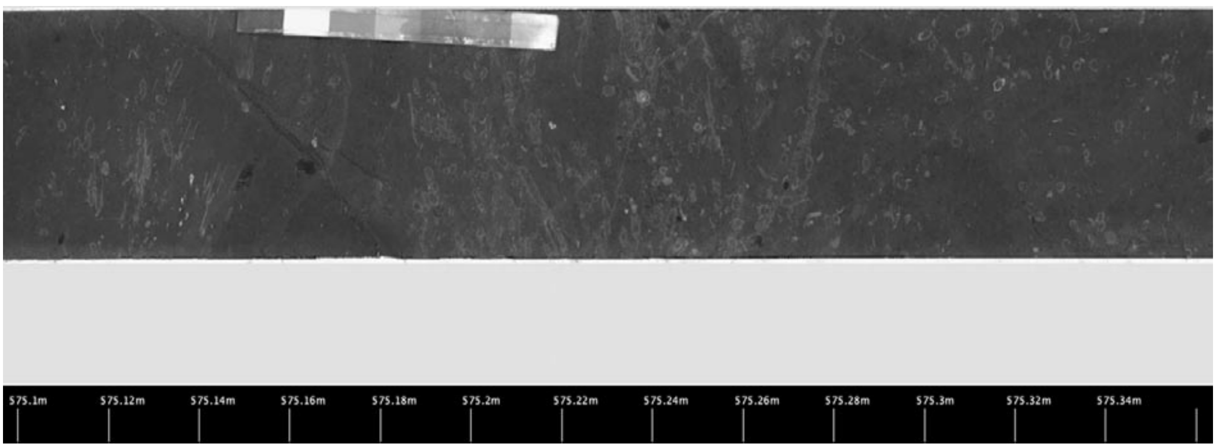

Fig. 2 – Facies 1: mudstone with common to abundant calcareous fossils, from 575.11-575.35 mbsf.

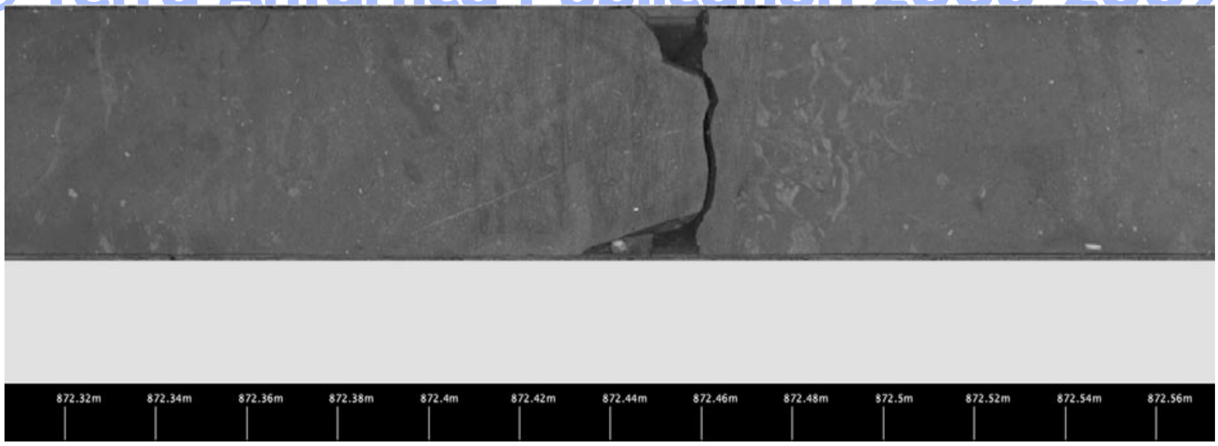

Fig. 3 – Facies 2: bioturbated sandy mudstone with dispersed clasts and bioturbation, from 872.38 to 872.50 mbsf.

The presence of generally small dispersed clasts indicates rainout from an ice shelf, icebergs or perhaps from debris windblown onto sea-ice. The fine-grained nature of the sediment and the presence of benthic organisms suggest an environment distal from direct glacial influence.

FACIES 3 - INTERSTRATIFIED FINE SANDSTONE AND MUDSTONE

This facies is composed of interlaminated to interbedded fine sandstone and siltstone. Colour varies in this facies down-core from mainly very dark gray to very dark greenish gray for the uppermost 900 meters to very dark gray to black within LSU 12 and 14 (904.66 – 996.69 mbsf, and 1040.28 – 1138.54 mbsf, respectively), and light to dark gray in LSU 13 (1040-1139 mbsf). This facies is rare above 436 mbsf and occurs in units of substantial thickness (>10 m) within LSUs 8.1, 8.3, 10, 12, and 13.

Within LSUs 8.1, 8.3, 10 and 12, interbedding of siltstone and very fine- to fine-grained sandstone, or interbeds of fine and coarse siltstone with very fine-grained sandstone occur. Medium to coarse-grained interbedded sandstone intervals are rare. Bedding typically occurs at the 1 to 2 cm-scale (Fig. 4), although locally bedding thicknesses range from 5 cm to a few decimeters. Within these beds, internal lamination structures occur locally, including planar and ripple cross-lamination. Bioturbation is common, locally obscuring the bedding structures. Fossils often occur, typically consisting of bivalve shell fragments and serpulid worm tubes. Clasts are typically dispersed, though are locally abundant, and range from coarse sand, granule, to occasionally pebble size. Soft-sediment (synsedimentary folds, small scale intrusions, and boudinage) and brittle deformation (microfaults) often occur within this facies. Basal contacts are in many cases sharp, and many are affected by soft-sediment deformation. Within LSU 13, this facies consists of sandy mudstone and muddy fine sandstone and includes interbedding at the centimeter to occasionally decimeter scale as well as interlaminated (pinstripe) intervals. Additionally, ripples with mud drapes and synaeresis cracks occur.

This facies is interpreted to have been deposited in a low energy environment based on the fine-grained nature of the sediment. In LSUs 8-12, suspension sediment settling and low energy tractional currents were the main depositional processes. Iceberg rafting contributed to the deposition of the larger clasts. In LSU 13, a tidally influenced environment is suggested by the presence of flaser bedding and mud drapes. Synaeresis cracks also suggest significant changes in salinity, typical of restricted, coastal environments.

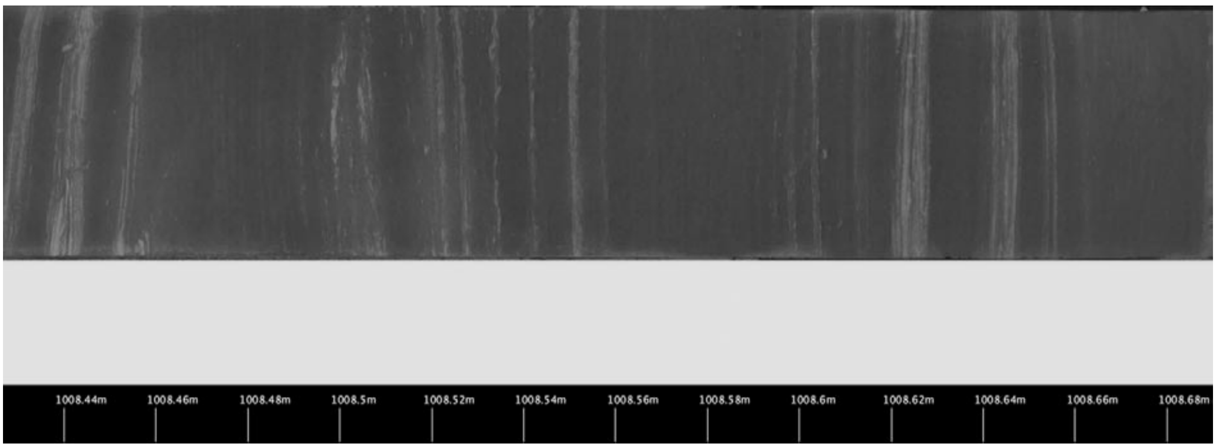

Fig. 4 – Facies 3: interstratified fine sandstone and mudstone showing rhythmic laminations from 1008.46 to 1008.66 mbsf.

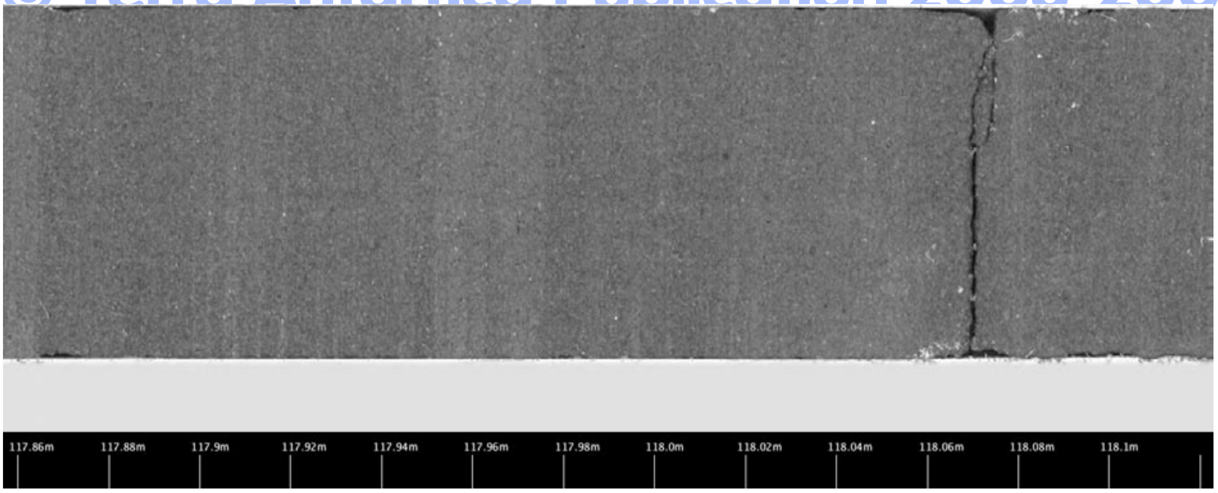

Fig. 5 – Facies 4: cross-bedded, ripple cross-laminated and planar-bedded, medium to locally coarse-grained sandstone from 117.84 to 118.13 mbsf.

FACIES 4 – CROSS-BEDDED, RIPPLE CROSS-LAMINATED, AND PLANAR-BEDDED SANDSTONE

This facies is composed of fine to medium- to locally coarse-grained sandstone that contains bedding and lamination structures, with dispersed to common clasts. The colour of the sediment is variable, ranging from olive-gray to greenish gray in LSU 3 (98.47-122.86 mbsf), to dark greenish gray to very dark gray in LSU 6-9, to locally greenish black to black from LSU 10 through 14 (296.34-778.34 mbsf). These colour differences may be ascribed to the variable volcanic content of the sediment (*e.g.*, LSU 6-8.4, 296.34-607.35 mbsf) and the presence of pyrite in the lower portion of the core (LSU 10-14, 648.74-1138.54 mbsf). Clasts are typically dispersed to rare in LSU 3, but are common to abundant in LSU 8.1 and 9 (436.18-502.69 mbsf and 607.35-648.74 mbsf, respectively), often present in discrete layers. Flat-laminated sandstones are most abundant (Fig. 5). Ripple cross-laminated and hummocky cross-stratified intervals are typically less than a meter thick, often occurring within thicker fine-grained sandstone units. Planar cross-beds and low-angle cross-stratification occur predominantly in medium to occasionally coarse sandstone. Soft-sediment deformation (loading structures) and brittle deformation (microfaulting) occur within this facies, especially near contacts. Some intervals are rich in shell fossils (Fig. 6).

This facies likely was deposited in a neritic environment, above storm-wave-base, with deposition occurring by traction sedimentation by currents and waves. The finer-grained sandstone units that contain ripple cross-lamination and hummocky cross-stratification were likely deposited within the lower shoreface, while the medium to coarse sandstone with planar lamination and thin beds were deposited in the middle to upper shoreface. Iceberg rafting processes were likely responsible for deposition of the larger clasts.

FACIES 5 - FINE MUDDY SANDSTONE OR SANDY MUDSTONE WITH DISPERSED CLASTS

This facies consists of moderately- to poorly-sorted, fine to very fine muddy sandstone or sandy mudstone with dispersed clasts (Fig. 7). This facies is predominantly massive with only locally crude stratification that is commonly soft-sediment deformed. Clast sizes are typically up to pebble grade, with a dominance of granule-sized clasts. Clast percentages are < 1% and clasts are generally present in clusters. Some beds have a dominant proportion of volcanic clasts, primarily scoria and pumice granules.

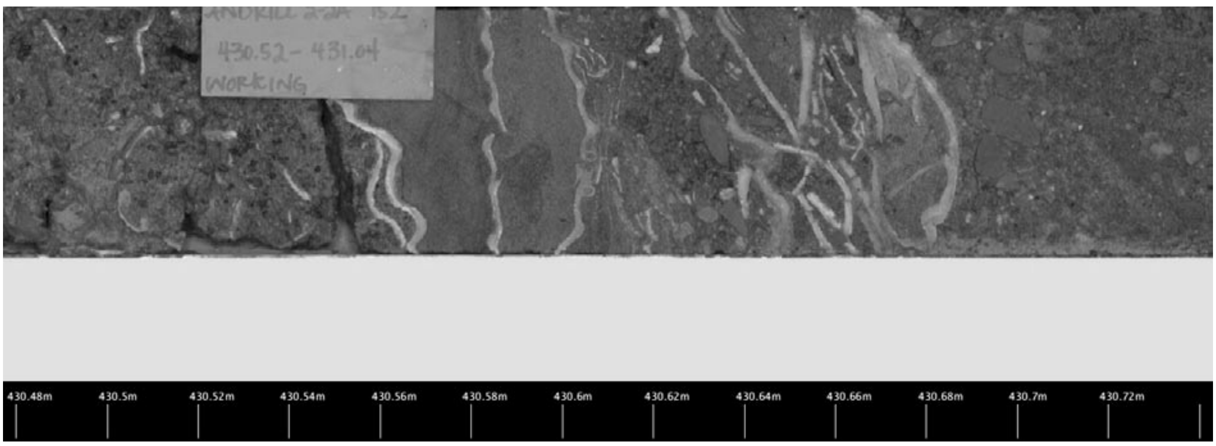

Fig. 6 – Facies 4: stratified sandstone with common calcareous fossils, particularly pectinid bivalve shells, from 430.49 to 430.73 mbsf.

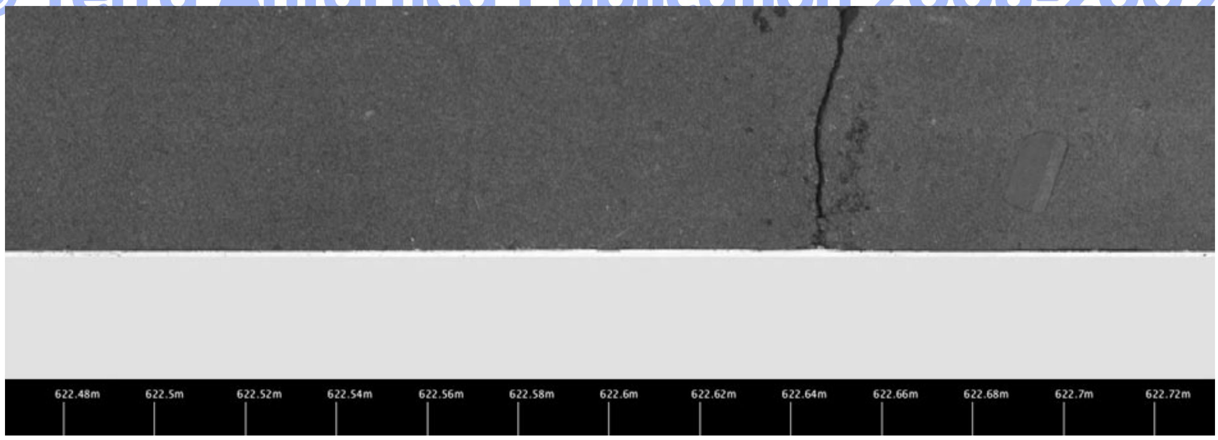

Fig. 7 – Facies 5: muddy fine sandstone with dispersed clasts with concentration of scoria granules at 622.6 mbsf.

Facies 5 can occur in association with clast-poor diamictite, which is distinguished from this facies through a higher clast content. Fossils occur dispersed throughout and include fragments of serpulid tubes, bivalve shells, bryozoa and foraminifera. An absence of biogenic silica is conspicuous. This facies is rarely bioturbated, and where it is, it is not possible to recognize individual ichnofossil taxa.

This facies represents hemipelagic sedimentation with deposition from icebergs and sea-ice in an ice-distal depositional environment, in the absence of currents. Where the clast component is composed of granules and where it is dominated by volcanic clasts, deposition is probably predominantly from sea-ice rather than from icebergs, which would carry a more polymictic clast assemblage derived from the hinterland. Laminated interbeds, which are extensively soft-sediment deformed, may indicate a periodically large terrigenous supply, either glacially or fluvially sourced.

FACIES 6 - INTERLAMINATED FINE SANDSTONE AND SILTSTONE WITH DIAMICTITE

This facies is characterized by mm- to cm-scale planar lamination, including pinstripe lamination of fine- to very fine-grained sandstone and siltstone (Fig. 8). Portions of this facies display rhythmic lamination consisting of sand-silt couplets with variations in thickness within packages of 10-20 laminae. Diamictite occurs as interbeds of up to 2 cm-thick within this facies and the proportion of diamictite generally increases downward within individual units. Locally, dm-scale normally graded sandstone to siltstone beds are associated with this facies at its base. Laminae can be soft-sediment deformed with loading, microfaulting, and flame structures, or with more extensive convolute bedding. The beds generally have dispersed clasts, and clasts are observed to depress underlying laminae with draped laminae at the top. A variable proportion of the clasts consists of diamictite clods or clasts. This facies is rarely bioturbated and the individual beds are typically <2 m-thick. This facies is present only in the lower portion of the hole, below ~500 mbsf.

This facies represents sedimentation in an ice-proximal glaciomarine environment, below wave-base or with sea-ice (fast ice) allowing possible suspension settling from meltwater plumes or small turbidity currents (underflow with minor traction). Dispersed clasts that show puncturing of underlying lamination and draping over the clast are interpreted as dropstones, *i.e.*, ice-rafted debris.

FACIES 7 - STRATIFIED DIAMICTITE

This facies represents diamictite with wispy lamination, mm- to cm-scale sand laminae or variations

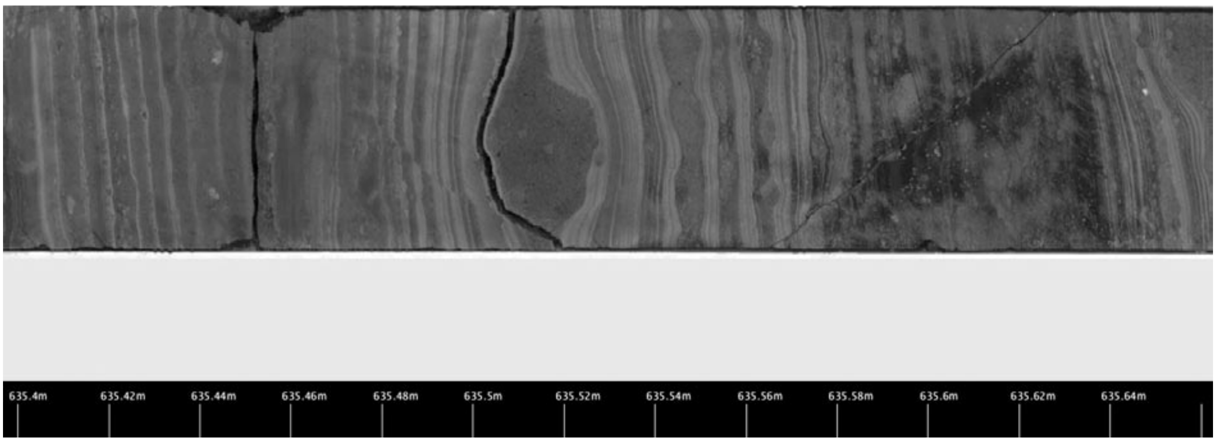

Fig. 8 – Facies 6: interlaminated fine to very fine sandstone and siltstone with common diamictite clasts or clods at 635.5 mbsf. Clasts are dropstones. Rhythmically interlaminated intervals are present, e.g., at 635.52-635.54 mbsf.

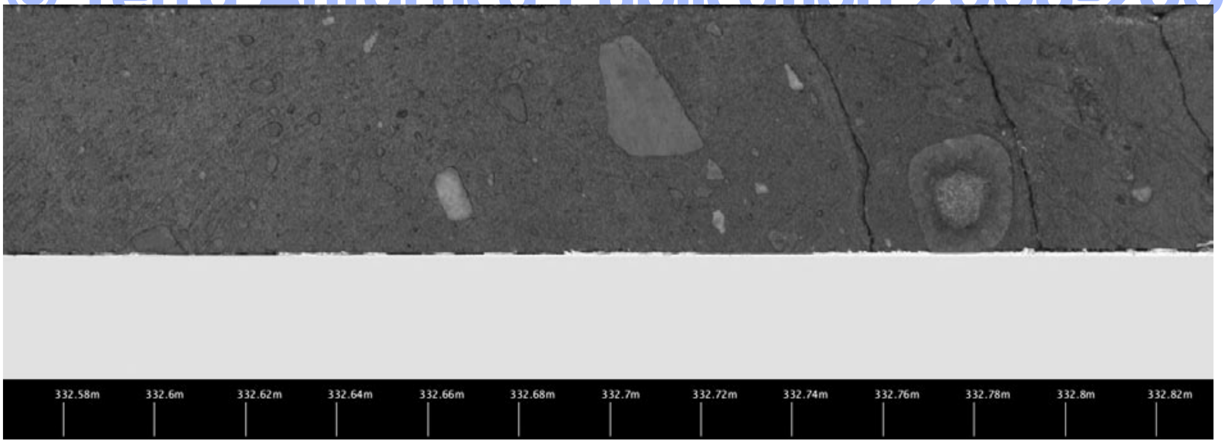

Fig. 9 – Facies 7: stratified clast-poor sandy diamictite at 332.7 mbsf. This image represents the sand-rich top of a stratified diamictite bed. The matrix of stratified diamictite beds generally coarsens upward from muddy to sandy.

in matrix grain-size on a cm-scale (Fig. 9). The stratification is often discontinuous and soft-sediment deformed. Stratified diamictite lithologies are generally clast-poor (<5% clasts) with a mud-rich or sand-rich matrix. Matrix grain-size generally increases upward from muddy (at the bottom) to sandy (at the top) within individual diamictite units. Clasts are generally of granule- and pebble-grade and often occur in clusters. Clast assemblages are either polymictic or rarely monomictic of volcanic origin. This facies locally has a significant fossil component, including siliceous microfossils, serpulid tubes, bivalve shells, bryozoa and foraminifera. It locally grades into fine muddy sandstone or sandy mudstone with dispersed clasts (<1% clasts) with diffuse and gradational boundaries. The thickness of individual units of this facies ranges up to ca. 13 meters. Stratified diamictite is the dominant diamictite facies below ~250 mbsf.

Facies 7 is interpreted to have been formed by a combination of hemipelagic sedimentation, with input from icebergs, in the presence of sluggish bottom currents. Deposition in a more ice-proximal glaciomarine environment on the most distal portion of a grounding line fan is envisaged.

FACIES 8 - MASSIVE DIAMICTITE

This facies comprises structureless to clast-stratified diamictite (Fig. 10). The diamictite lithologies are clast-rich or clast-poor and generally have a significant sand component in the matrix. Clast sizes are typically up to cobble-grade and clast composition is generally polymictic, although locally a large proportion of intraformational mudstone clasts is present. More clast-rich diamictite beds sometimes illustrate crude bedding on a dm- to m-scale through variations in clast abundance or sand percentage of the matrix, or they display an alignment of the long-axis of elongate clasts. Clast-poor massive diamictites locally have a significant fossil component, consisting of fragments of siliceous microfossils, serpulid tubes, bivalve shells and foraminifera. Some massive diamictites display pure and simple shear indicators, such as attenuated laminae, boudins, sedimentary augen (including comet structures around clasts), oriented fracture networks, conjugate fracture sets, *in situ* brecciation, or "boxwork" fracture networks with a light-colored fill. Intraclasts are common and possible clastic intrusions up to a scale of ca. 1 m-thick are present locally in this facies. Thickness of individual beds is up to 14 metres. Bed contacts are

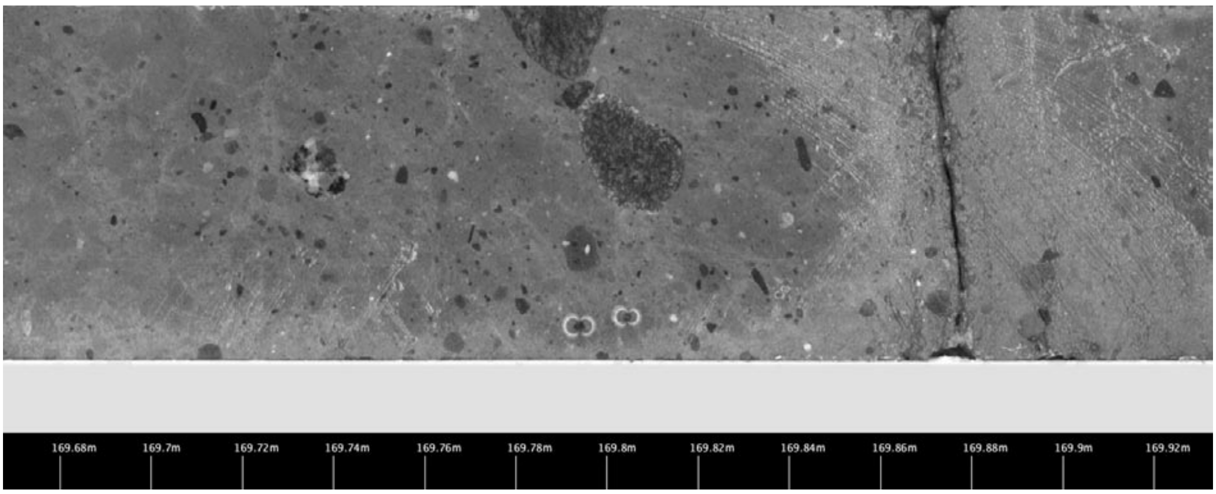

Fig. 10 – Facies 8: massive clast-rich sandy diamictite at 169.8 mbsf. This example has pervasive "boxwork" fracture networks with a light-colored fill.

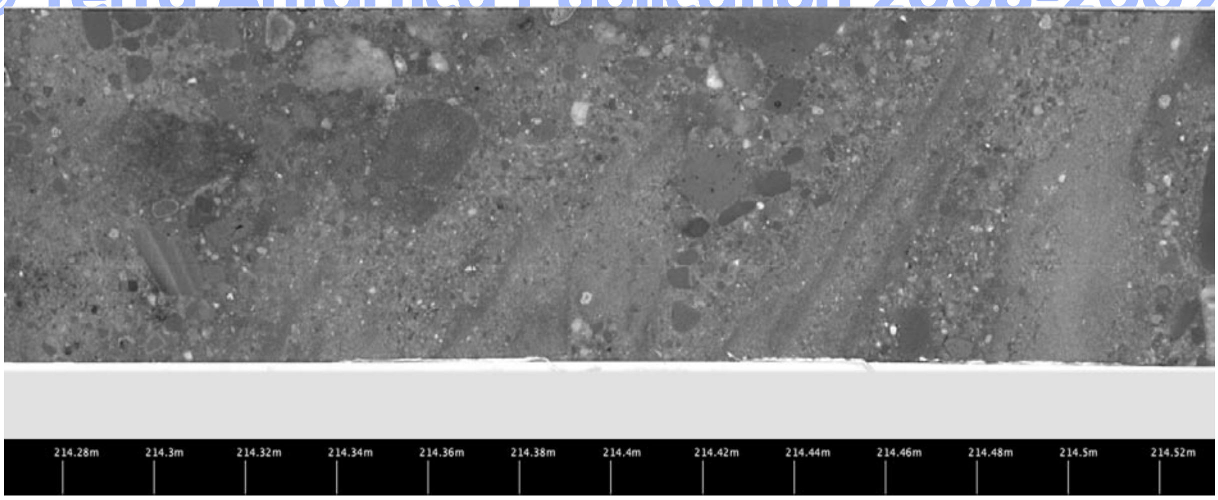

Fig. 11 – Facies 9: interbedded conglomerate and sandstone with possible planar cross-bedding at 215.4 mbsf.

generally sharp. Massive diamictite is the dominant facies in the upper 250 m of the core.

This facies is interpreted to have formed in subglacial to ice-proximal glaciomarine environments with or without remobilization of glacigenic debris. This facies may represent primary waterlaid till or remobilized till on a grounding line fan.

FACIES 9 - INTERBEDDED CONGLOMERATE AND SANDSTONE

Conglomerate lithologies are matrix-supported or clast-supported and occur generally interbedded with sandstone and occasionally with clast-rich sandy diamictite or minor siltstone lithologies (Fig. 11). Bed thickness is rarely >1 metre. Clast-supported pebble-granule conglomerate beds occur in association with coarse sandstone, and are relatively well-sorted to moderately sorted as well as clast-sorted, locally normal or reverse graded, planar bedded or cross-bedded. A relatively large proportion of clasts are rounded and clearly broken, half-round clasts are occasionally present. Intraformational mudstone clasts occur occasionally as rip-up clasts at the base of individual beds of this facies. The matrix-supported pebble-cobble conglomerate lithologies are relatively poorly-sorted with either mud, sand or mixed mud and sand matrix, and a variety of clast sizes. Bivalve shell fragments and serpulid tubes are locally present and occur in the coarsest intervals of the facies. The lower contacts of this facies are generally abrupt, inclined or loaded, except where lag deposits of clast-supported conglomerate overlie diamictite beds with sharp, planar boundaries.

Deposition in an ice-proximal environment in the presence of meltwater is envisaged for this facies. Matrix-supported conglomerate lithologies may be mass-flow deposits. Cross-bedded and planar bedded clast-supported conglomerate beds may be fluvioglacial-deltaic sediments. Where clast-supported conglomerate lithologies overlie diamictits and underlie bioturbated mudstone, they may represent transgressive lag sequences.

FACIES 10 – LAVA

This facies comprises black, moderately vesicular, porphyritic basaltic lava with phenocrysts of clinopyroxene and olivine (Fig. 12). The lava is limited to the depth interval 12.30 to 18.70 mbsf (LSU 1.2). The thickness and number of lava flows as well as contact relationships with other facies is unknown due to poor recovery (bagged samples).

The association of volcanic breccia (Facies 11) with lava in this interval suggests that they were deposited together as relatively thin autobrecciating sheet flows erupted from a proximal vent or fissure.

FACIES 11 – VOLCANICLASTIC: VOLCANIC BRECCIA

Facies 11 comprises reddish-black, monomict volcanic breccia of highly angular clasts of moderately to highly vesicular, porphyritic basaltic lava with phenocrysts of clinopyroxene and olivine (Fig. 13). The breccia is clast-supported and massive to weakly normally graded. Facies 11 is limited to LSU 1.2.

The reddish scoriaceous margins on some breccia clasts and the absence of autoclastic facies that typify magma-water interaction (*e.g.*, hyaloclastite), as well

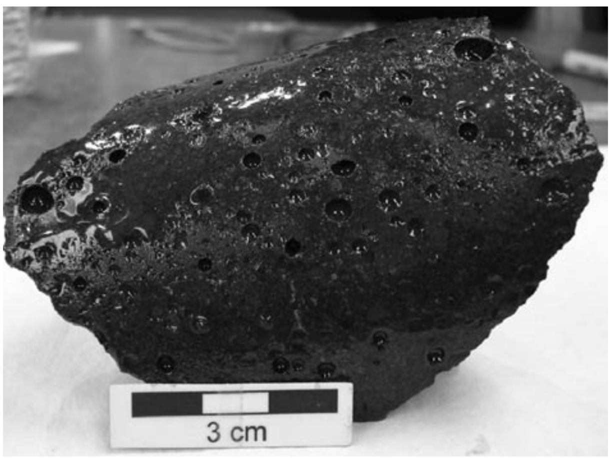

Fig. 12 – Representative example of Facies 10 (bagged lava) between 18.03 and 18.25 mbsf.

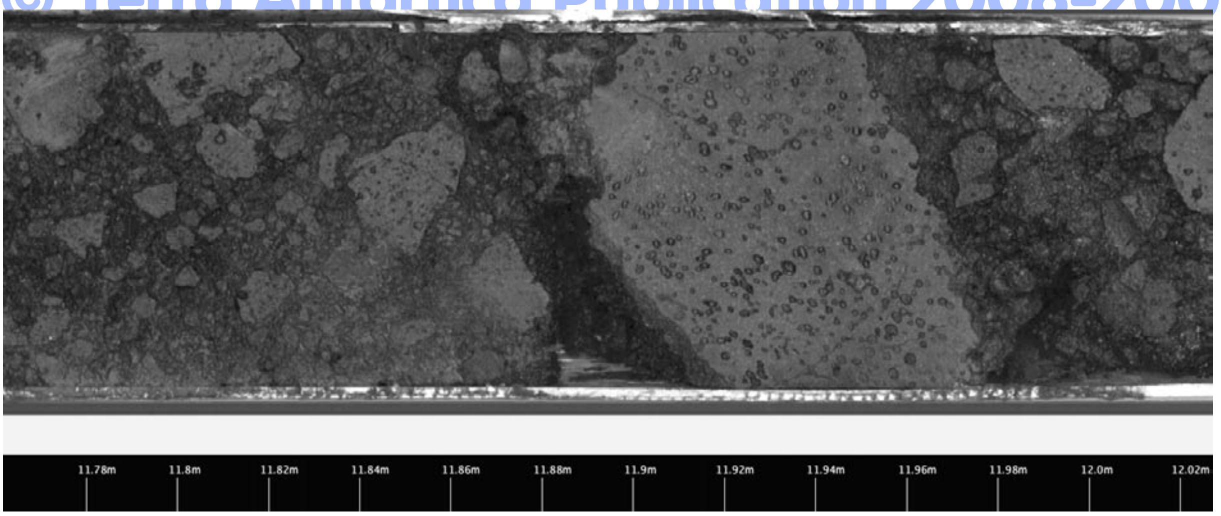

Fig. 13 – Facies 11: volcanic breccia between 11.80 and 11.99 mbsf, showing clasts of vesicular lava.

as large clast size and angular shape, all suggest autobrecciation of subaerially erupted lavas (Facies 10) from a proximal vent or fissure.

FACIES 12 – VOLCANICLASTIC: PYROCLASTIC LAPILLI TUFF

Lapilli tuff units are composed of glassy, juvenile clasts of coarse ash to lapilli grain size. They are generally well-sorted and lapilli are clast-supported. The vesicularity of the vitriclasts varies from pumaceous to scoriaceous to dense fragments. Normal grading with a gradational top and loaded base is present in one unit (640 mbsf, Fig. 14). Other units have been gently reworked and have gradational top and bottom contacts. Clasts in the reworked units vary from angular to sub-rounded and are clast-supported to matrix-supported.

The occurrence of pyroclastic units suggests open water conditions and/or the presence of thin annual sea-ice, which would allow instantaneous, or nearly instantaneous, uniform suspension settling of pyroclasts through the water column to form monomict tephra layers. Reworking of primary tephra layers has obscured grading and contact relationships in most units.

FACIES 13 – VOLCANIC SEDIMENTARY: BRECCIA AND SANDSTONE

Volcanic sediments are composed of texturally unmodified to modified juvenile clasts (>95%) that include very angular to rounded vitric pyroclasts and lava grains.

Clasts within the sandy volcanic breccia consist of angular blocks of vesicular, porphyritic basaltic lava supported within a matrix of volcanic sand (Fig. 15). The sandy matrix is composed of volcanic glass shards and subordinate volcanic lithics. Volcanic sandstones are ripple cross-laminated and composed of fresh to variably altered cuspate glass shards (<0.1 mm) and rounded to sub-rounded scoria and lava clasts.

These facies represent reworking of volcaniclastic deposits in shallow water. The occurrence of cuspate glass shards within the sand fraction indicates direct input of pyroclast fallout from explosive volcanic activity.

STRATIGRAPHIC STACKING PATTERNS

Three different facies motifs (Fig. 16) can be recognized after initial analysis of stratigraphic

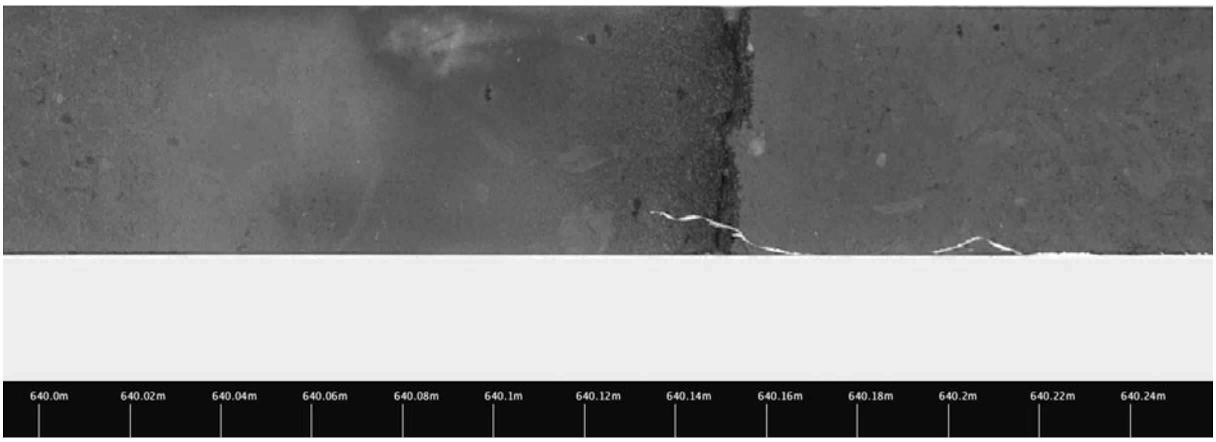

Fig. 14 – Facies 12: pyroclastic lapilli tuff between 640.00 and 640.25 mbsf, showing normally graded coarse ash with loaded base (dark layer).

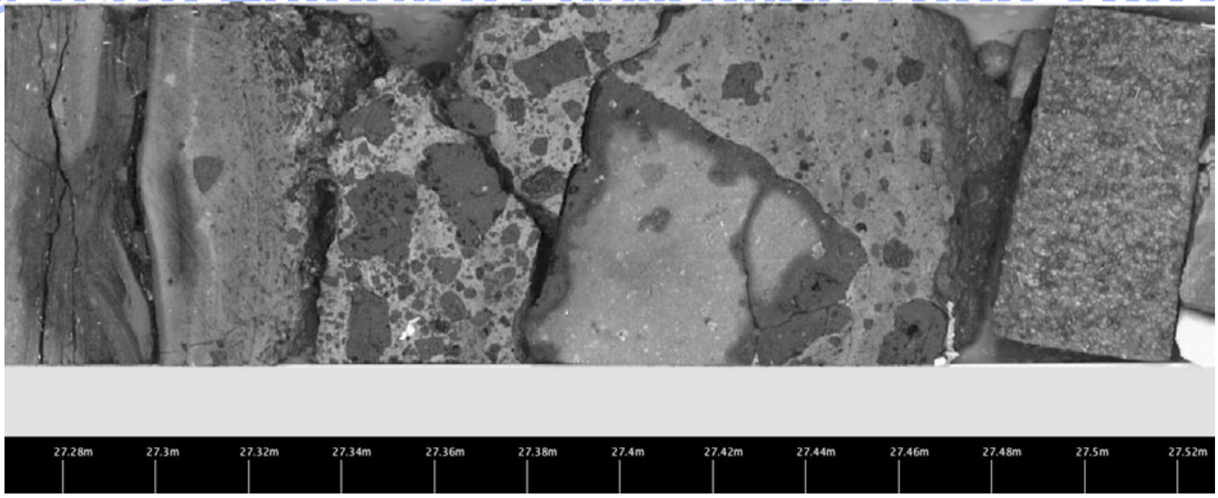

Fig. 15 – Facies 13: volcanic sedimentary lithologies between 27.30 and 27.50 mbsf, showing mainly sandy volcanic breccia.

stacking patterns in the SMS Project AND-2A core:

- Motif 1, which is present in the upper 241 m of the SMS core is dominated by massive sandy diamictite overlain with a sharp contact by thin beds of interlaminated sandstone and siltstone and ripple-laminated fine sandstone and minor stratified diamictite (Fig. 16).
- Motif 2, which is present primarily between 241 and 523 mbsf is characterized by a wider variety of lithofacies, starting with sharp-based conglomerate and sandstone units, overlain by stratified clast-poor diamictite. The diamictite beds are overlain by clayey siltstone, often bioturbated, which in turn are overlain by interlaminated sandstone and siltstone, which can be extensively soft-sediment deformed, and are overlain by diamictite, sharp-based conglomerate and sandstone beds (Fig. 16).
- Motif 3, which is present only below 523 mbsf, is dominated by fossiliferous massive and stratified diamictite beds. Sandstone lithologies with clasts and conglomerate beds are present at its base, overlain by stratified diamictite lithologies that grade upward into interlaminated siltstone and very fine sandstone with diamictite interbeds (Facies 6). These fine-grained beds are overlain by fossiliferous diamictite lithologies with common bivalve shell fragments and serpulid tubes, as well

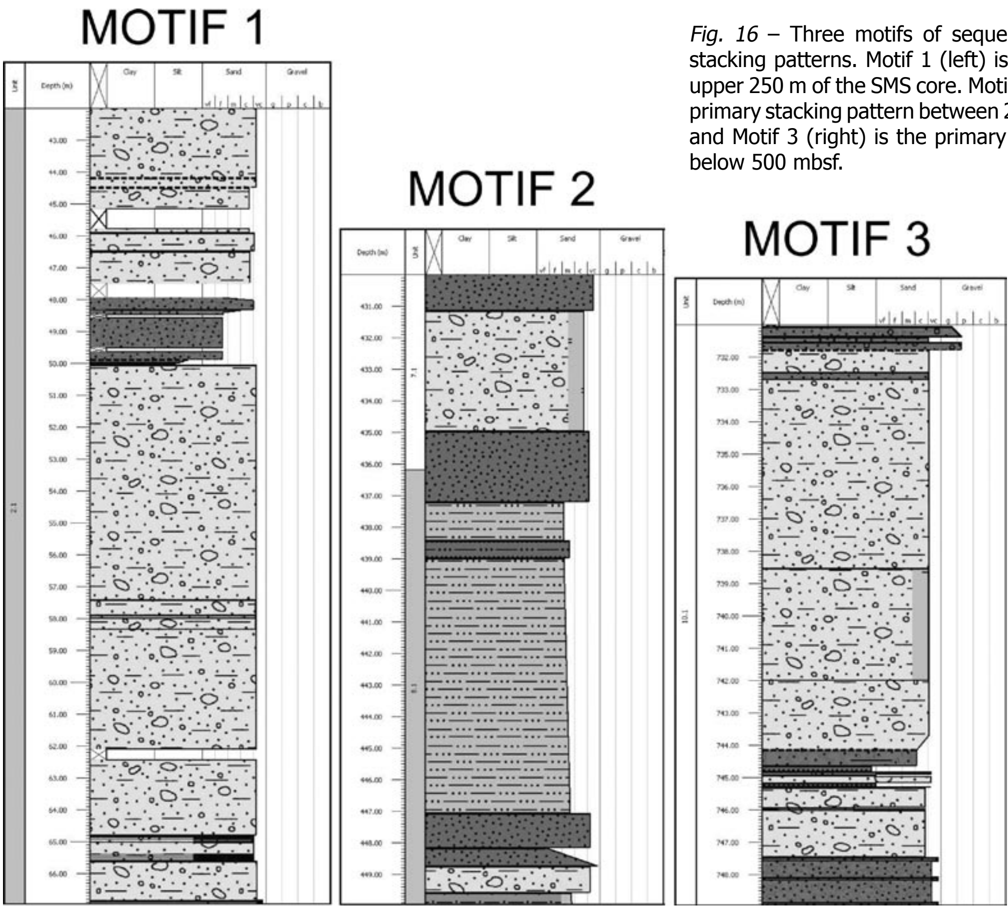

Fig. 16 – Three motifs of sequence stratigraphic stacking patterns. Motif 1 (left) is dominant in the upper 250 m of the SMS core. Motif 2 (centre) is the primary stacking pattern between 250 and 500 mbsf and Motif 3 (right) is the primary stacking pattern below 500 mbsf.

as a component of biogenic silica. Clast abundance increases upward in these units. The diamictite units are overlain by conglomerate with a sharp boundary (Fig. 16).

Processes responsible for generation of these stacking patterns and their distribution in the AND-2A core are most likely a combination of tectonic subsidence rates, glacial proximity (including the presence or absence of the West Antarctic Ice Sheet), glacio-isostasy and eustasy. Further details of the stacking patterns will be evaluated during the Science Documentation phase of research. One thick sandstone unit (LSU 3) and one thick mudstone unit (LSU 11) display internal stacking patterns, which require further investigation.

AEOLIAN SEDIMENT ON SEA-ICE IN SOUTHERN McMURDO SOUND

INTRODUCTION

Aeolian sediment consisting primarily of very-fine sand and silt was observed on the surface of the sea-ice in the vicinity of the SMS drillsite during drilling operations. This sediment is released into the water column and subsequently sinks to the sea-floor during annual sea-ice melting. However, there is a paucity of data quantifying the volume, distribution and composition of this sediment, or its potential contribution to overall sedimentation in the region.

A systematic snow sampling programme was carried out on the sea-ice along a wind-parallel transect near the SMS drillsite (Fig 17). This allowed the average annual volume of aeolian sediment to be calculated for the area. Further analysis of the samples for grain-size, particle shape and composition should contribute to an improved understanding of sedimentation in southern McMurdo Sound, and aid the interpretation of the AND-2-2A drillcore.

METHOD

Sampling comprised seventy five snow pit samples (50 x 50 cm down to sea-ice) every 500 m within three 2 km^2 sampling grids spaced 5 km apart in a north-south (wind parallel) transect (Fig. 17). The southern grid is centred near the edge of the McMurdo Ice Shelf "dirty ice" at 77°49.248S 165°21.795E. The second grid is adjacent to the SMS drillsite centred at 77°45.484S 165°21.685E and the northern grid centred at 77°41.721S 165°21.577E closer to the present ice edge. Bags of snow were melted in a heated container at the drillsite and suspended, allowing the sediment to settle out for a minimum of 10 hours. The water was then siphoned off and the residual sediment collected, bagged and labelled. In addition, a bulk sample of sediment was collected from the McMurdo Ice shelf near the Dailey Islands south of the sampling transect (77°51.909S 165°17.533E) to provide an example of probable source material for the windblown sediment.

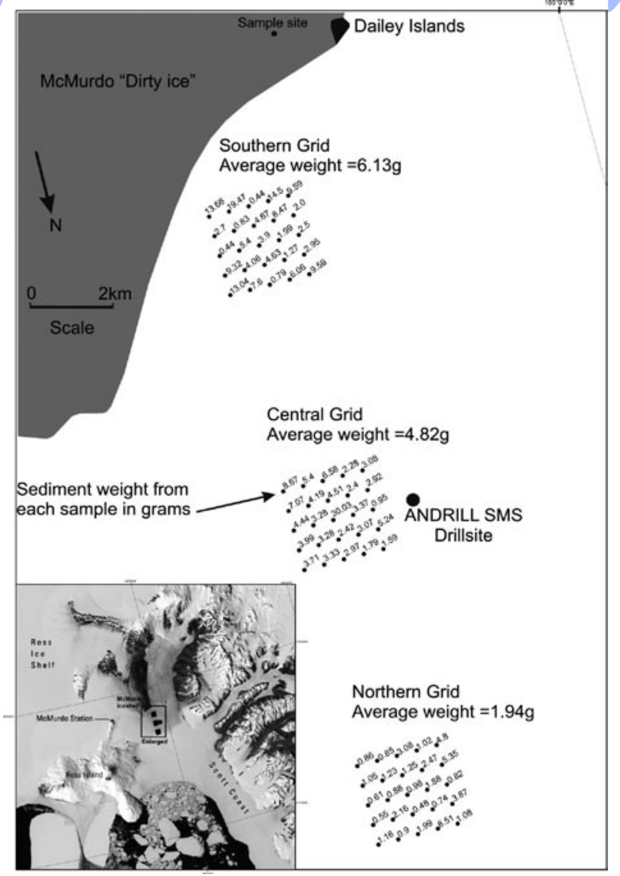

Fig. 17 – Map showing the location of sampling grids and weight of aeolian sediment from each snow pit in grams. McMurdo Sound image from LIMA Project: http://lima.usgs.gov

INITIAL RESULTS

The weight of sediment extracted from the snow pit samples shows wide variation within each grid, but average sediment weight shows a marked downwind decrease from 6.13 g per sample within the southern grid, to 1.94 g per sample in the northern grid closer to the ice edge. When these weights are extrapolated, they indicate that there is between 24 000 and 7760 kg of aeolian sediment per km^2 in this area.

Laser particle size analysis has not yet been carried out on these samples, but a visual assessment shows an obvious decrease in maximum grain size from the southern grid to northern grid (downwind). A preliminary visual inspection of the grain composition and shape shows a dominance of a wide variety of rock fragments, but also includes minor amounts of very-angular volcanic glass and well-rounded quartz grains, which suggests a complex provenance.

FUTURE WORK

Future work will focus on producing detailed grain-size and grain composition analyses to fully characterise the sediment and determine the provenance. These data will be compared to samples collected from the AND-2A drillcore to assist in further development of the sedimentation model. Furthermore, we plan to investigate the magnetic and geochemical properties

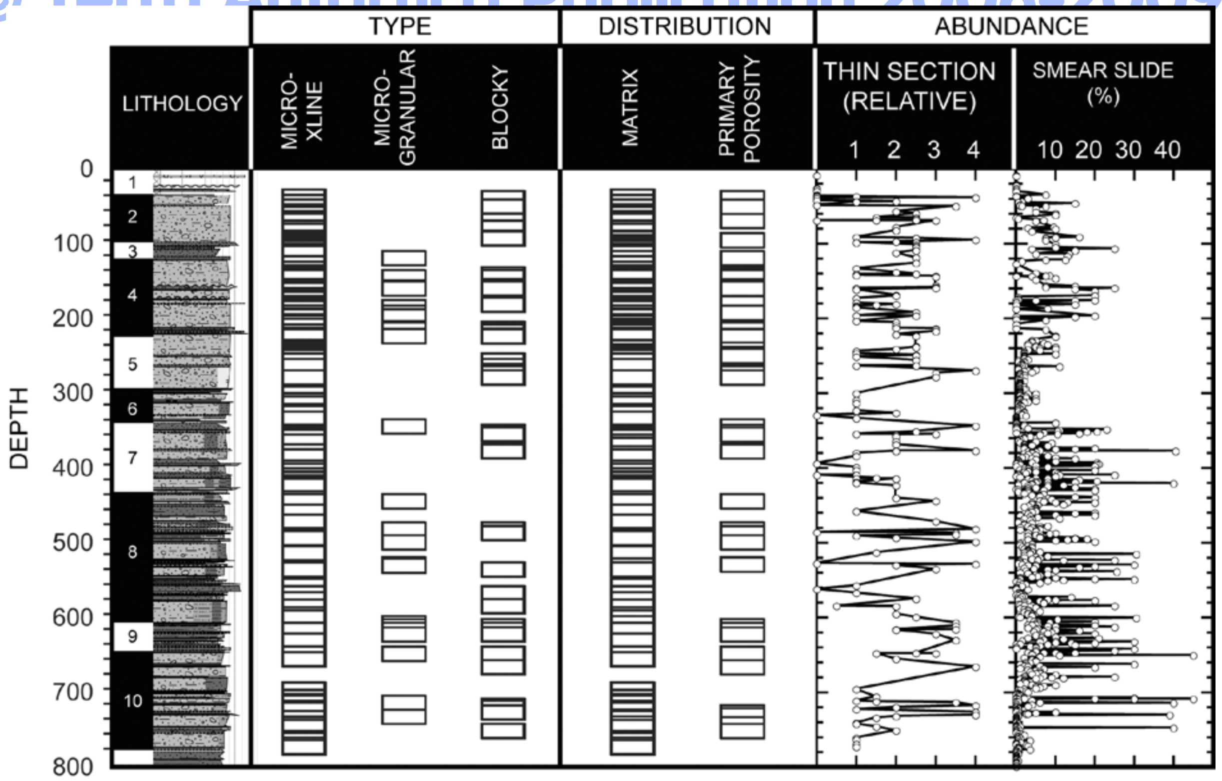

Fig. 18 – Summary of types, distribution, and abundance (0 = absent; 1 = trace; 3 = common; 4 = abundant) of secondary carbonate based on thin section petrography from 0 to 800 mbsf. Also shown for comparison is calcite abundance (%) based on smear slide analyses.

of the grains with a view to understanding the link between the iron content of aeolian sediment and algal blooms that occur in McMurdo Sound.

DIAGENESIS

This section of the report provides an overview of the major diagenetic features of the AND-2A Core LSUs 1 through 10, as observed during core description, smear-slide analysis, and thin section petrography. The major diagenetic processes include calcite replacement of fine-grained matrix, calcite cementation in primary pore space and late-stage fractures, dissolution and replacement of allochems, pyrite cementation, and devitrification, hydration, and zeolitisation of volcanic glass fragments. The main diagenetic features are discussed below.

CARBONATE DIAGENESIS

Diagenetic calcite occurs throughout the cored section (Fig. 18). Abundance estimates based on smear-slide observations suggests that, on average, 5.6 ± 8% of the fine-fraction in the cored section consists of secondary calcite, although abundance varies from 0 to 45%. LSUs 1, 5, and 6 are relatively calcite-poor, with the fine-fraction in these units containing less than 3% calcite. LSU 9 contains the highest average concentration of diagenetic calcite (9.0 ± 7%). At the scale of individual beds, the density of calcitisation varies from sparse, with isolated crystals present, to ubiquitous, with up to 50% of the host rock matrix replaced by microcrystalline calcite. In more densely cemented zones, calcite also forms isopachous overgrowths of blocky to bladed calcite on clasts of heavily weathered volcanic material, quartz grains, and feldspar crystals.

Thin-section petrography shows that calcite occurs in the following forms, listed in decreasing order of abundance: microcrystalline, microgranular, blocky, radiaxial bladed or fibrous, and spheroidal (Fig. 19). The microcrystalline calcite occurs mainly as dispersed crystals that appear to be replacing the fine-grained matrix of the host rock (Fig. 19A). The coarser forms, microgranular and blocky calcite, are often distributed in the matrix, but may also form isopachous rims around sand (often volcanic glass) grains. In some sandstones, these phases fill the primary intergranular pore space (Fig. 19B, C). Late-stage fractures are commonly filled with either mosaics of blocky cement or radiaxial bladed and fibrous calcite (Fig. 19D).

PYRITE AND PYRITISATION

Pyrite is nearly absent above *c.* 430 mbsf, but becomes common to abundant at greater depths. In some intervals, disseminated pyrite imparts a black colour to the sediments and obscures primary sedimentary features. This form of pyrite is most abundant in the following stratigraphic intervals: *c.* 555-597 mbsf (LSUs 8.3 and 8.4), *c.* 775-828 mbsf (LSU 11.1), c. 958 – 1011 mbsf (LSUs 12.1 and 13.1), and below *c.* 1040 mbsf (LSU 14.1). Although all lithofacies are affected to some degree, the black

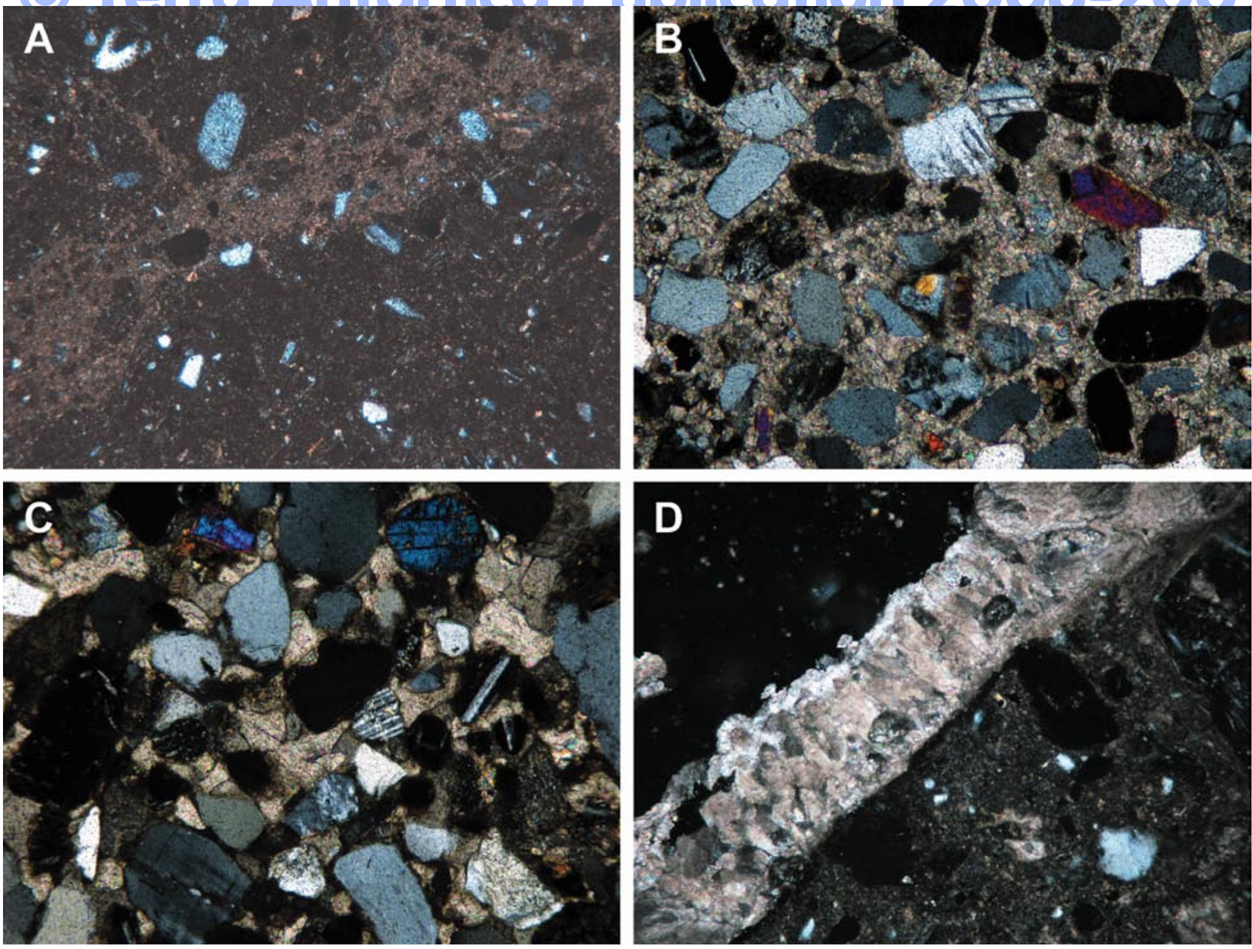

Fig. 19 – Photomicrographs showing range of occurrences of secondary calcite in primary and secondary pore space. (A) Deformed diamictite (AND-2A 126.24 mbsf) with irregular distribution of microcrystalline calcite dispersed through matrix. Field of view - FoV = 4 mm. (B) Sandstone (AND-2A, 344.36 mbsf) with intergranular pore space completely filled with microgranular calcite cement. FoV = 2 mm. (C) Sandstone (AND-2A 270.41 mbsf) with intergranular pore space completely filled with blocky mosaic of calcite cement. FoV = 2 mm. (D) Late-stage fracture (AND-2A, 169.25 mbsf) lined with isopachous rim of radiaxial fibrous calcite. FoV = 2 mm.

staining is most common in sandstone and mudstone lithologies. Within these intervals, pyrite is present as cement within the intraparticle pore space of skeletal grains and replaces volcanic glass. Between the heavily cemented intervals, pyrite cementation occurs in patches that range from discrete, cm-scale blebs of blackened sediment to more heavily cemented areas in which individual pyrite crystals may be distinguished in core. Below *c*. 444 mbsf, coarser pyrite occurs alone or in association with calcite and other minerals within late-stage fractures.

ALTERATION OF VOLCANIC GLASS

There are three types of glass present in the deposits. Until chemical analyses may be run, colour is used as a proxy for composition. On this basis, volcanic glasses fall into the following categories: (1) brown (mafic scoria) – blocky to vesicular with some plagioclase crystals; (2) clear (felsic pumice) – blocky to vesicular to long tube; and (3) pale green (alkaline pumice) – blocky to vesicular. Brown or green glass may be mingled with clear glass. Brown glass is present in almost every unit in the core. Clear glass is present in varying amounts below 140 mbsf. Green glass is only present below 535 mbsf. Unaltered glass is present in all samples examined, in close proximity to altered glass. As such, alteration may reflect a mixture of weathering at the source and submarine diagenesis.

The alteration of volcanic glass in the core tends to vary with glass type (Fig. 20). The brown glass at the top of the core in volcanic dominated LSU 1 commonly alters to palagonite and limonite/hematite with minor zeolite. Below 93 mbsf, zeolite becomes the most common phase with minor limonite/hematite, glauconite, and chlorite. Below ~440 mbsf, in the zone of pyritisation, brown glass tends to alter to opaque minerals (iron sulphides?) in addition to the dominant zeolite and rare glauconite. Vesicles may be filled with blocky calcite cement. Clear glass primarily alters to calcite, starting with infilling of the vesicles followed by replacement of the glass grain. Below ~440 mbsf clear glass also alters to zeolite, although a different zeolite mineral than that formed from the alteration of the brown glass. The green glass remains relatively unaltered. A small amount has altered to calcite and glauconite; such alteration increases slightly downcore.

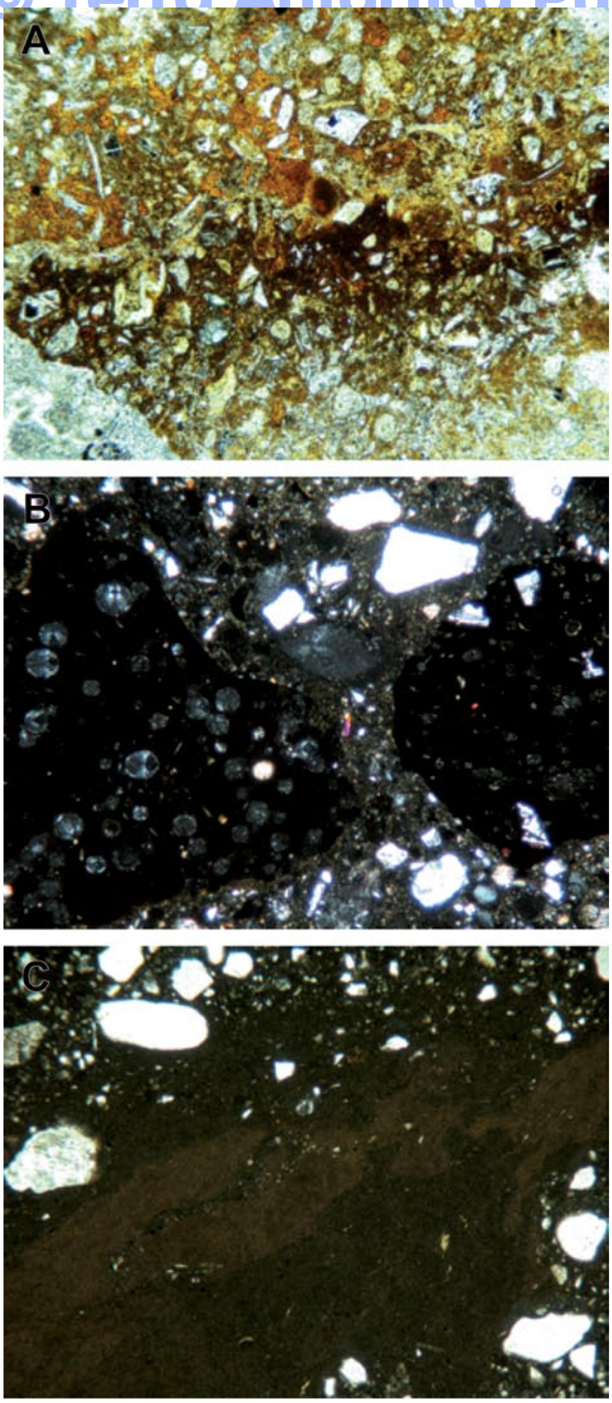

Fig. 20 – Photomicrographs showing alteration of brown (mafic) volcanic glass. FoV = 4 mm. (A) Alteration to palagonite and iron oxides and oxyhydroxides. (hematite/limonite) at 29.95 mbsf. (B) Alteration to zeolite and opaque minerals (pyrite?) in AND-2A 595.68 mbsf. (C) Alteration to zeolite in AND-2A 723.05 mbsf.

DISCUSSION AND CONCLUSIONS

When considered in concert with pore water geochemical profiles (see Pore Water Section in Panter et al., this volume), petrographic observations suggest that the presence of abundant volcanic glass has played a major role in the diagenetic alteration of the AND-2/2A core. Volcanic glass fragments are highly reactive and susceptible to alteration because they lack a well-developed crystal structure and tend to have a high surface area to volume ratio (Gifkins et al., 2005). In addition, experimental work shows that rates of glass alteration increase greatly at elevated temperatures and in the presence of alkaline fluids such as seawater (Lofgren, 1970; 1971). Both of these factors play a role in the AND-2/2A core: interstitial waters are high-alkalinity brines (see Pore Water Section in Panter et al., this volume) and downhole logging results indicate that the study site is affected by a relatively high geothermal gradient (see Wonik et al., this volume). Previous investigations of submarine diagenesis in volcaniclastic successions similar to that recovered by the ANDRILL SMS Project show that the major alteration processes include the hydration of volcanic glass, the formation of hydrous secondary minerals such as zeolites, layered silicates, and chlorite, and calcite precipitation (Egeberg et al. 1990; Marsaglia and Tazaki, 1992; Gifkins et al., 2005). As discussed above, these phases are present throughout much of the cored section, either replacing the host sediment or as cement in primary pore space.

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