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# Fracture Logging of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica

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**Abstract -** Fractures in AND-2A drillcore were documented in this study. Over 4100 fractures of all types were logged. A population of 510 steeply-dipping, petal, petal-centreline and core-edge induced fractures is present, reaching a maximum density of *c.* 10 fractures/metre. Subhorizontal induced extension fractures are also abundant. There are 1008 natural fractures in the core, including faults, brecciated zones, veins and sedimentary intrusions. Kinematic indicators document dominant normal faulting, although reverse faults are also present. The natural fractures occur in strata ranging in age from the Miocene to the Plio-Pleistocene.

## INTRODUCTION

The characterisation of fractures in drillcore provides important information on the structural and tectonic evolution of rift basins. The type and orientation of natural fractures in cores and borehole walls, together with age constraints provided by dating the strata they cut, can be used to constrain faulting history and paleostress directions associated with rifting in the western Ross Sea. Drilling-related fracturing, including borehole breakouts and tensile fractures in borehole walls and petal-centreline and disc fractures in core, provide a means to determine the orientations of the contemporary stresses in the crust surrounding the boreholes.

The Core Structure Measurements Group worked at the ANDRILL Southern McMurdo Sound Drill Site Lab and was responsible for obtaining core imagery and data needed to orientate the core to *in situ* coordinates, and for characterisation of natural and drilling-induced fractures in the core. Here we provide a summary of data acquired for core orientation and other applications, and an inventory of the fracture types documented by macroscopic logging of the AND-2A core.

## METHODS

### CORE ORIENTATION

#### *Whole-Core Scanning*

Whole-round core segments were scanned using the CoreScan II™ instrument manufactured by DMT, Germany. Segments up to one metre in length were scanned by revolving the core on rollers as a digital line scanner traversed the length of the core. Scan resolution is 10 pixels/mm. A few selected core segments were scanned at 20 pixels/mm. Each whole-core scan file is named based on the depth in metres below sea floor (mbsf) of the top of the core segment. Poorly indurated or highly fractured intervals of core could not be scanned because they would not maintain their integrity on the rollers. We were able to obtain whole-core images of 73% of PQ3 core (between 0-229.24 mbsf), 88% of HQ core (between 229.4 and 1011.87 mbsf), and 97% of NQ core (between 1011.87 and 1138.54 mbsf). A table providing file names and depths of each whole-core scan entitled "Whole Core Scans.pdf" is provided online at the SMS Project science drive (http://www.andrill.org), a secure site. Data will be available to the broader scientific community at the end of the SMS Project data moratorium period. Whole-core scans can also be viewed in the *Corelyzer* core visualization application.

#### *Intact Intervals of Core*

Intact core intervals are continuous lengths of core where no internal relative rotation has occurred. Boundaries of these intervals are either breaks between core runs, where the core ends could not be fitted together, or are fractures within a core run where rotation occurred during coring (Fig. 1). In the PQ core, 44% of core runs could be fitted together end to end, and intact core intervals reached a maximum of 12.91 m in length. In the HQ core, 66% of the core runs could be fitted at their ends, and intact core intervals up to 75.62 m-long were found. In the NQ core, 54% of the core runs could be fitted at their ends, and intact core intervals up to 16.87 m-long were found. A table listing intact intervals of core [$\geq$ 1m

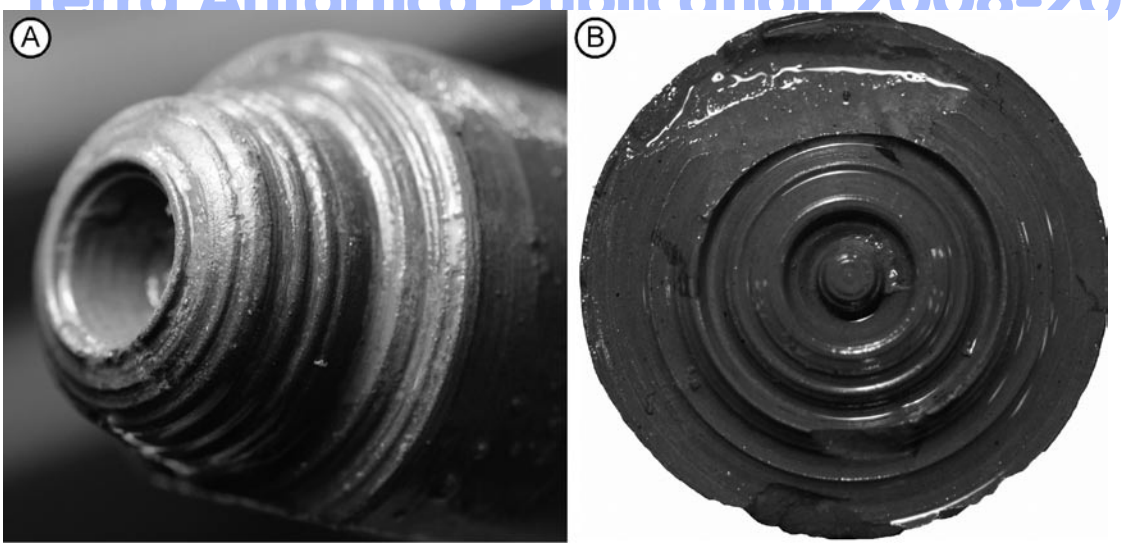


*Fig. 1* – Photograph of subhorizontal fractures at 789.23 mbsf (A) and 880.98 mbsf (B) with circular "potter's wheel" grooves documenting differential rotation of the core above and below. Core is 6.1 cm in diameter.

in length] entitled "Intact_Intervals_StratOrder.pdf" is provided online at http:/sms.andrill.org.

### *Core Orientation Procedure*

A 'core reference frame' was defined by scribing a red line and a blue line (180° apart) along the length of each core run (Fig. 2A), using core splits with slots machined along their axis. Whole-core measurements were made with respect to the red line (designated core 'north'). The curatorial team split the core perpendicular to the scribe lines, with the red line placed down in the archive core split and the blue line placed down in the working core split. Core samples taken parallel or perpendicular to the slabbed core face thus preserve orientation with respect to the scribe lines. We note that, though care was taken in the core scribing process, deviation of the scribe lines from straight and 180° apart did occur where core was under-size or where short, discontinuous core segments rotated in the scribing process. Red and blue lines may not have remained precisely 'down' in the core splits, and thus may not be perpendicular to the slabbed core face (Fig. 2B). Users requiring orientation should therefore measure the position of the scribe line relative to the slab face to assure correct orientation.

Whole-core images will be digitally 'stitched' together into complete intact core intervals during off-ice work. These intact core intervals will be compared to equivalent depth intervals of magnetically-orientated borehole televiewer (BHTV) imagery of the borehole walls to locate the same features (*e.g.*, fracture planes, bedding planes, large lonestone clasts) in both images. If matching features are identified, an average 'rotation angle' to match the position of core features to the orientated BHTV image will be computed for each intact core interval. This rotation angle can then be used to reorientate measurements or samples made with respect to the scribe lines into their correct *in situ* position when the core was in the ground (see Paulsen et al., 2002).

Other methods of determining core orientation in intervals that were not imaged by the BHTV include results from deployments of the Gyrosmart™ core orientation tool, which was deployed 54 times during AND-2A drilling. The tool recorded the rotation of the core from the end of coring at the base of the borehole to the drill-rig floor where the core was

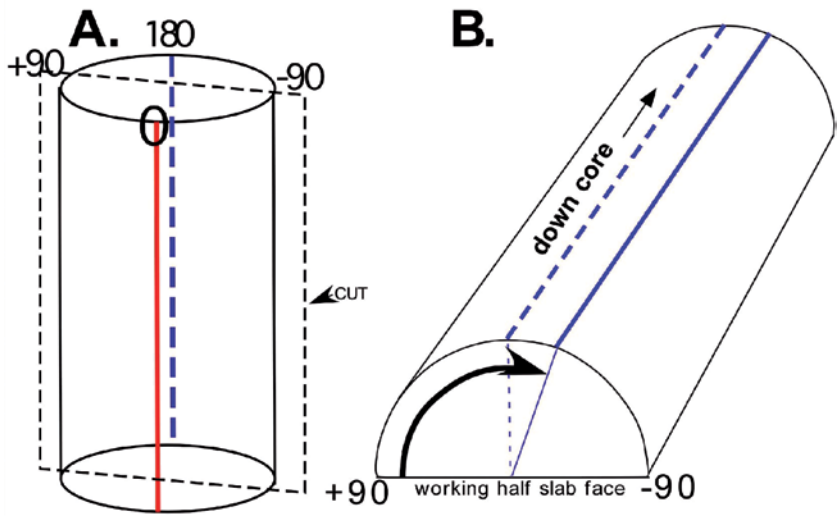


*Fig. 2* – Core reference frame used for core measurements and orientation. The red scribe line is designated as arbitrary 'North' and the blue scribe line is drawn 180° opposite (A). The core is cut perpendicular to these lines, and the blue scribe line is placed down in the working half of the core. Although the blue scribe line should be 90° from the slab face of the working half of the core (B), it is important to measure the true position of the line when taking orientated samples as various procedural problems may have caused misalignment (from Wilson et al., 2007).

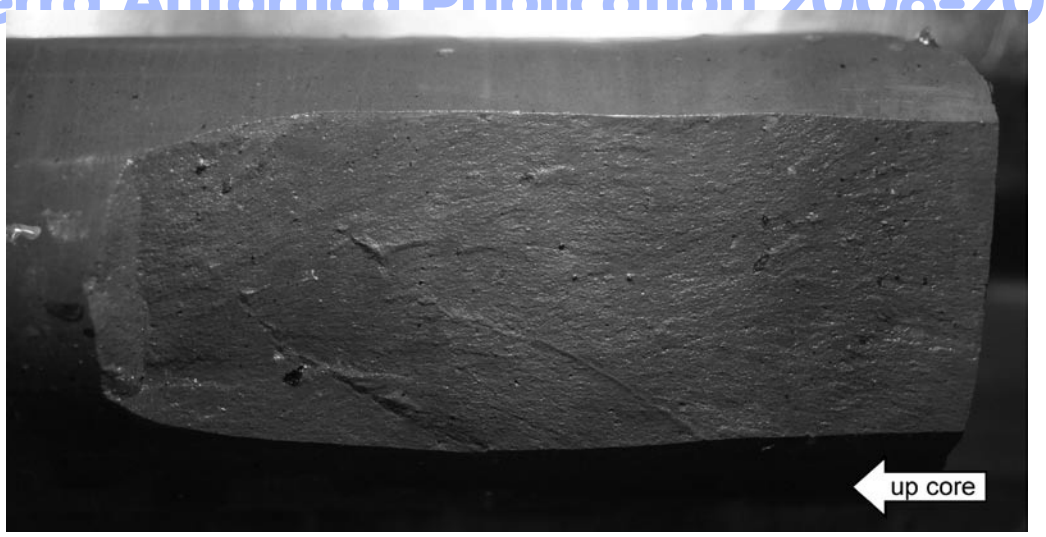


*Fig. 3* – Photograph of a low-angle core edge fracture in the AND-2A core at 864.58 mbsf. Note petal-type fracture curvature inward and downward from the margin and near vertical fracture following core axis, and hackle plume surface structure documenting down-core propagation. Core is 6.1 cm in diameter and ~12 cm-long.

placed in a known orientation. The rotation angles resulting from the Gyrosmart™ orientation procedure have the potential for providing orientation of the red scribe. Core intervals not covered by BHTV or the Gyrosmart™ core orientation tool may possibly be reorientated by: 1) matching bedding dip direction to the regional dip direction of strata in the AND-2A borehole, and 2) matching the orientation of steep drilling-induced fractures to the orientation of similar fractures in orientated core, if such fractures are found to have systematic trends.

## FRACTURE LOGGING METHODS

Fracture logging was carried out at the Drill Site Laboratory on the whole core. The depth of the top and bottom of each fracture was recorded in mbsf. Fracture dip and dip direction were measured relative to the core axis and the red scribe line, respectively. Macroscopic observation of fracture surface features (where open), and fracture fill types and textures were made to assess shear or extensional mode of fracture origin and to determine displacement sense and magnitude. Core structures were documented with digital photographs and samples were taken for microscopic characterisation. Over 4100 fractures of all types were logged in the AND-2A core.

## RESULTS

### INDUCED FRACTURES IN THE AND-2A CORE

Fractures that form during drilling (*i.e.* in the rock around the drill bit), coring (*i.e.* on entry or in the core barrel), or subsequent handling of the core are classed as "induced" fractures.

#### *Petal, Petal-Centreline, and Core-Edge Fractures*

Petal, petal-centreline, and core-edge fractures (Fig. 3) consist of steeply-dipping, typically curviplanar, extension fractures that propagate in the rock below the drill bit and then are partially captured in the core as drilling proceeds. Fractographic features, including arrest lines and fine hackle plumes, demonstrate propagation of these fractures inward and downward along the core axis (Fig. 3). The orientation of these fracture planes parallels the maximum horizontal stress in the crust and is perpendicular to the minimum horizontal stress (Lorenz et al., 1990). Once the core is orientated, we will be able to define horizontal stress orientations at the Southern McMurdo Sound (SMS) site from the steep drilling-induced fracture set.

The distribution of the 510 petal, petal-centreline, and core-edge fractures we identified is compiled in figure 4. The density of these fractures reaches up to *c.* 10 fractures/metre, but averages 0.45 fractures/metre over the entire length of core. Petal-centreline fractures and core-edge fractures occurred most commonly at or near the top of core runs, but also were present mid-run and, more rarely, near the base of runs. Petal, petal-centreline, and core-edge fractures are most abundant in mudstones, which commonly were more difficult to drill and were associated with higher pump pressures during drilling and are less common in the diamictite lithologies.

#### *Subhorizontal Drilling-, Coring-, and Handling-Induced Fractures*

Subhorizontal induced fractures of several types occur in the AND-2A core. Fractures across which the core has rotated are identified by the presence of circular grooves and/or their conical shape (Figs. 1A & 1B). These form as core rotates below or within the core barrel, and define breaks between continuous intact core intervals. Subhorizontal extension fractures can form when the core is broken off at the end of a run, when the rock is released from load upon entering the core barrel, during flexing of the core splits during transport, or due to handling during core processing. Surface fractographic features demonstrate opening of the fractures due to tension. Hackle plume

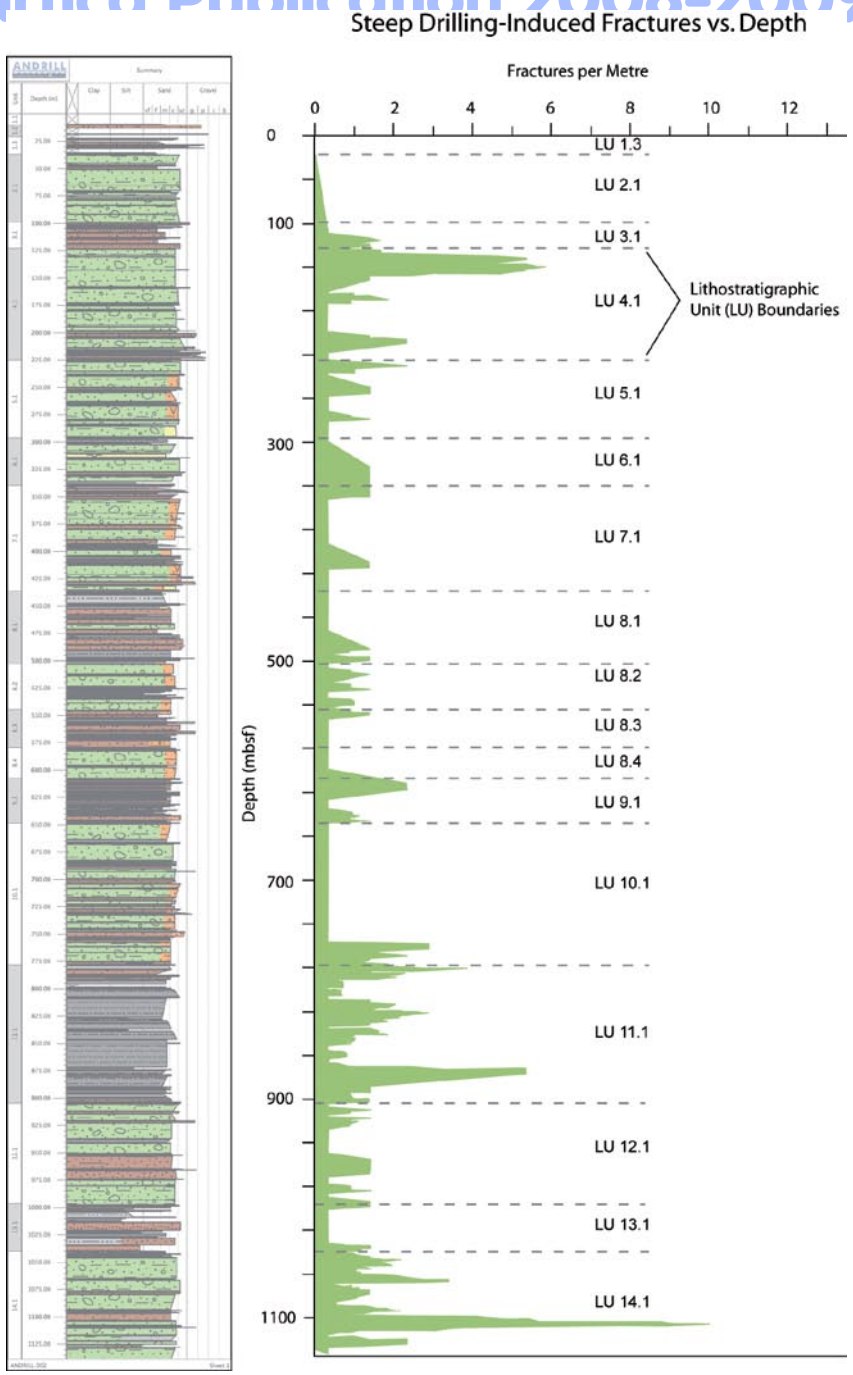


*Fig. 4* – Fracture density plot using a 10 meter moving average showing the number of petal, petal-centreline, and core-edge fractures per metre of core with relation to depth within the AND-2A core.

structures were common on these fractures in some core lithologies (Fig. 5). These induced fractures also provide constraints on the *in situ* stress regime (*e.g.*, Li and Schmitt, 1997).

## NATURAL FRACTURES IN THE AND-2A CORE

'Natural' fractures are pre-existing fractures in the rock that are intersected by coring. Natural fractures are identified based on their geometry and characteristics, such as truncation/offset of bedding, mineralization or brecciation. The distribution of the 1008 natural fractures identified in the core is compiled

*Fig. 5* – Photograph of subhorizontal fracture at 964.03 mbsf in the AND-2A core with hackle plume demonstrating induced, tensile fracture origin. Core is 6.1 cm in diameter.

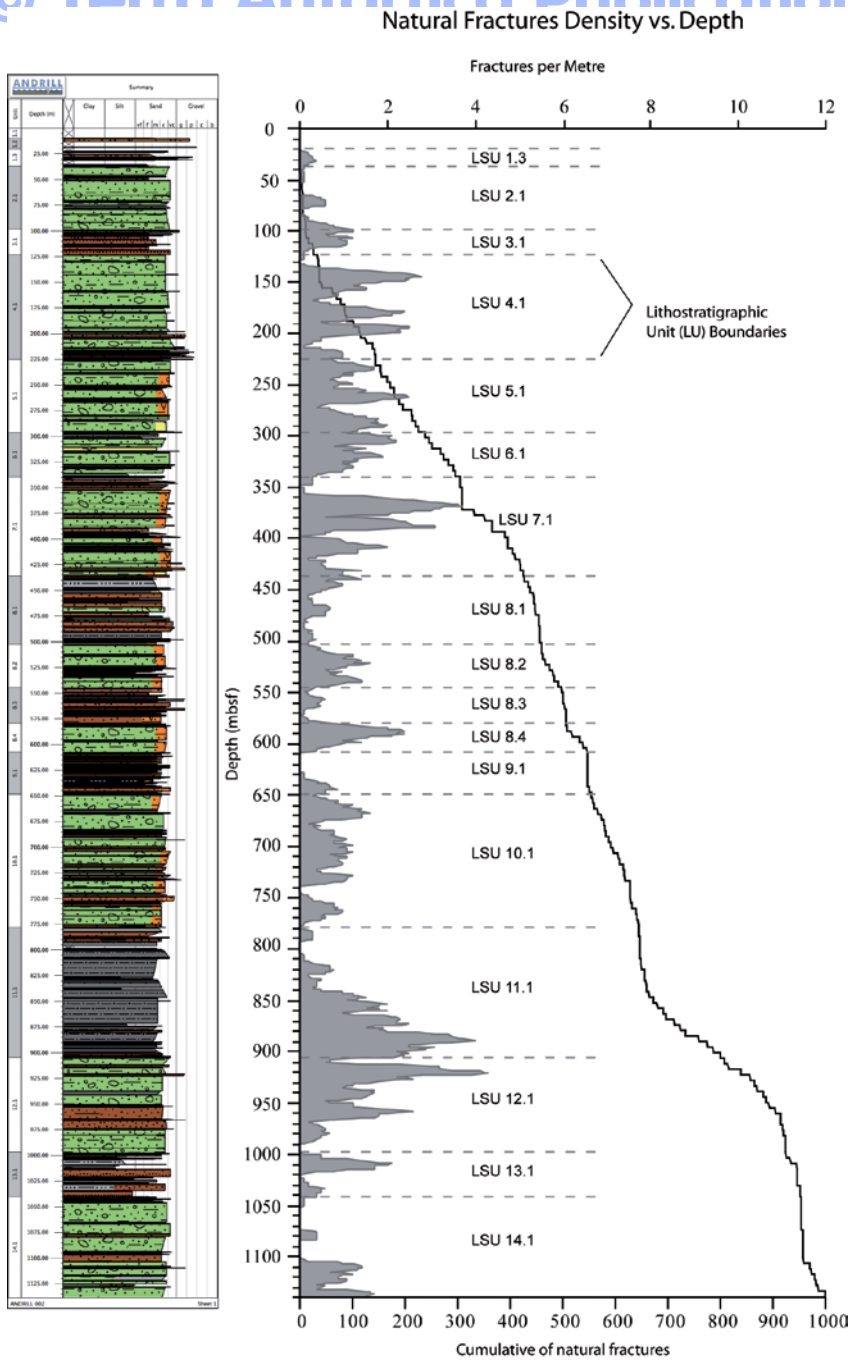


*Fig. 6* – Fracture density plot using a 10 meter moving average showing the number of natural fractures (faults, veins, and sedimentary instrusions) per metre of core with relation to depth, lithology, and lithostratigraphic unit boundaries within the AND-2A core.

and compared to core lithology in figure 6. Fracture densities up to *c.* 8 fractures/metre occur both in the upper and lower portions of the core. Overall, the average fracture density is 0.89 fractures/metre. Natural fractures are present in intervals currently estimated to be Plio-Pleistocene in age; the highest natural fracture occurs at 26.23 mbsf, and a population of systematic, steep conjugate natural fractures occurs as high as 65.11 mbsf. There is a zone of high fracture density between *c.* 357-440 mbsf, and a zone of high fracture density between *c.* 840-960 mbsf, both within intervals currently estimated to be Miocene in age. These structures will provide information on the paleostress and strain regime associated with deposition of the Neogene strata, including deformation within the West Antarctic rift system.

### *Faults*

Open fractures with polished, slickensided and striated surfaces (Fig. 7) are fairly rare throughout the core but, where present, commonly show striae parallel or close to the dip direction. Some faults have been completely filled by vein materials, which are discussed below. Mineralization along faults commonly includes calcite and pyrite.

Faults observed to offset bedding typically have offset magnitudes of a few millimeters (mm) up to 3 centimetres (cm). Some breccia zones and zones of dense faulting and/or veining in the core could mark faults with larger-magnitude displacement, but it is not possible to detect large offset magnitude in the core. Most faults that displace bedding have normal-sense dip separation (Fig. 8), but a subset have reverse sense shear (Fig. 9). Locally, reverse and normal faults are found in close proximity. These


*Fig. 7* – Photograph of a normal fault with down-dip striae in the AND-2A core at 913.96 mbsf. Core is 6.1 cm in diameter.

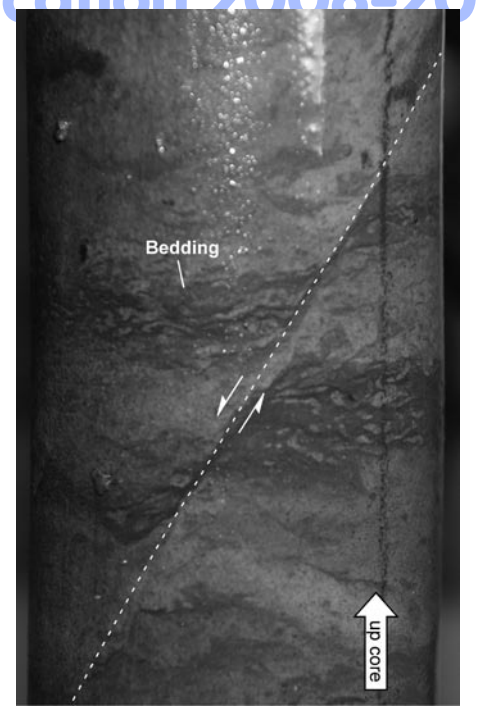


*Fig. 8* – Photograph of a fault displaying 1 cm normal offset of bedding in the AND-2A core at 1028.64 mbsf. Core is 4.5 cm in diameter.

instances suggest a complex strain field, perhaps associated with deformation due to soft sedimentary slumping or glacial overriding. The majority of faults in the core, however, have normal-sense displacement, 50-70° dip angles and locally have conjugate geometries, as expected for tectonic deformation in a rift regime. In a few cases, faults with mm-scale offset of bedding die out up- or down-core without displacing bedding above or below, characteristic of faulting penecontemporaneous with deposition. Locally, cataclastic zones occur at the base of clasts (Fig. 10), also suggesting faulting occurred, at least in part, penecontemporaneous with deposition. Discrimination between tectonic and glaciotectonic faulting will be a focus for further study.

### *Breccias*

Breccias of at least two distinct types occur in the AND-2A core. Brecciation involving injection of remobilised sedimentary matrix produces a 'jigsaw' breccia where clasts can be fitted together (Fig. 11). Elsewhere, zones or discontinuous pockets of calcite cemented breccia occur in tabular zones that are likely faults (Fig. 12).

### *Veins*

Veins are very abundant in the AND-2A core. Vein thickness ranges from <1 mm to 1 cm. Veins locally contain fibers, either perpendicular or parallel to vein margins. Where veins cut massive volcanic or basement clasts, the veins and/or voids along the veins are filled by euhedral crystals, indicating growth into open space. Vein fill minerals are commonly calcite. The presence of veins indicates abundant fluids, substantial pore pressures, and a strong role of fluids in deformation of the strata.

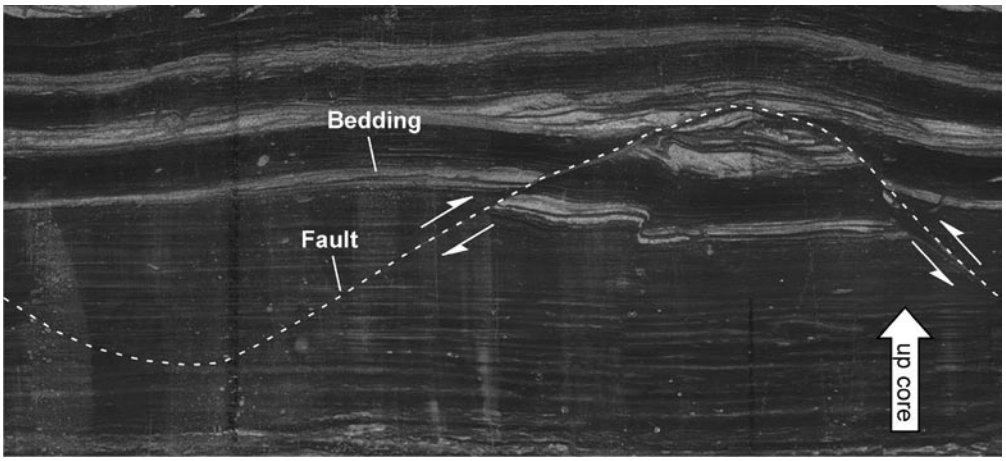


*Fig. 9* – Whole-round CoreScan II™ image of a reverse fault offsetting bedding at 1008.14 mbsf in the AND-2A core. Core is 6.1 cm in diameter.

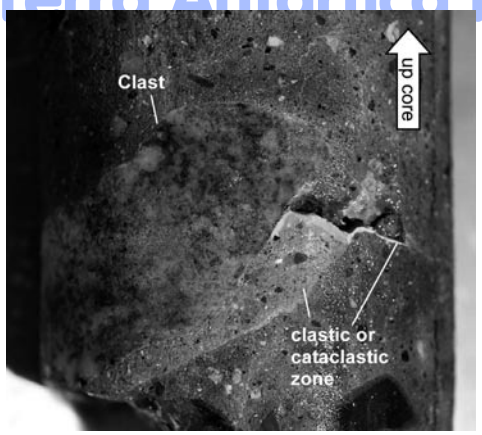


*Fig. 10* – Photograph of a clastic or cataclastic zone at the base of a clast in the AND-2A core at 138.66 mbsf. Core is 6.1 cm in diameter.

Many veins are clearly associated with fault planes. Attributes of veins interpreted as faults include dips between 50-75 degrees, typical of fault planes (Fig. 13), conjugate geometries typical of normal faults (Fig. 13), precipitation in steps or pull-aparts along fault surfaces (Fig. 14), arrangement in *en echelon* arrays defining normal-displacement shear zones, and occurrence along planes that have slickensided host rock surfaces (Fig. 7). Remarkably (for a vertical core), there are appreciable numbers of very steeply dipping (>75°) calcite veins, in one instance over 2.46 m-long.

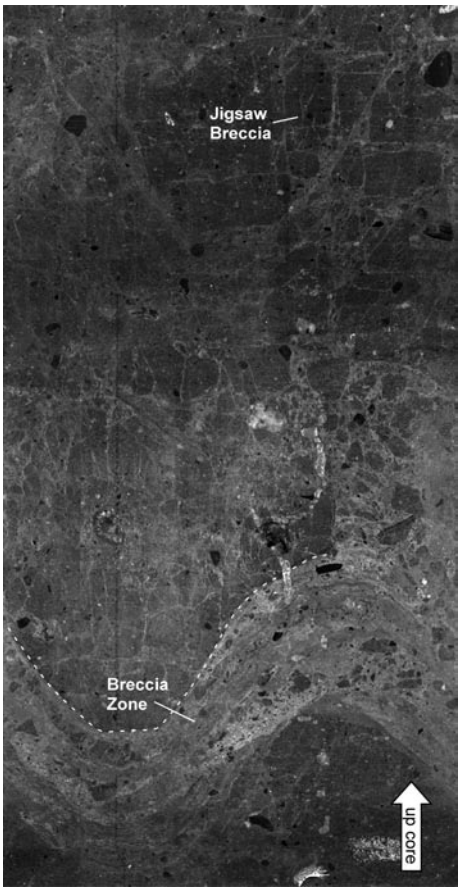


*Fig. 11* – Whole-round CoreScan II™ image of a 'jigsaw' breccia with a well-defined planar breccia zone near the base of the image at 649.29 mbsf in the AND-2A core. Core is 6.1 cm in diameter

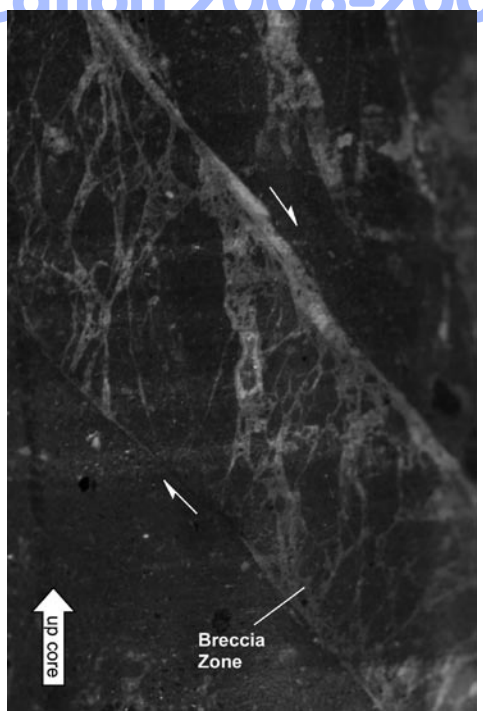


*Fig. 12* – Photograph of a calcite cemented breccia within a tabular normal fault zone at 920 mbsf in the AND-2A core. Core is 6.1 cm in diameter.

### *Sedimentary Intrusions*

Many closed fractures filled with granular material occur throughout the AND-2A core and appear to be sedimentary intrusions. Some intrusions clearly originate from sedimentary beds below and contain material derived from it; others are filled with clastic material of unknown origin. Irregular intrusions have thicknesses ranging from 2 to 15 mm. In many cases

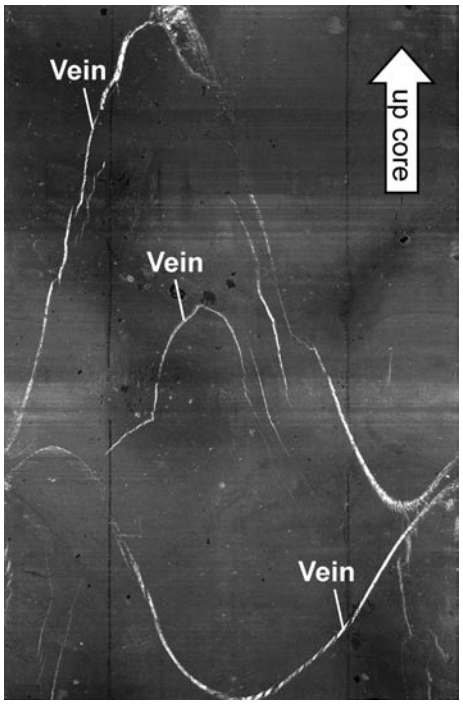


*Fig. 13* – Whole-round CoreScan II™ image of calcite veins with a rough conjugate geometry and dips typical of normal faults (50 to 75 degrees) at 896.72 mbsf in the AND-2A core. Core is 6.1 cm in diameter.

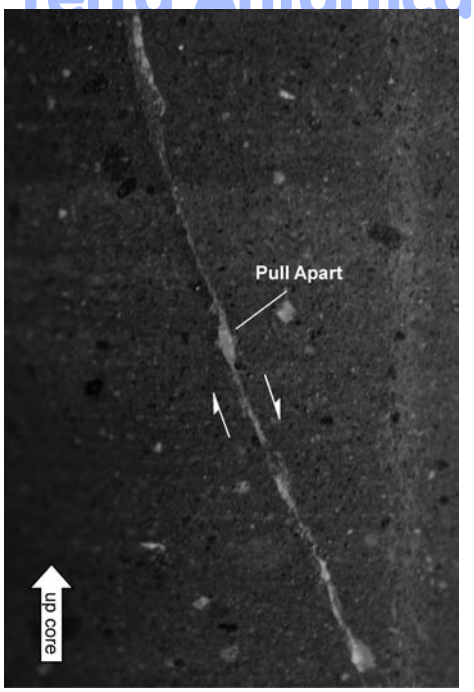


*Fig. 14* – Photograph of a calcite-filled pull apart indicating normal-sense fault displacement at 1173.62 mbsf in the AND-2A core. Core is 4.5cm in diameter.

intrusions have steep dips typical of fault planes and are filled with granular material of either clastic or cataclastic origin (Fig. 15). These are commonly cemented by calcite and/or pyrite. Microscopic analysis will clarify their origin.

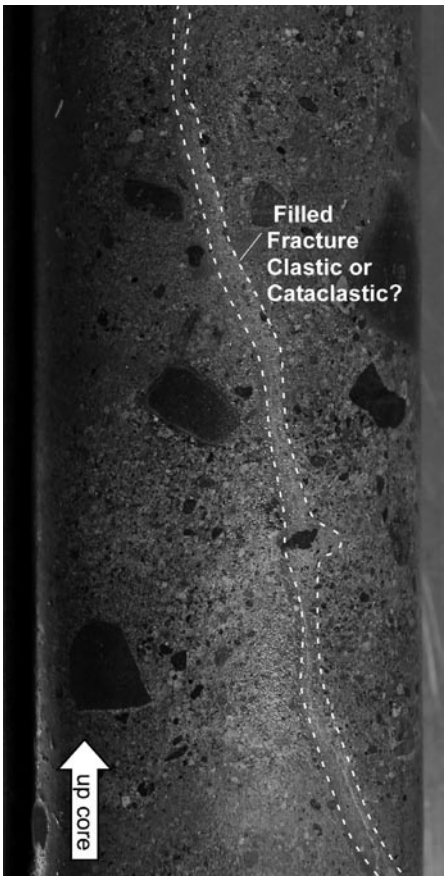


*Fig. 15* – Photograph of a clastic or cataclastic filled fracture (sedimentary intrusion?) at 533.58 mbsf in AND-2A core. Core is 6.1 cm in diameter.

## DISCUSSION

Both natural and drilling-induced fractures are abundant in AND-2A drill core. The most significant drilling-induced fractures are steeply-dipping petal, petal-centreline and core-edge fractures. These induced fractures will provide a record of the *in situ* stress orientations in the crust surrounding the borehole, once the core has been orientated. The most abundant natural fractures in the AND-2A core are normal faults and various types of calcite veins. There are also some reverse faults, abundant brecciated zones, and sedimentary intrusions in the core. The presence of sedimentary intrusions and veins documents high fluid pressures during deformation. After the core fractures have been orientated, comparison of their trends with seismically-mapped faults will help determine if the deformation is related to evolution of the West Antarctic rift system. This analysis, together with detailed correlation of the depth distribution of deformed intervals of the core with respect to episodes of glacial advance and retreat documented from the core strata, will help discriminate glaciotectonic and tectonic deformation. The abundant fractures in the AND-2A core will provide a detailed history of Neogene deformation of strata in the southern McMurdo Sound region, including paleostress and contemporary stresses driving the deformation.

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REFERENCES

Li Y. & Schmitt D., 1997. Well-bore bottom stress concentration and induced core fractures. *American Association of Petroleum Geologists, Bulletin*, **81**, 1909-1925.

Lorenz J.C., Finely S.J. & Warpinski N.R., 1990. Significance of coring induced fractures in the Mesaverde core, northwestern Colorado. *American Association of Petroleum Geologists, Bulletin*, **74**, 1017-1029.

Paulsen T.S., Jarrard R.D., & Wilson T.J., 2002. A simple method for orienting drill core by correlating features in whole-core scans and oriented borehole wall imagery. *Journal of Structural Geology*, **24**, 1233-1238.

Wilson T., Paulsen T., Läufer A., Millan C., & the ANDRILL-MIS Science Team, 2007. Fracture logging of the AND-1B Core, McMurdo Ice Shelf Project, Antarctica. *Terra Antartica*, **14**, 175-184.