Microstructural study of natural fractures in Cape Roberts Project 3 core, Western Ross Sea, Antarctica

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Abstract Microstructures in natural fractures in core recovered offshore from Cape Roberts, Ross Sea, Antarctica, provide new constraints on the relative timing of faulting and sedimentation in the Victoria Land Basin along the Transantarctic Mountain rift flank. This study characterizes the textures, fabrics and grain-scale structures from thin section analysis of samples of microfaults, veins, and clastic dikes. Microfaults are abundant and display two different types of textures, interpreted to record two different deformation modes: pre-lithification shearing and brittle faulting of cohesive sediment. Both clastic dikes and calcite veins commonly follow fault planes, indicating that injections of liquefied sediment and circulating fluids used pre-existing faults as conduits. The close association of clastic injections, diagenetic mineralization, and faulting indicates that faulting was synchronous with deposition in the rift basin.

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Introduction

The Cape Roberts Project (CRP) obtained sedimentary rock core from stratigraphic drilling offshore Cape Roberts, in the western Ross Sea, Antarctica, during the austral summers of 1997 (CRP-1), 1998 (CRP-2), and 1999 (CRP-3). The cores were recovered near the structural boundary between the Victoria Land Basin and the Transantarctic Mountains rift flank (Fig. 1), known as the Transantarctic Mountain Front, which trends NNW near Cape Roberts. One objective of the Cape Roberts Project was to study the rifting of Antarctica, in particular, the formation of the Victoria Land Basin and the Transantarctic Mountains Front (Cape Roberts Science Team (CRST), 2000). This study contributes to this objective by analyzing textures, fabrics and grain scale microstructures in the natural fractures from the *c.* 940 m of core recovered from CRP-3. These observations, together with the macrostructural features documented in the core, provide constraints on the mechanical state of the sediment during deformation and the relative timing of sedimentation and faulting during the evolution of the Victoria Land rift basin.

In the CRP-3 drillhole, the first 400 m of core is of Early Oligocene age and consists of fine-grained muddy sandstones, sandy mudstones, and diamictites (CRST, 2000). From 400 meters below sea floor (mbsf) to 823.11 mbsf, the core is of Early Oligocene to late Eocene (?) age and consists of sandstone and muddy sandstone (CRST, 2000). Minor sandstone and massive clast-supported dolerite conglomerate comprise the lowest Cenozoic strata from ~790 to *c.* 823.11 mbsf (CRST, 2000). The rest of the core, to the base at 939.42 mbsf, is mainly Devonian age quartzitic sandstone from the Beacon Supergroup (CRST, 2000).

Structures in CRP-3 core

The CRP-3 core contained abundant natural fractures, including veins, clastic dikes, faults, and breccia, described here after Wilson and Paulsen (2001). The natural fractures were classified during logging of CRP-3 core based on observations of fill materials, textures, and fracture surface features. Descriptive observations together with scale information are provided in Table 1. Not all core structures could be definitively assigned to a fracture type from core-based observations alone, and one goal of this study was to clarify the nature and origin of the natural fractures through characterization of microscopic textures and fabrics.

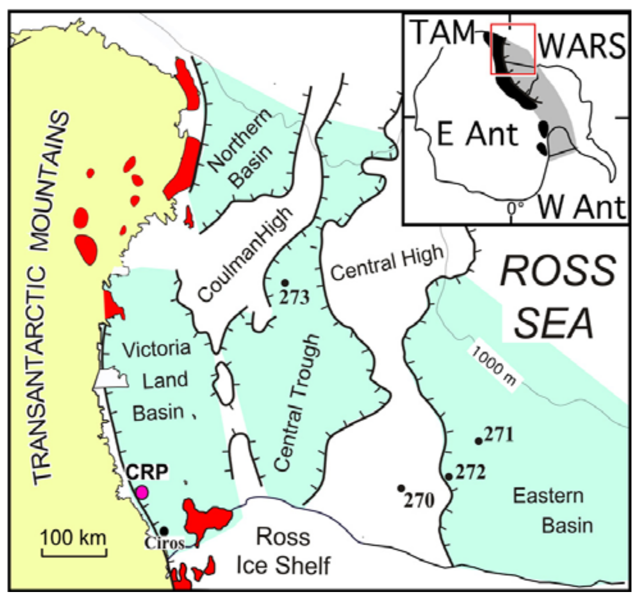

Figure 1. Rift basins of the Ross Sea. The Cape Roberts Project (CRP) drillholes located along the structural boundary between the Victoria Land Basin and the Transantarctic Mountains rift flank. Numbers denote DSDP drill sites. Inset map shows the Transantarctic Mountains (TAM; black) along the margin of East Antarctica and the West Antarctic rift system (WARS; grey shading) of West Antarctica.

Microfaults are abundant in the Oligocene sedimentary strata. The microfaults have typical offsets of up to several cm and conjugate geometries. Most microfaults have dips between 55 and 70°, well-developed slickensides, and calcite or calcite cement along the fault planes (Wilson and Paulsen, 2001). Microfaults in the Beacon sandstones show moderate dips and normal and reverse sense offset, but oblique angle striations and lineations on fault surfaces indicate a dominant oblique-shear sense displacement (Wilson and Paulsen, 2001).

Veins consist of precipitated crystalline calcite and, less commonly, pyrite. In some cases the vein-filled fractures have no evident bedding offset, in other cases veins fill faults or occur in conjugate geometries suggesting they formed along fault planes. Rarely, calcite veins show *en echelon* patterns that are composed of multiple, thin strands filled with calcite fibers, indicating they formed as opening-mode fractures. Structures classified as another type of vein, termed 'cemented bands', consist of calcite-cemented, planar bands that in many cases exhibit fault characteristics such as bedding offset and conjugate geometry.

Clastic dikes display sharp, planar boundaries and are abundant throughout the core and commonly have dips between 40 and 75°, suggesting they may also follow fault planes.

Microstructural characterization

Faults

Microfaults in the Oligocene strata of CRP-3 core have two distinct suites of microstructures (Table 1). One type of microfault shows either reverse or normal sense displacement and smearing and/or dragging of sediment within planar zones (Fig. 2). No fractured grains or brecciation of the host rock or shear zone material are observed in these faults, but localized alignment of grain long axes parallel to the zone boundaries is typical. Such features are common in sediment with high water content deformed prior to lithification (Antonellini *et al*., 1994), and are interpreted as soft-sediment shear zones where the sediment was only partially lithified to unlithified at the time of deformation. Other common microfaults are discrete planes or narrow zones that truncate bedding and, where observable, have normal-sense bedding displacement. These microfaults exhibit well-developed slickensided surfaces, grain-size reduction and cracking, and orientation of clays parallel to zone margins (Fig. 3). Calcite has precipitated in open voids and around clasts and commonly also replaces the matrix. These microfaults are interpreted as forming by brittle cataclasis of cohesive sedimentary material in the presence of abundant fluids.

Microfaults in the Beacon Sandstone are discrete, planar zones that sharply truncate bedding and have normal and reverse-sense displacement. The host rock grains commonly exhibit *in situ* 'jigsaw puzzle' fracturing and intragranular fractures and grain size reduction near the fault margins. This evidence of cataclasis of the quartz grains is interpreted to result from brittle faulting of material that was fully lithified at the time of deformation.

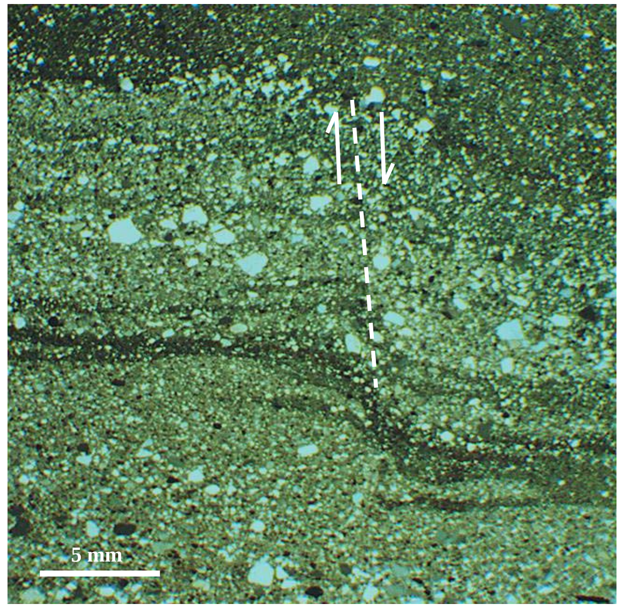

Figure 2. Shear zone with normal-sense displacement. Note flexure of bedding interpreted to indicate pre-lithification faulting (290.29 mbsf).

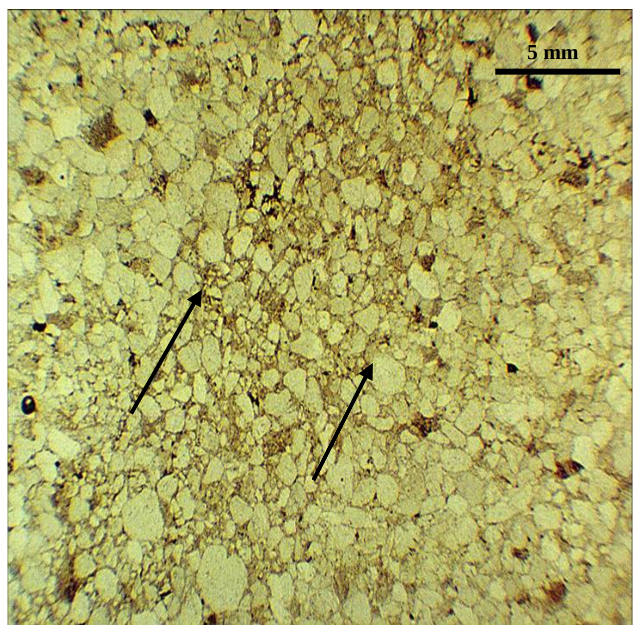

Figure 3. Most microfaults are planar zones with sharp boundaries, characterized by grains that are finer than in the host rock and by alignment of elongate grains parallel to walls (845.37 mbsf).

Veins

In the Oligocene sedimentary strata, veins are filled by calcite and, more rarely, pyrite. Calcite veins formed along faults with macroscopic displacements have calcite growing in open voids and/or filling open spaces in brecciated host rock. Rare calcite veins have clean, fibrous crystals oriented perpendicular to the vein walls that document precipitation in opening-mode fractures. Less commonly, veins with overlapping, tapering tips and *en echelon* geometry were present, a typical geometry for opening-mode fractures. Narrow, 'hairline' calcite veins are common, with moderate dips and conjugate sets typical of normal fault geometry. These veins must have been precipitated as tensile opening-mode fractures reactivating pre-existing fault planes. The vein type classified during core fracture logging as 'cemented bands', proved to consist of clastic material of larger grain size than the host rock, cemented by calcite. These structures are now interpreted as clastic dikes, not veins, and are described below.

Clastic dikes

Sedimentary dikes in the CRP-3 Oligocene strata have sharp, planar boundaries and dips consistent with those of normal faults. The fill consists of subangular to subrounded quartz grains that are coarser than the host rock (Fig. 4). Calcite and/or pyrite replace the matrix in the dikes. Clays are common and may be aligned parallel to the dike walls or occur in localized zones with inconsistent clay orientation A few 'apophyses' of dike material extend from planar dike walls and thin and taper upward (Fig. 4). There is no fracturing, grain size reduction, or fabrics in the host rock along the margins of the dikes that suggest a pre-existing fault fabric.

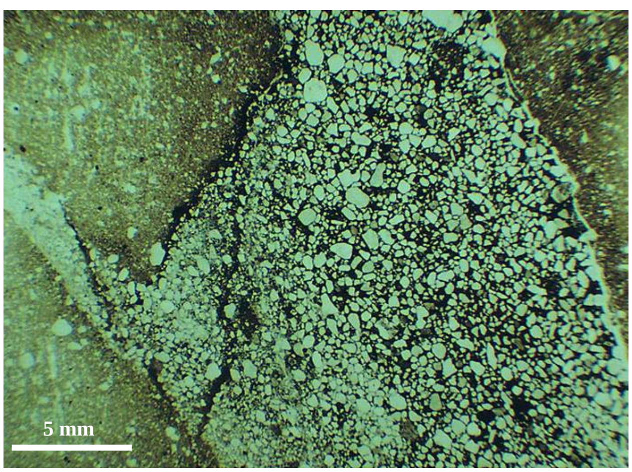

Figure 4. Clastic dike at 194.50 mbsf. Note apophyses extending upward and clastic fill that is coarser-grained than the host rock. The fill is cemented by calcite and pyrite (black material in matrix).

Discussion

Microfaults are the most abundant type of structure in the core. One type of microfault, characterized by narrow, planar, zones where sediment drags and/or is smeared along the zone, grain deformation and breakage is minimal, and clay and/or grains are oriented parallel to the zone margins, is interpreted as shear zones formed when the sediment was only partially lithified to unlithified at the time of deformation. A second microfault type consists of planar zones of material finer-grained than the host rock and characterized by sharp, discrete boundaries. Evidence of cataclasis, clay and/or grain alignment, and calcite precipitation in voids are all consistent with cataclastic faulting mechanisms acting on partially lithified to lithified material in brittle fault zones. Faults in the Beacon sandstone all are sharp, planar zones with obvious truncation and offset of bedding. The evidence of cataclasis found in the faults cutting Beacon sandstone is consistent with brittle shear of completely lithified sediment, as expected for Devonian rocks cut by Cenozoic faults.

Veins are less common than core observations indicated, because 'cemented bands' described as a vein type proved to be clastic dikes cemented by calcite. Calcite veins are commonly associated with faults, with calcite growing in open voids, filling open spaces in brecciated host rock, and growing as rims around clasts. Some calcite veins formed as opening-mode fractures with *en echelon* geometry. Other thin calcite veins must have formed by fluid precipitation along pre-existing, fault planes originally formed in conjugate geometries typical of normal faults. All these types of veins formed in sediment that was at least cohesive enough to fracture along discrete, planar surfaces, and may have been lithified.

Clastic dikes are more common than the core-based observations indicated. The larger grain size, the lack of fracturing or other fault-related fabrics, and the composition of the material in structures classed as either 'clastic dikes' or as 'cemented bands', indicate that the fills were not formed by shear-related cataclasis of the host rock and instead are sedimentary material injected into the host rock. The geometry of apophyses suggests an upward injection direction. The majority of the dikes in the Oligocene strata truncate bedding and have dip angles between 50 and 70°, similar to those of normal faults. Injection of clastic material requires opening of fractures, and the clastic dikes are interpreted to have injected along pre-existing fault planes. The sharp, planar boundaries suggest the sediment was cohesive at the time of dike emplacement, however, some degree of pore fluid in the sediments must have been present in order for the liquefied dike material to be injected. The relationship between upward injection direction and normal bedding offset, together with the evidence for ongoing compaction such as the presence of clasts pushing into and deflecting dike margins, suggest that clastic dikes were most likely using 'young' pre-existing faults as dewatering channels during ongoing compaction and lithification of the Oligocene strata.

Summary

Clastic dikes, veins, and faults are abundant throughout CRP-3 core and present at all depths and in a variety of lithologies. The microstructures identified in this study indicate that clastic dikes and some veins followed pre-existing fault planes for emplacement and precipitation. Some of the faults are shear zones formed while the sediment was ductile and only partially lithified. Other faults, showing brecciation and synchronous calcite precipitation in open space, are the result of deformation in sediment that must have been cohesive or possibly lithified. This progression from pre-lithification faults to post-lithification faults indicates faulting along the Transantarctic Mountain Front must have been synchronous with the Victoria Land Basin rifting and deposition of the sedimentary fill of the rift basin.

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Table 1. Summary description of CRP-3 core structures and their microstructures

Classification of Fracture Types: Core Logging	Core Observations of Structures	Microscopic Textures/Fabrics	Geometric Relationships	Interpreted Fracture Mode
Clastic Dikes	•3-10 mm wide •Calcite, pyrite cement •Branching upward •Sharp, planar margins	•Sharp, planar boundaries •Upward tapering apophyses •Host rock xenoliths •Clastic fill coarser than host rock •Subangular to subrounded grains •Clay aligned parallel to margins •No fractured grains	•Truncate bedding •Offset bedding •Dip angles 40–75° •Cut across dolerite boulders (in dolerite conglomerate shear zone)	•Clastic injection •Opening mode •Follow fault planes
Veins	•Calcite fill •Wavy margins •1 – 20 mm wide •Most < 4 mm wide •Some *en echelon* geometry	•Rare calcite fibers grow perpendicular to vein walls •Overlapping, tapering tips	•Dip angles 45–55° •Rare *En echelon* patterns •Crosscut bedding •Conjugate geometry	•Opening mode •Follow fault planes
Cemented Bands	•Sharp, planar margins •1-10 mm wide •Calcite cemented	•Strongly oriented clay fabric •Clastic fill coarser than host rock •Upward tapering apophyses •No intragranular fracturing •Minimal grain breakage	•Truncate bedding •Normal bedding offset •Conjugate geometry	•Clastic injection •Opening mode •Follow fault planes
Shear Zones	•Narrow, planar zones •< 1cm bedding offset	•Sediment smearing and/or dragging •Grain and clay alignment parallel to margins •No fractured grains •Calcite replacement in matrix	•Normal & reverse shear sense	•Pre-lithification faulting
Microfaults	•Discrete, planar zones •Offsets mm to > 5cm •Common slickensides •Some calcite cemented	•Grain and clay alignment parallel to margins •Brecciation of host rock •Angular grains and fragments •Sparry calcite in open voids •Some calcite cement	•Truncate bedding •Normal bedding offset •Dip 55 to 80°	•Cataclastic faulting of cohesive rock
Beacon Microfaults	•Discrete, planar zones •Offsets 2 – 7 mm •Some slickensides	•'Jigsaw puzzle' fractured grains •Grain size reduction •Angular fragments •Intragranular fractures	•Truncate bedding •Dip angles 45–55° •Normal & reverse bedding offset	•Cataclastic faulting of lithified rock