Facies Control on Diagenesis in Frozen Sediments: The Sirius Group, Table Mountain and Mount Feather, Dry Valleys, Antarctica

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Abstract - A petrographic study of the Sirius Group from two locations in the Antarctic Dry Valleys shows distinct differences in both the detrital and diagenetic components of the sediments. The predominantly glaciofluvial depositional environment at Table Mtn. produced a sediment with less matrix and better sorting than did the subglacial depositional environment at Mt. Feather. This set the stage for different diagenetic events to occur because burial histories at both locations are similar. Diagenesis in Sirius Group sediments consists of major modification to primary porosity, dissolution of mostly feldspar framework grains, and precipitation of authigenic chabazite and calcite. Dissolution porosity and authigenic cement dominate at Table Mtn., whereas the development of primary porosity and matrix fabric dominate at Mt. Feather. A working model suggests that at Mt. Feather the pores and matrix fabric developed under wet, periglacial conditions through repeated cycles of freezing and thawing or wetting and drying. This is inferred to have occurred when the diamicite was soft and moist during a period when the climate was warmer than present and when water was more abundant. At Table Mtn. dissolution porosity and precipitation of the authigenic cements, calcite and chabazite, occurred under permanently frozen conditions. This is possible because ionic migration may occur in frozen sediments along interfacial films of brine. These highly saline and alkaline films provide the chemical conditions under which calcite and chabazite can precipitate in dry, subzero conditions.

INTRODUCTION

The Sirius Group (McKelvey et al., 1991) is composed of consolidated, glacial sediments preserved in isolated outcrops along the Transantarctic Mountains for nearly 1500 km. Mayewski (1975) proposed that the Sirius Group was stratigraphically the oldest, wet-based glacial deposit in the Transantarctic Mountains and most subsequent observations concur with this. It is important because it represents the last occurrence of wet based glaciation before the onset of the present stage of dry, cold based glaciation in the Transantarctic Mountains. Thus, as a climatological indicator, the Sirius Group reflects the stability of the warm to cold transition of the East Antarctic ice sheet.

The age of the Sirius Group, which is critical to understanding the stability of the East Antarctic ice sheet, has been hotly debated (Harwood and Webb, 1998; Miller and Mabin, 1998; Stroeven et al., 1998) because of a lack of stratigraphic control and absence of datable material. However, in the Dry Valley region, stratigraphic relationships (Barrett and Powell, 1982; Denton et al., 1993), volcanic ash ages (Marchant et al., 1993) and cosmogenic exposure ages (Ivy-Ochs et al., 1995) strongly suggest that the Sirius Group mantles a mid-Miocene landscape.

In the Dry Valley region it is not clear if the Sirius Group was deposited as a near synchronous event at the base of the East Antarctic ice sheet (Barrett, 1996; Mayewski, 1975; Webb and Harwood, 1991) or at different times at the base of numerous alpine-type glaciers (Passchier, 2001; Stroeven and Prentice, 1997; Wilson et al., 2002). Mercer (1968) recognized that not only are Sirius Group outcrops geographically different, but they are also depositionally different. Hicock et al. (2003) showed that the Sirius Group, which crops out at Mt. Feather (Fig. 1), was deposited as a lodgment till as part of a wet based glacial outlet system when the Transantarctic Mountains were about 1,500 m lower than today. At Table Mtn. (Fig. 1), which is about 35 km in the paleo down stream direction from Mt. Feather, Goff et al. (2002) found the domination of glaciofluvial and glaciolacustrine facies and suggested they represented a distal part of the Sirius Group environment. Thus, in the Dry Valley region, at least two major facies of the Sirius Group are present; the subglacial deposits proximal to the paleo glacier and the fluvial-lacustrine deposits distal to the glacial system.

This paper investigates the petrological differences between these two facies in the Sirius Group at Table Mountain and Mount Feather. We aim to show that
differences in framework mineralogy reflect the facies differences visible on the outcrop. This is important because it will help in understanding other Sirius Group deposits where facies distinctions on the outcrop are not clear. However, early in the study, we also recognized that the petrology of the Sirius Group showed a long history of cold climate diagenesis, which was dependent on the nature of the depositional facies. This not only added weight to the antiquity of the Sirius Group but also provided a case study where it could be demonstrated that diagenesis was controlled by facies deposition and not burial conditions. This paper documents diagenesis, which is rare in glacial sediments, and it provides an example of diagenesis, which takes place under mostly frozen conditions.

SETTING

Antarctica has been a frozen continent for the past 15 m.y., and in the Dry Valleys, landscapes at high elevations (>1000 m) have developed under an extreme hyperarid, frigid regime in the virtual absence of running water (Denton et al., 1993; Marchant et al., 1993; Sugden et al., 1995). Thus, Sirius Group sediments in the Dry Valley region have remained under polar conditions and have only been exposed to small, if any, amounts of liquid water since deposition. At Mt. Feather and Table Mtn., moisture from windblown snow amounts to less than 5 cm per year and surface temperatures, which are rarely above freezing, average between 25 to 30° C (Pringle et al., 2003; Thompson et al., 1971). Sirius Group sediments, which crop out at both these areas, have a hardness of dried mud and are generally ice-free to a depth of about 50 cm. Below this depth, the sediments are ice-cemented and virtually impossible to excavate without powered equipment.

There are several mechanisms by which this ice at depth may have evolved. 1) Glacial meltwater may have entered the sediments at the time of their deposition or during a subsequent warm period (Campbell et al., 1998). 2) Vapour from the evaporation of snow diffused downward into the colder subsurface and accumulated as ice cement. 3) Brine films formed by salt accumulation at the surface could migrate downward into the ground at subzero temperatures and provide aqueous recharge of ice cement at depth (McKay et al., 1998). Dickinson and Rosen (2003) favour a combination of mechanisms two and three.

Despite the importance of the Sirius Group, its petrographic characteristics remain poorly understood. Work by van der Meer et al. (1998) on microfabrics in Sirius Group samples from Mt. Feather shows a combination of microstructures that indicate deposition under temperate subglacial conditions. Barrett et al. (1997), Dickinson (1998), and Dickinson and Grapes (1997) show from petrographic work on samples from Mt. Feather and Table Mountain that the Sirius Group contains up to 26% porosity and has undergone significant mineral diagenesis. Work presented in this paper shows there are distinct differences in the petrography of the Sirius Group from outcrop samples at these two sites, which are separated by about 35 km in distance and 700 m in elevation (Fig. 1).

Fig. 1 – A) Location map shows sample area at Mount Feather and Table Mtn. in the Dry Valley region. B) Geological map of Table Mtn., after Woolf et al. (1989), shows the two sampling sites. Cross section A-A’ (inset) shows location of two sub sites. C) Geological map of Mt. Feather, after McElroy & Rose (1987), shows the locations of the sampling sites.
MOUNT FEATHER

The Sirius Group crops out as a gently dipping veneer of sediments on the northeast ridge of Mt. Feather in a confined area of 0.6 km² at an average elevation of about 2,520 m (Fig. 1). It is a light grey, sandy diamicton containing boulders, gravel, sand, and mud, which were deposited subglacially (Hicock et al., 2003). The deposit, estimated to have a maximum thickness of 37 m (Brady and McKelvey, 1979), rests on an erosional unconformity cut into nearly flat-lying strata of the Beacon Supergroup. Three formations of the Beacon Supergroup exposed on the upper slopes of Mt. Feather are; 1) the Weller Coal Measures (Permian), 2) the Feather Conglomerate (Permian to Early Triassic) and 3) the Lashly Formation (Triassic). These formations are unconformably on the Feather Conglomerate (Permian to Early Triassic) and the Lashly Formation (Triassic). These formations are intruded by sills of the Ferrar Dolerite (Middle Jurassic). The Sirius Group at Mt. Feather is a diamicton, which lacks evidence of internal stratification and consists of a mixture of boulders, gravel, sand, and mud (Hicock et al., 2003). At the western cliff section, the Sirius Group lies unconformably on the Feather Conglomerate, however, the color and nature of the matrix strongly suggests that much of it has been inherited from the Lashly Formation.

TABLE MOUNTAIN

On the northwest flank of Table Mtn., Sirius Group sediments crop out in a series of ridges and hollows along a linear band about 2 x 5 km at an average elevation of about 1850 masl (Fig. 1). Cores from Table Mtn. show the Sirius Group to be at least 9.5 m thick, and, if adjusted for topography, it would have a minimum thickness of about 15 m (Goff et al., 2002). Similar to the exposures on Mt. Feather, Sirius sediments lie on a gently sloping erosional surface which truncates nearly flat-lying strata of the Beacon Supergroup. On the upper part of the slope, the Sirius Group lies unconformably on the Terra Cotta Siltstone (Early Devonian) and several thin sills of Ferrar Dolerite. On the lower part of the slope, the basal contact of the Sirius Group is not exposed, but it probably rests on the Windy Gully Sandstone. Goff et al. (2002) subdivided the Sirius Group at Table Mtn. into three facies; a gravelly sandstone, a sandstone, and a sandy conglomerate. The sandstone facies, predominantly glaciofluvial, is a well-sorted, fine-to medium grained sand and dominates the outcrop (Goff et al., 2002).

METHODS AND SAMPLING

Samples used in this study were collected in November of 1994 and 1996 as part of a project to determine the occurrence of diatoms in the Sirius Group (Bleakley, 1996). Three sites from each area were selected to collect representative samples of the Sirius Group (Fig. 1). For comparative purposes, framework mineralogy was determined on the outcrop scale as well as the microscopic scale. On the outcrop at each site, the lithology of 60 clasts with A-axes longer than 15 mm was determined along a transect of 10 m – 20 m (Tab. 1). For sieve and microscopic analysis, samples were collected near the centre of the transects from shallow pits as they were dug with a hammer from the surface down to the top of the ice-cemented (permafrost) horizon, which ranged from 30 to 50 cm deep. Approximately 0.5 kg of sample was chipped out in fist sized chunks from the floor of each pit at different depths as it was excavated.

Samples from the pits were analyzed for their grain size distribution of clay, silt, mud (clay + silt), sand, and gravel. Between 100 and 200 g of sample was disaggregated in distilled water with 10 minutes of mechanical stirring and gentle ultrasonic treatment. Most samples came apart easily but a 1 M solution of NaOH was used in lieu of distilled water on some of the samples from Table Mtn. to break down a zeolite cement. Samples were dried and weighed, and the gravel fraction (<2 mm) was physically removed and weighed separately. A 20 g split was wet-sieved into sand and mud fractions. The sand fraction was then dry sieved and the mud fraction analyzed by a Sedigraph 5100 (Tab. 1). Mean size and sorting (Tab. 1) were calculated from the moment method of Folk, 1980).

Grain mineralogy and the nature of pore spaces were determined by thinsection analysis. Whole samples 3 to 5 cm in diameter were vacuum impregnated with blue dyed epoxy (Shell Epon 815 with 15% BGE), after which, they were cut and ground to 30 microns for standard thinsection preparation. Modal analysis was determined from 300 point counts of each slide (Tab. 2). The blue dyed epoxy insures identification of natural porosity because artificial porosity, created by thinsection preparation, will be colorless. To eliminate ambiguity, criteria used to identify minerals and pores in thinsection were specified (Tab. 2). Because primary porosity is uncommon to glacial sediments, the dimensions of the pores, which are common in Sirius Group sediments were measured (Tab. 3). For Mt. Feather samples, the long (L) and short (S) axes of 100 pores in selected samples were measured and average pore size was determined as (L x S)0.5. However, pore sizes in the Table Mtn. samples were too small (<0.05mm) and irregular to measure with consistency. Selected samples were also chosen for X-ray diffraction (XRD) analysis of clays.

RESULTS WITH DISCUSSION

Distinct differences in the petrography of Sirius Group sediments exist between Mt. Feather and Table Mtn. (Tab. 3, Fig. 2). Variation within each of these
areas is also significant, but overlap in petrographic parameters between the two areas is negligible (Figs. 2, 3, 4).

**GRAIN SIZE AND CLAST LITHOLOGY**

Ternary plots show a clear separation in grain size between Mt. Feather and Table Mtn. (Fig. 2A). The grouping of points is more scattered for the gravel-included plot than for the gravel-free plot. This is probably because of the bias in the gravel size range caused by the relatively small-sized samples (100-200 g) used for analysis. Mt. Feather samples are more gravelly and muddy than Table Mtn. samples, which are sandy. The mean size of the gravel-free samples for Mt. Feather is coarse silt, but for Table Mtn. it is fine sand (Tab. 3). Sediments from Mt. Feather are extremely poorly sorted whereas those from Table Mtn. are very poorly sorted (Tab. 3). These differences reflect the differences in depositional environments from the well sorted glaciofluvial...

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**Tab. 1 — Grain size and clast lithology.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Sample Depth (cm)</th>
<th>Gravel Included (%)</th>
<th>Gravel-free (%)</th>
<th>Outcrop Lithology (% clasts &gt;1.5 mm)</th>
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<tr>
<td></td>
<td></td>
<td>Gravel</td>
<td>Sand</td>
<td>Mud</td>
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<tr>
<td>0-2</td>
<td>19.1</td>
<td>59.4</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td>2-7</td>
<td>15.4</td>
<td>64.5</td>
<td>20.1</td>
<td></td>
</tr>
<tr>
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<td>22.6</td>
<td>56.5</td>
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<td>17-27</td>
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<td>66.1</td>
<td>25.4</td>
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<td>21.9</td>
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<td>59.5</td>
<td>26.9</td>
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<td>7-10</td>
<td>---</td>
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</tr>
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</table>

* Mean phi size and sorting calculated by moment method (Folk, 1980)
* (on ground surface) Qtz=quartz; Dol=dolomite; Silt=slatestone; Sdirt=sandstone; C-Sdt=coarse sandstone; Q-Cgl=quartz conglomerate; Sh=shale
--- not measured

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**Fig. 2**— Ternary plots show A) grain size with gravel-free inset and B) framework grain distribution with rock fragment inset for Mt. Feather (open circles) and Table Mtn. (solid squares). IRF = igneous rock fragments, MRF = metamorphic rock fragments, SRF = sedimentary rock fragments.
deposits at Table Mtn. to the subglacial diamicton at Mt. Feather.

From the transect counts, Sirius Group sediments at Mt. Feather are dominated by clasts of coal and well rounded quartz, whereas at Table Mtn., they are dominated by sub-rounded to angular clasts of dolerite and sandstone (Tabs. 1 & 3). This reflects the different lithologies of the Beacon Supergroup that are in close proximity to Sirius Group sediments. At Mt. Feather, the Sirius lies close to outcrops of Weller Coal Measures and Feather Conglomerate, the source of the well rounded quartz pebbles, but at Table Mtn. it lies on top of the Windy Gully Sandstone (outside map area, Fig. 1), Terra Cotta Siltstone, and Ferrar Dolerite. That the composition of glacial sediments closely reflects the composition of the bedrock over which a glacier travels has been well documented (Benn and Evans, 1998; Hambrey, 1994).

**DETRITAL MINERALOGY**

On the microscopic scale, significant differences in detrital or framework grains also exist between Mt. Feather and Table Mtn. Most framework grains are recognized as having been derived from the local rock types; dolerite, sandstone, siltstone, and coal. The grains range from rounded to sub-angular, and...
large particles are generally rounder than small particles. Major framework grains, plotted on ternary diagrams (Fig. 2B), show a distinct separation. This probably is due to differences in source rocks because samples with similar size fractions have different mineralogies. Although Brady and McKelvey (1979) note the presence of metasedimentary clasts, we did not observe them on outcrop, but their presence as rock fragments (MRF) is unmistakable from thinsection mineralogy (Fig. 2B).

Minor framework grains, included as rock fragments in the quartz, feldspar, and rock fragment (QFR) plot (Fig. 2B), consist mainly of opaques and heavy minerals. Abundant opaque grains, which are mostly coal fragments, in the Mt. Feather samples reflect the nearby source from the Weller Coal Measures (Tab. 3). Although the Table Mtn. samples contain only trace amounts of coal grains, their presence indicates that they were transported at least 20 km from the closest known outcrop of the Weller Coal Measures. The reason for the greater abundance of heavy minerals in the Table Mtn. samples is not clear but must relate either to source material or depositional winnowing of Beacon sands in the glaciofluvial environment. Such winnowing of sands in the subglacial environment of Mt. Feather would be minimal.

All of the clay minerals in the Mt Feather and Table Mtn. samples are considered to be detrital as both thinsection and SEM observations showed no evidence for diagenetic clays. The greater amount of clay matrix at Mt. Feather reflects the subglacial depositional environment. Although variations in the amounts of clay minerals (Tab. 2) are not quantitative, their presence or absence must be related to variations in the source rocks. Notably, in Mt. Feather samples smectite is absent, but kaolinite gives a consistently strong peak.

**POST-DEPOSITIONAL ALTERATIONS**

Sirius Group sediments at both Mt. Feather and Table Mtn. have undergone several post-depositional alterations which include: 1) the modification of original or primary porosity, 2) the development of fabric in clay matrix, 3) the dissolution of framework grains, and 4) the precipitation of authigenic cement. The timing of pore formation is difficult to demonstrate, and for this reason we use the following definitions. Primary porosity is the void space between grains at the time of deposition and before lithification. This constraint is necessary because Sirius Group sediments appear to straddle the boundary of lithification. In the ice-cemented horizons, generally below 50 cm, the sediments are frozen, while above in the ice-free horizon, the sediments are dry and hard but very friable. Horizons of authigenic minerals also provide some degree of lithification. However, if the climate were warmer and the sediments were saturated with water, they would be soft and deformable and clearly un lithified. Under such a climatic regime, porosity

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**Fig. 3**—Plots shows distributions of authigenic cement (calcite + chabazite) and primary porosity as a function of depth. Values are averaged for the three sites in each area. Data are from table 2.
could form as a result of periglacial processes. Secondary porosity, usually defined as being created 

\textit{in situ} after sediment deposition, is used in this paper to include only the porosity that results from the dissolution of framework grains. Thus, for Sirius Group sediments, if the porosity is not formed by dissolution, it is deemed to be primary.

**Primary Porosity and Clay Matrix**

At Mt. Feather, primary porosity is highly variable and ranges from 1 to 22\%, averaging 10\%; while at Table Mtn. it is less variable and ranges from 0 to 10\% but averages 5\% (Figs. 3 & 4; Tabs. 2 & 3). Averaged porosity for the sites in each area shows no trend with depth (Fig. 3). In Mt. Feather samples, high porosity generally correlates to large pore sizes, averaging over 200 microns (long axis), and low porosity correlates to small pore sizes, around 30 microns (long axis). Variability is such that both porous and non-porous patches occur within the square centimeter area of a thinsection. The shape of the pores is generally elongate, but may range from large and nearly equidimensional pores to small cracks which parallel grain surfaces (Fig. 5A). These small cracks in the Mt. Feather samples may have resulted from shrinkage during drying, but, because the outcrop samples were dry with less than 10\% moisture, we assume that most of this shrinkage occurred on the outcrop rather that when the sample was dried prior to impregnation with blue-dyed epoxy for thinsectioning.

Micromorphological modification of primary porosity and clay matrix (termed plasma by (van der Meer, 1993)) to produce oriented fabrics are important to the syndepositional and post-depositional history of Sirius Group sediments. These fabrics result from the reorientation of clays, which is produced by stress fields from either the rotational movement of grains during subglacial deformation or from periglacial processes (van der Meer, 1993). In most samples it is not possible to determine which process may have produced the fabric. Oriented clays are seen as thin bands of birefringent alignments, and the strength of their orientation depends not only on the amount of clay but also on the stresses applied to the sediment (van der Meer, 1993).

In most of the Mt. Feather samples, two types of plasma fabrics, skelsepic (clay particles oriented around grains) and lattisepic (clay alignments at right angles to each other) are weakly to moderately developed. These matrix clays occur in large patches around grains and pores, and form birefringent halos around many pores (Figs. 5A & C). At Table Mtn., a masepic (clay particles oriented in bands of one direction) fabric dominates, and the clays occur in sub-parallel, laminae running between and around grains (Fig. 5B). Although some clay laminae are bedding features of the glaciofluvial facies at Table Mtn., other clay laminae as seen on the microscopic level are post-depositional, which is demonstrated by the birefringence of aligned clays.

In all of the samples a distinct relationship exists between clay matrix and primary porosity (Fig. 4). In glacial diamicts such as the Sirius Group at Mt. Feather, primary porosity must have been negligible because matrix clays would have occupied most all of the intergranular space, which is what is observed in modern subglacial deposits. In glaciofluvial sediments, such as the Sirius Group at Table Mtn., primary porosity would have been similar to that of other fluvial sediments and considerably greater than primary porosity in diamicts. To create the porosity seen in the Sirius Group sediments, matrix clays must have undergone a physical redistribution during syndepositional or post-depositional modification. The alignment of clays, which are detrital, is shown by their unit extinction parallel to their axis of alignment (Fig. 5C). Although the process that may have caused clay alignment is not clear, liquid water must have been present for this to occur. This may have occurred under wet periglacial conditions through repeated cycles of freezing and thawing or wetting and drying, which would result in elongate and crack-like pores. Thermal contraction from seasonal cooling can form polygonal ground (Marchant et al., 2002), which is present on Sirius Group outcrops at Table Mtn. and Mt. Feather, and this process may also have played a role in pore formation.

**Grain Dissolution**

The dissolution of framework grains to create secondary porosity is a relatively common (<4\%)
diagenetic feature in samples from Table Mtn. (Fig. 5D), but is only a minor (<1%) feature in samples from Mt. Feather. The partial to complete dissolution of grains is clearly a post-depositional event because these grains are unlikely to survive glacial transport. Most affected are feldspar grains, which characteristically dissolve along their crystallographic planes. Ferromagnesian grains also show signs of dissolution but to a lesser extent than feldspars. This difference must be related to the chemistry of the pore fluids, which cause dissolution. Dissolution is not restricted to the surface weathering zone because Jennings (1997) observed it at a depth of 6.5 m in core from Table Mtn., while Dickinson (1998) observed it at 2.5 m depth from Mt. Feather.

**Authigenic Cement**

Authigenic minerals, consisting of calcite and the zeolite mineral, chabazite, are present at Table Mtn. The chabazite is rich in sodium and has an average composition of:

$$(\text{Ca}_{0.9}\text{Na}_{1.9}\text{K}_{0.2})\text{Al}_{3.9}\text{Si}_{8}\text{O}_{24} \cdot 6\text{H}_{2}\text{O}$$

(Dickinson and Grapes, 1997).

In samples of this study from the ice-free horizon, the abundance of chabazite and calcite appear to decrease with depth (Fig. 3). Although the precipitation of the chabazite is clearly authigenic and requires a liquid phase, the mechanism by which precipitation occurs is less clear. Dickinson and Grapes (1997) suggested it was related to the boundary between the ice-free and ice-cemented horizons. As the ice-cement sublimes near the surface, a film of brine becomes more concentrated until precipitation occurs by efflorescence. However, because chabazite is pervasive to a depth of 9.5 m, Dickinson and Rosen (2003) suggested that brine films in the frozen sediments transported the solutes for precipitation. Gibson et al. (1983) also reported authigenic chabazite in the Prospect Formation of the Wright Valley from a site about 1000 m lower and 45 km north of Table Mtn. They found it in their deepest sample (80 cm) from the ice-cemented horizon about 40 cm below the base of the ice-free horizon.

The timing and relationship of chabazite and calcite precipitation are difficult to determine without a detailed examination of the ice-cemented horizon below our samples. However, their precipitation appears to overlap with grain dissolution. This is because both cements are distinctly more abundant in the primary pores than in the secondary pores (Fig. 3A).
suggesting that the minerals precipitate in secondary pore space as it becomes available. Many calcite crystals encase chabazite and this also implies the chabazite was there first. The precipitation of calcite may represent a wetter phase of climate because calcite precipitates in lower pH and less alkaline conditions than zeolites (Surdam, 1981). However, it is likely that dissolution and precipitation of authigenic minerals are continuous events that overlap each other in time.

The dissolution of grains and precipitation of authigenic cements necessitates a liquid phase for the transport of ions. A working model suggests that the primary pores and matrix fabric developed under wet, periglacial conditions through repeated cycles of freezing and thawing or wetting and drying. Chabazite and calcite probably precipitated later or after the sediment became permanently frozen. These minerals are typical of high pH, alkaline chemical environments that could exist in frozen ground along interfacial films of brine (Dickinson and Rosen, 2003). Highly saline and alkaline films may provide the chemical conditions under which minerals can precipitate and dissolve in dry, subzero conditions as well as in the ice cemented horizon at depth.

**SUMMARY AND CONCLUSIONS**

At the start of this study it was not clear if the grain dissolution and precipitation of authigenic minerals was related to surface weathering or diagenesis, which, by definition, is not confined to a surface horizon. However, their diagenetic nature was confirmed with the examination of cores from Mt. Feather (Dickinson, 1998) and Table Mtn. (Dickinson et al., 2003; Jennings, 1997), which showed similar alteration features to those observed in the surface samples of this study. Previous work showed that Sirius Group sediments at Table Mtn. and Mt. Feather were deposited in different sedimentary environments and our study now confirms that source rocks for the Sirius Group in each of these areas are also different. Both of these factors have produced differences in the mineralogy of the framework grains as well as in texture and grain size, which have then set the stage for different diagenetic events.

Since the deposition of the Sirius Group, both areas have had similar geologic and climatic histories. Although neither area has been buried by sediments and each has been subject to similar rates of erosion, they may or may not have been covered by glaciers at different times. Mt Feather is about 700 m higher in elevation than Table Mtn. and would have been colder by only 5°C. Thus, differences in diagenesis must be attributed to differences in source rocks and depositional environments rather than post-depositional histories. Furthermore, the depositional environment appears to be more important in controlling the diagenetic features than do the source rocks. This is based on preliminary thinsection examination of Sirius Group samples from two other locations in the Dry Valley region. Sirius Group deposits at Mt. Fleming and Allan Hills are subglacial diamicts similar to that at Mt Feather. These deposits have different source rocks but their diagenetic features are similar to those seen at Mt Feather, suggesting that depositional environment is more important than source rock.

Diagenesis in Sirius Group sediments consists of major modification to primary porosity, dissolution of mostly feldspar framework grains, and precipitation of authigenic minerals. Although no authigenic minerals were observed from Mt Feather, primary porosity at Mt Feather has been modified to a greater extent than at Table Mtn. We believe that porosity modification took place under periglacial conditions, which were wetter, and thus warmer than present. This is because it is difficult to conceive how the alignment of detrital clays could take place under either dry or frozen conditions. The mechanisms by which large pores are created in a clay matrix as seen in the Mt Feather sediments or by which detrital clays become aligned into laminated bands as seen in the Table Mtn. sediments remain unclear.

In contrast to primary porosity, grain dissolution and the precipitation of authigenic chabazite is much more prevalent at Table Mtn. than at Mt. Feather. We suggest this is largely because of the increased permeability in Table Mtn. sediments which have better sorting and less clay than Mt. Feather sediments. Because Sirius Group sediments in the Dry Valley region have been under polar conditions since deposition, dissolution and precipitation via a liquid phase must have been limited. The most probable mechanism to mobilize ions in a frozen environment appears to be brine films (Dickinson and Rosen, 2003), which can remain liquid to −50°C (Brass, 1980). While the brine film model may provide a mechanism for diagenesis, additional work is required to understand why chabazite, also reported from the Wright Valley (Gibson et al., 1983), preferentially precipitates in frozen, alkaline environments. This may become more clear if the brine film mechanism can be chemically modelled, and other occurrences of authigenic zeolites are found in the Dry Valleys.

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REFERENCES


Bleakley N.L., 1996. The geology of the Sirius Group at Table Mountain and Mount Feather, South Victoria Land, Antarctica, School of Earth Sciences, Victoria University of Wellington, 273.


