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Mineralogy and chemistry of a mesofauna-microbe bearing Early-Middle Miocene Antarctic paleosol

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With 5 Figures

Abstract

Fossil mesofauna and bacteria from a paleosol in moraine situated adjacent to the Inland Ice, and dating to the earliest glacial event in the Antarctic Dry Valleys opens several questions, the most important of which is the mineralogy and chemistry of the weathered substrate habitat in which Coleoptera apparently thrived at some point in the Early Miocene and perhaps earlier. Here Coleoptera remains were only located in one of six horizons in a paleosol formed in till deposited during the alpine glacial event (>15 Ma). XRD analysis of the bulk <2 mm matrix material and <2 µm clay fraction of the horizons constituting the paleosol, reveal a composition of primary minerals related to the source rock of the till which is mixed Beacon Supergroup quartzitic sandstone, felsic and mafic gneiss, granite and dolerite. All horizons contain variable amounts of quartz, albite and microcline which are compatible with the country rock as well as pyrophyllite sourced from metamorphic terrain and evaporites including laumontite, halite, gypsum and hexahydrite. Clay constituents include illite and chlorite, all of which are considered sourced from Antarctic shield rock or from preweathered surface environments. A tendency for quartz to decrease upward in the section may be a detrital effect or a product of dissolution in the early stage of profile morphogenesis when climate was presumably milder, the depositing glacier a temperate type. Discontinuous distributions of smectite, laumontite and hexahydrite may have provided nutrients and water to mesofauna and bacteria during the early stage of biotic colonization of the profile.

Mineralogie und Chemie eines antarktischen Paläobodens aus dem Frühen bis Mittleren Miozän

Zusammenfassung

Die fossile Mesofauna und Bakterien aus einem Paläoboden einer Moräne vor dem Inlandeis, die zum frühesten Gletscherstand der antarktischen Dry Valleys datiert wurden, stellen mehrere Fragen. Die wichtigste davon ist die Mineralogie und Chemie des verwitterten Substrats, offensichtlich dem Habitat, in dem Coleoptera im frühen Miozän oder früher lebten. Reste von Coleoptera wurden hier nur in einem von sechs Horizonten gefunden, in einem Paläoboden in einer Grundmoräne, die im alpinen Gletscherstand vor mehr als 15 Millionen Jahren abgelagert wurde. Röntgendiffraktionsanalyse des Matrixmaterials < 2 mm und der Tonfraktion < 2 µm der Horizonte des Paläobodens zeigen die Zusammensetzung des Gesteins der Grundmoräne, nämlich gemischten quarzitischen Sandstein der Beacon Supergroup, felsischen und mafischen Gneis, Granit und Dolerit. Alle Horizonte enthalten variable Mengen von Quarz, Albit und Mikroklin wie im Felsuntergrund, Pyrophyllit aus metamorphen Gebieten und Evaporite einschließlich Laumontit, Halit, Gips und Hexahydrit. Der Ton enthält Illit und Chlorit, als deren Ursprung das Gestein des Antarktischen Schilds oder verwitterte Oberflächen betrachtet werden. Dass der Quarz in den Profilen nach oben abnimmt, kann ein detritischer Effekt sein oder die Folge von Lösung im frühen Stadium der Morphogenese des Profils, als das Klima vermutlich milder und die Gletscher temperiert waren. Diskontinuierliche Verteilung von Smektit, Laumontit und Hexahydrit kann der Mesofauna und den Bakterien während des frühen Stadiums der biotischen Besiedlung Nährstoff und Wasser geliefert haben.

1. Introduction

Recent Paleogene and Neogene climatic reconstructions, particularly work by De Conto and Pollard (2003), Young et al. (2011) and Passchier (2011), indicate the initiation of Cenozoic ice began on the Gamburtsev Subglacial Mountains and other high mountains, as the global atmosphere cooled ~34 Ma during the Oligocene. Decline of atmospheric CO_2 and strengthening of the Antarctic circumpolar current combined to produce several ice margin fluctuations in synch with orbital rhythms, the latter probably related to emplacement of alpine moraines (Campbell and Claridge, 1987) in the New Mountain area of the Dry Valleys as discussed herein. Previous work by Lewis et al. (2007), Ashworth and Kuschel (2003) and Anderson et al. (2011) documents Middle Miocene cooling and demise of biota from East Antarctica, the Dry Valleys and the Antarctic Peninsula, all part of global climatic change underway in the Late Neogene that began in the latest Eocene/Early Oligocene transition. The tundra demise in the Transantarctic Mountains elucidated in these papers focuses on Neogene sediment and fossil biota with little reference to paleosols that are here seen to contain not only microfossils but paleoenvironmental evidence in the enclosing weathered sediment.

Paleosols are long-term recorders of parent material weathering and bioclimatic fluctuations (cf. Beyer et al., 1999; Bockheim, 1979, 1990; Mahaney, 1990; Mahaney et al., 2001; Birkeland, 1999; Retallack and Krull, 1999; Retallack et al., 2007). They serve as repositories of environmental perturbations that occur over varying lengths of time and in this case since at least the Middle Miocene. Adjacent to the Inland Ice, inordinately slow weathering in paleosols has produced small, but above detection limit concentrations of extractable Fe and Al (Mahaney et al., 2009), as well as exceedingly low concentrations of organic matter derived principally from the decay of microbial populations of bacteria and fungi. As reported by Mahaney et al. (2001), Fell et al. (2006) and Hart et al. (2011) the presence of *Beauveria bassiani,* an insectivorous fungi, restricted to salt-rich horizons in Antarctic pedostratigraphic complexes opens the question as to what insect taxa the fungi might be or have been associated with in this or some past climate. The question has been partly answered by the presence of fossil Coleoptera skeletons recovered from a paleosol in a moraine deposited by alpine ice. Certainly, the presence of fossil Coleoptera argues for a warmer climate in the interior of the Antarctic Dry Valleys at some time during the Middle Miocene or earlier (Marchant et al., 1993). Others (Wilson, 1973; Campbell and Claridge, 1987) believed the region carried alpine ice early in its erosional history, possibly during the Eocene. Evidence of wet-based alpine ice further argues for warmer climate, an amelioration presumably accompanied by an invasion of Coleoptera.

Antarctic paleosols are rare and known mainly from the work of Gibson et al. (1983), Campbell and Claridge (1987), Bockheim (1990), Beyer et al. (1999), Mahaney et al. (2001, 2009) and McLeod et al. (2009), but detailed XRD and SEM analyses of paleosol mineralogy and chemistry are rarer still. Previous work by Retallack and Krull (1999) and Retallack et al. (1998, 2007) documents the composition of soils/paleosols in tills and paleosols associated with ancient Permian/Triassic forests at Coalsacks Bluff, Antarctica. Recent discovery of exoskeletons and endoskeletons of fossil Coleoptera in a paleosol dating to the emplacement of alpine-age moraines during the early growth of temperate ice in the Dry Valleys (Marchant et al., 1993; Mahaney et al., 2012) makes the mineral and chemical composition of prime importance in understanding the habitat in which the mesofauna and bacteria flourished, possibly in the Early Miocene, albeit for an unknown length of time.

Mineralogical and chemical details of the paleosol horizon and entire moraine profile in which the fossil skeletons were recovered are presented here based on recent XRD and SEM/EDS analyses. The question of Early to Middle Miocene habitat constraints as they affected the colonization and evolution of Coleoptera and associated microbial communities is best answered by the analysis of mineral distributions and chemical trends down profile. Mycological analysis of nearby profiles, dated to 15 Ma, indicates *Beauveria bassiani* is a key fungal component of local paleosols, prevalent in salt-rich horizons (Claridge, 1977; Claridge and Campbell, 1968; Mahaney et al., 2001). Other recent investigations detail the presence of numerous species of bacteria (Hart et al., 2011; Mahaney et al., 2012) possibly reducing waste from fungal components and aeolian inputs. The main question is the degree to which the lithology of the 831 profile fostered the growth and development of an ecosystem during the early stage of alpine type glaciation in the Dry Valleys. To what degree did the lithology provide a habitat for microbes and mesofauna that colonized the site and what nutrients were released that allowed various life forms to thrive and proliferate, if even at an inordinately slow rate. These are the questions we seek to answer with this investigation.

2. Regional geology and field area

The lithology of the Transantarctic Mountains including the Taylor Glacier area includes the Beacon Supergroup of quartzitic sandstone and dolerites, an eminently simple stratigraphy. The topographic setting of broad glaciated valleys with alternate benches or steps is similar to the topography of South Africa where the landscape matured under semi-arid climatic conditions. Volcanic vents near McMurdo Station (Armstrong 1978) remain active and volcanoes such as Mount Terror in the Ross Island area have been only marginally modified by glaciation.

Glaciation in the Antarctic has been the subject of much debate with some arguing for an Early Paleogene onset of ice and others for Late Paleogene/Early Neogene startup (Campbell and Claridge, 1987; Cooper et al., 2008; Florindo and Siegert, 2009). The early phase of glaciation, whenever it began, is seen as temperate in geophysical type with wet-based ice evolving into cold-dry ice which persists to this time (Campbell and Claridge, 1987). Onset of this transition occurred at the termination of the Middle Miocene Climatic Optimum (Warny et al. 2009) and is broadly compatible with the age at least of the profiles at Aztec Mountain and those situated at lower elevation at New Mountain embayments (Fig. 1) (Mahaney et al., 2001, 2009). The climate during wet-based glaciation probably resulted in increased summer thaw and melt of both snow and ice and consequently somewhat marginally more water available for weathering and soil genesis. Because pedostratigraphic successions seem to prevail at lower elevations, the periodic invasion of ice from the lower Taylor Valley into New Mountain embayments probably occurred under cold conditions, the substrate frozen and armored, thus self-protected from encroaching ice. While buried paleosols in the New Mountain area appear to have been little disturbed by encroaching cold-based ice, evidence in other areas argues for considerable erosion and modification of the landscape (Cuffey et al., 2000; Lloyd Davies et al., 2009).

The ice that emplaced the moraine at site 831, higher on the slopes above prominent lower benches at New Mountain (e. g. sites 827–829, Fig. 1) is considered to have been warm based as evidenced by the greater prevalence of round sands carrying prolific v-shaped percussion cracks considered to result from fluvial transport (Mahaney, 2002), presumably affected by meltwater, compared with similar clasts

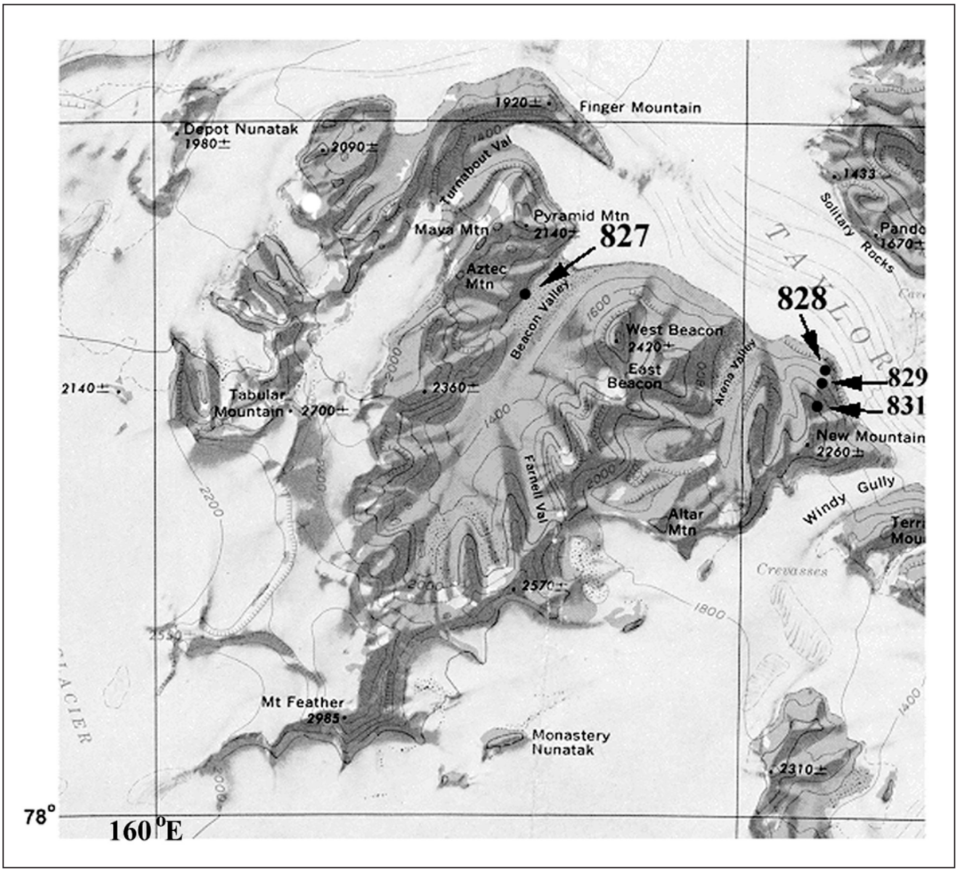

Fig. 1. Location of the 831 profile, New Mountain, Antarctica. The 831 site is 150 m above the embayment where sites 828 and 829 record multiple incursions of ice in the Middle Miocene. Site 827 near Aztec Mountain is close to the Inland Ice Sheet.

in the lower paleosols where angular grains and glacial crushing microfeatures predominate. While it might be possible to argue that round quartz could be inherited from the Beacon sandstone, it is impossible to explain the discrepancy in roundness microtexture frequencies between the 831profile discussed here, and detailed SEM analysis of nearby tills deposited by cold-based inland ice during the Middle Miocene Climatic Optimum or thereafter (Mahaney et al., 1996, 2001). All these paleosols belong to the Cold Desert group of Antarctic soils/paleosols (Campbell and Claridge, 1987) and are classed as subxerous or xerous with moisture regimes at lower moisture levels compared with coastal soil systems. Snowfall in the interior mountains near the Inland Ice is infrequent, at most, amounting to about six weeks per year and apparently on the rise in response to present day global warming (Parmesan, 2006). Water from snow melt may stay in liquid form for a few hours but intergranular water films may stay at temperatures well below zero because of the high salt content (Ugolini and Anderson, 1973; Wynn-Williams et al., 2000).

Lower sites at New Mountain are composed of greater amounts of dolerite relative to quartzitic sandstone; hence, a lower quartz dilution and higher pyroxene, olivine and Ca-plagioclase insure greater Fe content along with other chemical elements. At Site 831, the upper Cox horizon is similar with higher Fe and less sandstone, whereas the lower salt-rich horizons are quartz diluted with significantly lower Fe. As a result, the lithologies of the various horizons in 831 are not a simple two-phase system, the differing mineral contents reflect differences in source rock available to the glacier at different times. Initially, and for some time thereafter, ice depositing the 831 till sourced mainly sandstone and granite reverting later to a mix of dolerite and sandstone as reflected in the composition of the uppermost Cox horizon and pavement.

3. Materials and methods

The sample pit (831) was selected on a moraine ridge above the embayment where sites 828 and 929 are located (Fig. 1), the site excavated by hand, was cut back to expose fresh material. The soil horizon descriptions used here are genetic and follow guidelines set out by Mahaney et al. (2009), differing somewhat from the system of Campbell and Claridge (1987) which uses an alphabetical enumeration. In the earlier study of the 831 section by Mahaney et al. (2001), horizons were enumerated from A to Z with increasing depth in the profile. In a more recent paper (Mahaney et al., 2009), the usual downward succession of horizons of Fe-rich material over salt-rich material equates to Cox/Cz horizons in the Canadian soil classification system (CSSC, 1998), Soil Survey Staff (NSSC, 1995; Catt, 1990; Birkeland, 1999). Occasionally, where lower concentrations of oxides exist, a C designation (Birkeland, 1999) is invoked. The “ox” designation simply implies a color stronger than 10YR5/4 (Oyama and Takehara, 1970), a characteristic attributed to more extensive oxidation. The Cu designation refers to unweathered C horizon sediment (Hodgson, 1976). The ‘z’ designation (CSSC, 1998), is preferred for frozen salt-rich horizons over the USDA ‘n’ for unfrozen salt-rich horizons.

Soil color grades are assigned based on Oyama and Takehara’s (1970) soil chips. Approximately 500 g samples were collected from each horizon to allow for laboratory work, including particle size analysis following the procedures outlined by Day (1965). Samples were lightly sonicated and wet sieved to separate sands from clay and silt and particle size follows the Wentworth Scale with the sand/silt boundary at 63 µm while the clay/silt boundary (2 µm) follows the NSSC (1995). Light sonication may well have cleaned salt coatings off Fig. 4A.

Following particle size analysis, total dissolved salts were determined by electrical conductivity (Bower and Wilcox, 1965), pH by electrode in a 1:5 ratio, material: distilled H_2O ratio and C, N and H by Leco apparatus.

For the six samples described here, the <2 mm bulk fraction was ground using a McCrone micronising mill, the resulting slurry freeze-dried to precipitate soluble salts before being prepared as a random mount. In addition to analysis of the <2 mm fraction, the clay mineralogy of the <2 µm fraction followed after washing of soluble salts with pure water and removal of organic matter with H_2O_2. As described by Moore and Reynolds (1997), this fraction was extracted by centrifugation and samples were prepared by drying the resulting suspension onto glass slides. Ethylene-glycol (EG) solvation of the slides was achieved by exposing them to EG vapor at 70°C for a minimum of 12 hours. XRD patterns were recorded with a Bruker D5000 powder diffractometer equipped with a SolX Si(Li) solid state detector from Baltic Scientific Instruments using CuKα 1+2 radiation. Intensities were recorded at 0.04° 2-theta step intervals from 5 to 80° (6 sec counting time per step) and from 2 to 50° (4 sec counting time per step) for bulk and clay mineralogy determination, respectively.

Selected sands were subsampled and analyzed under the light microscope. From this grain population, a smaller number of samples were subjected to analysis by JEOL-840-JSM Scanning Electron Microscope (SEM) with Energy Dispersive Spectrometry (EDS) using a PGT System at the Department of Geology, University of Toronto, following methods outlined by Mahaney (2002). Photomicrograph and X-ray microanalyses were obtained at accelerating voltages of 10–20 keV and 10–15 keV respectively. Some of these micrographs were realized on polished thin-sections of Cz2 horizon sample using a Hitachi S2500 Scanning Electron Microscope (SEM) with Energy Dispersive Spectrometry (EDS) equipped with a Thermo Noram system at the Isterre laboratory, University of Grenoble. Photomicrograph and X-ray microanalyses were obtained at accelerating voltages of 16 keV.

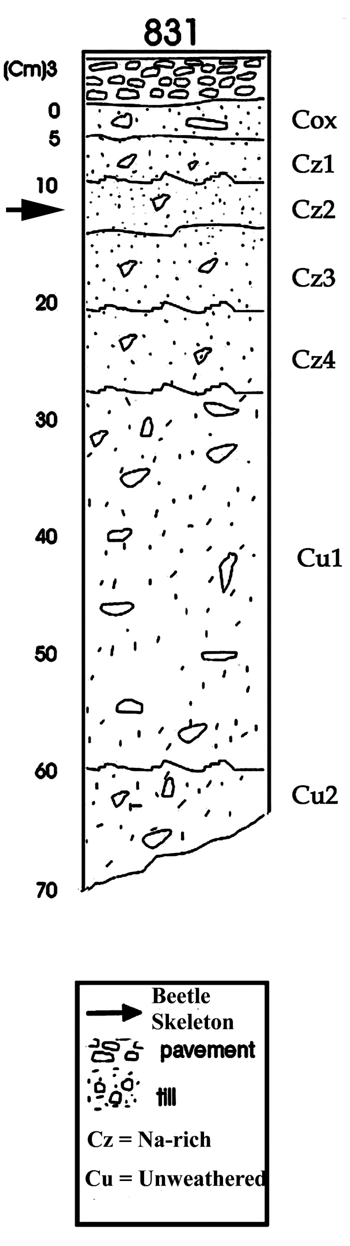

Fig. 2. The 831 section, a single stage profile formed in moraine emplaced by alpine ice during the early stage of glaciation in Antarctica.

4. Results

4.1 The profile

The 831 profile is a single stage paleosol with a 7–8 cm thick pavement, thickest of all pavements in the group of profiles described by Mahaney et al. (2001), which may relate to the inferred ameliorative paleoclimate and length of time the ice had to emplace the pebble blanket. The paleosol consists of seven horizons as shown in Fig. 2; two of the lowermost horizons – Cz4 and Cu1 – are similar in kind to the unweathered parent material (Cu2) below, although with a lower clast count. Horizons are thin, the two uppermost are about 5-cm thickness each, spacings within horizons increasing slightly down to the paleosol/parent material contact at just under ~30 cm depth. The Cox horizon under the pavement obtained its slightly stronger (brighter) color because of the higher dolerite content and release of Fe^{+3}, secondary Fe falling to about one-third the concentration in the Cz horizons below, color losing strength accordingly with depth (Table 1). All horizons carry sand textures with the exception of sandy loam in the Cz2 and Cu2. As expected, with little clay content the soil lacks any structure and the normal soil properties of consistence, plasticity and stickiness are meaningless to record. What strikes the observer are the color changes, finer textures in the Cz2 and Cu2 horizons and variations in clast content from soil to parent material. Actual distributions of sand, silt and clay were previously reported by Mahaney et al. (2001).

Table 1: Chemical and physical properties of horizons in the 831 Paleosol, Antarctica. Color follows the system of Oyama and Takehara (1970). Color in the pavement is darker by ~2 chroma of colors in the weathered sediment and variable.

Horizon	Depth (cm)	C (%)	H (%)	N (%)	pH (1:5)	E. C.[a] (mS)	Color
pavement	7–0	–	–	–	–	–	variable
Cox	0–5	<0.01	0.17	0.06	6.1	4.90	10YR5/6
Cz1	5–10	<0.01	0.23	0.23	7.6	13.40	10YR6/6
Cz2	10–14	0.04	0.88	0.37	7.2	7.53	10YR6/4
Cz3	14–22	<0.01	0.06	0.08	7.4	7.26	2/5Y7/4
Cz4	22–30	0.01	0.07	0.10	7.4	5.50	2.5Y7/4
Cu(1)	30–65	<0.01	0.06	0.08	7.5	2.43	2.5Y7/2

[a] Electrical conductivity.

Color variations (Table 1) from yellowish brown (10YR5/6) in the Cox horizon to bright yellowish brown (10YR6/6) in the Cz1 and 2 horizons indicate a shift from slightly higher Fe to slightly lower Fe below. The color gradation below in the Cz3 and Cz4 horizons is to paler yellow colors (2.5Y7/4 and 7/3), close to the usual color of near-fresh undifferentiated sediment. Variations in C with depth are near detection limits with the exception of the Cz2 horizon where it 'spikes' to 0.04 %. Hydrogen (Table 1) follows a similar trend rising to 0.88 %, a fluctuation correlated to the slight reduction in pH. The pH trend is from slight acidity in the Cox to slight alkalinity with depth in the profile. Variations in total salts as determined by electrical conductivity show the highest salt content in the Cz1 and 2 horizons, the latter horizon being the weathered zone where the Coleoptera were recovered.

4.2 XRD

The bulk (Fig. 3A) and clay (Fig. 3B) fractions were analyzed in all six horizons (Cox, Cz1, Cz2, Cz3, Cz4 and Cu1, see Table 2) with a focus on determining the degree of uniformity/heterogeneity down profile, and especially the lithology of the Cz2 horizon where the meso- and microfauna (bacteria) were recovered (Hart et al., 2011; Mahaney et al., 2012). Presumably with down profile movement of clay and nutrients, including Fe from the adjacent Cz1 horizon, the two uppermost horizons might be considered a tandem source of both moisture and chemical stimulants for metabolic functions. Because the bulk and clay fractions produce somewhat similar results, it is best at first to consider them together, and later to focus on those aspects of the clay fraction that differ from the bulk group of samples.

Through the pit profile 831 (Table 2) all horizons present a chlorite, quartz and illite assemblage, with albite / microcline observed only in horizons Cox and Cz2. In the upper part of the profile (Cox, Cz1, Cz2), gypsum was detected. This last phase was associated to the hexahydrite and calcite phase in the Cz2 horizon.

Table 2: Mineral assemblage for the six horizons of the profile 831 obtained by XRD analyses.

Mineral	**Quartz**	**Alb / Mi**	**Illite**	**Chlorite**	**Gypsum**	**Hexa**	**Calcite**	**Halite**	**Lau**	**Pyro**	**Smectite**
Horizon											
Cox	+	+	+	+*	+	*n. d.*	*n. d.*	*n. d.*	*n. d.*	*n. d.*	*n. d.*
Cz1	+	*n. d.*	+*	+*	+	*n. d.*	*n. d.*	*n. d.*	*n. d.*	*n. d.*	*n. d.*
Cz2	+	+	+	+*	+	+	+	*n. d.*	*n. d.*	*n. d.*	*n. d.*
Cz3	+	*n. d.*	+*	+*	*n. d.*	*n. d.*	*n. d.*	*n. d.*	+*	+*	*n. d.*
Cz4	+	*n. d.*	+	+*	*n. d.*	*n. d.*	*n. d.*	*n. d.*	+*	+*	+*
Cu1	+	*n. d.*	+	+*	*n. d.*	*n. d.*	*n. d.*	+*	+*	+*	*n. d.*

* observed in clay fraction <2 µm, *n. d.* not detected. Alb / Mi = Albite / Microcline; Hexa = Hexahydrite; Lau = Laumontite; Pyro = Pyrophillite.

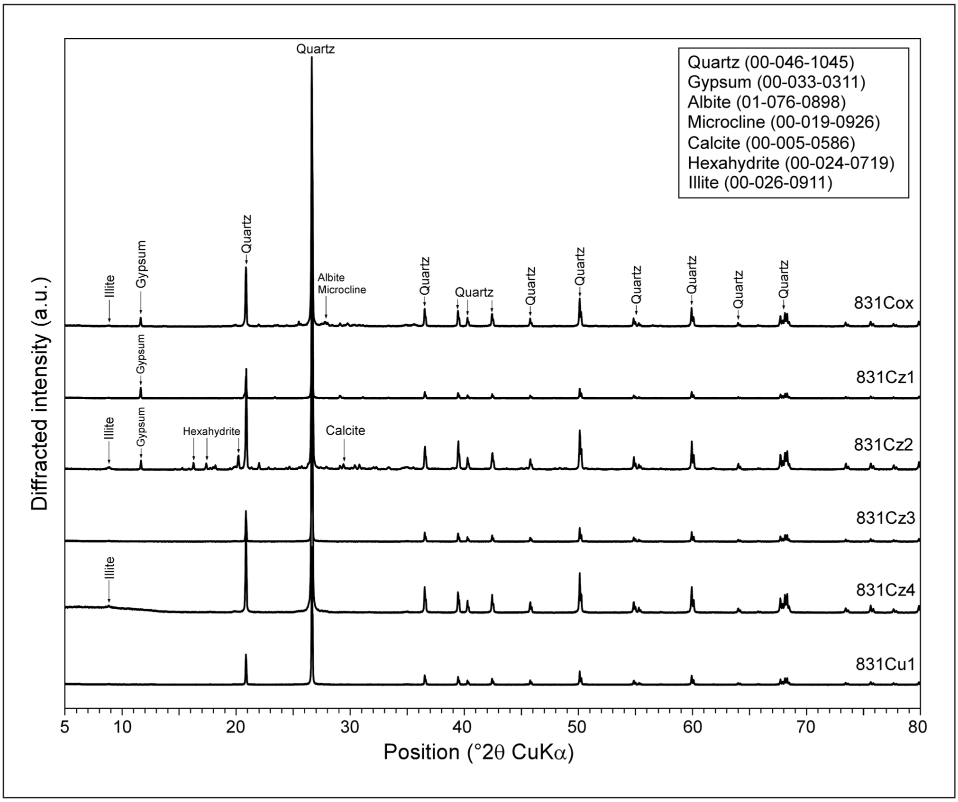

Fig. 3A: XRD diffractograms of the bulk (<2 mm) fraction and the XRD standard phase numbers from International Centre for Diffraction Data base (ICDD) are indicated.

In the lower part of the profile, Cz3, Cz4 and Cu1, laumontite and pyrophyllite were detected. Smectite was only present in the Cz4 horizon and halite appeared in the Cu1 horizon only.

The chlorite is of interest because of its Fe content (see below), a necessary requirement as an electron acceptor for some types of microbial anaerobic respiration (Jaisi et al. 2007). Laumontite, a member of the zeolite group is a hydrated calc-alumino-silicate which acts as a chemical filter and which allows ions and water to flow into and out of its crystalline structure, therefore acting as a chemical sieve. Hexahydrite, a hydrated Mg sulfate mineral (Palache et al. 1951), common in the two uppermost horizons may grow into thin but massive crystals, even ≥1 cm in diameter. With six water molecules it is nearly as heavy with water as with sulfur and magnesium and may be a source of moisture for the growth of microorganisms.

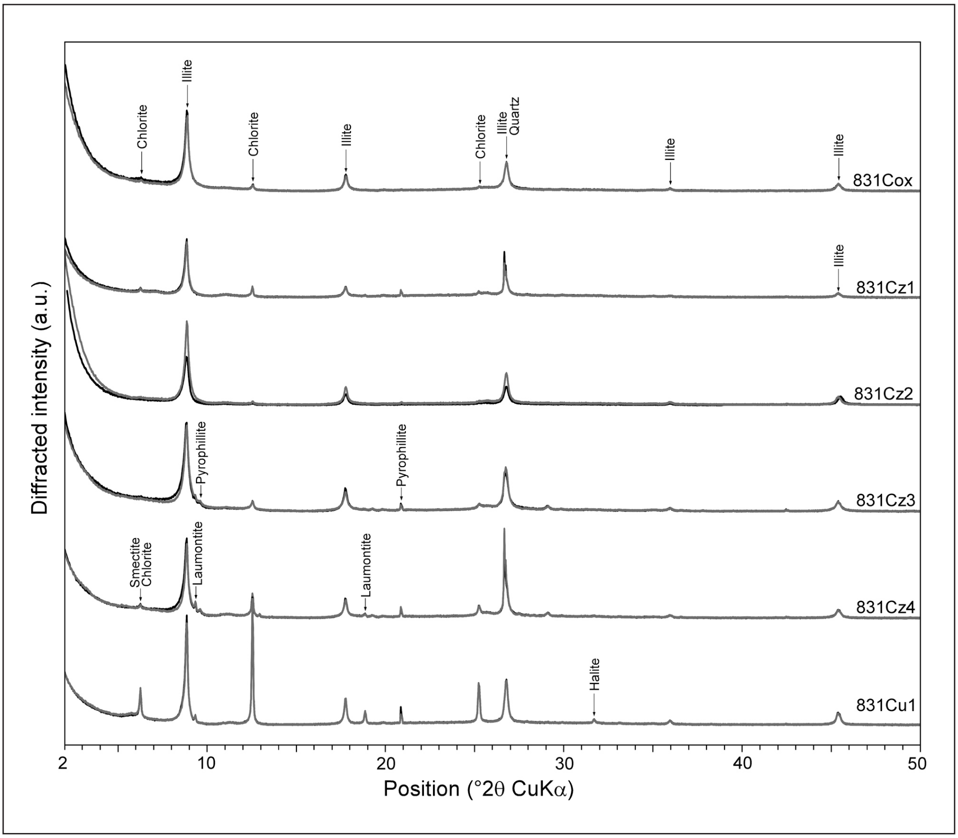

Fig. 3B: XRD diffractograms of the clay (<2 μm) fraction in the 831 profile.

Laumontite, like most zeolites, often forms inside vesicles of dolerite. With exposure to air and light, laumontite may dehydrate into leonhardite, but despite the porosity and freeze dried nature of the sediment, XRD analysis did not detect leonhardite. Within the 831 profile (Fig. 3A), concentrations of quartz were noticeably lower in the upper two horizons, possibly a product of dissolution over long time intervals when the climate was warmer and with greater tendency for meltwater production.

4.3 Coleoptera

Mesofauna were discovered by light microscopic analysis of sands in the Cz2 horizon only. These samples were coated with carbon, and following SEM analysis, EDS signatures were averaged out on other silicate minerals, the difference taken as normal

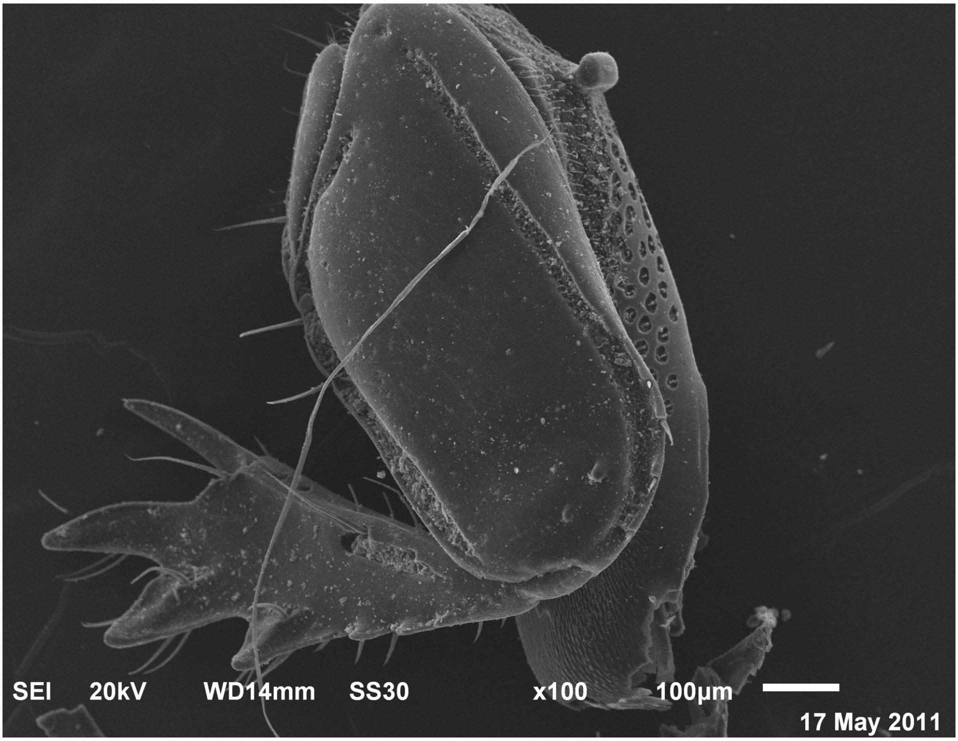

Fig. 4A: Coleoptera from Cz2 horizon with a nodule of unknown composition in upper right and a filament encrusted with salts crisscrossing a segment of the leg and procoxa of a Coleoptera specimen. Sensory hairs are intact with slight fractures to endoskeleton.

coating concentrations subtracted from high carbon peaks to establish the presence of organic material. Fig. 4A is representative of a relatively clean Coleopteran endoskeleton, the cleanest of all specimens recovered, but despite well preserved parts, identification of species proved impossible. The presence of well-preserved fossil Coleoptera from the upper 831 profile ranges from a leg segment and procoxa (Fig. 4A) of a specimen belonging to the family Scarabaeidae, possibly belonging to the genus Aphodius or Ataenius. The specimen demonstrates an articulated tibia, femur, trochanter and attached procoxa seen from the ventral side. Other descriptive body parts such as the abdomen and head-capsule were not found.

The long extended filamentous-like fiber shown in the SEM frame (Fig. 4A) could possibly be a hyphal mat created by a fungus (Webster and Weber, 2007). Although identification of fungal species was not carried out, previous work showed that the dominant culturable bacterial phylum for the 831-Cz2 horizon is *Actinobacteria* (Hart et al. 2011). *Actinobacteria* are well known as major contributors to the degradation of chitin (Trujillo 2008) and carry a wide degree of chitinases (Kawase et al., 2004).

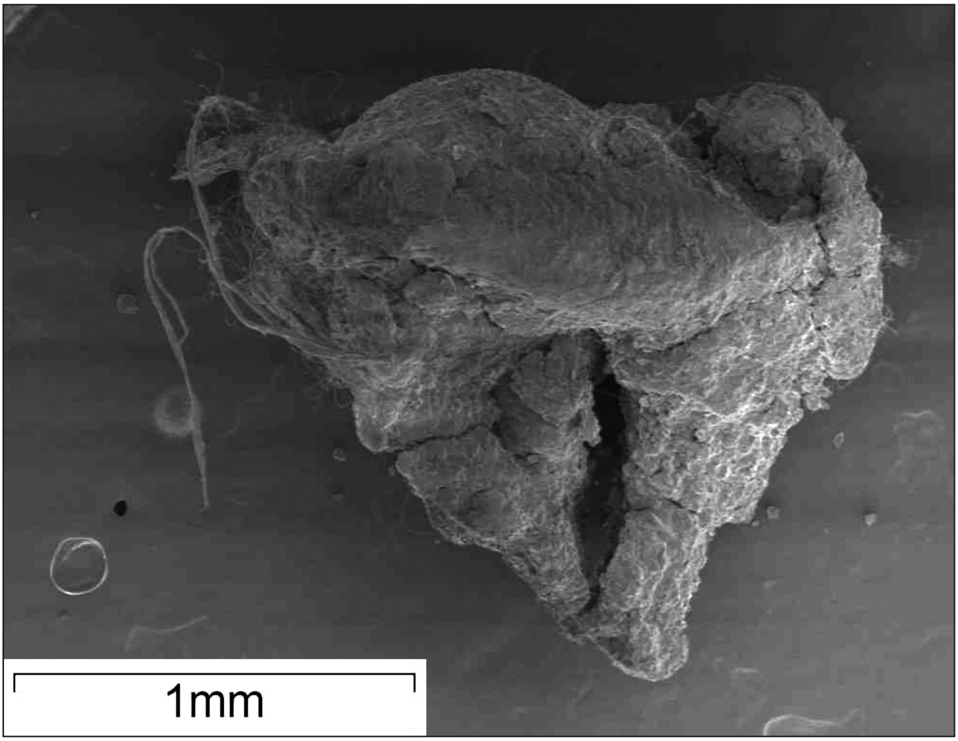

Fig. 4B: Grain assemblage that could be a salt-encrusted Coleoptera although the electron beam could only detect Ca, Na, Mg, Cl and S. However the form suggests wings and dorsal or ventral beetle parts thickly encrusted with salts.

Chemical spectra of both the filamentous form and the beetle show high concentrations of carbon along with salts enriched with S, Mg, Na and Cl. The image in Fig. 4B is possibly an encrusted beetle specimen, although with a thickened crust of salts unaffected by light sonication, it is impossible to confirm a biogenic composition. However, EDS spectra on the specimen indicates high C with lesser amounts of KCl. Imaged at 15 keV, with penetration of the electron beam limited to about 1 µm, most probably salt encrustations are ± 1 x 10^3 nm thick. The excessive carbon strongly indicates a beetle skeleton and is similar to the analysis undertaken of like specimens from the same horizon. The filamentous string-like forms attached to the skeleton in Fig. 4B are highly encrusted with salts and minor Si:Al (ratio of 2:1) suggesting, with K present, the presence of illite.

The occurrence of Mg and Fe chlorite within the sand fraction (Fig. 4C) may act as a source of Fe for microbe respiration, which aside from moisture, are important requirements for the growth and preservation of life forms, even in the Antarctic. The clear transformation of Mg chlorite to Fe chlorite is shown in the image and accom-

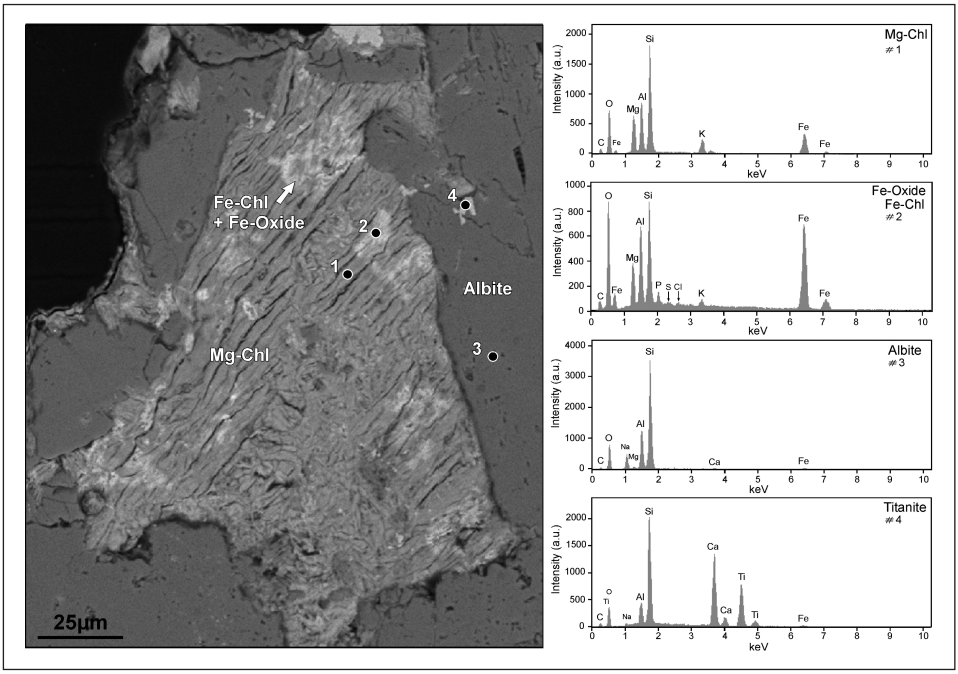

Fig. 4C: Albite chlorite intergrowth illustrating conversion of trioctahedral chlorite to dioctahedral Fe which could result from weathering under more ameliorative soil climate. The presence of P is a secondary precipitate that may have a biogenic origin.

panying EDS spectra in Fig. 4C. Most of the white forms on the image are secondary precipitates of P, most probably microbial products and very possibly produced over an inordinate length of time, i. e. from the Middle Miocene or longer.

4.4 Lithology

A range of grains, mostly quartz of variable grade sizes, is shown in Figs. 5A–D, all of which are representative of sands recovered from the 831 profile. Approximately 80 % of quartz sands in the 831 paleosol are subround to round suggesting considerable transport in meltwater. The frequency of adhering particles, considered the product of glacial abrasion (Mahaney, 2002) varies from sample to sample as shown in Figs. 5A-B, with some grains exhibiting higher frequency of v-shaped percussion cracks considered to be the hallmark of fluvial transport (Krinsley and Doornkamp, 1973; Mahaney, 2002). In contrast, some sands (Figs. 5E–F), from site 829 (location, Fig. 1) and heavily coated with salts, assume a subangular form typical of glacial crushing (Mahaney, 1995, 2002) and with masked grooves and striae resulting from glacial abrasion and transport.

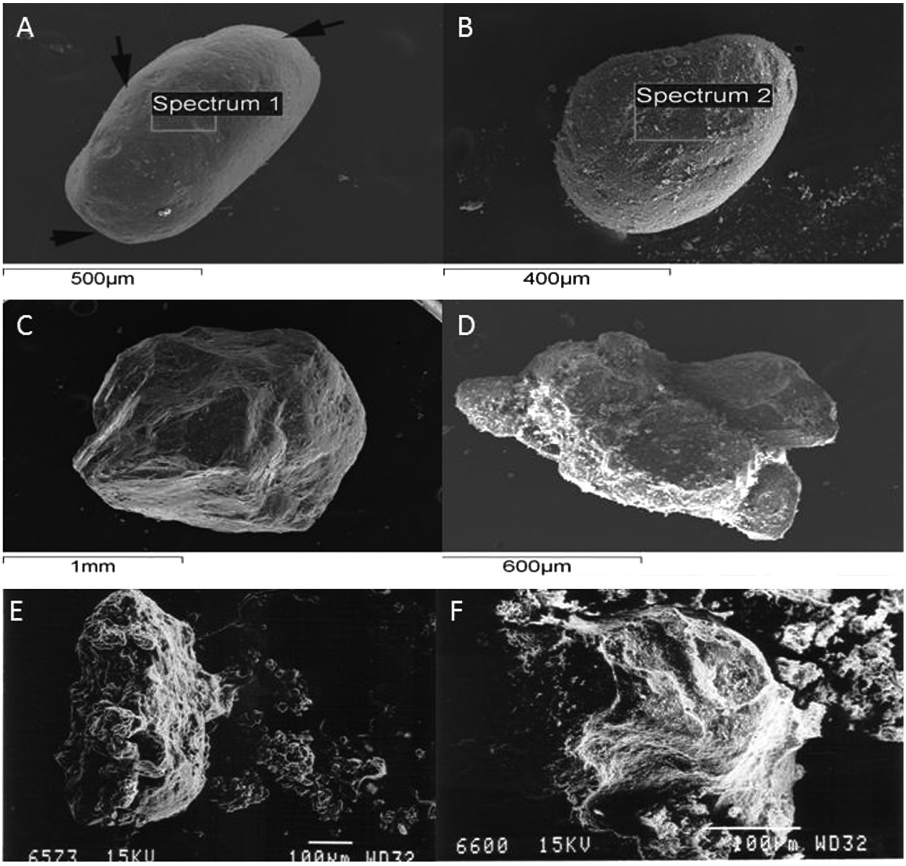

Fig. 5A: Subround quartz in the Cz2 horizon with v-shaped percussion cracks (arrows) indicating it had been tumbled in meltwater. **Fig. 5B:** Round quartz with higher count of adhering particles compared to A. **Fig. 5C:** Nearly eqiudimensional quartz with adhering particles and sharp, blunt edges. **Fig. 5D:** Salt encrusted subangular grains of quartz and orthoclase confirmed by EDS. **Fig. 5E:** complex subangular intergrowth in profile 829 of quartz (left) and orthoclase (right), the entire assemblage covered with $CaSO_4$ and small amounts of Fe, presumably Fe^{+3}. **Fig. 5F:** Subangular quartz grain (profile 829) thickly coated with salts, mainly $CaSO_4$ and small concentrations of secondary Fe.

5. Discussion

The 831 paleosol described here classifies within the Gelisol order in that it has semigelic materials within 100-cm of the soil surface and permafrost within 200-cm of the soil surface (NRCS, http://soils.usda.gov/). The dry frozen sand texture of the horizons consists of primary and secondary mineral gelic materials, with exceedingly low carbon, showing little evidence of cryoturbation. Hence, the 831 profile belongs to the Orthel suborder and keys closely to Anhyorthels, profiles with weathered gravels over salt-rich horizons (Cn or Cz) over frost cemented beds (Cf. in the U. S. taxonomy). While little is known about the properties and composition of soils/paleosols adjacent to the Inland Ice Sheet, the 831 profile exhibits similar horizon characteristics to the soil profile at Mt. Fleming Climate Station Site, Upper Wright Glacier, adjacent to margins of the Inland Ice Sheet. The elevation of the Mt. Fleming site is 1698 m, 5568 ft. and the location is 77°, 32' S; 166°, 17' E., ~150 m lower than the 831 site. The soil at Mt. Fleming is resident within a polygon consisting of coarse clastic material with a much higher gravel content compared with the pebbly sandy loam matrix of the 831 profile. However, the strongly weathered polygonal gravel of the Mt. Fleming soil, with colors (10YR5/4), closely akin to profile 831 (Table 2), and at a similar depth, suggest it may have a similar age, correlating with the alpine glacial event. Only weak evidence of cryoturbation is apparent in the 831 profile sketch shown in Fig. 2, the result of the sandy texture and dry frozen state of the weathered sediment from which the Coleoptera were recovered.

Sands in the 831-Cz2 horizon, thickly and thinly coated with salts, display differing degrees of roundness and angularity. For the most part, approximately 80 % of all grains analyzed are round or subround, many carrying a wealth of v-shaped percussion cracks from meltwater transport. In contrast, in sites 827–829, quartz consists of subangular to angular grains carrying varying degrees of glacial crushing, particularly subparallel fractures, striae, grooves and many microfeatures masked with salt encrustations. The degree to which Antarctic paleosols are coated with salts, stands in contrast to tills analyzed in other nearby sections and horizons (Mahaney et al., 2001; Mahaney, 2002) that lie below former active soil forming processes, more or less apart from active pedogenesis above in the profiles.

The Coleoptera recovered from the 831-Cz2 horizon described above are interpreted as burrowing beetles and were not found in overlying horizons, namely, 831-Cox and Cz1, or in the underlying horizons. The presence of beetle mesofauna may relate to the presence of *Beauveria bassiani,* an insectivorous species, which may be related to the Coleoptera in nearby New Mountain paleosols 828 and 829 (Mahaney et al., 2001). A search for similar Coleoptera fossils in all other profiles – 827–829 – failed to produce positive results. Because fungi were not targeted in the 831 profile, the relationship with *B. bassiani,* while possible, is at the moment only conjecture. However, because bacteria in the horizon have been established (Hart et al., 2011; Mahaney et al., 2012), it seems plausible to argue that bacterial colonies were metabolizing chitin compounds of the mesofauna and senescent fungi. Another possible link to Coleoptera in the microbial food web is the previous identification of *Micrococcus luteus* in the 831-Cz2 horizon (Hart et al., 2011). This bacteria has been associated as part of the natural flora of Coleoptera (Yilmaz et al., 2006; Cardoza et al., 2006) and is assumed to exist in a symbiotic fashion. Cardoza et al. (2006) isolated *M. luteus* from oral secretions of Coleoptera and argued that they act as primary defense agents against fungal infection. Although only speculative, the presence of these three organisms in the immediate Antarctic vicinity, and because they currently exist in a demonstrated food web at more temperate climates, hints at their interaction prior to the onset of full-polar conditions.

While fossil Coleoptera, interpreted to have an age between Pliocene and Middle Miocene, have been found further south in the Meyer Desert Formation near the Beardmore Glacier (Ashworth and Kuschel, 2003), the fossils from New Mountain described here would appear to belong to an earlier age when warm-based ice deposited the alpine moraine. Unlike the site described near the Beardmore, complete with fossil wood, moss, shells and leaf remains of *Nothofagus,* we recovered only the Coleoptera endo- and exoskeletons described herein and in Mahaney et al., 2012. The presence of well-preserved fossil Coleoptera from the upper 831 profile ranges from a leg segment (Fig. 4A) of a specimen belonging to the family Scarabaeidae, possibly belonging to the genus Aphodius or Ataenius, as described above. Given the presumed age of the specimen the amount of preserved detail is remarkable, especially the setae (hairs) still attached to fixed positions on the tibia and femur. The degree of preservation of body parts held together with connective tissue, well preserved morphology, and intact chitin lacking appreciable corrosion suggest a number of possible explanations. This specimen, the most highly preserved amongst all recovered samples, is either a recent contamination after sampling or the product of light sonication after salt encrustations were worn off. It is entirely possible the sample was frozen quickly, encrusted (armored) with salt at a later time prior to lab preparation. Given that the samples were collected in sterile double bags it is unlikely this one sample is a recent contaminant. Potential for the reanimation of dormant coleopterans is possible (Ring and Tesar, 1980; Ring, 1981), considering the more ameliorative climate of the laboratory, and the freeze-dried and stable state of the paleosols between emplacement of the tills and site sampling. Virtually all the Coleoptera recovered maintain some degree of salt encrustation despite the light sonication used in lab preparation of samples for particle size analysis.

The question of salt content in the beetle habitat and its relation to age of the skeletons might be answered several ways. Some specimens analyzed are robustly intact, relatively unencrusted with salt, as shown in Fig. 4A and might be relatively recent invaders of the site. Alternatively, it is possible laboratory pre-treatment with light sonication might have removed salt thus producing a well-articulated specimen. Other specimens (Fig. 4B, for example) are heavily encrusted with salts and could be considered coeval with an early stage of biotic invasion following deposition of the till. Variable degrees of encrustation may also derive from position in the horizon itself or from pre-treatment in the laboratory where the entire sample of the <2 mm fraction was subjected to particle size analysis and wet sieving, which may have cleaned up specimens thinly coated with salts. Whatever explanation is preferred, it is possible for some species of Coleoptera to exist in halophilic or hypersaline environments (Velasco et al., 2006). It seems, given the cold desert environment of the last ~15 Myr Antarctic environment, attenuated somewhat by the advent of an earlier evolutionary stage of temperate-style glaciation, that it is likely the Coleoptera described here inhabited the site earlier on in its history, dying off with the invasion of more severe dry-frozen conditions. The alternative hypothesis of Coleoptera living a fast-life cycle, invading the site during brief (6–8 week) summer seasons, and expiring with the advent of winter seems less plausible. Because Coleoptera burrows were not detected at the time of collection it would seem the specimens recovered relate to an early phase of pedogenesis following deposition of the moraine. The question of the influence of salt content and habitability can only be answered with a more widespread study of additional sites.

The mineralogy of the bulk matrix material of <2 mm fraction and the clay fraction (Figs. 3A–3B) show only minor differences between the two fractions. Within the bulk fraction quartz, calcite, halite and gypsum dominate in variable quantities down section. Within the clay fraction there is an increase in quartz down section that may relate to quartz dissolution in the upper three horizons, possibly the product of silica dissolution over an inordinately long period of time. Otherwise, the illite and illite-chlorite detected in both fractions are considered the product of decomposition of granite and hydrothermal metamorphic rock at some time in the past, probably all preweathered materials.

The presence of zeolite in the form of laumontite is of special interest in understanding the paleoecology of the site because of its ability to adsorb cations of nutritional importance to the mesofauna. While authigenic chabazite, another zeolite, is known in the Sirius Diamictite and interpreted as a weathering product (Dickinson and Grapes, 1997), laumontite detected in the 831 profile may well represent albitized plagioclase, either authigenic or allogenic in origin. Hexahydrite, as a hydrous molecule similar to laumontite, may well play a role in providing moisture in liquid phase to all life forms that inhabited the site in the past. The question of whether the mesofauna inhabited the site early on during the alpine phase of glaciation and died-off as the climate deteriorated or continued to thrive through the later Miocene, Pliocene and Quaternary, is unknown. Discordant coatings, with some Coleoptera in near-pristine condition and others coated with thick encrustations of salt and Fe, begs the question as to possible differences in age or simply position within the horizon. If, as suggested by the elevated concentration of secondary Fe (Mahaney et al., 2009), the alpine moraine is indeed considerably older than other moraines at New Mountain (sites 828 and 829), considered to have been emplaced by cold-based ice after the Middle Miocene Climatic Optimum of ~15 Ma [(Graham et al., 2002) (Sites 827, 828, 829; Mahaney et al., 2001)], it is likely the 831 profile underwent transition from an ameliorative climatic phase to a colder one. If so, this transition was likely coincident with the demise of the Coleoptera population, perhaps leaving bacteria either as endospores, in a state of freeze-dried stasis, or as psychrophiles.

The presence of limited foodwebs in the Dry Valleys have previously been demonstrated (Cowan et al., 2010; Pointing et al., 2009) and tend to be governed chiefly by the availability of liquid water (Barrett et al., 2007). As these organisms adhere to strict biochemical requirements, a strong influence is placed over them by the surrounding landscape and geochemistry in regards to nutrient availability. Minerals such as hexahydrite and laumontite release water molecules under dry and exposed conditions, while relatively more complex minerals such as illite can be used as a nutrient resource by microbes after weathering or enzymatic solubilization. The relatively high abundance of N in all of the sampled sites in comparison to the very low to nil determinations of C, indicate very low abundance of live microbial biomass (Simpson et al., 2007) at present. Because liquid water is known to exist, at least at the nanolevel in the Meserve Glacier (Cuffey et al., 2000), and hypothesized to exist in salt-rich horizons of paleosols (Mahaney et al., 2001), sufficient liquid water must have existed in the 831 paleosol after transition to cold-based ice, although microbes might have existed even with little liquid water as described above.

It is certain that the stratification of soil horizons observed here, both from color change and sediment analyses, is partly linked to microbial activity and to sediment sourcing by ice during the alpine phase of glacier growth as Antarctica cooled. The wide range of microorganisms present in such sediments – often at considerable depth, where anaerobic metabolism may predominate – has now been demonstrated both through our own research (Hart et al., 2011) and by others (Pointing et al., 2009; Dohm et al., 2011). In this study we have shown that Fe^{+3} electron acceptors, required for anaerobic microorganisms involved in both hetero- and auto-trophic processes, are present in plentiful supply. Indeed, it is possible the absence of Fe-chlorite in the Cox horizon is a result of higher levels of microbial activity in the top 5 cm of sediment. The presence of cyanobacteria – probably as endolithic organisms – in this ecosystem is highly likely in the Cox sediment (Pointing et al., 2009), and this biomass may ultimately serve as a key stimulus for a complex C-cycle, perhaps in the past involving the Coleoptera as well as diverse heterotrophic bacteria and fungi. The presence of chemoautotrophic bacteria in the Cz horizons is also very likely. Such organisms would be involved in Fe leaching processes that could have led to some of the changes observed in the XRD analysis (Niemela et al., 1994).

Despite these possibilities, there is no doubt that the overall level of microbial biomass present is likely to be orders of magnitude lower than what would be expected in a temperate weathered paleosol. Low microbial biomass may also mean that microbial respiration in the Cz horizons is not actually oxygen limited at all. Further metagenomic analysis of microbial populations in these samples could help to verify this possibility and define the complex microbial community that will certainly be present in the Cz horizons.

The high percentage of round quartz carry high percentages of v-shaped percussion cracks, recovered in the 831 section, which opens the question as to origin, specifically whether or not some or all of the grains could be the result of fluvial transport within the early alpine ice or sourced directly from the Beacon Supergroup sandstone. Comparison with quartz sand recovered from tills in nearby sites 828 and 829 at New

Mountain and site 827 at Aztec Mountain (Fig 1), as well as samples from till at other localities in the Dry Valleys (Mahaney et al., 1996), suggests grain roundness in 831 is the result of glacial processes. If otherwise, with rounded grains sourced from the Beacon sandstone, one would expect to find high percentages of round quartz in other Dry Valley till samples. It is impossible to discount some addition of round quartz grains from Beacon sandstone outcrops into the 831 till sediment but it appears the sudden high frequency of such grains in the 831 profile is due to glacial abrasion in meltwater.

The 831 paleosol carries a single story profile of 30 cm depth, a single stack of Cox/Cz horizons, similar in character to profiles at nearby sites at New Mountain and Aztec Mountain. The paleosol is within the climate of the polar desert soils of the Dominion Range with a present mean annual air temperature (MAAT) of –39° C and mean annual precipitation (MAP) of 36 mm (Retallack et al., 2001). While climatic sums on a monthly/daily basis are not available for site 831 (~1850 m), and/or comparable sites near the inland ice, the only short term climatic data is from McMurdo Station (elevation 24 m a. s. l., http://www.coolantarctica.com, data from Landcare, NZ). At McMurdo the average daily temperature in January is –2.9 °C, mean daily maximum temperature is –0.2 °C and the mean daily minimum is –5.5 °C. The annual mean temperature is –16.9 °C. Applying the normal dry adiabatic lapse rate of 10 °C/km to the McMurdo January means yields temperature summaries close to the means reported below for the Mt. Fleming site in Upper Wright Valley.

Of the nine stations instrumented and capable of collecting atmospheric and soil climatic data, only Mt. Fleming in Wright Valley (1700 m a. s. l., NRCS, http://soils.usda.gov/) has values close to Site 831 at New Mountain. Mean daily air temperatures collected for 2011 range from –7 °C to –35 °C (http://soils.usda.gov/survey/smst/antarctica/MtFleming/), whereas mean daily soil temperatures at the 2-cm soil level range from ~2 °C in summer to –40 °C in winter. While soil temperatures are for one year only (2011), and considering a longer instrumental record might give a wider spread of temperatures, it is apparent daily temperatures, while close to 0 °C are mostly well below freezing. While salt content in the Mt. Fleming paleosol is known to be limited to the 2–8 cm level it would appear to be less frequent than at the 831 site discussed here. Nevertheless, while salt content is sufficient to lower the freezing temperature, it probably does not raise the soil temperature to the 5 °C limit, which is within the lower limit allowable for most Coleoptera to persist at a site. Because the material in which the Coleoptera were recovered was dry frozen at the time of recovery, and barring any climatic perturbations that might have warmed the soil since the Middle Miocene Climatic Maximum, there is little possibility the samples date from less than 15 Ma with every possibility they are considerably older. With reference to the Fe extracts discussed below the samples are likely Early Miocene or older.

Because the Fe-extracts for the 831 sediment suggest an age older than the 15 Ma documented age of nearby cold-based tills (sites 828 and 829; Mahaney et al., 2009), it is likely soil morphogenesis began during the Early Miocene or earlier under a more ameliorative climate with higher MAAT and MAP. The Fe_d/Fe_t ratio, a measure of age since deposition (Arduino et al., 1986; Torrent and Cabedo, 1986; Mahaney et al., 1999, 2010) produces a quotient in the 831 profile twice as high as in the 828 and 829 profiles (Mahaney et al., 2009) dated at 15 Ma. While some of the Fe_d increase could be due to the earlier more temperate climate accompanying the growth of alpine ice, the much higher Fe_d ratio surely indicates greater relative age, even if absolute age control is lacking.

While the absolute age of the site is unknown, the evidence strongly suggests the sediment belongs to the alpine phase of Antarctic glaciation which began as warm-based ice in the highlands, eventually spreading to the Antarctic Shield as the climate deteriorated presumably in or before the Middle Miocene. How long the early alpine phase of glaciation lasted is unknown, but could easily range back into the Oligocene. If the 831 section is Oligocene in age, the bacteria and Coleoptera resident there could easily provide some of the oldest bacteria cells and chitin protein in Antarctica.

6. Conclusions

XRD and SEM/EDS analysis of the horizons in the 831 profile reveal a mix of minerals that provide a nutrient base for mesofauna and microbes known to have thrived there at least in the early stage of glacial growth, probably during the Early Miocene, possibly earlier. The 831-Cz2 horizon within the profile, resident with copious skeletons of Coleoptera and accompanying bacteria, is a case in point as the mesofauna required greater amounts of water and chemical nutrients for survival. Presumably, the presence of illite and chlorite, two Fe-bearing clays may have been sources of Fe necessary for respiration. Laumontite in the 831-Cz3 might have acted to sequester/filter ions and water. Hexahydrite a major source of water as well as salt, combined with halite, may have maintained a liquid supply of moisture at temperatures well below freezing. If quartz dissolution in the upper horizons actually produced silica wreckages these might have adsorbed small amounts of water of benefit to mesofauna and microorganisms.

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