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Paleoclimate of Antarctica reconstructed from clast weathering rind analysis

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ABSTRACT

Previous analysis of extractable Fe/Al in paleosols near New Mountain, Antarctica, suggests a pre-Middle Miocene, possibly Late Oligocene–Early Miocene age for paleosol 831 emplaced during the alpine event prior to the growth of the Inland Ice Sheet. Recent analysis of weathering zones in clasts with encrusted Fe/salts from the pebble pavement overlying the 831 paleosol reveals a succession of three weathering zones in a sandstone clast that record a paleoclimate transitioning from warm/wet (temperate) to cold/dry (polar). The first zone corresponds to an association of quartz cemented with berthierine (smectite–serpentine) and illite clay minerals. The second zone transitional from weathered clast to Na-encrusted rind contains smaller amounts of berthierine and illite formed in grains of partially dissolved quartz with minor salt content. Zone three corresponds to an ~3 mm (3×10^6 nm) thick mass of porous nitrate and gypsum. The contact between zones 2 and 3 appears to be correlative with the transition from temperate to polar ice which is considered to have occurred prior to or coincident with the Middle Miocene Climatic Optimum.

1. Introduction

Antarctic paleosol profiles have been studied (Campbell and Claridge, 1987; Retallack and Krull, 1999; Retallack et al., 2007; Bockheim, 2007, 2013; Bockheim and Ackert, 2007; Mahaney, 2015; Mahaney et al., 2001a; Mahaney, 2015; NRCS, http://soils.usda.gov/) in some detail whilst the overlying pebble pavement, complete with Fe/Na encrusted rinds, has been neglected. While the profiles reveal important information on weathering of polar desert sediment, even multiple weathering stages tied to oscillations of outlet glaciers, the pebble pavement is seen to contain in microcosm a longer and more detailed weathering record of the common lithologies — sandstone of the Beacon Supergroup and Ferrar Dolerite. While granite transported from the Antarctic craton and deposited in moraines forming the Middle Miocene Climatic Optimum (MMCO; Warny et al., 2009), it appears that sandstone and dolerite compose the dominant lithologies in older moraines belonging to the earlier alpine event.

Clast rinds have long been used for relative dating of glacial deposits (Birkeland, 1973, 1999; Mahaney, 1978, 1990; Colman and Pierce, 1981), for analysis of clast weathering processes (Sak et al., 2004), and for determination of the bio-influence in clast weathering (Jackson and Keller, 1970). Recently, clast sequences have been probed with high-resolution imaging instrumentation to assess biomineralization (Mahaney et al., 2013a, primary to secondary mineral genesis (Mahaney et al., 2012a), rinds on Mars as possible environmental niches to locate extant or fossil microbes (Mahaney et al., 2012b), and as inventory archives of cosmic impacts/airbursts (Mahaney et al., 2013b; Mahaney and Keiser, 2013). Some rinds have been shown to contain weathering zones that mimic horizons in local paleosols, the resident changes in weathering strength over time registered as an archive in both surface clasts and in the underlying sedimentary substrate (Mahaney et al., 2013b). Still, some rinds are known to become armored thus closing the interface with the atmosphere and biosphere (Mahaney et al., 2012a), with examples placing clasts in weathering lockdown. The prime importance of all these investigations is the wealth of paleoenvironmental data that is archived in weathering rinds, which, when sectioned and analyzed, reveal the slow consumption of primary minerals into myriad organic and inorganic compounds revealing in the process stages of weathering that often correlate with horizons in paleosols (Mahaney et al., 2013b).

As with coatings on sand fractions in soils/paleosols or on bedrock (Mahaney, 2002; Dixon et al., 2002; Gordon and Dorn, 2005), clast rinds likewise reveal a similar residential corpus of natural and anthropogenic activity that can be correlated with one another. Sand coatings down-section in paleosols may correlate with clast rinds in deposit surfaces providing parallel datasets that reinforce each other with regard to interpretations gleaned from parallel weathering trends. As indicated here, clast rind history of site 831 in the New Mountain area, Antarctica, is seen to contain a somewhat more chemically active and perhaps more longer-lived record compared with the underlying

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paleosol (Site 831, referenced from Mahaney et al., 2001a). Research into the pebble pavement beds of these Antarctic paleosols is designed to answer several seminal questions related to sediment origin and age. First, to what degree did most of the matrix sediment deposited with the coarse clastic load either suffer deflation or respond to the warm/wet temperate climate to find residence in the profile below? Second, does proximity of the pebble pavement to the surface subaerial environment lead to selectively greater presence of water to insure hydrolysis and slow growth of clay minerals compared with the drier underlying paleosol? Is the presence of berthierine with kaolinite layers in the weathered clast and its absence in the paleosol suggestive of a more active weathering environment in the pebble bed? Is the nitratine ($NaNO_3$) ~3 mm thick salt bed adhered to the upper clast rind conclusive evidence of a rapid transition to cold/dry polar climate either during the MMCO or before?

Analysis by XRF of an ~8 mm × ~8 mm section of a clast from the Ant-831 pebble bed would appear to answer many of the above mentioned questions.

2. Regional geology

The Transantarctic Mountains, including the Taylor Glacier–New Mountain area (Fig. 1A location relative to McMurdo station; Fig. 1B location relative to the Dry Valleys), consist of sedimentary layers overlying a basement of granites and gneisses. The sedimentary layers include the Beacon Supergroup (Stewart, 1934; Shaw, 1962) consisting mainly of arkosic sandstone locally intruded by doleritic dikes and sills (Ferrar dolerite). This mix of sandstone, dolerite, granite and gneiss comprise the main lithology of the field area, although granite was not found in the Ant-831 paleosol because these are source lithologies not available to alpine ice. The topographic setting includes steep slopes alternating between benches similar to the landscape of South Africa where surface features have formed under arid climates (Campbell and Claridge, 1987; Mahaney et al., 2001a). In the McMurdo area, centers of volcanism date from 10 to 15 Ma (Armstrong, 1978) and are little modified by subsequent glacial and mass wasting activity. Volcanoes, such as Mount Terror in the Ross Island area, retain a conical shape indicating little modification by glacial/mass wasting processes.

Granitic basement rocks form an erosion surface along much of the Transantarctic Mountains and are overlain by Devonian to Jurassic nearly horizontal beds of continental sandstone, originally named the Beacon sandstone (Ferrar, 1907) from outcrops near the Taylor Glacier. These sandstones were later extended to include all grades of clastic rocks from conglomerates to siltstone transitioning upward into thick quartz-rich sandstones of Devonian age, the source of sediments examined here. As suggested by Campbell and Claridge (1987); Barrett (1981) and Bradshaw (2013) these sediments were sourced from basement rocks of East Antarctica.

Glaciation in East Antarctica, according to some workers, was initiated during the Late Oligocene to Early Miocene (Marchant et al., 1993; Lewis et al., 2007; Bo et al., 2009; Passchier, 2011; Anderson et al., 2011), and possibly earlier in the Eocene (Wilson, 1973). Whatever the time of initiation, glaciation began with warm-based ice growing in the mountain areas, developing similar to what exists today in middle latitude areas (Campbell and Claridge, 1987). During part of the Quaternary, climate may have been colder than today and the degree to which this affected alpine ice is unknown. Cold-based ice is believed to have deposited moraines at lower elevations, such as in the Aztec and New Mountain areas as described by Mahaney et al. (2001a). Incursions of ice from outlet glaciers of the Inland Ice that invaded elevated benches are thought to have protected rather than eroded underlying moraine deposits, a situation produced by plastic deformation within the glacier rather than basal sliding (Owen et al., 2009). While the underlying substrate could have been frozen, thus protecting it from erosion, the excellent preservation of buried moraine and paleosols formed within argue for incursions of cold-based ice.

Evidence of the periodic buildup of ice overtopping divides and flowing into embayments comes from areas like New Mountain and Aztec Mountain, with some sites showing evidence of multiple events starting sometime in the Middle Miocene (Mahaney et al., 2001a). At New Mountain, each deposition event was followed by weathering and soil formation with each soil morphogenesis event followed by changes of mass balance and incursion of ice and renewed deposition of till, followed again by soil morphogenesis. Each paleosol built up concentrations of salt in lower horizons juxtaposed with higher Fe in upper horizons, judging by field colors taken at the time of collection, and Fe extractions recovered from profiles (Mahaney et al., 2009). The pebble pavement on the surface of these multi-story paleosols represents a long Middle to Late Neogene weathering event not interrupted by subsequent incursions of ice from the nearby Taylor Glacier (Fig. 1B), weathering of pebble clasts progressing along with weathering in associated deposits. The pebble pavements on the surface of multi-story paleosol sections presumably represent slow winnowing of fines over inordinately long time frames whereas similar pebble caps on alpine moraines may represent a still longer event.

The soil/paleosol in the Ant-831alpine moraine belongs to the Cold Desert Class of Antarctic soils identified by Campbell and Claridge (1987), here and elsewhere (Mahaney et al., 2009) referred to as paleosols. Similar to younger paleosols at New Mountain and Aztec Mountain the paleosol moisture regime in Ant-831 is classed as xerous to subxerous, significantly drier than moisture in pedons of coastal Antarctica, an area warmer and with higher precipitation (Campbell and Claridge, 1987). Snow melt from infrequent summer snowfall tends to wet the pebble pavement and upper horizons in the paleosol body, but because of the high salinity liquid water may exist in intergranular films (Ugolini and Anderson, 1973; Wynn-Williams and Edwards, 2000; Cuffey et al., 2000), thus allowing weathering to continue and provide nutrients for microbe growth. During intense freezing episodes, Ugolini and Anderson (1973) showed that ionic transfer in saline solution may occur through sediment grains of all grade sizes.

Lithology within the 831 paleosol is comprised of dolerite and sandstone exclusively whereas younger sites at New Mountain and Aztec Mountain contain similar lithologies plus significant granite and gneiss.

3. Methods

3.1. Field sedimentary analysis

The 831 section detailed here was selected and excavated in a moraine ridge deposited by alpine ice above the embayment below where sites 828 and 829 are located (see Mahaney et al., 2014b for location of sites). The site, excavated by hand, was sectioned to expose in situ sediment. The paleosol horizon descriptions reported here (Fig. 2) are genetic following horizon designations used previously by Mahaney et al. (2009) adopted from the NSSC (1995) and the Canadian Soil Classification (CSSC, 1998). As with all paleosol sections analyzed, the usual horizon downward succession follows Fe-rich material underlain with salt-rich sediment or Cox/Cz horizons following the US soil classification systems (Soil Survey Staff, 1999; and NSSC, 1995; Birkeland, 1999). The Cox designation is used when the sediment color (Oyama and Takehara, 1970) is stronger than 10YR 5/4 (Birkeland, 1999). The ‘u’ designation in the C horizon nomenclature refers to unweathered sediment. (Hodgson, 1976).

3.2. X-ray fluorescence

Micro-X-ray fluorescence analyses were performed on a polished surface section (Fig. 3A) using an EDAX Eagle III spectrometer at ISTerre (Grenoble, France). The X-ray tube corresponds to an Rh anode operating at 400 μA with an acceleration voltage of 20 kV. Polycapillary lenses were used to focus the X-ray beam down to 50 μm full-width-at-half-maximum at the sample surface. An energy-dispersive X-ray detector

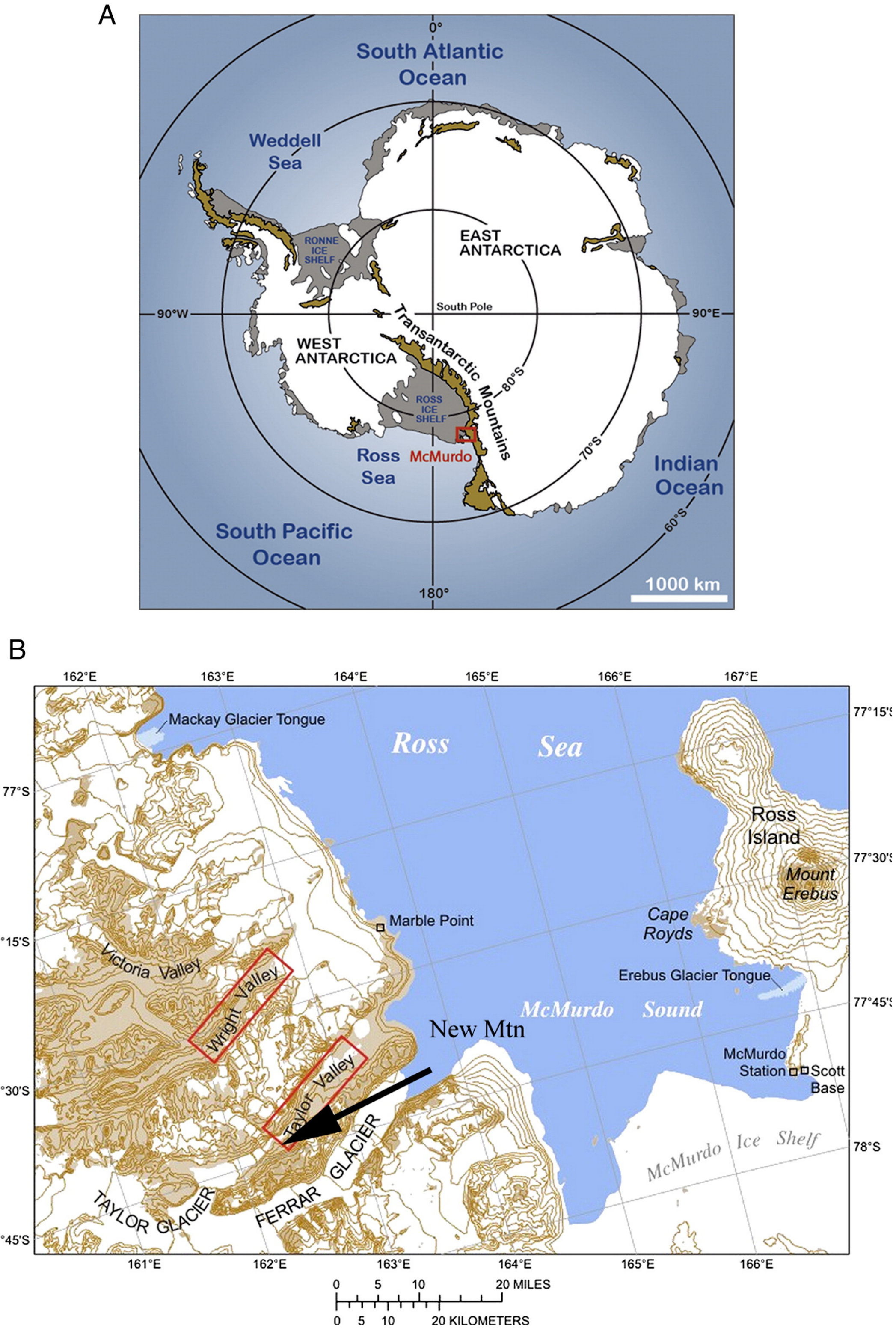

Fig. 1. A, Location of McMurdo Station on Antarctica; B, location of the 831 paleosol near New Mountain, Antarctica. The Mt. Fleming paleosol is located in upper Wright Valley near the Inland Ice.

with resolution of 140 eV was used to measure fluorescence spectra. Chemical maps were obtained with a matrix of 256 × 200 pixels, a 40-μm step interval in both directions, and a dwell time of 1 s per pixel. For each map, the color scale corresponds to the intensity of the Kα-lines of the different elements (Al, Fe, Mn K, Na, Ca, S, Si) calculated from the integration of a specified region of interest (ROI) of the energy range of the XRF spectra.

4. Results

4.1. Pebble pavement

The 831-paleosol pebble pavement is ~3 cm in thickness, similar in most respects to pebble pavement thicknesses in younger profiles dating from the MMCO (Mahaney et al., 2001a). Beyond horizon thickness,

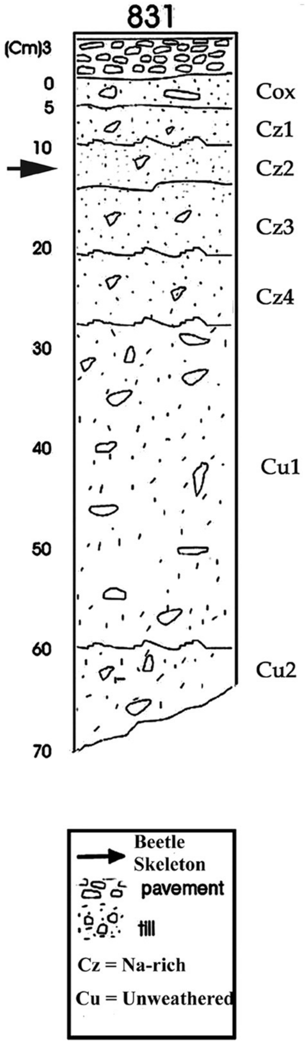

Fig. 2. The 831 paleosol section showing the pebble pavement underlain with a mineral profile comprising a Cox horizon overlying a succession of Cz (salt rich) horizons and Cu (unweathered C-parent material).

the two sets of younger pavements (827, 828 and 829) vs the older 831 bed, differ with clast color expression, thickness of rind development, and where present, thickness of Na-salt encrustation. Surface pebble colors (Oyama and Takehara, 1970) in the younger clast set range from 10YR 4 and 5 values to 7.5YR 4 and 5, variations arising from differences in clast lithology. In the older age set of pebbles in Ant-831, clast colors are dominantly in the 5YR and occasionally in the 2.5YR hue range, mostly with values of 4 and 5 with high chroma. Colors of encrusted salts are all light but still correlate with chips on the 2.5YR to 5YR pages.

Rind thicknesses within the Ant-831 sample group ($n = 55$) range from 4 to 15 mm (4×10^6–15×10^6 nm) and contain appreciable archived data from clast weathering in conjunction with the atmosphere and hydrosphere, often with occasional biogenic influences judging by colors that become brown in the 5YR–2.5YR 3 value with low chroma which may suggest microbial action, residue from bacteria and fungi (Hart et al., 2011; Mahaney et al., 2001a), possibly even Coleoptera (Mahaney, 2015) which are known to have thrived in the early stage of paleosol development in the 831 section.

Encrustations of salt occurring on pebble clasts are probably extant due to position within the pavement in the shadow of larger clasts protecting up to an ~3 mm thick Na/Ca/Nox concentration with occasional fine dust of chlorite/mica/illite composition (identified by XRD) within as matrix material. This weathering record, often in sharp contrast with the weathered lithic surface below, is thought to mark the transition from warm/wet to cold/dry glaciation as outlined below. In fact, the generation of clay minerals seen here in the Ant-831 clast is similar to the geochemical source and weathering histories reported for the Sirius Group Strata in the Transantarctic Mountains by Passchier (2004).

4.2. Rinds

The Na-encrusted rind (Fig. 3A) is a typical example of salt-encrusted clasts in the pebble pavement of the 831 paleosol and carries a salt body adhering to a weathered clast of Beacon sandstone. Three weathering zones can be clearly distinguished in the polished section of Fig. 3A where all zones are clearly shown in stark relief with somewhat greater magnification.

At low magnification, the image (Fig. 3B) shows considerable detail of the salt encrustation and its sharp contact with the weathered clast, each quartz grain within outlined by a matrix of berthierine, and Fe alumino silicate clay belonging to the kaolinite–serpentine group, a common component of Arctic soils. Berthierine, an iron-rich trioctahedral III layer silicate (100 line, 7.04 Å), is a major component of the A and C horizons of the Jaeger soil series in the Canadian Arctic, typical of Arctic desert soils, its preservation considered to result from restricted soil moisture (Kodama and Foscolos, 1981). It is possible that this 7 Å polytype formed in the later stages of clast weathering as the climate transitioned from warm/wet to cold/dry, its presence lower in the rind the product of water movement within the clast.

As a parallel to A/C(ox)/Cu tundra soils (Jaeger soil series) described above, the weathered clast described here contains a microcosm of clast weathered zones (zones 1 and 2) that are not unlike horizons in paleosols and might aptly be designated as a series of Cz or Cox horizons, similar, but in inverted form to what exists in the Ant-831 paleosol below with its succession of Cox/Cz/Cu horizons, or in other paleosols in the immediate research area (Mahaney et al., 2001a, 2014b). While Ah horizons do not exist in the interior of the Dry Valleys, colloidal humus being not available to assist in the genesis of berthierine as in Arctic locales. In other, similar, but much younger situations in the Alps, rinds of Late Glacial age sometimes show weathering zones of high to low weathering interfacing fresh internal lithics, micro-corollaries of Bw/Cox/Cu horizons common in Late Glacial paleosols (Mahaney et al., 2013b). Even in this clast weathered Ant-831 example, zone 2 could be subdivided on the basis of color/oxide release into two separate horizons or subdivisions situated between zones 1 and 3.

Grains in Zone 1 (Fig. 4A), nested within a matrix of berthierine and illite, consisting of fine to coarse sand grade sizes, some fragments within the silt grade. Grades in this sample are shown to range from subangular to subround, angularity dominating among the finer grade sizes. All quartz surfaces depict rough edges with embayments of varying sizes which could result from abrasion during transport or mechanical/chemical weathering following emplacement. The chemistry in this zone, highlighted by high Fe and concentrations of illite and berthierine, may also contain various secondary oxides and hydroxides, some translocated from nearer the outer zone of the clast (Zone 2). In contrast, Zone 2 contains less Fe and more quartz, berthierine and illite shown at higher magnification to be more widely dispersed in pockets between grains and within fractures, the latter possibly the result of mechanical action on chemically weakened grains. The low Fe and high quartz in Zone 2 (Fig. 4B), distinct from Zone 1 (Fig. 4A), may reflect variable leaching or mineralogies. Despite the differences in scale between the two figures it could be that the upper quartz-rich zone became armored over time prior to the transition from warm/wet to cold/dry paleoclimate.

Zone 3, depicted in Fig. 3A and B, is composed of gypsum, quartz fragments and nitratine. The gypsum is a common salt component of the 831 paleosol but the nitratine is unique as an allochthonous substance presumably derived from marine sources. The quartz and

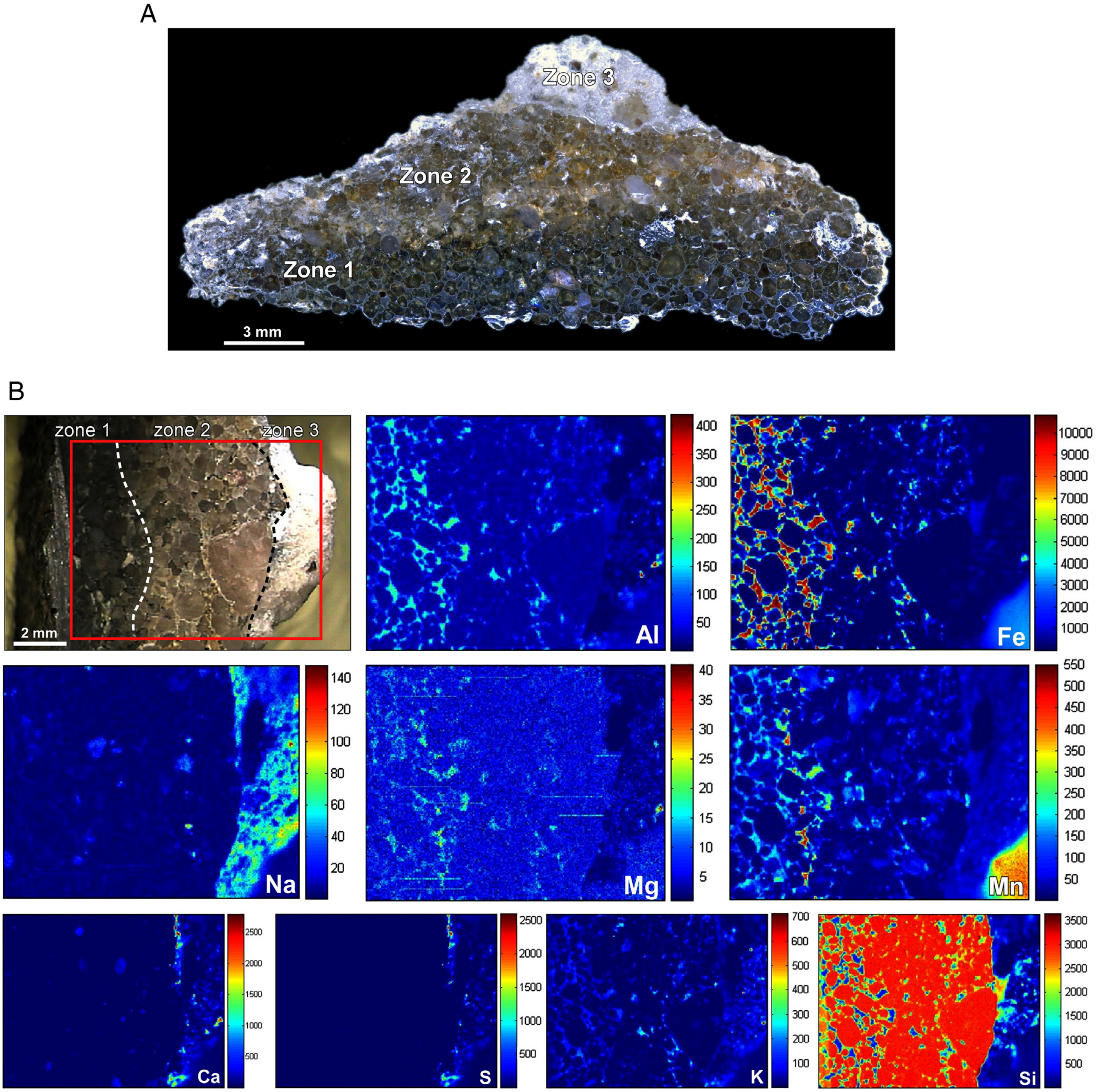

Fig. 3. A, Clast of micaceous sandstone (source presumably from Beacon Supergroup) showing variable weathered zones within the upper clast merging across a sharp contact with ~3 mm of Na encrusted salt, the transition boundary assumed to represent the change from warm/wet to cold/dry glacial paleoclimate with an indeterminate age in the Early Miocene or Late Oligocene. Elemental groups clearly delineate weathering zones 1, 2 and 3, the latter presumably the long slow accumulation of salt following the transition from warm/wet to cold/dry climate; B, polished section of the clast shown in panel A showing clear divisions between weathering zones.

plagioclase fragments within the lower part of this zone may represent the degradation of the former outer clast, possibly mechanically weathered by invading salts following the changeover into cold/dry climate, or as allochthonous sediment delivered by aeolian processes as the salt mass expanded (Fig. 5).

4.3. Paleosol

The Ant-831 paleosol, formed in alpine drift deposited during the early stage of warm-wet glaciation, is similar in morphogenesis to the paleosol at Mt. Fleming in upper Wright Valley, one of two documented paleosols belonging to this early phase of Antarctic glaciation. While the Mt. Fleming paleosol contains semi-gelic sediment within the top 100 cm of the profile and permafrost within 2 m of the surface, the 831 paleosol (Mahaney, 2015) falls within the Gelisol order (Natural Resources Conservation Service; http://soils.usda.gov/). With dry frozen sand and horizons composed of primary and secondary gelic sediment, low carbon, and lacking evidence of cryoturbation, the profile classifies to the Orthel suborder of Anhyorthel, that is, a profile with gravel (pebble bed) over salt-rich horizons (Cz), overlyingpermafrost. While the properties of the 831 profile are similar to the paleosol at Mt. Fleming Climate Station, adjacent to the Inland Ice Sheet, the Mt. Fleming

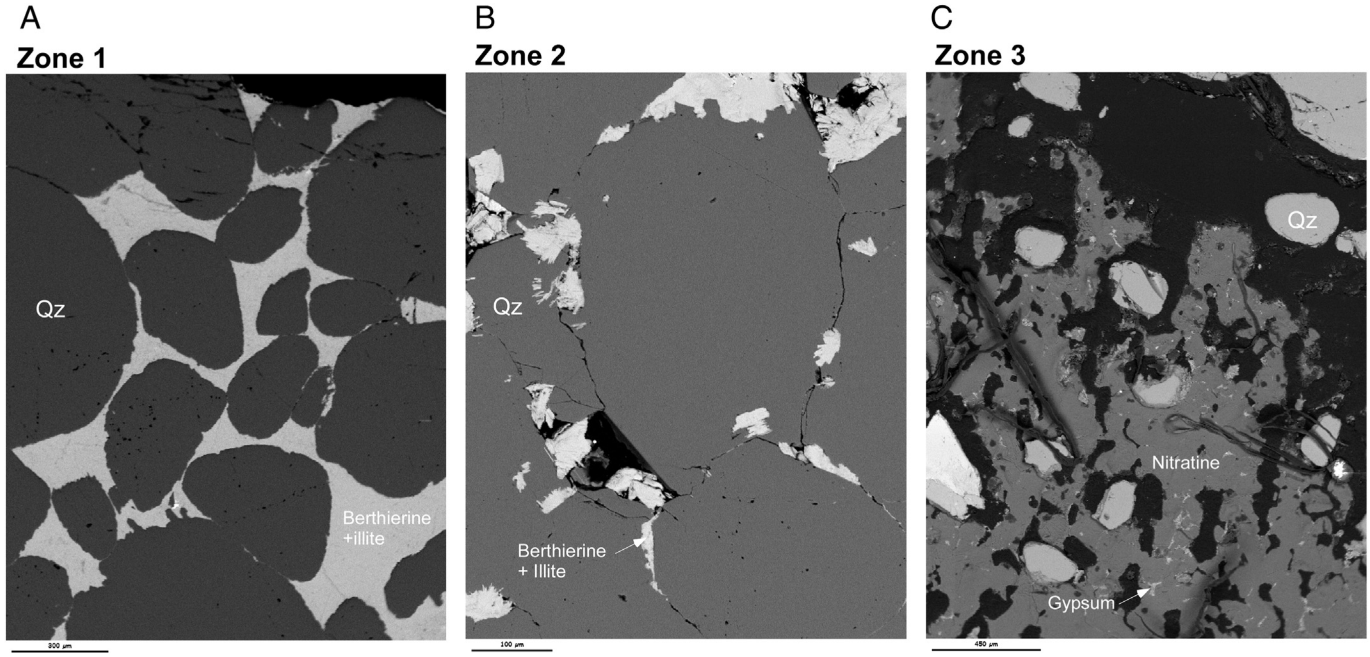

Fig. 4. A, Character of quartz grains in zone 1 embedded with thick accumulations of berthierine and illite. As shown in Fig. 3 Fe is higher in zone 1; B, lower concentrations of berthierine and illite; C, the lower part of zone 3 contains high concentration of nitrate and gypsum enclosing quartz and feldspar grains derived from breakup of the clast during the transition stage to Na encrustation.

paleosol site, at 1698 m (77° 22.67082 N and 161° 48.03439 E), is 150 m lower and formed within a polygon, and hence, contains more coarser sediment compared with the 831 paleosol. It is likely that the semigelic characteristic of the Mt. Fleming paleosol results from a more active layer at some time in the past, one with a transition from somewhat finer to coarser sediment load, and capable of producing polygons.

Lacking Ah/B horizons, the 831 profile (Fig. 2) contains the usual pavement/Cox/Cz/Cu horizon sequence with Fe release confined mainly to the pavement (important in rind formation) and weathering of what dolerite or mica exists from Beacon Supergroup sediment, higher oxidation levels restricted to normal movement of soil moisture (~10 cm), these surface horizons overlapping a series of Cz salt-rich horizons and fresh undifferentiated parent materials (Cu horizons). Colors within the paleosol horizons are one or two value/chroma lighter than in the pebble pavement probably due to mixing of Fe and salt. Particle size distributions within the profile show that clay is generally less than 5% with an increase of 10% in the Cz2 horizon, the one horizon containing Coleoptera fossil material and remnant bacteria endospores (Hart et al., 2011) considered to have existed as part of an ecological network during the warm wet phase of Antarctic glaciation. A similar increase of clay content in the Cu horizon could relate to former microbial activity but no Coleoptera fossils were found resident there when all samples were reanalyzed as part of a general microscopic search of all bulk samples.

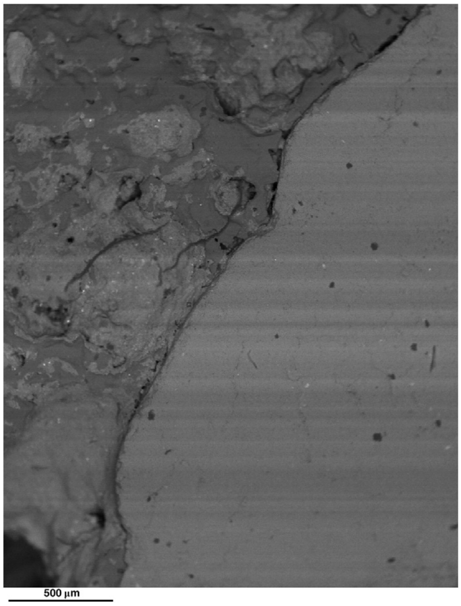

Fig. 5. Border of zones 2 and 3 with a 50–100 µm wide transition area where salts, nitratine and gypsum lie intermixed with quartz and feldspar possibly weathered mechanically by salt crystal growth.

5. Discussion

Weathering rind analysis in the Antarctic has been a neglected source of paleoenvironmental information over the time that research has been carried out in earnest, that is, the last 5 decades or so. Because weathered regolith almost always classifies as of paleosol – not soil – vintage, the vast majority of pedons are classed as forming under more than one climate, either before during or following the MMCO of ~15 Ma (Graham et al., 2002), and most but not all, contain pebble pavements. Some buried pedons (Mahaney et al., 2001a) lack pebble pavements presumably because incoming ice managed to leave a weathered entity in place after removing the pavement, perhaps because the soil/paleosol was frozen, and therefore armored and able to withstand an advancing glacier, while the pavement was not cemented and unfrozen. Whatever the longevity of the pavement, it is seen here to provide a wealth of evidence related to presumably a variable weathering of Beacon sandstone over an inordinate but unknown amount of time, presumably almost entirely during the early alpine phase of warm/wet glaciation in Antarctica. The slow rate of clast consumption during the oxide release/clay mineral genesis penetrating deeper into the lithic body must have become even slower during the genesis of berthierine in Zone 1, perhaps in the later stage of chemical decomposition. Moreover, as with all rinds (Mahaney et al., 2013b; Mahaney et al., 2012a,b), fluid penetration is necessary to continue rind growth over time, fluid volume and mobility determined by microclimate and rind armoring. In this case, it appears the outer rind of the Ant-831 clast did not become armored, lost some of its surface to erosion prior to incorporation of clast material into the salt encrustation, with occasional meltwater carrying some salt inward into the weathered clast.

Since rinds are thought to contribute hydrolyzed and oxidized products to soils and paleosols (Mahaney et al., 2013b), it is probable that some of the oxides and hydroxides in the 831 paleosol were derived from the overlying pebble pavement. We cannot be certain what the ratio of deflated fines to paleosol-incorporated fines might be, only that surely with strong katabatic winds common off the Inland Ice, it is surely high, perhaps a dominant force. The presence of clay minerals within the surface rind complex certainly contrasts with the clay mineral composition within the 831 paleosol, the latter known (Mahaney et al., 2001a) to contain detrital minerals deposited as preweathered sediment and sourced from higher elevations. The presence of berthierine with kaolinite layers supports the proposition that not only was water more prevalent within the pebble bed compared with the developing soil underneath but that weathering was sufficient to leach the clasts sufficiently to produce a Si:Al (1:1) clay mineral complex. During the initial wet/weathering episode reconstructed here it may be that snow falling on the pebble pavement may have moistened surface clasts to a greater extent than the infrequent snowfall that occurs locally at present.

The sharp contact of the nitratine ($NaNO_3$) ~3 mm thick salt bed within the upper clast rind supports a rapid transition of warm/wet alpine ice to cold/dry polar climate either during the MMCO or before? Since the transition is undated in this instance, the only evidence for clast weathering prior to the MMCO is the higher concentration of secondary Fe and Al in the 831 paleosol (Mahaney, 2015; Mahaney et al., 2009), which suggests that clast weathering occurred at an earlier time.

Because Antarctic paleosols are known to carry extant bacteria and fungi (Hart et al., 2011) and fossil Coleoptera (Mahaney, 2015; Mahaney et al., 2014b) weathering rinds might be expected to carry similar microbial species. Salt films on and around mineral grains and massive salt encrustations adhering to clasts as outlined here might be expected to contain microbes and possibly even Coleoptera despite the expected thermal regime differences between clasts in pebble pavements and sediment matrices in pedons. Salt in high concentrations as in the clast matrices discussed here may well contain intercellular water in liquid form down to −50 °C sufficient to sustain microbial growth. Because endolithic lichen growth is known to occur in Antarctica (Fink et al., 2013) it is likely, despite none being found in this study, that such life forms may exist in pebble pavement in some localities. While no extant or fossil microbes were found in this study their presence in similar micro-topographic situations is possible and should be actively searched for when possible.

Sand coatings in both the Ant-831 (Mahaney, 2015) and other paleosols in the New Mountain and Aztec Mountain areas (Mahaney et al., 2001a, 2009) carry archives similar to what is described in the clast weathering rind reported here and offer additional information not only on weathering but on microbe/Coleoptera composition, both extant and fossil. Such coatings are a mix of secondary Fe (oxides and hydroxides), pyrophosphate-extractable Al (Alp) a proxy for organic carbon, and acid ammonium oxalic acid extracts (Al_o), the derivative of Al_o–Al_p a proxy for imogolite and allophane (Parfitt and Childs, 1988; Mahaney, 2015; Mahaney et al., 2001b, 2014a), all of which offer insight into, in some cases, first 'rapid' polar weathering during warm/wet times to slow polar weathering during subsequent cold/dry climate. A glimpse into such examples can be found in Mahaney et al. (2001a, Fig. 7) and Mahaney et al. (2014b), Figs. 4A, B and 6).

Comparison of variations in rind thickness can be found in Mahaney et al. (2012b, 2013a, 2016) with examples of rapid growth in the tropical mountains over 100×10^3 to 2×10^6 years (Figs. 3–7) gauged against rind development in Antarctica since the MMCO (Fig. 8A–C). Such contrasting measurements show that rind growth while governed largely by climate may be subject to perturbations by lithologic and time variations, and even very old rinds on various terrestrial platforms may yield considerable differences between maximum and minimum thicknesses (example Fig. 2 in Mahaney et al., 2012a). Even older rinds of Noachian age (~4 Ga) in meteorites on Mars, known from observations and measurements carried out by the Opportunity Rover, when fully studied, may well contain not only enviable paleoenvironmental records but evidence of life, either extant or fossil (Mahaney et al., 2012b).

6. Conclusions

The Beacon Supergroup sand from the Ant-831 pebble pavement provides an ~8 × ~8 mm image of clast and Na encrustation, with XRF analysis recording chemical changes from deep within the clast to its outer weathered edge transitioning across a narrow contact upward into the salt body. The described weathering zones 1 and 2 record weathering processes, presumably largely oxidation, hydrolysis, and hydration operating since at least the Early Miocene, and quite possibly reaching into the Late Oligocene, perhaps to the very early stage of warm/wet mountain glaciation that preceded the growth of the Inland Ice sheet. Zone 3 records the chemical composition of the Na-encrustation; first, in the lower contact zone mixed materials derived from the weathered clast which suggests some loss of weathered compounds with growth of the salt efflorescence, and later near total salt accumulation with only minor clast input. The $NaNO_3$ encrustation is an allochthonous addition to the clast, the Na likely sourced mostly from marine sources as described by other workers (Campbell and Claridge, 1987) at other sites.

Because clast rind armor varies in cementation and porosity, gradations ranging from almost no cementation to near rigid armor, it would appear from this analysis that minor infusions of clast material in the lower Na encrustation indicate some of the weathering rind was lost to salt efflorescence as it developed in the early stage of transition from warm/wet to cold/dry glaciation. With increasing upward growth of salt the input of stray clastic material becomes negligible, detected particles presumably from airfall influx; or possibly, given that we do not know the exact x–y attitude of the clast in the pavement or its likely change in position over time, from a local source. Detected particles within Zone 3 may even have been sourced from afield as the Inland Ice Sheet advanced. What is known from this data is that presumably for the first time the Antarctic paleoclimatic transition from warm/wet to cold/dry is seen to be written into a weathering rind record in a common pebble pavement typical of Antarctic paleosols in general.

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