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MUD AGGREGATES FROM THE KATBERG FORMATION, SOUTH AFRICA: ADDITIONAL EVIDENCE FOR EARLY TRIASSIC DEGRADATIONAL LANDSCAPES

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ABSTRACT: **Mudclast aggregates are documented in the Lower Triassic, anabranching fluvial deposits of the Katberg Formation, Karoo Basin, South Africa. Here, aggregates are: (1) coarse silt to fine sand size, (2) of a heterogeneous texture consisting of several clay clasts, some of which display the presence of clay skins, (3) uniquely shaped, not simply filling pore space between other grains as matrix, and (4) in association with reworked carbonate nodules and mud-chip rip-up clasts. They occur in basal channel lags, trough fills of megaforms, and at the tops of channel-fill sequences; there is no evidence of mud aggregates in paleosol intervals. Two chemical types of aggregates are identified. One type is enriched in carbon and depleted in calcium, and is interpreted to have originated in an upper soil horizon; the second is depleted in carbon and enriched in calcium, and is interpreted to have originated at some depth in the soil profile. These attributes, in conjunction with the presence of calcite-cemented nodules concentrated in channel lags, are used to interpret the former presence of paleoVertisols across the Early Triassic Karoo landscape prior to landscape degradation.**

INTRODUCTION

The lithological, paleopedological, and geochemical features of paleosols provide insight into processes operating across ancient landscapes which, in turn, act as a proxy for the paleoclimate under which each soil type formed (e.g., Sellwood and Price1994; Sheldon and Tabor 2009). Various pedogenic structures may form in seasonally controlled soils, depending on the chemical, physical, and mechanical changes operating on sediment mineralogy. One pedogenic feature, the mud aggregate, may form when swelling clays are alternately wetted and dried, resulting in the organization of sand-size particles (62.5 µm–2 mm) composed of silt-and-clay particles (< 3.9 µm). These features are recognized in modern (e.g., Rust and Nanson 1989; Wakelin-King and Webb 2007a, 2007b) and Phanerozoic soils (Marriott and Wright 1993, 1996, 2006), where they may occur either as part of an *in situ* soil profile (e.g., Rust and Nanson 1989), as reworked clasts in fluvial deposits (Nanson et al. 1986), or in both coeval floodplain and river deposits (e.g., Wakelin-King and Webb 2007a). Presently, mud aggregates occur in several modern dryland settings, where their texture is described as "granular" (Rust and Nanson 1989). These include: (1) Coopers Creek, Lake Eyre Basin, South Australia (Nanson et al. 1986); (2) Fowlers Creek, New South Wales (Wakelin-King and Webb 2007b); (3) eolian deposits of the Strzelecki and Tirari Deserts (Dare-Edwards 1984; Fitzsimmons et al. 2009), Queensland, Australia; and (4) clay-pelleted sand from the Biskra region of the Sahara, Algeria (Williams 1966). In contrast, Brooks (2003) identifies sand-size aggregates in annual, high-discharge deposits of the muddy, meandering Red River, Manitoba, Canada, developed under a moderately dry climate.

Gierlowski-Kordesch and Gibling (2002) provide a comprehensive overview of aggregate features, factors influencing their genesis, and their occurrences in deep time. To date, deep-time mud-clast aggregates are considered to be associated with Vertisols and are recognized from across the Phanerozoic. They are reported as early as the Cambrian (Retallack 2008), and are common from the Silurian (Driese et al. 1992) and Devonian (e.g., Marriott and Wright 1993; Love and Williams 2000), into the Triassic (Müller et al. 2004) and the Cretaceous (Buck et al. 2004), and throughout the Tertiary (e.g., Jacobs et al. 2005; van Itterbeeck et al. 2007; Nordt et al. 2011). The current contribution adds to this list by demonstrating the presence of mudclast aggregates in the Lower Triassic Katberg Formation in the Beaufort Group of the Karoo Basin, South Africa.

BEAUFORT GROUP, KAROO BASIN

The Karoo Basin of South Africa generally is considered to be a retro-arc foreland basin that developed in southern Gondwana during the Late Carboniferous to Early Jurassic, filled with a sedimentary sequence known as the Karoo Supergroup (Catuneanu et al. 2005; Johnson et al. 2006). Four lithostratigraphic groups (i.e., Dwyka, Ecca, Beaufort, and "Stormberg") are recognized based on differences in the sedimentary characteristics of the basin fill. The Beaufort Group, the largest and most extensive of the Karoo Supergroup's units, commences with the transition from deep-water turbidite successions and coastal prodeltaic deposits, found in the uppermost Ecca Group, to fully subaerial and predominantly fluvial deposits in the Middle Permian (Rubidge et al. 2000, 2012). The Ecca–Beaufort contact is diachronous. Thus, when sediments derived from the Cape Fold Belt to the south commenced fluvial deposition in the southern part of the basin, contemporaneous, subaqueous Ecca Group deposits in the Volksrust Formation continued in the northern distal sector (Rubidge 2005). This coastline prograded north as the basin filled, and continental fluvial deposition extended throughout the entire basin by the end of the Permian (Rubidge 2005).

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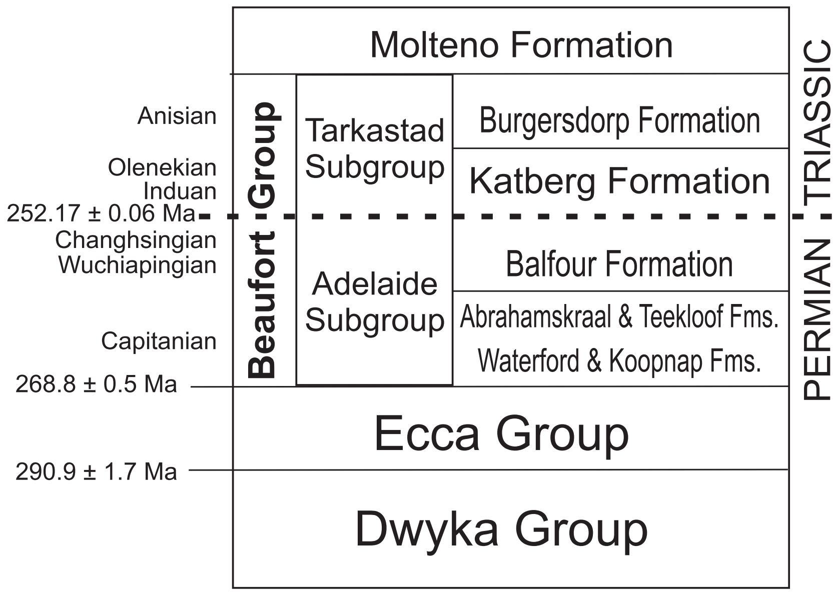

FIG. 1.—Generalized stratigraphy of the Karoo Supergroup and the position of the Katberg Formation. Chronometric age for the Permian–Triassic boundary is from Shen et al. (2011); the Beaufort–Ecca boundary date is based on the International Chronostratigraphic Chart of the International Commission on Stratigraphy, December 2012 version; the Dwyka–Ecca boundary date from Stollhofen et al. (2008).

The Beaufort Group attains a maximum thickness in excess of 3 km in the proximal sector of the basin (Johnson et al. 2006; Fig. 1) and is subdivided into a lower (Permian–Triassic) Adelaide Subgroup and an upper (Lower–Middle Triassic) Tarkastad Subgroup. Regional variation resulted in different stratigraphic nomenclatures being recognized for outcrops of the Adelaide Subgroup in the southwestern, southeastern, and northern parts of the basin (Johnson et al. 2006). The most complete stratigraphic sequence arguably is found in the southeastern part of the basin, the location of the current study, and consists of the Koonap, Middleton, and Balfour formations. The uppermost Balfour Formation incorporates both the Wuchiapingian and Changhsingian (Prevec et al. 2010), and spans the Permian–Triassic Boundary.

The Tarkastad Subgroup is restricted to the eastern half of the basin (cropping out to the east of 24° E longitude) and consists of only two formations. The lowermost Katberg Formation is defined as an arenaceous or predominantly arenaceous unit (Johnson et al. 2006) with subordinate thin (2–10 m), red and greenish gray mudstones (Stavrakis 1980). While a maximum thickness of more than 1000 m has been reported in proximal exposures near the East London coast, this formation thins to ~ 350 m in the study area (Johnson et al. 2006), which is situated more than 180 km from the Cape Fold Belt to the south. The formation spans the Induan (Smith 1995) and lower Olenekian (Damiani et al. 2000), and is considered equivalent to the Verkykerskop Formation which crops out in the north of the basin (Groenewald 1989; Johnson et al. 2006). An unconformity separates the Verkykerskop Formation from the underlying Normandien Formation (Hancox et al. 2002), and Neveling (2004) proposed that only the former unit should be correlated with the middle Katberg Formation because the lowermost and uppermost sections of the Katberg Formation are restricted to the proximal part of the basin. The predominantly argillaceous Burgersdorp Formation (Johnson and Hiller 1990), which overlies the Katberg Formation, is assigned an Upper Olenekian to Anisian age (Hancox et al. 1995) and is separated by a basin-wide unconformity (spanning the Ladinian; Hancox 2000) from the overlying Molteno Formation of the "Stormberg" Group.

Traditionally, the Permian section of the Beaufort Group is interpreted as having accumulated in a meandering fluvial environment (Smith 1987; Smith et al. 1993). However, perennial braided-river deposits also are reported from the base of several upwards-fining, third-order fluvial sequences in the Koonap, Middleton (Catuneanu and Bowker 2001), and Balfour (Catuneanu and Elonga 2001) formations. These are described as grading upwards into sand-dominated meandering (the predominant fluvial model) and, sometimes, fine-grained meandering deposits. Paleoclimatic models controlling these sediments are still largely speculative. Semiarid (Keyser 1966; Smith et al. 1993; Visser 1995) and warm-arid (Scheffler et al. 2006) conditions have been proposed for the Lower Beaufort Group, although sedimentological indicators of aridity (e.g., gypsisols, calcisols) are isolated in space and time in the main Karoo Basin. Conversely, paleobotanical evidence, including mineable coal, indicates a cool, wet temperate climate in the coeval Lebombo Basin (Bordy and Prevec 2008), and wetland vegetation is recorded from the northeast, beyond the extent of this study, in the coeval Normandien (recognized formal stratigraphic unit) and Estcourt (unrecognized formal stratigraphic unit) formations (Selover and Gastaldo 2005). Sedimentological, paleosol, and geochemical evidence also are used to propose poorly drained, wet floodplains for the Adelaide Subgroup, which is interpreted as having accumulated under humid to temperate climatic conditions (Smith 1995; Catuneanu and Elonga 2001; Tabor et al. 2007).

Shallow, low-sinuosity fluvial regimes are proposed for the Katberg Formation and its distal equivalent (Stavrakis 1980; Hiller and Stavrakis 1984; Groenewald 1989; Haycock et al. 1997; Neveling 2004). Pace et al. (2009) provide the first update of this model, recognizing that the lowermost Katberg Formation was deposited under oscillating wet to seasonably dry conditions throughout the earliest Triassic. The stratigraphic record represents remnants of aggraded and polyphase paleosols and shallow, wide channels formed in an anabranching regime. The mudrock-dominated Burgersdorp Formation and its distal equivalent Driekoppen Formation (Groenewald 1989), which overtop it, record deposition in both low-sinuosity and high-sinuosity fluvial systems (Hiller and Stavrakis 1984) and are assigned a late Olenekian to Anisian age (Hancox et al. 1995).

MATERIALS AND METHODS

Katberg Formation materials from Carlton Heights, Eastern Cape Province (31° 17.702″ S, 24° 57.093″ E; Fig. 2A, B) originate from the exposure along a roadcut of the N-9 highway (Fig. 3). These include: (1) lithologies reported by Gastaldo and Rolerson (2008) as *Katbergia*-bearing paleosols, (2) pedogenic conglomerate lags reported by Pace et al. (2009; Fig. 4A) at the base of their Fine and Very Fine-Grained

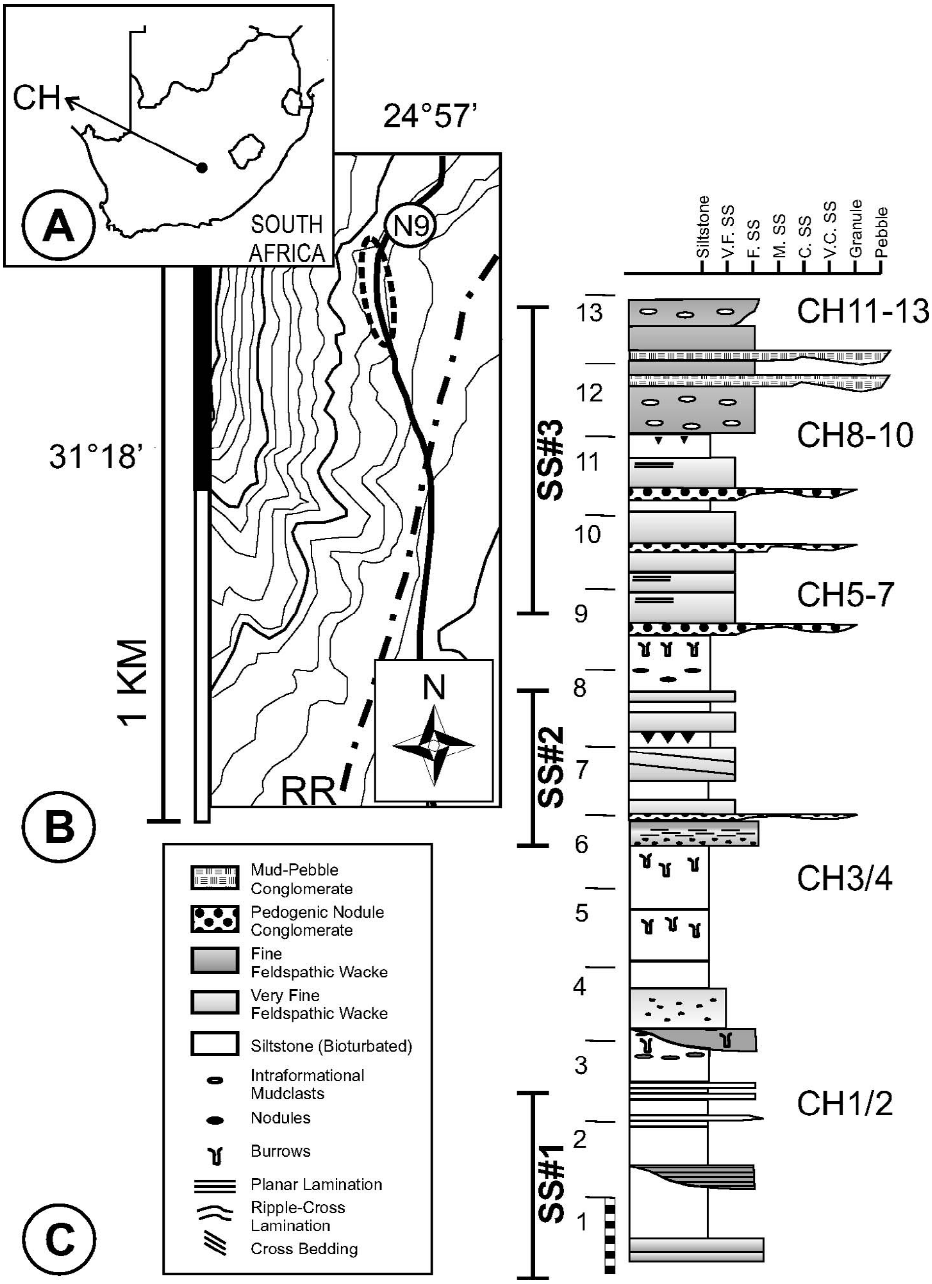

FIG. 2.—Locality maps and stratigraphic section of the Lower Triassic Katberg Sandstone. **A)** Outline map of South Africa with pedogenic conglomerate exposures at Carlton Heights (CH). **B)** Outcrop of Katberg Sandstone sampled along the N-9 motorway is shown in the dashed line ellipse (S 31.29415°, E 24.95057° WGS84 Meridian). **C)** Stratigraphic section from Gastaldo and Rolerson (2008) against which are placed the limits of SS#1, SS#2, and SS#3 identified by Pace et al. (2009) and the sample identifications (CH1–CH13) used in the current study (see Fig. 3). Scale in meters.

Feldspathic Wacke facies, interpreted as anabranching fluvial channels, (3) hand samples recovered from the top of the basal sandstone (CH09-1,2; SS#1 of Pace et al. 2009), the intervening *Katbergia*-bearing paleosol (CH09-3/4), and (4) nine mud-chip conglomerate and siltstone trough fills that are a part of Pace et al.'s (2009) Fine-Grained Feldspathic Wacke facies in the third (Fig. 4B; CH09-5/13 SS#3) sandstone body (Fig. 2C; Pace et al. 2009).

Thin sections of the above lithologies were prepared either at Colby College or by Applied Petrographic Services, the latter of which are embedded in blue epoxy to facilitate identification of pore space. Stratigraphic "up" is marked with a notch on sandstones, but poorly cemented and weathered siltstone slides consist of rock fragments without orientation. Macroscopic and microscopic examination were facilitated with a Leitz macroscope and a Nikon petrographic microscope under plane- and cross-polarized light, respectively. Mud aggregates were identified using the criteria established by previous authors (e.g., Rust and Nanson 1989; Ékes 1993; Gierlowski-Kordesch and Gibling 2002; Müller et al. 2004), including aggregate clasts exhibiting an individual, unique shape, and not simply filling pore space between other grains as matrix. Each aggregate is comprised of several clay grains within its boundaries, indicating that it is truly an aggregate, with the possible presence of clay skins; these coexist with reworked carbonate nodules and rip-up clasts. Aggregate differentiation was based on clast appearance in plane- and cross-polarized light. The diameters of aggregates and quartz grains were measured using NIS-Elements image processing software, and a random sampling of 300 clasts was made for aggregates and quartz, where encountered.

In addition to petrographic analysis, SEM was employed to determine aggregate and mineral-grain mineralogy. EDS spectra were collected at the University of Maine at Orono facility with an AMRay 1820, equipped

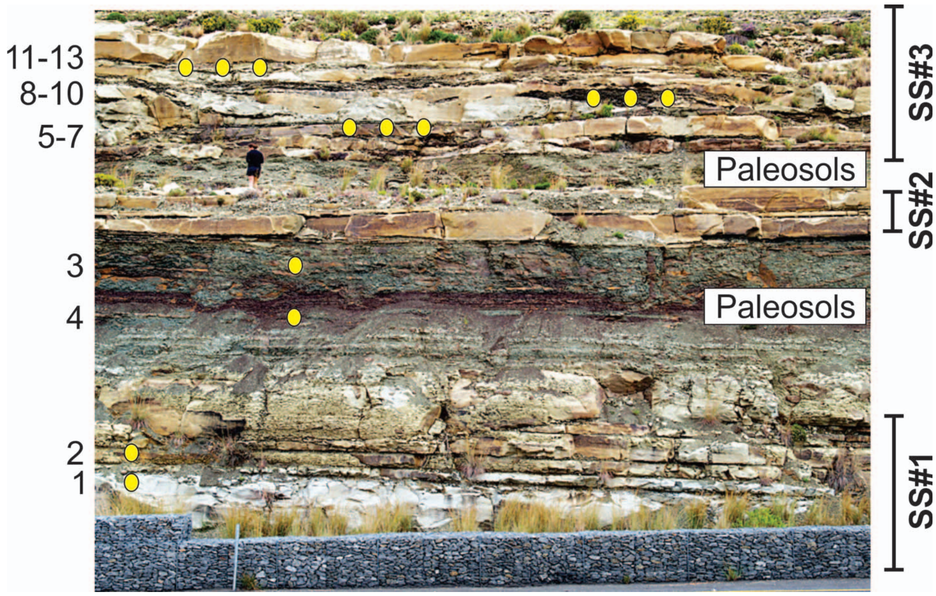

FIG. 3.—Photograph of the Katberg Sandstone exposure along the R-9 motorway against which the limits of SS#1, SS#2, and SS#3 identified by Pace et al. (2009) are shown as benches, and the intervening paleosol intervals. Yellow dots mark the stratigraphic position of hand samples, and numerals indicated the Carlton Heights sample numbers collected in 2009 (e.g., CH09-01) that supplement prior sampling. See Pace et al. (2009, their figs. 11, 12) for lateral variability of facies in the outcrop.

with EDAX, with standardless samples run at 20 kV. Back-scatter electron images were processed from non-carbon-coated samples, and semiquantitative chemical data also were collected.

RESULTS

Mud aggregates and clasts are found in anabranching-channel deposits of the lower part of the Katberg Formation, including pedogenic conglomerate-channel lags, mud-chip conglomerate, and siltstone in trough fills of barforms, and in the capping facies of channel-fill deposits, primarily in SS#3 (Pace et al. 2009). No mud aggregates were identified in paleosol thin sections. Primary structures in which mud aggregates may be concentrated, as described by other workers (Margoulis and Nanson 1996; Gierlowski-Kordesch and Gibling 2002), are not seen in thin sections, but preservation potential of individual aggregates was increased when surrounded by quartz clasts buffering them from being crushed during compaction (Fig. 5). Aggregates display a heterogeneous texture and brownish-orange color in thin section, and range in shape from elongate to subangular and subrounded. They do not appear to be feldspar clasts weathered to clays because unaltered feldspars account for as much as 50% of the Fine Grained Feldspathic Wacke and Very Fine Grained Feldspathic Wacke lithofacies of Pace et al. (2009). There is a higher proportion of mud aggregate to quartz clasts in the interbedded, planar sandstone and siltstone interval capping SS#1 (Fig. 5A; Pace et al. 2009) than in the trough fills of SS#3 (Fig. 5B, C; Pace et al. 2009). This may be a function of the hand sample sectioned or the fact that megaform troughs also include centimeter-scale mud chips (Fig. 4B), the probable source of aggregate clasts when such soil remnants are disassociated and broken down.

The diameter of clasts in thin sections of fluvial bodies ranges from fine sand to coarse silt, resulting in a sand:silt ratio of 46:54 in samples from SS#1 (CH09-01 and CH09-02) and 77:23 in the trough fills of SS#3. Aggregate diameter ranges from fine sand (270 μm) to coarse silt (44 μm; Fig. 6), averaging 107 μm (very fine sand) in the channel-fill interval of the SS#1 (Fig. 6A), and averages 126 μm (fine sand) in the siltstone with mud-chip conglomerate found in trough fills of SS#3 (Fig. 6B). Quartz clasts from SS#1 range from 16 μm to 234 μm, with an average size of 66 μm (very fine sand), and from 16 μm to 326 μm in SS#3 trough fills, averaging 98 μm (very fine sand). It can be seen that the aggregates are more coarsely skewed than the quartz in a cumulative frequency plot of only the sand-size clasts from each sample suite (Fig. 6C).

Semiquantitative oxide data were gathered for aggregates originating in channel overbank (CH09-01B), trough fills (CH09-05; Fig. 7A, B), and conglomerate lag (PC1; Fig. 7C, D) samples. Aggregate clay mineralogy could not be differentiated at high resolution because of limitations on data collection, but aggregates tend to be homogeneous in composition (Table 1). Analysis of specific clay grains within aggregates, as well as averages for the entire clast, resulted in virtually identical data with significant EDS spectral peaks of SiO_2 (~ 60 wt%) and Al_2O_3 (> 20 wt%). Other peaks include K_2O, FeO, MgO, and Na_2O at < 10 wt% each, with pedogenic nodule conglomerate and channel samples being similar. More carbon is found in samples originating from channel deposits (CH09-05, PC-1) than in the interbedded siltstone-and-sandstone beds capping SS#1 (CH09-01; Fig. 8). One pedogenic conglomerate lag aggregate has a high CaO peak, indicative of carbonate cement commonly found in this lithology (Pace et al. 2009). Neighboring minerals also were analyzed, and their compositions include quartz, potassium feldspar, and a range of plagioclase feldspars.

DISCUSSION

Informal field recognition of the Lower Triassic Katberg Sandstone relies on the first appearance of pedogenic carbonate conglomerate as channel-lag accumulations above the green-gray paleosols of the Palingkloof Member in which the ichnogenus *Katbergia* (Gastaldo and Rolerson 2008) becomes common. The conditions under which these sandstones accumulated are characterized variously, but with an overarching premise of aridity developed in response to the end-Paleozoic mass extinction resulting in a fundamental change in fluvial architecture (e.g., Smith 1995; Ward et al. 2000, 2005). More recently, a study at high stratigraphic resolution undertaken at the Carlton Heights locality reports that the basal sandstone bodies in the Katberg Formation are multilateral fluvial deposits, appearing to display multistories only when coalesced laterally, in which both interfluvial wet paleosols (Gastaldo and Rolerson 2008) and within-channel evidence for seasonally dry conditions exist (Pace et al. 2009). The presence of the pedogenic carbonate-nodule lags of various geometries, overlying erosional surfaces, are interpreted as the erosional remnants of aridisols, representing the only evidence for

FIG. 4.—Lithologies in which mud aggregate clasts are recognized. **A)** Pedogenic conglomerate lag from the base of SS3 showing small calcareous nodules with shapes ranging from rods to ellipses to amorphous. Bone fragments often are found in this facies. Scale in centimeters and millimeters. **B)** Mud-chip conglomerate found in troughs of barforms with individual clasts ranging from subangular to subrounded in shape, and centimeter to decimeter in size. Mud chips are in either a siltstone, sandy siltstone, or sandstone matrix. Scale in centimeters and decimeters.

more seasonally dry conditions in the earliest Triassic (Pace et al. 2009). At the time of publication, these authors had not identified mud aggregates in the system which now are demonstrated to be a component of these channel deposits.

Mud aggregates of the Katberg Formation occur as silt- and sand-size clasts in the channel-fill sequence of SS#1 (Pace et al. 2009), and in both pedogenic carbonate-nodule lags and trough fills of megaforms in which mud-chip conglomerate is concentrated of SS#3. Their occurrence is similar to that reported from other fluvial deposits composed of recycled sediment (e.g., Marriott and Wright 1996; Müller et al. 2004; Wright and Marriott 2007). Aggregate shape ranges from subangular to subrounded, conforming to shapes previously reported from other depositional settings (Margoulis and Nanson 1996; Gierlowski-Kordesch 1998; Gierlowski-Kordesch and Gibling 2002; Wakelin-King and Webb 2007), and are best preserved when surrounded by quartz clasts, as also reported in other fluvial deposits (Fig. 5; e.g., Rust and Nanson 1989). The size of Katberg Formation aggregates, though, is slightly larger than that of the feldspathic quartzose sand in which they are preserved, and characterized as a fine-sand-size clast versus a very fine-sand-size clast for quartz grains (Fig. 6). This grain-size difference reflects their hydraulic diameter and the minimum critical threshold conditions of incipient motion. When average grain diameters are plotted on the Hjulström diagram as modified by Sundborg (1956), both suites of clasts are entrained when flow velocity exceeds 0.35 ms^{-1} at a water depth of 1 m and 0.45 ms^{-1} at a water depth of 10 m, intimating that both grain sizes acts similarly. But, when plotted on Paphitis' (2001) empirical threshold curves for entrainment, clast movement begins at a critical shear velocity of 0.011 ms^{-1} for the quartz grains whereas the critical shear velocity to move the aggregates is 0.125 ms^{-1}.

Chemical evidence indicates that some mud aggregates include a carbonate cement, whereas others are calcium poor. Conversely, there are aggregates enriched in carbon versus aggregates in which little or no carbon is found. These chemical differences reflect the provenance and early diagenetic history of the aggregates.

Pace et al. (2009) interpret the presence of pedogenic carbonate nodules of various shapes, ranging from amorphous to elliptical to rod-shaped, and sizes, millimeter to centimeter scale, to have originated from erosional truncation of aridisol (calcisol) precursors, none of which are found conserved in the stratigraphy. They compare the Katberg Sandstone to the dryland anabranching landscape of the Lake Eyre Basin, Australia, where Calcic Vertisols act as the provenance of both aggregates and carbonate nodules (e.g., Nanson et al. 1986; Rust et al. 1989; Gibling et al. 1998; North et al. 2007). And, a comparison with the Vertisols reported from the Old Red Sandstone (Marriott and Wright

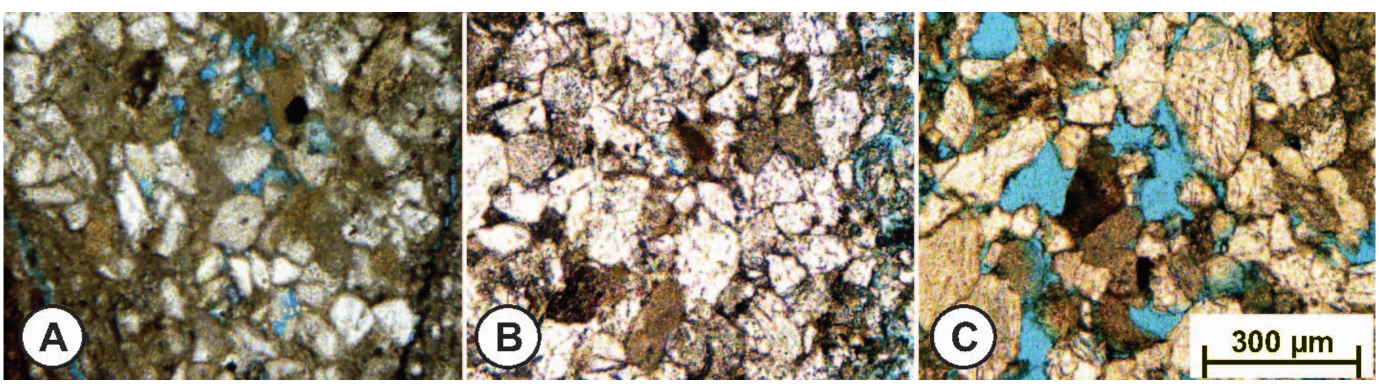

FIG. 5.—Thin-section photomicrographs of quartz sand and sand-sized mud aggregates (agg). **A)** Sample CH09-01b from the top of the lowermost fluvial body (SS#1; see Fig. 3) in which very fine planar sandstone bodies are interbedded with siltstone. Aggregates are elongate to subrounded. **B)** Sample CH09-05 from a siltstone with mud-chip conglomerate at the base of the third fluvial sandstone body (SS#3) showing elongate to subrounded aggregates. **C)** Sample CH09-13 from a siltstone with mud-chip-conglomerate trough fill near the top of the uppermost fluvial sandstone (SS3) showing subrounded to elongate aggregates. All images at same scale; 300 µm scale as in Part C.

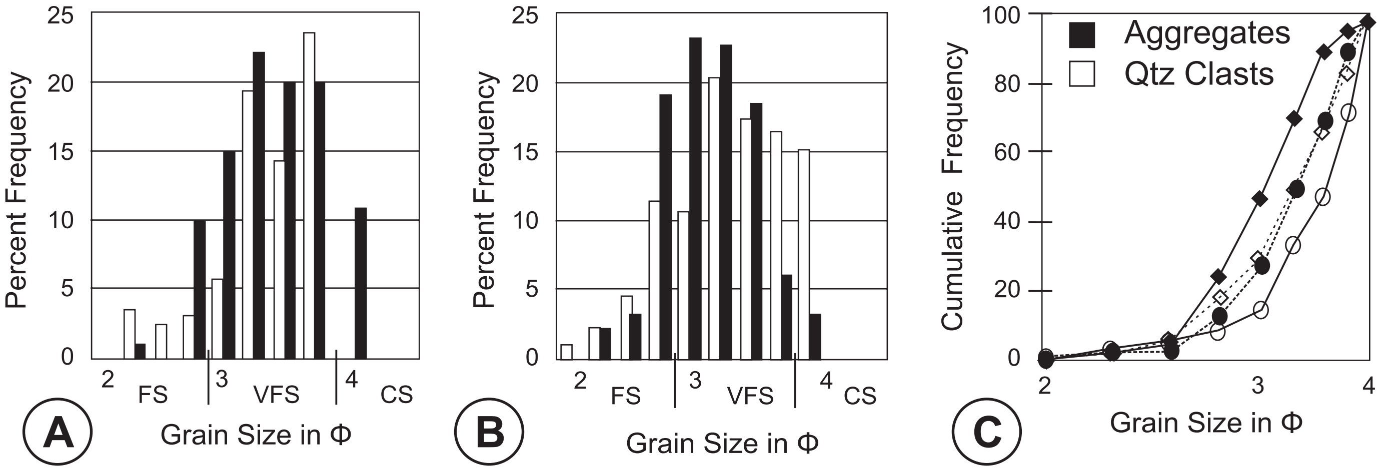

FIG. 6.—Grain-size distribution of quartz clasts (white) and mud-aggregate (black) clasts, composed of two or more clasts identified in thin section. **A)** Histogram of clast sizes from samples CH09-01 and CH09-02 from the top of SS1, plotted in quarter Phi intervals. **B)** Histogram of clast sizes from samples CH09-05 to CH09-13 from SS2 and SS3 fluvial bodies, plotted in quarter Phi intervals. **C)** Cumulative frequency curves for grain-size data. Aggregate data from SS1 are plotted as closed, black circles; quartz clasts are plotted as open circles. Aggregate data from SS2 and SS3 are plotted as closed, black diamonds; quartz clasts are plotted as open diamonds. In both datasets, aggregate distribution is slightly coarser than the encasing quartz clasts.

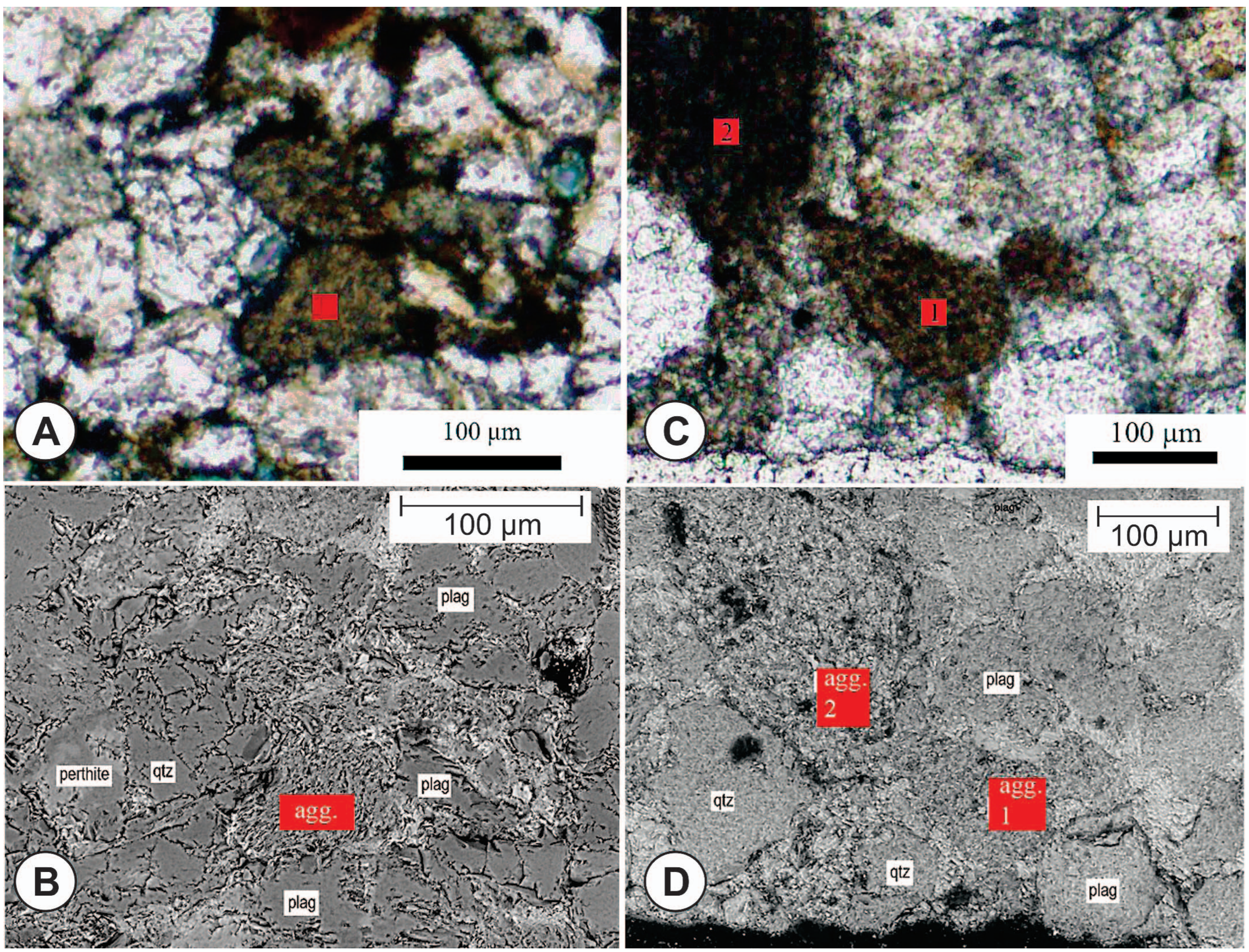

FIG. 7.—Aggregate mudclast and backscatter images from thin section. **A)** Photomicrograph of aggregate grain (CH09-05) in which red square denotes position in clast analyzed with EDS (see Table 1, Fig 8). **B)** Backscatter electron image on which the mineralogy of clasts is identified (qtz = quartz, plag = plagioclase, perthite = perthite). **C)** Photomicrograph of grains sampled from pedogenic nodule conglomerate (PC1 of Pace et al. 2009). Red square denotes site analyzed with EDS. **D)** Backscatter electron image on which the mineralogy is indicated. (qtz = quartz, kspar = potassium feldspar, plag = plagioclase, bt = biotite). All scale bars = 100 µm.

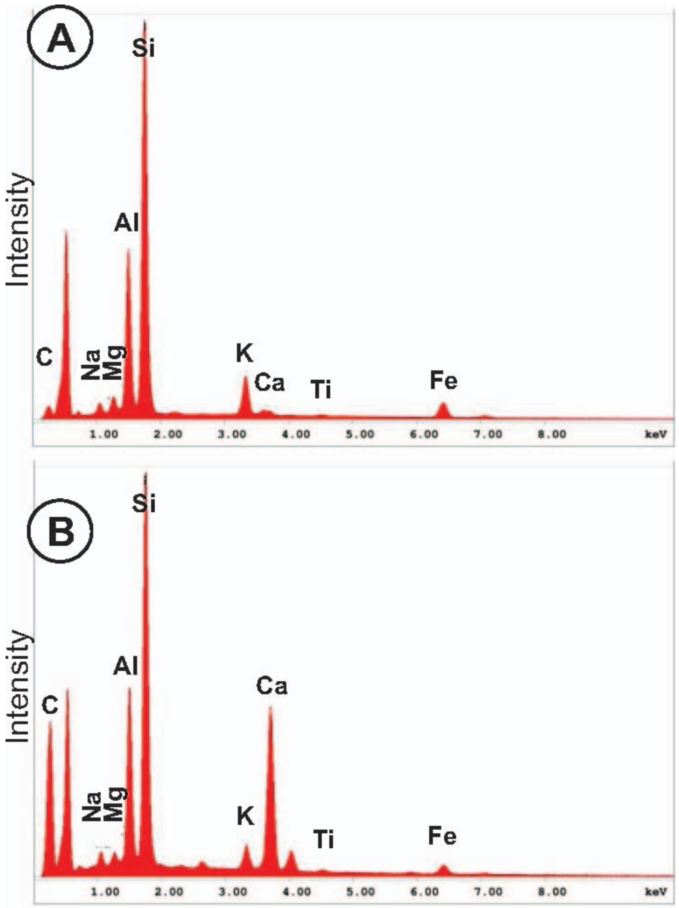

FIG. 8.—EDS spectra of aggregate grains from the third sandstone bench (SS#3; Pace et al. 2009) at Carlton Heights. **A)** Spectrum of sample CH09-05 from a trough fill in the base of the SS#3 (see Fig. 3) showing the presence of more carbon than calcium. **B)** Spectrum of sample PC1 from the pedogenic nodule conglomerate at the base of SS#3 showing less carbon and more calcium.

2006) is noted. But, Pace et al. (2009) defer on interpreting whether Vertisols had been the source of these clasts due to the absence of: (1) any paleosol profile, in the first 100+ meters of section, in which horizonation includes pedogenic carbonate concretions, and (2) the identification of mud aggregates in channel deposits. The recognition of mud aggregates as bedload in association with pedogenic conglomerate lags and mud-chip conglomerate trough fills, along with their geochemistry, adds evidence to support the presence of Early Triassic Calcic Vertisols in the Karoo Basin.

There are several features of Vertisols, and the landscapes in which their erosional remnants occur, that conform to sediments in the Katberg Formation. For example, Rust and Nanson (1989) describe Vertisols in the Eyre Basin as consisting of a stratified soil profile, wherein clay aggregates are typical of the upper horizons and small gypsum and/or calcrete nodules, occurring at a depth of 1.5–2.0 m, mark the lowest level of pedogenic alteration. The factors responsible for clay-aggregate formation and stabilization include the "self mulching" mechanisms operating in the upper soil horizons (Margoulis and Nanson 1996), the proportion of shrinking and swelling clays and their speciation, early cementation and the effects of solutes, and the presence of organic matter (Rust and Nanson 1989). A similar stratified profile, including the distribution of aggregates and pedogenic carbonates, is reported from the Old Red Sandstone Vertisols (Marriott and Wright 1993). Here, aggregates are found in the upper soil horizon underlain at depth by *in situ* carbonate, gypsum, or iron-bearing nodules that range in shape from discs to spheres, with diameters from 0.5 to 1.0 cm, and rods, which may be up to 15 cm in length. This profile is indicative of only stage I–II on Machette's (1985) scale of pedogenic development. Evidence for Devonian Vertisol erosion and truncation is the lateral occurrence of intraformational calcrete-clast conglomerates as channel-lag deposits, originating from either the B_{ca} or C_{ca} horizons, along with the presence of mud aggregates in bedload deposits (Marriott et al. 2005; Wright and Marriott 2007). Similarly characterized paleoVertisols and their erosional remnants are reported by Müller et al. (2004) from the Triassic of the North Sea. In contrast, it is only the erosional remnants of paleoVertisols that are preserved in the Katberg Formation, while a different paleosol type is recorded in the siltstones (Gastaldo and Rolerson 2008). Hence, Pace et al. (2009) proposed that the pedogenic carbonate conglomerates represent periods of widespread, regional landscape degradation.

The co-occurrence of mud aggregates with pedogenic carbonate nodule lags, consisting of variously shaped clasts of centimeter-scale size, at (1) the base of erosional channel bodies and (2) in mud-chip conglomerate-bearing trough fills of channel megaforms, is additional evidence indicating the erosion, truncation, and degradation of early Triassic landscapes. But, the presence of mud aggregates, currently recognized as a soil-ped forming either in Vertisols or Podzols (Rust and Nanson 1989), in association with both types of paleosol residua, points to the former presence of Vertisols in the Karoo Basin. The calcium-poor aggregates with a higher carbon content are interpreted as originating from an upper soil, such as the A or Ah horizon, where mineral matter is enriched with decayed organics. The calcium-rich aggregates exhibiting a low carbon content are interpreted as originating from a soil horizon in which some precipitation of carbonate occurred, presumably in a lower B horizon, above which calcite-cemented nodules formed, such as in a C_{ca} horizon. This model is supported by the association of calcium-rich aggregates in conglomerate lags, which may be indicative of a more active erosive phase, compared to the sandstone-and-mudchip conglomerates from which the calcium-poor aggregates were collected (Pace et al. 2009). Presently, Podzol genesis occurs in humid boreal, temperate, and tropical climates, and these soils are not known to precipitate carbonate nodules at depth (Anderson et al. 1982). Hence, the Vertisol is the only alternative modern soil type in which all these features are found and can be ascribed to the Early Triassic landscapes in the Karoo Basin.

The amount of "time" lost by erosion and concentration of these soils in the lower Katberg Formation cannot be quantified. But, the presence

TABLE 1.—*Semi-quantitative analyses of oxide composition using EDAX from Carlton Heights mud aggregates including CH09-01 from the top of the basal sandstone system, CH09-05 from a mud-chip conglomerate-bearing siltstone interval above the pedogenic conglomerate lag (PC1, PC2) of the upper sandstone body of Pace et al. (2009).*

Sample	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	FeO	Total
CH09-01	1.53	2.14	23.91	59.41	5.29	0.79	0.75	6.18	100
CH09-05	1.65	2.12	21.84	61.63	5.05	0.66	0.46	6.60	100
PC1	1.41	1.28	18.19	67.94	2.25	5.46	0.52	2.94	100
PC2	1.89	1.35	19.30	48.83	2.35	22.32	0.69	3.29	100

of calcium and carbon in different aggregates may indicate genesis from only a single vertic profile. Under such conditions, authigenic calcite would have precipitated at depth (Rust and Nanson 1989), and the low quantities of carbon in this aggregate population intimates organic matter decomposition, which also occurs at depth in the soil. In contrast, low calcium and higher carbon abundance in other aggregates intimates that they originated from the upper soil horizon, where organic matter incorporation is highest and carbonate precipitation is nonexistent. But, the two aggregate types also may have resulted from the erosion of slightly different coeval Vertisols as a function of landscape spatial heterogeneity. In the Lake Eyre Basin, for example, Rust (1981) reports the presence of trees lining channels in which water is retained when other parts of Cooper Creek are dry, and Wakelin-King and Webb (2007a, 2007b) note that the area proximal to the uplands along Fowlers Creek is the site of aggregate formation, with transport of these clasts into the adjoining floodplain. But, until *in situ* Vertisols can be found in the Lower Triassic, it will be impossible to know the extent of their development in the basin at this time, and it would be premature to speculate on the spatial origin of different Vertisol types.

The climate under which Vertisols can form is wide, ranging from seasonably wet under subhumid to humid conditions (Nordt and Driese 2009) to seasonably dry and semiarid (Rust and Nanson 1989). Those in which pedogenic iron, carbonate, or gypsum precipitates form at some soil depth trend towards the more highly seasonal and drier climate states (e.g., Semeniuk and Searle 1985). As proposed by Pace et al. (2009), the early Triassic sedimentary sequence of the Karoo Basin records aggradational and degradational cycles wherein periodic oscillations from more seasonably wet composite or stacked paleosols built up across the landscape, only to be aridified during periods of landscape stasis. Vertisols formed during these intervals of stasis in which soil horizonation resulted in carbon-rich aggregates in the upper soil profile, carbon-poor and calcareous aggregates occurred beneath, and formation of pedogenic carbonate nodules (precipitated in atmospheric equilibrium; Gastaldo and Rolerson 2008) at depth. A subsequent return to strong, seasonally wet (probably near monsoon-like) conditions resulted in the removal of the entire Vertisol profile, leaving evidence of their previous existence only in channel deposits of the prominent anabranching systems of the Katberg Formation.

Over the past two decades, the recognition of paleoVertisols (e.g., Nordt and Driese 2010) and their interpretation of climate (e.g., Nordt et al. 2006) have become commonplace. Hence, mud-clast aggregates should be a more common feature in the stratigraphic record, but they still appear to be spatially and temporally isolated. This may be a function of: (1) the closed basinal settings in which many cases of mud aggregates have been documented (e.g., Talbot et al. 1994; Gierlowski-Kordesch and Rust 1994; Gierlowski-Kordesch 1998; Gierlowski-Kordesch and Gibling 2002; Marriott and Wright 2006) where there is a higher preservation potential, (2) the diagenetic histories of reported instances (Wolela and Gierlowski-Kordesch 2007), or (3) the fact that these clasts are present but often are overlooked. Their presence in the Katberg Sandstone is additional documentation that mud aggregates are a component of an interior continental basin, adding to the list of depositional settings in which these sedimentological features are preserved, and noting another case where aggregate textures are found in a closed basin.

SUMMARY

Mud aggregates are identified in fluvial facies of the Katberg Formation, Lower Triassic, of the Karoo Basin, South Africa, occurring in association with: pedogenic carbonate-nodule conglomerate found as lag deposits over erosional surfaces, mud-chip conglomerate deposited as trough fills of barforms, and in capping channel-fill sequences of an anabranching regime (Pace et al. 2009). Morphological features—subangular, rounded to elongate silt- to sand-size aggregate clasts of a heterogeneous texture and color—conform to previously published criteria that allow their recognition in thin section (Rust and Nanson 1989; Gierlowski-Kordesch and Gibling 2002; Müller et al. 2004). Aggregates are of fine sand size and slightly larger than the very fine quartz clasts in which they are mixed, and this association accounts for their preservation (Rust and Nanson 1989). Two geochemical types of aggregates occur: one type in which there is a higher carbon and a low calcium concentration, and another type in which there are low carbon and high calcium values. No mud aggregates are identified in thin sections of *Katbergia*-bioturbated paleosols (Gastaldo and Rolerson 2008), nor are pedogenic carbonate nodules present in any paleosol profile in the section (Pace et al. 2009). The presence of two aggregate types associated with residua of eroded and truncated paleosols, small pedogenic carbonate nodules, and centimeter-scale mud chips, are used to infer the former presence of paleoVertisols in the early Triassic of the Karoo. No other evidence currently exists in the post Permian–Triassic Boundary stratigraphy of this paleosol type, reinforcing Pace et al.'s (2009) interpretation of the significant role degradational landscapes played in the post-extinction sedimentary record. The recognition of mud aggregates in the Karoo Basin, a closed, interior continental basin, adds another case study to the growing body of literature intimating that pedogenic mud aggregates are preserved preferentially in closed depositional basins since the Devonian.

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