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Sedimentology and palaeontology of the Upper Karoo Group in the Mid-Zambezi Basin, Zimbabwe: new localities and their implications for interbasinal correlation

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Abstract

The Triassic–Jurassic Upper Karoo Group of the Mid-Zambezi Basin (MZB; Zimbabwe) includes a thick succession of terrestrial sediments with high palaeontological potential that has been neglected since the 1970s. Here, we review the Upper Karoo Group stratigraphy, present detailed sedimentological work and identify new vertebrate-bearing sites at several measured sections along the southern shore of Lake Kariba. These fossil-bearing sites fall within the Pebbly Arkose and Forest Sandstone formations, and are the first to be recorded from the region since the discovery of *Vulcanodon karibaensis* nearly 50 years ago. The unique and diverse assemblage of aquatic and terrestrial fauna reported includes phytosaurs, metoposaurid amphibians, lungfish, non-dinosaurian archosauromorphs and non-sauropod sauropodomorph dinosaurs. This improvement of Upper Karoo Group biostratigraphy is important in refining its temporal resolution, and impacts both regional and global studies. Finally, the new fossil sites demonstrate the palaeontological importance of the MZB and its role in providing a holistic understanding of early Mesozoic ecosystems in southern Gondwana.

1. Introduction

The Karoo-aged rift basins across southern and eastern Africa act as important time-capsules of depositional and evolutionary history, tracking long-term climatic and evolutionary change (Cooper, 1982; Banks *et al.* 1995; Catuneanu *et al.* 2005; Rubidge, 2005; Roopnarine *et al.* 2018). However, inter- and intra-basinal correlations are difficult as relatively little work has been conducted to constrain the depositional ages of Karoo-aged sequences outside the main Karoo Basin (MKB), despite their rich palaeontological records (Cooper, 1982; Banks *et al.* 1995; Catuneanu *et al.* 2005; Rubidge, 2005; Roopnarine *et al.* 2018). One such basin in northern Zimbabwe and southern Zambia, the Mid-Zambezi Basin (MZB), contains Karoo-aged sediments of late Carboniferous – Middle Jurassic age that have been little studied since the 1970s (Oesterlen, 2003; Barber, 2018).

The MZB preserves sedimentary deposits belonging to the Lower and Upper Karoo groups that are capped by the Batoka Basalt (Smith *et al.* 1993; Johnson *et al.* 1996; Oesterlen, 2003; Zerfass *et al.* 2004; Catuneanu *et al.* 2005). The Upper Karoo Group is considered the equivalent of the MKB's Stormberg and Drakensberg groups (Catuneanu *et al.* 2005). While the presence of shared taxa with the MKB has been confirmed in the Lower Karoo Group sequences (Lepper, 1992; Lepper *et al.* 2000; Sidor *et al.* 2014), the growing importance of the Upper Karoo Group strata from the MZB of Zimbabwe stems from the presence of fossil vertebrate groups that are currently unknown in other potentially contemporaneous southern African basins (see Raath *et al.* 1972*a*, *b*, 1992; Bond & Falcon, 1973; Cooper, 1984; Viglietti *et al.* 2018; Barrett *et al.* 2020). The presence of this material highlights the need to further explore and re-evaluate the palaeontology and stratigraphy of the Zimbabwean MZB, as well as correlating it with neighbouring southern African basins, such as the Cabora Bassa (CBB), Mana Pools and Luangwa basins.

Our team, comprising members from the University of the Witwatersrand (South Africa), National Museums and Monuments (Zimbabwe), the Natural History Museum (United Kingdom) and the University of Johannesburg (South Africa) as well as other local experts,

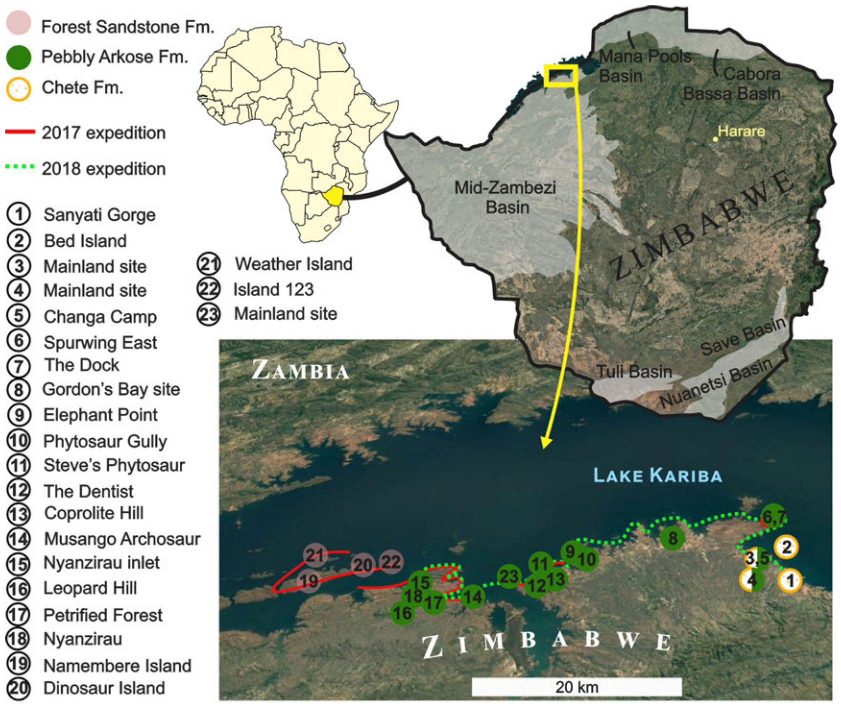

Fig. 1. (Colour online) Mid-Zambezi Basin field sites along the southern shoreline of Lake Kariba, Zimbabwe. Sites are numbered and the stratigraphic position for each site is indicated. See online Supplementary Table S1 for detailed site location information. Map data: Google, CNES/Airbus and Maxar Technologies 2020.

recently conducted fieldwork over two field seasons (2017–2018) within Matusadona National Park and on several islands along the southern shoreline of Lake Kariba (Zimbabwe; Fig. 1). Many of the new fossil vertebrate localities mentioned here were originally identified by SFE during exploratory sorties in the area.

Here, we provide a historical review of the work conducted on the Upper Karoo Group in the MZB of Zimbabwe, describe new field sites (Fig. 1) and document the taxa they have yielded, many of which were previously unknown (or rare) in southern Africa.

2. Historical review

Foundational palaeontological work was conducted in the MZB of Zimbabwe by Geoffrey Bond and colleagues (e.g. Bond, 1955, 1972; Raath, 1967; Bond *et al.* 1970; B Wahl, unpub. thesis, University of Rhodesia, 1971; Bond & Falcon, 1973). The last fossil collections to focus on the Upper Karoo Group strata around Lake Kariba were mainly concerned with 'Dinosaur Island' (Island 126/127) where one of the earliest sauropods, *Vulcanodon karibaensis*, was discovered (Bond *et al.* 1970; Raath, 1972*b*; Cooper, 1984; Viglietti *et al.* 2018).

From a sedimentological perspective, previous workers have been interested primarily in the mineral resources of the Upper Karoo Group and, given the diversity of researchers, a varied nomenclature has been used to describe and correlate local or regional Zimbabwean Upper Karoo stratigraphy (e.g. Macgregor, 1941; Gair, 1959; Bond, 1967, 1972; Bond & Falcon, 1973; Marsh & Jackson, 1974; Stowe, 1974; Stagman, 1978; BC Hosking, unpub. M.Sc. thesis, University of Zimbabwe, 1981; Oesterlen & Millsteed, 1994; Hiller & Shoko, 1995; Oesterlen, 1999, 2003; Catuneanu *et al.* 2005; Ait-Kaci Ahmed, 2018; Barber, 2018). In most cases, no defined type localities or specific reference sections were proposed to either standardize lithostratigraphic descriptions or aid comparisons between the various units in the sub-basins. Correlations between areas and basins have therefore relied heavily on lithological characters and stratigraphic relationships.

Macgregor (1941; refined by Sutton, 1979 and consolidated by Bond, 1967) was the first to propose divisions within the Upper Karoo Group of the Matabola sub-basin (MZB), Zimbabwe. He denoted several unique lithofacies on which the current terminology is mostly based (Fig. 2) and subdivided the sequence into a tripartite sedimentary system: (i) Basal Conglomerate (Escarpment Grit); (ii) Fine Red Marly Sandstone Unit/Pebbly Arkose Unit; and (iii) Forest Sandstone Unit.

Bond (1967) and Bond & Falcon (1973) recorded two fining-upwards tectonosedimentary cycles within the Upper Karoo Group: cycle 1 is represented by the Escarpment Grit, overlain by the Ripple Marked Flagstone unit (not identified by Macgregor, 1941) and the Fine Red Marly Sandstone; and cycle 2 is represented by the Pebbly Arkose to Forest Sandstone transition, with both related to distinct tectonic pulses. Tavener-Smith (1962), Drysdall & Kitching (1962) and Rust (1973) considered these pulses to be visible in other basins and correlatable (e.g. with the Cabora Bassa and Luangwa basins; see Fig. 2) and related to major phases of rifting initiated during Early Triassic time.

More recently, there have been several proposals to reorganize Upper Karoo lithostratigraphy within the MZB. BC Hosking (unpub. M.Sc. thesis, University of Zimbabwe, 1981) suggested the consolidation of the Ripple Marked Flagstone, Fine Red Marly Sandstone and Pebbly Arkose units into the informal Tashinga Formation (Fig. 2). We believe this formation to be named after Tashinga Camp (in Matusadona National Park), although not all of the relevant lithologies are exposed there. The use of the Tashinga Formation was recently applied to outcrops along the shoreline of Lake Kariba by Barrett *et al.* (2020). In contrast, Ait-Kaci Ahmed (2018) suggested that the Upper Karoo Group could be divided into the Escarpment (composed of the Escarpment Grit and Fine Red Sandstone members), Pebbly Arkose and Forest Sandstone formations (Fig. 2). However, Barber's (2018) MZB lithostratigraphy proposes the Chete, Pebbly Arkose and

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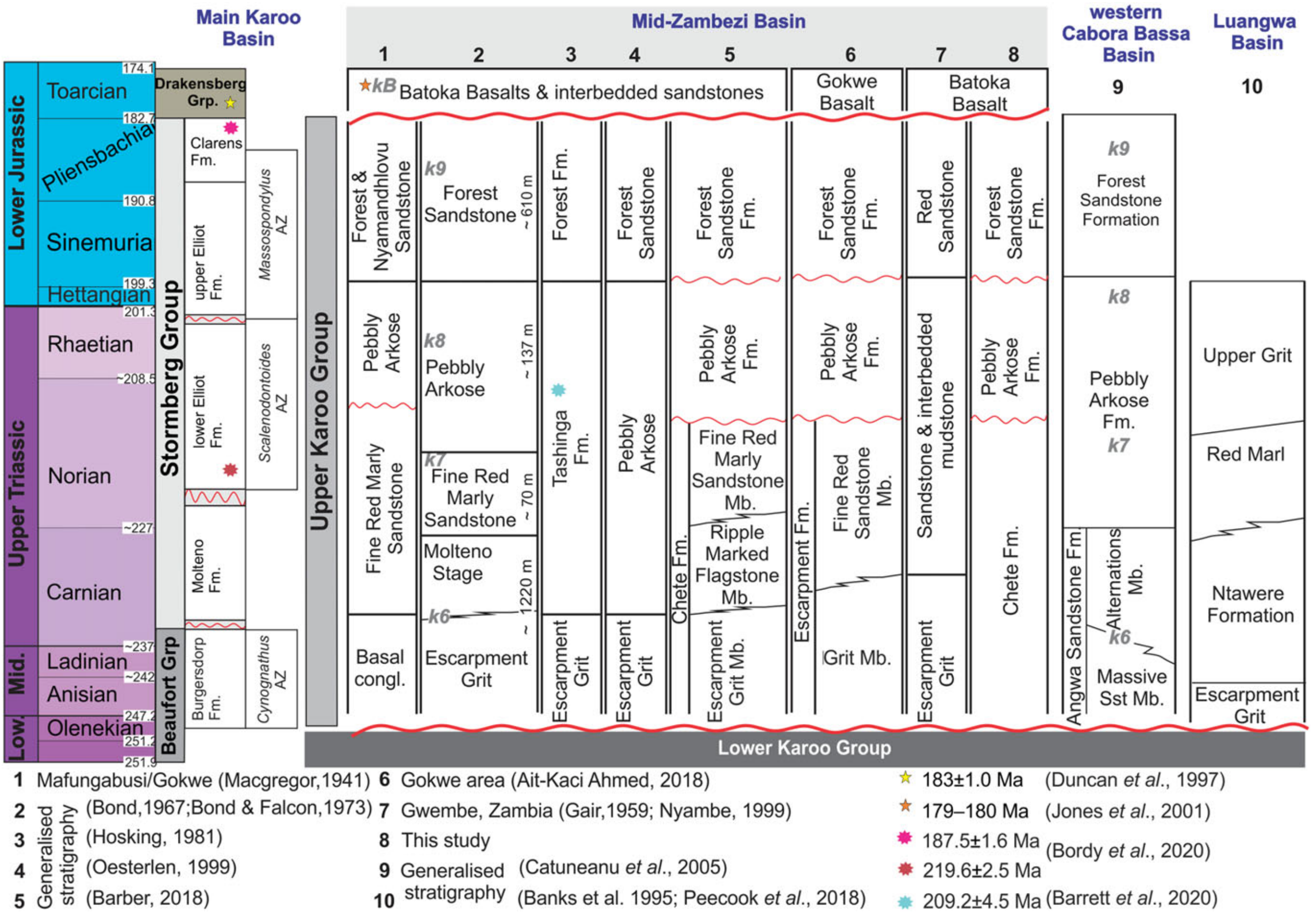

Fig. 2. (Colour online) Summary of the Upper Karoo Group lithostratigraphic nomenclature from the Mid-Zambezi, Cabora Bassa and Luangwa basins. Wavy red lines represent unconformities. Bond's (1967) lithostratigraphic symbols 'k6 – k9, kB' are shown. Small stars = ^{40}Ar-^{39}Ar ages from the Drakensberg Group and Batoka flood basalts; larger stars = U-Pb detrital zircon ages. Abbreviations: Fm. = Formation; Mb. = Member.

Forest Sandstone formations and downgrades the Escarpment Grit, Ripple Marked Flagstone and Fine Red Marly Sandstone units to members within the Chete Formation. These he interprets as diachronous, gradational, fining-upwards sequences and coeval facies equivalents initiated by the first phase of rifting. The naming of the Chete Formation is based on the exposures of these members in the Chete Safari Area (Zimbabwe) and on Chete Island (Zambia). Below we provide additional detail on these Upper Karoo Group lithostratigraphic units.

2.a. Escarpment Grit Member, Chete Formation

The oldest lithostratigraphic unit of the Upper Karoo Group has been referred to as either the basal conglomerate, Escarpment Grit (Macgregor, 1941), Escarpment Formation (BC Hosking, unpub. M.Sc. thesis, University of Zimbabwe, 1981), Grit Member (Escarpment Formation; Ait-Kaci Ahmed, 2018) or Escarpment Grit Member (Chete Formation; Barber, 2018; Fig. 2). It is regarded as a persistent arenaceous unit occurring throughout the rift valleys of Zimbabwe and Zambia (Drysdall & Kitching, 1962; Oesterlen & Millsteed, 1994; Oesterlen, 1998). Within the MZB, an erosional unconformity divides it from either the underlying Lower Karoo Group's Madumabisa Mudstone Formation or older basement rocks (Bond, 1952; Lepper, 1992).

The Escarpment Grit Member and its lithological correlatives in other basins have often been considered to be palaeontologically barren (Bond & Falcon, 1973), but fossilized wood has been noted in the Zambian portion of the MZB (Gwembe area; Gair, 1959; Tavener-Smith, 1960; Barbolini *et al.* 2016). In terms of its relative age, Cox (1969) correlated the Escarpment Grit in the Luangwa Basin of Zambia with the *Cynognathus* zone of the Upper Beaufort Group in the MKB, which was then considered to be upper Scythian (= upper Early Triassic) in age, and the overlying Molteno Beds as likely Ladinian–Anisian in age. Others also considered the Escarpment Grit Member to be contemporaneous with the Upper Beaufort Group, although opinions on the relative age of this unit have differed (Drysdall & Kitching, 1963; Anderson & Anderson, 1970; Johnson *et al.* 1996). By contrast, Watkeys (1979), Nyambe & Utting (1997), Nyambe (1999) and Catuneanu *et al.* (2005) considered the Escarpment Grit Member, as well as the Massive Sandstone Member (lower Angwa Sandstone Formation) from the CBB (Oesterlen & Millsteed, 1994; d'Engelbronner, 1996), as stratigraphic equivalents of the Molteno Formation, but of upper Scythian (= Olenekian) rather than Middle Triassic age.

In the Luangwa Basin of Zambia, a *Cynognathus* Assemblage Zone-type fauna (Upper Beaufort Group equivalent, MKB) has been identified in the Ntawere Formation that overlies the Escarpment Grit in this basin (Sidor, 2011; Peecook *et al.* 2018; Roopnarine *et al.* 2018; Smith *et al.* 2018; Wynd *et al.* 2018). Recently, Peecook *et al.* (2018) identified two distinct faunal assemblages in the lower and upper Ntawere Formation that they correlated with the MKB's *Cynognathus* B and C subzones (*Trirachodon-Kannemeyeria* and *Cricodon-Ufudocyclops* subzones; Hancox *et al.* 2020), respectively. On the basis of current age assessments for the *Cynognathus* Assemblage Zone in the MKB, this would give a relative age for the Ntawere Formation of Middle Triassic (Anisian–Ladinian), but with a potential uppermost age as young as Carnian (Peecook *et al.* 2018; Sidor & Hopson, 2018; Wynd *et al.* 2018; Hancox *et al.* 2020). A similar age has been suggested for the fossiliferous Lifua Member (Manda Formation) of the Ruhuhu Basin of Tanzania (Smith *et al.* 2018). These assertions indicate that the Escarpment Grit in Zambia must be either equivalent in age or, more likely, older than the *Cynognathus* Assemblage Zone, that is, similar in age to the Katberg or lower Burgersdorp formations (Early Triassic) of the MKB, as has been suggested for the Kingori Member (Manda Formation, Tanzania; Smith *et al.* 2018). We therefore tentatively consider the oldest potential age for Escarpment Grit sedimentation as Early–Middle Triassic in the Karoo-aged basins. However, it must be stressed that the correlation of Escarpment Grit units in these basins has been purely on lithology and stratigraphic position, with no other data to support the temporal equivalency of these units.

2.b. Ripple Marked Flagstone Member or Molteno Stage, Chete Formation

Conformably overlying the Escarpment Grit Member in the MZB is a unit that has been termed either the Ripple Marked Flags (k7; Fig. 2; Bond, 1967), Ripple Marked Flagstones or the Ripple Marked Flagstone Member of the Chete Formation (Barber, 2018; Fig. 2). The Ripple Marked Flagstone Member was described and informally named by Watson (1960) based on observations made in the Hwange area and Binga District (Milibizi Sub-basin, MZB) of Zimbabwe and does not appear to have a uniform distribution throughout the MZB. It is a cyclic unit of conglomerates and alternating fine-grained sandstones, siltstones and mudstones (orange-purple to grey in colouration), and is known for its *Dicroidium*-bearing floral assemblages (Lacey, 1961; Bond & Falcon, 1973; Stowe, 1974).

Pioneering work to describe the MZB's *Dicroidium*-bearing flora was conducted by Lacey (1970, 1976) with revisions by Anderson & Anderson (1983). Other *Dicroidium*-bearing assemblages are known from near Somabuhla, on the Binga Road, west of the Ruzuruhuru (Luizikukulu) River, the Sengwa estuary, and near the old confluence of the Sengwa and Zambezi rivers (Bond & Falcon, 1973), as well as from the Alternations Member of the Angwa Sandstone Formation (western CBB: Broderick, 1984; Barale *et al.* 2006).

The presence of *Dicroidium*-bearing floral assemblages has led some researchers to correlate the Ripple Marked Flagstone Member with the MKB's Molteno Formation. However, other workers have alternatively considered the Escarpment Grit, Ripple Marked Flagstone and Fine Red Marly Sandstone units as potential Molteno equivalents (Raath *et al.* 1992). Bond & Falcon (1973) designated the Ripple Marked Flagstone Member, together with the underlying Escarpment Grit Member, as a single megacycle and a potential MZB Molteno Stage. However, they hypothesized that it represented the northern and presumed older equivalent of the MKB's Molteno Formation (the latter is considered to be Carnian in age; Anderson & Anderson, 1984).

Correlation of the Escarpment Grit, Ripple Marked Flagstone and Fine Red Marly Sandstone members of the MZB to the neighbouring CBB's Alternations Member, upper Angwa Sandstone Formation (Broderick, 1990), was discussed by Oesterlen & Millsteed (1994) and Barber (2018). Fossils within the Alternations Member range from *Dicroidium*-bearing floral assemblages (i.e. Manyima site; Barale *et al.* 2006) to freshwater bivalves ('*Unio*' *karrooensis* Cox, 1932) and various invertebrate trace fossils. Barale *et al.* (2006) proposed a Late Triassic (Carnian) age for the Alternations Member in the western CBB and this is constrained by the occurrence of rhynchosaurs within the lower horizons of the overlying unit (Raath *et al.* 1992). The Zambian MZB's Sandstone and Interbedded Mudstone Formation (thought to be lateral equivalents of the Ripple Marked Flagstone/Fine Red Marly Sandstone members) contains palynomorph taxa interpreted by Nyambe & Utting (1997) as representing the presence of Molteno Formation-type equivalent floras. In the Matabolo/Sengwa Sub-basin (Zimbabwe), *Dicroidium*-bearing floras are reported from the Grit Member (Ait-Kaci Ahmed, 2018).

2.c. Fine Red Marly Sandstone Member, Chete Formation

Overlying the Ripple Marked Flagstone Member is a series of red beds known as Fine Red Marly Sandstone (Fig. 2; Bond, 1972; Bond & Falcon, 1973). More recently, this unit has either been subsumed into the Tashinga Formation (Fig. 3; BC Hosking, unpub. M.Sc. thesis, University of Zimbabwe, 1981) or downgraded to a member of the Escarpment Formation (Fine Red Sandstone Member; *sensu* Ait-Kaci Ahmed, 2018) or the Chete Formation (Fine Red Marly Sandstone Member; Barber, 2018). Barber (2018) considered the Fine Red Marly Sandstone Member to be laterally gradational with the Ripple Marked Flagstone Member, whereas Ait-Kaci Ahmed (2018) considered it gradational with the underlying Grit Member. Barber (2018) noted a type area for the Fine Red Marly Sandstone Member within the Matabola Sub-basin (= Upper Sengwa Sub-basin of Lepper, 1992) of the MZB near Gokwe.

The Fine Red Marly Sandstone Member is reported as *c.* 70 m thick and as a local marker horizon by Bond (1967) and Bond & Falcon (1973), although the distinct characters for its identification were not elaborated. The Fine Red Marly Sandstone Member has been described as a cyclic succession of mottled cream to red/maroon mudstones, siltstones (argillaceous beds) and sandstones (calcareous arenites, grits and arkosic arenites) with the presence of calcareous and ferric nodules, and is not considered fossiliferous (Bond, 1972; FG Böhmke & RG Duncan, unpub. technical report, 1974; Stagman, 1978; Barber, 2018). In the MZB, Grant (1970) and Marsh & Jackson (1974) reported the only mapped occurrence of the Fine Red Marly Sandstone Member SW of Bumi Hills (close to some sites of our recent fieldwork).

Macgregor (1941) and later authors (Bond, 1967; Bond & Falcon, 1973) recorded a minor unconformity between the Fine Red Marly Sandstone and the overlying Pebbly Arkose, although it was not described. Stagman (1978, p. 90) noted an 'eroded surface at the base of the Pebbly Arkose' that is locally designated by a thin bed of 'hardened fragments of underlying sandstone', whereas Ait-Kaci Ahmed (2018) identified an erosional disconformity at this boundary. These are likely related to the tectonic pulses outlined by Tavener-Smith (1958, 1960), Bond (1955) and Bond & Falcon (1973).

Bond (1972) noted similarities in lithology between the Fine Red Marly Sandstone and the Elliot Formation of the MKB, despite the apparent lack of fossils in the former. However, he also proposed

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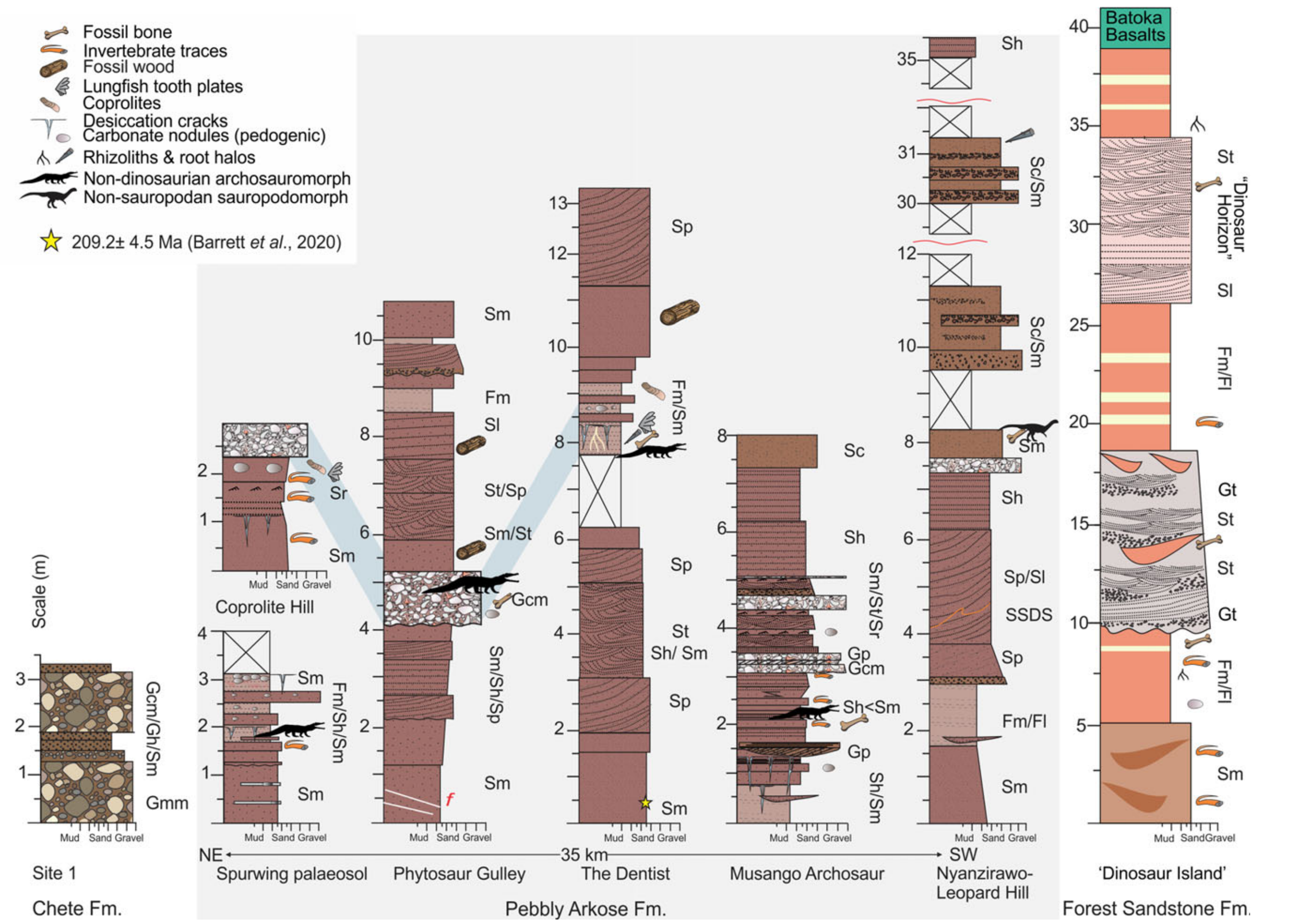

Fig. 3. (Colour online) Measured sections of the Chete, Pebbly Arkose and Forest Sandstone formations (Upper Karoo Group) in the Mid-Zambezi Basin. Occurrences of phytosaur, lungfish and unidentified fossil bone material are indicated. Lithofacies codes are provided and discussed in the text and Table 1. Abbreviation: Fm. = Formation.

that the Fine Red Marly Sandstone might be temporally correlated with the Molteno Formation, with similar lithofacies developing earlier in Zimbabwe because of plate tectonics (see also Visser, 1984). Catuneanu *et al.* (2005) proposed that the Ripple Marked Flagstone, Fine Red Marly Sandstone and Pebbly Arkose units are likely all Elliot Formation equivalents, based on lithology and stratigraphic relationships, but older in age than those in the MKB and ranging from Scythian (= Olenekian) to Anisian.

2.d. Pebbly Arkose Formation

In the MZB, the Pebbly Arkose Formation is a thin unit with a thickness of *c.* 79–137 m (Bond, 1967; Bond & Falcon, 1973; Fig. 2) and was either incorporated into BC Hosking's (unpub. M.Sc. thesis, University of Zimbabwe, 1981) informal Tashinga Formation or described as the separate Pebbly Arkose Formation (Bond & Falcon, 1973; Ait-Kaci Ahmed, 2018; Barber, 2018). Barber (2018) describes it as composed of thickly bedded, medium- to coarse-grained pebbly arenites to arkoses. In the MZB, it has been considered to have both a conformable and unconformable boundary with the under- and overlying units (Bond & Falcon, 1973; Ait-Kaci Ahmed, 2018; Barber, 2018).

The Pebbly Arkose Formation is well known in the CBB, where it can reach thicknesses of *c.* 850 m in the eastern part of the basin and *c.* 1500–2000 m in the SW (Oesterlen & Millsteed, 1994; Barber, 2018). There it comprises two facies: (i) a lower 'coarse-grained facies', composed predominantly of very coarse- to coarse-grained, pebbly, massive, arkosic sandstone that dominates at the base of the succession, and (ii) an uppermost 'finer-grained facies' that consists of fining-upwards cycles of medium- to coarse-grained, moderate- to poorly sorted, graded sandstones that transition into purple, micaceous (and pebbly) siltstones and mudstones (Oesterlen & Millsteed, 1994).

The Pebbly Arkose Formation, in both the MZB and CBB, is known for its large silicified tree trunks (*Rhexoxylon*, *Dadoxylon*, *Mesembrioxylon*; e.g. Deteema Fossil Forest in Hwange National Park) that occur at several stratigraphic levels within the unit (Bond & Falcon, 1973; Bond, 1974; Stagman, 1978; Oesterlen & Millsteed, 1994). The coarse-grained sandstones and minor mudstones of the Upper Grit from Zambia's Luangwa Basin are also known for their fossil tree trunks (Drysdall & Kitching, 1962) and, given tentative correlations by Tavener-Smith (1960) and Rust (1973), we suggest that the Upper Grit may be partly correlated with the Pebbly Arkose Formation in the MZB and CBB (see Fig. 2). An unconformity is also registered between the Luangwa Basin's Red Marl and Upper Grit (as per Dixey, 1937).

In 1974, the first fossil vertebrate material, consisting of large lungfish tooth plates, was found in the Pebbly Arkose

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Formation within the MZB. These were discovered on an island in the Bumi River estuary (*c.* 16° 51′ S; 28° 28′ E) and reported by Bond (1974; Raath *et al.* 1992). Recently, Barrett *et al.* (2020) documented the first fossil assemblage from the upper part of the 'Tashinga Formation' (dominated by phytosaurs, lungfish and metoposaurid amphibians) and provided a maximum depositional age of 209 ± 4.5 Ma (LA-ICPMS; see Barrett *et al.* 2020; see also online Supplementary Table S1, available at http://journals.cambridge.org/geo) for these assemblages along the southern shoreline of Lake Kariba. Rhynchosaurs, cynodonts and basal sauropodomorph dinosaurs were also reported from the Pebbly Arkose Formation in the western CBB near the Angwa River in the Dande West area (Raath *et al.* 1992; C. Griffin, pers. comm., 2020).

Bond (1972) considered the Pebbly Arkose Formation in the MZB to represent equivalents of the upper parts of the Red Beds Stage within the MKB (= Elliot Formation) based on fossil occurrences within the Pebbly Arkose Formation (fossil wood) and overlying Forest Sandstone (i.e. shared presence of the sauropodomorph dinosaur *Massospondylus*). Catuneanu *et al.* (2005) described the Elliot Formation equivalents from the MZB and CBB (Upper Angwa Sandstone Formation and Pebbly Arkose Formation) as Olenekian–Norian in age, that is, older than the Elliot Formation in the MKB (which is considered to be Norian–Sinemurian; Bordy *et al.* 2020; Viglietti *et al.* 2020*a*, *b*). However, the co-occurrence of rhynchosaurs, cynodonts and early sauropodomorph dinosaurs within the Pebbly Arkose Formation in the western CBB convincingly suggest a Late Triassic age, which is congruent with recent work by Barrett *et al.* (2020).

2.e. Forest Sandstone Formation

The uppermost Upper Karoo Group unit, the Forest Sandstone or Forest Sandstone Formation, is described as a series of pinkish-white to pale-brown, fine- to medium-grained, well-sorted sandstones, which can be subdivided into a calcareous lower unit showing evidence for subaqueous deposition and an aeolian upper unit with large-scale cross-bedding (Thompson, 1975; Stagman, 1978; Watkeys, 1979; Cooper, 1981). Marsh & Jackson (1974) described a series of facies in the Forest Sandstone Formation near Bumi Hills and these are named, from stratigraphic lowest to highest: the Coarse White Sandstone, Calcareous Nodule Sandstone, the Red Beds and the Dinosaur Horizon. The latter overlies the Red Beds on Dinosaur Island, and is where *Vulcanodon* was retrieved by Bond *et al.* (1970; see Viglietti *et al.* 2018). Barber (2018) considers the Forest Sandstone Formation to uncomformably overlie the Pebbly Arkose Formation in the MZB, and this contact is denoted by a basal conglomerate interpreted as fossil regolith.

The Forest Sandstone Formation can be traced across several of the Karoo-aged basins in Zimbabwe and southern Africa (Johnson *et al.* 1996; Catuneanu *et al.* 2005). Lithological similarities to the aeolian-lacustrine Clarens Formation in the MKB have been observed, and these units have been correlated as time-equivalents by some authors (Johnson *et al.* 1996; Bordy & Catuneanu, 2002*a*, *b*). Alternatively, others have suggested that the Forest Sandstone Formation is time-equivalent to the upper Elliot and lower Clarens formations (Bond & Falcon, 1973; Raath, 1981). Drysdall & Kitching (1962) noted that Dixey (1937) suggested portions of the Upper Grit in the Luangwa Basin could be correlated to this Forest Sandstone Formation, although this has never been verified.

In addition to *Vulcanodon*, the Forest Sandstone Formation has yielded coelophysoid bonebeds, sauropodomorphs (notably specimens referred to *Massospondylus*), a 'protosuchid' crocodylomorph (cf. *Notochampsa* sp.), sphenodontid rhynchocephalians and tridactyl dinosaur trackways (Raath, 1969, 1981; Gow & Raath, 1977; Raath *et al.* 1992). Bone material was often noted to be coated in black manganese oxides (Bond, 1974; Raath, 1981). Importantly, *Massospondylus* is an index taxon for the *Massospondylus* Assemblage Zone in the MKB (Viglietti *et al.* 2020*a*) and has been used as an index taxon for the Forest Sandstone Formation (e.g. sites at Chitake in Mana Pools National Park and at the Mana-Angwa gorge in Chewore Safari Area, Raath *et al.* 1970; and at Chelmer Spruit near Nyamandhlovu, Attridge, 1963). However, referrals of the MZB material to *Massospondylus carinatus* require confirmation in light of recent taxonomic work (see Barrett *et al.* 2019; Bordy *et al.* 2020).

2.f. Summary of historical work

In summary, the Upper Karoo Group sedimentary successions preserved in these adjacent, but geographically separate, depositional basins and sub-basins show similar lithological characteristics and are believed to correlate with similar Triassic–Jurassic sequences in the MKB (Catuneanu *et al.* 2005). Although this review attempts to make some tentative interbasinal correlations, it also highlights the many caveats required when attempting to link these geographically adjacent, but potentially spatially and temporally distinct, stratigraphic assemblages. A key limitation is the scarcity of shared index fossils (see Wynd *et al.* 2018; Barrett *et al.* 2020; Bordy *et al.* 2020; Viglietti *et al.* 2020*a*, *b*). Moreover, Late Triassic – Early Jurassic continental rocks in southern Gondwana appear to be poor in primary volcaniclastic deposits (see Bordy *et al.* 2020), making independent age-dating difficult, although some success has been seen with detrital zircon geochronology in the MZB (Barrett *et al.* 2020). Because of these ambiguities, this review is important to the growing debate on the age and correlation of Gondwana's Triassic record.

3. Materials and methods

A total of 23 new georeferenced sites of sedimentological and palaeontological interest were identified along the southern shoreline of Lake Kariba in the MZB of northern Zimbabwe (Fig. 1; online Supplementary Tables S1–S3, available at http://journals.cambridge.org/geo). Standard field techniques were used to measure, document and record macroscopic observations of the host sedimentary rocks and to construct stratigraphical sections (Fig. 3) at several sites (Miall, 1996, 2014). For all lithofacies descriptions and codes, see Table 1. We documented the stratigraphical positions and facies associations of the fossil material identified from these sites. Structural observations and faulting were also taken into account (online Supplementary Material, available at http://journals.cambridge.org/geo). All collected fossil material is now deposited at the Natural History Museum of Zimbabwe (Bulawayo, NHMZ); a full list with justifications for taxonomic identifications can be found in online Supplementary Table S2 (see also Barrett *et al.* 2020).

4. Results

Sedimentological data collected here delineate several sites (Figs 1, 3; online Supplementary Table S1, available at http://journals.cambridge.org/geo) with facies and facies associations that we define as either distinctive or shared features of the

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Table 1. Lithofacies, facies assemblages and architectural elements noted in the Upper Karoo Group exposures, Mid-Zambezi Basin, Zimbabwe (following Miall, 1996, 2006)

Facies assemblage	Elements	Symbol	Description	Lithofacies code	
Forest Sandstone Formation					
Sm, Sh	Sandy bedforms	SB	Sheet-shaped sandstone deposits that laterally pinch out	Gmm	Massive, matrix-supported gravel
Fm, Fl, P	Overbank/floodbank fines	OB	Gradational lower contacts with SB; sharp contacts with HO and CH	Gcm	Massive, clast-supported gravel
Gcm, Gt	Scour hollows	HO	Concave to asymmetrical hollow with asymmetrical fill as component of CH	Gh	Horizontally stratified gravel
Gt, St, Sl, Sp	Channels	CH	Sheet-like to lens-shaped, multi-story fill, erosional bases, sharp to gradational tops	Gt	Trough cross-bedded gravel
Sl, Sh	Crevasse splay	CS	Tabular/sheet-like; sharp lower and upper contacts with FF	Gp	Planar cross-bedded gravel
Pebbly Arkose Formation					
Gmm, Gcm, Gp, Gh, Gmg, St, Sc, Sp, Sl	Channels	CH	Sheet-like to lens-shaped, multi-story fill, erosional bases, sharp to gradational tops	Gcm-1	Massive, clast-supported intraformation pedogenic nodule conglomerate
Gcm-1, Gmm, Sc	Sediment gravity flows	SG	Sheets interbedded into SB	Gmg	Normal grading, matrix-supported gravel
St, Sp, Sl, Sh	Sandy bedforms	SB	Sheet to wedge as minor component of CH and GB	Sm	Massive sand
Gt, Gp, St, Sp	Scour hollows	HO	Curved, concave to asymmetrical hollow with asymmetrical fill	Sh	Horizontally bedded sand
St, Sp, Sl, Sh	Downstream-accretion macroform	DA	Concave-up internal erosion surfaces; lens-shaped	St	Trough cross-bedded sand
St, Sp, Sl, Sh	Lateral-accretion macroform	LA	Minor lens to wedge-shaped, internal lateral-accretion surfaces	Sp	Planar cross-bedded sand
Sh, Sl, Sp	Laminated sands sheet	LS	Horizontally laminated, sheet-like interbedded in OB	Sl	Low-angle cross-bedded sand
Fm, Fl, P	Overbank/floodbank fines	OB	Moderately thick blanket muddy siltstone	Sr	Ripple cross-laminated sand
St/Sp, Sr, Fl	Crevasse splay	CS	Tabular/sheet-like interbedded in OB	Sc	Massive, matrix-supported clast-bearing sand
Gcm, Sp, St, Sr	Crevasse channel/abandoned overbank distributary channel	CR	Ribbon, lens- to wedge-like, fining upwards with erosional lower boundary interbedded in OB	Scm	Massive, pebbly, matrix-supported, coarse-grained sand
Chete Formation (Escarpment Grits Member)					
Gp, Gh, Gmg, St, Sp, Sl, Scm	Channels	CH	Sheets to lens-shaped, multi-story fill, erosional bounding surfaces	Fm	Massive silt/mud
Gmm, Gcm, Gp, Gh, Gmg	Gravel bedforms	GB	Tabular	Fl	Laminated silt/mud
Gmm, Gcm, Gmg within GB	Sediment gravity flows	SG	Sheet-like interbedded into GB	P	Palaeosol
St, Sp, Sl, Scm, Sh	Sandy bedforms	SB	Sheet to wedge as minor component of CH and GB		
Gt, Gp, St	Scour hollows	HO	Concave to asymmetrical hollow with asymmetrical fill as component of GB/CH		

Upper Karoo Group units mentioned in this study. Although recently adopted by Barrett *et al.* (2020), we have chosen to discontinue the use of the informal 'Tashinga Formation' given our new field observations and in light of recent geological reports on the MZB sub-basins (Ait-Kaci Ahmed, 2018; Barber, 2018). Here, we have adopted the use of the Chete, Pebbly Arkose and Forest Sandstone formations for the Lower Sengwa/Gwembe Sub-basin of the MZB, as described by Barber (2018). Following Barber (2018), we regard the Escarpment Grit, Ripple Marked Flagstone and the Fine Red Marly Sandstone as members of the Chete Formation in the Lower Sengwa (Lepper, 1992) or Gwembe (Barber, 2018) Sub-basin of the MZB. We support the distinction of the Pebbly Arkose Formation proposed by both Ait-Kaci Ahmed (2018) and Barber (2018) for both the Gwembe (Lower Sengwa) and Matabolo (Upper Sengwa) sub-basins of the MZB. We confirm the distinction of the Forest Sandstone Formation and discuss each unit separately in the following. Finally, we present the new palaeontological information collected at each of these sites (Fig. 3).

4.a. Sedimentological results and interpretation

4.a.1. Chete Formation

Outcrops of the Escarpment Grit Member were studied on the mainland near Sanyati Gorge (Site 1; Figs 3, 4; online Supplementary Table S1) where they had been mapped previously (see Brassey, 1951). Here the Escarpment Grit Member rests unconformably on the Palaeoproterozoic chevron-folded muscovite schist, biotite gneiss and associated amphibolite of the Matusadona Range (Fig. 4a). At Site 1, the Escarpment Grit Member consists of brown to russet, massive, graded and bedded gravelly facies that dip shallowly (< 5°) towards the north (Fig. 4b). It is characterized by clast-supported, very fine gravel (granules) to cobble conglomerates (Gcm) with lesser matrix-supported conglomerates (Gmm) that are sheet-like and have erosional bases (dashed line in Fig. 4b). These are both typically poorly to moderately sorted, with sub-rounded clasts and polymodal grain size distributions, and do show weakly developed normal and inverse grading. Clasts have an average size range of 0.4–12 cm with occasional boulders of *c.* 20–40 cm diameter. Clasts are generally rounded and discoidal in shape, and tend to exhibit crude imbrication that is directed northwards.

This gravelly facies is either massive (Gcm) or shows crude to horizontal bedding (Gh; Fig. 4b) defined by the alignment of clasts and their vertical decrease in grain size. Upwards fining is also noted (Gmg, normal grading) and inverse grading is present (Fig. 4). Interbedded within the gravelly facies are ≤ 60–120 cm lenses or thin ribbons of massive- to horizontally bedded, coarse- to medium-grained sandstone (often containing sporadically dispersed granules and pebbles).

Further away from the fault scarp and towards Bed Island (Fig. 4c–e; online Supplementary Table S1), this gravelly facies becomes finer-grained, better-sorted and bedded (*c.* 20–50 cm thick, localized trough-cross beds; St, Fig. 4c, d), and increases in the proportion of coarse- to medium-grained sandstone content. The presence of horizontally bedded, thin (< 45 cm) gravel–sand couplets with erosive or scour surfaces are common. Impressions of wood clasts (≤ 8 cm in length; Fig. 4e) within a matrix composed of micaceous, very coarse- and medium-grained sandstone are present and show secondary growth of Fe/Mn nodules. Bed Island, although finer-grained, preserves thick, massive to thin, graded trough cross-bedded and horizontally bedded coarse- to medium-grained sand bodies with basal conglomerate lags (Fig. 4c, d).

In attempting to define and map the upper contact of the Chete Formation with the overlying Pebbly Arkose Formation, we noted several sites (i.e. mainland Sites 2 and 3, and near the Changa Camp; online Supplementary Table S1), where there is a decrease in average grain size and an interfingering relationship of coarser- and finer-grained facies corresponding to a colour change. Here red siltstones (occasionally showing palaeopedogenesis) and mauve-reddish, normal-graded, massive- to trough cross-bedded, coarse-grained and pebbly sandstone become dominant (Fig. 5a, c, f). However, due to similarities in lithologies, the exact placement of an upper contact was hard to define and further hindered by the lack of lateral and vertical outcrop along our field transects. This contact has been reported as unconformable (Ait-Kaci Ahmed, 2018; Barber, 2018) and here we have represented it with the increasing occurrence of carbonate (as caliche and nodules) and the development of palaeosols (which are potentially convenient for field mapping, but this observation requires verification).

4.a.2. Pebbly Arkose Formation

The Pebbly Arkose Formation, around the southern shoreline of Lake Kariba, can be subdivided into sandstone and fine-grained facies associations. The sandstone facies assemblage is dominated by fine- to very coarse-grained and pebbly, sandstones (Sm, St, Sp, Sl, Sc, Sr; Table 1) with minor intraformational conglomerates (lags; Gcm, Gh, Gp; Table 1). The sandstones are micaceous, maroon to reddish-brown and grey-cream, thinly to thickly (*c.* 0.3–1.2 m) bedded, tabular and lenticular in geometry (Fig. 5). All lithofacies may display granule- to pebble-sized stringers that can define a bedding plane, or be randomly dispersed throughout the sandstone matrix.

Stacked sandstone units exhibit a poorly developed fining-upwards trend defined by undulating erosional bases with/without channel lag conglomerate (Fig. 5a, c), and are capped by massive mudstones and siltstones (Fm units; Table 1) or erosively down-cut by overlying sandstone beds. These stacked sandstones can form multi-storied units (≤ 4 m thick as exposed) that extend laterally over > 200 m where outcrop is available. Trough (St) and planar-cross bedding (Sp) are the dominant sedimentary structures with lesser massive sandstone units (Sm; Fig. 5a, c, d). Medium- to fine-grained sandstones that display horizontal (Sh) and ripple cross-lamination (Sr) are less common and, when present, form the uppermost sedimentary structures in a weakly fining-upwards sandstone unit.

At the field sites visited, a single trough (scour structure) to grouped trough cross-bedding co-sets of *c.* 0.5–1.5 m thick occur (Fig. 5). Co-set thickness decreases upwards in a stacked package that was not measured as more than 4 m. Bedding planes may have mud drapes (millimetre thick) that can be bioturbated by simple, non-branched, non-ornamented, horizontal traces in epirelief (cf. *Planolites* isp.). These sandstone units are interbedded with or grade laterally into less thick muddy-siltstone units (*c.* 1.5–2 m thick) (i.e. Leopard Hill geotraverse).

Very coarse- to coarse-grained sandstones with pebble laminae are thickly bedded (≥ 1.5 m) with thin (< 5–10 cm; Fig. 5f) bands of conglomerate or pebble lags and laminae. The alternation of coarse-grained sandstone and bands of conglomerate, or pebble lags and laminae, suggest punctuated, fluctuating flow speeds.

Convolute bedding and soft-sediment deformation structures on both a small (< 15 cm; single bed) and large (> 60 cm) scale were documented (Fig. 5d). We also recorded wood fragments

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Fig. 4. (Colour online) (a) Unconformable contact exposed near Sanyati Gorge, Zimbabwe between the Chete Formation (Upper Karoo Group) and older pre-Karoo, chevron-folded muscovite schist of the Matusadona Gneiss Formation. (b) Escarpment Grit Member gravelly facies on the mainland near Sanyati Gorge: massive to crudely bedded granule to cobble, polymictic conglomerates that are largely poorly to moderately sorted, clast- and matrix-supported and interbedded with very-coarse-grained sandstones. (c) Coarse-grained sandstones and conglomerate exposure on Bed Island. (d) Normal-graded and massive conglomerates and very-coarse-grained to coarse-grained sandstones from Bed Island. Note secondary manganese nodule growth and staining. (e) Impressions of fossil wood clasts within a micaceous coarse-grained sandstone. See Table 1 for acronyms and facies codes.

(< 2–50 cm) and larger fossil logs (> 1.5 m length) within massive and trough-cross bedded, coarse- to medium-grained sandstone successions, respectively (e.g. the Petrified Forest site, *ex situ* fossil wood).

The Pebbly Arkose Formation's fine-grained facies assemblage is composed of maroon-red to pale cream, micaceous, thinly bedded (< 2 m), and often variegated (mottled), siltstones and mudstones (Fm, Fl; Fig. 5e, g, i; overbank deposits; Table 1).

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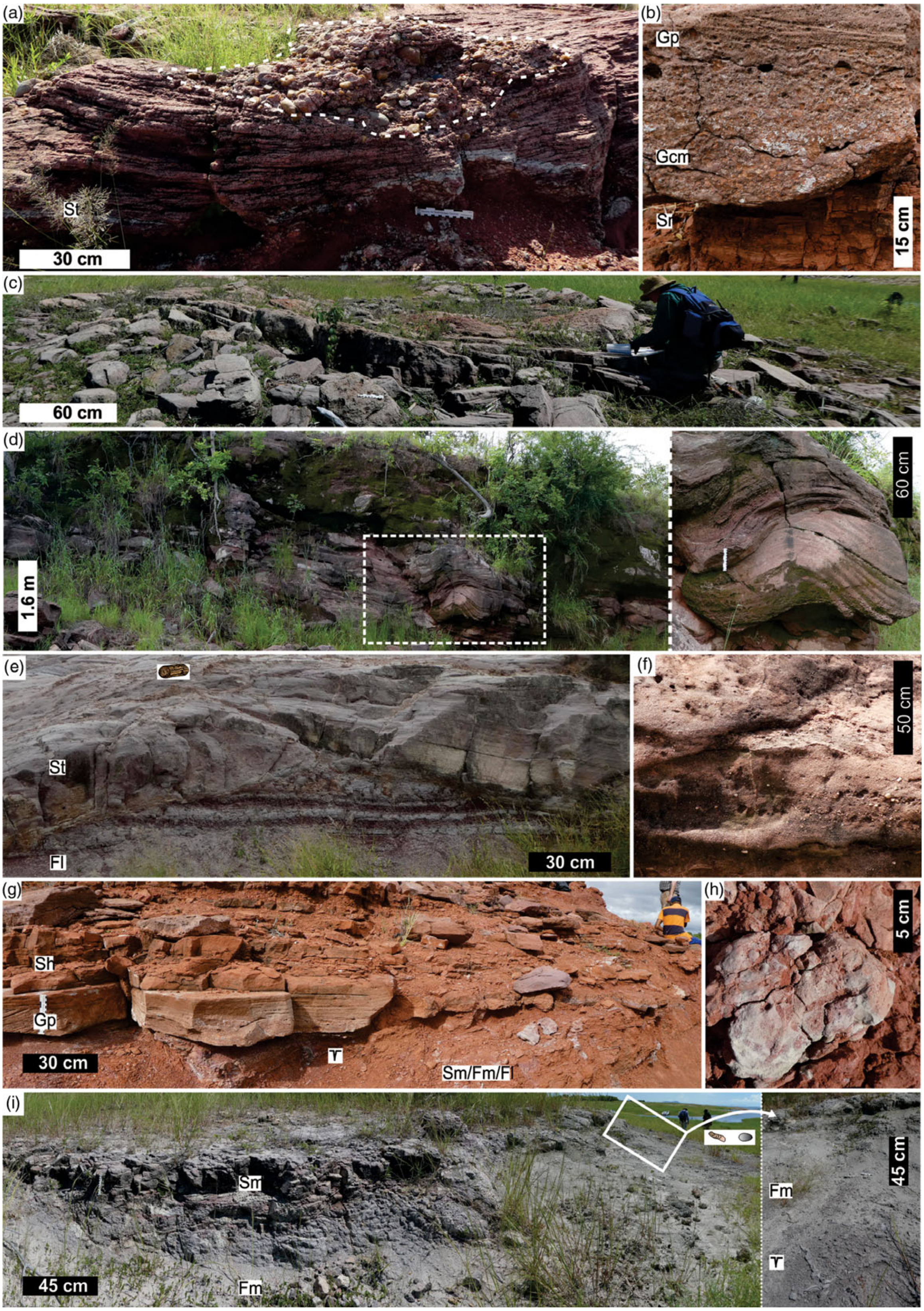

Fig. 5. (Colour online) Exposures of the Pebbly Arkose Formation. (a) Typical trough cross-bedded, pebbly, very-coarse-grained sandstone near Sanyati River. (b) Pedogenic nodule and mudchip conglomerate with waning-energy sedimentary structures (massive–planar cross-bedded–horizontal lamination). (c) Abandoned, fining-upwards, pebbly trough cross-bedded sandstone channel in overbank fines on the mainland near site 2. (d) Multi-storey, low-angle and planar cross-bedding showing (inset) upwards directed soft sediment deformation structure (small-scale fold, likely related to a seismic tremor) (Leopard Hill geotraverse). (e) Laminated lacustrine (Fl) deposit down-cut by trough cross-bedded sandstone containing fossil logs ≤ 1.2 m in length. (f) Pebbly Arkose: very-coarse- to coarse-grained, maroon sandstone, generally massive (Sm) with pebble stringers (Scm). (g) Pedogenically altered muddy-siltstone overbank facies (Fm/Fl) with sandstone-filled desiccation cracks and *in situ* vertebrate material interbedded with lenticular, fining-upwards planar cross-bedded conglomerate (Gp) and sandstones. (h) Carbonate-rich bioturbated siltstone. (i) Palaeopedogenic alteration overbank Fm units capped by sheet-like fine- to medium-grained sandstones (Sm). See Table 1 for acronyms and Figure 3 for symbols.

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These pedogenically modified floodplain deposits are associated with lesser sandstones (Sp, Sm, Sh, Sl, Sr) and intraformational conglomerate (Gcm, Gcm-1, Gmm, Gh, Gp; Table 1; Figs 3, 5). Many of the fossiliferous sites listed here are within these finer-grained deposits, for example, the Spurwing East Palaeosol, The Dentist, Coprolite Hill, Steve's Phytosaur and the Musango Archosaur sites (Fig. 5e, g, i).

Conglomerate lenses and fine-grained sandstones are also present as thin (< 35 cm; Fig. 5g) laterally discontinuous sheets, and these may be massive (Sm), horizontally laminated (Sh) and/or preserve climbing ripple cross-lamination (Sr). Minor sheet, asymmetrical to lenticular, trough (St), planar (Sp) to low-angle (Sl) cross-stratified sandstone units (average *c.* 1–2 m thick) are present within the overbank deposits (Fig. 5g). These are either isolated within the finer-grained facies or (may) show lateral accretion (e.g. Phytosaur Gulley, Musango Archosaur), and have either undulating lower boundary surfaces showing scouring ≥ 1 m deep (e.g. Phytosaur Gulley) or sharp bases. Single, lenticular St channel units may scour into floodplain fine-grained sediments (e.g. Musango Archosaur).

Thin (< 40–50 cm thick) sandstone sheets, occasionally coarsening upwards, occurring within the finer-grained facies are interpreted as overbank flooding (Miall, 2006, 2014). Ichnofossils (back-filled burrows, vertical and horizontal burrows; Fig. 5h) are common on mud-lined, upper bedding planes in isolated channel sandstones.

Pedogenically modified overbank deposits (palaeosols) in the Pebbly Arkose Formation can be recognized by their mottled red-grey colouration and the presence of pedogenic nodules, coprolites, occasional calcareous fossil rootlets (rhizoliths and rhizohalos; Fig. 5g, i), bioturbation (horizontal and vertical invertebrate burrows; Fig. 5h, i) and sandstone-filled desiccation cracks (< 40 cm long: Fig. 5i; The Dentist). Pedogenic carbonate nodules are present within the fine-grained facies and occur as either *c.* 10–20 mm or *c.* 40–60 mm largely unfused glaebules. Bioturbation is extremely common in both the sandstones and muddy siltstone of this facies (Fig. 5h, i). Bioturbation measured in the various sections and outcrop varies from grade 1–3 (moderate) to grade 5 (intense), with complete bioturbation (grade 6–100%) rare but present, using the bioturbation index (BI) of Taylor & Goldring (1993).

Throughout the Pebbly Arkose Formation, conglomerates are a minor component and appear as basal lags (i.e. mud-chip to pebble conglomerate channel lags), as thin (< 50 cm) massive sheets composed of granules to medium-sized pebbles and/or intraformational mud-chips or as reworked, localized, pedogenic nodule conglomerates (Gcm-1; Fig. 5a, b). These are all generally massive (Gmm, Gcm), but may also show planar cross-bedding (Gp) and/or horizontal bedding (Gh) and erosional bases (Fig. 5a).

Reworked, pedogenic nodule conglomerates (Gcm-1; Fig. 5b) are a distinct lithofacies (Gcm-1), characteristic of the strata found along the southern Kariba shoreline. They are clast-supported, moderately to poorly sorted, and consist of rounded to sub-angular clasts of quartz, mudstone, sandstone, pedogenic carbonate nodules and (often) fragmentary fossil bone. For instance, the fragmentary phytosaur material at Phytosaur Gulley (Fig. 3) was contained within this intraformational conglomerate. A distinctive carbonate matrix predominately fuses the clasts in these conglomerates. Clast size, sorting and rounding is variable between our studied sites, as are the fossil occurrences. Facies Gcm-1 forms tabular sheets with sharp lower boundaries (e.g. Phytosaur Gulley, Leopard Hill geotraverse), and the thickness of these units varies over the range *c.* 25–75 cm and with a lateral extent of ≤ 100 m.

4.a.3. Forest Sandstone Formation

Viglietti *et al.* (2018) documented a total of 43 m of vertical strata exposed on Island 126/127 (Dinosaur Island; Figs 3, 6; online Supplementary Table S1). Within this interval, four sedimentary facies associations (lettered A to D) were recognized that we believe correspond to Marsh & Jackson's (1974) Forest Sandstone Formation facies descriptions. Facies A is the lowermost facies located in this study area, and is represented by a red-brown, fine-grained sandstone *c.* 5 m in thickness (Fig. 6j). The sandstone is normally structureless, except for laterally discontinuous lenses of bioturbated, poorly sorted sandstone that show some horizontal lamination. Facies B represents a silty sandstone with mottled bioturbated horizons that are common (Fig. 6h). Carbonate nodules, plant fossil fragments with black mineralization and rhizoliths are also encountered, along with rare, isolated, but identifiable, vertebrate material (Fig. 6h, i). Facies C is a light-grey, coarse-grained, trough cross-bedded sandstone that contains multiple erosional boundaries and intraformational lags (Fig. 6e, f). These lags sometimes contain fragmentary and undiagnostic bone material, as observed on Namembere Island (Fig. 6k, l). Facies D is a medium- to coarse-grained (but well-sorted) sandstone containing large (>1 m) cross-beds that sometimes contain black heavy mineral preservation concentrated on foreset boundaries, has a distinctive, loosely compacted texture, and forms steep unstable cliffs in outcrop, which matches historic accounts of Marsh and Jackson's (1974) Dinosaur Horizon (Fig. 6c, d).

4.b. Palaeontology

4.b.1. Spurwing Island

Spurwing Island hosts several fossil-bearing sites (e.g. The Dock, Spurwing East Palaeosol; Figs 7, 8a; online Supplementary Tables S1, S2) in addition to being the source of historically collected but undescribed vertebrate material (Fig. 9; PMB and JNC, pers. obs., NHMZ collections; M. A. Raath, pers. comm., 2019). These occur above trough cross-bedded, medium-grained, mauve sandstones and within a finer-grained facies composed of very fine-grained, silty sandstone and siltstones that often display palaeopedogenic alteration features such as mottling, bioturbation, desiccation cracks and pedogenic nodules. At The Dock site (Fig. 7), postcranial elements of taxonomically indeterminate non-sauropod sauropodomorph dinosaurs, including vertebrae, a proximal tibia, an astragalus, phalanges and other fragmentary limb bones, were recovered as well as a possible theropod dinosaur phalanx (Fig. 7e) and other indeterminate bone fragments. At the East Palaeosol site, an articulated hindlimb of a non-dinosaurian archosauromorph was discovered (Fig. 8a, b).

4.b.2. Phytosaur Gulley

The sedimentology of the Phytosaur Gulley site is described in Barrett *et al.* (2020; online Supplementary Table S2). The units above the waterline consist of several stacked sandstone units (Sm, Sl, Sp) that are sheet-like to tabular in geometry and moderately bedded (< 1–1.5 m thick) with minor interbedded overbank fines (Fm). Interbedded within this sandstone package is a *c.* 1-m thick, sheet-like pedogenic nodule conglomerate (Gcm-1) that has an erosive basal contact with the underlying Sm. The reworked, pedogenic nodule conglomerate horizon contains relatively abundant phytosaur remains including jaw fragments and teeth

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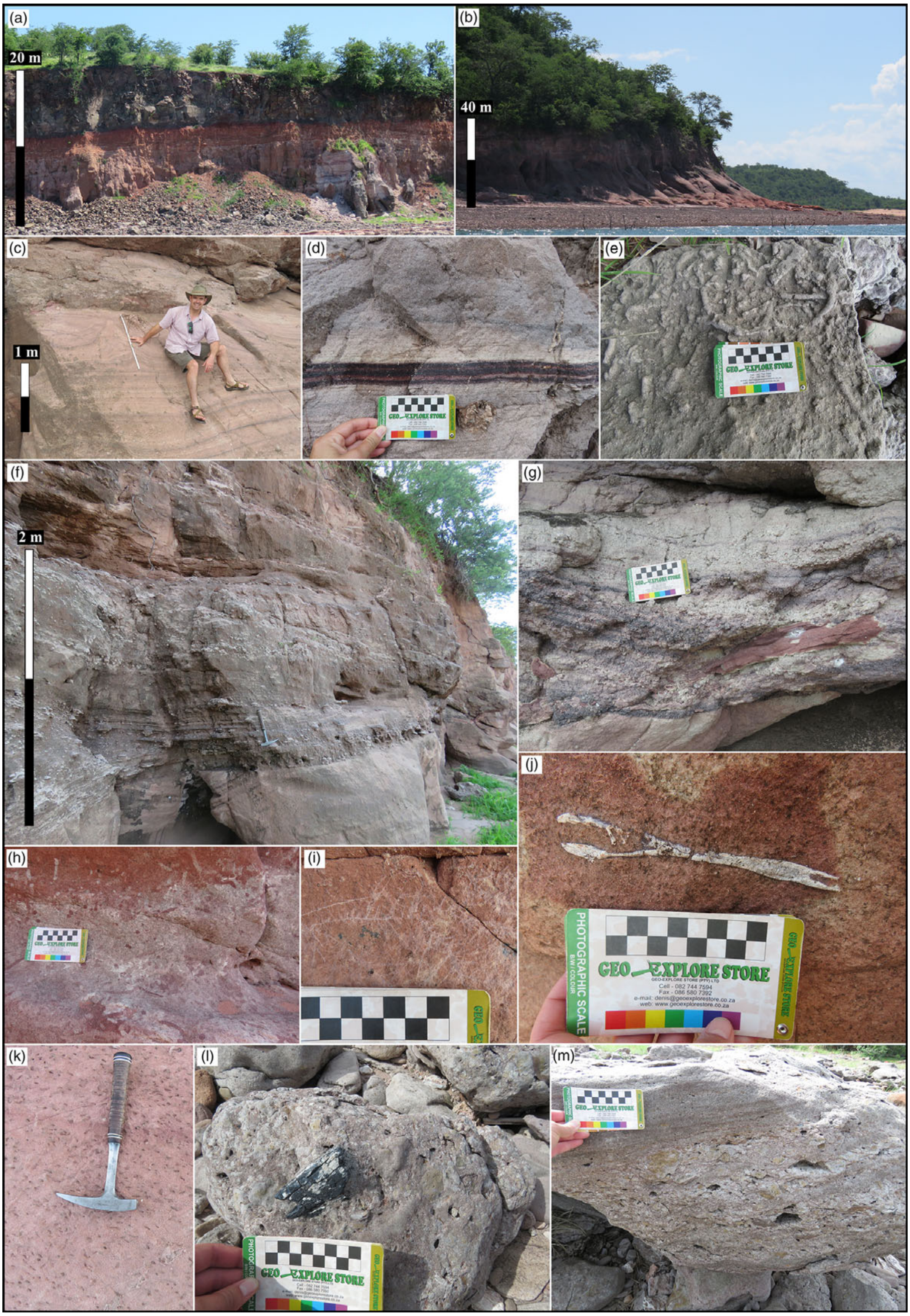

Fig. 6. (Colour online) Exposures of the upper Forest Sandstone Formation on 'Dinosaur' (a–j) and Namembere Islands (k, l). (a) Contact between the Forest Formation and Batoka Basalt. (b) Exposure on the northern portion of 'Dinosaur Island' where *Vulcanodon karibaensis* was recovered from a sandstone horizon immediately below a basalt layer. (c) Facies D from Viglietti *et al*. (2018), also known as the Dinosaur Horizon of Marsh & Jackson (1974). Note the presence of slightly undulating bedding and soft sediment deformation. (d) Common heavy mineral horizons in Facies D. (e) Calcified trace fossils on upper bedding places of Facies C (Viglietti *et al*. 2018). (f) Typical outcrop of Facies C on Dinosaur Island. Note the multiple erosion boundaries (with basal lags on foresets) and presence of planar and trough-cross-bedding. (g) Facies C erosional scour showing large mudstone rip-up clasts. (h) Palaeosol horizon in Facies B showing bioturbation horizon in red siltstone. (i) Fossil rootlet halos in Facies B. (j) Isolated cervical neural arch of a sauropodomorph dinosaur found in Facies B. (k) Massive and heavily bioturbated horizon in Facies A (Viglietti *et al*. 2018). (l) Examples of fossil bone fragments in a basal lag deposit on Namembere Island, west of Dinosaur Island. This site is attributed to the Facies C horizon on Dinosaur Island. (m) Basal lag deposit comprising mud chips and carbonate nodules. Fragmentary fossil bone is present but rare.

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Fig. 7. (Colour online) Fossils collected from surface exposures of the Pebbly Arkose Formation at Spurwing, The Dock locality. Two sacral vertebrae of an indeterminate reptile (NHMZ 2471) in (a) ventral, (b) dorsal, (c) ventral and (d) dorsal views. Manual phalanx of a ?theropod dinosaur (NHMZ 2518) in (e) extensor and (f) medial views. Astragalus of a sauropodomorph dinosaur in (g) proximal and (h) anterior views (NHMZ 2519). Proximal left tibia of a ?sauropodomorph dinosaur (NHMZ 2456) in (i) lateral and (j) medial views. Manual bones of a ?sauropodomorph dinosaur (NHMZ 2455) (k) distal end of penultimate phalanx and proximal end of ungual in medial or lateral view, (l) articulated partial phalanges and (m) articulated partial phalanges in medial or lateral view.

(Barrett *et al.* 2020). Dermal bones attributed to metoposaur temnospondyls were also identified (Barrett *et al.* 2020). Fossil bone material was recovered from this lithofacies only. Fossil wood was recovered from the trough cross-bedded medium- to coarse-grained sandstones overlying Gcm-1. Barrett *et al.* (2020) placed these sites in the upper 'Tashinga Formation', but they should be regarded as within the Pebbly Arkose Formation as described here.

4.b.3. Musango Archosaur site

The Musango Archosaur site is located *c.* 1 km SW of Musango Safari Camp. The logged section is *c.* 9 m thick (Figs 3, 8c) and consists of alternating massive muddy siltstone, thinly bedded, muddy, very-fine grained sandstones to fine- to medium-grained sandstone and subordinate conglomerate (clast- and matrix-supported) beds. The finer-grained deposits are interbedded with minor sheet-like and isolated, asymmetrical channel-like sandstone bodies (Sm, Sh and Sp, Sr; Fig. 5g, i). The latter is fine- to medium-grained, thin (≤40–50 cm thick) and laterally restricted (<1.2 m in length). Several of the channel sandstones have erosional and gullied bases that are draped by a matrix-supported intraformational conglomerate and show lateral accretion. Cross-bedding planes (Sp) are denoted by granular lags in these lowermost channel sandstones. Within the siltstone units, weakly developed palaeosols are noted by the presence of rare pedogenic nodules and sandstone-filled desiccation cracks (*c.* < 40 cm long; Fig. 5i). Many laterally restricted (< 5 m) sheet-like sandstone units coarsen upwards and show bioturbated mud-draped upper bedding plane surfaces.

Fossil vertebrate material was found within a pedogenically altered and heavily bioturbated (BI = 6; Taylor & Goldring, 1993) muddy siltstone, which is interbedded between two thin (<30 cm), laterally continuous, fine-grained sandstone beds. The material collected from this site is still being prepared for study but appears to represent an associated, but partial, non-dinosaurian avemetatarsalian skeleton based on the morphology of the astragalus (Fig. 8c–e; online Supplementary Tables S1, S2).

4.b.4. The Dentist and Coprolite Hill

The Dentist and Coprolite Hill site complex was discussed in Barrett *et al.* (2020; online Supplementary Table S2). Here, lungfish, metoposaurid and phytosaur remains, as well as coprolites, were recovered from a variegated red-grey silty-mudstone that represents an overbank area and palaeosol deposit. These sites were considered to represent the upper 'Tashinga Formation' in Barrett *et al.* (2020), but now fall within the Pebbly Arkose Formation as described here.

The Dentist and Coprolite Hill sites represent an almost purely aquatic vertebrate fauna, and they have yielded no material of

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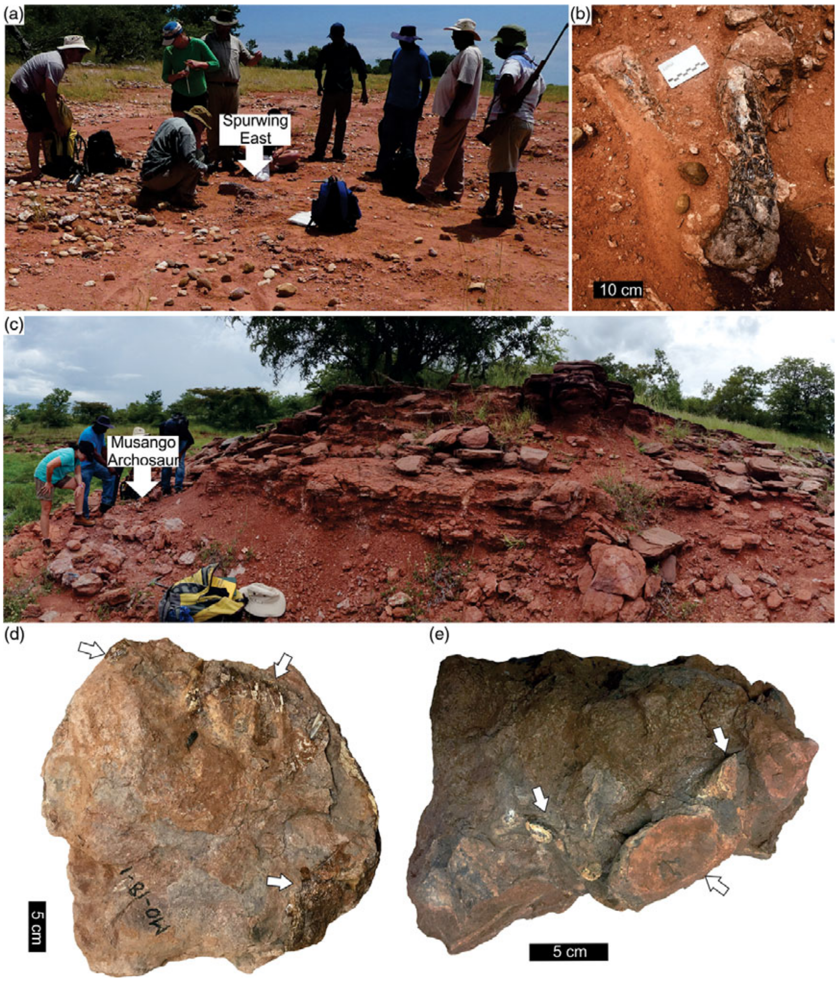

Fig. 8. (Colour online) (a) Exposures looking north at the Spurwing East Palaeosol locality (Pebbly Arkose Formation). (b) *In situ* femur, tibia and fibula of an indeterminate archosaur at the Spurwing East Palaeosol locality (field number SW-18-4). (c) Exposures at the Musango Archosaur locality looking ENE (Pebbly Arkose Formation). Arrow indicates the position of a non-dinosaurian avemetatarsalian skeleton. (d) Block of fossiliferous sediment from the Musango Archosaur locality; arrows indicate fossilized bone (field number MO-18-1). (e) Block of fossiliferous sediment from the Musango Archosaur locality, arrows indicate fossilized bone (field number MO-18-1).

Fig. 9. (Colour online) Historically collected isolated vertebrate (?dinosaur) bones from Spurwing Island (NHMZ QG 143/NHMZ 11634). (a) Diaphysis of an indeterminate limb bone, (b) partial manual ungual, (c) centrum of caudal vertebra, (d) centrum of caudal vertebra, (e) manual phalanx, (f) centrum of indeterminate vertebra, (g) centrum of indeterminate vertebra and (h) indeterminate bone fragment.

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Fig. 10. (Colour online) (a–j) Selection of hematite-coated coprolites (field number MS-18-2) from the Pebbly Arkose Formation of the Coprolite Hill locality. (d, d') Part and counterpart of a single coprolite showing internal structure.

sauropodomorph dinosaurs to date. Notable finds include partial mandibles, numerous teeth and osteoderms of phytosaurs (Barrett *et al.* 2020). These fragments were unassociated and numerous individuals are likely to be represented; the mandibular fragments alone indicate the presence of at least three differently sized individuals. These phytosaur remains represent the first known occurrence of the clade in sub-Saharan mainland Africa (Barrett *et al.* 2020), but more material will be required to determine its taxonomic affinities. Several taxonomically indeterminate ziphodont archosaur teeth were also recovered from this locality and may represent either those of dinosaurs (theropods or herrerasaurids) and/or another carnivorous archosaur clade (e.g. a non-crocodylomorph pseudosuchian). Lungfish tooth plates are very common and might represent a new taxon (T. Challands, pers. comm., 2017; Barrett *et al.* 2020). Vertebrate coprolites are locally common at this site (Fig. 10).

4.b.5. Petrified Forest

The Petrified Forest site occurs in a *c.* 5-m thick, medium-grained, light red-brown, trough and planar cross-bedded sandstone unit, with many internal erosional boundaries and intraformational lags. It includes a large number of fossilized logs preserved over an area of *c.* 50 m^2 in the Pebbly Arkose Formation. The tree trunks (Fig. 11a, b) are *ex situ* and are often located at the bases of thick sandstone channels or between troughs. Tree trunks can reach up to *c.* 1 m in diameter and *c.* 1.5–5 m in length (Fig. 11b). While none of these tree trunks has been formally identified, previous work by Marsh & Jackson (1974) identified them as *Rexoxylon* (Corystospermales, or tree-fern-like) or *Dadoxylon*/*Ausraloxylon* (Cordaitales, or conifer-like) (Bamford, 2004; online Supplementary Tables S1–S3).

4.b.6. Nyanzirau dinosaur site

The Nyanzirau site occurs along the Leopard Hill geotraverse (Fig. 3) and is associated with a medium-grained, massive sandstone that overlies a pedogenic nodule conglomerate (with intraformational mud chips and occasional fossil vertebrate material) of the Pebbly Arkose Formation. The Nyanzirau fossil material (Fig. 11d–i) consists of *ex situ* but associated elements of a medium-sized sauropodomorph dinosaur, including several teeth, dorsal vertebrae, caudal vertebrae, ilia, manual phalanx I-1, a manual ungual, a partial femur and fragmentary long bones (Fig. 11d–i; online Supplementary Tables S1, S2). All of this material is heavily encrusted in a black, manganese-rich coating, which can vary from 2 to 20 mm in thickness. The bone is black in colour and bone surfaces beneath the manganese crust are very well-preserved.

4.b.7. Gordon's Bay

Around Gordon's Bay (Fig. 1) there are several outcrops of medium-grained, trough cross-bedded red to cream sandstones of the Pebbly Arkose Formation, from which weathered bone material, phytosaur teeth and fragmentary fossil wood (Fig. 12a–c) were obtained (field number GB-18-3; online Supplementary Table S1). These are isolated *ex situ* occurrences of heavily weathered material, but they can be used to infer potential for future exploration (Fig. 12a–c).

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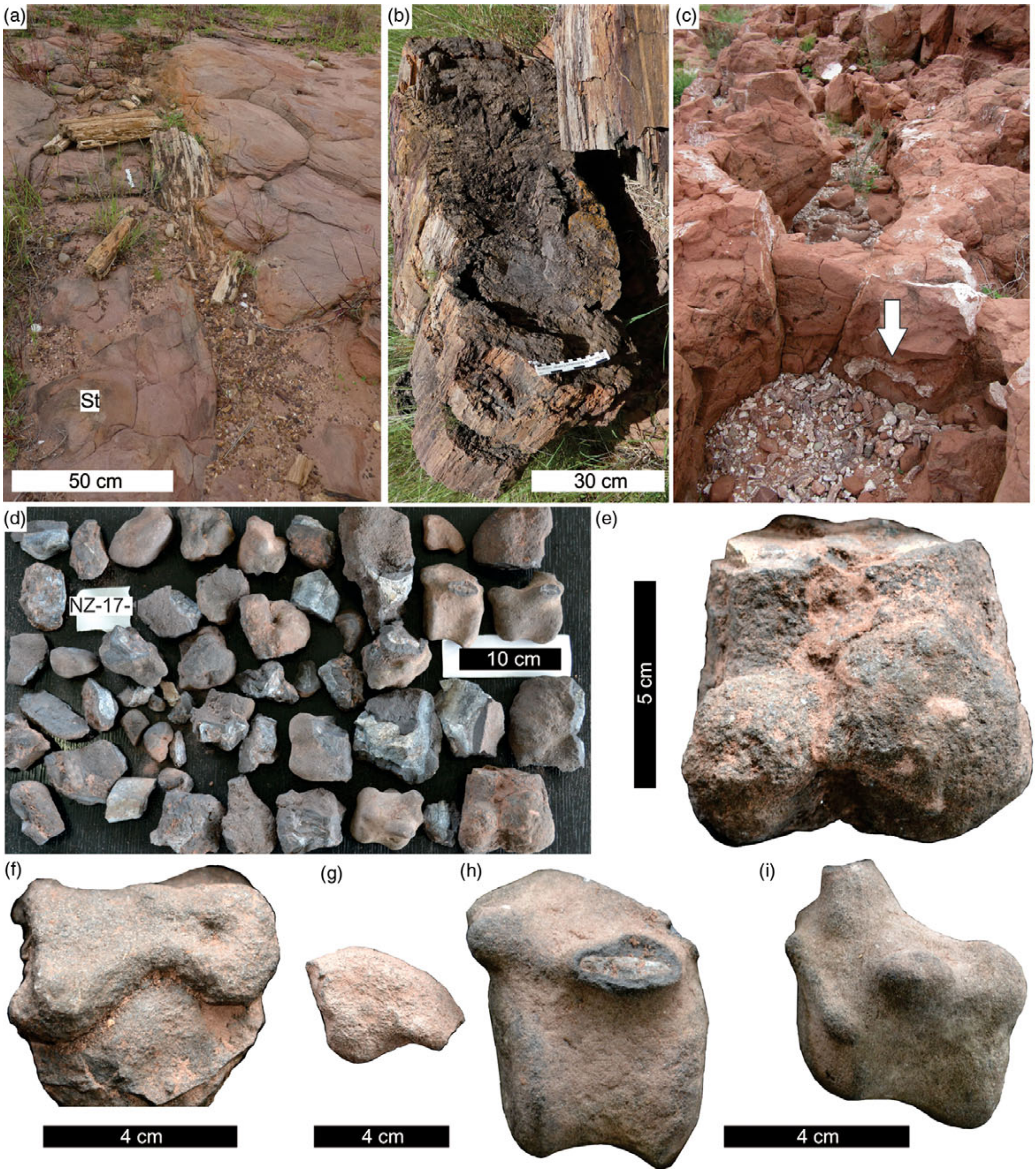

Fig. 11. (Colour online) Fossil wood within the Pebbly Arkose and Forest Sandstone formations. (a) *c.* 1.2 m long log, with long axis roughly parallel to flow, between two trough cross-bedded sandstones (Pebbly Arkose Formation). (b) Cross-section of fossil wood at the Petrified Forest Site (Pebbly Arkose Formation). (c) Namembere Island tree trunk casts and associated silicified rhizoliths (arrowed; Forest Sandstone Formation). (d) Nyanzirau site fossil material (sample number NZ-17-1) collected within the Pebbly Arkose Formation. All material was *ex situ* but associated, and represents postcranial elements of a medium-sized sauropodomorph dinosaur. Note manganese encrustation. (e) Distal femur in ventral view. (f) Manual phalanx I-1 in ?lateral view. (g) Manual ungual in ?lateral view. (h) Proximal caudal vertebrae in right lateral view. (i) Distal caudal vertebra in lateral view.

4.b.8. Elephant Point

A historically collected vertebra (NHMZ QG 2145; Fig. 10d–h; online Supplementary Tables S2, S3) and fossil wood were collected in 1986 by M.A. Raath (TJB, pers. obs.; Fig. 12a–e) from this locality. It was previously considered to have been recovered from Forest Sandstone Formation exposures, and no other site information is attached to this specimen. In our revisiting of Elephant Point and adjacent areas, the sedimentology of these sites places them within the Pebbly Arkose Formation. Unfortunately, this site has currently only yielded weathered and fragmentary material (Fig. 12i), and much of Elephant Point is underwater during times of high lake levels, which prevented us from revisiting the locality in 2018.

4.b.9. Namembere Island

Namembere Island is located to the west of Island 126/127 (Fig. 1; online Supplementary Tables S1, S2) within the Forest Sandstone Formation. Exposed sections usually comprise coarse-grained, light greenish-grey, cross-bedded sandstone with calcareous horizons, giving these layers a pustular texture. Intraformational conglomerates are common although they are not laterally continuous. These units contain rounded, dark greenish-brown mudstone

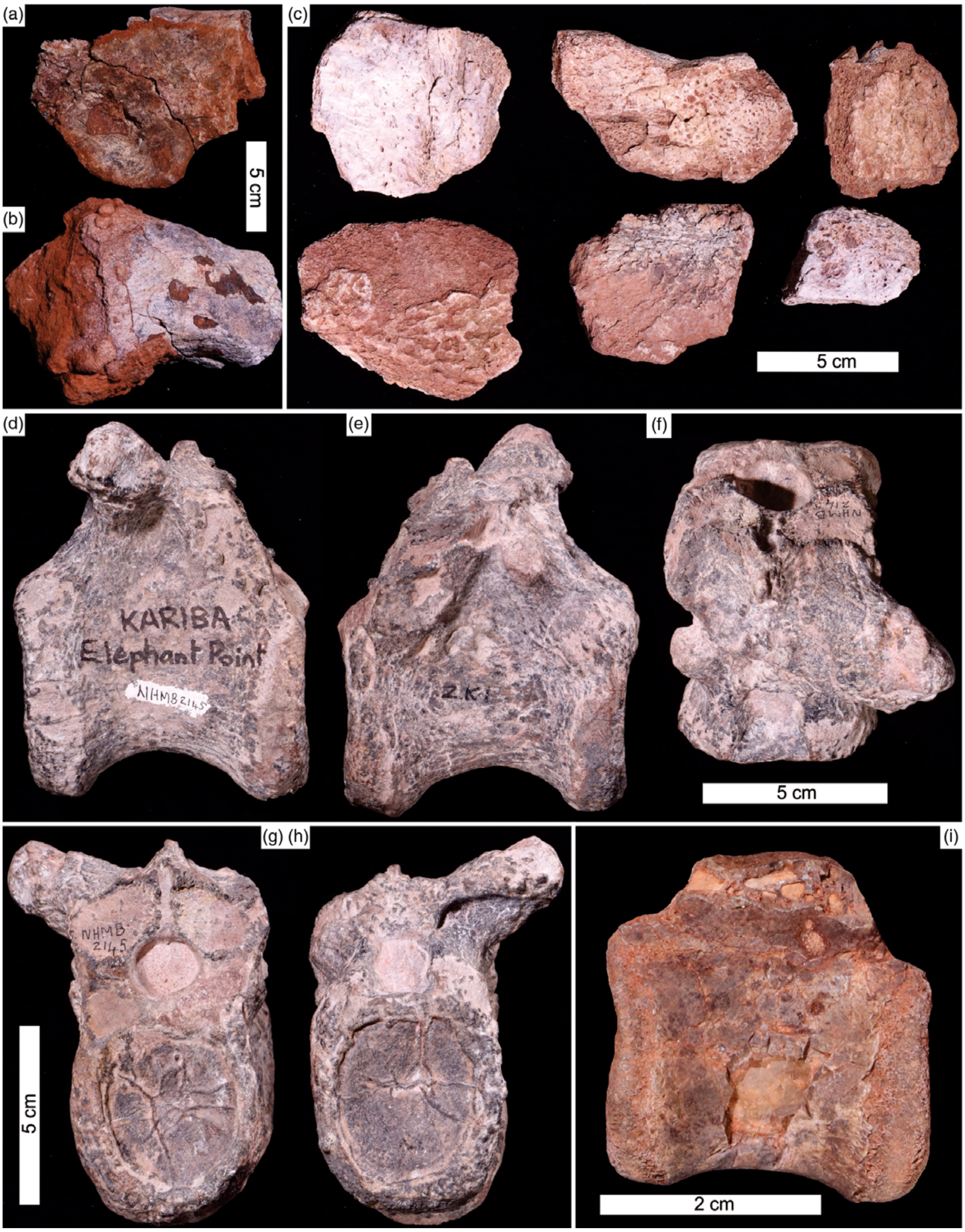

Fig. 12. (Colour online) Gordon's Bay site material (field number GB-18-1) showing (a, b) indeterminate ?dinosaur limb bone and (c) fragments of sculptured ?phytosaur cranial bone (field number GB-18-3). Elephant Point site in the Pebbly Arkose Formation showing anterior dorsal vertebra of saurischian dinosaur in (d) right lateral, (e) left lateral and (f) dorsal views. Posterior dorsal vertebra of saurischian dinosaur in (g) posterior and (h) anterior views (NHMZ 2145). (i) Centrum and partial neural arch of caudal vertebra of indeterminate tetrapod in lateral view, collected in 2018 (field number EP-18-1).

clasts, many bone fragments, and isolated fossil vertebrate elements with a distinctive black and blue preservation (Fig. 6; Facies C *sensu* Viglietti *et al.* 2018). Underlying this sandstone is a reddish-brown sandstone with bioturbated horizons (Facies B *sensu* Viglietti *et al.* 2018). This site is placed within the Forest Sandstone Formation based on its sedimentology, which is very similar to that described on Island 126/127 (Viglietti *et al.* 2018).

Fossil material from Namembere Island site consisted of mostly unidentifiable bone fragments, but a proximal humerus, partial fibula, caudal vertebrae and a distal tibia were identified from the intraformational conglomerates (Fig. 13). Given their morphology and medium to large size, this material likely pertains to sauropodomorph dinosaurs; however, given the fragmentary nature of the material, none was collected. Additionally, Namembere Island

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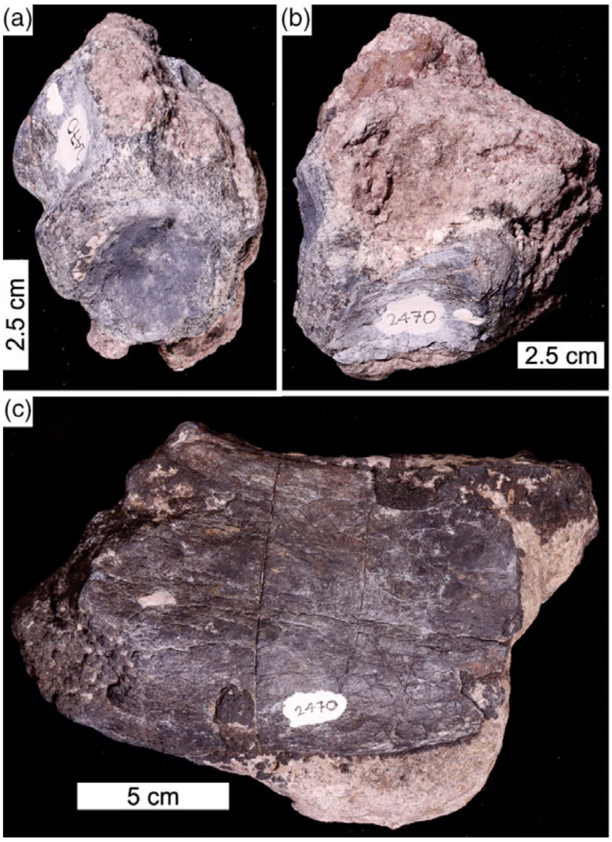

Fig. 13. (Colour online) Namembere Island site material (NHMZ 2470) within the Forest Sandstone Formation. (a, b) ?Sacral centrum and (c) partial ?femur of an indeterminate dinosaur.

hosts a palaeosol horizon in which *in situ* tree stumps have been eroded (Fig. 11c), leaving voids where the silicified and calcareous rhizoliths remain.

4.b.10. Island 126/127 (Dinosaur Island)

This site is discussed extensively in Viglietti *et al.* (2018) with a stratigraphic revision indicating that strata exposed on Island 126/127 are of the Forest Sandstone Formation and overlying Batoka Basalt (Fig. 3). Surveys of Island 126/127 did not yield any noteworthy new material, making the *Vulcanodon* quarry a singular find. Most of the bone fragments identified during this investigation were located within the coarse-grained trough cross-bedded sandstone facies of the Forest Sandstone Formation (Facies C *sensu* Viglietti *et al.* 2018). An isolated neural arch referable to a massospondylid sauropodomorph was identified in a siltstone referred to as Facies B (*sensu* Viglietti *et al.* 2018), but was not collected. Bone at this locality is white in colour and well-preserved.

5. Discussion

This investigation has highlighted a series of sedimentologically and palaeontologically important sites with potential to provide critical information on the faunal, palaeoenvironmental and temporal framework for the Triassic–Jurassic terrestrial ecosystems of southern Gondwana.

Our preliminary sedimentological work (Viglietti *et al.* 2018; Barrett *et al.* 2020) used a revised Upper Karoo Group stratigraphy and the informal ‘Tashinga Formation’ (BC Hosking, unpub. M.Sc. thesis, University of Zimbabwe, 1981) for exposures around the southern shoreline of Lake Kariba. However, we now regard use of the ‘Tashinga Formation’ as untenable, as we can confirm a subdivision of lithofacies around Lake Kariba that corresponds to the previously described Escarpment Grit, Ripple Marked Flagstone, Fine Red Marly Sandstone and Pebbly Arkose (see Section 2). As such, we have abandoned the use of the ‘Tashinga Formation’ in the MZB for units across Matusadona National Park and have adopted the use of the Chete, Pebbly Arkose and Forest Sandstone formations for the Lower Sengwa/Gwembe Sub-basin of the MZB (Barber, 2018).

Due to limited exposures, we were not able to further characterize the upper, lower and lateral boundaries of the Chete Formation members or strongly define their relationship with the overlying Pebbly Arkose Formation. These boundaries need to be better defined by future work. Nevertheless, for our fieldwork, demarcating the occurrence of fossil finds and for regional correlations, distinguishing the Chete and Pebbly Arkose formations is useful. Moreover, delineating type sections from the various sub-basins would assist in consolidating lithostratigraphic descriptions (Ait-Kaci Ahmed, 2018; Barber, 2018). Lastly, additional means of validating lithological correlations (i.e. bio- and magnetostratigraphy and geochronology) are necessary to provide robust constraints on their temporal correlatives. Moreover, given the uncertainty of the ages of Upper Karoo Group equivalents in the various Karoo-aged basins (see historical review in Section 2), radiometric dating and further refinement of the lithostratigraphy is critical.

5.a. Reconstructing the palaeoenvironments of the fossiliferous sites

Sedimentological work within the Upper Karoo Group of the MZB has established a progressive shift in depositional environments through time from alluvial fan and braidplain deposits, through the fluvio-lacustrine and sheet-flood systems to fluvio-aeolian deposits. In combination with the biostratigraphical record, the Upper Karoo Group of the MZB exhibits the same long-term climatic trends as the Stormberg Group of the MKB (Smith & Kitching, 1997; Bordy *et al.* 2004; Sciscio & Bordy, 2016) and the Triassic globally (Lucas, 2018), with temperate, humid regimes succeeded by increasingly arid climates.

The Chete Formation is considered to be the result of uplift and erosion along the rift basin margins that resulted in the development of several wedge-like alluvial fans and braided river systems (Barber, 2018). In our study, Chete Formation exposures describe a gravelly facies association (Gmm, Gcm, Gh and imbrication) supporting high-energy debris- to stream-flow processes that wane (as shown by a decrease in clast size within a bed and between sites) (Miall, 1977, 2006; Ridgway & Decelles, 1993), and suggest upper braided fluvial plain deposition.

The overlying fossiliferous and palaeopedogenically altered sites of the Pebbly Arkose Formation, in contrast, are epitomized by the lithofacies Fm that represents sediments that have settled from suspension on the floodplain or in an overbank pond (Fl), and have subsequently undergone exposure, desiccation and palaeopedogenesis (e.g. Fig. 5g, i). The thinly laminated (millimetre-scale) Fl facies, although a minor component and of limited lateral extent (< 4 m), likely denotes localized permanent lacustrine conditions (e.g. Fig. 5e). Much of the fossil material reported here (Fig. 3; online Supplementary Tables S1, S2), found within pedogenically altered floodplain intervals, had either been transported and deposited there during flooding events or died *in situ* (e.g. the partially articulated material at the Spurwing East Palaeosol and Musango Archosaur sites) (Fig. 9).

In general, palaeosol development, as illustrated by colour mottling, sandstone-filled desiccation cracks, rhizoliths, rhizocretions, pedogenic nodules, bioturbation and the occurrence of coprolites (Figs 5g–i, 10; e.g. Coprolite Hill, Steve's Phytosaur Site), is common. The caliche and fused or dispersed pedogenic carbonate nodules (Fig. 5h, i) denote the local palaeohydrological conditions, indicating active movement of the water table (Kraus, 1999; Retallack, 2001), and overall are indicative of subtropical to semi-arid palaeoenvironments (Khadkikar *et al.* 1998; Tanner *et al.* 2006) within perennial fluvial systems. Bioturbation is common in both overbank units, especially around *in situ* fossil material (e.g. Musango Archosaur) and on the mud-draped bedding planes of sandstones (Fig. 5g, h). These invertebrate ichnites (horizontal and vertical burrows of 4–20 mm diameter, which are occasionally back-filled) indicate periodically water-saturated and nutrient-laden sediments. Lastly, the sandstone-filled desiccation cracks in several Fm profiles illustrate wet–dry conditions, and those that are deep (> 25 cm) and infilled by laminated sediments indicate long periods of drying and passive infill (present at Spurwing East Palaeosol, The Dentist; Figs 5i, 9).

Interbedded within overbank units are tabular to lenticular, planar to low-angle cross-stratified sandstone (and mud chip/nodule conglomerate) channel units showing lateral accretion (e.g. Phytosaur Gulley, Musango Archosaur; Fig. 5g) and with undulating lower boundary surfaces (showing scouring ≤ 1 m deep; e.g. at Phytosaur Gulley). These indicate high-sinuosity fluvial channels and laterally migrating distributary channels scouring the floodplain. Associated with these overbank deposits are lithofacies Gcm-1, representing a reworked pedogenic nodule conglomerate that can be fossiliferous and indicates localized floodplain scouring (Fig. 5b).

Complementing the palaeopedogenically altered sites, the Pebbly Arkose Formation's sandy facies represent sand-dominated, mixed-load fluvial systems. These fluvial channel fills are characterized by erosive bases (with minor conglomerate/mud chip lags) and concurrent weakly developed, fining-upwards sequences of both grain size (pebbly, coarse- to fine-grained sand) and waning energy sedimentary structures (St, Sp, Sm, lesser Sr) (Fig. 5; Miall, 2014). Multi-story, stacked sandstone units likely denote compound bar deposits. Lateral accretion surfaces were not readily observed indicating, again, a dominance of vertical aggradation. The number of trough cross-bedded sets in a single exposure likely indicates constant discharge of a perennial fluvial channel (Miall, 1996, 2014).

Overall, the contrasting high- and low-energy sedimentary structures in the Pebbly Arkose Formation represent the effects of fluctuating climate or strong seasonality in conjunction with tectonism. Strongly differentiated seasonal variations were proposed by Bond (1967, p. 189) in an analysis of well-defined growth rings in the fossil wood found 'either at the top of the Molteno Stage or the bottom of the Red Beds' (Fine Red Marly Sandstone Member). Fossilized wood in the Pebbly Arkose Formation needs to be studied to see if it records the same conditions; nevertheless, well-preserved silicified fossil wood (Fig. 11a, b; both fragments < 2–50 cm in length and logs > 1–2 m in length) indicates the proximity of local woodland areas (hinterland areas, abandoned channels or channel margins) and suggests their stripping during seasonal flood discharge and burial between migrating channel bars (Fielding & Alexander, 2001). To date, all of the fossil wood noted within the Pebbly Arkose Formation is allochthonous and has been found within channel sandstones with their long axis parallel to flow (Fig. 11a).

Finally, the Pebbly Arkose Formation is notable for the occurrence of soft-sediment deformation structures recorded in sandstones (St-Sp sets), which range from convolute bedding to small-scale folds (Fig. 5d and inset). These may be produced by either rapid burial of water-saturated sediment leading to an increase in pore pressure, causing fluid escape and/or a seismic tremor. Given the Upper Karoo Group tectonic setting, it is likely they represent small seismic events.

5.b. Palaeontological diversity and proposed age relationships

The emerging diversity of the vertebrate fauna from the Upper Karoo Group includes taxonomic and palaeoecological components that were previously unknown from southwestern Gondwana, and suggests similarities to better-known palaeoecosystems from northern Pangaea (e.g. Upper Triassic Chinle Formation of the USA; Irmis, 2005; Martz *et al.* 2014; Barrett *et al.* 2020). As this material is prepared and more fieldwork conducted, these MZB sites may reveal more detailed biostratigraphic correlations with neighbouring basins.

Although biostratigraphy has been the primary means of dating and correlating the Upper Karoo Group in the Mid-Zambezi, Mana Pools and Cabora Bassa basins, a single $^{40}Ar/^{39}Ar$ radiometric date of *c.* 179–180 Ma (Toarcian; Jones *et al.* 2001; volcanic phase P3; Moulin *et al.* 2017) has been obtained from the Batoka Basalt. The Batoka Basalt caps the sedimentary sequence in northwestern Zimbabwe and gives an older Pliensbachian $^{40}Ar/^{39}Ar$ plateau age of 186.3 ± 1.2 Ma (Rogers *et al.* 2004; Tuli Basalt) in southwestern Zimbabwe. These basalts are considered to be the northern extension of the Karoo Large Igneous Province (KLIP) and are correlated with the upper Sabie River basalts (central Lebombo) based on geochemical and palaeomagnetic evidence (Jones *et al.* 2001; Moulin *et al.* 2017). Importantly, the age of the MZB Batoka Basalt denotes that they were emplaced in a separate episode after – or towards the end of – the main magmatic pulse (P2) in the MKB (volcanic phase P2; 180–183 Ma; Drakensberg Group; Duncan *et al.* 1997; Jourdan *et al.* 2007; Moulin *et al.* 2017), while the Tuli Basalt age is coeval with the earliest onset of volcanism in the MKB (*c.* 189 Ma; Moulin *et al.* 2017).

The relative ages of the basalts across Zimbabwe have to be considered when using them as minimum ages for the underlying sedimentary sequences. The age of the Forest Sandstone Formation is based on the conformably upper boundary with the overlying basalts, in addition to biostratigraphical correlations with the upper Elliot and Clarens formations of the MKB (Hettangian–Pliensbachian; Early Jurassic; Fig. 2; Knoll, 2005; Bordy *et al.* 2020). These correlations draw upon the co-occurrence of *Megapnosaurus rhodesiensis* and *Massospondylus* in the Mana Pools, Tuli and Mid-Zambezi basins (Bond *et al.* 1970; Raath, 1972*a*, *b*; Cooper, 1981) as well as a 'protosuchid' crocodylomorph (cf. *Notochampsa* sp.; Raath, 1981) in the CBB.

Currently, this spread of fauna from the Forest Sandstone Formation suggests a range between Rhaetian/Hettangian and Sinemurian/early Pliensbachian when compared to the MKB (Bordy *et al.* 2020). However, based on the spread of ages for the overlying basalts, the uppermost age of the Forest Sandstone Formation in the northern MZB may be younger and/or reflect the longer duration of sedimentation than the same formation in the south (i.e. the Samkoto Formation, previously Forest

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Sandstone, in the Zimbabwean Tuli Basin; Rogers *et al.* 2004) and relative to the MKB (uppermost Clarens Formation maximum depositional age of 187.5 ± 1.6 Ma; Bordy *et al.* 2020). As such, Zimbabwean Tuli Basin Clarens-type sedimentation is likely temporally more closely associated with that in the MKB, given the overlying Tuli Basalt age, than with the northernmost Forest Sandstone Formation within the MZB (Gwembe Sub-basin), but this needs further testing. Given the likely > 180 Ma age of the *Vulcanodon* site (Island 126/127), its proximity to the overlying Batoka Basalt and interbasinal faunal correlations, a Pliensbachian age is more plausible (the uppermost age estimate proposed by Viglietti *et al.* 2018). It is possible this site could be coeval with the acme of volcanism within the MKB (181–183 Ma; Duncan *et al.* 1997; Moulin *et al.* 2017) given the younging of Karoo volcanism across southern Africa. In any case, this older than previously considered age enabled recalibration of several nodes within sauropod phylogeny, and indicated an extended period of time where true sauropods and sauropodomorphs overlapped (Viglietti *et al.* 2018). A deeper inquiry is clearly needed regarding the likely diachronous nature of Forest Sandstone Formation deposition across the Karoo-aged basins in Zimbabwe, as related to regional changes in depositional conditions (Visser, 1984).

Determining the ages of the Upper Karoo Group units underlying the Forest Sandstone Formation across Zimbabwean Karoo-aged basins has been inhibited by the lack of shared fauna. Until recently, the conformably underlying Pebbly Arkose Formation in the MZB has yielded only fossil wood (*Rhexoxylon*, *Dadoxylon*, *Mesembrioxylon*) and a lungfish toothplate. The new maximum depositional age of 209.2 ± 4.5 Ma (late Norian or early Rhaetian) from the Pebbly Arkose Formation (previously upper 'Tashinga Formation'; Barrett *et al.* 2020) is the first independent date for these units. It is further supported by the presence of phytosaurs (and other aquatic vertebrates; Barrett *et al.* 2020), which have a stratigraphically restricted distribution, occurring most frequently in deposits of Norian–Rhaetian age. These are considered to have gone extinct by either the end of the Triassic (Parker & Irmis, 2005; Rayfield *et al.* 2009; Stocker & Butler, 2013) or during the earliest Jurassic (Lucas & Tanner, 2018).

The phytosaur-bearing interval is, therefore, most likely an equivalent of the lower Elliot Formation (*Scalenodontoides* Assemblage Zone, MKB; Kitching & Raath, 1984; Knoll, 2004; Bordy *et al.* 2020; Viglietti *et al.* 2020*b*) based on the MKB upper Stormberg Group geochronology and despite the current absence of shared taxa. Other localities in the Pebbly Arkose Formation, while yielding only fragmentary specimens so far, have revealed the potential for associated archosaur and dinosaur remains (e.g. Musango Archosaur, The Dock, Spurwing East Palaeosol) representing previously undocumented vertebrate taxa. Their discovery provides a clearer understanding of how the MZB correlates biostratigraphically with other extra-African basins (e.g. Rewa Gondwana Basin, India, Datta *et al.* 2019; Colorado Plateau, Basin and Range, USA; Martz *et al.* 2017) and with those in southern and eastern Africa. Unfortunately, given that we have yet to map the lower and upper boundaries of the Chete and Pebbly Arkose formations accurately, we cannot place these localities into a more detailed intraformational stratigraphic context. Similarly, this makes it problematic to define the upper and lower age limits of the Pebbly Arkose Formation.

The presence of reworked, bone-bearing, pedogenic nodule conglomerates, palaeosols and scour-and-fill features suggest periodic erosion and non-deposition, and the presence of cryptic unconformities during Pebbly Arkose Formation time. Moreover, the rift basin itself controls shifts in subsidence rates, and evidence for tectonic activity (e.g. small-scale folding; Fig. 5d) in close association with debris-flow processes indicates periodic higher sediment accumulation as, most likely, a result of renewed faulting. Lastly, differential subsidence within a basin can also affect basinal facies thickness patterns (Alexander & Leeder, 1987; Einsele, 2000), which can make intrabasinal correlation equivocal. Differential subsidence might also explain the exceptional thickness discrepancies between lithostratigraphically correlated units such as the Pebbly Arkose Formation in the CBB and the MZB.

In comparison to other Karoo-aged basins, the MZB's Pebbly Arkose Formation can be correlated lithostratigraphically with the Pebbly Arkose Formation in the Cabora Bassa and Mana Pools basins and, at least, part of the Sandstone and Interbedded Mudstone Formation from the Gwembe Sub-basin in Zambia and the Upper Grit of the Luangwa Basin (Fig. 2). Stratigraphically, the Pebbly Arkose Formation may be correlated to the Upper Unit and Red Beds/Mpandi Formation (Tuli Basin in South Africa and Zimbabwe, respectively; Bordy & Catuneanu, 2001; Rogers *et al.* 2004), which have been correlated to the upper Elliot Formation (MKB; Rhaetian–Pliensbachian; Bordy *et al.* 2020).

Biostratigraphically, Pebbly Arkose Formation units in each of these basins do not share any diagnostic fauna. Palynological work from the Mana Pools Basin suggests that the Pebbly Arkose Formation there is Carnian–Rhaetian in age (d'Engelbronner, 1996; Nyambe & Utting, 1997). In the CBB, the lower Pebbly Arkose Formation contains faunal components, such as hyperodapedontine rhynchosaurs, a gomphodontosuchine cynodont and undescribed early-branching sauropodomorph dinosaur material (Raath *et al.* 1992; C. Griffin, pers. comm., 2020), that are suggestive of a Carnian age, particularly when considering the close geographic and stratigraphic association of the *Dicroidium*-flora from the underlying unit (Alternations Member; Raath *et al.* 1992). The faunal associations from the lower Pebbly Arkose Formation in the CBB therefore must be older (*c.* Carnian) than the current associations in the MZB's Pebbly Arkose Formation (*c.* Norian), and cannot be directly correlated.

Together, these data suggest that the MZB's Pebbly Arkose Formation and CBB's Pebbly Arkose Formation represent diachronous deposition of similar lithofacies across the basins that were not time-equivalent. However, other factors such as lack of age constraints between the basins, erosional loss or non-deposition, or the prevalence of different palaeoenvironments, might also affect faunal composition between the different rift basins. It is also important to acknowledge the function of palaeotopographic barriers, such as the Chizarira Block/Matusadona Block, which may restrict dispersal of flora, fauna and even sediment accumulation in these respective basins and sub-basins. This has implications for lithological correlatives in neighbouring Karoo-aged Basins.

The uppermost age considered for the Chete Formation (i.e. the Fine Red Marly Sandstone Member) underlying the Pebbly Arkose Formation is Carnian–Norian. Currently, the Fine Red Marly Sandstone Member has no age-diagnostic fossils, but it is unconformably overlain by the Pebbly Arkose Formation and has a lower gradational boundary with the *Dicroidium*-bearing Ripple Marked Flagstone Member. The former indicates an approximate Norian age and the latter a Carnian age. However, it is important to note that ages of *Dicroidium*-bearing floral assemblages have not been assessed using independent dating methods (such as radiometric dating of detrital or primary zircons). Furthermore, Bond & Falcon (1973) suggested that a simple correlation of the MKB's

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Molteno Formation to the Ripple Marked Flagstone Member may be misleading, and proposed that this flora might have been established in northern Zimbabwe earlier than in the MKB. They suggested that this was plausible based on the assumption that the MZB's lower palaeolatitudal position relative to the MKB might have favoured the earlier establishment of this flora (Bond & Falcon, 1973).

Globally, the oldest reported *Dicroidium* is potentially Olenekian in age (Sydney Basin; Retallack, 1977); in southern Africa, the oldest report of *Dicroidium* (*D. hughesii*) is from the *Cynognathus* B-subzone (*Trirachodon-Kannemeyeria* Subzone) of the Burgersdorp Formation, which is considered Middle Triassic (Anisian) in age (upper Beaufort Group; Anderson & Anderson, 1984; Anderson *et al.* 2020; Hancox *et al.* 2020). In recent years, the true age of South Africa's Early–Middle Triassic record, which plays a central role in global tetrapod biostratigraphy (Lucas, 1998), has been called into question by SHRIMP isotope dilution – thermal ionization mass spectrometry (ID-TIMS) dates retrieved from the Gondwanan record in Argentina (Ottone *et al.* 2014). However, these ages are disputed (see Lucas, 2018).

In the Karoo-aged basins of Zambia and Tanzania, units that can be correlated to the Chete Formation of the MZB were recently reviewed. Peecook *et al.* (2018) and Wynd *et al.* (2018) challenged the Anisian age that had previously been proposed for the upper Ntawere Formation (Luangwa Basin, Zambia) and the lower Lifua Member of the Manda Beds (Ruhuhu Basin, Tanzania; Catuneanu *et al.* 2005; Nesbitt *et al.* 2017) because their vertebrate assemblages show more similarities to the Ladinian and Carnian faunas of South America (Ezcurra *et al.* 2014; Ottone *et al.* 2014; Martinelli *et al.* 2017; Mancuso *et al.* 2018). Indeed, a *Dicroidium*-flora assemblage was previously reported for the upper Ntawere Formation and has been correlated with the Carnian Molteno Formation floras (Lacey & Smith 1972; Lacey 1974). In the same vein, the Middle Triassic age of the MKB *Cynognathus* C-subzone (*Cricodon-Ufudocyclops* Subzone; Hancox *et al.* 2020) was questioned by Ottone *et al.* (2014), who obtained SHRIMP U–Pb zircon dates indicating that the Puesto Viejo Group (which contains the *Cynognathus*/*Diademodon*-bearing Río Seco de la Quebrada Formation, Argentina) is Carnian in age. This would make the upper Burgersdorp Formation and the upper *Cricodon–Ufudocyclops* Subzone (Beaufort Group, MKB) more likely to be coeval with Carnian deposits in southern Gondwana (Hancox *et al.* 2020). The upper Burgersdorp Formation's *Dicroidium* flora could assist with this assessment, although they may be longer ranging than previously considered in the MKB (extending into the early Anisian; upper part of the *Trirachodon*–Kannemeyeria Subzone; Hancox *et al.* 2020). Conversely, this may also indicate that its vertebrate assemblage represents a longer period of time. Altogether, the lower Upper Karoo Group units from the MZB and CBB point to a Late Triassic age for these units that may have a lowermost age range (i.e. Escarpment Grit/Ripple Marked Flagstone members and Alternations Member, respectively) that overlaps with the older units in the Luangwa and Ruhuhu basins. A Middle Triassic – Carnian age for the MZB's Chete Formation is therefore plausible, and a Late Triassic – Early Jurassic age for the Pebbly Arkose and Forest Sandstone formations is reinforced by recent palaeontological finds.

6. Conclusion

The Pebbly Arkose Formation contains a diverse assemblage of aquatic and terrestrial fauna that are not currently known from other Karoo-aged basins but have global significance. Palaeoenvironmentally, the Pebbly Arkose Formation and its associated fauna and flora indicate a climate that experienced seasonality with wet-warm conditions succeeded by periodic (short-term) drying. Our review of the Upper Karoo Group provides a conservative age range of ?Carnian–Toarcian (i.e. Chete Formation–Batoka Basalt) for the exposures along the southern shoreline of Lake Kariba. However, an older Middle Triassic age cannot be ruled out for the Chete Formation. Finally, we caution against using uncritical comparisons of lithological similarities and stratigraphic position as a means of correlation between Karoo-aged basins, as it is likely that many lithologically similar units are diachronous (e.g. MZB Pebbly Arkose Formation versus CBB Pebbly Arkose Formation). This has major implications for correlations between neighbouring Karoo-aged Basins (i.e. Cabora Bassa, Luangwa and Ruhuhu basins of Zimbabwe, Zambia and Tanzania, respectively) where lithostratigraphy has been the primary means of correlation because of their dissimilar fossil-bearing assemblages and the current lack of radiometric dates.

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References

Ait-Kaci Ahmed A (2018) The geology of the country between Chireya and Goredema, Gokwe North and Gokwe South Districts. *Zimbabwe Geological Survey Bulletin* **105**, 1–86.

Alexander J and Leeder MR (1987) Active tectonic control on alluvial architecture. In *Recent Developments in Fluvial Sedimentology* (eds FG Ethridge, RM Flores and MD Harvey), pp. 243–52. Society of Economic Paleontologists and Mineralogists, Tulsa, Special Publication no. 39.

Anderson HM and Anderson JM (1970) A preliminary review of the biostratigraphy of the uppermost Permian, Triassic and lowermost Jurassic of Gondwanaland. *Palaeontologia Africana* **13**, 39–59.

Anderson JM and Anderson HM (1983) *Palaeoflora of Southern Africa, Molteno Formation (Triassic) Part 1. Introduction; Part 2. Dicroidium.* Rotterdam: Balkema, 227 pp.

Anderson JM and Anderson HM (1984) The fossil content of the Upper Triassic Molteno Formation, South Africa. *Palaeontologia Africana* **25**, 39–59.

Anderson HM, Barbacka M, Bamford MK, Holmes WK and Anderson JM (2020) *Dicroidium* (foliage) and affiliated wood Part 3 of a reassessment of Gondwana Triassic plant genera and a reclassification of some previously attributed. *Alcheringa* **44**, 64–92.

Attridge JA (1963) The Upper Triassic Karroo deposits and fauna of southern Rhodesia. *South African Journal of Science* **59**, 242–47.

Bamford MK (2004) Diversity of the woody vegetation of Gondwanan Southern Africa. *Gondwana Research* **7**, 153–64.

Banks NL, Bardwell KA and Musiwa S (1995) Karoo rift basins of the Luangwa Valley, Zambia. In *Hydrocarbon Habitat in Rift Basins* (ed. JJ Lambiase), pp. 285–95. Geological Society of London, Special Publication no. 80.

Barale G, Bamford MK, Gomez B, Broderick TJ, Raath MA and Cadman A (2006) A fossil peat deposit from the Late Triassic (Carnian) of Zimbabwe with preserved cuticle of Pteridospermopsida and Ginkgoales, and its geological setting. *Palaeontologia Africana* **41**, 89–100.

Barber B (2018) Review of the geology and summary of the known fossil fuel potential of the Karoo and younger rocks in Zimbabwe. *Zimbabwe Geological Survey Bulletin* **107**, 1–99.

Barbolini N, Bamford MK and Tolan S (2016) Permo-Triassic palynology and palaeobotany of Zambia: a review. *Palaeontologia Africana* **50**, 18–30.

Barrett PM, Chapelle KEJ, Staunton CK, Botha J and Choiniere JN (2019) Postcranial osteology of the neotype specimen *Massospondylus carinatus* Owen, 1854 (Dinosauria: Sauropodomorpha) from the upper Elliot formation of South Africa. *Palaeontologia Africana* **53**, 114–78.

Barrett PM, Sciscio L, Viglietti PA, Broderick TJ, Suarez CA, Sharman GR, Jones AS, Munyikwa D, Edwards SF, Chapelle KEJ, Dollman KN, Zondo M and Choiniere JN (2020) The age of the Tashinga Formation (Karoo Supergroup) in the Mid-Zambezi Basin, Zimbabwe and the first phytosaur from sub-Saharan Africa. *Gondwana Research* **80**, 445–60.

Bond G (1952) The Karroo System in Southern Rhodesia. In *Symposium of Gondwana Stratigraphy, International Geological Congress* (ed. Anonymous), pp. 209–222. Algiers: International Union of Geological Sciences.

Bond G (1955) A note on dinosaur remains from the Forest Sandstone (Upper Karroo). *Occasional Papers of the National Museum of Rhodesia* **2**, 795–800.

Bond G (1967) A review of Karroo sedimentation and lithology in Southern Rhodesia. In *IUGS Reviews Prepared for the 1st Symposium on Gondwana Stratigraphy* (ed Anonymous), pp. 173–195. Haarlem, Netherlands: International Union of Geological Sciences.

Bond G (1972) Milestones in Rhodesian palaeontology (1901–1971). *South African Journal of Geology* **75**, 149–58.

Bond G (1974) The stratigraphic distribution of plant and animal macro-fossils in the Karoo System of the Mid-Zambezi region. *Arnoldia* **7**, 1–6.

Bond G and Falcon R (1973) The palaeontology of Rhodesia, with a section on the palynology of the Middle Zambezi Valley. *Rhodesia Geological Survey Bulletin* **70**, 1–121.

Bond G, Wilson JF and Raath MA (1970) Upper Karroo pillow lava and a new sauropod horizon in Rhodesia. *Nature* **227**, 1339–39.

Bordy EM, Abrahams M, Sharman GR, Viglietti PA, Benson RBJ, Mcphee BW, Barrett PM, Sciscio L, Condon D, Mundil R, Rademan Z, Jinnah Z, Clark JM, Suarez CA, Chapelle KEJ and Choiniere JN (2020) A chronostratigraphic framework for the upper Stormberg Group: implications for the Triassic-Jurassic boundary in southern Africa. *Earth-Science Reviews* **203**, 103120, doi: 10.1016/j.earscirev.2020.103120.

Bordy EM and Catuneanu O (2001) Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. *Journal of African Earth Sciences* **33**, 605–29.

Bordy EM and Catuneanu O (2002a) Sedimentology and palaeontology of upper Karoo aeolian strata (Early Jurassic) in the Tuli Basin, South Africa. *Journal of African Earth Sciences* **35**, 301–14.

Bordy EM and Catuneanu O (2002b) Sedimentology of the lower Karoo Supergroup fluvial strata in the Tuli Basin, South Africa. *Journal of African Earth Sciences* **35**, 503–21.

Bordy EM, Hancox PJ and Rubidge BS (2004) A description of the sedimentology and palaeontology of the Late Triassic–Early Jurassic Elliot Formation in Lesotho. *Palaeontologia Africana* **40**, 43–58.

Brassey JM (1951) Geological map of the country between the Bumi and Sanyati rivers, Zambezi Valley. *Southern Rhodesia Geological Survey*, published map, scale 1:100,000.

Broderick TJ (1984) A geological interpretation across a portion of the mid-Zambezi Valley lying between the Mkanga and Hunyani Rivers, Guruve District. *Annals of the Geological Survey of Zimbabwe* **9**, 59–79.

Broderick TJ (1990) An interpretation of the geology of the Cabora Bassa Basin, mid-Zambezi Valley. *Annals of the Geological Survey of Zimbabwe* **14**, 1–11.

Catuneanu O, Wopfner H, Eriksson PG, Cairncross B, Rubidge BS, Smith RMH and Hancox PJ (2005) The Karoo basins of south-central Africa. *Journal of African Earth Sciences* **43**, 211–53.

Cooper MR (1981) The prosauropod dinosaur *Massospondylus carinatus* Owen from Zimbabwe: its biology, mode of life and phylogenetic significance. *Occasional Papers National Museums and Monuments of Zimbabwe* **6**, 690–840.

Cooper MR (1982) A mid-Permian to earliest Jurassic tetrapod biostratigraphy and its significance. *Arnoldia* **9**, 77–104.

Cooper MR (1984) A reassessment of *Vulcanodon karibaensis* Raath (Dinosauria: Saurischia) and the origin of the Sauropoda. *Palaeontologia Africana* **25**, 203–31.

Cox CB (1969) Two new dicynodonts from the Triassic Ntawere Formation, Zambia. *Bulletin of the British Museum (Natural History), Geology* **17**, 257–94.

Cox LR (1932) Lamellibranchia from the Karroo beds of the Ruhuhu coalfields, Tanganyika Territory. *Quarterly Journal of the Geological Society of London* **88**, 623–33.

d'Engelbronner ER (1996) New palynological data from Karoo sediments, Mana Pools basin, northern Zimbabwe. *Journal of African Earth Sciences* **23**, 17–30.

Datta D, Ray S and Bandyopadhyay S (2019) Cranial morphology of a new phytosaur (Diapsida, Archosauria) from the Upper Triassic of India: implications for phytosaur phylogeny and biostratigraphy. *Papers in Palaeontology*, published online 5 December 2019, doi: 10.1002/spp2.1292.

Dixey F (1937) The geology of part of the upper Luangwa Valley, north-eastern Rhodesia. *Quarterly Journal of the Geological Society of London* **93**, 52–76.

Drysdall AR and Kitching JW (1962) The Karroo succession of the upper Luangwa Valley, northern Rhodesia. *South African Journal of Geology* **65**, 75–91.

Drysdall AR and Kitching JW (1963) A re-examination of the Karroo succession and fossil localities of part of the Upper Luangwa Valley. *Northern Rhodesia Geological Survey Memoir* **1**, 1–62.

Duncan RA, Hooper PR, Rehacek J, Marsh J and Duncan AR (1997) The timing and duration of the Karoo igneous event, southern Gondwana. *Journal of Geophysical Research: Solid Earth* **102**, 18127–38.

Einsele G (2000) *Sedimentary Basins: Evolution, Facies, and Sediment Budget*, second edition. Berlin and Heidelberg: Springer-Verlag, 792 pp.

Ezcurra MD, Trotteyn MJ, Fiorelli LE, Von Baczko MB, Taborda JR, Iberlucea M and Desojo JB (2014) The oldest rhynchosaur from Argentina: a Middle Triassic rhynchosaurid from the Chañares Formation (Ischigualasto–Villa Unión Basin, La Rioja Province). *Paläontologische Zeitschrift* **88**, 453–60.

Fielding CR and Alexander J (2001) Fossil trees in ancient fluvial channel deposits: evidence of seasonal and longer-term climatic variability. *Palaeogeography, Palaeoclimatology, Palaeoecology* **170**, 59–80.

Gair HS (1959) The Karroo System and coal resources of the Gwembe District, north-east section. *Bulletin of Geological Survey of Northern Rhodesia* **1**, 1–88.

Gow CE and Raath MA (1977) Fossil vertebrate studies in Rhodesia: sphenodontid remains from the Upper Triassic of Rhodesia. *Palaeontologia Africana* **20**, 121–22.

Grant D (1970) A red-bed facies in the Upper Karoo of the Middle Zambezi Valley and its lithological correlation. *Detritus* **5**, 21–26.

Hancox PJ, Neveling J and Rubidge BS (2020) Biostratigraphy of the *Cynognathus* Assemblage Zone (Beaufort Group, Karoo Supergroup), South Africa. *South African Journal Geology* **123**, 217–38.

Hiller K and Shoko U (1995) The hydrocarbon potential of the Zambezi Valley in Zimbabwe. *Zimbabwe Geological Survey, Special Paper*, 1–27.

Irmis RB (2005) The vertebrate fauna of the Upper Triassic Chinle Formation in northern Arizona. *Mesa Southwest Museum Bulletin* 9, 63–88.

Johnson MR, Van Vuuren CJ, Hegenberger WF, Key R and Shoko U (1996) Stratigraphy of the Karoo Supergroup in southern Africa: an overview. *Journal of African Earth Sciences* **23**, 3–15.

Jones DL, Duncan RA, Briden JC, Randall DE and Macniocaill C (2001) Age of the Batoka basalts, northern Zimbabwe, and the duration of Karoo Large

Igneous Province magmatism. *Geochemistry, Geophysics, Geosystems* **2**, 2000GC000110, doi: 10.1029/2000GC000110.

Jourdan F, Féraud G, Bertrand H, Watkeys MK and Renne PR (2007) Distinct brief major events in the Karoo large igneous province clarified by new $^{40}Ar/^{39}Ar$ ages on the Lesotho basalts. *Lithos* **98**, 195–209.

Khadkikar AS, Merh SS, Malik JN and Chamyal LS (1998) Calcretes in semi-arid alluvial systems: formative pathways and sinks. *Sedimentary Geology* **116**, 251–60.

Kitching JW and Raath MA (1984) Fossils from the Elliot and Clarens formations (Karoo sequence) of the northeastern Cape, Orange Free State, and Lesotho, and a suggested biozonation based on tetrapods. *Palaeontologia Africana* **25**, 111–25.

Knoll F (2004) Review of the tetrapod fauna of the "Lower Stormberg Group" of the main Karoo Basin (southern Africa): implication for the age of the Lower Elliot Formation. *Bulletin de la Societe géologique de France* **175**, 73–83.

Knoll F (2005) The tetrapod fauna of the Upper Elliot and Clarens formations in the main Karoo Basin (South Africa and Lesotho). *Bulletin de la Société géologique de France*, **176**, 81–91.

Kraus MJ (1999) Paleosols in clastic sedimentary rocks: their geologic applications. *Earth-Science Reviews* **47**, 41–70.

Lacey WS (1961) Studies in the Karroo floras of Rhodesia and Nyasaland. Part 1. A geological account of the plant-bearing deposits. *Proceedings of Transactions of the Rhodesian Science Association* **49**, 26–53.

Lacey WS (1970) Some new records of fossil plants in the Molteno Stage of Rhodesia. *Arnoldia* **4**, 1–4.

Lacey WS (1974) Some new African Gondwana plants. *Symposium of Morphological and Stratigraphical Paleobotany: Papers* **2**, 34–41.

Lacey WS (1976) Further observations on the Molteno flora of Rhodesia. *Arnoldia* **7**, 1–14.

Lacey WS and Smith CS (1972) Studies in Karroo Floras. Part 4. Karroo floras from the Upper Luangwa Valley, Zambia. In *Proceedings of the Second International Gondwana Symposium, South Africa*, pp. 571–74.

Lepper J (1992) Lower Karoo in the Mid-Zambezi Basin (Zimbabwe). *Geologisches Jahrbuch. Reihe B, Regionale Geologie Ausland* **82**, 3–38.

Lepper J, Raath MA and Rubidge BS (2000) A diverse dinocephalian fauna from Zimbabwe. *South African Journal of Science* **96**, 403–05.

Lucas SG (1998) Global Triassic tetrapod biostratigraphy and biochronology. *Palaeogeography, Palaeoclimatology, Palaeoecology* **143**, 347–84.

Lucas SG (2018) The Late Triassic Timescale. In *The Late Triassic World: Earth in a Time of Transition* (ed LH Tanner), pp. 1–25. Cham: Springer, Topics in Geobiology, no. 46.

Lucas SG and Tanner LH (2018) The missing mass extinction at the Triassic–Jurassic boundary. In *The Late Triassic World: Earth in a Time of Transition* (ed LH Tanner), pp. 721–85. Cham: Springer, Topics in Geobiology, no. 46.

Macgregor AM (1941) Geology of the Mafungabusi Gold Belt. *Southern Rhodesia Geological Survey Bulletin* **35**, 1–26.

Mancuso AC, Benavente CA, Previtera E, Arcucci AB and Irmis RB (2018) Carnivore coprolites from the lower Carnian (Upper Triassic) Chañares Formation, northwestern Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* **489**, 15–28.

Marsh A and Jackson A (1974) The geology of the area south west of the Bumi Hills. *Detritus* **9**, 15–20.

Martinelli AG, Eltink E, Da Rosa ÁA and Langer MC (2017) A new cynodont from the Santa Maria formation, south Brazil, improves Late Triassic probainognathian diversity. *Papers in Palaeontology* **3**, 401–23.

Martz JW, Irmis RB and Milner AR (2014) Lithostratigraphy and biostratigraphy of the Chinle Formation (Upper Triassic) in southern Lisbon Valley, southeastern Utah. *Utah Geological Association Publications* **43**, 397–448.

Martz J, Kirkland J, Milner A, Parker W and Santucci V (2017) Upper Triassic lithostratigraphy, depositional systems, and vertebrate paleontology across southern Utah. *Geology of the Intermountain West* **4**, 99–180, doi:10.31711/giw.v4.pp99-180.

Miall AD (1977) A review of the braided-river depositional environment. *Earth-Science Reviews* **13**, 1–62.

Miall AD (1996) *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology*. Berlin: Springer-Verlag, 582 pp.

Miall AD (2006) *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology*. Heidelberg: Springer-Verlag, 582 pp.

Miall AD (2014) *Fluvial Depositional Systems*. Heidelberg: Springer International, Springer-Verlag, 316 pp.

Moulin M, Fluteau F, Courtillot V, Marsh J, Delpech G, Quidelleur X and Gérard M (2017) Eruptive history of the Karoo lava flows and their impact on Early Jurassic environmental change. *Journal of Geophysical Research: Solid Earth* **122**, 738–72.

Nesbitt SJ, Butler RJ, Ezcurra MD, Barrett PM, Stocker MR, Angielczyk KD, Smith RMH, Sidor CA, Niedźwiedzki G, Sennikov AG and Charig AJ (2017) The earliest bird-line archosaurs and the assembly of the dinosaur body plan. *Nature* **544**, 484–87.

Nyambe IA (1999) Tectonic and climatic controls on sedimentation during deposition of the Sinakumbe Group and Karoo Supergroup, in the mid-Zambezi Valley Basin, southern Zambia. *Journal of African Earth Sciences* **28**, 443–63.

Nyambe IA and Utting J (1997) Stratigraphy and palynostratigraphy, Karoo Supergroup (Permian and Triassic), mid-Zambezi Valley, southern Zambia. *Journal of African Earth Sciences* **24**, 563–83.

Oesterlen PM (1998) The geology of the Dande West area Lower Zambezi Valley. *Bulletin of the Zimbabwe Geological Survey* **98**, 1–85.

Oesterlen PM (1999) Some new results from the Mid-Zambezi Basin. *Annals of the Zimbabwe Geological Survey* **19**, 16–20.

Oesterlen PM (2003) Geological summary of the Karoo basins of Zimbabwe. *Annals of the Zimbabwe Geological Survey* **21**, 1–20.

Oesterlen PM and Millsteed BD (1994) Lithostratigraphy, palaeontology, and sedimentary environments of the western Cabora Bassa Basin, lower Zambezi Valley, Zimbabwe. *South African Journal of Geology* **97**, 205–24.

Ottone EG, Monti M, Marsicano CA, Marcelo S, Naipauer M, Armstrong R and Mancuso AC (2014) A new Late Triassic age for the Puesto Viejo Group (San Rafael depocenter, Argentina): SHRIMP U–Pb zircon dating and biostratigraphic correlations across southern Gondwana. *Journal of South American Earth Sciences* **56**, 186–99.

Parker WG and Irmis RB (2005) Advances in Late Triassic vertebrate paleontology based on new material from Petrified Forest National Park, Arizona. *New Mexico Museum of Natural History and Science, Bulletin* **29**, 45–58.

Peecook BR, Steyer JS, Tabor NJ and Smith RMH (2018) Updated geology and vertebrate paleontology of the Triassic Ntawere Formation of northeastern Zambia, with special emphasis on the archosauromorphs. *Memoir of the Society of Vertebrate Paleontology* **17**, 8–38.

Raath MA (1967) Notes on the occurrence of fossil bone in the Sipolilo Musengezi Area, Rhodesia. *Detritus* **2**, 18–20.

Raath MA (1969) A new coelurosaurian dinosaur from the Forest Sandstone of Rhodesia. *Arnoldia* **4**, 1–25.

Raath MA (1972a) The succession of life in the Rhodesian Gondwana period. *Detritus* **7**, 11–19.

Raath MA (1972b) Fossil vertebrate studies in Rhodesia: a new dinosaur (Reptilia: Saurischia) from near the Trias-Jurassic boundary. *Arnoldia* **30**, 1–37.

Raath MA (1981) A protosuchid crocodilian from the Forest Sandstone Formation (Upper Karoo) of Zimbabwe. *Palaeontologia Africana* **24**, 169–74.

Raath MA, Oesterlen PM and Kitching JW (1992) First record of Triassic Rhynchosauria (Reptilia: Diapsida) from the Lower Zambezi Valley, Zimbabwe. *Palaeontologia Africana* **29**, 1–10.

Raath MA, Smith CC and Bond G (1970) A new Upper Karoo fossil locality on the lower Angwa River, Sipolilo District, Rhodesia. *Arnoldia* **4**(35), 1–10.

Rayfield EJ, Barrett PM and Milner AR (2009) Utility and validity of Middle and Late Triassic 'land vertebrate faunachrons'. *Journal of Vertebrate Paleontology* **29**, 80–87.

Retallack GJ (1977) Reconstructing Triassic vegetation of eastern Australasia: a new approach for the biostratigraphy of Gondwanaland. *Alcheringa* **1**, 247–78.

Retallack GJ (2001) *Soils of the Past: An Introduction to Paleopedology*. Oxford: Blackwell Science.

Ridgway KD and Decelles PG (1993) Stream-dominated alluvial fan and lacustrine depositional systems in Cenozoic strike-slip basins, Denali fault system, Yukon Territory, Canada. *Sedimentology* **40**, 645–66.

Rogers RR, Rogers KC, Munyikwa D, Terry RC and Singer BS (2004) Sedimentology and taphonomy of the upper Karoo-equivalent Mpandi

https://doi.org/10.1017/S0016756820001089 Published online by Cambridge University Press

Formation in the Tuli Basin of Zimbabwe, with a new $^{40}Ar/^{39}Ar$ age for the Tuli basalts. *Journal of African Earth Sciences* **40**, 147–61.

Roopnarine PD, Angielczyk KD, Olroyd SL, Nesbitt SJ, Botha-Brink J, Peecook BR, Day MO and Smith RMH (2018) Comparative ecological dynamics of Permian-Triassic communities from the Karoo, Luangwa, and Ruhuhu basins of southern Africa. *Memoir of the Society of Vertebrate Paleontology* **17**, 254–72.

Rubidge BS (2005) 27th Du Toit Memorial Lecture: re-uniting lost continents– fossil reptiles from the ancient Karoo and their wanderlust. *South African Journal of Geology* **108**, 135–72.

Rust IC (1973) Tectonic and sedimentary framework of Gondwana Basins in Southern Africa. In *Gondwana Geology* (ed. KSW Campbell), pp. 537–64. Canberra: Australian National University Press.

Sciscio L and Bordy EM (2016) Palaeoclimatic conditions in the Late Triassic-Early Jurassic of southern Africa: a geochemical assessment of the Elliot Formation. *Journal of African Earth Sciences* **119**, 102–19.

Sidor CA (2011) New information on the Middle Triassic cynodonts of Tanzania and Zambia. *Ameghiniana* **48**, R113.

Sidor CA, Angielczyk KD, Smith RMH, Goulding AK, Nesbitt SJ, Peecook BR, Steyer JS and Tolan S (2014) Tapinocephalids (Therapsida, Dinocephalia) from the Permian Madumabisa Mudstone Formation (Lower Karoo, Mid-Zambezi Basin) of southern Zambia. *Journal of Vertebrate Paleontology* **34**, 980–86.

Sidor CA and Hopson JA (2018) *Cricodon metabolus* (Cynodontia: Gomphodontia) from the Triassic Ntawere Formation of northeastern Zambia: patterns of tooth replacement and a systematic review of the Trirachodontidae. *Memoir of the Society of Vertebrate Paleontology* **17**, 39–64.

Smith R and Kitching J (1997) Sedimentology and vertebrate taphonomy of the *Tritylodon* acme zone: a reworked palaeosol in the Lower Jurassic Elliot Formation, Karoo Supergroup, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* **131**, 29–50.

Smith RMH, Eriksson PG and Botha WJ (1993) A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of southern Africa. *Journal of African Earth Sciences* **16**, 143–69.

Smith RMH, Sidor CA, Angielczyk KD, Nesbitt SJ and Tabor NJ (2018) Taphonomy and paleoenvironments of Middle Triassic bone accumulations in the Lifua Member of the Manda Beds, Songea Group (Ruhuhu Basin), Tanzania. *Memoir of the Society of Vertebrate Paleontology* **17**, 65–79.

Stagman JG (1978) An outline of the geology of Rhodesia. *Rhodesia Geological Survey Bulletin* **80**, 1–126.

Stocker MR and Butler RJ (2013) Phytosauria. In *Anatomy, Phylogeny and Palaeobiology of Early Archosaurs and their Kin* (eds SJ Nesbitt, JB Desojo and RB Irmis), pp. 91–117. Geological Society of London, Special Publication no. 379.

Stowe CW (1974) Notes on the Karoo succession at Sinamwenda, Kariba. *Detritus* **9**, 20–24.

Sutton ER (1979) The geology of the Mafungabusi Area. *Rhodesia Geological Survey Bulletin* **81**, 1–318.

Tanner LH, Lucas SG and Alonso-Zarza AM (2006) Calcareous paleosols of the Upper Triassic Chinle Group, Four Corners region, southwestern United States: climatic implications. *Geological Society of America, Special Papers* **416**, 53–74.

Tavener-Smith R (1958) The development of the Mid-Zambezi Valley in Northern Rhodesia since early Karroo times. *Geological Magazine* **95**, 105–18.

Tavener-Smith R (1960) The Karroo System and coal resources of the Gwembe District. South-western Section. *Northern Rhodesia Geological Survey Bulletin* **4**, 1–84.

Tavener-Smith R (1962) Karroo sedimentation in a part of the Mid-Zambezi Valley. *South African Journal of Geology* **65**, 43–74.

Taylor AM and Goldring R (1993) Description and analysis of bioturbation and ichnofabric. *Journal of the Geological Society* **150**, 141–48.

Thompson AO (1975) The Karoo rocks in the Mazunga Area, Beitbridge District. *Rhodesia Geological Survey Bulletin, Short Report* **40**, 1–79.

Viglietti PA, Barrett PM, Broderick TJ, Munyikwa D, MacNiven R, Broderick L, Chapelle K, Glynn D, Edwards S, Zondo M, Broderick P and Choiniere JN (2018) Stratigraphy of the *Vulcanodon* type locality and its implications for regional correlations within the Karoo Supergroup. *Journal of African Earth Sciences* **137**, 149–56.

Viglietti PA, McPhee BW, Bordy EM, Sciscio L, Barrett PM, Benson RBJ, Wills S, Chapelle KEJ, Dollman KN, Mdekazi C and Choiniere JN (2020a) Biostratigraphy of the *Massospondylus* Assemblage Zone (Stormberg Group, Karoo Supergroup), South Africa. *South African Journal of Geology* **123**, 249–62.

Viglietti PA, McPhee BW, Bordy EM, Sciscio L, Barrett PM, Benson RBJ, Wills S, Tolchard F and Choiniere JN (2020b) Biostratigraphy of the *Scalenodontoides* Assemblage Zone (Stormberg Group, Karoo Supergroup), South Africa. *South African Journal of Geology* **123**, 239–48.

Visser JNJ (1984) A review of the Stormberg Group and Drakensberg volcanics in southern Africa. *Palaeontologia Africana* **25**, 5–27.

Watkeys MK (1979) Explanation of the geological map of the country west of Beitbridge. *Rhodesia Geological Survey Short Report* **45**, 62–65.

Watson RLA (1960) The geology and coal resources of the country around Wankie, Southern Rhodesia. *Southern Rhodesia Geological Survey Bulletin* **48**, 1–55.

Wynd BM, Sidor CA, Whitney MR and Peecook BR (2018) The first occurrence of *Cynognathus* in Tanzania and Zambia, with biostratigraphic implications for the age of Triassic strata in southern Pangea. *Memoir of the Society of Vertebrate Paleontology* **17**, 228–39.

Zerfass H, Chemale F JR, Schultz CL and Lavina E (2004) Tectonics and sedimentation in southern South America during Triassic. *Sedimentary Geology* **166**, 265–92.