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Stratigraphy of the *Vulcanodon* type locality and its implications for regional correlations within the Karoo Supergroup

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A B S T R A C T

Vulcanodon karibaensis is one of the earliest-branching members of Sauropoda and a forerunner of the largest terrestrial animals ever to have lived. Its stratigraphic position has most recently been given as Toarcian (latest Early Jurassic), making it a contemporary of the northern African taxon *Tazoudasaurus*, but some literature suggests that it may be considerably older. This uncertainty obscures our understanding of the timing of major sauropod evolutionary events, such as the onset of the major body size increases that characterize the clade. To improve constraints on the geological age of *Vulcanodon*, we revisited the type locality and collected new, higher precision stratigraphic and sedimentological data. Our results show that *Vulcanodon* is from lower in the stratigraphy than previously documented, lying within the uppermost Forest Sandstone rather than the interbedded sandstones of the Batoka Basalt Formation. Sedimentological data suggest that the upper part of the Forest Sandstone correlates with the Clarens Formation of the main Karoo Basin, implying that *Vulcanodon* is likely Sinemurian–Pliensbachian in age, and potentially ~10–15 million years (Ma) older than previously thought.

1. Introduction

Lake Kariba, one the world's largest artificial reservoirs, lies within the northeastern end of the Mid-Zambezi Basin, an en-echelon rift basin created by Permo-Carboniferous crustal extension and Triassic strike-slip movements which preserves sedimentary deposits that correlate with the main Karoo Basin's Dwyka, Ecca, and Beaufort groups (the Mid-Zambezi's Lower Karoo Group), and the Stormberg and Drakensberg groups (the Mid-Zambezi's Upper Karoo Group) (Smith et al., 1993; Johnson et al., 1996; Zerfass et al., 2004; Catuneanu et al., 2005) (Fig. 1).

The type specimen of the early sauropod dinosaur *Vulcanodon karibaensis* was discovered on Island 126/127 in Lake Kariba in 1969 by harbourmaster Mr. A. Gibson, who saw it exposed in a sandstone layer within a cliff face on the north-western coast of the island (Raath, 1972). He notified Professor Geoffrey Bond (of the University of Rhodesia, now the University of Zimbabwe), who later collected the material with his then student Mike Raath during a series of fieldtrips in 1969–1970 (Raath, 1972). Island 126/127 lies north of the south-central shoreline of Lake Kariba and consists of sediments and lavas assigned to the Mid-Zambezi Basin's

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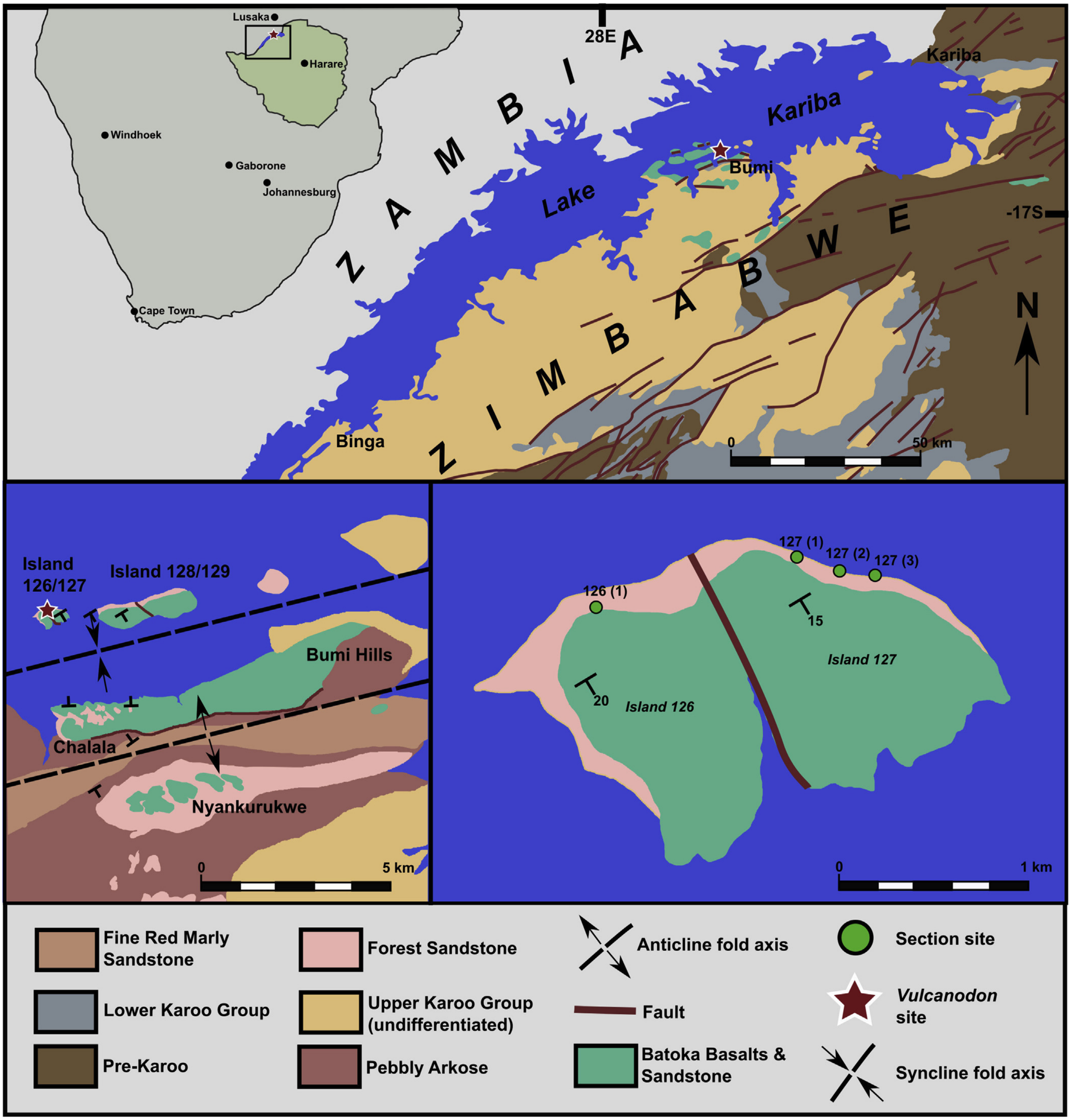

Fig. 1. (Top) Map of Lake Kariba showing the regional geology of the Zimbabwean side of the lake. Star indicates the position of Island 126/127 and the *Vulcanodon karibaensis* site under investigation. (bottom left) Close-up of the local geology near Island 126/127, including faults and local structural geology. (bottom right) Island 126/127 showing the position of the four vertical sections measured. Geological map adapted from Wahl (1971), Marsh and Jackson (1974) and Tim Broderick's field observations (Zimbabwe Geological Survey).

uppermost Upper Karoo Group, namely deposits of both the Forest Sandstone and Batoka Basalt formations (Fig. 1).

The *Vulcanodon* type locality was interpreted by Bond et al. (1970) and Raath (1972) as within a sandstone layer that was sandwiched stratigraphically between two lava flows within the Batoka Basalt Formation, but at the time the age of these lavas was unknown. Following contemporary accounts for the ages of these units, these authors proposed that the sandstones and lavas of the Bakota Basalt Formation were deposited close to the Triassic/Jurassic boundary, probably within the lowermost Jurassic, and they inferred a maximum Hettangian age for *Vulcanodon*. This age determination was followed subsequently, but without further comment, by various other authors (e.g. Weishampel et al., 2004). However, subsequent Ar–Ar dating of lava flows within the Batoka Basalt Formation indicated ages between ~180 and 179 Ma (Jones et al., 2001), which is up to 4 Ma younger than those of the Drakensberg Group in the main Karoo Basin (Duncan et al., 1997). These new radioisotopic dates were used by Yates et al. (2004) to propose a revised age for *Vulcanodon*, placing it in the Toarcian, after the initiation of widespread volcanism within the region.

Bond (in Wahl, 1971) referred to the Bakota Basalt Formation lavas locally as the 'Big Porphyry' because they contain many large (>4 mm) feldspar phenocrysts and amygdales (~10–30 cm across). Bond et al. (1970) identified pillow basalts within this unit on neighboring islands, and Wahl (1971) noted the presence of the Forest Sandstone below the Big Porphyry. The 'Big Porphyry' was later given the formal name Lower Basalt (the lowest unit in the Batoka Basalt Formation) by Marsh and Jackson (1974), who confirmed the presence of the Forest Sandstone and the *Vulcanodon*-bearing horizon below the Lower Basalt on Island 126/127. However, Bond et al.'s (1970), and later Raath's (1972), initial stratigraphic scheme for the *Vulcanodon* site (situated within the Batoka Basalt Formation) has been more frequently cited in the dinosaur literature (Yates et al., 2004; Allain and Aquesbi, 2008), even though Cooper (1984) mentioned the Forest Sandstone as the source of this material. In his reassessment of *Vulcanodon*, Cooper (1984) provided no evidence of his stated stratigraphic position, although he did cite Marsh and Jackson's (1974) work in a different context.

In 2016, Lake Kariba posted record-low lake levels, exposing shoreline features that had not been exposed for more than 20 years. Our research team used this window of opportunity to prospect the lake shoreline, reinvestigating historical fossil localities and searching for new ones. The aim of this paper is to present a reassessment of the stratigraphic position of *Vulcanodon*, based on direct field observations from Island 126/127. Given that *Vulcanodon* is regarded as one of the oldest known sauropod taxa, determining its exact stratigraphic position is of great importance in unravelling sauropod origins, when and how they diverged from non-sauropod sauropodomorphs, and whether they overlapped extensively in time and space with the latter.

2. Methods

To revise the stratigraphy and sedimentology of the type locality of *Vulcanodon karibaensis*, we measured four stratigraphic sections along the northern perimeter of Island 126/127, where gently south-dipping (~15–20°) strata were exposed (see Fig. 2 and supplementary information). This was done using a Jacob's staff and Abney level. Different lithologies were identified, traced out laterally, and given a distinct facies association. The stratigraphic position of new fossil material was also identified, and its facies association documented. These four sections were then used to create a single composite section for the island, including the *Vulcanodon* type locality (Fig. 3). We also incorporated structural observations from Island 126/127, as well as other exposed outcrop across the Lake Kariba shoreline, to critically test that we had obtained the correct stratigraphic relationships, particularly between the various basalt layers (Fig. 1).

3. Results

Our four measured sections documented a total of 43 m of vertical strata exposed on Island 126/127. Within this interval, five facies associations (lettered A to E; Fig. 3) were documented, one of which is an igneous deposit. Using these sections, we could update the stratigraphic position of *Vulcanodon karibaensis* (Fig. 3).

Facies A (FA) is the lowermost facies located in this study and is represented by a red-brown fine-grained sandstone ~5 m in thickness. The sandstone is soft in outcrop and normally structureless, except for laterally discontinuous lenses of bioturbated, poorly sorted sandstone that show some horizontal lamination.

Facies B (FB) represents a silty sandstone. This unit overlies FA, and this contact is gradational. The maximum thickness for this unit is ~15 m, but it outcrops at different stratigraphic levels on the measured sections. Mottled bioturbated horizons are common, as are pale olive horizons. These bioturbation structures are infilled with siltstone and appear to be invertebrate burrows. Carbonate nodules, plant fossil fragments with black preservation, and fossil rootlets are also encountered, along with rare, isolated, but identifiable, vertebrate material (including specimens referable to a massospondylid sauropodomorph, none of which is diagnostic to genus level (Fig. 2). This sandstone is not easily weathered in outcrop and forms steep-to-near-vertical exposure. FB also underlies the Lower Basalt (FE) on Island 126/127, and does so over the entire field area.

Facies C (FC) is a light grey, coarse grained (clasts ~2 mm), trough cross-bedded sandstone that is ~8 m in thickness. It sharply overlies and underlies FB. FC contains multiple erosional boundaries, often including an intraformational lag comprising pebble (~4 mm) and cobble-sized (>64 mm) clasts of mud and sandstone. These lags sometimes contain fragmentary and undiagnostic bone material.

Facies D (FD) is a medium to-coarse-grained (but well-sorted) sandstone that is ~8 m in thickness. FB underlies and overlies this unit (and in some places interbeds FD), and in all cases the contacts are sharp. FD contains large (>1 m) crossbeds that sometimes contain a black mineral preservation concentrated on foreset boundaries, has a distinctive, loosely compacted texture, and forms steep unstable cliffs in outcrop (Fig. 2). Although the exact location of the *Vulcanodon* material could not be determined, historic accounts (Marsh and Jackson, 1974) point to the *Vulcanodon* quarry being located within FD on Island 126/127.

Finally, Facies E (FE) represents the Lower Basalt of the Batoka Basalt Formation. On Island 126/127 it is highly porphyritic and comprises large (4–10 mm) feldspar phenocrysts and amygdales (10–30 cm), but on nearby islands the Lower Basalt also contains pillow basalts, and interbedded sandstones and basalts that lie stratigraphically above this unit. It overlies FD, but a thin (<5 m) bed of FB contacts FE sharply and includes a 1 m baked margin. Interestingly, no other basalt layer was documented below this unit on Island 126/127 (see Fig. 2 and supplementary photomosaic). The vertical sections were logged as close to the water's edge as possible, and the lake levels at the time of this investigation (~478 m), and during the time of the investigations by Bond et al. (1970) and Wahl (1971) (~483 m) were very similar.

4. Discussion

4.1. Facies associations of island 126/127

The Forest Sandstone is described as consisting of pinkish-white to brownish, fine-to medium-grained, well-sorted sandstone, which is calcareous in its lower part and cross-bedded higher up (Thompson, 1975; Cooper, 1981). Following Thompson (1975), the lower part seems to contain subaqueous deposits, whereas the upper parts are aeolian in origin (Watkeys, 1979). Interestingly, the facies of the Forest Sandstone bear many similarities to those of the aeolian-lacustrine Clarens Formation in the main Karoo Basin, and both units have been correlated as time-equivalents by previous workers (Johnson et al., 1996; Bordy and Catuneanu, 2002a, b).

Marsh and Jackson (1974) described similar facies to those recorded in this study within the Forest Sandstone, although they admitted that their stratigraphic relationships were not extensively mapped. Marsh and Jackson's (1974) facies include the 'Red Beds', which comprise fine red sandstones that are resistant to weathering, and a lower soft weathering pink sandstone in association

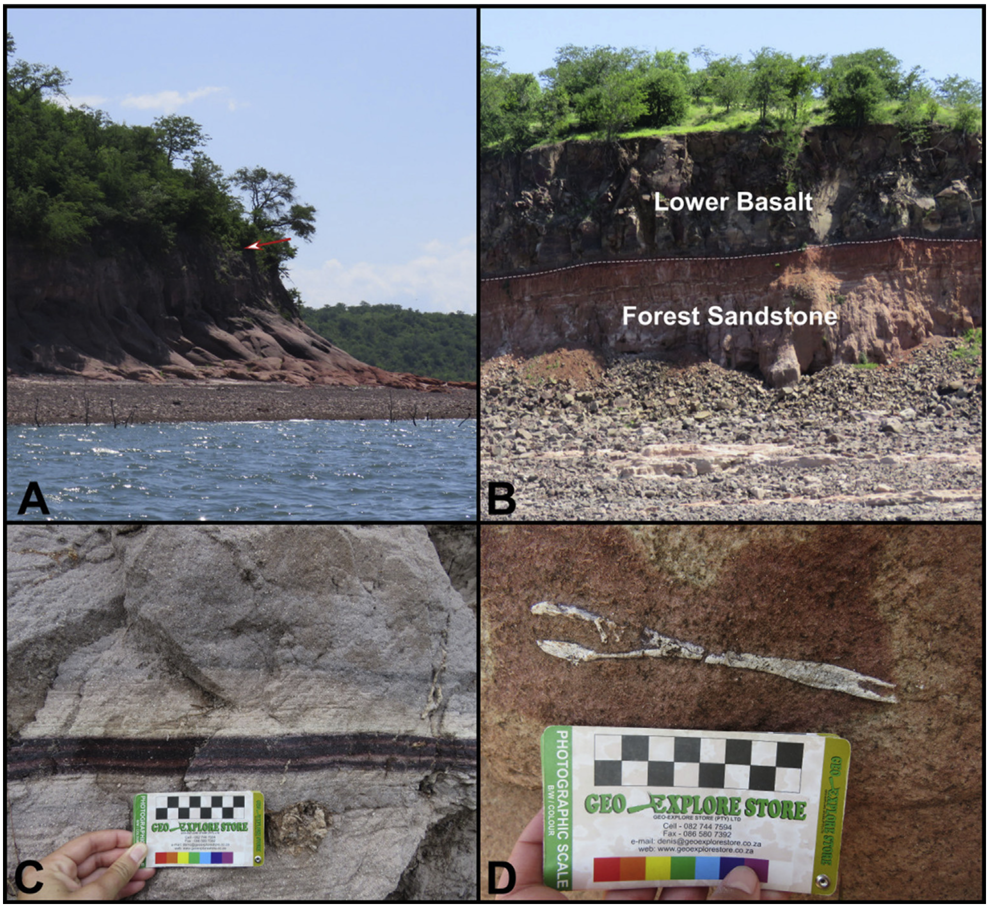

Fig. 2. A. Exposure on the northern portion of Island 126/127 where *Vulcanodon karibaensis* was recovered from a sandstone horizon immediately below a basalt layer capping the Upper Karoo Supergroup. Arrow points to basalt/sandstone contact that is obscured by tree line. B. A close up of the contact between the basalt and the underlying sandstone, which were identified as the Lower Basalt and Forest Sandstone Formation, respectively, by Marsh and Jackson (1974) and confirmed by this study. C. The 'Dinosaur Horizon' (Facies FD) where *Vulcanodon* was recovered. Note the concentrated heavy mineral deposition. D. A fragmentary cervical neural arch with the elongate morphology diagnostic of a massospondylid sauropodomorph found ~25 m below the *Vulcanodon* horizon on the measured section. This specimen was found in Facies FB on section 126(1).

with carbonate nodules. Their second facies is named the 'Coarse White Sandstone', which is described as being overlain by the 'Red Beds'. Their final and uppermost facies is the 'Dinosaur Horizon' in which the *Vulcanodon* material was located. The latter is described as a white, loosely compacted sandstone that directly underlies the Batoka Basalt Formation.

These observations concerning the varied facies present on Island 126/127 and across the adjoining mainland to the south bear many similarities to those identified in this study. Firstly, the 'Red Beds' of Marsh and Jackson (1974) are most likely a combination of our study's Facies A and B, their 'Coarse White Sandstone' describes our Facies C, and the 'Dinosaur Horizon' describes Facies D. Their detailed descriptions of the interbedded sandstones of the Batoka Basalt Formation, as seen elsewhere on other islands and the mainland, bears little similarity to the facies we documented on Island 126/127, and these sandstones were not mapped at this site by Marsh and Jackson (1974). Facies D is present on the north−western portion of Island 126/127 (see supplementary photomosaic), even if the vertical section from this part of the island does not document the facies (see Fig. 2). Historic accounts document the *Vulcanodon* quarry from the northwestern portion of the Island, but the exact position is not known. Thus, Marsh and Jackson's (1974) detailed accounts of the facies on Island 126/127 have been invaluable in determining the most likely stratigraphic position for *Vulcanodon*.

4.2. Structural geology of the field area

The structural geology of the field site also supports the observations of Marsh and Jackson (1974) on the stratigraphic position of *Vulcanodon* and the conclusions of this study. Wahl (1971) and Marsh and Jackson (1974) described the structural geology of the area in detail, and both studies identified gentle folding between Island 126/127 and the mainland to the south. This resulted in a series of parallel synclines and anticlines that trend east-northeast (Marsh and Jackson, 1974). Important to this study is a synclinal axis between Island 126/127 and the mainland. Island 126/127 represents the northern, south-dipping limb of a syncline, therefore sediments exposed on the island must be older because sediments become younger towards synclinal axes. The presence of the stratigraphically higher Batoka Basalt Formation confirms this further south, closer to the syncline axis (Fig. 1). Vertical offsets by normal faults, particularly those running parallel to the synclinal axis, were also identified during this study, and often presented confusing stratigraphic scenarios. As a result, it possible that these structural features might have led earlier studies to document multiple basalt horizons in the area rather than a single flow exposed at multiple heights, due to the locally fragmented stratigraphy. Thus, the structural geology supports our stratigraphic conclusions and nothing in our study contradicts these structural data, and Island 126/127 represents the south dipping northern

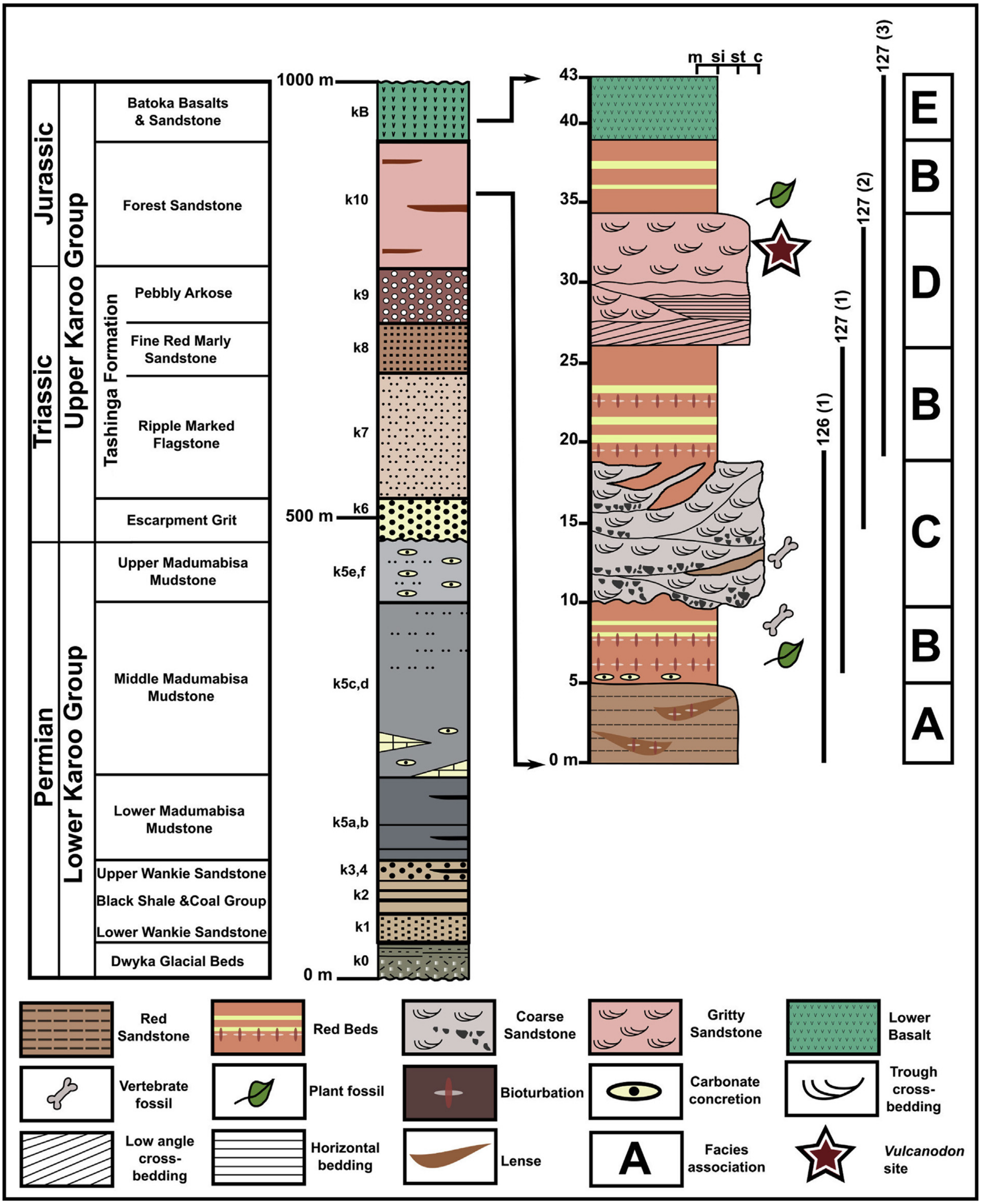

Fig. 3. A composite section adapted from Johnson et al. (1996) showing the stratigraphy of the Mid-Zambezi Basin in Zimbabwe. The position of the *Vulcanodon karibaensis* type locality in the stratigraphic column is shown. In addition, a detailed stratigraphic column of the site shows the position of *Vulcanodon*, new fossil material, and facies associations (A–E) encountered in the Forest Sandstone and Batoka Basalt formations. Note that all the facies, except for Facies FE, which is igneous, are sandstones. The "k" symbols to the left of the composite section are the original names for lithological units given by Geoffrey Bond.

limb of the northern synclinal system (Fig. 1).

4.3. Revised stratigraphy for Vulcanodon karibaensis

Although previously documented as sandwiched between two basalt layers (Bond et al., 1970; Raath, 1972), no basalt layer could be located stratigraphically below the *Vulcanodon* type locality, even when the facies associations were traced westwards on other islands (e.g. Namembere, Partridge, Weather, and 40 Mile islands). The Forest Sandstone was mapped as being below the Lower Basalt

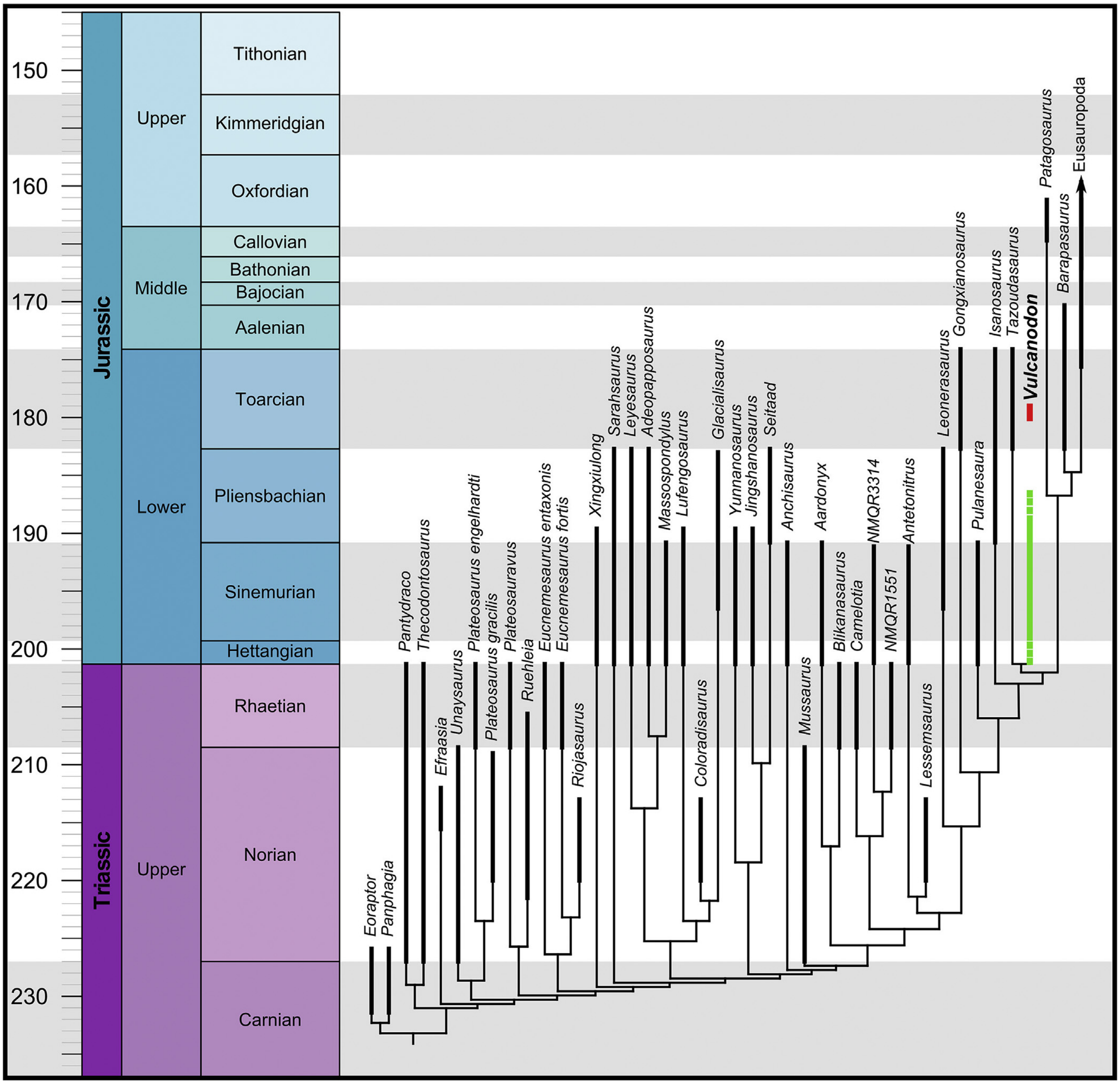

Fig. 4. Time-calibrated phylogenetic tree for basal sauropodomorph relationships showing the most recently proposed temporal placement of *Vulcanodon* (red) and the revised temporal hypothesis presented in this work (green). The solid section of the green line indicates the most probable temporal distribution of *Vulcanodon*, but note the dotted sections indicating that it could be as old as the Hettangian. The tree is the most stratigraphically consistent (according to the MSM* metric) of several most parsimonious topologies presented in McPhee et al. (2017). Scale on left is in millions of years before present, tick marks represent intervals of 1 Ma. Boundaries between periods, epochs, and ages are taken from Cohen et al. (2013). Age occurrences of taxa follow McPhee et al., 2017. Time scaling of the tree and figure generation were carried out in R (R Core Team, 2016), using the strap package (Bell and Lloyd, 2014). Eusauropoda are included and non-sauropodomorpha are excluded for clarity.

layer identified by Wahl (1971), and similarly mapped as such on Island 126/27 by Marsh and Jackson (1974), so this review confirms previous stratigraphic mapping that *Vulcanodon* was found in the uppermost Forest Sandstone, and not within interbedded sandstones of the Batoka Basalt Formation contrary to the descriptions of Bond et al. (1970) and Raath (1972). It is possible that Bond et al. (1970) and Raath (1972) mistook a dense layer of fallen basalt blocks, which fringes much of the shoreline around Island 126/127's northern perimeter, for a second, lower basalt layer. Although these blocks form a continuous pavement, the current lower lake level and small gaps in this layer clearly reveal that they have fallen and lie on top of Facies A and B, rather than forming a genuine boundary with these units. From identifying the facies present on Island 126/127, this study can now pinpoint the most plausible position of *Vulcanodon* as coming from the upper portion of our Facies D, or Marsh and Jackson's (1974) 'Dinosaur Horizon'.

Until recently, *Vulcanodon* was regarded as the earliest-branching sauropod and it served as an exemplar for understanding the transition between non-sauropod sauropodomorphs ('prosauropods') and members of Sauropoda (Raath, 1972;

Cruickshank, 1975; Cooper, 1984; Upchurch, 1995; Wilson and Sereno, 1998; Yates and Kitching, 2003). If Toarcian or late Pliensbachian–Toarcian in age (i.e. post-dating the onset of Drakensberg volcanism) (Yates et al., 2004), *Vulcanodon* would have been much younger than most of its closest relatives, including *Antetonitrus*, *Leonerasaurus* and *Pulanesaura*, and a contemporary of other more deeply-nested sauropods, like *Tazoudasaurus* (Allain and Aquesbi, 2008; McPhee et al., 2015).

Our new data indicate that *Vulcanodon* lived prior to the onset of Drakensberg volcanism, in the upper part of the Forest Sandstone of the Mid-Zambezi Basin. This unit has been proposed to correlate with the Clarens Formation (Sinemurian–Pliensbachian: Bordy and Catuneanu, 2002a, b), and it follows that *Vulcanodon* is older than previously proposed (contra Yates et al., 2004). The Forest Sandstone has been identified in at least three disjunct southern African Karoo-aged basins (Visser, 1984; Catuneanu et al., 2005), but the lack of detailed faunal correlations and radiometric age assessments preclude the identification of a more precise age for the *Vulcanodon* layer. However, the presence of the theropod genus *Coelophysis*, and the sauropodomorph species *Massospondylus carinatus* in the lower part of the Forest Sandstone in the Mid-Zambezi, Mana Pools, and Tuli basins (Cooper, 1981) provides some evidence for a maximum age for the lower layers of the Forest Sandstone of Rhaetian/Hettangian, similar to Bond et al.'s (1970) original age assessment. This is due to the co-occurrence of these taxa in the Upper Elliot Formation of the main Karoo Basin, which is estimated to have been deposited during this period (Kitching and Raath, 1984; Sciscio et al., 2017). Visser (1984) postulated that the Stormberg-equivalent units in more northerly basins could be older than their main Karoo equivalents due to the pole wandering path, and migration of the climate belts north to south as Gondwana drifted equatorward. Moreover, Visser (1984) suggested that in the Mid-Zambezi basin, there may be an uncomformity between the Forest Sandstone and the overlying Batoka Basalt formations. Therefore, the *Vulcanodon* stratum, which is situated only a few metres below the contact with the Batoka Basalt Formation, could be as old as the Rhaetian or as young as the Pliensbachian. A Sinemurian–Pliensbachian age seems most likely for this taxon, given its stratigraphic proximity to the Toarcian-aged Lower Basalt, implying an age that might be up to ~10–15 million years older than previous estimates (Yates et al., 2004).

The stratigraphic age of *Vulcanodon* proposed herein closes the stratigraphic gap between it and other earlier diverging taxa, such as *Pulanesaura* and *Leonerasaurus* (see McPhee et al., 2015), and provides a new calibration point for the node subtending *Vulcanodon* in sauropod phylogeny (Gravisauria: Allain and Aquesbi, 2008). Current debates surrounding the definition of Sauropoda have generated controversy regarding the taxa that should be included in the clade, and several of these (e.g. *Gongxianosaurus*, *Ishanosaurus*) are also very poorly dated, which undermines their utility for unravelling sauropod origins (see Allain and Aquesbi, 2008; McPhee et al., 2015). However, the proposed Sinemurian–Pliesbachian age for *Vulcanodon*, a taxon that is uncontroversially regarded as a sauropod (Upchurch, 1995; Wilson and Sereno, 1998; Upchurch et al., 2004; Allain and Aquesbi, 2008; Pol et al., 2011; McPhee et al., 2015), demonstrates that sauropods lived alongside non-sauropodan sauropodomorphs for an extended period and that the diversification of this clade began early in the Early Jurassic, rather than close to the Early/Middle Jurassic boundary as assumed previously (Upchurch and Barrett, 2005; Allain and Aquesbi, 2008; McPhee et al., 2015) (Fig. 4).

5. Conclusions

Vulcanodon karibaensis is the oldest known definitive sauropod dinosaur and is found in the Mid-Zambezi Basin of north-western Zimbabwe. Previous work on the type locality noted that it was recovered from a sandstone unit between two basalt layers. Although subsequently questioned, this observation was not tested until our study. Identification of five facies associations and the lack of evidence for a lower basalt layer below the *Vulcanodon* site confirm, for the first time, that this iconic taxon lies stratigraphically within the uppermost Forest Sandstone.

Since the upper Forest Sandstone is hypothesized as time-equivalent to the Clarens Formation in the main Karoo Basin, this confirms an earlier Jurassic age for *Vulcanodon* than has been suggested previously, pushing back the diversification of true sauropods by up to 10–15 million years. This closes the stratigraphic gap between *Vulcanodon* and other earlier-diverging sauropods, and helps to calibrate many of the major events in this group's evolution.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jafrearsci.2017.10.015.

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