A Review of Stratigraphic, Geochemical, and Paleontologic Data of the Terrestrial End-Permian Record in the Karoo Basin, South Africa

15

Johann Neveling, Robert A. Gastaldo, Sandra L. Kamo,
John W. Geissman, Cindy V. Looy,
and Marion K. Bamford

Abstract

The Karoo Basin has long been considered to contain the type stratigraphic succession for the terrestrial expression of the end-Permian mass extinction. A detailed extinction model, based on biostratigraphic and geologic data, has proposed rapid environmental change that coincides with a vertebrate biozone boundary, which was postulated to have been caused by increased aridity. Our sedimentologic, geochronologic, palaeomagnetic, and geochemical data collected from reported boundary sections, show that the link between the floral and faunal turnover and marine end-Permian event is tenuous. A review of existing, as well as our own palaeontological data, interpreted within a robust stratigraphic and sedimentologic framework, further indicate that ecological change was more subtle and protracted than currently modeled, and reflects the complex way in which the ancient Karoo landscape responded to changes in several extrinsic factors.

15.1 Introduction

The continental stratigraphic record in the Karoo Basin, South Africa, plays a central role in our understanding of the terrestrial ecosystem response to the end-Permian mass extinction. The basin formed in southern Gondwana during the Late Paleozoic and contains a sedimentary succession that records deposition from the Late Carboniferous to Middle Jurassic. Research on the events reported to be associated with the end-Permian crisis focused on an interval encompassing the two uppermost lithologic members recognized in the Balfour Formation, a part of the fully continental Beaufort Group. The Elandsberg Member consists predominantly of greenish gray mudstone and is overlain by the Palingkloof Member, characterized by greenish gray and grayish red mudstone which is, in turn succeeded by the largely arenaceous Katberg Formation (SACS 1980).

15.2 Background

The rich fossil record of tetrapods preserved in the Beaufort Group allowed for the establishment of an eightfold (Fig. 15.1) biozone subdivision (Rubidge 1995; see also Chap. 14 in this book). The origin of this scheme can be traced to that of Broom (1906), who proposed a sixfold subdivision and presumed the *Lystrosaurus* beds (i.e., the *Lystrosaurus* AZ in the modern scheme) to be Early Triassic in age; all preceding units were considered Permian. The

J. Neveling (✉)
Council for Geosciences, Pretoria, South Africa
e-mail: jneveling@geoscience.org.za

R.A. Gastaldo
Colby College, Waterville, ME, USA

S.L. Kamo
Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Canada

J.W. Geissman
University of Texas at Dallas, Richardson, TX, USA

C.V. Looy
University of California at Berkeley, Berkeley, CA, USA

M.K. Bamford
Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, South Africa

Fig. 15.1 Lithostratigraphy, biostratigraphy, and chronometric ages of the Beaufort group. Stippled line 1 represents the previously reported position of the PTB (Smith and Botha-Brink 2014). Stippled line 2 represents the hypothesized position of the PTB proposed by Gastaldo et al. (2015). The empty arrows depict the stratigraphic positions of volcanic ash beds that yielded the U-Pb ID-TIMS ages reported by Gastaldo et al. 2015 (*) and Rubidge et al. 2013 (**). The stippled double arrow depicts the position of the boundary interval described in the literature (Smith and Ward 2001; Smith and Botha-Brink 2014). The solid double arrows depict the approximate stratigraphic distance from the porcellanite reported by Gastaldo et al. (2015) to the base (∼440 m) and top (∼60 m) of the *Daptocephalus* AZ. The position of the base of the *Daptocephalus* AZ is based on Viglietti et al. (2016)

assignment of these lower biozones, of which the *Dicynodon* Assemblage Zone (AZ) is the youngest (Keyser and Smith 1978), received wide acceptance (Rubidge 1995; Rubidge et al. 2013). In contrast, the Triassic age of the *Lystrosaurus* AZ had been questioned, but most workers by the 1980s, agreed with its assignment to the earliest Triassic (see summary in Neveling 2004). The *Dicynodon* AZ, which recently has been redefined as the *Daptocephalus* AZ (Viglietti et al. 2016), traditionally has not been considered to share any taxa with the *Lystrosaurus* AZ (Kitching 1977), although Hotton (1967) first reported overlap in the stratigraphic ranges of the index taxa. Anderson and Cruickshank (1978) first correlated the sharp faunal turnover between these two biozones with the end-Permian crisis. This was supported by Smith (1995), who argued that the faunal turnover at the top of the *Daptocephalus* AZ was broadly time-equivalent with the extinction in the marine record.

In the first detailed study of this biozone contact, Smith (1995) demonstrated overlap of more than 20 m in the stratigraphic ranges of the, then, index taxa *Dicynodon* and *Lystrosaurus*, based on investigations at the Bethulie locality (southern Free State). The faunal boundary was placed at the base of the Palingkloof Member, which was interpreted to record a change in fluvial architecture from high sinuosity to low sinuosity river systems. This change in sedimentary regime was attributed to both increasing aridity and uplift in the Cape Fold Belt.

After incorporating data from additional sections, the position of the faunal boundary subsequently was reassigned to the lower part of the Palingkloof Member (Smith and Botha 2005, 2006), while a distinct lithofacies sequence was described (with subtle variation) as characteristic of the boundary interval (Fig. 15.1). In summary, the base of the interval comprises massive, greenish gray siltstone with subordinate, thick sandstone bodies in which fossils of the *Daptocephalus* AZ are preserved. This interval is interpreted to represent meandering fluvial deposits (Ward et al. 2000). The highest record of the *Daptocephalus* AZ is reported from an overlying interval of massive, mottled maroon and greenish gray mudrock, with thin tabular sandstone bodies (Smith and Ward 2001; Botha and Smith 2006; Smith and Botha-Brink 2014). A third facies, first introduced by Ward et al. (2000) and subsequently associated by many with the Permo-Triassic Boundary (PTB) itself, is described as consisting of very thinly bedded (Tucker, 1989) siltstone–mudstone couplets, each 1–3 cm thick (Smith and Ward 2001; Smith and Botha-Brink 2014). This 3–5 m thick interval has been referred to as "…*a stratigraphically unique unit*…" (Smith and Ward 2001, p.1148) that can "…*be used as a mappable unit…and a datum*…" (Smith and Botha-Brink 2014, p. 103) to correlate between widely distributed sections (Smith and Botha-Brink 2014, p. 110). This assumption was contradicted by Ward et al. (2012), who reported the facies from horizons above and below the PTB. Massive maroon and olive-gray siltstone, in which the *Lystrosaurus* AZ fauna is preserved, overlies this facies, followed stratigraphically by the multistoried channel sandstones of the Katberg Formation.

Ward et al. (2000) proposed that a shift in climatic conditions initiated the transition from high to low sinuosity fluvial architectures. According to their model, long-term deterioration of the terrestrial ecosystem, with a final pulse of increased ecological stress, culminated in wide-spread die-off of vegetation (Ward and Smith 2001; Ward et al. 2005; Smith and Botha 2005). The proposed vegetational collapse and loss of the *Glossopteris* flora caused the demise of the *Daptocephalus* AZ fauna, and the loss of vegetation cover resulted in the deposition of their laminated interval, which they identified as a datum throughout the basin.

This model, however, was developed in the absence of palaeobotanical data. The plant record for the central and southern parts of the basin of this interval, at the time, was considered almost barren. Subsequent studies have demonstrated the presence of macrofossil plants and palynomorphs where they were considered to be absent (Prevec et al. 2010; Gastaldo et al. 2015). Smith and Ward (2001), supporting Smith (1995) and subsequently followed by Smith and Botha (2005, 2006; Smith and Botha-Brink 2014), proposed aridification as the most likely causal mechanism of environmental stress. This interpretation was based on changes in fluvial style, reddening of floodplain paleosols, vertebrate taphonomy, and reinterpretation of the red siltstones as loess deposits (Smith 1995; Smith and Ward 2001; Smith and Botha-Brink 2014). Yet, tetrapod fossil data suggest that these conditions were not sufficiently severe to prevent rapid, post-extinction recovery of the vertebrate fauna (Botha and Smith 2006).

Until recently, no geochronologic data were available to validate the hypothesized correlation of the *Daptocephalus-Lystrosaurus* AZ contact with the end-Permian marine extinction. Hence, chemostratigraphic and magnetostratigraphic methods were attempted. Macleod et al. (2000) correlated a negative $\delta^{13}C$ excursion, obtained from pedogenic carbonate nodules (and supported by a smaller excursion from vertebrate tusks) within the interval of biostratigraphic overlap, with the PTB. Yet, Gastaldo et al. (2014) demonstrated that this correlation is doubtful because most pedogenic carbonate cements from this interval were formed in poorly drained soils and, therefore, do not reflect the isotopic composition of atmospheric CO_2. Ward et al. (2005) presented magnetostratigraphic records from sections spanning this interval and used a composite polarity record for the Karoo Basin to correlate with the extant global geomagnetic polarity time scale for the PTB. Although their data show the end-Permian interval to lie within a normal polarity magnetozone, which Lucas (2009) interpreted as evidence that this biozone contact predates the marine extinction, their overall polarity pattern for Old Lootsberg Pass could not be repeated by Gastaldo et al. (2015).

15.3   Materials and Methods

Detailed sedimentological investigations were undertaken at all reported PTB localities including Old Lootsberg Pass (Blaauwater 67), Blaauwater 65, Lootsberg Pass (Lucerne 70), Old Wapadsberg Pass (Farm 527), and the Bethulie locality (Bethel 763, Heldenmoed 677; Fig. 2). Stratigraphic sections were measured using standard field methods and a Jacob staff with leveling eyepiece. Architectural elements

and lateral facies relationships were identified using photomosaics, some obtained using drone technology, and correlating sections by tracing bounding surfaces along strike physically in the field.

15.4   Observations and Discussion

Recently acquired data do not corroborate the widely accepted model of an abrupt, three-phased faunal turnover, and facies sequence advanced in the literature. A reassessment of published biostratigraphic data from the Bethulie locality reveals discrepancies in the stratigraphic position reported for some specimens (e.g. RS67 in Smith and Botha-Brink 2014, Figs. 4 and 12, Supplementary Table 1) and variances between the reported and actual stratigraphic position of specific collection sites relative to the inferred PTB (Battifarano et al. 2015). A similar field-based review of reported fossil localities at the Old Wapadsberg locality suggests that at least two *Daptocephalus* AZ specimens (RS174, reported as *Dicynodon lacerticeps*; RS175, *Lystrosaurus maccaigi*) overlap the stratigraphic ranges of the *Lystrosaurus* AZ faunal elements, such as *Lystrosaurus murrayi* (e.g. RS102, RS103), by more than 30 m, contradicting published stratigraphic ranges (Smith and Botha-Brink 2014, Fig. 12). This suggests that vertebrate taxon ranges need to be reassessed and implies that the taxa of the *Daptocephalus* AZ may not have experienced a phased, near coeval extinction, but coexisted with the fauna of the overlying *Lystrosaurus* AZ for a much longer time than currently assumed.

Accurate stratigraphic placement of biostratigraphic data points is hampered by a dearth of dependable, local and regional geological datums in the studied succession. The reported laminated siltstone–mudstone "event bed" interval (Smith and Ward 2001) is absent from the sections we measured on the farm Blaauwater 65, as well as from two gulley sections on the farm Lucerne 70 known to yield fossils from the boundary interval. This facies also is absent from the proposed biozone boundary at Old Lootsberg Pass (Blaauwater 67). In contrast, we documented very thinly bedded siltstones at two stratigraphic intervals, separated by about 50 m of section (Fig. 15.3), above the placement of the vertebrate-defined PTB. Similarly, several laminated siltstone intervals are exposed above the proposed boundary at Old Wapadsberg Pass.

Lateral correlation of the exposures at Old Lootsberg Pass demonstrates that the laminated siltstone intervals are laterally equivalent to multistoried channel sandstones (Fig. 15.3). This corroborates our earlier observations at Bethulie (Gastaldo et al. 2009), which were subsequently

Fig. 15.2 Locality map showing the Lootsberg-Wapadsberg and Bethulie localities. The shadowed area in the small-scale map of South Africa represents the Karoo Supergroup
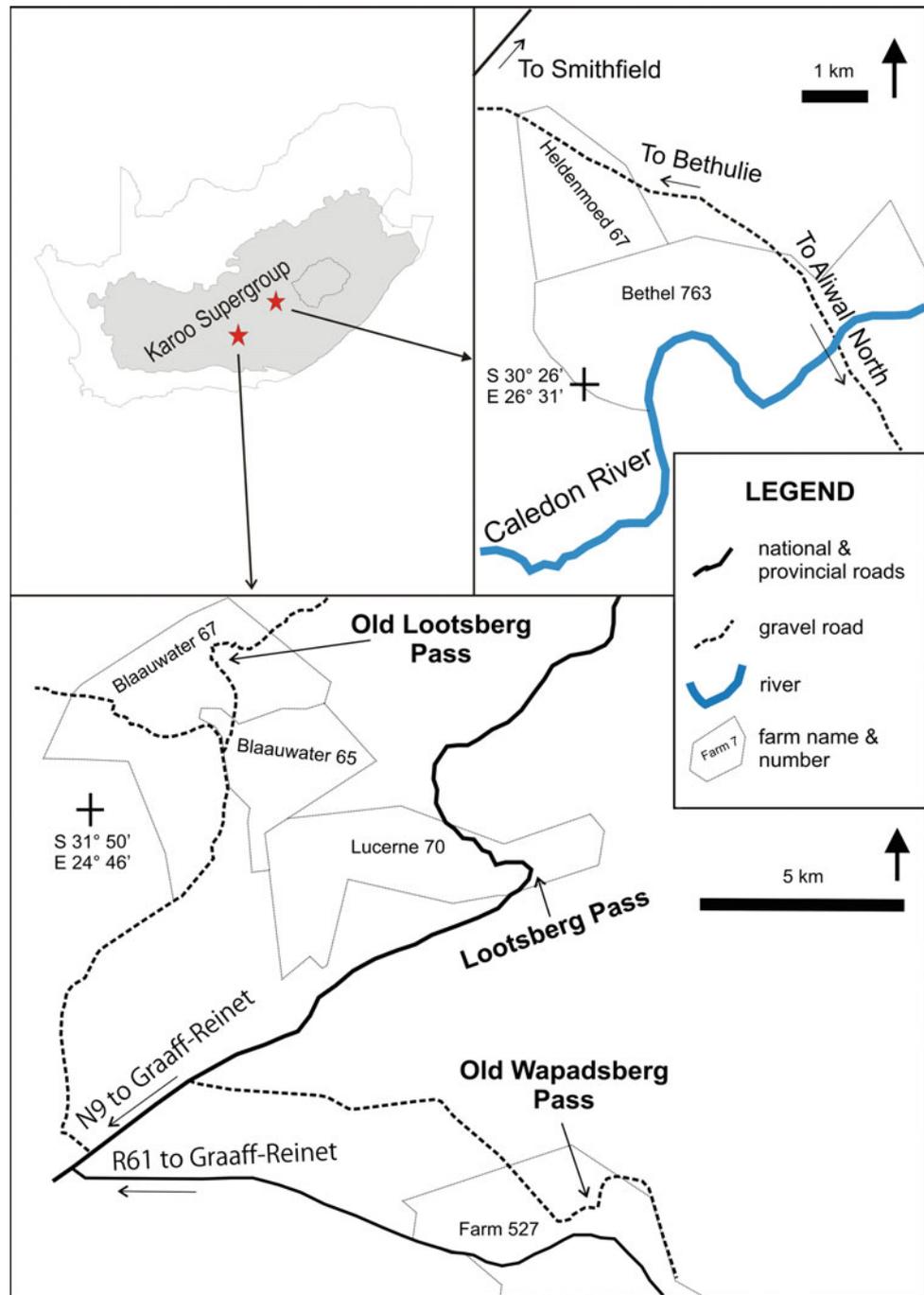
acknowledged by Ward et al. (2012), that this facies is neither unique nor isochronous. Its occurrence at multiple horizons and well-established, lateral association with channel deposits support the interpretation that it represents the distal facies associated with channel avulsion events on the early *Lystrosaurus* AZ landscape, as presently recognized.

Evidence for rapid environmental change or extreme aridity as a biological kill mechanism remains tenuous. The proposed loessic origin of the massive gray-red siltstones of the lowermost *Lystrosaurus* AZ is not supported by the

lateral variation displayed by this lithology above the reported biozone boundary at several localities (Gastaldo and Neveling, 2016). Thick units of greenish gray siltstone at Old Lootsberg Pass grade into grayish red siltstone over a lateral distance of less than 1 km (Fig. 15.3); a similar condition exists at Bethulie, where a lateral change in silt-stone color can be traced over a distance less than 0.2 km. Both occurrences are incompatible with the unit's proposed aeolian origin. Rather, this alteration is interpreted as

Fig. 15.3 Seven stratigraphic sections, with palaeontological data, measured at the Old Lootsberg Pass locality and correlated by tracing bounding surfaces in the field. Only seven of the original 11 sections (identified by number) are shown here. The position of the *Daptocephalus—Lystrosaurus* AZ boundary (previously correlated with the PTB) is based on the supplementary data of Smith and Botha-Brink (2014), used in conjunction with global positioning system coordinates provided by Smith. The lateral distances between selected sections are depicted by the double arrows
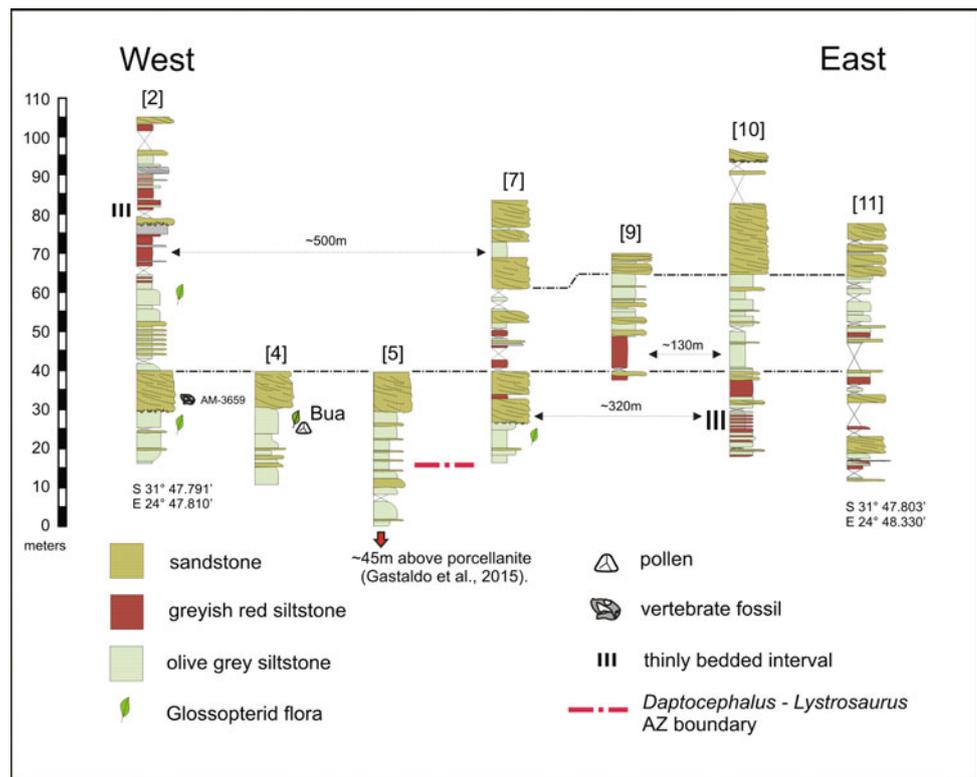
indicative of varying local pedogenic conditions on the ancient floodplain.

With the exception of paleo-calcic Vertisol remnants contained in lenses of reworked nodule conglomerate (Pace et al. 2009; Gastaldo et al. 2013), geochemical data (Tabor et al. 2007; Gastaldo et al. 2014) indicate that the pedogenic horizons above and below the reported vertebrate biozone boundary developed in seasonally to perennially wet soils. Moist soil conditions are supported by the paleobotanical record of a glossopterid flora (Prevec et al. 2010), 10–55 m above the reported biozone boundary at Old Lootsberg Pass; the upper localities occur within the *Lystrosaurus* AZ (Gastaldo et al. 2015). The presence of pollen produced by gymnosperms (e.g., conifers and peltasperms) not represented in the macrofloral assemblages, and representing taxa that are considered to represent vegetation that grew on well-drained soil conditions, are indicative of pedogenically drier conditions somewhere in the basin. Macrofossils with similar botanical affinities only made their appearance in post-extinction Karoo Basin floras (Anderson and Anderson 1985). The sudden appearance of reworked nodule conglomerates containing Vertisol remnants is also indicative of a shift to a more seasonally dry climate, but the extrinsic factors that influence fluvial style include both climate and tectonism (Allen et al. 2013). The fact that a change in fluvial depositional style persisted in the overlying Katberg Formation, combined with its thickness (SACS 1980) and

changes in fluvial style observed upsection, suggest that tectonic influence has been underestimated in recent fluvial models for this interval.
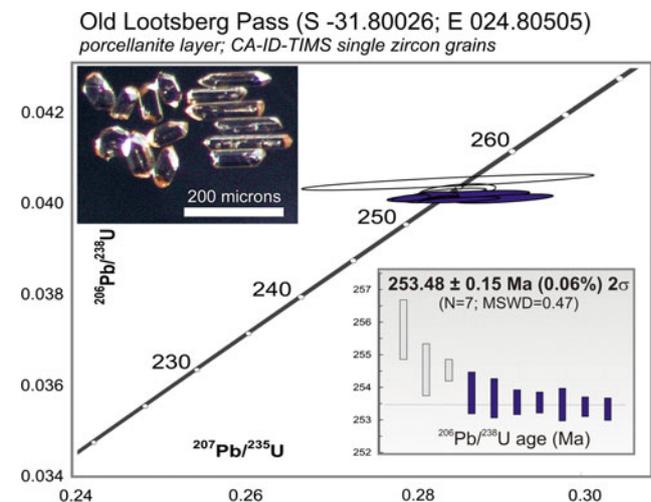
Fig. 15.4 Concordia diagram showing U-Pb ID-TIMS data for chemically abraded, single zircon grains from a volcaniclastic layer ∼60 m below the purported *Daptocephalus-Lystrosaurus* AZ contact, Old Lootsberg Pass section, Karoo Basin, South Africa. The procellanite bed is dated at 253.48 ± 0.15 Ma based on the seven youngest zircon grains (of eleven grains dated). Insets are: a photomicrograph of representative zircon grains similar to those that were analyzed; a plot of $^{206}Pb/^{238}U$ ages (data for oldest not plotted)

A U-Pb ID-TIMS age of 253.48 ± 0.15 Ma (Fig. 15.4) recently was reported from a silicified ash bed situated ~ 60 m below the inferred biozone boundary (as based on data presented by Smith and Botha-Brink 2014) at Old Lootsberg Pass. This maximum depositional age determination is early Changhsingian (Gastaldo et al. 2015). When compared with existing U-Pb ages for older Adelaide Subgroup strata (Beaufort Group; Rubidge et al. 2013), reported biozone thickness for the *Daptocephalus* AZ (Viglietti et al. 2016), and high stratigraphic position of the ash bed within this biozone (Fig. 15.1), the most parsimonious conclusion is that there is a very low probability that the faunal turnover between the *Daptocephalus* and *Lystrosaurus* AZs represents the terrestrial expression of the marine mass extinction event. This interpretation is supported by new magnetostratigraphic data that show the upper part of the *Daptocephalus* AZ, with the exception of one thin reverse polarity magnetozone immediately above the silicified bed, and the lower part of the *Lystrosaurus* AZ is located predominately in normal polarity magnetozones. This differs significantly from the global pattern close to the PTB, and indicates that it is unlikely that the biozone transition crosses the PTB. It also implies that the fauna of the latter biozone was already well established by the latest Permian.

15.5   Conclusions

Recent results indicate that the previous efforts to utilize magnetic polarity and chemostratigraphic data from the Karoo Basin to correlate stratigraphy in the Beaufort Group with the global PTB record are untenable. This is underscored by recent geochronologic data reported from this interval at Old Lootsberg Pass. An assessment of lateral facies relationships demonstrates that it is impossible to accurately correlate successions between different localities, or even between outcrops at a single locality, without tracing boundary surfaces in the field. Hence, without the development of a lithostratigraphic framework in which lateral relationships are understood, only generalizations about paleobiological data can be attempted.

A reassessment of biostratigraphic data suggests that the faunal turnover between the *Daptocephalus* and *Lystrosaurus* AZs was not of a cataclysmic nature (Roopnarine and Angielczyk 2015). Rather, we hypothesize that the turnover was more protracted than current models suggest. This is mirrored by the paleobotanical and palynological record, with the presence of the wetland glossopterid flora in the lowermost *Lystrosaurus* AZ, and the simultaneous presence of drought-tolerant forms, representing vegetation outside of the macrofloral taphonomic window. Although this suggests, together with pedogenic data, that there was a gradual trend in increasing seasonality, conditions were not as dry as portrayed, implying that increasing seasonal drying, alone, cannot explain the faunal change. Rather, we argue that a more nuanced interpretation should be adopted for this transition. The sedimentologic and biostratigraphic records of the uppermost Balfour Formation provide evidence for the varying ways in which the fluvial landscape responded, at different tempos, to a number of extrinsic factors including climate change, tectonic influences and, perhaps, also faunal migration, on local to regional scales.

References

Allen, J.P., Fielding, C.R., Rygel, M.C., Gibling, M.R (2013) Deconvolving signals of tectonic and climate controls from continental basins: An example from the Late Palaeozoic Cumberland Basin, Atlantic Canada. Journal of Sedimentary Research 83: 847–872.

Anderson, J.M., Anderson, H.M. (1985) Palaeoflora of southern Africa. Prodomus of South African megafloras Devonian to Lower Cretaceous. Balkema, Rotterdam, Netherlands.

Anderson, J.M., Cruickshank, A.R.I. (1978) The biostratigraphy of the Permian and the Triassic, Part 5. A review of the classification and distribution of Permo-Triassic tetrapods. Palaeontologia africana 21: 15–44.

Battifarano, O.K., Churchill, A. N., Gastaldo, R.A., Neveling, J., Geissman, J.W. (2015) Lithostratigraphy and lateral variation in vertebrate biostratigraphy near the Permian-Triassic boundary at Bethulie, South Africa. In: Abstracts of the GSA Annual Meeting, 47(7), Baltimore, Maryland, USA, 1–4 November 2015.

Botha, J., Smith, R.M.H. (2006) Rapid vertebrate recuperation in the Karoo Basin of South Africa following the End-Permian extinction. Journal of African Earth Sciences 45: 502–514. doi:10.1016/j.jafrearsci.2006.04.006.

Broom, R. (1906). On the Permian and Triassic faunas of South Africa. Geological Magazine, Decade 5(3): 29–30.

Gastaldo, R.A. Kamo, S.L., Neveling, J., Geissman,, J.W., Bamford, M., Looy, C.V. (2015) Is the vertebrate defined Permian–Triassic Boundary in the Karoo Basin, South Africa, the terrestrial expression of the End Permian marine event? Geology 43: 939–942. doi:10.1130/G37040.1.

Gastaldo, R.A., Knight, C.L., Neveling, J., Tabor, N.J. (2014) Latest Permian paleosols from Wapadsberg Pass, South Africa: Implications for Changhsingian climate. Geological Society of America Bulletin126: 665–679. doi:10.1130/B30887.1.

Gastaldo, R.A., Neveling, J. (2016) Anatomy of a mass extinction: Sedimentological and taphonomic evidence for drought-induced die-offs at the Permo- Triassic boundary in the main Karoo Basin, South Africa: Comment. Palaeogeography, Palaeoclimatology, Palaeoecology 447: 88–91.

Gastaldo, R.A., Neveling, J., Clark, C.K., Newbury, S.S. (2009) The terrestrial Permian-Triassic boundary event bed is a non-event: Geology 37: 199–202. doi:10.1130/G25255A.1.

Gastaldo, R.A., Pludow, P.A., Neveling J. (2013). Mud aggregates from the Katberg Formation, South Africa: Additional evidence for Early Triassic degradational landscapes. Journal of Sedimentary Research, 83: 531–540.

Hotton, N. (1967) Stratigraphy and sedimentation in the Beaufort Series (Permian-Triassic), South Africa. In: Teichert, Yochelson (Eds.), Essays in Paleontology and Stratigraphy, University of Kansas Special Publication 2: 390–428.

Keyser, A.W., Smith, R.M.H. (1978) Vertebrate biozonation of the Beaufort Group with special reference to the western Karoo Basin. Annals of the Geological Survey 12: 1–35.

Kitching, J.W. (1977) The distribution of the Karoo vertebrate fauna. Memoir of the Bernard Price Institute for Palaeontological Research, University of the Witwatersrand 1.

Lucas, S.G. (2009) Timing and magnitude of tetrapod extinctions across the Permo-Trioassic boundary. Journal of Asian Earth Science, 36, 491–502. doi:10.1016/j.jseaes.2008.11.016.

MacLeod, K.G., Smith, R.M.H., Koch, P.L., Ward, P.D. (2000) Timing of mammal-like reptile extinctions across the Permian-Triassic boundary in South Africa. Geology 28: 227–230.

Neveling, J. (2004) Stratigraphic and sedimentological investigation of the contact between the *Lystrosaurus* and the *Cynognathus* Assemblage Zones (Beaufort Group: Karoo Supergroup). Council for Geoscience Bulletin 137.

Pace, D.W., Gastaldo, R.A., Neveling, J. (2009) Aggradational and Degradational Landscapes in the Early Triassic of the Karoo Basin and Evidence for Dramatic Climate Shifts Following the P/Tr Event. Journal of Sedimentary Research 79: 276–291.

Prevec, R., Gastaldo, R.A., Neveling, J., Reid, S.B., Looy, C.V. (2010) An autochthonous glossopterid flora with Latest Permian palynomorphs from the *Dicynodon* Assemblage Zone of the southern Karoo Basin, South Africa: Palaeogeography, Palaeoclimatology, Palaeoecology 292: 391–408. doi:10.1016/j.palaeo.2010.03.052.

Roopnarine, P.D., Angielczyk, K.D. (2015) Community stability and selective extinction during the Permian-Triassic mass extinction. Science 350: 90–93. doi:10.1126/science.aab1371.

Rubidge, B.S. (ed). (1995) Biostratigraphy of the Beaufort Group (Karoo Supergroup). South African Commission on Stratigraphy, Biostratigraphic Series 1.

Rubidge, B.S., Erwin, D.H., Ramezani, J., Bowring, S.A., De Klerk, W.J. (2013) High-precision temporal calibration of Late Permian vertebrate biostratigraphy: U-Pb zircon constraints from the Karoo Supergroup, South Africa. Geology 41: 363–366. doi:10.1130/G33622.1.

Smith, R.H.M. (1995) Changing fluvial environments across the Permian-Triassic boundary in the Karoo Basin, S. Africa and possible causes of tetrapod extinctions: Palaeogeography, Palaeoclimatology Palaeoecology 117: 81–104.

Smith, R.H.M., Botha, J. (2005) The recovery of terrestrial vertebrate diversity in the South African Karoo Basin after the end-Permian extinction. Compte Rendu Palevol. 4: 555–568.

Smith, R.H.M., Botha-Brink, J. (2014) Anatomy of a mass extinction: Sedimentological and taphonomic evidence for drought-induced die-offs at the Permo-Triassic boundary in the main Karoo Basin, South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 396: 99–118. doi:10.1016/j.palaeo.2014.01.002.

Smith, R.M.H., Ward, P.D. (2001) Pattern of vertebrate extinctions across an event bed at the Permian-Triassic boundary in the Karoo Basin of South Africa. Geology 28: 227–230.

South African Committee for Stratigraphy. 1980. Stratigraphy of South Africa. Part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/ Namibia, and the republics of Bophuthatswana, Transkei and Venda. Geological Survey, South Africa, Handbook 8: 535–548.

Tabor, N.J., Montañez, I.P., Steiner, M.B., Schwindt, D. (2007) δ^{13}C values of carbonate nodules across the Permian-Triassic boundary in the Karoo Supergroup (South Africa) reflect a stinking sulfurous swamp, not atmospheric CO2. Palaeogeography, Palaeoclimatology, Palaeoecology 252: 370–381.

Tucker, M.E. (1989) The field description of sedimentary rocks. Geological Society of London Handbook. Open University Press, United Kingdom.

Viglietti, P.A., Smith, R.M.H., Angielczyk, K.D., Kammerer, C.F., Fröbish, J., Rubidge, B.S. (2016) The *Daptocephalus* Assimblage Zone (Lopingian), South Africa: A proposed biostratigraphy based on a new compilation of stratigraphic ranges. Journal of African Earth Science 113: 153–164.

Ward, P.D., Montgomery, D.R., Smith, R.H.M. (2000) Altered river morphology in South Africa related to the Permian-Triassic extinction. Science 289: 1740–1743.

Ward, P.D., Botha, J., Buick, R., Dekock, M.O., Erwin, D.H., Garrison, G., Kirschvink, J., Smith, R.H.M. (2005) Abrupt and gradual extinction among Late Permian land vertebrates in the Karoo Basin, South Africa. Science 307: 709–714. doi:10.1126/science.1107068.

Ward, P.D., Retallack, G.J., Smith, R.M.H. (2012) The terrestrial Permo-Triassic event bed is a non-event Comment. Geology. 40: e256.