



# Waterford Formation in the south-eastern Karoo: Implications for basin development

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Extensive research on the rocks of the Karoo Supergroup has shown that this sequence, which contains an unsurpassed record of Permian–Jurassic tetrapods, records a largely unbroken stratigraphic succession from 300 Ma to 180 Ma. This Gondwanan succession was deposited in a changing environmental setting reflecting glacial marine through deltaic to fluvial and aeolian desert conditions. The contact between the Eccca and Beaufort Groups (at the top of the Waterford Formation of the Eccca Group) in the southern and western Karoo represents a change in depositional environment from a subaqueous to a subaerial delta plain. By contrast, the Waterford Formation has not yet been recognised in the south-eastern Karoo Basin, which might imply that a major unconformity is present between the Fort Brown Formation of the Eccca Group, deposited in a prodelta environment, and the overlying fluvially deposited Koonap Formation of the Beaufort Group. From careful documentation of lithofacies and sedimentological data, it can be demonstrated that the Waterford Formation is indeed present in the south-eastern part of the basin and that no major unconformity is present – a fact that has implications for the mapping of Karoo rocks in the Eastern Cape Province of South Africa, for understanding the depositional environment of ‘reptilian’ fossils from the lowermost Beaufort in this part of the Karoo basin, and for basin development models.

## Introduction

The Karoo Supergroup, deposited in a subsiding retro-arc foreland basin environment,<sup>1,2</sup> records a largely unbroken stratigraphic succession from the Carboniferous to the mid-Jurassic and is internationally renowned for its wealth of fossil tetrapods.<sup>3</sup> More recently it was suggested that the initial Karoo Basin formed as a result of block subsidence along major marginal faults.<sup>4</sup> The nature of the lithostratigraphic contacts between the four groups of the Karoo Supergroup (Dwyka, Eccca, Beaufort and ‘Stormberg’) has been the subject of much discussion. Whilst consensus has been reached regarding the Dwyka–Eccca contact<sup>5</sup> and the Beaufort–‘Stormberg’ contact,<sup>6,7</sup> the Eccca–Beaufort contact is still the subject of debate.<sup>8,9,10,11,12</sup> Researchers agree on the contact in the southern and western Karoo Basin<sup>9,13,14</sup> where it is taken at the top of the Waterford Formation of the Eccca Group and represents a shoreline transition from a subaqueous delta plain to a subaerial delta plain environment. By contrast, in the south-eastern part of the basin (map sheet: Republic of South Africa 3326, Grahamstown, 1:250 000 Geological Series 1995), the Waterford Formation has not been recognised and the Eccca–Beaufort contact is presently placed at the top of the Fort Brown Formation (Eccca Group) and the base of the Koonap Formation (Beaufort Group).<sup>15</sup> As the Fort Brown Formation is considered to have been deposited in a deep water prodelta environment<sup>9,15,16,17</sup> and the Koonap in a subaerial fluvial environment,<sup>15,16,18</sup> acceptance of this mapping could imply that a major unconformity exists between the Fort Brown and Koonap Formations, which is in sharp contrast to currently accepted basin development models. However, the basal part of the Koonap Formation contains characteristics of deltaic sedimentation<sup>14,19</sup> and should be remapped as Waterford Formation.<sup>20</sup>

## Results

Extensive fieldwork in the area covering the contact between the Eccca and Beaufort Groups in the area north of Grahamstown has revealed the presence of three separate facies associations corresponding to those present across the Eccca–Beaufort contact in the south-western, western and central parts of the Karoo Basin<sup>9</sup> (Figures 1 and 2).

Facies Association 1 comprises mainly a thick argillaceous sequence of dark bluish-grey (10B 2.5/1) to greyish-black (5B 3/2) siltstone. Thin (< 1 cm) light brown (5YR 5/8) siltstone laminae become more prevalent towards the top of Facies Association 1 suggesting an increase in depositional energy.<sup>21</sup> Bedding plane surfaces display fragmentary fossilised plant material equivalent to the coffiegrounds previously described in the uppermost Fort Brown Formation in the south-western part of the basin,<sup>9</sup> as well as horizontal feeding traces and vertical and horizontal

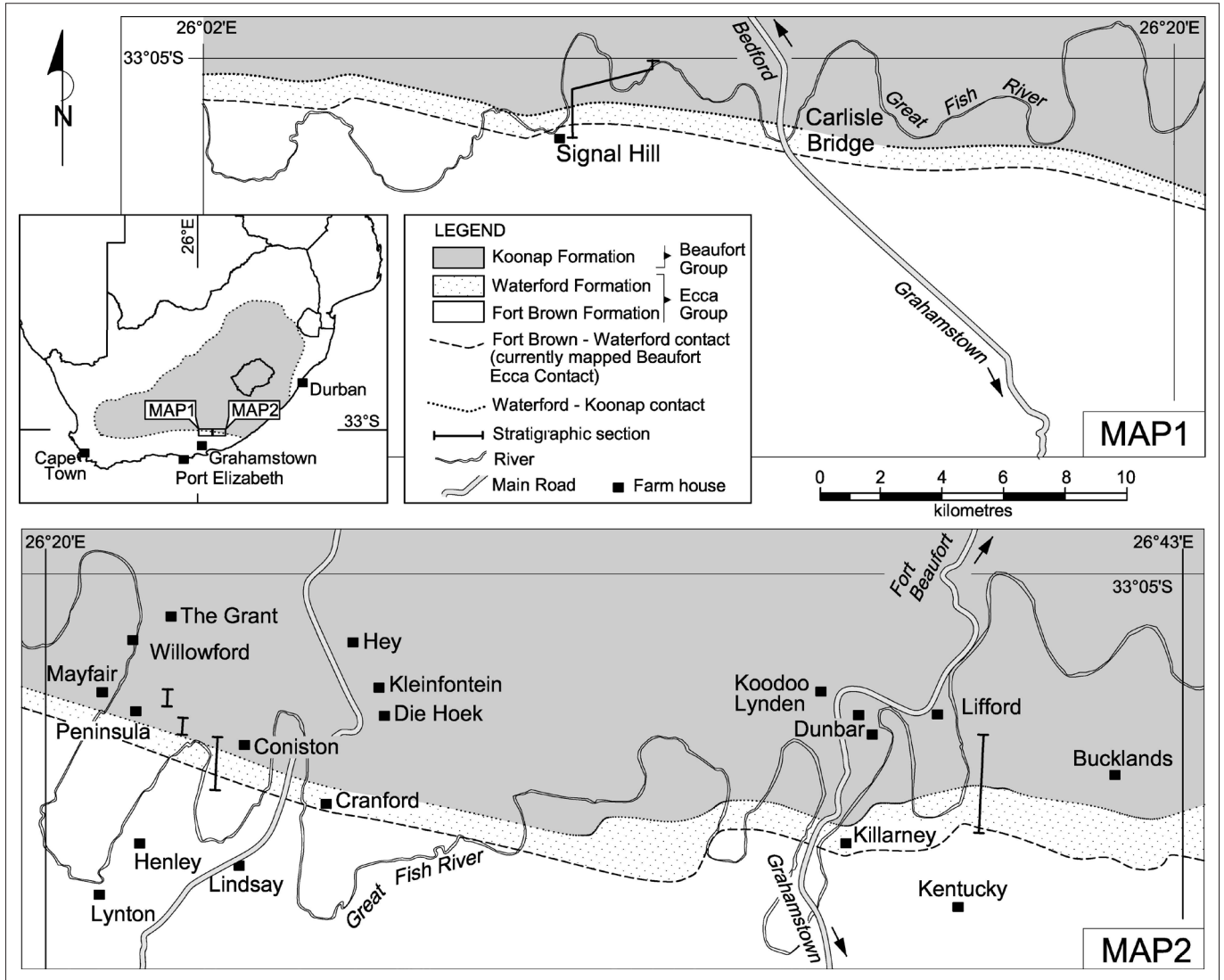


FIGURE 1: Geological map of the study area showing the distribution of the Fort Brown, Waterford and Koonap Formations.

burrows. The fine-grained nature of the rocks, coupled to the paucity of cross lamination indicates deposition primarily by suspension settling.<sup>22</sup> The dark colouration is ascribed to a high organic content, as is the case with the equivalent facies in other parts of the basin.<sup>9,16</sup>

Facies Association 2, which is more arenaceous, comprises five facies which can be recognised throughout the study area, and in fact across the entire basin: Facies A to E. Facies A consists of alternating beds of mudrock and sandstone with abrupt lower contacts (Figure 3). The sandstones are brownish-grey (5YR 4/1) ripple-laminated units whereas the siltstones are dark blue to grey (10BP 2.5/1) and are horizontally laminated. Symmetrical ripples with straight or sinuous crests are present on the sandstones. The only fossils are densely packed horizontal feeding traces on some ripple surfaces. Alternating sandstone and mudrock beds within this facies represent deposition under fluctuating energy conditions. The finer-grained beds consist of flat bedding indicative of low energy deposition by suspension settling,<sup>23</sup> whereas ripple lamination in the arenaceous beds, as well as in the abrupt and erosional bases, indicate deposition under

lower flow regime conditions.<sup>24</sup> The repetitive nature of the beds indicates a pulsatory depositional system.

Facies B comprises dark blue to grey (10B 2.5/1), horizontally bedded siltstones with abrupt or gradational lower and upper contacts. Horizontal invertebrate burrows and fragmentary palaeoniscid fish scales have been recorded. This facies occurs at different stratigraphic horizons in the Facies Association 2 sequence but is more abundant in the lower horizons (Figure 2).

Facies C comprises thin (< 0.5 m) light brown (5YR 5/8) sandstone beds which are horizontally or ripple laminated and have erosional bases. The lateral extent of the beds is difficult to ascertain as a result of poor outcrop. The facies comprises only a small percentage of the overall lithology of Facies Association 2 and is more common towards the upper part (Figure 2). The thin nature of the beds and abrupt upper and lower contacts, together with their lenticular geometries, suggests that these represent subaqueous splay and channel fills.<sup>9,25</sup>

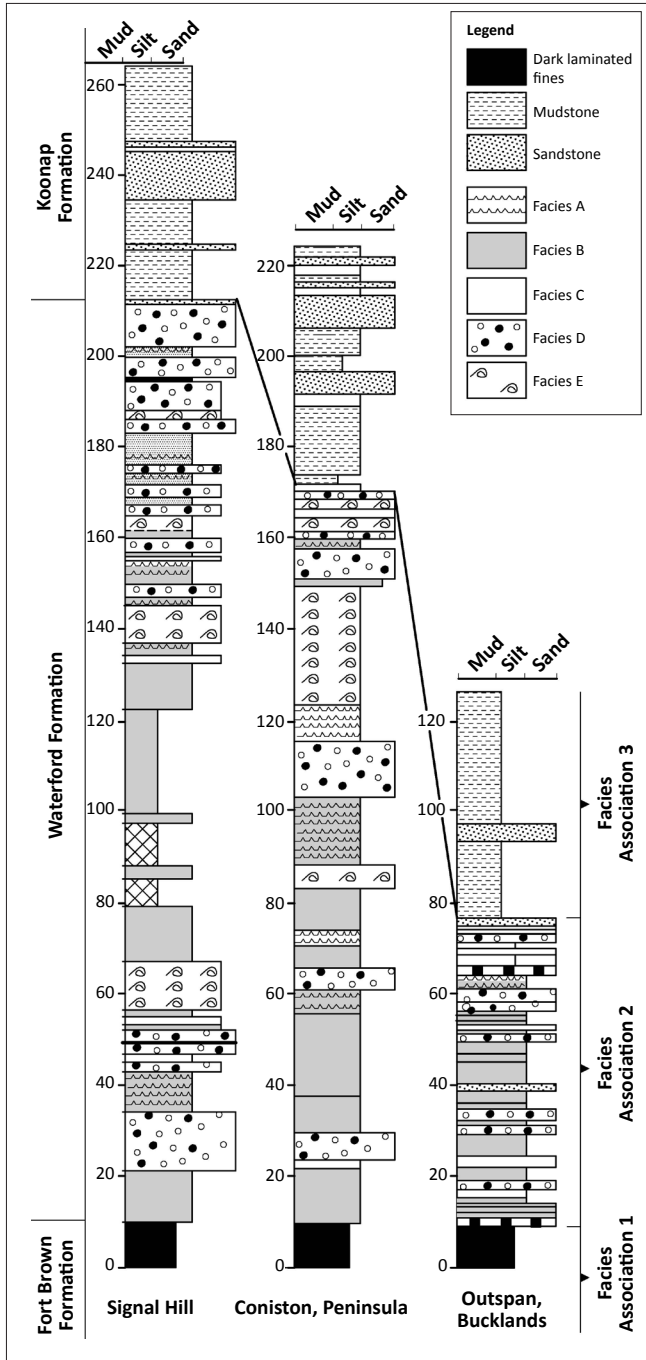


FIGURE 2: Stratigraphic sections through the Fort Brown, Waterford and Koonap Formations at the three study sites in the Grahamstown district.

Facies D comprises thick (> 0.5 m) beds of bluish-grey (5B 7/1) horizontally or ripple-laminated sandstone. The convex basal contacts are erosional and in many places contain flame structures when underlain by argillaceous beds. The sandstones are more extensive than those of Facies C and may extend more than 100 m laterally. This facies becomes more abundant towards the top of the Facies Association 2 sequence, producing an overall upward coarsening trend to the succession. Matrix supported, well-rounded intraformational mud pebble horizons with no apparent imbrication occur in places within Facies D sandstones, whilst thin mud flakes resembling 'acicular structures'<sup>23</sup> also occur at various horizons. These structures



Scale: geological hammer.

FIGURE 3: Rhythmic sandstone-mudstone couplets of Facies A on Coniston.



Scale: 60-mm lens cap diameter.

FIGURE 4: Ball-and-pillow structure in Facies E sandstone, Signal Hill.

are thought to represent the crests of ripples that have been reworked during high-energy subaqueous flow.<sup>26,27</sup> The erosive nature of the basal contacts suggest relatively high energy conditions as is indicated by flat bedding and dense pebble beds.<sup>28</sup> This lithofacies is considered to represent distributary mouth bar and subaqueous channel deposits.<sup>9</sup>

Facies E incorporates 0.5-m to 26-m thick sandstones with soft-sediment deformation structures (Figure 4). Preserved internal beds display horizontal and ripple cross lamination. Basal contacts are abrupt or loaded, with flame structures present when the bed overlies an argillaceous facies. The upper contact of this lithofacies is abrupt. The facies is abundantly present throughout the study area (Figure 2). The absence of orientated slump axes suggests that the soft sediment deformational structures are not the result of slumping, but are rather ball-and-pillow structures caused by a density inversion where relatively dense strata have collapsed into the less-dense underlying beds.<sup>29</sup>

Facies Association 3 overlies Facies Association 2 throughout the study area as is the situation in the south-western part



of the basin.<sup>6</sup> Facies developed in this part of the succession are similar to those recognised for the south-western part of the basin<sup>6</sup> and comprise eight fluvially generated lithofacies following the scheme of Miall<sup>30,31</sup>. Description of these facies is the subject of another article.

## Conclusion

The fact that the five facies of Facies Association 2 are the same as those described for the Waterford Formation in the southern and western part of the basin,<sup>9,13</sup> coupled with the fact that this facies association is situated stratigraphically between the Fort Brown and Koonap Formations, indicate that this succession should be remapped as Waterford Formation, as it is known elsewhere in the basin. This facies association presently occurs within the lower part of the Koonap Formation and overlies the argillaceous Fort Brown Formation. This proposed Waterford Formation, which we have mapped throughout the study area (Figure 1), thins in an easterly direction from 210 m at Carlisle Bridge to 70 m north of Fort Brown. Despite the fact that it is relatively thin, it is easily recognisable and mappable and should be included in future revisions of the Grahamstown geological map. The Waterford Formation in the south-eastern part of the Karoo Basin was deposited in a subaqueous delta plain depositional environment.<sup>9,17,19</sup> Recognition of its presence indicates that no subaerial unconformity is present on the Beaufort–Ecca contact in this part of the basin and has implications for basin development models. This fact resolves the apparent enigma of the presence of an unconformity at the contact in this part of the basin. The absence of a subaerial unconformity is in line with current basin models that suggest the generation of accommodation space in the foredeep from Fort Brown to Waterford times, with the boundary between the Waterford Formation and the Beaufort Group representing the changeover from a filled phase of shallow marine deposition, to an overfilled phase of fluvial deposition.

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## Competing interests

We declare that we have no financial or personal relationships which may have inappropriately influenced us in writing this article.

## Authors' contributions

B.S.R. was the project leader and was responsible for writing the article; P.J.H. assisted with the project article and writing the paper; R.M. undertook his MSc in the study area and was responsible for mapping and stratigraphic sections.

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