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A BIO- AND LITHO- STRATIGRAPHIC STUDY OF THE ECCA-BEAUFORT CONTACT IN THE SOUTHEASTERN KAROO BASIN (ALBANY DISTRICT, EASTERN CAPE PROVINCE)

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UNIVERSITY OF THE WITWATERSRAND, 2007

DECLARATION

I declare that this dissertation is my own unaided work except where indicated in the text. This dissertation has been submitted for the Degree of Master in Science at the Faculty of Science, University of the Witwatersrand, Johannesburg and at no other academic institution.

.....
(R. Mason)

..... day of ..... 200.....

ACKNOWLEDGEMENTS

The following people have all contributed to this project and the author wishes to extend his deepest gratitude to them:

Tony and Lynne Phillips
Colin and Joyce Were
Richard Were
Reg and Daphne Bowker
Vaughn Sparrow
Koenie de Preez
Kevin and Adele Bowker
Brad Fyk
Prof. Bruce Rubidge
Dr John Hancox
Dr Marion Bamford
Dr Billy de Klerk
Dr Emese Bordy
Dr Sharad Masters
John Nyaphuli
Nthapo Ntheri
Charlton Dube

ABSTRACT

The rocks of the Carboniferous to Jurassic aged main Karoo Supergroup of South Africa preserve an internationally significant and stratigraphically continuous retro-arc foreland depositional sequence. This succession documents environmental change from glacial-marine, through fluvio-deltaic to continental fluvial and aeolian, culminating in rift associated continental flood basalt extrusions. The fluvio-deltaic transition from marine to continental deposition has been the subject of much recent research and corresponds with the position of the Ecca-Beaufort contact. Over the entire basin this transition comprises three separate lithofacies associations deposited in the prodelta, deltafront and delta plain environments. Anomolously the southeastern contact is currently mapped as reflecting fluvial deposits of the Koonap Formation lying unconformably on prodelta deposits of the Fort Brown Formation.

Detailed study across the Ecca-Beaufort contact in this part of the basin now reveals the same lithological transition as is present in the rest of the basin. Contrary to previuos work, this has shown that the Waterford Formation is indeed present in this part of the basin. This in effect means that the Grahamstown map sheet (1:250 000, Map 3326) requires modification to include this Formation and the new contact placement of the Ecca-Beaufort contact occurs some 70 to 120m above the presently mapped contact.

Fossils collected during this and previous studies show that biostratigraphically *Tapinocephalus* Assemblage Zone fauna occurs in the rocks of the Koonap Formation in this part of the basin, indicating that the Ecca-Beaufort contact in the southern part of the basin youngs towards the east. This supports the prograding shoreline deposition model that has been previously proposed for the Ecca-Beaufort contact.

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ABBREVIATIONS

can : canine
canf : caniniform
exp. r : expanded ribs
ext. n : external nare
inc : incisor
max : maxilla
oc : occipital condyle
orb : orbit
par : parietal
pc : postcanine
po : post-orbital
pmx : premaxilla
pt : pterygoid
sq : squamosal
to : temporal opening
trans : transverse flange
vert : vertebra

1 INTRODUCTION

1.1 Karoo Basin

The rocks of the Karoo Supergroup in the main Karoo Basin of South Africa represents an outcrop area extending over two thirds of the surface area of South Africa. Sedimentary strata within the basin were deposited from the Late Carboniferous to the Early Jurassic (Smith 1990, Smith et al. 1993, Johnson et al. 1996) and, within the Beaufort Group, contain a rich diversity of fossils, which make up the most complete Middle Permian to Late Triassic record of terrestrial life (Hancox and Rubidge 2001). Much work has been undertaken on the lithostratigraphy (Johnson 1976, S.A.C.S 1980, Smith 1990, Johnson et al. 1996, Rubidge 2005), palaeontology (Kitching 1977, Rubidge et al. 1995, Hancox and Rubidge 1997, Hancox and Rubidge 2001), depositional environments (Smith 1980, Visser et al. 1980, Kingsley 1981, Wickens 1994, Smith 1990) and basin development (Pysklywec and Mitrovica 1999, Catuneanu et al. 1998, Turner 1999, Bordy et al. 2004, Bordy et al. 2005), however the southeastern part of the basin remains poorly understood.

The Karoo Supergroup is comprised of the Dwyka, Ecca, Beaufort and “Stormberg” groups comprise the Karoo Supergroup (S.A.C.S. 1980). Due to the lithological differences between the northern and southern parts of the basin, in particular for the Ecca Group (Ryan 1967), different stratigraphic nomenclatures exist around the main Karoo Basin (S.A.C.S. 1980).

Much discussion has been focused on the nature of the lithostratigraphic contacts between the four groups of the Karoo Supergroup. While consensus has been reached regarding the Dwyka - Ecca contact (Visser 1979) and the Beaufort - "Stormberg" contact (Visser 1984, Hancox 1998), the Ecca-Beaufort contact remains problematic and has been the subject of much debate (Visser and Loock 1974, Rubidge 1987, Zawada and Cadle 1987,

Smith and Zawada 1988, Rubidge et al. 2000). Consensus has been achieved regarding the contact in the southern and western Karoo Basin (Rubidge et al. 2000, Welman et al. 2001, Wright 2002) but the nature of the contact in the southeastern part of the basin is poorly documented.

Recent research (Catuneanu et al. 2002) has shown that deposition in the main Karoo Basin was affected by flexural tectonics, resulting in a foredeep region in the southern Karoo Basin, and a forebulge region in the northern Karoo Basin. The stratigraphic succession which is the subject of this thesis lies within the foredeep region, and comprises the upper Ecca and lower Beaufort groups. Subaqueous deposition as a result of prograding deltas in the foredeep of the Karoo Basin resulted in the deposition of sediment which today comprises rocks of the upper Ecca. Current basin modelling indicates that subaqueous delta-front deposits occur along the entire southern margin of the Karoo Basin (Wickens 1994, Rubidge et al 2001). However current mapping shows that these deltaic deposits, represented by the Waterford Formation, are absent east of 26°E. As currently mapped (map sheet 3326), the Ecca-Beaufort contact east of 26°E shows the Fort Brown Formation (deep water prodelta deposits) followed by the Koonap Formation (subaerial fluvial deposits). This mapping implies the absence of delta front (subaqueous delta plain) deposits and hence the presence of an unconformity at the position of the Ecca-Beafort contact.

Should this anomaly prove real then additional flexural tectonics may be unaccounted for in current basin development models, The exact nature of the stratigraphy within the southeastern Karoo Basin is therefore re-examined in this thesis.

1.2 Ecca Group

1.2.1 Stratigraphy

The rocks of the Ecca Group were first formerly recognised by Jones (1867)

as the "Ecca Beds" and were differentiated from the overlying "Beaufort Beds" in that the Beaufort Group rocks contained reptilian fossils. The "Ecca Beds" were later renamed the "Ecca Series" by Rogers (1903) in his fourfold subdivisioning of the "Karroo System". The work of Rogers (1903) provided the basic stratigraphic framework on which all subsequent work was based.

Rossouw (1953) subdivided Rogers' Ecca "Series" in the southern Karoo Basin into a Lower-, Middle- and Upper Ecca Stage. Johnson (1976) renamed the Ecca "Series" in the southern Karoo Basin as the Ecca Group, following international stratigraphic nomenclaterial practice. A the same time the Lower, Middle and Upper Ecca "Stages" became formalised as the Ripon, Fort Brown and Waterford formations. The underlying Prince Albert Shale and Whitehill formations (formerly the Upper Dwyka Stage) were also included into the Ecca Group (Johnson 1976). Johnson (1976) further proposed that the intercalated grey and yellow shales overlying the Whitehill Formation should be recognised as the Collingham Formation. With minor modifications this stratigraphic framework was accepted by the South African Committee for Stratigraphy (S.A.C.S. 1980) and is at present the recognized stratigraphic framework for the southern Karoo Basin.

Within the Ecca Group, the Fort Brown and Waterford formations (Johnson 1976, S.A.C.S. 1980), which encompass the middle and upper parts of the Ecca Group (Rossouw 1953), are the focus of this study. The Waterford Formation overlies the Fort Brown Formation for much of the southern Karoo Basin with the exception of the areas east of 26°E. In these eastern areas, the Fort Brown Formation represents the uppermost unit of the Ecca Group (Johnson 1976, S.A.C.S 1980) and the Waterford Formation is considered to thin and wedge out towards the east (Johnson 1976).

The Fort Brown Formation represents a thick, relatively homogenous argillaceous sequence that, at present, contains no stratigraphic subdivisions (S.A.C.S 1980). The basal contact of the Fort Brown Formation with the

underlying arenaceous Ripon Formation is considered conformable and is represented by the uppermost sandstone horizon present (Johnson 1976). The sandstones representing this contact wedge out laterally, resulting in a variable stratigraphic height for this contact (Johnson 1976, Kingsley 1977).

Johnson (1976) subdivided the arenaceous Waterford Formation into the Main, Middlewater Shale and Transitional members. These members were accepted by S.A.C.S (1980) with the Middlewater Shale Member being renamed the Britskraal Member, however the Britskraal Member is considered to be present only between 24°E to 26°E (Johnson 1976, S.A.C.S. 1980). The lower contact with the Fort Brown Formation is considered to be conformable and is represented by an increase in sandstone horizons.

The stratigraphic units encompassing the upper Ecca Group in the western parts of the main Karoo Basin differ from those in the southern parts (S.A.C.S 1980, Wickens 1994). While the Waterford Formation extends to the western part of the basin, the underlying Fort Brown Formation is replaced by the Tierberg Formation (Johnson et al. 1996).

1.2.2 Lithology

The Fort Brown and Waterford formations display significantly different lithologies. Much of the Fort Brown Formation comprises dark grey to black flat bedded and ripple-laminated mudrocks. Calcareous concretions may occur throughout the Formation (Johnson and le Roux 1994). Isolated sandstone horizons occur in the basal and uppermost reaches (Kingsley 1977). The sandstones may be massive or contain horizontal, cross- or wavy stratification. The inconsistent stratigraphic position of these sandstone horizons has hampered the placement of an upper boundary for the Fort Brown Formation, and therefore the Ecca Group, in the areas east of 26°E (Johnson and le Roux 1994).

The Waterford Formation is considerably more arenaceous than the underlying Fort Brown Formation and contains a suite of distinctive sedimentary features (Johnson 1976, Rubidge 1988, Rubidge et. al 2000). Intercalated beds of mudstones and siltstones are abundant, with the surfaces of the siltstones preserving rippled topography. Large ball-and-pillow structures are common within sandstone beds (Johnson 1976, Rubidge 1988, Rubidge et al. 2000).

1.2.3 Depositional Environment

The rocks of the Ecca Group were deposited in the main Karoo Basin during the Early and Middle Permian (Smith et al. 1993). The southern margin of the basin comprised high-lying areas formed during the Cape Orogeny (Rubidge 2005). Sediments were derived from these high-lying areas and deposited in the basin, which became progressively shallower with time. The basal formations of the Ecca Group (Prince Albert, Whitehill and Collingham formations) represent sedimentation at the greatest water depth (Kingsley 1977). The overlying Ripon Formation comprises extensive turbidite deposits, while the rocks of the Fort Brown Formation are considered to represent deposition at a shallower water depth to that of the underlying sequences (Johnson 1976, Visser and Loock 1979). The sedimentary rocks of the Waterford Formation are postulated to have been deposited in shallow water proximal to the palaeoshoreline (Johnson 1976, Rubidge 1988, Rubidge et al. 2000). The depositional setting of the Fort Brown and Waterford formations are of particular relevance to this study and are therefore discussed further.

The depositional setting of the Fort Brown Formation is considered to be that of a prodelta (Johnson 1976, Kingsley 1977, 1981, Rubidge 1988, Johnson and le Roux 1994) with the conformably overlying Waterford Formation considered to represent a delta front depositional setting (Johnson 1976, Rubidge 1988). Elements of the inter-distributary bay, subaqueous channels, levees and splays have been identified (Rubidge 1988, Rubidge et al. 2000)

and lend support to this interpretation. The entire deltaic sequence, encompassing the prodeltaic deposits of the Fort Brown Formation, the delta front deposits of the Waterford Formation and the subaerial delta plain deposits of the Koonap Formation (Beaufort Group), is considered to be regressive in nature (Rubidge et al. 2000).

1.3 Beaufort Group

1.3.1 Stratigraphy

Rogers (1903) formulated the "Karroo System" which he in turn subdivided into four ‘Series’. He considered the "Beaufort Series" to incorporate the sedimentary rocks, which contained reptile fossils. Further divisions, based on fossil assemblages (Broom 1906, Kitching 1970), were proposed, but these biostratigraphic subdivisions did not resolve the lithostratigraphy of the Beaufort Group. Johnson (1976) proposed that the Beaufort Series be renamed the Beaufort Group according to the internationally accepted nomenclature (ISSC. 1976). Johnson (1976) also proposed a new stratigraphic framework for the Beaufort Group, which was later accepted by the South African Committee for Stratigraphy with minor modifications (S.A.C.S. 1980), and remains the currently recognized framework.

The Beaufort Group in the southern Karoo Basin is divided into the lower Adelaide Subgroup and the overlying Tarkastad Subgroup on the basis that the Tarkastad Subgroup has a greater abundance of sandstone and red mudstone. The lithostratigraphic boundary between the two subgroups is considered to be the base of the Katberg Sandstone (Johnson 1976, S.A.C.S 1980). The Adelaide Subgroup contains part of the rock sequence that concerns this project and is therefore discussed further.

The Adelaide Subgroup extends throughout the southern Karoo Basin although the nomenclature of the subordinate formations differs east and west

of 24°E. In the western part of the basin the Adelaide Subgroup comprises the Abrahamskraal and Teekloof formations, while in the eastern areas it comprises the Koonap, Middleton and Balfour formations (S.A.C.S 1980). The lateral correlation between these two sets of formations is uncertain and has been described as gradational (Smith et al. 1993). The Abrahamskraal and Koonap formations are considered to be laterally equivalent while the Teekloof Formation is considered to be laterally equivalent with the Middleton and lower Balfour formations (Smith 1990, Smith et al. 1993). The study area lies east of 24°E where the Adelaide Subgroup comprises the Koonap, Middleton and Balfour formations.

The Koonap Formation is the lowermost lithostratigraphic unit of the Beaufort Group present in the southern Karoo Basin east of 24°E. It was originally included in the "Ecca Series" as the "Upper Ecca" by Mountain (1946). Johnson (1966, 1976) renamed it the "Koonap Formation" and placed it in the Beaufort Group. The Koonap Formation initially included three members at the base, namely the Waterford, Middlewater Shale and Transitional members, which were later removed and placed in the Ecca Group as the Waterford Formation (Johnson 1976). The lithostratigraphic contact with the underlying Ecca Group differs east and west of 26°W. To the west of the study area the Koonap Formation overlies the Waterford Formation and the contact is considered to be an arenaceous unit representing a palaeoshoreline (Rubidge 1987, Rubidge et al. 2000). To the east the Waterford Formation is considered to be absent, and the Ecca-Beaufort contact is placed at the top of the Fort Brown Formation (Johnson 1976). This study attempts to add clarity to this poorly understood contact as this has implications for the current basin development models proposed for the Karoo Basin (Catuneanu et al. 1998, Rubidge et al. 2002).

1.3.2 Depositional environment

The rocks of the Adelaide Subgroup in the Southern Karoo Basin are

considered to represent terrestrial fluvial deposits (Johnson 1976, Kingsley 1977, Visser and Dukas 1979, Stear 1980, Kingsley 1981, Rubidge 1988), deposited in the foredeep of the southern Karoo Basin during the Late Permian (Catuneanu et al. 1998, Catuneanu and Bowker 2001). The Koonap and Middleton formations comprise sandstones deposited by high sinuosity fluvial systems with extensive argillaceous overbank deposits (Kingsley 1981, Catuneanu et al. 1998, Catuneanu and Bowker 2001). The fluvial systems within the Koonap and Middleton formations in the eastern part of the Eastern Cape Province are considered to be controlled by the palaeoslope and the proximity to the southern limb of the Cape Fold Belt (Catuneanu and Bowker 2001).

1.3.3 Palaeontology and Biostratigraphy

Since the first discovery of fossil tetrapods in the Beaufort Group by Andrew Geddes Bain (1856), these rocks have yielded a significant number of tetrapod fossils. Their presence or absence has in the past been used to distinguish the Beaufort from the underlying Ecca Group (Rogers 1903). Early workers noted that the faunal composition of the rocks of the Beaufort Group was not homogenous throughout the succession and Seeley (1892) was the first to propose a biostratigraphic subdivision for this Group in which he recognised 1) a lower Zone of Pareiasaurians, 2) a middle Zone of Dicynodonts, and 3) an upper Zone of highly specialised Theriodonts. Broom (1906) proposed a more refined system with six biozones, which formed the basis for all subsequent biostratigraphic work. Watson (1914) proposed minor changes to Broom's (1906) classification including the renaming of the *Pareiasaurus* beds as the *Tapinocephalus* Zone.

Kitching (1970, 1977) re-examined the biostratigraphy of the Beaufort Group. He did not regard the *Procolophon* zone of Broom (1906) and Watson (1914) as a valid zone due to its extremely thin nature, and the co-occurrence of *Procolophon* with *Lystrosaurus,* and so included this zone within the

Lystrosaurus Zone. Kitching (1970, 1977) also replaced the *Endothiodon* and *Kistecephalus* zones with the *Cistecephalus* and *Daptocephalus* zones. This resulted in a five-fold biostratigraphic subdivision for the Beaufort Group. Keyser and Smith (1977) introduced the term "Assemblage Zones" to describe the biostratigraphy and proposed seven assemblage zones within the Beaufort Group. They subdivided the *Tapinocephalus* Zone into the Dinocephalian and *Pristerognathus/Diictodon* Assemblage Zones and similarly the *Cistecephalus* zones into the *Aulacephalodon bainii* and *Tropidostoma microtrema* assemblage zones. Keyser (1979) and S.A.C.S. (1980) introduced slightly different nomenclature for the assemblage zones in which they named each of the zones after the two most diagnostic fossils found within. Rubidge et al. (1995) reverted back to naming the assemblage zones after only a single diagnostic fossil in accordance with current internationally accepted naming practice.

A new assemblage zone, The *Eodicynodon* Assemblage Zone, was included at the base of the Beaufort Group to incorporate the oldest and most primitive therapsid fauna found within the main Karoo Basin. This assemblage zone has a limited extent and is restricted to the base of the Abrahamskraal Formation in the southwestern Karoo Basin (Rubidge 1990, Rubidge 1995).

The biostratigraphy of the southern Karoo is well known in the western parts of the Beaufort basin, but is presently unknown in the southeastern areas (S.A.C.S. 1995). It is known that the assemblage zones present directly above the Ecca-Beaufort Group contact are younger in both northerly and easterly directions relative to the southwestern Karoo Basin (S.A.C.S. 1995, Modesto et al. 2001, Welman et al. 2001, Rubidge et. al 2002). This suggests that the biozone(s) present in the eastern part of the Eastern Cape Province are younger than the *Eodicynodon* Assemblage Zone. Modesto et al. (2001) reported a dinocephalian fauna in the lowermost part of the Koonap Formation north of Grahamstown, suggesting the presence of the *Tapinocephalus* Assemblage Zone in the lower part of Koonap Formation. No tetrapod fossils

were recovered from the immediate vicinity of the Ecca - Beaufort contact and so exactly which assemblage zone present on the contact is unknown. A similar situation also exists with regards to the Koonap-Middleton formation contact.

1.3.3.1 *Eodicynodon* Assemblage Zone

The *Eodicynodon* Assemblage Zone was proposed by Rubidge (1990) as the lowermost biozone of the Beaufort Group to embrace rocks containing the primitive dicynodont *Eodicynodon* and the primitive dinocephalian *Tapinocaninus*. This assemblage zone is currently considered to occur only along the southwestern margin of the Karoo Basin. The rocks in which fossils of the *Eodicynodon* Assemblage Zone occur were originally included in the Ecca Group (Barry 1970) but are now considered to form the base of the Abrahamskraal Formation (Rubidge 1988, Rubidge 1990, Rubidge 1995). The tetrapod fossil fauna from this assemblage zone is considered to be most primitive present in the rocks of the Karoo Basin (Rubidge 1987, Rubidge 1988)

1.3.3.2 *Tapinocephalus* Assemblage Zone

Boonstra (1969) performed a comprehensive survey of the fossils collected from the *Tapinocephalus* Zone of the southern Karoo Basin, in which he compared both the number of species and specimens to the three subdivisions proposed by Rossouw and de Villiers (1952). Boonstra (1969) found that the overall number of described species decreased from the lower to the upper subdivision of the *Tapinocephalus* Zone. He also analysed the relative abundance of herbivorous, carnivorous and insectivorous species within the *Tapinocephalus* Zone and noted a sharp decrease in the abundance of all taxa from the lower to the upper *Tapinocephalus* Zone. Boonstra (1969) further noted that the number of dicynodont specimens increased dramatically from the lower to middle *Tapinocephalus* Zone and

then abruptly decreased. A similar but less dramatic change was also noted for the Therocephalia.

Loock et al. (1994) noted a similar change in the faunal composition within the *Tapinocephalus* Assemblage Zone, with the lower part being dominated by large dinocephalians and the upper part by small dicynodonts. More importantly this faunal changeover was correlated with the contact between the Koornplaats and Wilgerbos members of the Abrahamskraal Formation. It is not known whether a similar situation exists in the southeastern parts of the main Karoo Basin.

Smith and Keyser (1995) did not support the three subdivisions of the original *Tapinocephalus* Zone (Rossouw and de Villiers 1952, Boonstra 1969). They consigned the upper *Tapinocephalus* Zone (Boonstra 1969) to the *Pristerognathus* Assemblage Zone and recognised the *Tapinocephalus* Assemblage Zone as containing *Tapinocephalus* (Dinocephalia) and *Bradysaurus* (Captorhinida) and not *Eodicynodon* (Dicynodontia) or *Tapinocaninus* (Dinocephalia). Overall they considered the presence of large dinocephalians and small dicynodonts to be characteristic of this assemblage zone. The *Tapinocephalus* Assemblage Zone is considered to be present in the southwestern Karoo Basin (Smith and Keyser 1995). For much of the area the base of this zone coincides with the Ecca-Beaufort boundary, with the exception of the southwestern margins of the Karoo Basin where the older *Eodicynodon* Assemblage Zone underlies it.

1.3.3.3 *Pristerognathus* Assemblage Zone

Keyser and Smith (1977) proposed that the Upper *Tapinocephalus* Zone (Boonstra 1969) be recognised as the *Pristerognathus* / *Diictodon* Assemblage Zone. The lower boundary was marked by the absence of dinocephalians and the upper boundary by the absence of the therocephalian *Pristerognathus*. Keyser and Smith (1979) noted that the fossil content of this

assemblage zone was low in comparison with the other assemblage zones. This assemblage zone is present in the southwestern Karoo Basin and is considered to thin towards the north and east (Smith and Keyser 1995).

As shown above, different assemblage zones are present in the rocks of the Ecca-Beaufort contact around the main Karoo Basin. Progressively younger assemblage zones are present along the contact in both a northerly and easterly direction, which has been used as supporting evidence for the diachroneity of the Ecca-Beaufort contact (Welman et al. 2001, Modesto et al. 2001, Rubidge et al. 2002). The assemblage zones present in the lower Beaufort of the southeastern part of the Karoo Basin are presently unmapped but Modesto et al. (2001) have reported the presence of *Tapinocephalus* Assemblage Zone fossils in this area.

1.4 Ecca-Beaufort Contact

1.4.1 Lithostratigraphy

The exact stratigraphic position of the Ecca-Beaufort contact has been the subject of debate as a result of the different criteria used by various workers (Mountain 1946, Visser and Loock 1974, Visser et al. 1980, Smith and Zawada 1988, Zawada and Cadle 1988, Rubidge 1988, Rubidge et al. 2000). The interpretation of the contact has varied from that of the first appearance of red mudstones (Mountain 1946) to a change in the suite of lithological and palaeontological characters (Rubidge et al. 2000).

Mountain (1946) and Rossouw et al. (1953) regarded the contact between the Ecca and Beaufort groups in the southern Karoo as the lowermost red mudstone. The basis for this contact was that these mudstones reflected a change in climatic conditions prevailing at the time of deposition, and so could possibly allow for correlation across the southern Karoo. Later workers pointed out that the stratigraphic height of the lowest red mudstone is highly

variable (Johnson 1976, Keyser and Smith 1979, Johnson and le Roux 1994).

Keyser and Smith (1977) performed extensive collecting of vertebrate fossils in the western part of the basin in order to establish correlations between the biozones and the lithostratigraphy. An important observation was made in that, firstly, the basal strata of the Beaufort Group were diachronous, and so the boundaries between lithological entities needed to be defined on lithological criteria as apposed to the then current chronostratigraphic definitions. The definition of the base of the Beaufort Group in the western part of the basin was considered by Keyser and Smith (1979) to be the lowest occurrence of red mudstone on the sole basis that it was easily identified and therefore mappable.

Visser and Loock (1974) recognised a transition from prodelta deposits of the upper Ecca Group to fluvial deposits in the lower Beaufort Group in the central Free State Province. The Ecca - Beaufort Group contact was here considered to be a transitional zone representing delta front deposition. The lithological contact proposed was considered to be the base of a “zone showing slump structures” (Visser and Loock 1974 pg 372). Visser and Loock (1974) also recognised that the proposed lithostratigraphic contact could not be synchronous by definition. Nel (1977) and Lemmer (1977) considered the lithological contact between the Ecca and Beaufort groups in the Free State to be the first prominent sandstone above the shales of the Tierberg Formation on the basis that this was an easily recognisable and mappable feature. They recognised the change from deepwater to deltaic and fluvial deposition and, as such, concurred with Visser and Loock (1974).

S.A.C.S. (1980) defined a number of criteria, which distinguished the sedimentary rocks of the Ecca Group from those of the Beaufort Group. The differences are summarised in Table 1.

Ecca Group.	**Beaufort Group.**
Argillaceous rocks display platy weathering.	Argillaceous rocks display blocky weathering.
No red mudstones are present.	Red mudstones are present.
Cross-stratified sandstones are rare.	Cross-stratified sandstones are common.
Upward-fining fluviatile sequences are absent.	Upward-fining fluviatile sequences are present.
The Ecca Group consists primarily of fines.	The Beaufort Group has a significant abundance of sandstone.
Mesosaurus is the only tetrapod fossil fauna found in the Ecca Group.	Terrestrial tetrapod faunas are common.

Table 1: Summary of major differences between the lithologies of the Ecca and Beaufort groups (S.A.C.S 1980).

These criteria are useful in distinguishing the Ecca Group from the Beaufort Group and have been expanded upon by Rubidge et al. (2000). S.A.C.S. (1980) regarded these differences as representing a change from a marine to a terrestrial depositional environment. The Ecca-Beaufort Group boundary was considered to be diachronous in nature but S.A.C.S. (1980) did not elaborate on any specific placement of the lithostratigraphic boundary, probably indicating the uncertainty of the boundary's placement at that time.

Jordaan (1981) considered a number of possible alternatives for the positioning of the contact in the western Karoo Basin. He concluded that the top of the delta plain deposits provided a clear lithostratigraphic boundary as

this separated the predominantly argillaceous fluvial flood plain deposits from the underlying arenaceous delta plain deposits.

Rubidge (1987, 1988) disagreed with Jordaan's (1981) interpretation in that the Ecca-Beaufort contact in the southern Karoo Basin did not show a sudden change from subaerial delta plain deposits to fluvial deposits. He considered the contact to be at the top of thesubaqueous delta plain (delta front) deposits of the Waterford Formation and also noted that this transition occurred only once in the sequence. Rubidge (1987, 1988) considered the palaeontological representation across the contact to manifest a distinct change in palaeo-environments. Tetrapod fossils and well-preserved plant impressions were reported to occur above the palaeoshoreline but were absent below it. Silicified wood and finely commuted plant material were found beneath the shoreline position but were absent above it. These differences were used as additional criteria to differentiate between the deltaic and fluvial environments, and similarly the rocks of the Ecca and Beaufort groups.

Zawada and Cadle (1987) considered the work that had been done by previous workers on the Ecca-Beaufort contact in the Free State Province (Visser and Loock 1974, Nel 1977, Lemmer 1977) in order to define a recognisable boundary. They argued that the contact should be defined purely on lithological criteria, as these are less interpretative in nature. The authors considered four possible lithological boundaries. They favoured the first prominent sandstone as being representative of the contact, as this was considered to be an easily identifiable feature in the northern part of the basin where the outcrop is poor.

The recognition of the change in depositional environments represented by the rocks of the upper Ecca and lower Beaufort groups (Johnson 1976; Jordaan 1981; Rubidge 1988) has led to the use of combinations of characters in the description of the contact. Rubidge (1988) and Rubidge et al. (2000) regarded sedimentary characteristics, as well as palaeontological

changes, as important indicators of the position of the contact.

Rubidge (1987, 1988) and Rubidge et al. (2000) considered the contact between the Ecca and Beaufort groups in the Southern Karoo to be represented by a palaeo-shoreline. The shoreline separated the delta front and delta plain depositional environments and so, importantly, established a link between the depositional environments and the lithostratigraphic boundary. These authors also considered the sequence as a whole to represent a continuous progradation of deltaic deposits into the Ecca Sea which is a similar model to those proposed by Johnson (1976) and Kingsley (1981).

The Ecca-Beaufort contact in the KwaZulu-Natal Province is poorly understood. Here the Ecca-Beaufort contact is currently placed at the boundary between the Volksrust (Ecca Group) and Estcourt (Beaufort Group) formations (S.A.C.S 1980). Wright (2002) placed the contact in the Estcourt Formation where he considered a change from a subaqueous to subaerial depositional environment to occur. The criteria used for this boundary placement are similar to those proposed in other parts of the Karoo Basin (Johnson 1976, Kingsley 1981, Rubidge et al. 2000).

In the area north of Grahamstown the Ecca-Beaufort contact is mapped as the contact between the Fort Brown Formation (Ecca Group) and the Koonap Formation (Beaufort Group) (Johnson 1976). Here the contact is currently defined as "a horizon above, which a marked increase in the relative sandstone abundance occurs" (Johnson and le Roux 1994 pg 18). This is clearly anomalous with the rest of the southern Karoo Basin and thus requires further investigation.

1.4.2 Depositional Environment

Consensus has largely been achieved with regards to the depositional

environments that resulted in the lithologies of the upper Ecca and lower Beaufort groups. Most workers in the southern and western Karoo Basin agree that the sedimentary rocks of the Upper Ecca represent subaqueous deposition. In particular the upper reaches of thick argillaceous sequence contained within the laterally equivalent Fort Brown and Tierberg formations of the upper Ecca are considered to have been deposited in the prodelta environment (Smith et al. 1993). The rocks of the Waterford Formation are considered to have been deposited in a delta front setting with the overlying rocks of the Beaufort Group representing subaerial deposition (Visser and Loock 1974, Johnson 1976, Nel 1977, Lemmer 1977, Kingsley 1981, Rubidge 1988, Johnson and le Roux 1994, Rubidge et al. 2000)

An alternative to the fluvial-deltaic model for the Ecca-Beaufort transition in the northeastern part of the Northern Cape was put forward by Smith and Zawada (1988). They accepted that the Tierberg Shales of the upper Ecca were deposited in deep water, however challenged the idea that the transition represented a deltaic setting. They proposed instead that the transitional rocks between the Ecca and the Beaufort groups represented a shallow marine shelf. The sedimentary features within the transition were attributed to wave and storm processes. Kingsley (1981) considered the rocks of the Fort Brown and Koonap formations in the Eastern Cape Province to represent a transition from deepwater and delta front depositional environments through to fluvial depositional environments. His interpretation agrees with that of Johnson (1976) and similar models were proposed by later workers in the southern Karoo Basin (Visser and Loock 1974, Nel 1977, Rubidge et al. 2000). Kingsley considered the onset of delta front deposition to occur in the upper part of the Fort Brown Formation. This depositional model is currently accepted for the rocks in the eastern part of the Eastern Cape Province (Johnson and le Roux 1994).

1.5 Age

Palaeontological evidence and biostratigraphic correlation has indicated that the Ecca-Beaufort contact is diachronous around the basin (Welman et al. 2001). The fauna of the *Eodicynodon* Assemblage Zone represents the oldest terrestrial tetrapod fauna found within the rocks of the Beaufort Group (Rubidge 1990, Rubidge 2005). This assemblage zone is restricted to the southwestern margin of the Karoo Basin indicating that the rocks of the Beaufort Group in that region are oldest (Rubidge 1995). The tetrapod fauna present in the rocks of the lowermost Beaufort Group in the northwestern and eastern parts of the Karoo Basin are younger than those of the *Eodicynodon* Assemblage Zone and so indicate that the Ecca-Beaufort contact youngs in a northerly and easterly direction (S.A.C.S. 1995, Welman et al. 2001, Modesto et al. 2001).

The age of the Ecca-Beaufort contact in the foredeep region of the main Karoo Basin is considered to be Late Kazanian to Early Tatarian (Catuneanu et al. 1998, Catuneanu et al. 2002) with palaeontological evidence indicating that the contact becomes progressively younger in an easterly direction (Rubidge et al. 1995; Gow and de Klerk 1997; Modesto et al. 2002).

Consensus has been reached in the southern, western and central Karoo Basin regarding the depositional setting of the upper Ecca and lower Beaufort groups (Jordaan 1981, Kingsley 1981, Rubidge 1988, Rubidge et al. 2000). The lithological contact in these areas is currently recognised as a change in depositional style reflected in the lithologies present (Rubidge et al. 2000). While the depositional setting of the upper Ecca and lower Beaufort groups in the southeastern part of the basin broadly concurs with that proposed for the southern and western parts of the basin (Jordaan 1981, Kingsley 1981, Rubidge 1988, Rubidge et al. 2000), the lithological contact has not been properly defined. The Ecca-Beaufort contact in the southeastern part of the basin is currently mapped at the contact between the Fort Brown and Koonap

formations, and is regarded as transitional in nature (Johnson and le Roux 1994). This project attempts to resolve the positioning and definition of the contact in the southeastern part of the Karoo Basin by using a combination of sedimentological and palaeontological studies, as has been recently used in other parts of the basin (Rubidge et al. 2000).

2 AIMS AND METHODS

In the southeastern Karoo Basin the Ecca - Beaufort contact has in the past been mapped (Figure 1) at the boundary between the Fort Brown (upper Ecca) and Koonap (lower Beaufort) formations (Geological Sheet 3326 Grahamstown). The nature of this contact is poorly understood with the top of the Fort Brown Formation being considered as “a horizon above which a marked increase in relative sandstone abundance occurs” (Johnson and le Roux 1994, pg 18). Johnson and le Roux (1994) conceded that the boundary is ambiguous and refer to the contact as the “Fort Brown – Koonap transition zone” (pg 18). As previously noted this at odds with the situation to the west where the Waterford formation occurs between the Fort Brown and Koonap formations. The primary aim of this study attempts to address this ambiguity by accurately mapping out the contact based on the currently accepted criteria for the southern and western Karoo Basin.

2.1 Study Area

Exposure of the upper Ecca and lower Beaufort groups in the Albany district north of Grahamstown is poor due to the relatively high vegetational cover. This has led to a limited understanding of the contact between these two groups. The geographic position of the upper Ecca and lower Beaufort groups (Figure 2) was established using the 1:250 000 geological maps (Map 3326 Grahamstown), 1:50 000 topographic maps (sheets 3326AA, 3326AB, 3326BA) and 1:10 000 aerial photographs (Job 1005, strip 991 - 1005).

Three sites, providing reasonable exposure from the uppermost Ecca and lowermost Beaufort groups were chosen during a reconnaissance field visit during February 2004 (Figure 3, Figure 4, Figure 5). At this time tetrapod fossils had recently been recovered from the vicinity of the central study site,

which assisted in the understanding of the biostratigraphy of the lowermost Beaufort Group in this area (Modesto et al. 2001, Rubidge *pers. comm*).

2.2 Aims

The primary aims of this study are as follows:

1: To accurately document the lithostratigraphy and identify the facies on the contact between the Ecca and Beaufort groups.
2: to document all significant palaeontological occurrences and there exact stratigraphic positions.
3. Establish the depositional setting for the rocks of the Upper Ecca and Lower Beaufort groups present in the study area.
4. Establish the vertebrate assemblage zone(s) present in the rocks of the lowermost reaches of the Koonap Formation.

2.3 Methodology

At each of the chosen sites the lithological succession covering the currently mapped Ecca-Beaufort contact was measured using a Jacobs' staff and Abney level to create three vertical profiles (Figure 6). This method allowed for the accurate measurement of moderately dipping strata as is present in the study area.

The structural setting within the study area consists of open synclines and anticlines, which resulted from the Cape orogeny (Kingsley 1977, Johnson and le Roux 1994). Fortunately, for the purposes of measuring stratigraphic sections, the folding is not severe resulting in only gentle to moderate dip angles. The study sites were searched thoroughly for fault structures, which are a common occurrence in the area. Fault structures were found in the eastern study site but the displacement is minimal.

The Ecca-Beaufort contact in the southern Karoo Basin has been the subject of recent research, which has resulted in the identification of three distinct lithofacies associations (Rubidge 1988, Rubidge et al. 2000). In order to establish the nature of the contact in the study area, the facies definitions within these associations are used.

Lateral profiling is an essential tool for interpreting the depositional style of sedimentary sequences (Miall 1977, 1996). The type section of the Koonap Formation was used for lateral profiling as it provided the best exposures in the form of road cuttings. Line diagrams displaying the bounding surfaces and sedimentary structures were drawn onto photographic mosaics. The methods follow those proposed by Miall (1996).

Geostatistically a Chi-Squared test was used to find associations between facies and so provide the basis for erecting lithofacies associations. The interpretation of depositional environments is considered to be more reliable when based on lithofacies associations as apposed to individual facies (Boggs 1995). In addition lateral profiling was used to assist in interpreting the fluvial depositional environment. Results were compared with results from the southern Karoo Basin (Kingsley 1981, Rubidge 1988, Rubidge et al. 2000).

Palaeontological data was collected by searching available outcrop. Due to the rarity of fossil tetrapod remains in the area, all tetrapod specimens were collected. The associated lithology and taphonomy was recorded, as well as the coordinates of the fossil with the aid of the Global Positioning System (GPS) and 1:50 000 topographic maps. Specimens were prepared at the Bernard Price Institute for Palaeontology (BPI). Fossil plant material is more common and good examples were photographed. Unusual palaeobotanical specimens were collected and the lithological setting and GPS coordinates recorded. All the collected specimens were mechanically prepared with the aid of compressed air drills. The locality and co-ordinates of the fossil was

recorded and the stratigraphic position recorded on the vertical profiles. This information is presented in Appendix A.

3 GEOLOGY OF STUDY AREA

The study area, as currently mapped (Scale 1:250 000 Geological Sheet 3326 Grahamstown), covers the rocks of the Fort Brown and Koonap Formation, thus incorporating the Ecca-Beaufort contact.

In the southern parts of the study area the Fort Brown Formation is easily identified by an extremely flat topography. This geomorphology is due to the highly argillaceous composition of this Formation, resulting in a high weathering rate. The geomorphology of the Koonap Formation differs markedly from the Fort Brown Formation as differential weathering of this unit generates a positive topographic relief. This is due to the presence of prominent sandstone horizons, which are laterally continuous for a few hundred meters. The Koonap Formation is however predominantly also argillaceous and contains thick packages of fines. These weather easily resulting in numerous gullies running in an east-west direction. The high argillaceous content is responsible for a high rate of alluvium generation, which in turns obscures much of the potential outcrop in the area.

In order to describe the lithology the concept of “lithofacies” is used (Reading 1984). Lithofacies define horizons with a unique set of sedimentological features. The lithofacies definitions follow that of Rubidge (1988), Miall (1996) and Rubidge et al. (2000) and which have been successively applied to other parts of the southern Karoo Basin at the equivalent stratigraphic interval (Rubidge 1988, Rubidge et al. 2000). The bases of the facies are defined according to Reading (1984). In accordance with previous work (Rubidge 1988) the lithofacies are grouped into three “Lithofacies Associations” which allows for a direct comparison with other parts of the southern Karoo Basin.

The overall grainsize composition of the three lithofacies associations are recorded in Table 2 below. All measurements are based on the observable

outcrop. Lithofacies Association 2 (Table 2) has the highest sandstone abundance at all three sites which contrasts with the other two Lithofacies Associations.

	Western		Central		Eastern	
	Fines	Sandstone	Fines	Sandstone	Fines	Sandstone
LFA1	>99%	<1%	>99%	<1%	>99%	<1%
LFA2	36%	64%	27%	73%	57%	43%
LFA3	63%	27%	77%	23%	64%	36%

Table 2: Percentage of fines versus sandstone of the three facies associations at the three study sites.

3.1 Lithofacies Association 1.

This lithofacies association occurs beneath the lowermost sandstone (Figure 6) and comprises a thick argillaceous sequence, which upon weathering results in a distinctive flat topography.

Dark blueish-grey (10B 2.5/1) to greyish-black (5B 3/2) mudstone predominates and comprises thin planar beds with abrupt bases (Figure 7). Thin (<1cm) light brown siltstone laminae become more prevalent towards the top of Facies Association 1 interval suggesting a slight increase in depositional energy (Ridente and Trincardi 2005). Thin (0.5m thick) sandstone bodies with convex bases and relatively flat top surfaces (Figure 8) are present in the uppermost part of this lithofacies association at Coniston but were not observed at other localities in the study area. Calcareous horizons are present within this facies at Signal Hill (Figure 9) but were not observed elsewhere.

Bedding plane surfaces contain a variety of trace fossils, abundant vertical and horizontal burrows, infilled with siltstone and fine-grained sandstone (Figure

10) were observed throughout the study area. Horizontal feeding traces (Figure 11) were also found to be abundant at all localities. Plant fossils are present on the bedding plane surfaces throughout the study area but typically comprise small fragments of leaves and stems (Figure 12). Abundant weathered out wood fragments were observed on the farm Signal Hill but were not found in the areas to the east.

The fine-grained nature of the rock coupled to the paucity of cross-lamination indicates that it was deposited by suspension settling (Selley 2000). The dark colouration is probably due to a high organic content as with equivalent facies in other parts of the southern Karoo Basin (Johnson 1976; Rubidge et al. 2000).

3.2 Lithofacies Association 2.

This lithofacies association comprises five lithofacies which can be recognised throughout the study area.

3.2.1 Facies A.

Facies A comprises alternating beds of sandstone and mudstone and is present throughout the study area but is more abundant in the western areas particularly at Signal Hill. The eastern study area contained only a single horizon in the upper reaches of the section measured on Fort Brown-Peninsula Outspan (Figure 6).

The coarser-grained beds consist of brownish grey (5YR 4/1) ripple-laminated sandstone while the finer-grained beds comprise dark blueish-grey (10BP 2.5/1) horizontally laminated siltstone and mudstone. The contact between the beds is always abrupt. Symmetrical ripples are abundant in the coarser-grained beds. Amplitudes range from 5 to 40mm with wavelengths ranging from 30 to 130mm resulting in an average ripple index of 7.3 (n=33). The crest

lines are either straight (Figure 13) or sinuous (Figure 14). Both sharp and round crested ripples were observed with the latter suggesting post-depositional reworking by the oscillatory motion of waves (Reineck and Singh 1973).

Fossils are is not abundant in the sandstone beds at any of the study sites with the only fossils comprising densely packed horizontal feeding traces on some of the exposed ripple surfaces (Figure 15).

The beds within this facies represent deposition under different energy conditions. The finer-grained beds contain low energy flat bedding which indicates that deposition occurred primarily via the process of suspension settling (Boggs 1996). The ripple-lamination present in the coarser-grained beds, as well as the abrupt and erosional bases, indicate higher flow regime conditions (Reineck and Singh 1973). The rhythmicity of the beds suggets that the depositional system was pulsatory in nature.

3.2.2 Facies B

This lithofacies incorporates dark blue/grey (10B 2.5/1), horizontally bedded fine-grained mudstones or siltstones (Figure 16). The lower and upper contacts of this lithofacies are either abrupt or gradational.

Facies B is present at all localities and is more abundant in the lower reaches of the Facies Association 2 sequence (Figure 6). At places it grades vertically or laterally into Facies A.

Bioturbation in the form of horizontal burrows is present at many places within this facies. A single example of a burrow structure similar to that of *Plagiomus* (Anderson 1974) was observed on Signal Hill (Figure 17), but the structure differs from *Plagiomus* in that it is substantially smaller in size. Fragmentary palaeoniscid fish scales were observed within this facies at Carlisle Bridge (Figure 18).

3.2.3 Facies C.

This facies (Figure 19) comprises thin (<0.5m) light brown (5YR 5/8) sandstones that have a lenticular geometry. The lateral extent of the beds is difficult to ascertain due to the limited extent of the available outcrops. Internally the beds are either horizontally or ripple-laminated. The bases are always erosional. No fossils were observed in these beds.

Facies C is present at all localities but comprises a small percentage of the overall lithologies. The beds are more common towards the upper part of the Facies Association 2 sequence (Figure 6) The thin nature of the beds and abrupt upper and lower contacts together with their lenticular geometry covering a wide area suggets that these represent subaqueous splay and channels (Rubidge 1988).

3.2.4 Facies D.

Facies D comprises thick (>0.5m) beds of blue-ish grey (5B 7/1) horizontally bedded sandstone. Glauconite was found to be present in some samples (Figure 20). The individual beds vary from 20cm to 1m in thickness. Internally the beds are either horizontally or ripple-laminated. The convex basal contacts (Figure 21) are always erosional and in many places contain flame structures where the sandstone overlies a finer-grained bed Figure 22). These sandstones are more laterally extensive than the Facies C sandstones and may extend in the excess of 100m. The maximum extent could not be ascertained because of the limited lateral extent of the available outcrop.

This facies is present at all localities and becomes more abundant towards the top of the Facies Association 2 sequence, thus producing the overall upper coarsening trend of this sequence (Figure 6).

Dense intraformational mud pebble horizons occur at places within Facies D sandstones (Figure 23). The pebbles are well rounded, fine-grained in nature

and may be up to 40mm in diameter. Imbrication is not apparent. Thin mud flakes resembling the 'acicular structures' of Rubidge (1988) also occur at various horizons. These structures are thought to represent the crests of ripples that have been reworked during high-energy subaqueous flows (Stauffer 1967, Tankard 1986).

The erosive nature of the basal contacts indicates relatively high energy conditions during the deposition of the beds as is indicated by flat bedding and dense pebble beds (Massari et al. 1986) This lithofacies is considered to represent density flows in subaqueous channels (Rubidge et al. 2000).

3.2.5 Facies E.

This lithofacies incorporates sandstones that contain prominent soft-sediment deformation in the form of ball-and-pillow structures (Figure 24). Facies E is abundant throughout the study area with particularly thick sequences present at Coniston (Figure 6). The beds comprise fine-grained sandstone and mudstone/siltstone. Most often the original bedding has been obscured by the intensity of the processes resulting in the soft sediment deformation. In places the primary sedimentary structure is occasionally preserved where the deformation is less intense. Preserved internal beds display horizontal and ripple cross-lamination.

The basal contacts of this lithofacies are generally abrupt or loaded, with flame structures present when the bed overlies an argillaceous lithofacies. The upper contact of this lithofacies is abrupt. The thickness of beds sets ranges from 0.5m to 26m. No trace fossils were observed in this lithofacies and this is probably due to the intense deformation that appears to have obscured any traces originally present.

The absence of co-orientated slump axes indicates that these structures are not slump structures but rather ball-and-pillow structures (Mills 1983). Ball-and-pillow structure result from a density inversion where relatively dense

strata collapse into less-dense underlying beds (Mills 1983). Elsewhere in the Karoo basin soft-sediment deformation has been interpreted as indicating the collapse of subaqueous channel banks (Rubidge et al. 2000).

3.3 Lithofacies Association 3.

Eight lithofacies, following the scheme of Miall (1977, 1996), were recognised in this lithofacies. These lithofacies occurred at all three study sites.

3.3.1 Facies Fl: Laminated Fines

Lithofacies Fl was defined by Miall (1996) as comprising interbedded siltstone and mudstone lamina. This lithofacies is the most abundant fine-grained fluvial facies in the study area and occurs at all localities (Figure 6). Beds comprise olive grey (75 GY 4/2) to olive brown (5YR 4/4) mudstone and siltstones. Greyish red (5R 4/2) beds are present on The Grant and Bucklands. The bases of the units may be abrupt or gradational.

Horizons of calcareous nodules occur within certain laminated beds at all localities in association with skew planes (Figure 25) indicating that these nodules were formed postdepositionally. Well-preserved tetrapod fossils and plant impressions were recovered from this facies on The Grant and Bucklands.

Suspension settling is responsible for the deposition of this lithofacies (Harms and Fahnestock 1965). This process is common in pools of water created during the flooding of the interchannel areas (Kraus 1999, Boggs 1996). Additionally, abandoned channels may also contain thick beds of laminated fines (Ghosh et al. 2006). The red colouration present at the top of the succession is typical of well-aerated soils and represents a change from reducing to oxidising conditions within the depositional succession (Retallack 1990, Kraus 1999).

3.3.2 Facies Fp: Pedogenic Carbonates

Facies Fp is regarded here as a subaerial facies containing structures relating to soil formation. Pedogenic carbonates are not abundant in the area but are present at all localities (Figure 6).

This facies comprises horizons of pale yellow (5Y 8/3) or weak red (5R 4/2) calcareous nodules and occur exclusively within horizontally laminated mudstones and siltstones. The maximum observed lateral extant of these horizons was approximately 20m reflecting the poor nature of the exposures rather than actual lateral extent. Skew planes are often present in association nodules. The slickenslides have steep dips (>60 degrees) and have no apparent preferred dip direction.

Nodules vary in size from 5mm to 600mm and are ellipsoidal in shape (Figure 26) with the long axis of the nodules lying within the bedding plane of the sedimentary strata containing the nodules. The external texture of the nodules is typically smooth. Septarian cracks are not common and were observed on Kwandwe and Bucklands (Figure 27). The width of the cracks ranged from 10mm to less than 1mm. Mudstone, probably derived from the laminated fines that the nodules occur in, fills the cracks.

Horizons of non-coalesced calcareous nodules are considered to represent weakly developed paleosols (Retallack 1990). The flattened nature of the nodules is similar to that reported in the other parts of the Karoo Basin where the process responsible for the flattening is considered to be the continuous aggradation of sediment during the precipitation of the nodules (Smith 1980). Associated slickenslides indicate that lithification occurred before the compaction of the sediment in which the nodules developed. Large, well-developed septarian nodules occur within the lowermost stratigraphic interval in the eastern study area indicating that a palustrine depositional environment existed.

3.3.3 Limestone facies

An unusual horizon comprising a brownish grey (5YR 4/1) limestone with an abrupt base was observed on The Grant. This horizon is 0.5m thick and comprised wavy lamina (Figure 28), which bear a strong resemblance to those present in algal matts horizons. The horizon extended for approximately 50m suggesting that it may be a lenticular body. Although this horizon was the only of its type observed in the area, it is important as a well-preserved dinocephalian skull and post-cranial elements were recovered from it (Figure 29). Carbonate horizons such as this are characteristic of lucustrine environments and have been documented in a variety of overbank deposits around the world (Puigdefabregas et al. 1986, Hirst and Nichols 1986).

3.3.4 Facies Sm: Massive sandstone

This facies comprises sandstone that displays no apparent primary structure. The lack of primary sedimentary structure may be atttributed to a wide variety of causes (Reineck and Singh 1973, Miall 1996) and can be the result of dewatering of the sediment after rapid dumping, slumping, metamorphism, or biological activity.

This lithofacies is not abundant but is present at all localities. The colour of the sandstone is moderate yellowish-brown (5Y 5/4). Large pyrite crystals were observed in this lithofacies on Bucklands (Figure 30) and freshly broken samples give off a distinct hydrogen sulphide odour.

3.3.5 Facies Sh: Horizontally stratified sandstone

Horizontally stratified sandstones consisting of tabular sets of faint horizontal laminae (Figure 31) are not abundant but are present at all localities. The co-sets comprise different lithologies ranging from fine-grained sandstone to darker siltstone separated by poorly defined horizontal contacts. The finer-grained sets may contain ripple lamination. The basal contacts of the beds are either abrupt or erosional. Parting lineations, which are considered to be

excellent palaeocurrent indicators were not observed in the study area. This facies was deposited under upper flow regime conditions (Reineck and Singh 1973)

3.3.6 Facies Sr: Ripple-laminated Sandstone

Ripple cross-lamination (Figure 32) is an extremely common primary sedimentary structure in fluvial environments and occurs widely throughout the stratigraphy of the study area (Figure 6).

The colour of these fine-grained sandstones varies from pale yellow (5Y 7/4) to pale yellowish brown (10YR 6/4). The basal contacts of this facies are either gradational or abrupt. Current ripples are present (Figure 33) and have a wavelength of 10mm to 60mm with amplitudes varying from 2 mm to 10 mm. An average of 7.11 was recorded for the ripple indices (n=10).

Bioturbation comprising horizontal feeding trails occur ripple surfaces (Figure 34). Body fossils are not abundant, but cranial material of a small unknown dicynodont was collected from this facies on The Grant.

Ripple cross-lamination is the product of ripple migration during the formation of ripples under low flow regime conditions (Allen 1982). Such conditions are extremely common in a variety of fluvial environments especially during waning flow (Reineck and Singh; Miall 1996).

3.3.7 Facies St: Trough cross-stratified sandstone.

In lateral profile orientated parallel to flow, trough cross-stratification consists of dipping lamina, resembling planar cross-stratification. However when viewed tangential to flow, the laminae are curved downwards conformable to the shape of the scour trough (Reineck and Singh 1973). Three dimensionally the lithofacies consists of troughs, with the axis of the trough orientated parallel to the downstream direction. This structure is considered to provide reliable palaeocurrent directions as they closely follow the course of the

thalweg (Miall 1996).

Trough cross-stratified sandstones (Figure 35) are found at all localities but are less abundant than ripple-laminated sandstones. The sandstone is greyish orange (10YR 7/4). When observable, the basal contact of trough cross-stratified beds is erosional. This lithofacies typically grades upwards into horizontal and ripple laminated sandstones in conjunction with a decrease in grainsize.

Beds vary in thickness from 0.1m to 1m. Exposed bedding plane surfaces were seldom encountered in the study area due to the generally poor outcrops, but when present, small-scale rib-and-furrow structures were observed. The width of the troughs ranges from 5cm to 30cm with depths seldom exceeding 1cm.

Trough cross-stratification is considered to be the result of the downstream migration of three-dimensional dunes, which form under the upper part of lower flow regime conditions (Reineck and Singh 1973). The dunes in plan view are lobate in shape. A scour shaped hollow is situated on the downstream side of the dunes and when sediment is deposited in the hollow the characteristic scour-shaped lamina is the result (Harms and Fahnestock 1965, Miall 1996).

In fluvial environments this lithofacies is considered to be common in the deeper parts of the channel where flow velocity is relatively high (Miall 1977). The upward transition to different fluvial facies is important as this indicates a change in flow regime conditions (Reineck and Singh 1973). The upward transition from flat bedding to ripple cross-lamination is common at all localities and indicates a waning in flow velocity (Boggs 1995).

3.3.8 Facies Se_i: Scour-filled sands with lag deposits.

Miall (1977) defined Facies Se_i as erosional scour surfaces filled with

mudstone clasts and lag material in a massive sandstone matrix. Such beds are present in the arenaceous horizons of Facies Association 3 throughout the study area. The beds are typically less than 10cm and are found exclusively at the base of tabular bedded sandstone beds. The conglowereates are matrix supported.

Clasts comprise sub-rounded intraformational mudstone which are less than 30mm in diameter (Figure 36). Imbrication is not apparent. The surrounding matrix comprises fine to medium-grained sandstone with no apparent bedding. No fossils were found in this facies with the exception of a single piece of amphibian bone material on Bucklands.

The mudstone clasts are derived from the overbank environment and either represent scouring of the floodplains during flood conditions, or the erosion of the clay soil sub-surfaces adjacent to the banks. Alternatively the collapse of cut-banks on the meander bends could have provided the intraclasts (Miall 1996). In any case the angular nature of the fine-grained clasts indicates limited transportation and rapid deposition. The lack of bedding structure in the sandstone matrix suggests that deposition occurred rapidly (Boggs 1996).

3.4 Statistical Analysis of Facies Associations

Facies Associations can be constructed by a number of methods including the visual inspection of vertical profiles and core logs, facies relationship diagrams and Markov Analysis. Visual inspection of vertical profiles and logs is the simplest method but may be subject to interpretational bias and so statistical techniques should rather be used (Miall 1973, Reading 1984, Xu et al. 1988).

Three facies associations were previously identified in the southern Karoo Basin (Rubidge 1988, Rubidge et al. 2000). All the facies within these associations have been identified in the study area. However, it is important to

establish whether these facies are indeed limited to three discreet stratigraphic intervals. The chi-squared test is used to assess the number of transitions between facies of different associations based on the following hypotheses:

Null Hypothesis: A random number of transitions exists between the three lithofacies associations.

Alternate Hypothesis: Only a single transition occurs between Lithofacies Association 1 and Lithofacies Association 2 and similarly between Lithofacies Association 2 and Lithofacies Association 3. No transition occurs between Lithofacies Association 1 and Lithofacies Association 3.

The stratigraphic sections measured at the each of three sites were tested separately (Appendix A). Chi-squared values of 83.069, 206.029 and 97.059 were obtained for the western, central and eastern sections respectively. The null hypothesis is rejected ($\alpha = 0.01$, *d.f.* = 2) indicating that the facies associations are indeed separate. A markov transition diagram is presented of the stratigraphic sequence present on the farms Signal Hill, Peninsula and The Grant (Figure 37).

3.5 Fluvial Architectural Analysis

The concept of architectural analysis was introduced by Miall (1985) as a tool for the interpretation of fluvial depositional environments. Analysis of fluvial environments has shown that similar vertical sequences can be deposited by different processes, rendering vertical analysis potentially misleading (Reading 1984). Architectural analysis involves the analysis of the three dimensional geometry of sedimentary horizons with the contacts between the horizons being referred to as bounding surfaces. The hierarchy or order of the bounding surfaces reflects increasing time and magnitude of the depositional system (Rust 1978, Miall 1985, 1996). A number of elements are currently recognised in fluvial environments and are placed into two broad groups namely channel and overbank elements (Miall 1996). The combination of elements within an outcrop can be used to identify the type of fluvial style (Miall 1985, 1996).

Overbank elements have received substantially less attention than channel elements which is unfortunate as the lower Beaufort Group comprises predominantly overbank fines (Smith and Keyser 1978, Smith 1987, Rubidge 1988, Kingsley 1980). Laterally extensive outcrop is scarce in the study area.

3.5.1 Channel Architectural Elements

3.5.1.1 Subaqueous Channels

Although traditionally lateral profiling has only regarded fluvial deposits (Miall 1996) this technique may be applied to the Lithofacies Association 2 deposits in the study area. On the farm Bucklands, an exposure is present along the course of the Great Fish River at 33° 05' 45”S 26° 39' 08”E (Figure 5) which is orientated north-south and faces westwards.

This exposure comprises a number of beds comprising Facies D sandstones. As discussed previously, this facies has recognised by Rubidge (1988) and

Rubidge et al. (2000) to represent density flows within subaqueous channels. This exposure contains a fourth order surface (Labelled 4, Figure 38), which separates two channel sets. Above the fourth order surface are a number of concave up third order bounding surfaces (Labelled 3, Figure 38), which represent the erosive bases of subaqueous channels and splays. The lithology of these channel elements comprises horizontal bedding with occasional thin conglomeratic horizons, which occur throughout the beds. Within the channel elements are a number of faint second order bounding surfaces (Labelled 2, Figure 38). Another channel element containing second order bounding surfaces occurs below the fourth order surface.

3.5.1.2 Fluvial Channels (Element CH)

Miall (1996) considers this architectural element to define channels with simple fining=upward fill sequences. A channel may comprise a number of separate macroforms in which case it is recommended these be described separately. The erosional base of a channel is concave-up and typically represents a third order bounding surface. The upper surfaces are a flat third order surface. The geometry of a channel includes the depth, width to depth ratio and sinuosity, all of which assist in describing the nature of the channel.

Good channel deposits are present as cliff exposures along the Grahamstown – Fort Beaufort road at 33° 03' 23” S, 26° 39' 09” E. The 450m long exposure (Figure 39) strikes between 0 and 45° and the strata dip at 13° towards the north. The stratigraphic height of these cliffs was previously measured by Kingsley (1977), who recorded that the uppermost channel element was 1244m above the lowermost sandstone. This places the first occurrence of this element 1169m above the base of the Facies Association 3 interval.

A number of channels are present in the exposure (labelled CH, Figure 39). These channels shallowly dip from the south downwards to the north. The termination points of the channels are not present in the outcrop and,

considering the lateral extant of the outcrop, suggest a high width to depth ratio. Sandstone thickness ranges from 4 to 10m.

The channels do not erode into one another and are vertically stacked with substantial floodplain fines between them. This arrangement suggests a significant quantity of accommodation space during the time of deposition (Miall 1997).

3.5.1.3 Lateral / Downstream Accretion Macroforms (Elements LA/DA)

Lateral Accretion Macroforms (LA) represent the lateral accretion of sediments within a channel, as apposed to the vertical aggradation of sandy bedform and channel elements. LA macroforms are bounded by third and fourth order surfaces (Rust 1978) and contain dipping internal bounding surfaces as a result of the incremental lateral accretion mechanism (Miall 1996).

LA macroforms are accreted obliquely to the channel axis whereas Downstream Accretion (DA) macroforms are accreted within a channel, with the accretion surfaces dipping in the downstream direction. LA and DA macroforms are therefore distinguished from one another by the comparison of the orientation of the dipping surfaces with that of the internal cross-bedding. If the difference between these orientations is greater than sixty degrees then the element is considered to be a LA macroform. If the difference is uncertain then the element is termed a DA/LA macroform (Miall 1996).

LA/DA macroforms are present within the channel elements described above at 33° 03' 23” S, 26° 39' 09” E (labelled LA, Figure 39). The channels contain second order bounding surfaces, which dip at 15° and less in a southerly direction. The vertical nature of the exposure made it impossible to collect palaeocurrent data, and so it cannot be determined whether they are accreted in a lateral or downstream direction. Thus in this case these elements are termed as LA/DA elements.

3.5.2 Overbank Architectural Elements

Overbank deposits encompass the predominantly fine-grained sediments deposited in the interchannel areas (Miall 1996). In the Karoo these deposits have received less attention, with respect to architectural analysis, than the channel deposits due to the low preservation potential as a result of dessication, dewatering and pedogensis. Recently overbank deposits have been shown to be more complex than previously thought (Willis and Behrensmeyer 1994, Slate et al. 1996, Kraus 1999). These elements are represented by floodplain fines, which is the most common architectural element in the Koonap Formation.

3.5.2.1 Floodplain Fines (FF)

Floodplain fines (FF) encompass the fine-grained sediments that have been deposited in the interchannel areas. Fine-grained sediment is transported from the channel into the overbank environment during flood events in suspension. The sediment settles out as the flow energy decreases, typically resulting in thick packages of laminated fines where sufficient accommodation space is present. The low preservation potential of these deposits often obscures both primary and secondary structure which has led to these deposits been somewhat neglected (Miall 1996). Well preserved floodplain deposits may however provide a wealth of climatic and depositional information (Retallack 1990, Slate et al. 1996, Kraus 1999).

The Facies Association 3 stratigraphic sequence is dominated by fine-grained floodplain deposits, which comprises 64 to 77% of the overall lithology of this Facies Association. Figure 39 presents a thick sequence of floodplain elements (labelled FF) in the exposure previously discussed for the channels contained within. The floodplain elements comprise horizontally laminated mudstones and siltstones separated by second order surfaces.

4 PALAEONTOLOGY

Kingsley (1977) reported the presence of an isolated tetrapod bone from the Upper Ecca within the study area but this was not collected. Recently Modesto et al. (2001) and Gow and de Klerk (1997) recovered well-preserved fossils from the farms The Grant and Schrikwaters Poort respectively in the area north of Grahamstown which represent the first identifiable tetrapod specimens recovered from the Koonap Formation in the eastern part of the Karoo basin. These few fossils and those subsequently collected all have biostratigraphic significance. The following fossils have been recorded in the study area as the biostratigraphy of the Lower Beaufort Group in the study area is currently unknown due to the paucity of tetrapod fossils (Rubidge et al. 1995). The following fossils have been recovered from the study in this and previous studies:

Specimen number	Specimen identification	Collection	Locality	Coordinates
BP/1/6166	dicynodont	BPI	The Grant	33° 04' 18" S 26° 23" 43" E
BP/1/6222	*Broomia* (juvenile)	BPI	The Grant	33° 03' 31" S 26° 23" 42" E
BP/1/6128	*Eunotosaurus*	BPI	The Grant	33° 04' 30" S 26° 23" 31" E
AM 6556	anteosaurid dinocephalian	AM	The Grant	33° 05' 50" S 26° 24" 38" E
BP/1/6221	therapsida (?)	BPI	Kwandwe	33° 06' 09" S 26° 37" 12" E
BP/1/6228	therocephalian	BPI	The Grant	33° 04' 30" S 26° 23" 31" E
BP/1/6226	amphibian	BPI	Bucklands	33° 04' 01" S 26° 39" 49" E

Table 2: list of fossils recovered from the study area during this and previous studies.

4.1 Therapsida

4.1.1 Dinocephalia

Cranial and postcranial material of a large tetrapod (AM 6556) was collected in 2002 (Rubidge *pers comm*) from a carbonaceous sandstone on The Grant (central study site). The horizon is occurs 315m above the base of the Lithofacies Association 3 contact (Figure 6). Isolated fragmentary post-cranial

elements were found in association with the cranial material, but not collected. In addition *Glossopteris* leaf impressions were found in association with the cranial material.

AM 6556 comprises a skull and isolated postcranial elements (Figure 40). The presence of a single temporal opening, skull roof with pachystotic thickening and intermeshed incisors identify the specimen as a dinocephalian. In addition, the lack of an enlarged canine tooth and the presence of incisors which have enlarged heels identify it as belonging to *Tapinocephalidae* (Rubidge 1991). As the taxonomy of tapinocephalid dinocephalians has not been refined it is not possible to assign this specimen to a generic level (Rubidge *pers comm*).

4.1.2 Dicynodontia

Only one dicynodont skull was collected in the study area. This specimen (BP/1/6166) was collected from a ripple-laminated sandstone horizon on The Grant, situated 945m above the Ecca-Beaufort contact in the central study site (Figure 6).

This fragmentary specimen comprises the anterior part of the snout, as well as a relatively broad intertemporal region (Figure 41). The presence of a pair of large canines and the absence of any other dentition identify the specimen as a dicynodont (King 1988). The wide intertemporal region indicates that the specimen represents a primitive dicynodont. This specimen may represent either *Eodicynodon*, *Robertia*, *Pristerodon* or *Emydops* (King and Rubidge 1993), however the poor preservation of the skull, in particular the palate, prevents further identification.

4.1.3 Therocephalia

Specimen BP/1/6228 consists of the large, relatively well-preserved skull and mandible of a therapsid (Figure 42) that was recovered from a siltstone horizon 740m above the Ecca-Beaufort contact on The Grant (Figure 6). The specimen was found in close proximity to a specimen of *Eunotosaurus* (BP/1/6218) and 3m above a fine-grained sandstone horizon containing

equisetalean plant fossils preserved in growth position.

The dorsally facing temporal fenestra are large and are separated by a narrow intertemporal region. Sub-orbital vacuities are present in posterior region of the palate. Palatal fenestrae are present in the anterior part of the palate and these are confluent with internal nares. These features identify this specimen as a therocephalian. The relatively large size of the skull indicates that this is a primitive therocephalian (van den Heever 1994).

The following features indicate that the specimen belongs to the Pristerognathidae: post-canine teeth with serrations on the posterior surfaces, relatively large canines and the presence of three lower incisors, vomers are narrow and unfused vomers; well developed postfrontal (van der Heever 1987). Basal therocephalians comprise the families Scylacosauridae and Lycosuchidae (van der Heever 1987). The presence of nine upper post-canines, the possible presence of teeth on the pterygoid boss, a ventromedial crest on the posterior portion of vomer, a ventromedian crest on the pterygoid, the ventral rim of transverse process of pterygoid, which does not sweep posteriorly at midline vacuity and a narrow elongated interpterygoid vacuity suggest that this specimen belongs to the Scylacosauridae. However it has two features considered to be characteristic of the Lycosuchidae. Firstly the anterior border of orbit lies in front of the transverse midline of the skull, and secondly teeth are present on the transverse process of the pterygoid. The only scylacosaurid therocephalian that has teeth on the pterygoidal process is *Lycedops scholtzi*. However *L scholtzi* differs from BP/1/6228 in that it has only 4 upper post-canines and the anterior border of orbit is posterior to the transverse midline of the skull.

On the balance of the evidence BP/1/6228 appears to represent a new species belonging to the Scylacosauridae.

4.1.4 Other

A fragment of jaw material (BP/1/6221) was collected from a ex-situ coarse-grained sandstone on the farm Fort Brown – Peninsula Outspan. The exact stratigraphic position is uncertain but occurs within 100m of the lowermost sandstone in the western study site, and is in the lowermost part of LFA3 (Figure 6).

The material consists of a badly eroded, partial upper mandible (Figure 43). The remains of a single large tooth are present as well as impression of a second tooth. The poor state of preservation of the teeth obscures any previously present diagnostic characters. The large size of the teeth suggests that this fragment belongs to a large theriodont.

4.2 Parareptilia

4.2.1 *Broomia*

The impression of cranial and post-cranial material of a small animal (BP/1/6222) (Figure 44) was collected from an argillaceous horizon (Rubidge *pers comm*) 1200m above the Ecca-Beaufort contact on The Grant (Figure 6). This horizon is approximately 50m above the lowest occurring red mudstone.

The skull and mandible are dorso-ventrally compressed with the left dorsal surface of the skull as well as the palate exposed. The skull is relatively short and possesses a large orbit. A single small lower temporal opening is present, but is incompletely preserved and appears to be very small. This feature indicates that the specimen belongs to the Parareptilia. Close inspection of the skull surface indicates the presence of sculpturing on the dermal roofing bones. This feature in conjunction with a lack of horns identifies the specimen as a milleretid (Gow 1972).

A left manus is preserved and comprises an elongated ulnare. This character,

in conjunction with the relatively short skull and small lower temporal opening, identifies this specimen as *Broomia* (Gow 1972). The pelvic girdle is preserved as impressions. Interestingly the pelvic bones are unfused suggesting that the specimen is a juvenile.

4.2.2 *Eunotosaurus*

BP/1/6218 was recovered from a siltstone horizon on The Grant at 740m above the Ecca-Beaufort contact (Figure 6) in close proximity to the scylacosaurid therocephalian (BP/1/6228). The specimen consists of an articulated vertebral column and associated ribs (Figure 45). Four thoracic vertebrae, all in articulation with each other, are present, each with an attached pair of dorso-ventrally expanded ribs. Three caudal vertebra are present but are not articulated with each other. Pelvic girdle material is present, but not well preserved.

Although the specimen lacks cranial elements and much of the axial skeleton, the antero-posteriorly expanded ribs identify the specimen as the parareptile *Eunotosaurus* (Gow and de Klerk 1999).

4.3 Amphibia

Cranial elements (Figure 46) of a large tetrapod (BP/1/6226) were recovered from a mudstone-dominated interval, 540m above the Ecca – Beaufort contact on Bucklands (Figure 6). (The presence of pitted dermal ornamentation, a large flat skull, and numerous conical teeth with labyrinthodont infolding indicate that the skull is of a temnospondyl amphibian.

4.4 Pisces

Isolated scales of palaeoniscid fish were observed within Facies Association 2

at Carlisle Bridge. Because of the fragmentary nature of the specimen it is not possible to identify it further. No fish remains were observed in Facies Associations 1 or 3.

Linear, parallel traces were observed on the surface of a fine-grained sandstone within Facies Association 2 on Bucklands (Figure 47). These traces resemble *Undichna bina*, and are considered to have been made by the fins of palaeoniscid fish (Anderson 1974).

4.5 Flora

4.5.1 Silicified Wood

Silicified wood fragments are present in association with the mudstones of Facies Association 1. Numerous fragments which had weathered out of the mudstones, are present on Signal Hill. That these fragments do not display rounded edges suggests that they had not been transported extensively after being weathered out of the host rock. The high local concentration of the fragments also indicates a minimal distance from the source. Isolated silicified fragments were observed at all the other localities, however these displayed prominent weathering and rounding and so probably had been extensively transported.

4.5.2 Plant Fossils

Glossopteris leaf impressions are extremely abundant within the olive-green mudstones of Facies Association 3. Complete leaves are seldom observed as the weathering of the mudstones obliterates extensive bedding plane surfaces. The few complete leaves observed display the distinctive midrib and venation of *Glossopteris* (Figure 48).

Equisitalean stem impressions are commonly found within laminated olive-brown mudstones and siltstones. Complete stem impressions are rare, but fragmentary impressions are common (Figure 49). A number of equisitalean

fossils preserved in growing position were observed within a single ripple-laminated, fine-grained sandstone horizon on The Grant (Figure 50). This was the only locality in which this mode of preservation was observed.

Sphenophyte stem impressions were observed within laminated siltstones on Bucklands and Fort Brown – Peninsula Outspan. The impressions present on Kwande contained attached seed structures (Bamford *pers comm*) (Figure 51) indicating an extremely limited degree of transportation.

A large infill structure was observed on Bucklands in fine-grained sandstones. The structure is straight and cuts the bedding planes at approximately 45°. No evidence is present suggesting that it is a burrow structure and so it is more parsimonious that it represents the cast of a plant stem (Figure 52).

4.6 Trace fossils

4.6.1 Burrows

The mudstones of Facies Association 1 and 2 contain a significant number of horizontal and vertical burrows. These burrows reach up to 15mm in diameter and are infilled with siltstone and fine-grained sandstone. No internal structures are preserved in the burrows.

A horizontal burrow displaying concave internal structures (Figure 17) was observed in a facies B horizon within the lower part of the Facies Association 2 sequence on the farm Signal Hill. The burrow was approximately 10mm wide. This burrow closely resembles *Plagiomus* (Anderson 1974) in terms of structure, but has a considerably smaller diameter than those previously described.

4.6.2 Horizontal Traces

Horizontal traces are common on the surfaces of the argillaceous rocks within

Facies Association 1, 2 and 3. The traces on the mudstones of Facies Association 1 are up to 15mm wide and reach up to 0.5m in length (Figure 11). They display a low sinuosity. Similar traces occur on ripple surfaces (Figure 15) within the Facies Association 2 sequence and reach up to 5mm in width and up to 1m in length. The origin of these linear traces is uncertain but probably represent invertebrate feeding behaviour. Horizontal traces are not abundant within Facies Association 3, but were observed on rippled beds on the Grant (Figure 34).

5 DISCUSSION

5.1 Stratigraphy

5.1.1 Lithostratigraphic units

This study has focused on the stratigraphic interval currently mapped as comprising the upper Fort Brown and Koonap formations. These two stratigraphic units form part of the Ecca Group and the Adelaide Subgroup of the Beaufort Group respectively. The interval is underlain by the Ripon Formation (Ecca Group) and overlain by the Middleton Formation (Adelaide Subgroup) (Johnson 1976, S.A.C.S 1980).

According to the literature (see chapter 1) the Fort Brown Formation is the uppermost unit of the Ecca Group in the southeastern part of the basin (Johnson 1976, Kingsley 1977, S.A.C.S 1980). The Fort Brown Formation is currently defined as a highly argillaceous unit comprising dark grey/black shales with subordinate sandstones occurring in the basal parts (Johnson 1976). The overlying Koonap Formation is defined as an argillaceous unit comprising olive/green mudstones with subordinate fluviatile sandstones (Kingsley 1981, Johnson and le Roux 1994).

In the study area the Fort Brown and Koonap formations are easily identified on a broad scale. This is particularly so in the eastern and central areas where the higher arenaceous content of the latter generates a positive topography whereas the Fort Brown Formation generates a negative topography. The poor outcrop in the western areas makes identification more difficult although good exposures are present along the Great Fish River. As currently mapped (Map 3326 Grahamstown) the Fort Brown Formation incorporates Lithofacies Association 1 as set out earlier in this dissertation, while Lithofacies Associations 2 and 3 have been mapped as Beaufort Group (Koonap Formation).

5.1.1.1 Fort Brown Formation

The Fort Brown Formation comprises Lithofacies Association 1 sedimentary rocks. Dark grey laminated mudstone comprises the bulk of Lithofacies Assemblage 1, but fine-grained sandstones become more abundant in the upper stratigraphic levels. This lithology is the same as described for the Fort Brown Formation in the southern Karoo Basin (Johnson 1966, 1976, Kingsley 1977, 1980, Rubidge 1988, Johnson and le Roux 1994).

In the southeastern Karoo Basin, the study area for this thesis, the upper part of the Fort Brown Formation is considered to contain a significant arenaceous zone (Johnson and le Roux 1994). This differs from the definition for the rest of the southern Karoo Basin, where the arenaceous stratigraphic unit in the upper Ecca Group represents the Waterford Formation (Johnson 1976, Rubidge 1988). This study has shown that the arenaceous zone above Lithofacies Association 1 has a unique set of facies that differentiates it both from Lithofacies Association 1 and 3. Lithofacies Association 1 therefore represents the entire Fort Brown Formation, and the overlying arenaceous zone of Lithofacies Association 1 represents a distinct and previously unmapped stratigraphic entity.

The contact between the Lithofacies Association 1 and 2 sequences is, at most localities, represented by the lowermost Facies D or Facies E sandstone, which is easily identified in the field.

5.1.1.2 Waterford Formation

Overlying the Fort Brown Formation in the study area is an arenaceous unit comprising mainly Lithofacies Association 2. In the study area this unit is not currently documented as a separate stratigraphic entity (Johnson and le Roux 1994) and is currently mapped as being within the Beaufort Group. This unit is

present throughout the study area and is well exposed along the banks of the Great Fish River at all three localities studied thus defines a mappable unit. Sandstone comprises between 35% and 49% of the lithofacies association with dark grey fines comprising the remainder. The sandstones appear to be laterally continuous.

The presence of a second stratigraphic unit overlying the Fort Brown Formation differs from previous interpretations for this part of the Karoo Basin (Johnson 1976, Kingsley 1977, S.A.C.S. 1980, Johnson and le Roux 1994). Johnson and le Roux (1994) considered a transitional zone to exist between the Fort Brown and Koonap formations, which comprised a significantly high arenaceous lithology. This equates with the upper arenaceous unit found in this study in both stratigraphic position and lithology, although the thicknesses cannot be compared, as the exact thickness of the transitional zone was never recorded by Johnson and le Roux (1994).

In an earlier study Kingsley (1977, 1981) considered the Fort Brown to comprise the uppermost unit of the Ecca Group in the southeastern Karoo Basin. Interestingly, regarding the sedimentary cycles he interpreted for the Koonap Formation, he recorded an arenaceous lowermost cycle with distinctive dark grey to black shales. The lithological description closely matches that of the arenaceous unit of the Lithofacies Association 2 recorded in this study. Additionally the lowermost cycle was considered to occur directly above the lowermost prominent sandstone in the upper Fort Brown Formation and so is stratigraphically in the same position as the arenaceous unit. Kingsley (1977) did not regard this arenaceous lower package as a separate stratigraphic unit although he commented that it did bear some similarities to the Waterford Formation. In light of this and the stratigraphic position of the arenaceous unit, it is parsimonious that it is equivalent to the Waterford Formation and so warrants further comparison.

The Waterford Formation at the type locality comprises three informal

members: the Main Member, Middlewater Shale Member and the Transitional Member, the latter being the highest stratigraphically (Johnson 1976). The Main Member and Transitional Member contain a significant percentage of sandstone (50 - 59% and 30 – 70% respectively). The overlying Koonap Formation may contain a maximum of 30% sandstone while the Middlewater Shale Member and Fort Brown Formation contain less than 5% sandstone (Johnson 1976). The relatively high sandstone abundance of 35 - 49% recorded for Lithofacies Association 2 in the study area indicates that, in terms of overall lithology, this facies is more representative of the Waterford Formation (excluding the Middlewater Shale Member) than either the Koonap or the Fort Brown formation. In addition the presence of the five characteristic facies (A,B,C,D,E) which are described for Lithofacies Association 2 in the study area, are the same as those described for the Wasterford Formation in the southwestern part of the basin (Rubidge 1988, Rubidge et al. 2000). In the study area the three members of the Waterford Formation erected by Johnson (1976) could not be identified. Similarly Rubidge (1988) was unable to identify these members in the southwestern Karoo Basin.

The presence of dark grey mudstones in Lithofacies Association 2 differentiates this stratigraphic unit from the overlying Koonap Formation, which contains olive green mudstones (Johnson and le Roux 1994) but is similar to the Waterford Formation described in the rest of the southern Karoo Basin (Johnson 1976, Rubidge et al. 2000). It is therefore here proposed that the arenaceous interval encompassing Lithofacies Association 2 is equivalent to the Waterford Formation (Johnson 1976), and in turn the transitional zone as defined by Johnson and Le Roux (1994).

5.1.1.3 Koonap Formation

In the study area the Waterford Formation is overlain by an interval comprising Lithofacies Association 3. In contrast Lithofacies Association 1 and 2 do not contain olive green mudstones, but instead dark grey to black laminated fines.

Sandstone comprises between 21% and 17% of the total stratigraphic section. This abundance is marginally lower than that of Johnson (1976) who considered the Koonap Formation to comprise 20 – 30 % sandstone, with the exception being the area north of Waterford where sandstone comprised only 10 – 15 % of the overall lithology. The abundances recorded in this study for Facies Association 3 are substantially lower than that of the Waterford Formation in the areas further west and obviously greater than that of the Fort Brown Formation, which is almost entirely argillaceous. In terms of lithology, LFA 3 therefore conforms most closely with that of the Koonap Formation (Johnson 1976, Johnson and le Roux 1994). In terms of colour the sandstones observed in the study area were generally yellow brown (5Y 5/4) to greyish orange (10YR 7/4). This is similar to colours previously reported by various authors for the Koonap Formation (Johnson 1976, Kingsley 1977, Johnson and le Roux 1994).

Two-dimensional profiling shows that the sandstones occurring within Facies Association 3 represent wide floodplain channels. While the sandstones alone do not indicate a fluvial nature or otherwise, a number of associated sedimentary features indicate a non-marine depositional setting. These include subaerial features such as slickenslides, calcareous nodules and fossils of exclusively terrestrial origin. Therefore the Lithofacies Association 3 sandstones conform to those defined for the Koonap Formation in the southeastern Karoo Basin (Johnson and Le Roux 1994).

Good exposures of the Koonap Formation occur predominantly in the eastern areas, where the topographic relief is more pronounced. The type section contains an excellent cliff exposure north of Fort Brown. Minor exposures also occur along the banks of the Fish River. Unfortunately the exposures further away from the Great Fish River are poor in quality, due to a progressively higher vegetational and soil cover. The Middleton Formation contains significantly better exposures due to a pronounced topographic relief, probably

as the result of its higher arenaceous content.

5.1.1.4 Fort Brown - Waterford contact

The contact between the Fort Brown and Waterford Formation, as defined by Johnson (1976), is a conformable, intertongued transition of approximately 50m to 100m in thickness. Lithologically the contact is considered to represent a marked increase in the abundance of sandstone (Johnson 1976, S.A.C.S. 1980). As the Main Member is the basal unit of the Waterford Formation the contact definition for the Fort Brown – Waterford Formation is synonomous with its lower contact.

More recent work has refined the definition by considering the base of the lowermost prominent sandstone to represent the base of the Waterford Formation (Rubidge 1988, Rubidge et al. 2000). Such a definition is considered more useful as the base of the lowermost sandstone is not open to interpretation as is the case of a transitional contact. This type of contact is present at all three sites and is easily identified from aerial photography (Figure 55) which will simplify any further mapping in the area. Thus the definition used here brings the stratigraphy in the study area into line with the rest of the southern Karoo Basin (Rubidge 1988, Rubidge et al. 2000).

5.1.1.5 Waterford - Koonap contact

Much work has been undertaken on the Ecca-Beaufort contact in the rest of the Karoo Basin (Johnson 1976, Nel 1977, Lemmer 1977, Rubidge 1988, Rubidge et al. 2000, Modesto et al. 2001, Welman et al. 2001). The contact in the southeastern Karoo Basin has been largely neglected with only a few broad scale studies having being conducted (Kingsley 1977, Johnson and le Roux 1994).

Recent workers have used a combination of lithological and palaeontological

characters to define the Ecca-Beaufort contact (S.A.C.S 1980, Rubidge 1988, Rubidge et al 2000). These features separate the subaqueous and subaerial depositional environments of the Ecca and Beaufort groups. As this study has recognised the presence of the Waterford Formation in the area for the first time the contact will be defined based on the current criteria for the rest of the southern Karoo Basin (Rubidge et al. 2000).

In the study area the contact is best defined on the basis of a number of co-occurring subaerial features, which are tabulated below:

	Ecca	Beaufort
Skew planes in mudrock intervals	absent	present
Pedogenic nodules	absent	present
Ball-and-pillow structures	common	absent
Terrestrial vertebrate fossils	absent	present
Conglomeritic horizons throughout sandstone beds	common	Conglomerates restricted to the bases of sandstone beds
Colour of fines	Dark grey/black	Olive brown to red

Table 3: Sedimentary and palaeontological features differentiating the Ecca and Beaufort groups in the study area.

The colour of the mudstones of the Koonap Formation is olive green, which is considered to be typical of the lower Beaufort (S.A.C.S 1980, Rubidge et al 2000). The colour may however be variable (Kingsley 1977, Johnson 1976) and so colour alone is not a sufficient criteria to define the contact. Complete plant fossils, some in growing position occur frequently in the rocks of the Koonap Formation and so may assist in the placement of the boundary. In a few places relatively large pieces of plant material were noted in the Waterford Formation, and so the presence of absence of relatively complete plant

material must be applied with circumspection.

Tetrapod fossils have been used, as a lithological feature, to assist in the placement of the contact in areas west of 24°E (Rubidge 1987, Rubidge 1988). While this has been successfully used in the afore-mentioned areas, the paucity of fossil bone in the study area means that this is not a very useful feature.

The mottled nature of the Waterford Formation sandstones has been regarded as a typical Ecca Group feature (S.A.C.S 1980, Rubidge et al. 2000). While mottling is abundant in the Waterford Formation in the study area, mottled sandstones do occur at higher stratigraphic intervals in the Koonap Formation. This has been previously noted by Johnson (1976) who recorded that some sandstones within the Koonap Formation displayed white speckling.

5.2 Thicknesses

Thickness variation of the upper Ecca and lower Beaufort groups in the southern Karoo Basin have been the focus of recent basin development research (Catuneanu et al. 1998, Rubidge et al. 2000, Catuneanu et al. 2002). As the Waterford Formation has now been recognised in the eastern part of the southern Karoo Basin its thickness has implications for both basin development modelling and regional stratigraphic mapping.

Delta lobe switching has been suggested as a cause for thickness variations (Johnson 1976), as is supported by studies on modern deltaic systems (e.g Somoza et al. 1998).

5.3 Biostratigraphy

The terrestrial environments of the Late Permian were dominated by

therapsids, with amphibians and anapsid reptiles present as well. The biostratigraphic scheme for the main Karoo Basin has been based largely on the occurrence of tetrapods, in particular therapsid taxa (Rubidge et al. 1995, Hancox and Rubidge 2001).

Presently the biostratigraphy of the southeastern parts of the main Karoo Basin is undefined with respect to the lower Beaufort Group (Rubidge et al. 1995). Johnson (1976) considered the rocks of the Koonap Formation to be devoid of fossil reptiles, while Kingsley (1977) reported the presence of only small unidentifiable bone fragments in the lower Beaufort Group and Fort Brown Formation. More recently Gow and de Klerk (1997) described a specimen of *Eunotosaurus* that was recovered from outcrops of the Koonap Formation on the farm Schrikwaterspoort. This indicated for the first time that identifiable tetrapod fossils were indeed present in the lower Beaufort Group in this part of the basin, indicating the presence of the upper *Tapinocephalus* or *Pristerognathus* Assemblage Zone (Keyser and Smith 1978). Following the discovery of the *Eunotosaurus* specimen a dinocephalian was recovered from the Koonap Formation on the farm, The Grant (Modesto et al. 2001). Intensive recent collecting has yielded more tetrapod fossils, which raises the possibility of assigning a biozone of the lower Beaufort Group to the strata of the study area.

The presence of dinocephalia, scylacosaurid therocephalians, and the enigmatic parareptile *Eunotosaurus* from 300m above the Ecca-Beaufort contact suggests that the Koonap Formation within the study area falls within the range of the *Tapinocephalus* Assemblage Zone (Rubidge et al. 1995). The only dinocephalian was collected 315m above the Ecca-Beaufort contact while the *Eunotosaurus* and therocephalian were collected 845m above the Ecca-Beaufort contact.

The specimen of *Broomia* was recovered from a mudstone horizon 1541m above the base of the Koonap Formation. This stratigraphic position is 50m

above the lowermost maroon mudstone which occurs beneath the mapped base of the Middleton Formation (Johnson and le Roux 1994). Although this specimen came from above the first maroon mudrock and thus outside the startigraphic range of the study area it is nonetheless biostratigraphically important as the holotype and the only other specimen is considered to be from the *Tapinocephalus* Assemblage Zone (Keyser and Smith 1995).

In summary the Koonap Formation in the study area contains a fossil fauna that is representative of the *Tapinocephalus* and *Pristerognathus a*ssemblage zones. The presence of a dinocephalian in the lower part of the Formation suggests that the *Tapinocephalus* Assemblage Zone is present, while the fauna in the upper part of the Koonap Formation (*Eunotosaurus* and basal therocephalia) is suggestive of the *Tapinocephalus* or *Pristerognathus* assemblage zones. The biozone present at the Ecca-Beaufort contact is unclear due to the absence of identifiable fossil tetrapods from the stratigraphic horizons.

5.4 Depositional Environments

5.4.1 Fort Brown Formation

Horizontally bedded mudrocks dominate the Fort Brown succession. Siltstone and fine-grained sandstone lamina become more common towards the top of the succession. The mudrocks are dark in colour due to the high organic content and the reducing conditions under which the sediment was deposited (Johnson 1976, Rubidge 1988). This thick homogenous formation has been considered to be the result of deposition within a prodeltaic environment (Figure 53, Kingsley 1977, Johnson 1976, Rubidge 1988, Johnson and le Roux 1994).

Within the prodeltaic environment the areas furthest from the sedimentary source contain the finest-grained sediments where the settling from

suspension is the dominant process (Reinech and Singh 1973). The areas nearer to the source contain a progressively higher arenaceous content in the form of siltstone lamina and thin sandstone horizons deposited by weak traction currents (Nouidar and El Hassan 2002). Within the study area the uppermost part of the Fort Brown contains siltstone laminae indicating that these parts were deposited at shallower depth, during a forced or normal regression, than the underlying strata. This type of succession is common in prograding deltaic environments (Oomkems 1970, Dreyer et al. 1999). The small channel structures present on Signal Hill are likely to be the result of mass flows, which have been documented in prodeltaic sequences such as that preserved in the Venetian Basin, southern Italy (Massari et al. 1986).

The fragmentary nature of the fossil plant material from the Fort Brown Formation was derived from high-energy environment in which the material is rapidly broken down. This material was then transported and deposited within the low energy prodeltaic sequence represented by the Fort Brown Formation. The associated burrows are horizontal to sub-horizontal that is considered to be characteristic of a low energy system (Seilacher 1967).

The absence of ripple cross-lamination within the mudrocks indicates that the deposition occurred beneath wave base (Blatt. et al. 1972, Reineck and Singh 1973, Dreyer et al. 1999). Much of the Fort Brown Formation in the southern Karoo Basin is considered to have been deposited beneath wave base, with ripples occasionally being present in the uppermost interval (Rubidge 1988). The onset of cross-lamination coincides with an increase in arenaceous content, which is characteristic of the overlying Waterford Formation.

5.4.2 Waterford Formation

An upward coarsening trend exists in the Waterford Formation from an argillaceous lower interval, to highly arenaceous upper reaches. As the Waterford Formation comprises exclusively subaqueous facies it is parsimonious that the sequence represents part of a deltaic environment

(Figure 53, Galloway and Hobday 1983, Massari et al. 1986) as has been previously suggested for the southern Karoo Basin (Rubidge 1988, Rubidge et al. 2000).

The major difference between the Waterford and Fort Brown formations is the large number of arenaceous lithofacies in the former. These lithofacies contain abundant cross-bedding, which is typical of a higher energy depositional environment (Reineck and Singh 1973). This contrasts with the underlying Fort Brown formation that comprises horizontal lamination exclusively. The arenaceous lithofacies, in conjunction with the upward coarsening trend has led a number of authors to regard the Waterford Formation as having being deposited in a delta front environment (Johnson 1976, Jordaan 1981, Rubidge 1988, Rubidge et al. 2000).

The most prominent arenaceous lithofacies within the Waterford Formation is Facies D. The tabular-bedding and clay pebbles contained within the sandstone body rather than at the base are typical of sandstones beds within the upper delta front environment (Oomkems 1974, Massari et al. 1986, Nouidar and El Hassan 2002, Browne and Naish 2003). Such sandstones have been considered to represent bar fronts, as are preserved in the Mississippi delta (Gould 1970). Bar front sands have flat erosive bases which contrasts with many found in the study area, which display convex erosive bases. Convex bases suggest channelised flow and so the Facies D sandstones in the study area most likely represent subaqueous channels (Hiscott et al. 1986, Rubidge et al. 2000). Horizontal bedding, lack of grading and the presence of clay pebbles beds are typical of grain flows, which are common in subaqueous channelised systems (Stauffer 1967, Collinson 1968, Baas 2004).

A sample of a Facies D sandstone revealed the presence of the clay mineral glauconite, which is considered to indicate marine depositional conditions (van Andel 1967, Selley 2000; Odin 1988). Odin and Fullager (1988) considered

glauconite to be abundant in open marine environments with the presence of bottom currents. These currents were considered to be important as they prevented a rapid accumulation of sediment, which has the affect of inhibiting glauconite mineralization. Glauconite formation additionally requires low temperatures (less than 15°C) and either weakly oxidising or reducing conditions (Selley 2000; Odin 1988). The water depth of formation is considered to range from 100 to 1000m and, as this is a large range, glauconite is considered as a poor bathymetric indicator (Selley 2000).

Glauconite facies have been has been found in delta front sequences (Massari et al. 1986) such as the Niger Delta (Odin 1988; Dreyer et al. 1999) where glauconite grains are present within deltaic muds at depths of 50m beneath sea level and below. Within the Niger Delta glauconitic grains are most prevalent between 100 and 250m beneath sea level. Deeper occurring grains are considered to be perigenic in nature in that they are derived from higher up on the delta slope (Odin 1988).

Another common facies within the Waterford Formation is Facies E with the distinctive abundance of soft sediment deformation features. These are common in subaqueous environments particularly in those with a relatively high sediment influx such as delta fronts (Oomkems 1970, Goodbred and Kuehl 2000). A number of workers have reported these to be abundant in the Waterford Formation (Johnson 1976, Rubidge 1988, Rubidge et al. 2000). Rubidge (1988) attributed the slump structures present in the Waterford Formation to the collapse of subaqueous channel banks, which a common occurrence in deltas (Collinson 1968, Nouidar and El Hassan 2002). Within the study area soft-sediment deformation is extremely common in the Waterford Formation. However the dominant deformation feature is ball-and-pillow structures as opposed to slump structures. The distinction between the two types lies is the presence of co-orientated slump axes within ball-and-pillow structures (Mills 1983).

Ball-and-pillow structures result from the downward movement of sediment as a result of reverse density gradation. This is the situation whereby more dense sediment is deposited on top of more porous (less dense) sediment. This contact is unstable and portions of the overlying sediment will load into the less dense underlying strata (Mills 1983). On a smaller scale flame structures further indicate the presence of reverse gravity gradation, as these are common along the contacts between coarser-grained beds such as Facies E and underlying finer-grained beds such as Facies B. A shallowly dipping depositional surface probably existed, as this would favour the vertical loading of sediment as opposed to lateral slumping, which results in a predominance of slumping (Mills1983).

The distinctive interbedded nature of Facies A is a common feature within the interdistributary bay environment of deltas (Hiscott et al. 1986, Okazaki and Masuda 1989, Dreyer et al. 1999). These sequences result from the regular crevassing of subaqueous channels, which provides the coarser sand fraction (Elliott 1974). The finer-grained units represent periods of time where crevassing is not prevalent and suspension settling is the main depositional mechanism (Boggs 1995). In modern systems the ratio of the coarser fraction to the finer material decreases distally (Okazaki and Masuda 1989, Orton and Reading 1993). Within the Waterford Formation the sand to mud ratio varies in a similar fashion that most likely reflects a proximal – distal relationship (Rubidge et al. 2000). Wave ripples are common on the exposed surfaces of the coarser beds indicating that the depositional surface was relatively shallow and above wave base (Blatt et al. 1972, Einsele 1992). The palaeocurrent direction of the ripples (Figure 54) indicates north to northeasterly current direction, which concurs with other work performed in the southern Karoo Basin (Ryan 1967, Johnson 1976, Kingsley 1977, 1981, Rubidge 1988).

Facies B is defined as thick, horizontally laminated and stratified packages of organic rich fines, and is considered to represent deposition in the distal areas of interdistributary bays (Rubidge et al. 2000). The fine-grained nature and

lack of cross-lamination supports this and suggests that deposition from suspension was the dominant process (Selley 2000). Some packages of Facies B contain thin, ripple laminated sandstone lamina suggesting a transitional relationship with Facies A. Similar facies have been reported in the distal parts of recent delta front systems (Orton and Reading 1993, Somoza et al. 1998)

5.4.3 Koonap Formation

A fluvial depositional environment has been suggested for the Koonap Formation in the study area (Johnson and le Roux 1994). This has been based upon the presence of upward-fining cycles, which are considered to be a distinctive fluvial feature (Allen 1970). Vertically orientated skew planes and pedogenic carbonate layers are present in the mudstones of the Koonap Formation and these features are unique to fluvial overbank environments (Smith 1980, Retallack 1990, Miall 1996). These features, in conjunction with the presence of terrestrial fossils and absence of marine fossils, indicate that the Koonap Formation was deposited in a subaerial environment.

Horizontally laminated sandstone is the result of deposition under lower flow regime conditions. This bedding is common in fine-grained deposits formed at relatively shallow water depths with flow velocities of approximately 1m.s-1 (Miall 1996). Cross-laminated beds typically overly horizontally-laminated sandstones in the study area, indicating a decrease in energy conditions (Boggs 1995). Current ripples and rib-and-furrow structures indicate a wide variation in palaeocurrent direction, but generally in a northerly direction (Figure 54). Ripple Horizontally laminated sandstones are less abundant than cross-stratified sandstone beds reflecting the predominance of low energy deposition (Reineck and Singh 1973).

Angular clasts are present at the scoured bases of some sandstone beds in Facies Association 3. Such conglomeratic lags at the base of sandstone units are considered to be a feature of fluvial depositional environments (Reineck

and Singh 1973). Considering the fine-grained nature of the clasts, as well as the angularity, the proximal floodplain environment would be a likely source (Rubidge 1988). The collapse of cutbanks in high sinuosity rivers commonly results in matrix-supported conglomerates with angular clasts (Allen 1970, Reineck and Singh 1973, Miall 1988), and so may represent a possible process for the deposition of the angular, fine-grained clasts in the study area.

Skew planes are a fairly abundant sedimentary feature in the olive-green laminated mudstone of the Koonap Formation. Slickenslides are considered to form by the vertical movement of soil peds in response to periodic drying of the subsoil (Smith 1980, Retallack 1990). Slickenslides occurring in green soils with poor horizonation are considered to be a feature of vertisols occurring in temperate climates (Miller et al. 1996). They form under a wide variety of conditions (Prather 1984, Kraus 1999) but are restricted to the floodplain environments, suggesting that the laminated mudstones containing these features represent floodplain deposits. Smith (1980) noted that the skew planes surfaces of the Beaufort Group contain a red-brown ‘clay skin’. Calcareous nodules occur in association with slickenslides indicate that the former is subaerial in nature. Clay skins are common within the argillaceous horizons of the study area and possibly formed as a result of meteoric and flood waters moving down the slickenslide surfaces (Smith 1980).

Nodules are formed by the precipitation of carbonate from groundwater when the rate of evapo-transpiration exceeds precipitation, and so are common in relatively hot dry climates (Retallack 1990). Nodules are not abundant in the area suggesting that precipitation typically exceeded evapo-transpiration. As individual nodules are present rather than well-developed continuous calcareous horizons palaeosol development is considered to have been poor, which may reflect a high water table (Retallack 1990). It therefore appears that the overbank environment was inundated with water for long periods, probably reflecting a fairly moist climate. The distinctive flattened nature of the nodules may be attributed to syndepositional deformation caused by the increasing

weight of the overlying soil, as has been suggested for similar nodules in other parts of the Karoo Basin (Smith 1980). This suggests that the rate of sedimentation within the floodplain environment was continuous and relatively rapid (Kraus 1999).

Fossil material was recovered most often from the finer-grained rocks of Facies Association 3. Such fossils included the impressions of terrestrial plants and terrestrial tetrapod body fossils. The abundance of relatively complete leaf, stem and occasional seed impressions indicate that the original plant material was not transported a great distance as this would have broken the plant structures. In addition some of these plants are preserved in growing position. The abundance of plant remains suggest that the overbank environment was well-vegetated (Rubidge 1988). Substantial plant communities would have only existed in the overbank environment if water was abundant. The nature of the preserved pedogenic nodules indicates a high water table (Retallack 1990, Kraus 1999) and long periods of inundation, which would have supported high plant numbers.

In contrast to the abundant plant remains, relatively few tetrapod fossils were recovered. It is parsimonious to suggest that the well-vegetated floodplain could have supported a significant tetrapod fauna. Catuneanu and Bowker (2001) suggested that the reason for the paucity of tetrapod fossils might be indicative of a high water table, which would have resulted in the dissolving of the original bone material before fossilisation. The nature of the pedogenic features also suggests a high water table supporting this hypothesis (Retallack 1990, Kraus 1999).

The well developed limestone horizon (limestone facies p42) present on The Grant is unusual as this lithology is seldom encountered in the lower Beaufort Group strata and has yet to be reported in the southeastern Karoo Basin. Stear (1980) observed similar horizons in the Abrahamshraal and Teekloof formations within the Beaufort West area. He reported that these brown

weathering horizons contained wrinkled lamina, which he considered to be algal structures. The description conforms closely with the horizon on The Grant. Loock et al. (1994) reported the presence of a palaeoplaya horizon within the Abrahamskraal Formation which contained stomatolitic structures. The presence of stomatolitic structures suggests that this horizon is of a similar nature to that described by Stear (1980) as well as that described in the present study.

Algal mats commonly occur within hyper-saline standing bodies of water (Reineck and Singh 1973). The calcium carbonates deposited by the algae form lamina which conform to the surface of the algal mat which typically is undulatory. Therefore this horizon was probably deposited by the biological activity of algae within a shallow, hypersaline body of water present in the overbank environment.

The combination of the various fluvial elements has resulted in the erection of a number of fluvial models (Miall 1996). These models have been applied to various studies within the Karoo Supergroup (Hancox 1998, Neveling 2002) but have yet to be applied to the lower Beaufort Group in the Eastern Cape Province. Within the study area a number of architectural elements are present in the Koonap Formation. These include lateral accretion elements, floodplain channels and floodplain fines. The latter is by far the most common element in the sequence. This combination of elements points to the presence of a fine-grained meandering river system (Miall 1985, 1996).

The abundance of floodplain fines is also characteristic of fine-grained meandering systems (Blatt et al. 1975, Miall 1985) in particular floodplains of delta plain environments such as the late Quaternary Ganges-Brahmaputra delta (Goodbred and Kuehl 2000). Horizontal and ripple lamination predominate in this environment and reflect low energy deposition (Reineck and Singh 1973). The sediment is deposited from suspension in standing bodies of water, which would have been abundant after the flooding of the

overbank environment (Kraus 1999, Leeder 1975, Smith 1980, Willis and Behrensmeyer 1994).

Wide channel macroforms, comprising lateral accretion elements, are present in the area. These channels are typical of high sinuosity systems (Miall 1985). More importantly the channels are stacked vertically indicating continual deposition and thus an availability of accommodation space. High sinuosity, low energy systems are typical of such successions (Miall 1997).

5.5 Sequence Stratigraphy

Catuneanu et al. (1998) recognised eight second order cycles within the Karoo first order cycle (or megasequence). These second order sequences are separated by subaerial unconformities, which have been linked to the orogenic events within the Cape Fold Belt (Halbich et al. 1983). Together the Fort Brown, Waterford and Koonap formations are considered to represent a second order cycle (Catuneanu et al. 2001).

Fourth order sequences are considered not to be definable in the southeastern part of the Karoo basin due to the absence of regionally observable unconformities at this scale (Catuneanu and Bowker 2001). This is a result of the lack of a suitable number of lateral exposures from which to trace out possible fourth order unconformities. This situation was found to be true by the present author as only the western part of the area contained suitable outcrop for lateral profiling.

The deposition of the upper Ecca and lower Beaufort groups occurred during the third tectonic event (265.8Ma) within the Cape Fold Belt (Catuneanu et al. 1998, Rubidge 2005). During this time the sedimentary supply exceeded the rate of accommodation space generation resulting in a normal regression (Rubidge et al 2000). Sediment was derived from a source situated to the

southeast (Johnson 1991). In the southern Karoo Basin there is no subaerial unconformity present in the Ecca – Beaufort contact interval (Rubidge et al. 2000). As this sequence follows the maximum transgression of the Ecca Sea, the deltaic succession preserved in the Waterford and Koonap formations is considered to form part of a highstand systems tract (Rubidge et al. 2000).

The sequence in the study area is similar in many aspects to that further west (Rubidge et al. 2000). No subaerial unconformity is present on the contact in the study area suggesting that the sequence may be part of a high stand systems tract. The absence of a shoreline facies, as described by Rubidge (1988) in the south-western part of the Karoo Basin may be explained by the post-depositional erosion and diagenesis. Additionally a thick subaerial sequence forming the Koonap Formation, overlying the delta front succession, is considered to be a typical feature of highstand systems tracts (Miall 1997). The thick succession suggests that the Karoo Basin at this time was underfilled. This is supported by the vertical stacking nature of the fluvial units present in the Koonap Formation (Catuneanu et al. 1998).

6 Conclusion

The Ecca-Beaufort contact has received much attention over the past three decades, which has resulted in a clearer understanding of the lithostratigraphy, biostratigraphy and depositional environments of this sequence. While the nature of this contact in the western and southern Karoo Basin has been resolved the southeastern areas have received little previous attention. With the discovery of tetrapod fossils in this part of the basin renewed interest has allowed for a re-evaluation of the Ecca – Beaufort contact.

Lithostratigraphically the Ecca – Beaufort contact in the south-eastern part of the basin was previously considered to occur at the contact between the Fort Brown (upper Ecca) and Koonap formations (lower Beaufort) in the form of a transitional zone. This study has revealed the presence of three separate lithofacies associations across the Ecca-Beaufort contact in the study area. These lithofacies associations, named 1-3, document respectively a prodelta, deltafront and high sinuosity fluvial environment. These lithofacies associations have been divided into a number of lithofacies which correspond with those previously recognised for the Ecca-Beaufort transition in the southwestern part of the Karoo Basin (Rubidge 1988, Rubidge et al. 2000) and have been named according to the same scheme used by these authors.

Lithofacies Association 1 corresponds with the Fort Brown Formation of the Ecca Group while Lithofacies Association 3 corresponds with the Koonap Formation of the lower Beaufort Group. Lithofacies Association 2 is lithologically similar to that described for the Waterford Formation by Rubidge (1988) and comprises the same five lithofacies (A-E). This is the first time that the presence of the Waterford Formation has been positively documented for the southestern part of the Karoo Basin (Figure 55) and means that the Grahamstown geological map (geological mapsheet 3326) must be modified accordingly.

As for the rest of the basin the contact between the Ecca and Beaufort groups in the south eastern part of the basin now falls between the Waterford and Koonap formations (Rubidge 1988, Rubidge et al. 2000, Welman et al. 2001) and not between the Koonap and Fort Brown formations as currently mapped. This means that the apparent unconformity present between the Fort Brwon and Koonap formations, as implied by the geological map, is not present and that a conformable depositional sequence is present in this part of the basin. The Ecca-Beaufort contact in the southeastern part, as is the situation in the southern and western parts of the basin (Rubidge 1988, Rubidge et al 2000, Welman et al 2001), reflects a shoreline transition which occurs only once in the stratigraphic succession.

A wide diversity of fossil tetrapods have now been recovered from the Koonap Formation and include rhinesuchid amphibians, tapinocephalid dinocephalians, therocephailians, dicynodonts and the parareptiles *Eunotosaurus* and *Broomia*. This is only the second record of *Broomia* from the Beaufort Group, and the fact that the specimen is more complete than the holotype, provides further understanding of the cranial and post-cranial anatomy of this genus (Cisneros, Rubidge *pers comm*). These fossils reveal that the upper *Tapinocephalus* and/or *Pristerognathus* Assemblage Zones are present in the Koonap Formation in the study area. So far no fossils of the *Eodicynodon* Assemblage Zone have been recovered from the study area.

The presence of fossils of the upper *Tapinocephalus* Assemblage Zone in the lower Koonap Formation implies that the Ecca-Beaufort contact youngs towards the southeast and reflects a northeasterly prograding shoreline in response to basin tectonic development, as previously documented for the basin (Rubidge et al. 2000, Rubidge 2005).

This study has shown that the Waterford Formation is present in the southeastern part of the Main Karoo Basin. The Ecca-Beaufort contact is now

placed at the top of this formation and and thus the contact is stratigraphically the same as that in the rest of the southern Karoo Basin. While biostratigraphically important fossils remain scarce in the study area, enough fossil evidence is present to suggest that the fauna of the *Tapinocephalus* Assemblage Zone are present in the Koonap Formation. This provides new insight into the rocks of the lower Beaufort in the southeastern Karoo Basin where both the stratigraphy and biostratigraphy are poorly understood.

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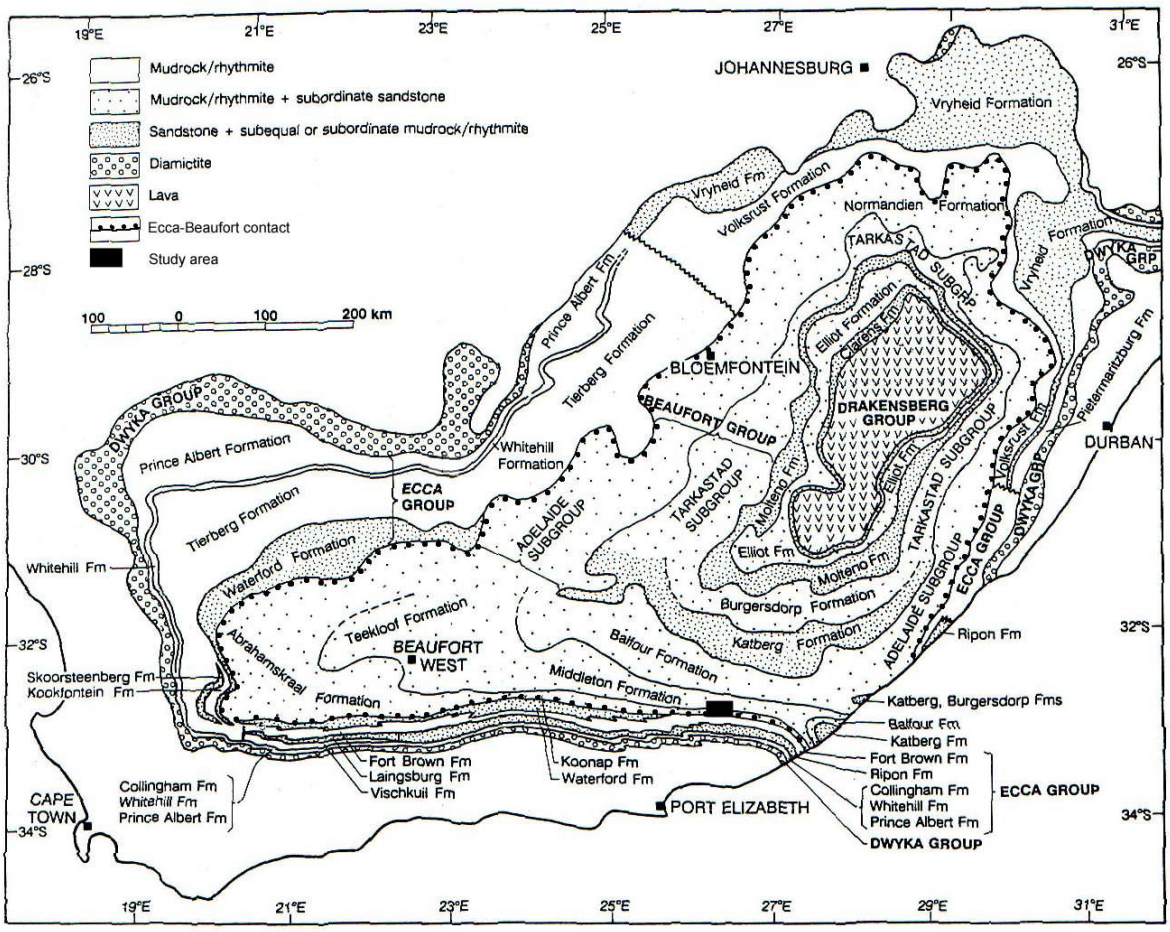

Figure 1: The outcropping of the Karoo Supergroup strata, with special reference to the Ecca-Beaufort contact and the study area (modified from Johnson et al. 1996).

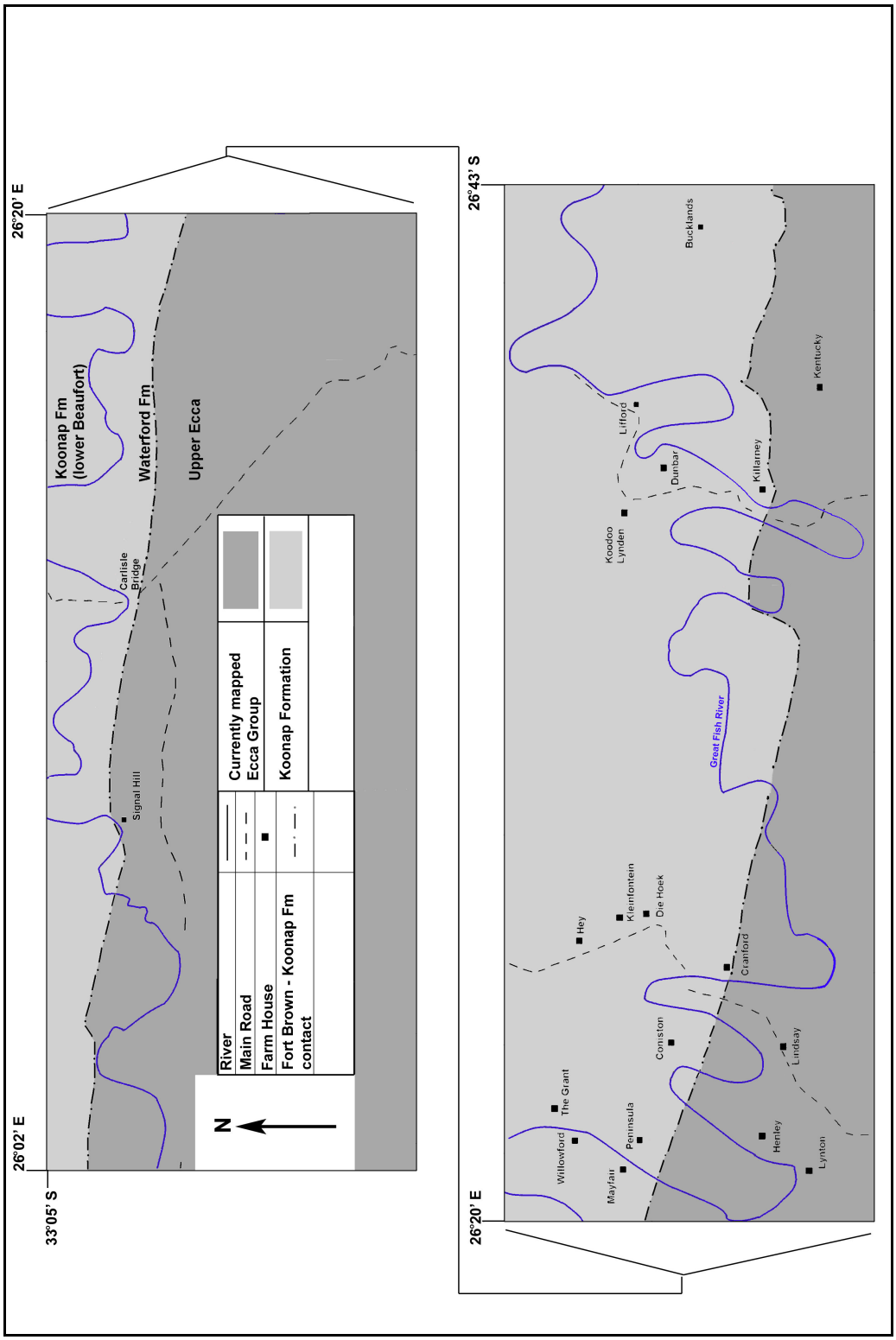

Figure 2: Map showing a simplified stratigraphy of the study area as currently mapped (Johnson and le Roux 1994). Important farms and locations are shown.

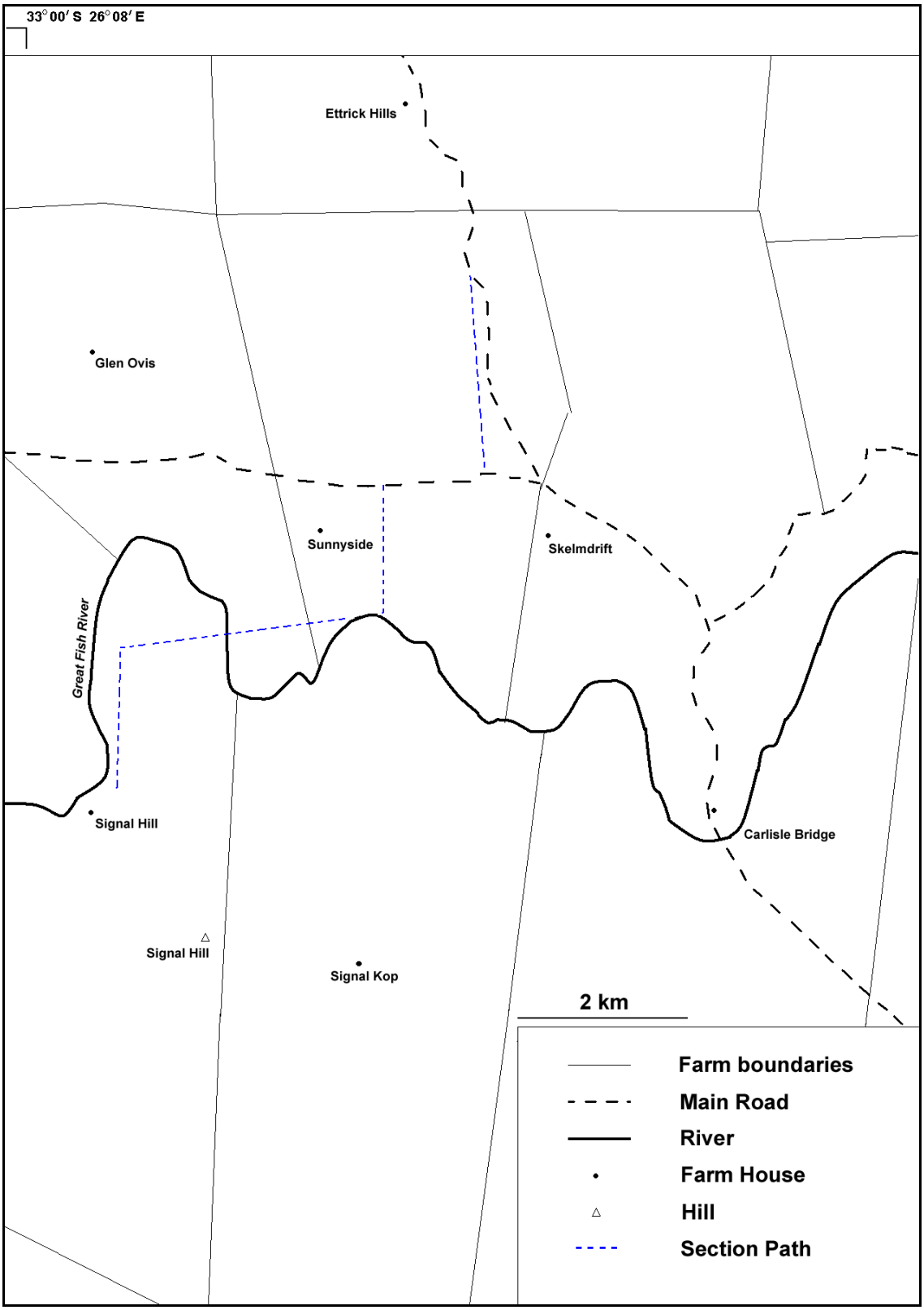

Figure 3: Map of the western study area.

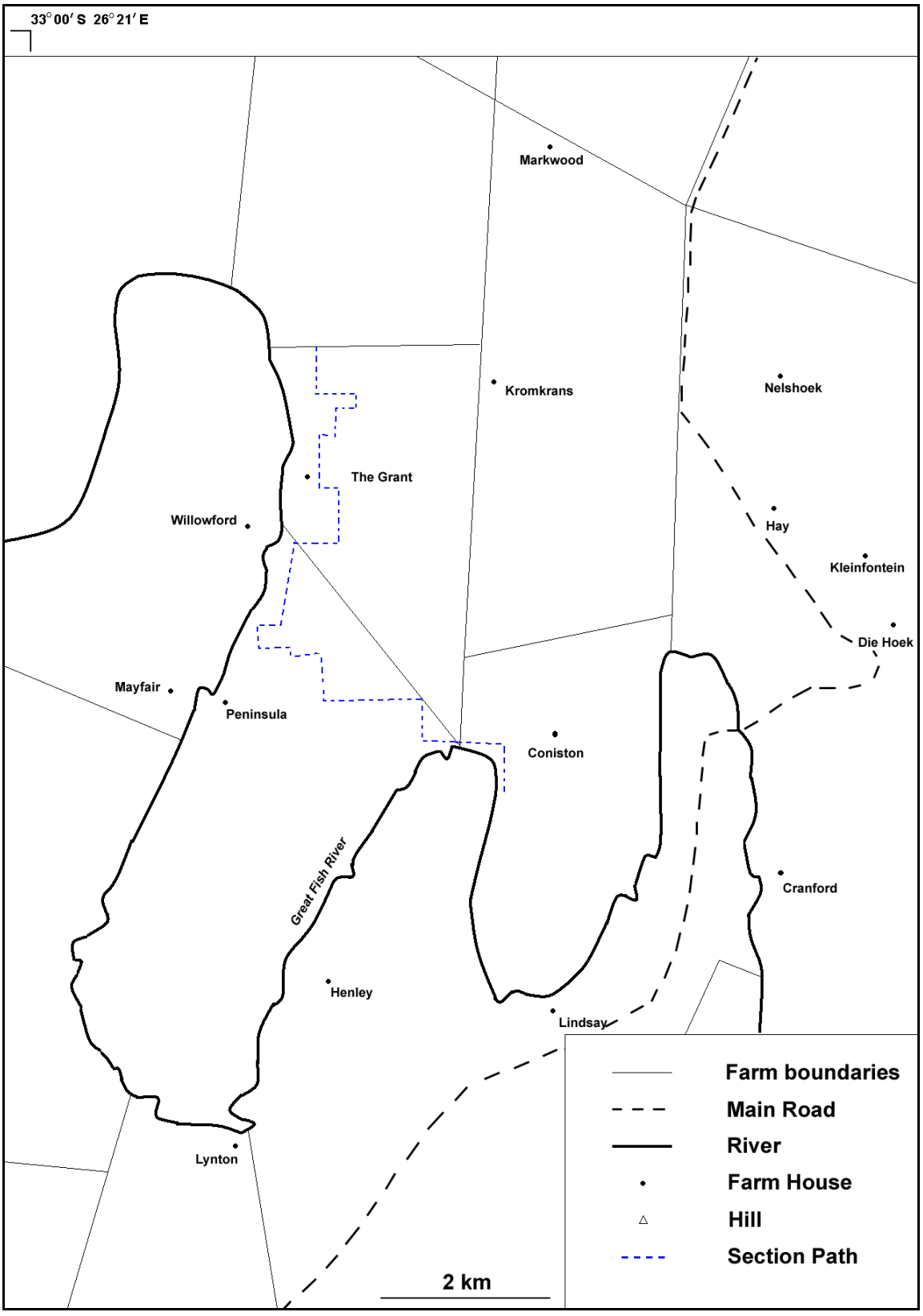

Figure 4: Map of the central study area.

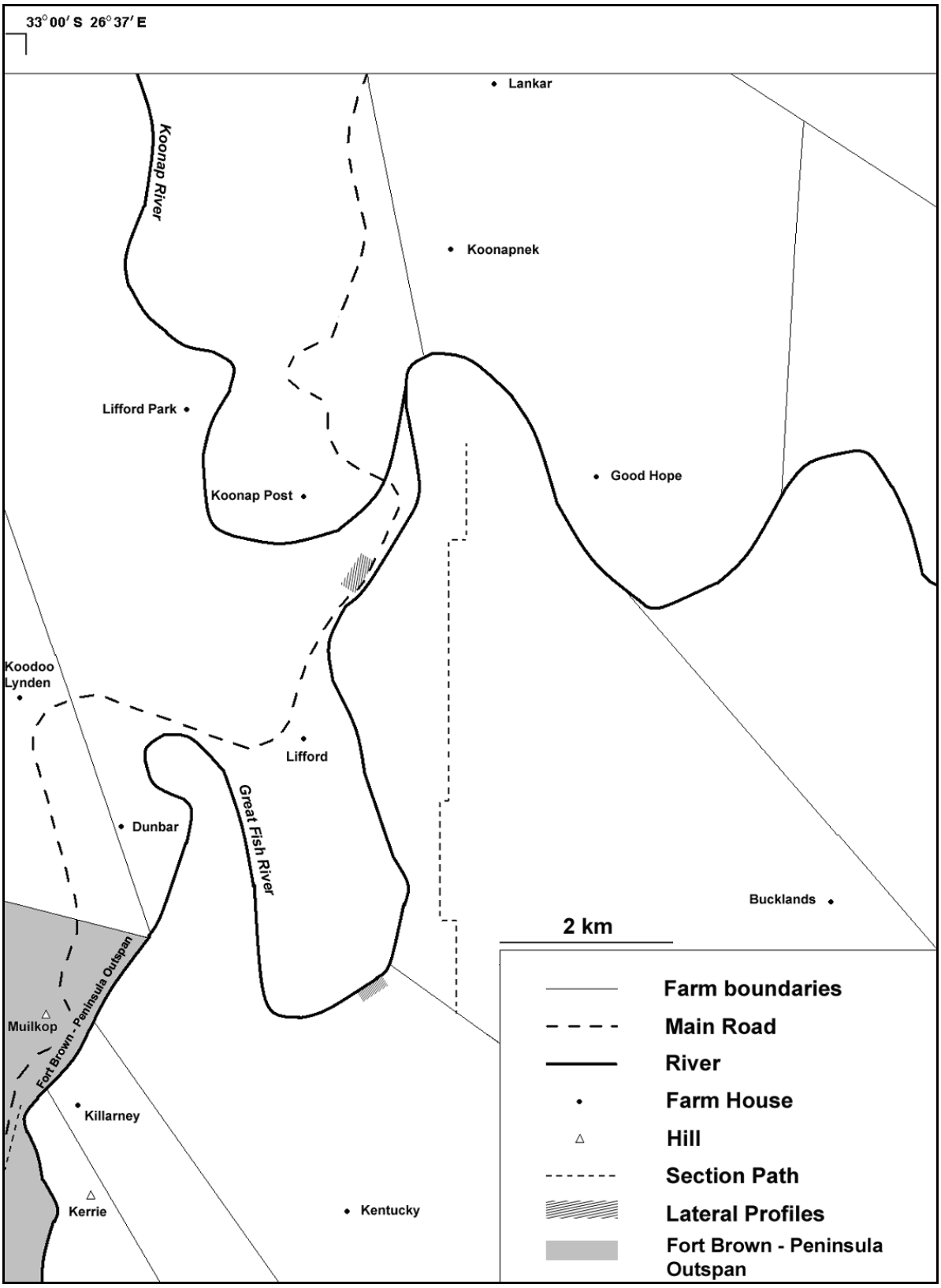

Figure 5: Map of the eastern study area

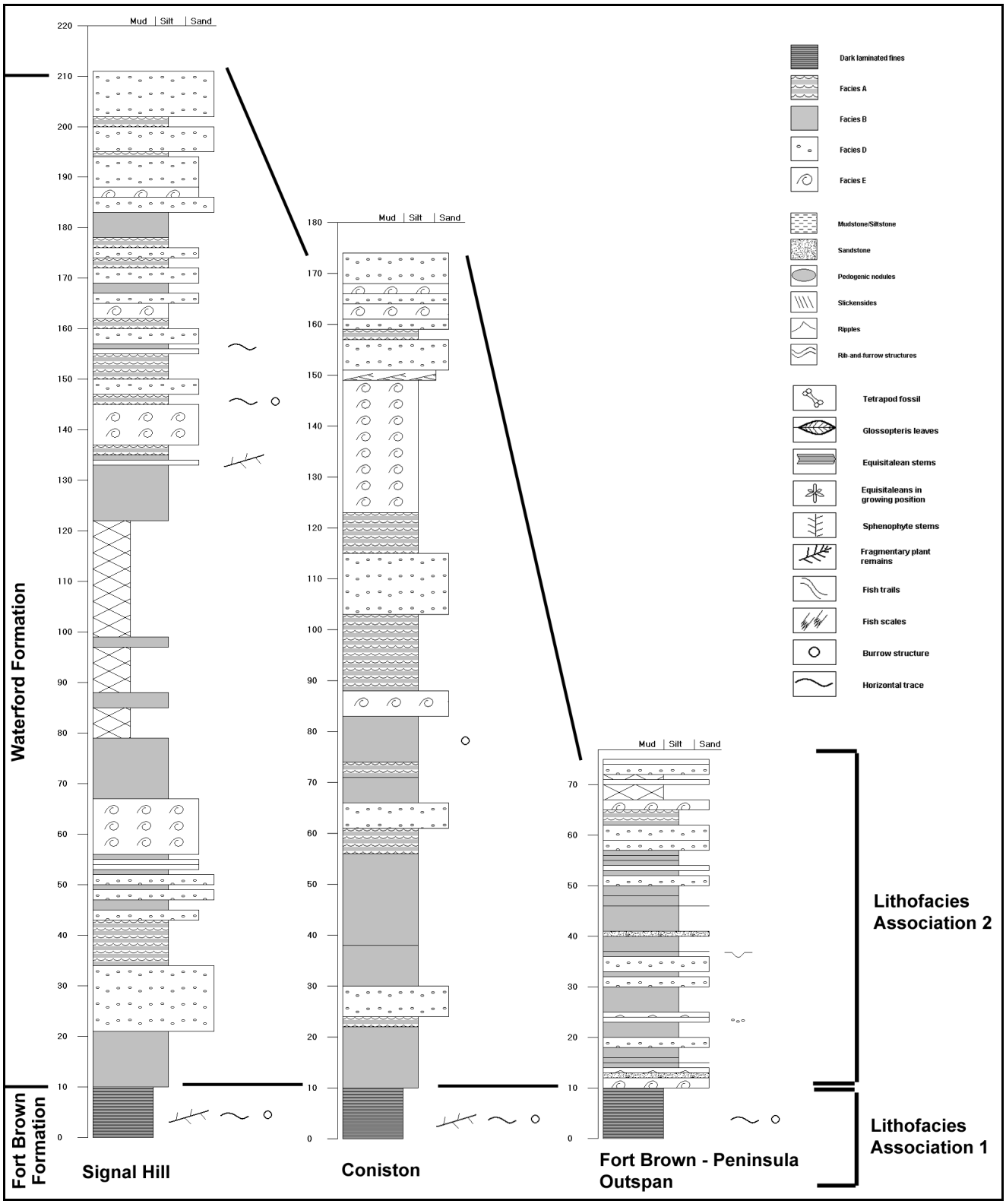

Figure 6: Stratigraphic sections of Lithofacies Association 1,2 and the lower parts of 3 as measured within the three study areas.

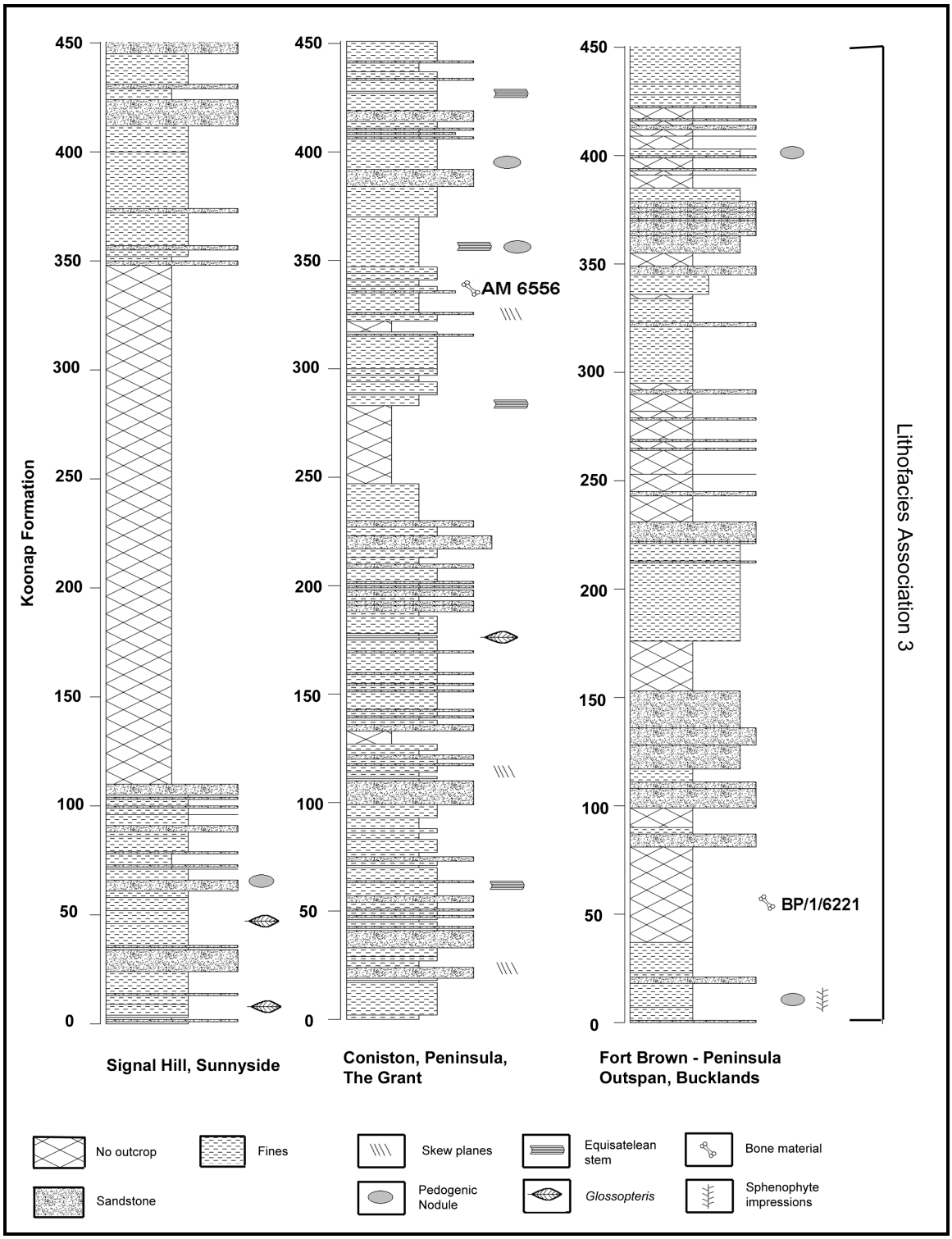

Figure 7 *cont*.: Stratigraphic sections of Lithofacies Association 3 as measured within the three study areas from the top of Lithofacies Association 2 to the lowermost maroon mudstones.

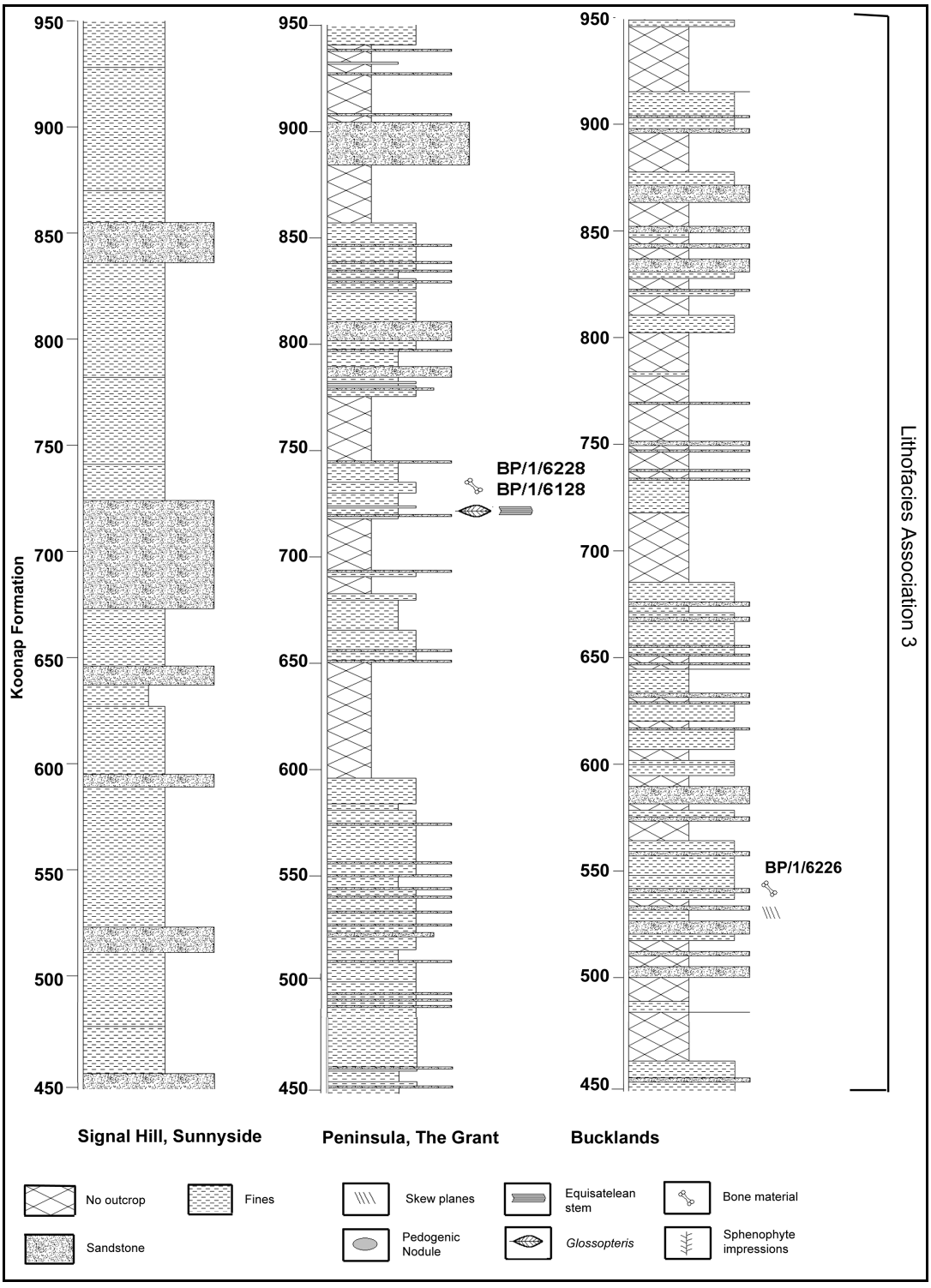

Figure 7 *cont.*: Stratigraphic sections of Lithofacies Association 3 as measured within the three study areas from the top of Lithofacies Association 2 to the lowermost maroon mudstones.

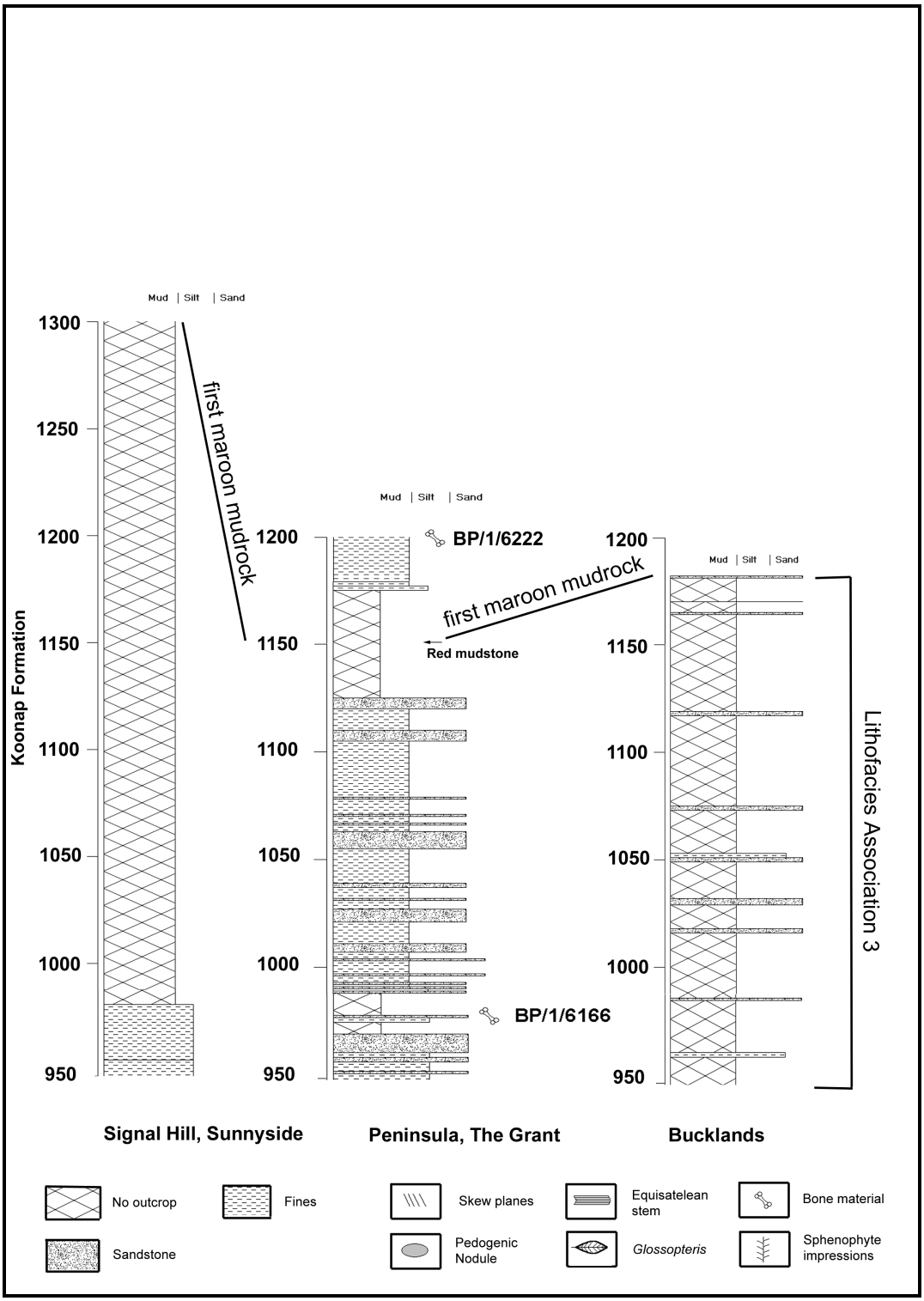

Figure 7 *cont.*: Stratigraphic sections of Lithofacies Association 3 as measured within the three study areas from the top of Lithofacies Association 2 to the lowermost maroon mudstones.

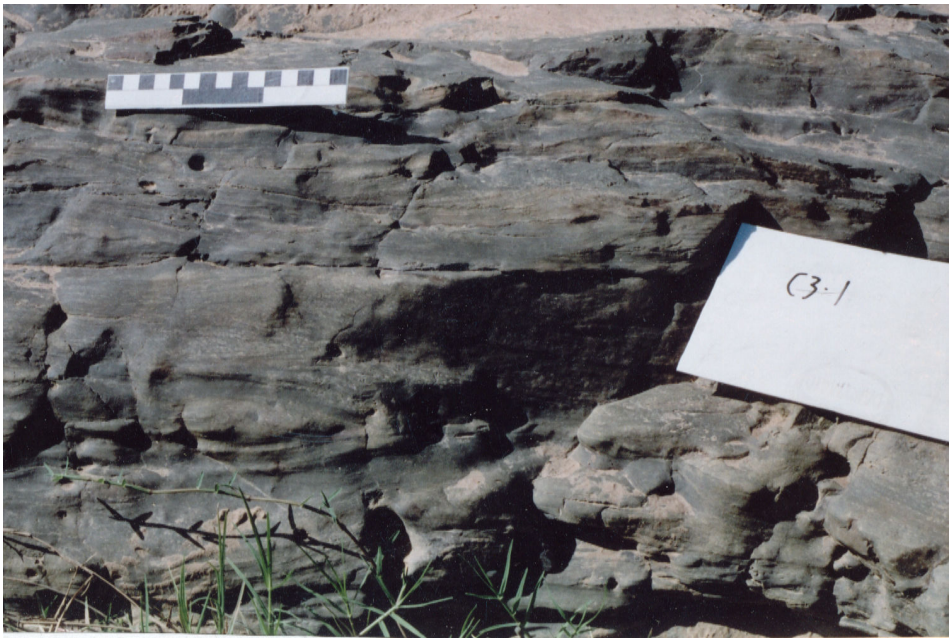

Figure 7: Laminated mudstones, deposited within the prodeltaic environment, of Lithofacies Association 1, Coniston (Scale: 15cm scale bar).



Figure 8: Planar bedded mudstones of Lithofacies Association 1 incorporating sandstone lenses (arrows), Signal Hill. (Scale: 60mm lens).



Figure 9: A 20cm thick calcareous horizon within Facies Association 1, Signal Hill.



Figure 10: Infilled invertebrate burrows within prodeltaic mudstone deposits, Coniston (Scale: 15cm scale bar).



Figure 11: Horizontal invertebrate traces within prodeltaic mudstone deposits, Coniston. (Scale: 15cm scale bar).



Figure 12: Fragmented plant remains (arrows) on a mudstone surface, Signal Hill. (Scale: 1cm divisions on scale bar).



Figure 13:Ripple surfaces within a Facies A sandstone located on Signal Hill. (Scale: 15cm scale bar)

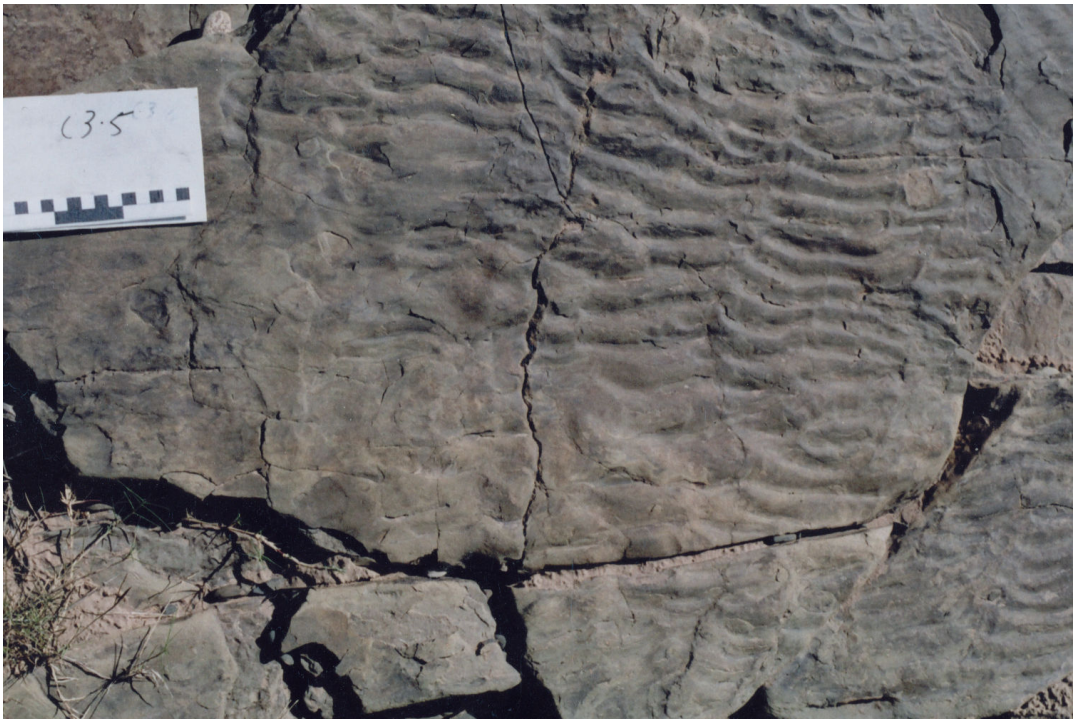

Figure 14: Sinuous ripples with rounded crests indicating reworking by wave action withiin the delta front depositional environment, Signal Hill (Scale: 15cm scale bar).



Figure 15: Invertebrate feeding traces (arrows) on a rippled sandstone. (60mm lens cap for scale).



Figure 16: Laminated mudstones deposited in the distal interdistributary environment, Fort Brown – Peninsula Outspan. (Scale: 1cm divisions on scale bar).



Figure 17: An undescribed invertebrate trace, with an ichnomorphology similar to *Plagiomus*,found within lower delta front deposits located on Signal Hill. (Scale : 6 cm lens cap).

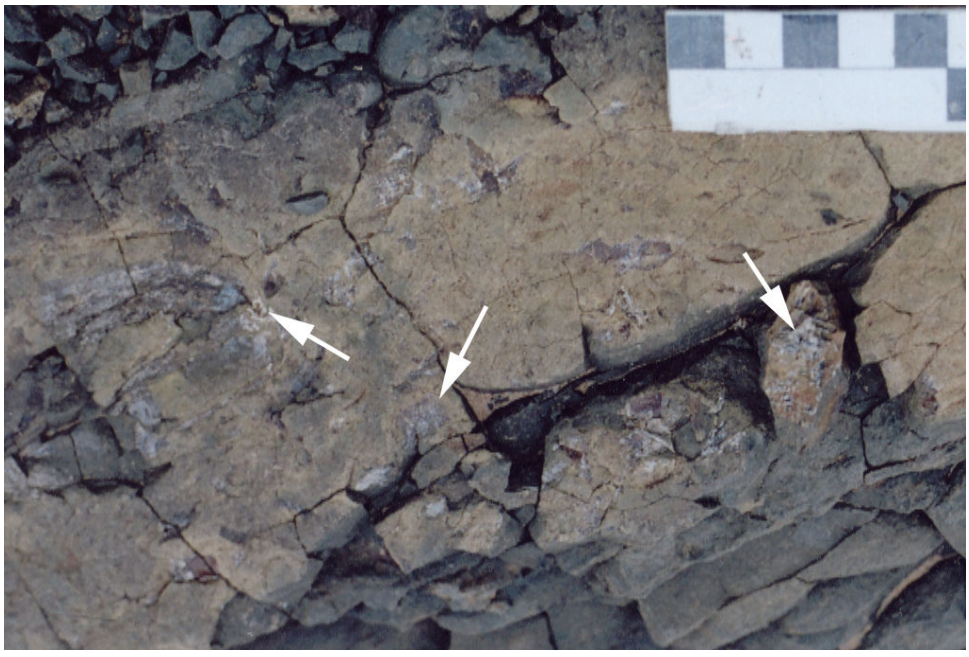

Figure 18: Palaeoniscid fish scales (arrows) found in delta front deposits located near Carlisle Bridge. (Scale: 1cm minor divisions on scale bar).



Figure 19: 0.2m thick subaqueous splay (arrow) within delta front deposits, Signal Hill.

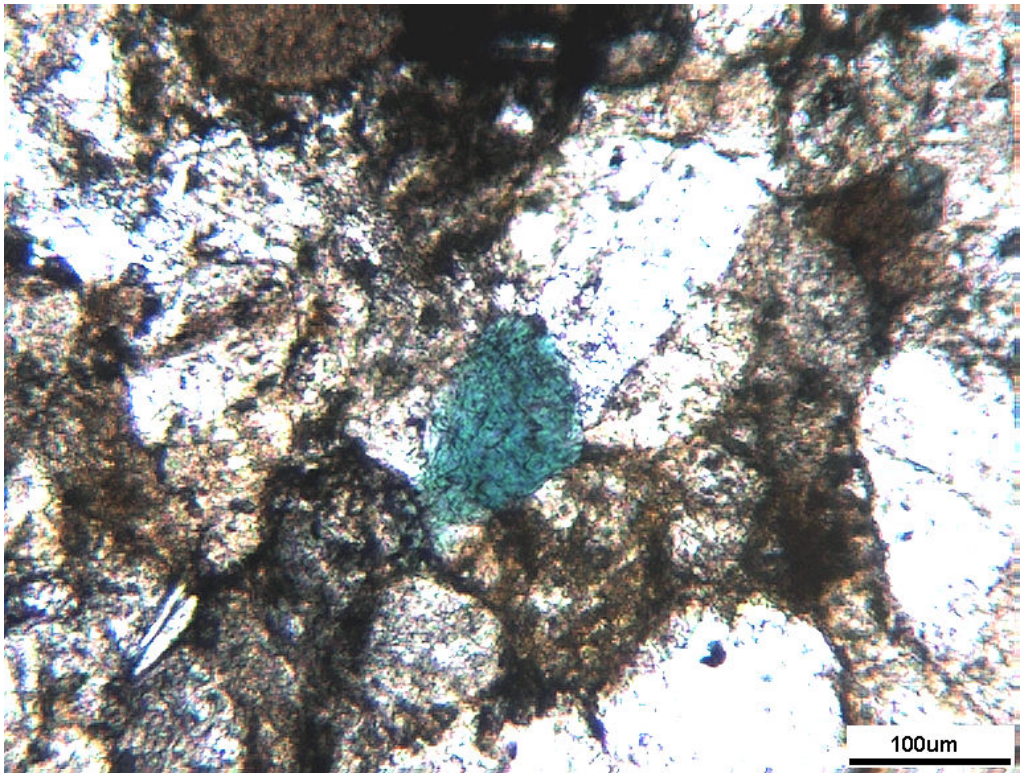

Figure 20: Photo-micrograph showing a glauconite grain present in a Facies D sandstone, Signal Hill (Scale bar = 100μm).



Figure 21: Convex erosional bases (highlighted) of subaqueous channels within an 8m high exposure, Bucklands.

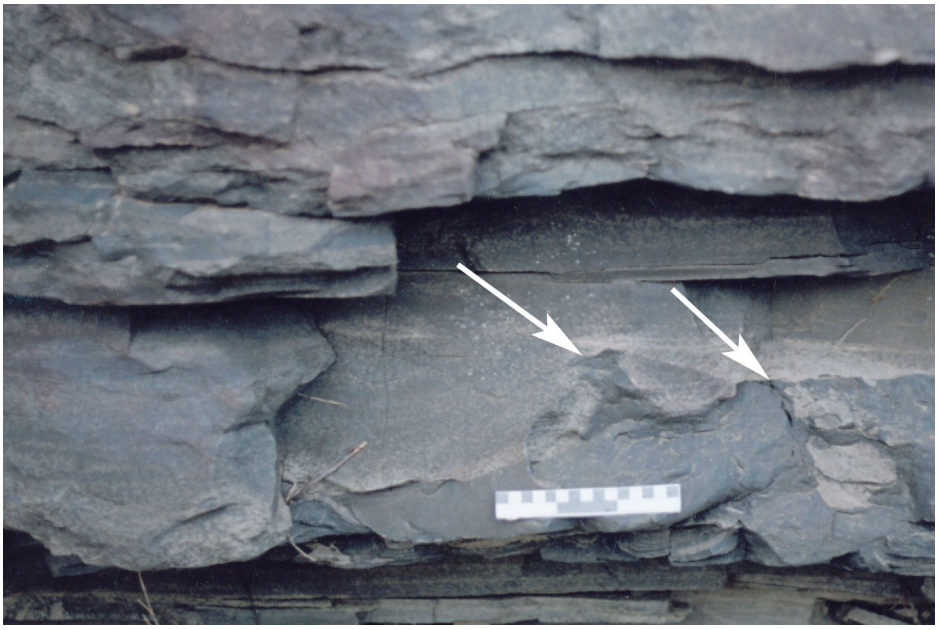

Figure 22: Flame structures (arrows) found at the base of a slumped layer, Coniston. (Scale: 15cm).

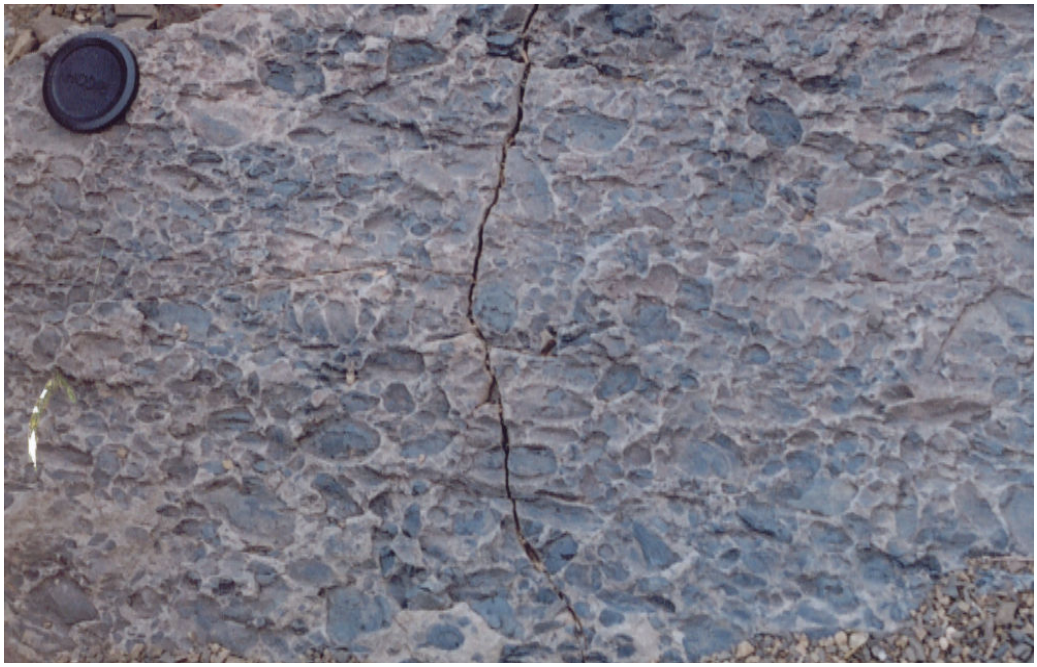

Figure 23: A clast-supported intraformational mud-clast conglomerate within a subaqueously deposited channel. (Scale: 60mm lens cap).



Figure 24: Ball-and-pillow stucture in Facies E sandstone, Signal Hill. (Scale: 60mm lens cap).



Figure 25: Slickensided surface within the overbank depositional environment, Bucklands. (Scale: 6 cm lens cap).



Figure 26: Calcareous pedogenic nodule within the overbank depositional environment, Bucklands. (Scale: 6 cm lens cap).



Figure 27: Septarian nodule, Fort Brown – Peninsula Outspan. (Scale: 5cm major divisions).



Figure 28: A sample of limestone, displaying wavy lamina, from The Grant (1cm minor divisions on scale bar).



Figure 29: Limestone horizon containing a dinocephalian scapula, The Grant (Scale: 6 cm lens cap).



Figure 30: Pyrite crystals within a massive sandstone, Bucklands. (Scale: 10cm scale bar).



Figure 31: Horizontally bedded sandstone, Bucklands. (Scale: 23mm diameter coin).



Figure 32: Ripple-laminated sandstone, The Grant. (scale: 60mm lens cap).



Figure 33: Ripples within fluvially deposited sandstone, The Grant. (Scale: 15cm pencil).



Figure 34: Horizontal feeding traces, The Grant. (Scale: 15cm pencil).

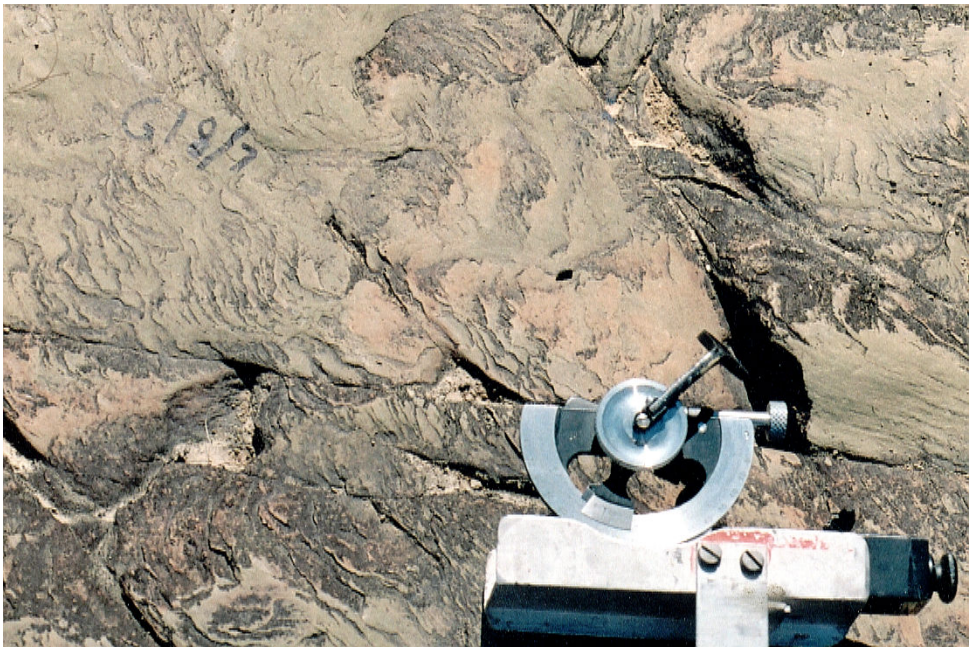

Figure 35: Rib-and-furrow stuctures on the surface of a trough cross-stratified sandstone, The Grant. (Scale: 20cm long abney level).

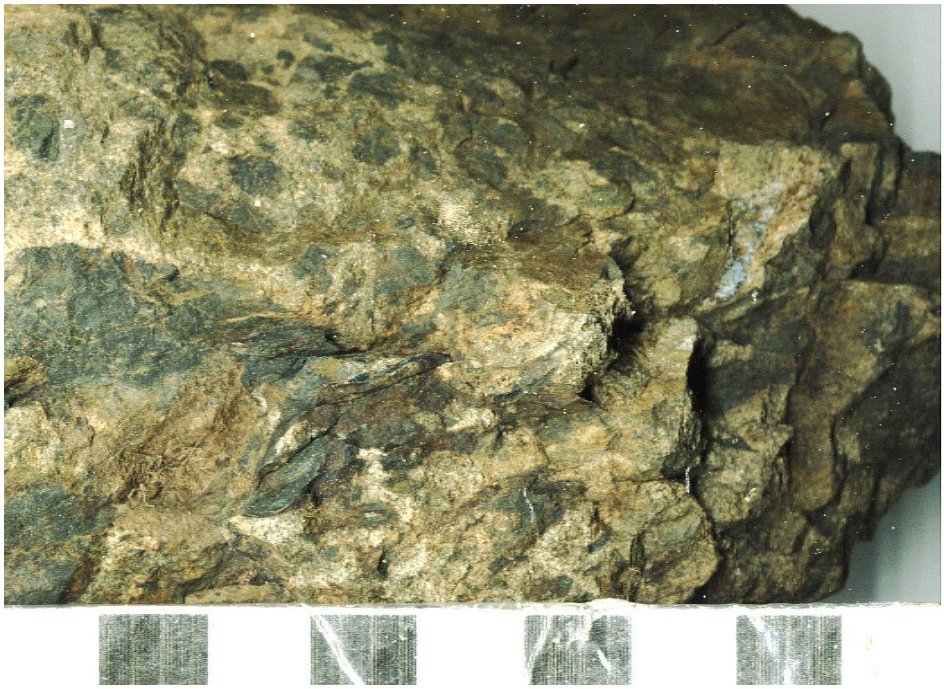

Figure 36: Intraformational conglomerate comprising sub-rounded mud clasts in a sandstone matrix. (1cm divisions on scale bar).

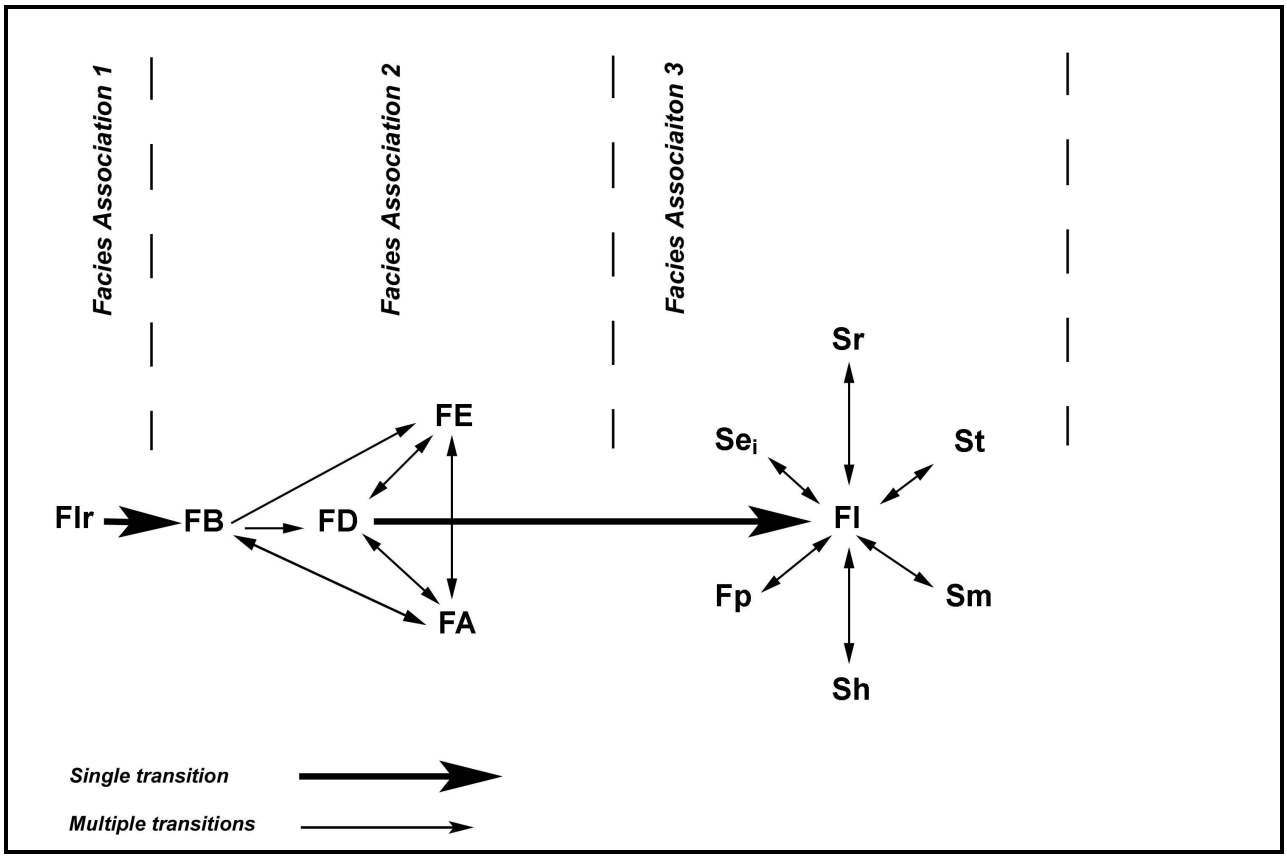

Figure 37: A Markov diagram displaying the transitions of the facies within the stratigraphic sequence present on the farms Signal Hill, Peninsula and The Grant. Facies codes follow those used on the stratigraphic sections.

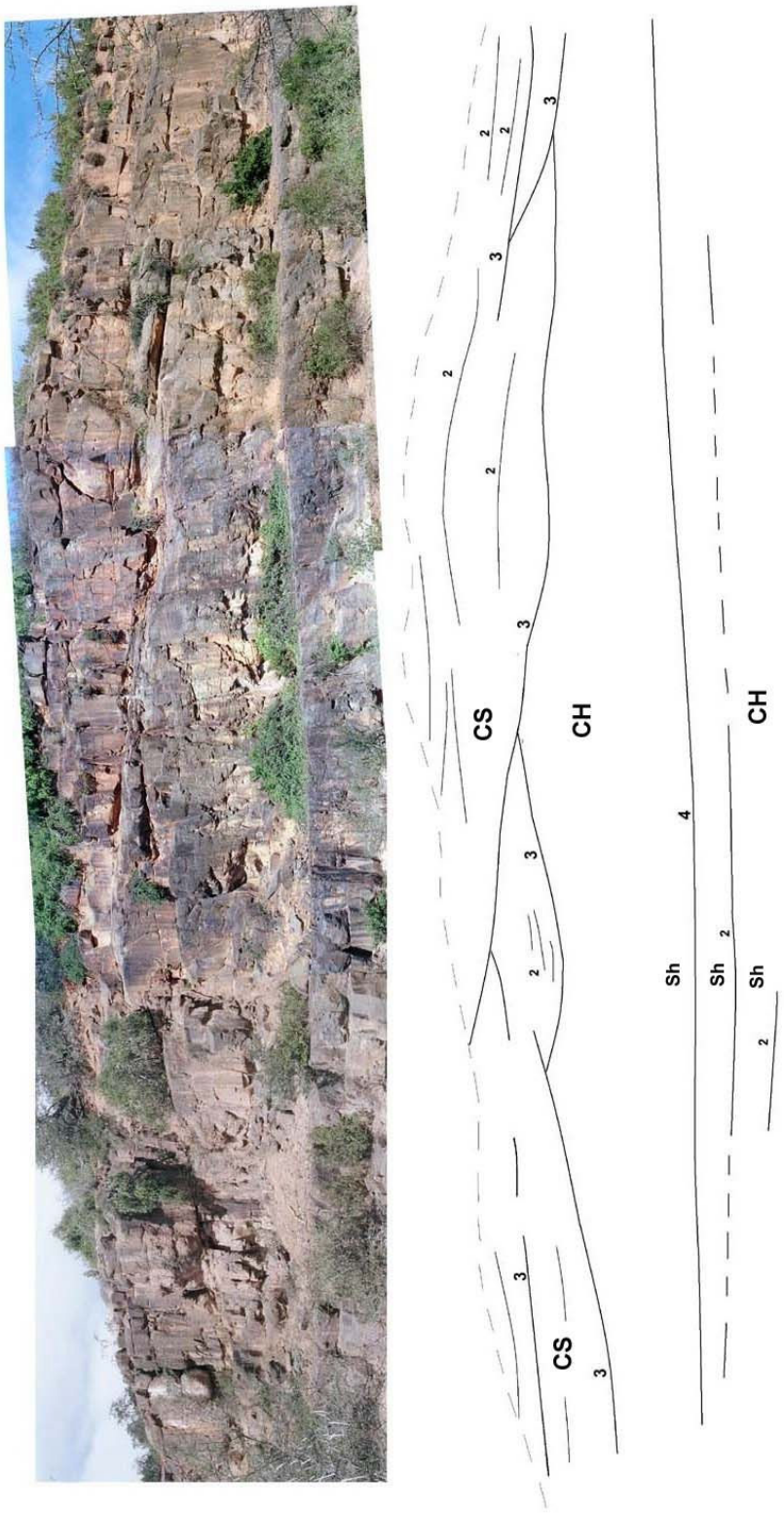

Figure 38: Lateral profile of subaqueous channels within Facies Association 2 at 33° 05' 45”S 26° 39' 08”E on Bucklands. Numbers refer to the order of the bounding surface.

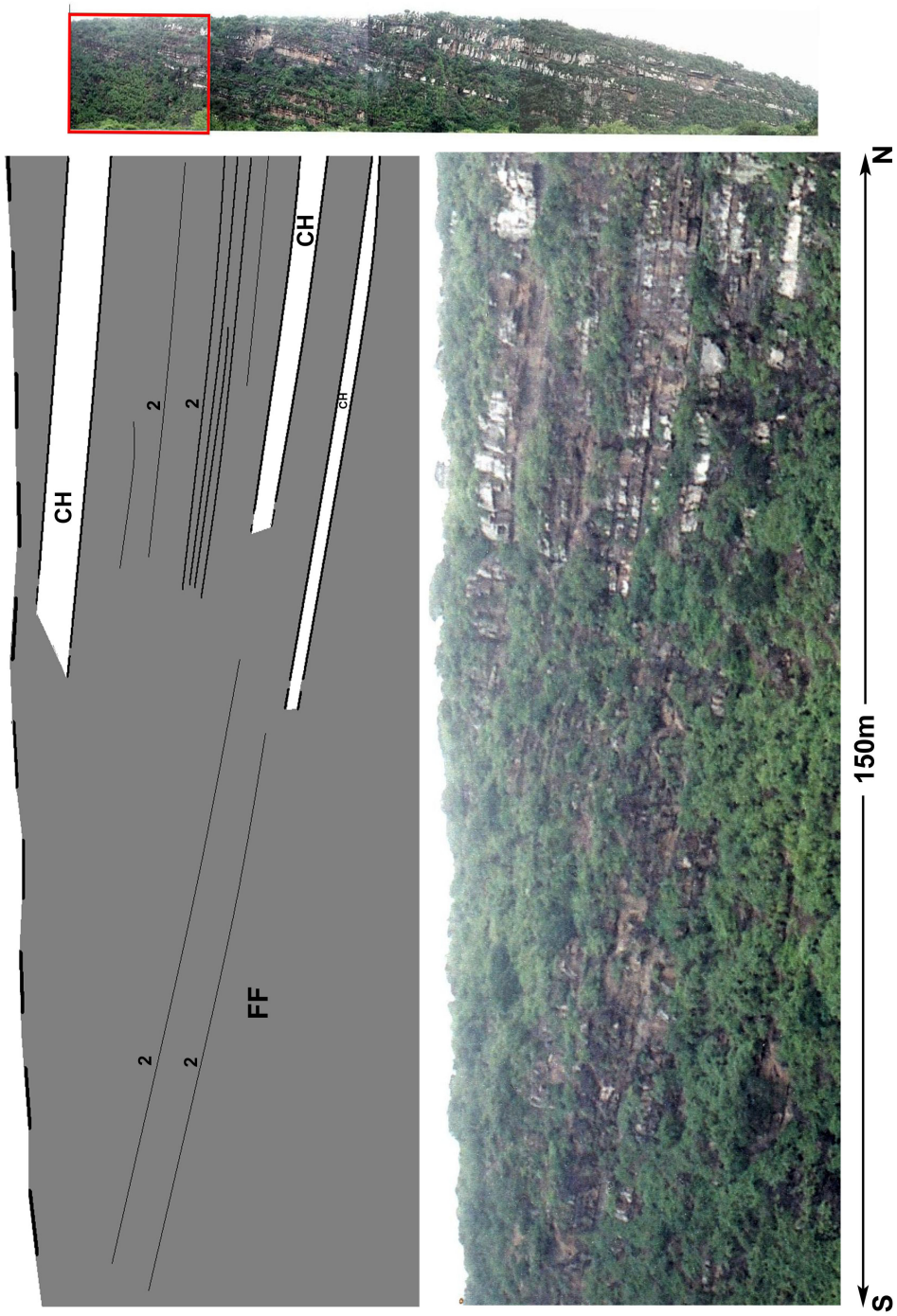

Figure 39: Lateral profile of vertically stacked fluvial sandstone bodies of Lithofacies Association 3 exposed north of Fort Brown on the Grahamstown – Fort Beaufort Road (33° 03' 23" S, 26° 39' 09" E). Numbers refer to the order of the bounding surface.

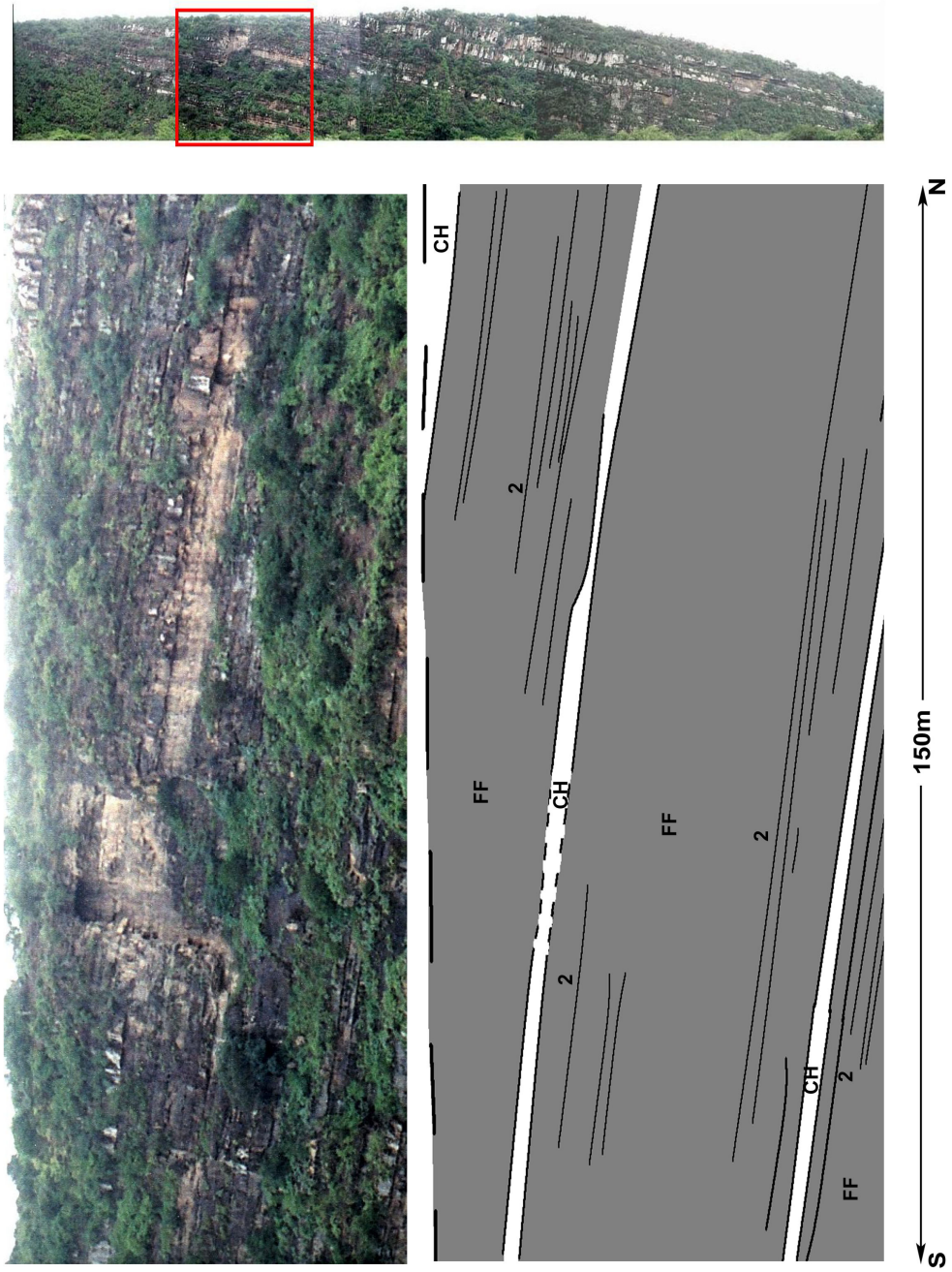

Figure 39 *cont*..: Lateral profile of vertically stacked fluvial sandstone bodies of Lithofacies Association 3 exposed north of Fort Brown on the Grahamstown – Fort Beaufort Road (33° 03' 23" S, 26° 39' 09" E).

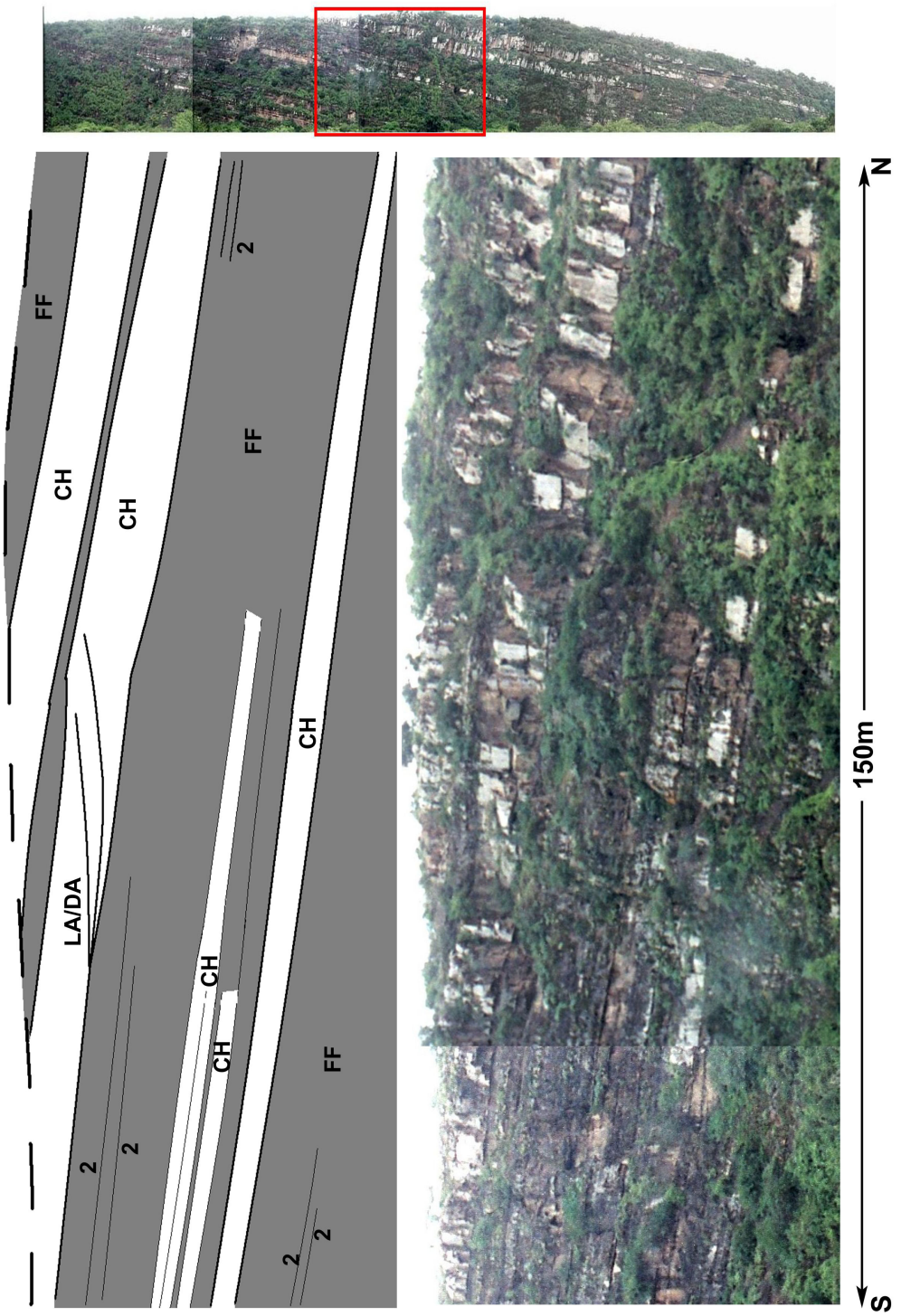

Figure 39 *cont.*: Lateral profile of vertically stacked fluvial sandstone bodies of Lithofacies Association 3 exposed north of Fort Brown on the Grahamstown – Fort Beaufort Road (33° 03' 23" S, 26° 39' 09" E).

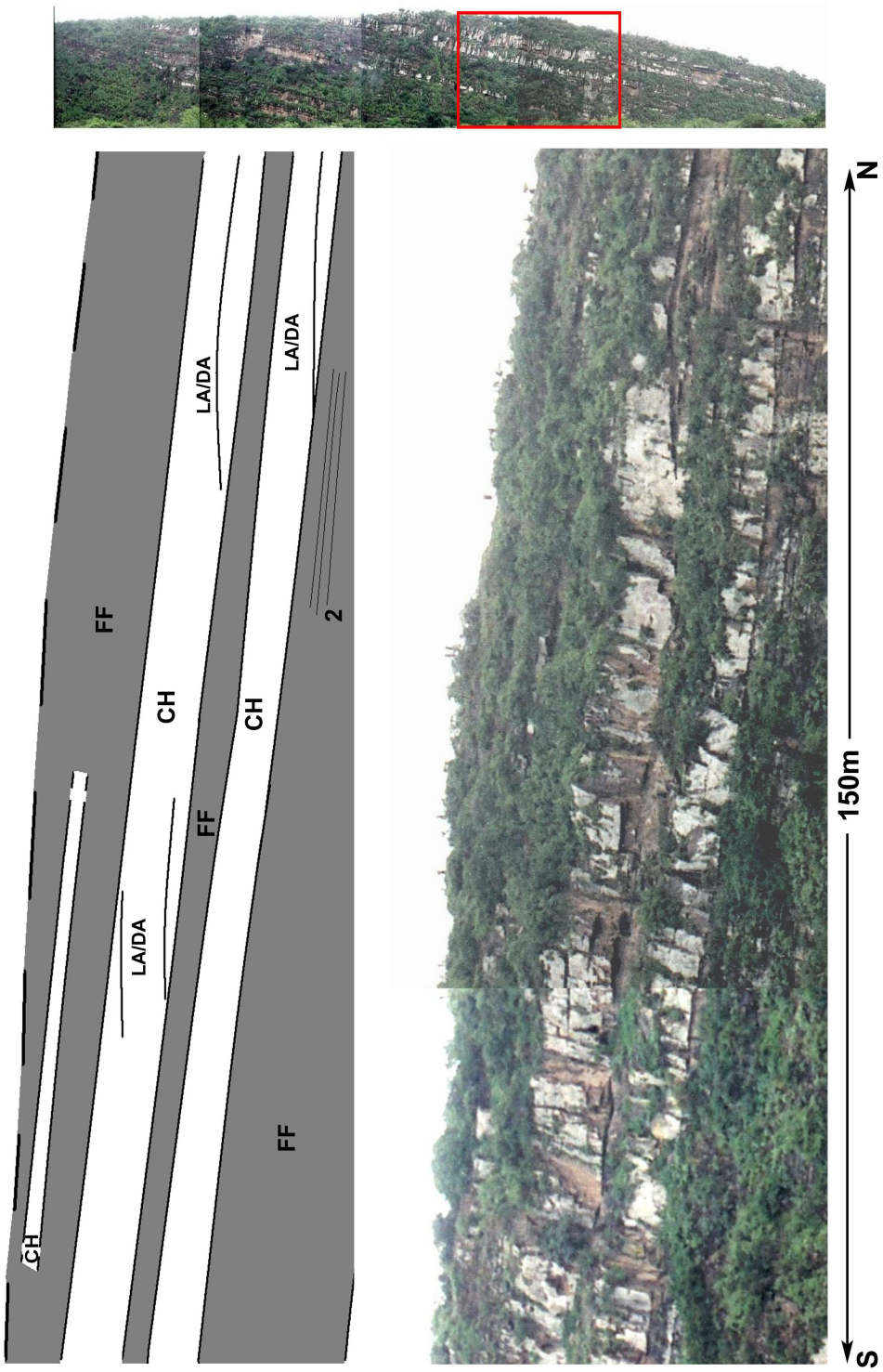

Figure 39 *cont*.: Lateral profile of vertically stacked fluvial sandstone bodies of Lithofacies Association 3 exposed north of Fort Brown on the Grahamstown – Fort Beaufort Road (33° 03' 23" S, 26° 39' 09" E).

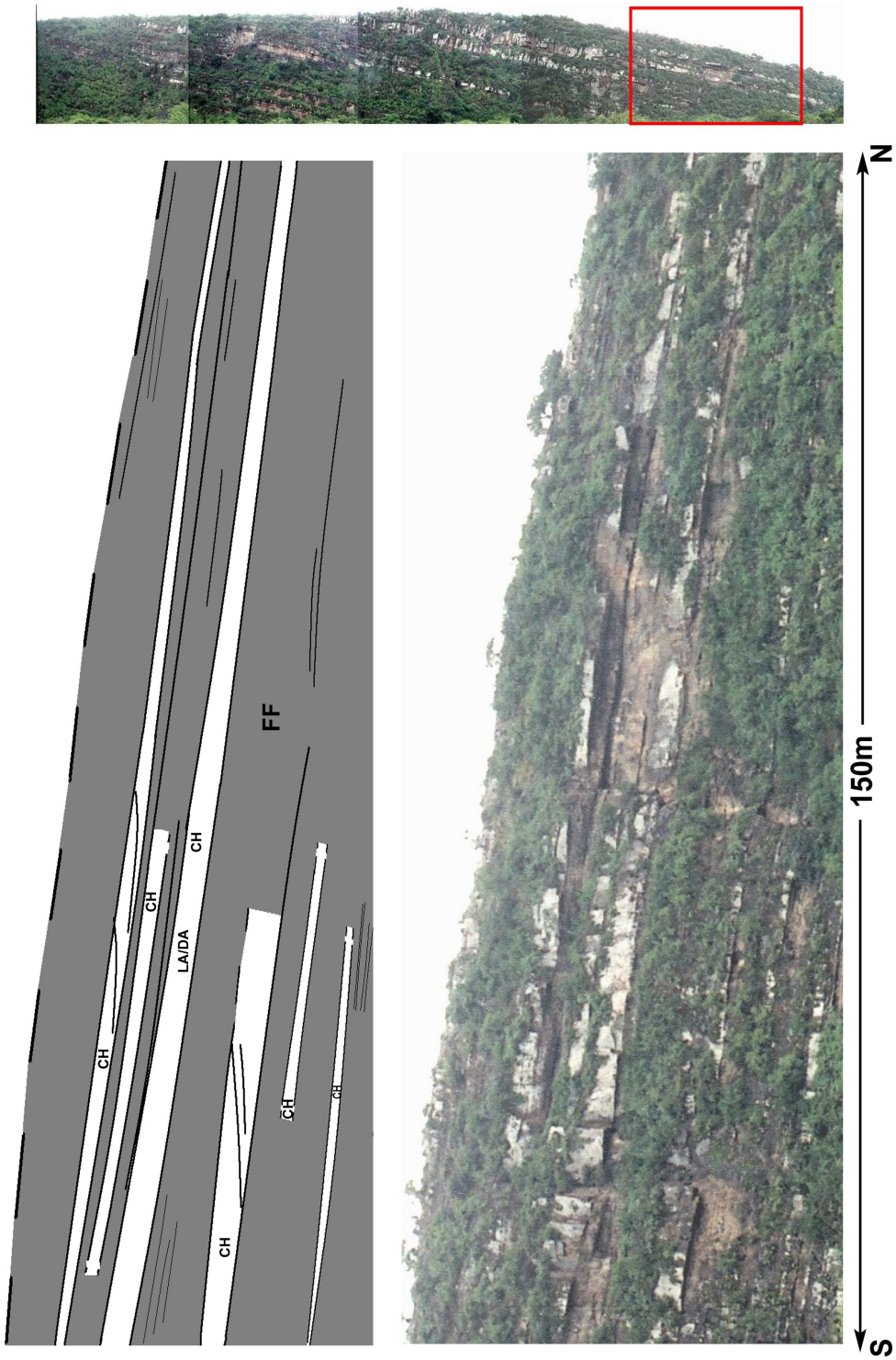

Figure 39 *cont*.: Lateral profile of vertically stacked fluvial sandstone bodies of Lithofacies Association 3 exposed north of Fort Brown on the Grahamstown – Fort Beaufort Road (33° 03' 23" S, 26° 39' 09" E).

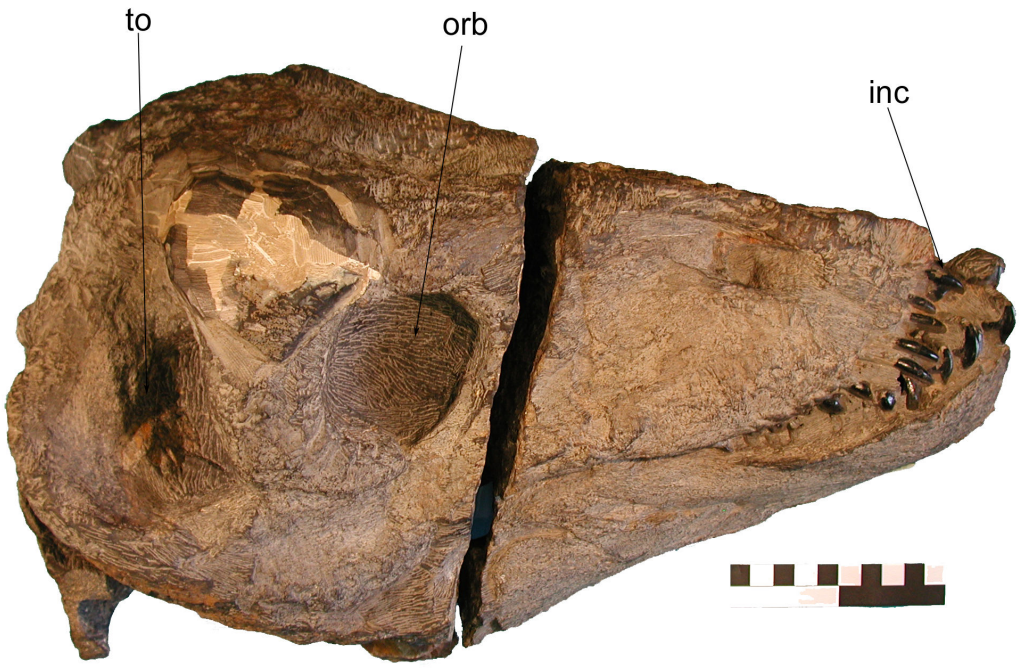

Figure 40: Lateral view of a new tapinocephalid dinocephalian (AM6551) discovered on The Grant. Scale: 1cm minor divisions on scale bar.

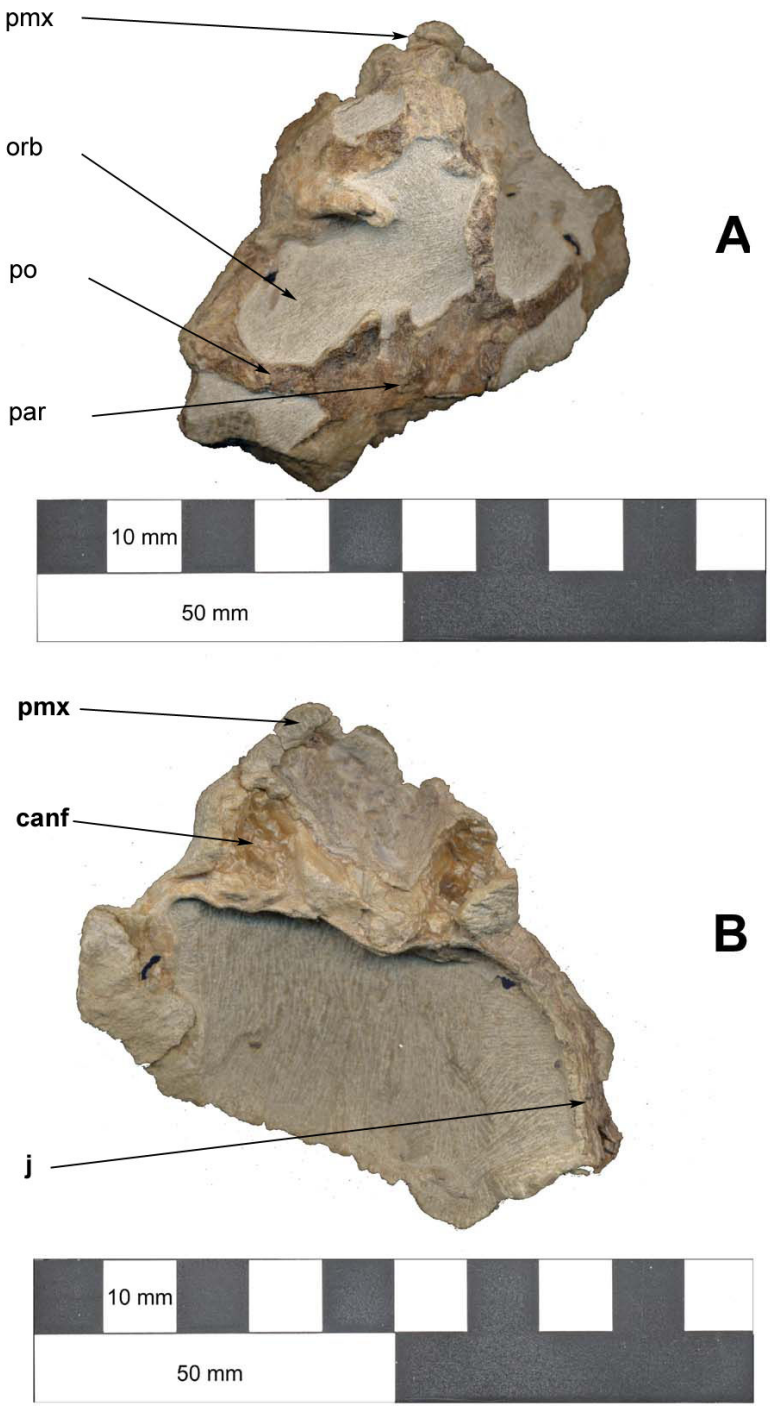

Figure 41: Dorsal (A) and ventral (B) views of the skull of unidentifiable dicynodont (BP/1/6166) discovered on The Grant (central study site). Scale: 1cm minor divisions on scale bar.

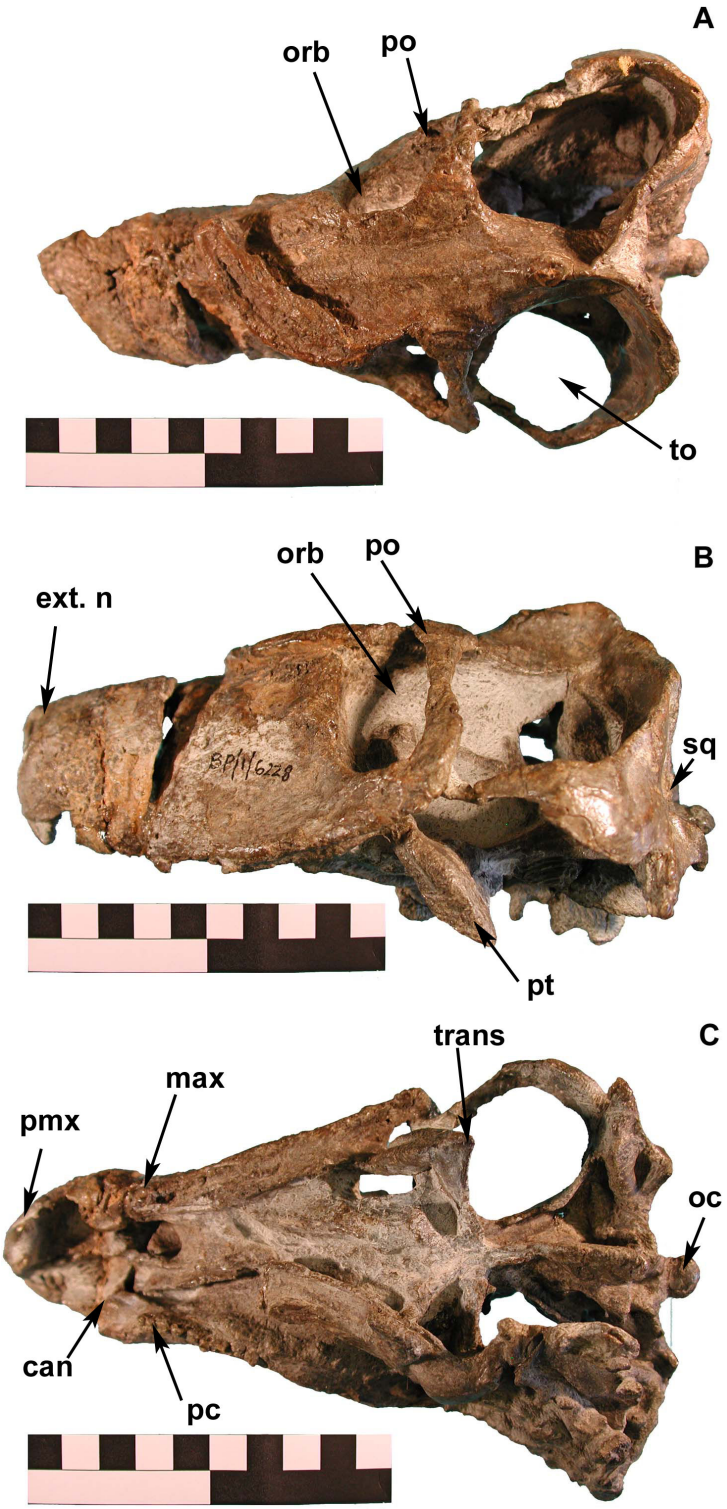

Figure 42: Dorsal (A), lateral (B) and ventral (C) views of a scylacosaurid therocephalian skull (BP/1/6228) discovered on The Grant (central study site). Scale: 1cm minor divisions on scale bar.



Figure 43: Tooth and fragmentary jaw material of an unidentifiable theriodont (BP/1/6221) discovered on Fort Brown – Peninsula Outspan. Scale: 1cm minor divisions on scale bar.

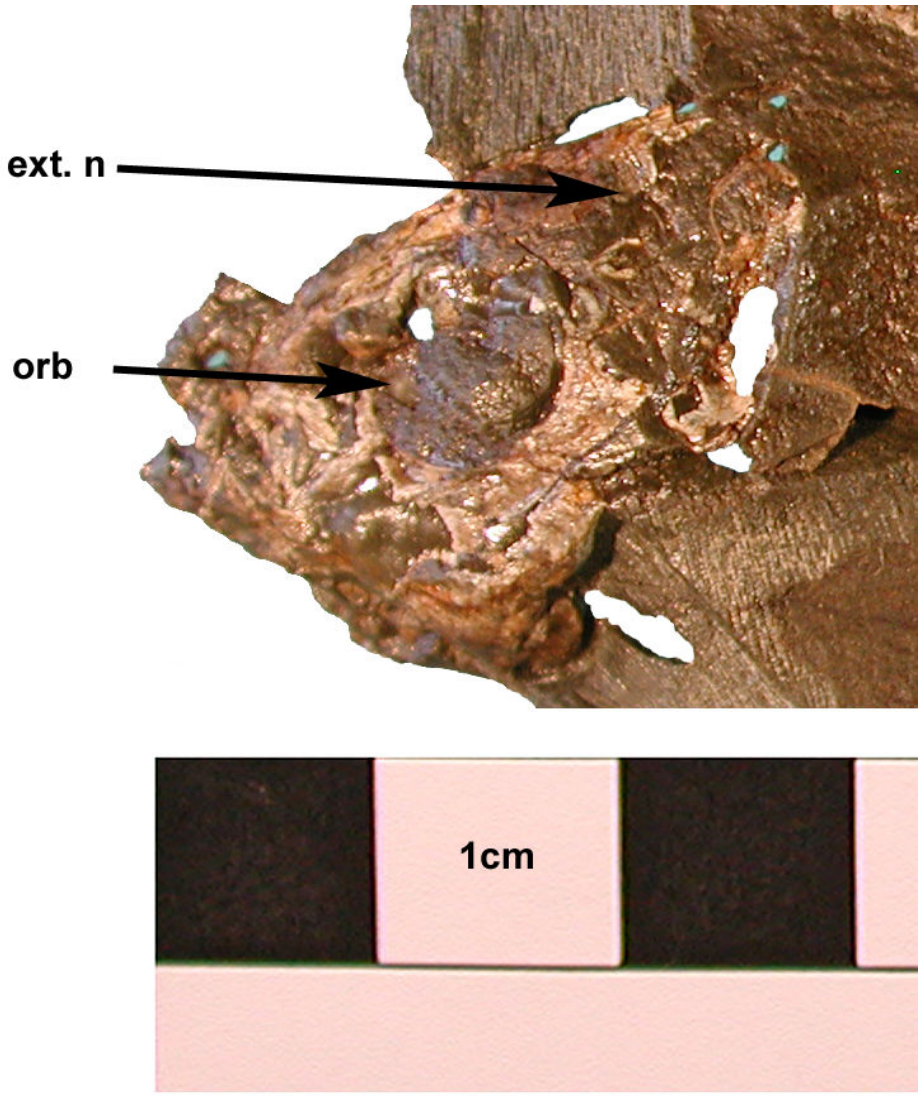

Figure 44: Dorsal view of the skull and post-cranial elements of a juvenile of *Broomia* (BP/1/6222). Scale: 1cm minor divisions on scale bar.

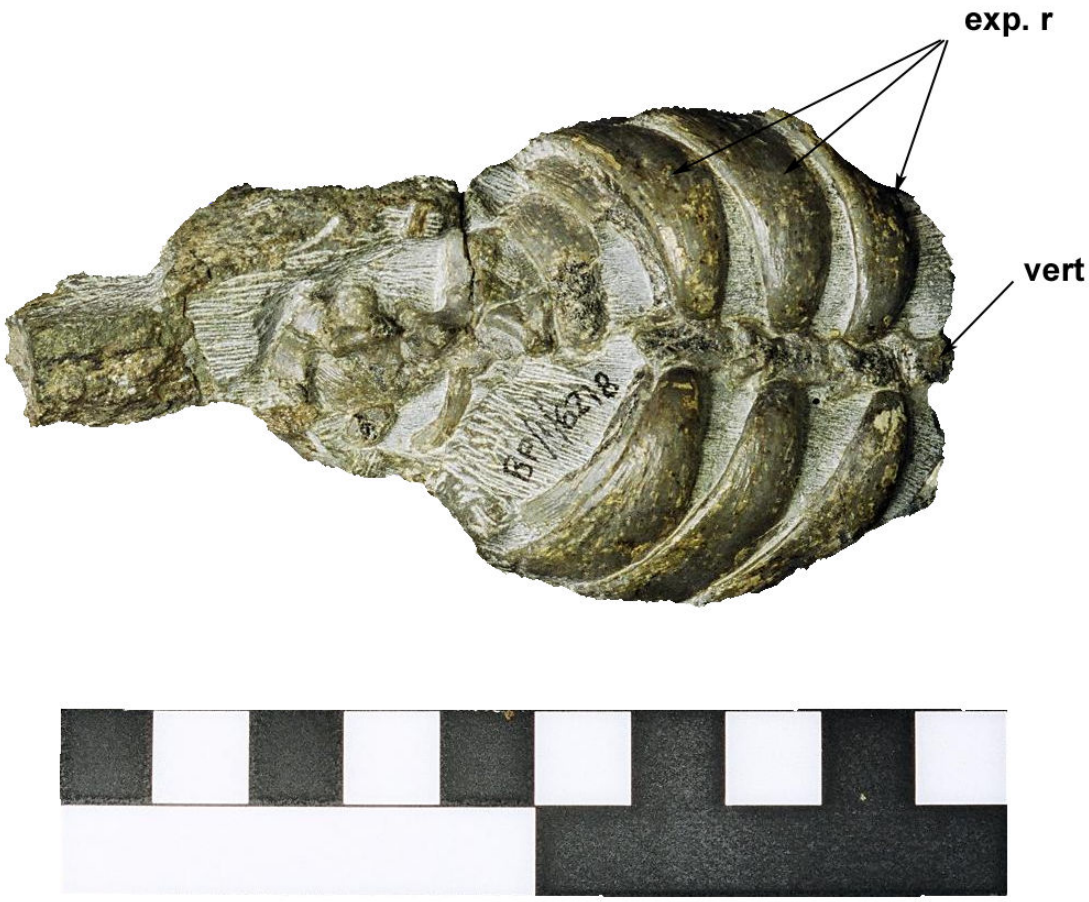

Figure 45: Dorsal view of the articulated post-cranial elements of a *Eunotosaurus* (BP/1/6218) discovered on The Grant (central study site). Scale: 1cm minor divisions on scale bar.

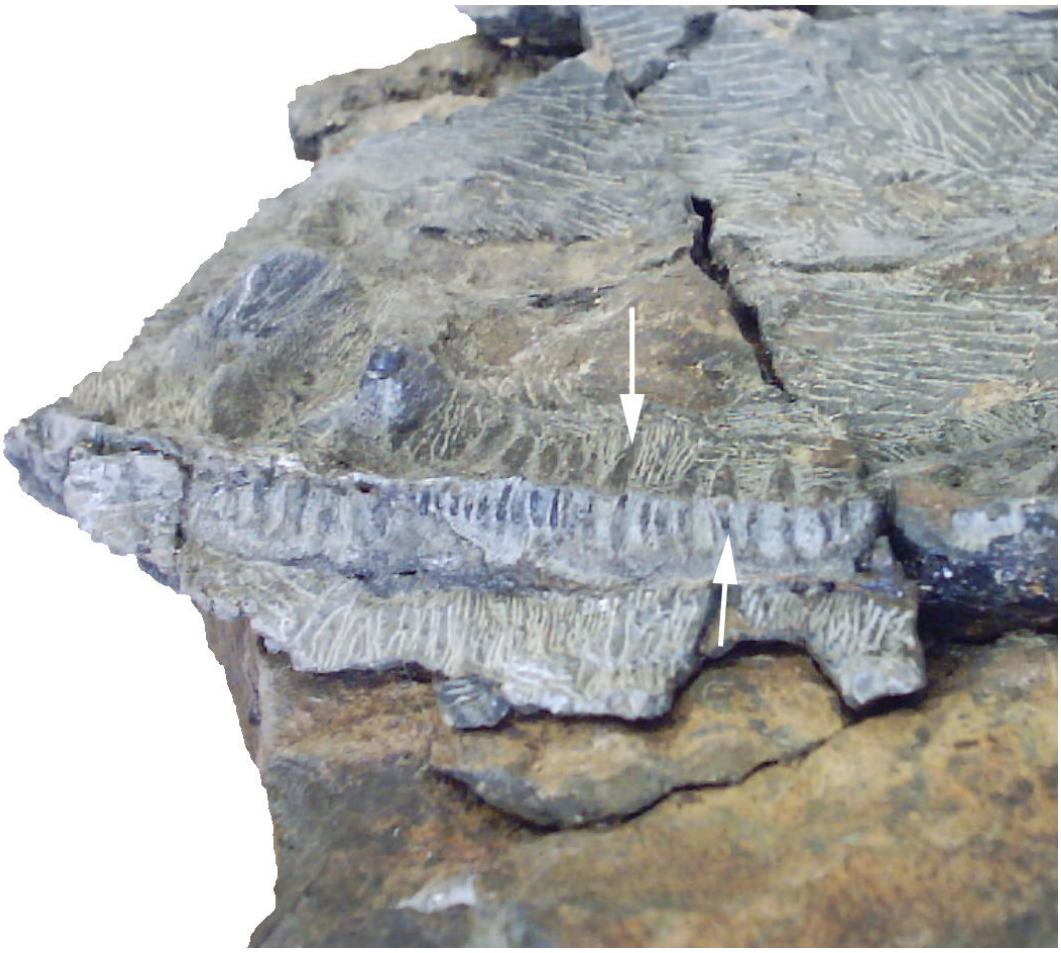

Figure 46: Ventral view of the palate of a rhinesuchid amphibian (BP/1/6226) discovered on Bucklands. (Teeth indicated by arrows).



Figure 47:Parallel traces resembling *Undichna bina* (Anderson 1974), Bucklands. 15cm pencil for scale.



Figure 48: *Glossopteris* leaf impressions, Bucklands (15cm pencil for scale).



Figure 49: Equisitalean stem impression, The Grant. (1cm wide pencil for scale).



Figure 50: Equisatalean plant fossils in growing position, The Grant. (1cm minor divisions on scale bar).



Figure 51: Sphenophyte stem impressions with attached seed structures (arrows), Kwandwe.

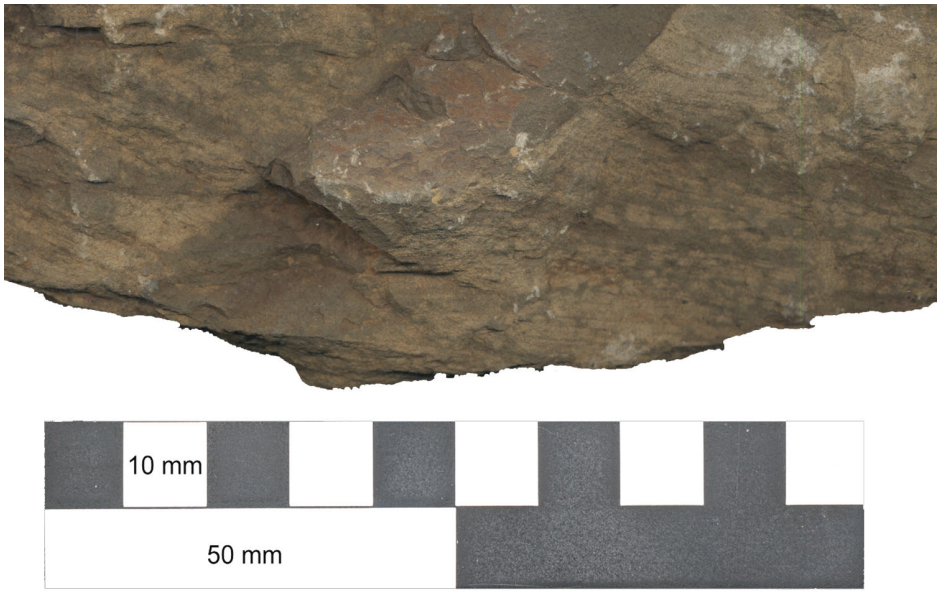

Figure 52: Mudstone-filled stem impression, Bucklands.

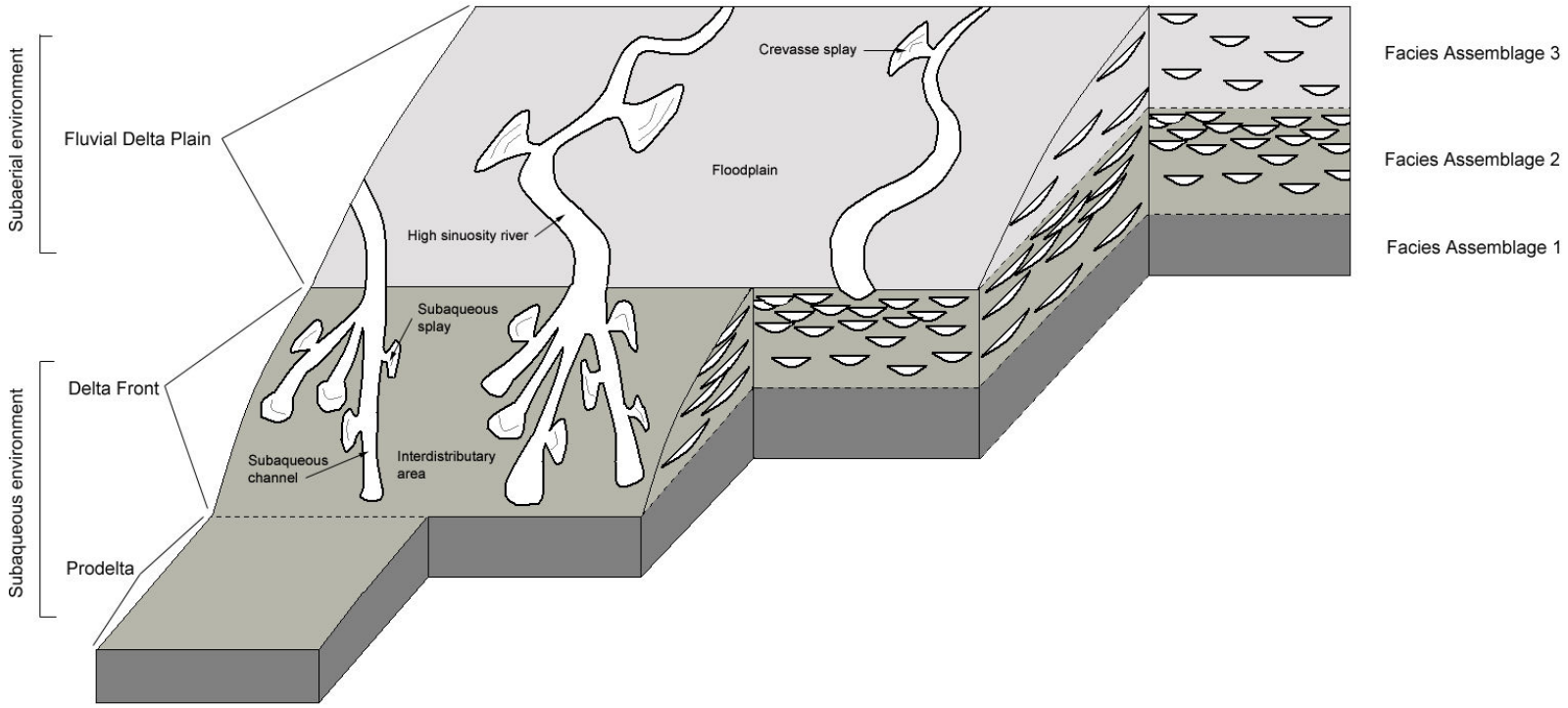

Figure 53: Depositional environment of the upper Ecca and lower Beaufort groups in the southeastern Karoo Basin (after Rubidge 1988).

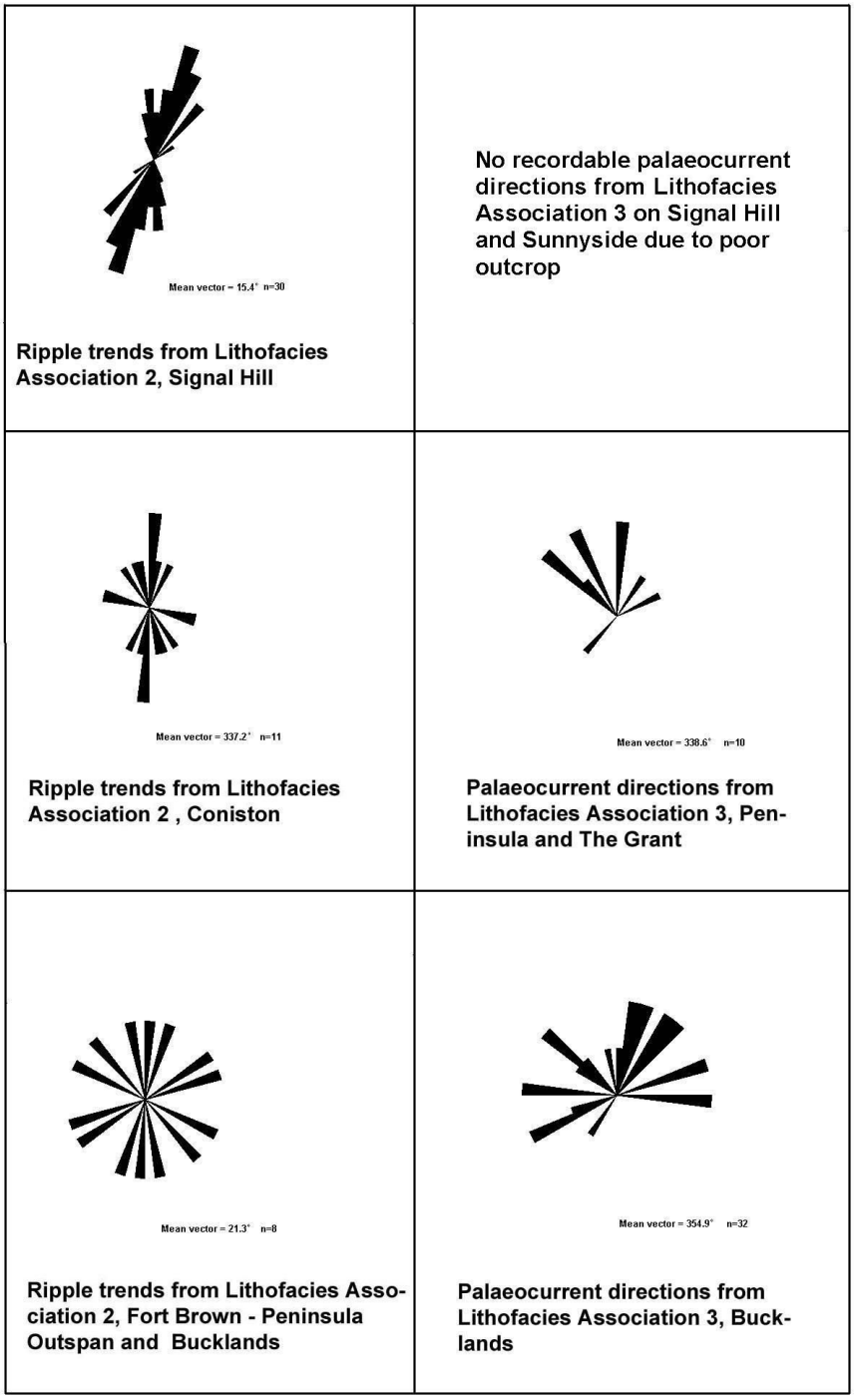

Figure 54: Paleocurrent data. The palaeocurrents for Lithofacies Association 3 represent current directions taken from ripples and rib-and-furrow structures, while those for Lithofacies Association 2 represent current directions taken from ripples.

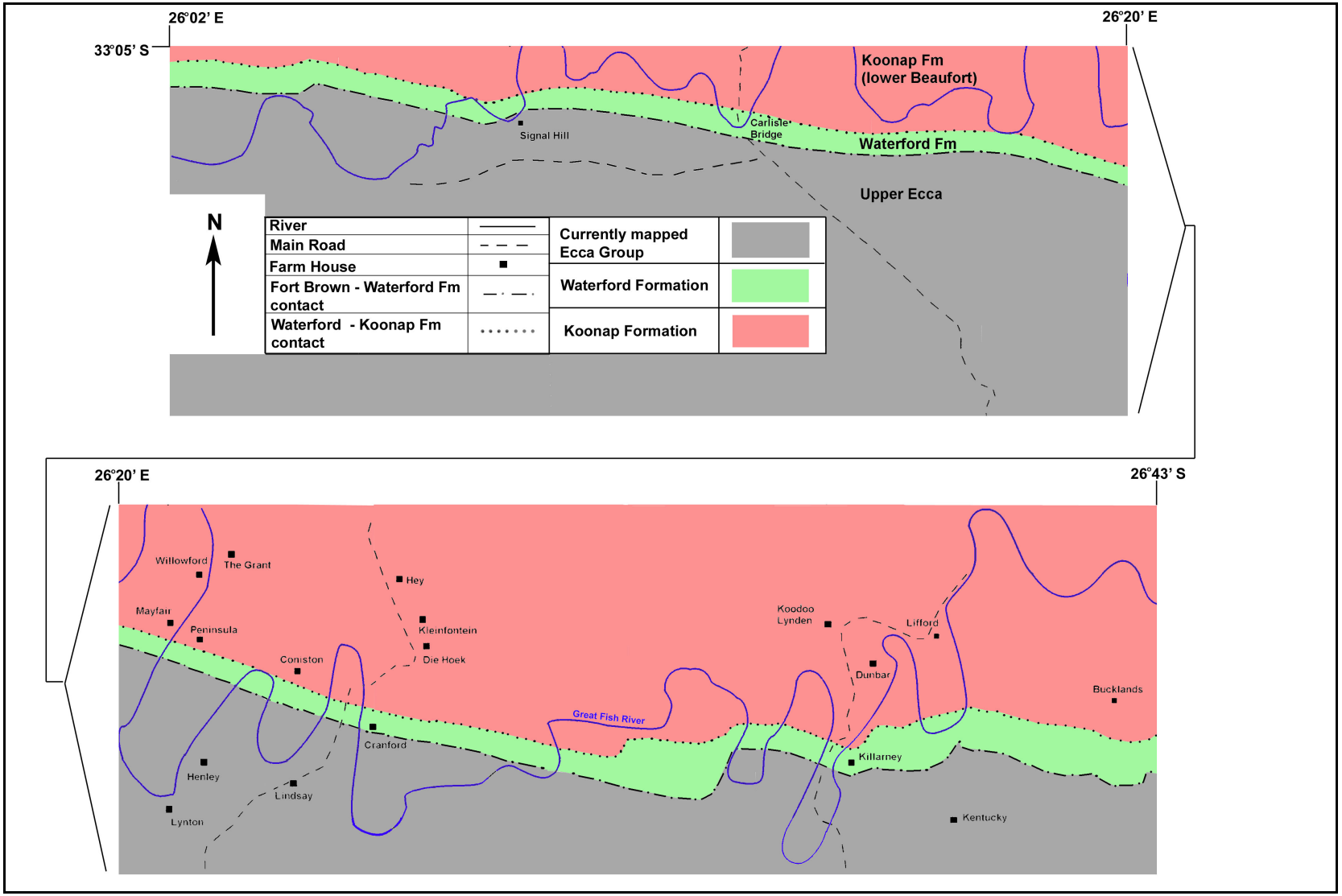

Figure 55: New contacts between the Fort Brown, Waterford and Koonap Formations in the study area. The three study sites are. highlighted

Appendix A: Statistical Analysis of Facies Association

West	Obs.	Exp.	N	X2	v.f	X^2 (0.01,2)
			87			
LFA1 - LFA2	1	29		27.034		
LFA2 - LFA3	1	29		27.034		
LFA1 - LFA3	0	29		29.000		
				83.069	2	13.816

Central	Obs.	Exp.	N			
			210			
LFA1 - LFA2	1	70		68.014		
LFA2 - LFA3	1	70		68.014		
LFA1 - LFA3	0	70		70.000		
				206.029	2	13.816

East	Obs.	Exp.	N			
			101			
LFA1 - LFA2	1	33.67		31.696		
LFA2 - LFA3	1	33.67		31.696		
LFA1 - LFA3	0	33.67		33.667		
				97.059	2	13.816

X2: **Test Statistic**

Obs: **Observed frequency**

Exp: **Expected frequency**

N: **Number of samples**

v.f: **Degrees of freedom**

X2(0.01, 2): **Chi-squared value**

LFA1 – LFA2: **Lithofacies association 2 bed overlies Lithofacies association 1 bed**

LFA2 – LFA3: **Lithofacies association 3 bed overlies Lithofacies association 2 bed**

LFA1 – LFA3: **Lithofacies association 3 bed overlies Lithofacies association 1 bed**

The test staistic is calculated as follows:

$$X2 = (Obs - Exp)^2 / Exp.$$