A reinterpretation of the Wagendrift Quarry, Estcourt, KwaZulu-Natal Province, and its implications for Karoo Basin Paleogeography

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ABSTRACT

The South African Karoo Basin preserves a continental record across the Permian/Triassic Boundary in which both plant and vertebrate fossil assemblages may co-occur. The Upper Permian part of the Beaufort Group, a shallow-water fluvial succession spans this boundary. The Estcourt Formation previously was interpreted to be part of this group representing shallow bay fill, the result of overbank deposition. This interpretation implies that sedimentation occurred along the margins of a large, shallowing basin during the Late Permian. Recent work in a series of outcrops at Wagendrift Dam, near the town of Estcourt, requires a reinterpretation of this setting.

Three outcrops consist of eight facies, six of which are characteristic of a submarine turbidite system. Basal-most massively bedded sandstones, interpreted as submarine channel deposits are overlain by millimeter-scale, fining upwards couplets of siltstone to mudstone that are distal turbidite in origin. Millimeter-scale bedding is undisturbed and bioturbation is limited, indicating deposition within a low oxygen zone. Ripple cross laminated and ball-and-pillow sandstones, overlain by a finer, massive siltstone are indicative of more proximal turbidites, which is further supported by the presence of large, localized olistoliths (slump blocks) in which internal bedding is preserved. Millimeter-to-centimeter scale upwards-fining successions of planar to ripple cross laminated beds of coarser (fine sand, coarse silt) sedimentary rocks overlain by finer siltstone represent a continuation of proximal turbidite conditions. Thick, ripple-bedded sandstones cap the section, representing a major change in depositional setting into a turbidite fan channel system. The sedimentological characteristics of this succession suggest that although these rocks are assigned to the Latest Permian Beaufort Group, they are, in fact, part of the Ecca Group. Palynomorphs recovered from the quarry are of Late Permian age and consist of taeniate and non-taeniate bisaccate pollen, and spores. Assignment of the assemblage, based on partial canonical correspondence analysis, places the Wagendrift palynoflora in the lower part of Aitken's Biozone VI (Volkrust Formation; Wujiapingian). These results indicate that turbidite sedimentation similar to that in the southern and western part of the basin persisted into the Late Permian of KwaZulu-Natal.

Introduction

The rocks that comprise the Karoo Supergroup of South Africa record sedimentation from the Late Carboniferous to the Early Jurassic (Dwyka, Ecca, Beaufort and "Stromberg" groups), and generation of the igneous Drankenberg Group (Smith *et al.*, 1993; Johnson *et al.*, 1997). Sedimentation began following the retreat of Late Carboniferous-Middle Permian glaciers towards the southeastern Cape Fold Belt highlands that resulted in a deep-water environment (Smith, 1990). The subsequent shallowing of this basin witnessed emplacement of fluvio-lacustrine and desert deposits (Johnson *et al.*, 1997) within the retroarc foreland basin (Catuneanu *et al.*, 1998).

Karoo sedimentation began in the Carboniferous-Permian with deposition of tillites, sandstones, and mudstones of the Dwyka Group, which lie unconformably atop Paleozoic and Precambrian bedrock (Smith, 1990). Dwyka sedimentation is linked to multidirectional ice-lobe orientations, ranging from north to northeast, east and south, during glacial retreat (Smith, 1990 and references therein). As these glaciers disappeared, sedimentation shifted from high to lower energy depositional regimes in which sediments accumulated in a deep lake or landlocked sea (Cairncross *et al.*, 2004). This basin was filled gradually by Permian deposits that represent a primarily prograding sediment shelf, which is marked by Bouma-style turbidite deposits, and are assigned to the Ecca Group (Smith, 1990; Johnson *et al.*, 1997). These turbidite-dominated deposits extend from the south and southwestern parts of the basin (Collingham, Vischkuil, and Ripon Formations) to the west and north (Laingsburg Formation.; Johnson et al., 1997). These are overlain by prodelta, shallow shelf, and deltaic deposits. Towards the east, the Ecca facies grade into primarily deltaic and lacustrine deposits with a shift to shallow water, meandering fluvial channels and floodplain lacustrine regimes characteristic of the Permian-Triassic Beaufort Group (Smith, 1990; Johnson *et al.*, 1997). Fluvial and lacustrine depositional environments persisted throughout the Triassic into the Early Jurassic (Molteno and Elliot Formations) until facies reflect a change to eolian deposits with dune fields and playas (Clarens Formation). Sedimentation ended with Gondwanan rifting and formation of the Middle Jurassic Drakensberg intrusive and extrusive rocks (Smith, 1990; Duncan *et al.*, 1997).

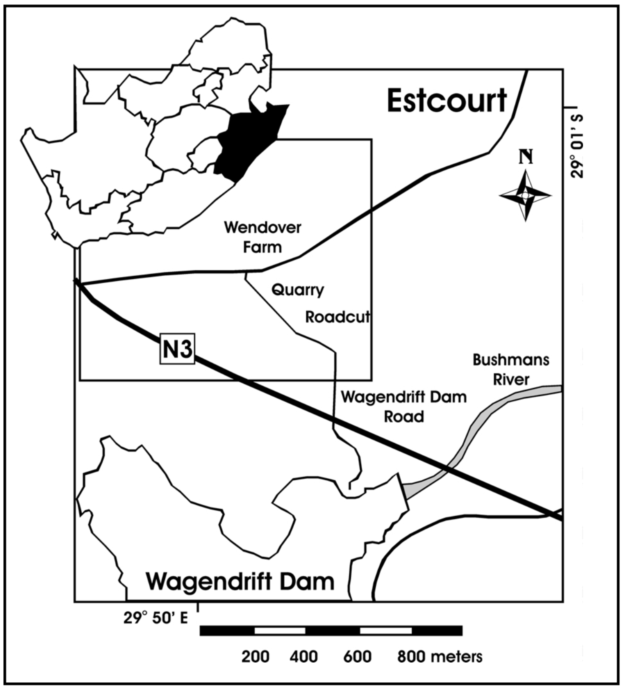

Figure 1. Generalized locality map of collection sites near Wagendrift Dam in Estcourt, KwaZulu-Natal Province (blackened). Three outcrops are exposed in this area within a quarry, a roadcut, and a donga. All three localities are near the Wendover Farm, as marked on the 1:50,000 map (2929BB) of Estcourt Quadrangle.

The Estcourt Formation is part of the Beaufort Group and is restricted to KwaZulu-Natal Province. It consists of about 400 m of carbonaceous mudstone and sandstone with sparse, intermittently distributed coals (Johnson *et al.*, 1997). It is mapped currently as the edge of Lower Beaufort deposits in the basin. Van Dijk *et al.* (1978) interpreted the exposure at the Wagendrift Dam section as bayfill overbank deposits representing the shallowing of internal deep-water settings. This interpretation places Wagendrift and, hence, the Estcourt Formation within the Beaufort Group despite a diachronous Ecca/Beaufort transition from the south to the north within the basin (Modesto *et al.*, 2001). This temporal relationship suggests that there may be some variability in the stratigraphic assignments of these rocks, which is further supported by a reevaluation of the Wagendrift section. This study was undertaken in an attempt to evaluate the previously interpreted depositional environment as part of an overall broader project investigating terrestrial diversity trends across the Permian/Triassic boundary (Sims *et al.*, 2004; Gastaldo *et al.*, in press).

Locality Description

The Estcourt Formation is located in the Mooi River/Bergville/Ladysmith area (Figure 1) in KwaZulu-Natal Province of South Africa (Johnson *et al.*, 1997). Several outcrops occur to the southwest of the town of Estcourt, near the Beechwood campgrounds of the Wagendrift Nature Reserve. The section consists of 3 outcrops in close proximity to each other. The primary and most laterally extensive outcrop is a 'quarry' exploited for road material and first described by Van Dijk *et al.* (1978). It is exposed at the intersection of two roads across from the Wendover Farm, and is 116 m in length, 7 m high with a strike of 193° and a dip of 2° to the northeast. The second outcrop is immediately (~100 m) to the southeast of the quarry along a small private roadcut. It is approximately 50 m in length and 6 m high. The last exposure is within a series of dongas exposed on the Wendover Farm. The donga section was examined but not measured due to limited exposure and the lack of stratigraphic control because of tectonic disruption as the result of Jurassic dolerite intrusions. In general, the dolerite intrusions hamper the regional-scale correlation of the studied units. The project focus was on the quarry and road-cut outcrops because each contained laterally extensive, continuous beds oriented perpendicular to each other providing for some three-dimensional control.

Lithological Description

The Wagendrift section consists of massive beds of fine sandstone, couplets of siltstone/mudstone and sandstone/siltstone, along with several interbedded sandstones exhibiting various primary sedimentary structures (*e.g.*, ripples, balls-and-pillows). The section also includes a large, laterally extensive bed of diagenetically altered siltstone, and a thin, homogenous bed of fine grained, microcrystalline tuff. The section is subdivided into eight lithofacies based on sediment characteristics and cyclical depositional patterns (Figure 2). Facies are laterally extensive, consistent between outcrops, and several key beds can be traced from exposure to exposure. The true thickness of the studied sedimentary unit is unknown, and its base was taken at the top of the local dolerite sill (Figures 2; 3).

Facies 1. Yellowish Gray Very Fine Sandstone.

The basalmost lithotype consists of four beds of yellowish gray (5Y 7/2) very fine sandstone, with beds ranging in thickness from 32 to 75 cm, in direct contact with the underlying dolerite sill (Figure 3). This facies is found only in the road cut. One sandstone bed contains matrix supported intraformational mud clasts, whereas the others are massive. No other primary sedimentary structures of any scale were observed. In thin section, this lithology consists of subangular to subrounded, very fine (mean = 0.08 mm) quartz (98% Qtz, N=300) clasts.

Facies 2. Dark to Dusky Yellowish Brown Very Fine Sandy Siltstone

This unit overlies the basal sandstone and consists of a fining-upwards succession of undetermined thickness (minimum 60-80 cm) of dark to dusky yellowish brown (10 YR 4/2-2/2, weathered dark yellowish orange to moderate yellowish brown, 10 YR 6/6- 5/4) very fine sandy siltstone (Figure 4). The minimum thickness estimate is due to the exposure beginning at the base of the quarry. There are no primary structures and the unit

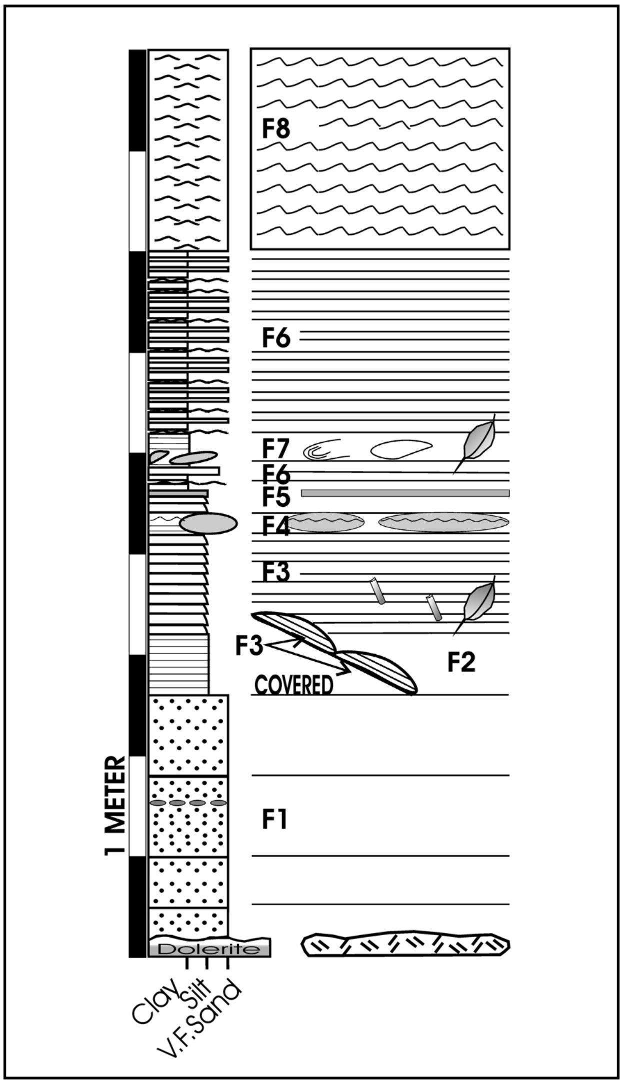

Figure 2. Stratigraphic column with schematic line drawing. The basal sandstone with intraformational mudclasts characterizing facies 1 (F1) represents turbidite channel deposits. The chaotic deposits laterally adjacent to olistolith slump blocks characterize facies 2 (F2). Facies 3 (F3) represents distal turbidite deposition. Facies 4, 6 and 7 (F4, F6, F7) represent more proximal turbidite deposits as expressed by fining upward successions with planar, rippled, and ball-and-pillowed sandstone beds at the base. Facies 5 (F5) is a thin ash bed. The rippled sandstones of facies 8 (F8) represent a more proximal position relative to the turbidite channel.

has been extensively weathered, such that recovery of a sample for thin section analysis was precluded. The extensively weathered unit is laterally adjacent to three olistoliths (slump blocks, Figure 4) at the northwest end of the quarry section. The contact with the overlying facies is sharp.

Facies 3. Light Brown Coarse Siltstone/Yellow to Pale Olive Mudstone Successions

Conformably overlying Facies 2 is a thick (102 cm) unit consisting of couplets of upward-fining successions of mm-to-cm scale planar/ripple cross laminated beds of light brown (5YR 6/4) coarse siltstone to very fine sandstone overlain by yellow to pale olive (5Y 6/4 to 10Y 6/2) siltstone to mudstone (Figure 4). The basal sandstone lamina of each couplet becomes thicker and more prominent upsection with a minimum thickness of 0.1 cm and a maximum of 1.2 cm. Sandstone beds in the lower part are mm-scale laminations, whereas they become thicker (cm-scale) and more pronounced upsection. The average thickness of sandstone beds is 0.3 cm (N=29). This lithofacies is identical to that found within the slump blocks in the northwest corner of the quarry (Figure 4). In cross section, these blocks are convex at their upper surface and lie laterally adjacent to each other. Blocks decrease in size from northwest to southeast. No block is exposed completely, but each has an estimated thickness of at least 15 cm and is 30 cm in length. The upper contact of the blocks with the overlying conformable couplets, which onlap each block, is weathered allowing for easy recognition.

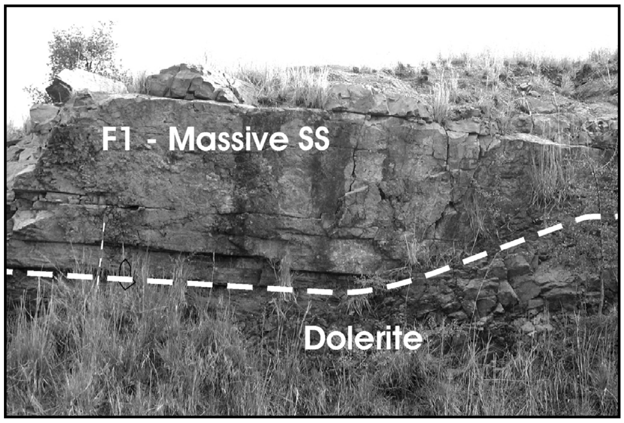

Figure 3. Basal sandstone as exposed at the roadcut section where it is in direct contact with the underlying dolerite. The contact is irregular, and the altered zone in the sedimentary rocks appeared to be minor in the field (thin section analysis was inconclusive).

Rare horizontal and vertical burrows are scattered in this facies along with rare plant fossils that are preserved as impressions parallel to bedding. The cylindrical vertical burrows average 0.3 cm in diameter and are 2.5 to 3.0 cm long, while the elliptical horizontal burrows average 0.6 cm in diameter with an undetermined length. One *Fugichnia* (escape structure) was observed. Small *Glossopteris* leaves and a whorl of *Phyllotheca cf. australis* (Lacey et al., 1975) are found isolated and dispersed in the basalmost siltstone/mudstone couplets (Figures 5A to C). Plant fossils were not recovered from this facies higher in the section although Cindy Looy (personal communication, 2003) has recovered pollen (Figures 5D; G). Paleocurrent data are based on the rippled sandstone beds and distributed bimodally. They show flow directions either from the northeast [mean vector = 50°, N=21] or southwest [mean vector = 228°, N=10] (Figure 6). Thin section analysis revealed thick laminae (5 to 10 mm), with fining-upward successions of very fine sandstone (mean d=0.10 mm) to medium siltstone (mean d=0.03 mm), separated by gradational to abrupt-

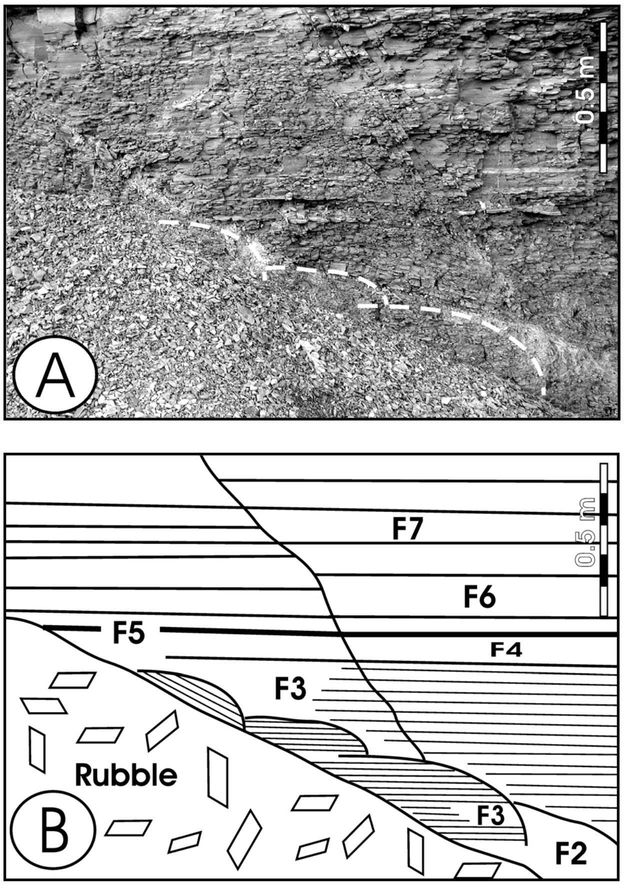

Figure 4. Olistolith and chaotic deposit overlain by laminated siltstone (**A**) with line drawing to scale (**B**). The olistolith and chaotic deposit are heavily weathered, and often rubbly, but are easily distinguished in the field. This initial short-lived event is overlain by sediments of more periodic depositional events. Scale = 0.5 m.

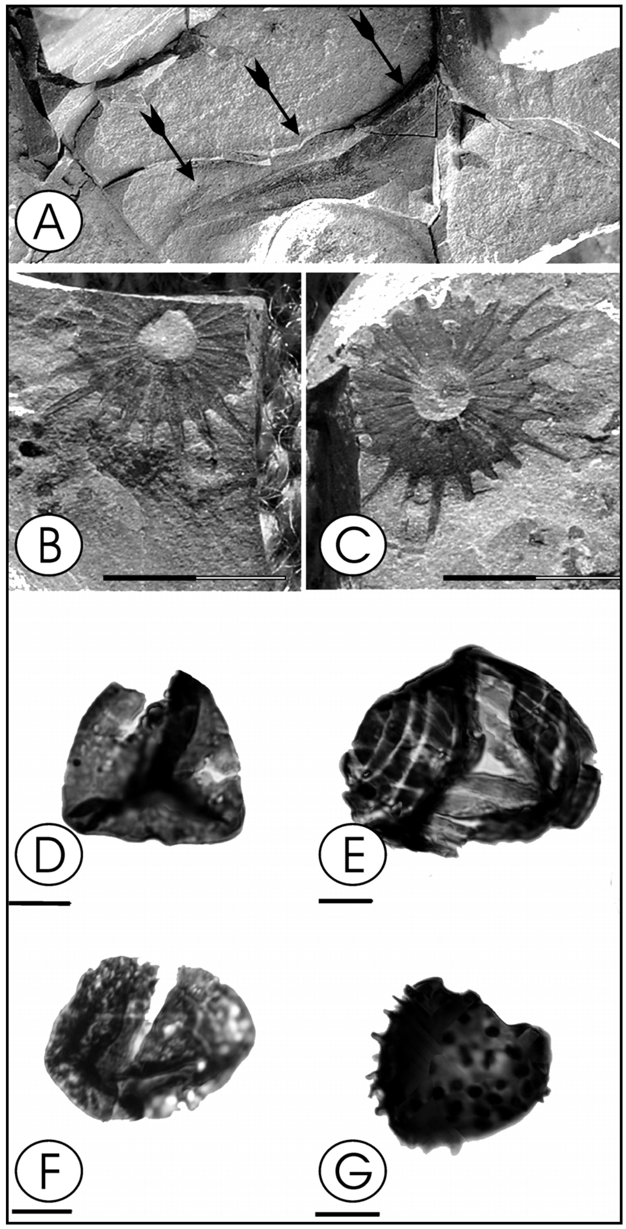

Figure 5. Plant remains in the Wagendrift Quarry section. (**A**) Small, isolated *Glossopteris* sp. leaf (at arrows) on bedding plane of siltstone-mudstone couplets (Facies 3). Leaf length 4 cm. (**B**) and (**C**) Isolated whorls of *Phyllotheca* sp. on bedding planes of siltstone-mudstone couplets. Scale = 10 μm. (**D**) *Deltoidospora directa*, a simple deltoid, trilete spore associated with Mesozoic ferns. Scale = 10 μm. (**E**) *Weylandites lucifer*, a nonsaccate pollen grain of Late Permian age. Scale = 10 μm. (**F**) *Lueckisporites virkkiae*, a bisaccate taeniate pollen grain of Late Permian age. Scale = 10 μm. (**G**) *Horriditriletes ramosus*, an acavate trilete spore. Scale = 10 μm.

contacts. The grain mineralogy consists of 98% quartz (N=300), with the remaining 2% as small (0.4 mm), irregular, platy fragments of an isotropic mineral.

Facies 4. Diagenetic Nodule-Rich Olive Gray Siltstone

Conformably overlying Facies 3 is a planar/ripple cross laminated bed of very pale to grayish orange (10YR 8/2-7/4) coarse siltstone to very fine sandstone, overlain by 15 to 20 cm of a homogenous, massive bed of olive gray (5Y 3/2) coarse siltstone (Figure 2). The primary structures in this interval are similar to Facies 3 but have been altered diagenetically, as evidenced by their rust-color and friability. This interval contains grayish red to dark reddish brown (10R 4/2-3/4) coarse siltstone nodules of average 175 cm in length (N=27) and 25 cm in thickness (N=10; Figure 7). Bounded on the bottom by rippled sandstone (average 10 mm in thickness (N=2)), the nodules, themselves, may be restricted to one upward-fining succession, or may envelope several upward-fining successions. From west to east, this interval becomes increasingly nodule-rich, finally resulting in a horizon that is completely altered. Cindy Looy (personal communication, 2003) has recovered pollen as well as a dispersed organic fraction from this interval. Thin section analysis of the massive siltstone in which the nodules occur shows that the angular, quartz dominated fine to very fine sandstone (mean d=0.13 mm) gradationally fines into a coarse siltstone (mean d=0.05 mm). The clasts in the nodule are poorly sorted with the majority of the grains consisting of very fine sand (mean d=0.10 mm), but with larger (mean d=0.2 mm), angular, isotropic minerals scattered within the

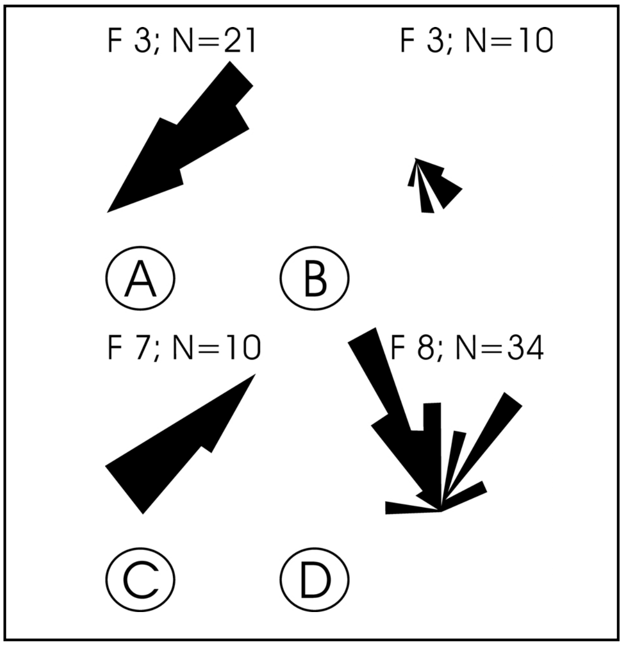

Figure 6. Paleocurrent measurements at the quarry section. (**A** and **B**) are taken from ripple orientations in Facies 3, (**C**) is taken from the toes of balls in Facies 7, and (**D**) is taken from the ripple orientations in Facies 8. The multidirectional nature of ripples in these facies precludes an interdistributary bay interpretation.

otherwise massive lithology. Grain composition could not be determined due to the apparent weathering that occurred within this unit.

Facies 5. Yellowish Gray Tuff

A sharp contact separates Facies 4 from a laterally persistent lamina of yellowish gray (5Y 8/1) fine tuff (Figure 7). It is crystalline in texture, and of a consistent thickness of 0.75 cm across the quarry outcrop. In the field, it appears to be overlain gradationally by at least a 24 cm succession of Facies 6. However, the contacts of this layer with the underlying and overlying facies are abrupt in thin section. The bottom of this bed consists of angular, elongate, quartz dominated, fine sand-sized clasts (d=0.20 mm). Grain size remains constant from bottom to top, but grain shape changes from angular elongate to subangular/subrounded. The mineralogy is quartz dominated (98%), with scattered and isolated elongate isotropic grains (2%). Samples sent to the geochronology laboratory at the Massachusetts Institute of Technology (M.I.T.), U.S.A., contain no datable zircons (D. Erwin, personal communication, 2005).

Facies 6. Rippled/Planar/Cross-bedded Very Pale to Grayish Orange Siltstone/Olive Gray Very Fine Sandstone

Overlying Facies 5 are successions of planar/ripple cross laminated intervals of very pale to grayish orange (10YR 8/2-7/4) coarse siltstone to very fine sandstone overlain by a homogenous, massive bed of olive gray (5Y 3/2) very fine sandstone (Figure 7). When viewed in thin section, cm-scale successions consist of medium (mean d=0.35 mm) to very fine sandstone (mean d=0.10 mm). The rippled sandstone beds average 15 mm in thickness (N=2). The bottom and top contacts of each are sharp, and grain size coarsens upwards. Cindy Looy (personal communication, 2003) has recovered pollen in this facies.

Facies 7. Very Pale to Grayish Orange Very Fine Sandstone with Ball-and-Pillow Structures

A thick, contorted bed of very pale to grayish orange (10YR 8/2-7/4) coarse siltstone to very fine sandstone exhibits ball-and-pillow and flame structures of various scales. This is overlain by a homogenous, massive bed of olive gray (5Y 3/2) coarse siltstone (Figure 7). Ball-and-pillow structures are typically 5 to10 cm high and 20 to 40 cm wide. Small (<3 cm) leaves of Glossopteris are preserved within the structures at various angles to bedding. Leaves may be inclined or perpendicular to bedding, or contorted within the sandstone. No leaves were found parallel to bedding. Paleocurrent measurements taken on the toe of each ball structure are to the southeast (Figure 6) with an average mean vector of 145° (N=10). When viewed in thin section, this lithotype consists of fine sand (mean d=0.2 mm) arranged within contorted bedding structures.

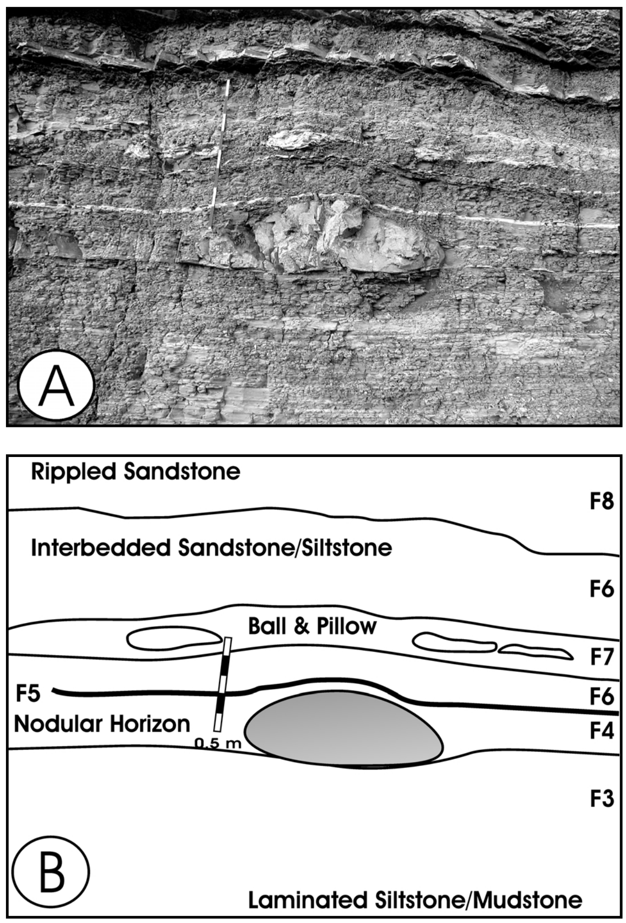

Figure 7. Facies observed at the quarry section. (**A**) Photograph of quarry wall where facies are exposed. (**B**) Schematic line drawing to scale indicating facies contacts. See text for detailed facies descriptions.

Facies 8. Ripple Bedded Very Pale to Grayish Orange Coarse Siltstone

Conformably capping the interlaminated succession are thick (5-10 cm), rippled beds of very pale to grayish orange (10YR 8/2-7/4) coarse siltstone to medium sandstone (Figure 8). The average wavelength of the ripples is 6 cm (N=19); maximum ripple thickness is 2 cm (N=40). The average paleocurrent is N (mean vector 358°); however, directions vary between northwest and northeast (N=34, Figure 6). Contacts between beds are sharp. Thin sections revealed that this is medium-grained sandstone showing no micro-cross lamination within beds. This facies is similar to Facies 1 in both composition and texture; however, it occurs as thin beds with rippled tops, whereas Facies 1 is primarily massive.

Summary

A basal sandstone containing intraformational mudclasts is capped by a homogenous, weathered siltstone that is laterally adjacent to small olistoliths in which bedding is preserved and undisrupted. These are overlain by a lithology consisting of fine-grained laminated sediments, which is the same as that found in the small olistoliths. These laminated sediments are millimeter-scale and consist of siltstone-mudstone couplets near the base, and gradually coarsen upsection to sandstone-siltstone couplets as sand proportions increase. Dispersed, isolated small leaves are preserved parallel to bedding in the basal decimeters of the interval. Near the top of the interlaminated interval, discrete ripple-laminated and ball-and-pillow structures become more common. Small, distorted *Glossopteris* leaves are found within the ball-and-pillows. Paleocurrent vectors of rippled beds vary and reflect either a northeasterly or southwesterly direction; paleocurrents measured from ball-and-pillow structures are to the southeast. A 25 cm interlaminated interval has been overprinted diagenetically by the formation of concretions. A thin, gray tuff comprised of silt-sized clasts overlies the nodular interval and extends across the outcrop. The interbedded and interlaminated succession is capped with very thinly bedded rippled sandstone exhibiting paleocurrents to the North. Several units preserve a pollen assemblage of low diversity (see below).

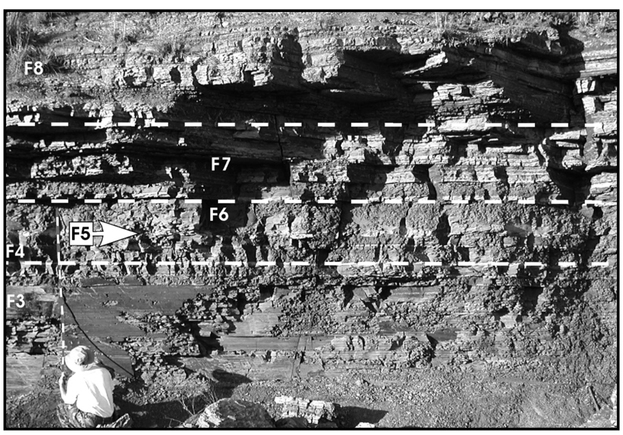

Figure 8. Observed stratigraphy at the quarry exposure of turbidite facies, marking a shift from distal turbidite deposition (Facies 3) at the base, to more proximal turbidite deposition (Facies 4, 6 and 7) mid-section, to near channel deposits (Facies 8) at the top.

Interpretation

Three criteria are used to help identify turbidite successions in the rock record and include:

(1) monotonously interbedded sandstones and mudstones,
(2) sharp-based upwards fining sandstone to mudstone mm-to-cm scale successions, and
(3) parallel/rippled/crosslaminated sandstones overlain by homogenous fine clastics (Walker, 1984).

As such, the observed Wagendrift facies consisting of a basal massive sandstone, upward coarsening mm-scale sandstone-siltstone couplets, and rippled sandstone capped by massive fines are consistent with a turbidite interpretation. In addition, the identification of olistoliths, as well as ball-and-pillow structures, indicates that depositional energy levels were consistent with those of turbidites (i.e., occasionally high coupled with rapid sedimentation rates).

Bouma (1962) defined 5 typical subdivisions within an ideal succession, representing changing energy levels throughout the course of a single turbidity current. Hsü (1989), on the other hand, believes that these five beds can be condensed to two, representing the change from rapid, pulsed deposition to a more gradual settling. Bouma unit A consists of a graded, massively bedded sandstone representative of high flow velocity and rapid deposition. Unit B consists of parallel bedded sandstone to siltstone and is indicative of high flow velocity. Unit C marks a drop in flow velocity from A and B, as evidenced by rippled/wavy laminations. Further reduction in flow velocity results in unit D, marked by laminated siltstone and mudstone. Finally, unit E is marked by pelagic sedimentation of mud presumably left in suspension by the turbidity current. The lithological expression of this latter feature is a laminated mudstone. Hsü (1989) notes that a lower, horizontally laminated unit (Bouma A and B) can be distinguished from overlying cross-laminated sediments (Bouma C). All other facies are rare in Hsü's (1989) model (Bouma D), or are considered to be of a different origin entirely. Bouma E facies are considered by Hsü (1989) to represent background sedimentation not associated with the actual turbidity event. Based on these models, the Wagendrift facies conform to turbidite deposits and have, thus, been individually interpreted as to their context within a turbidite-dominated system.

The basal thick sandstone (Facies 1) is indicative of a shallow (2 m deep), low energy channel consisting of several stacked, massively bedded aggradational surfaces in which intraformational mudclasts occur. The presence of mudclasts indicates some physical scouring of a preexisting dewatered sediment package that was eroded and transported down current. The absence of primary sedimentary structures within this massive sandstone suggests a high-energy environment. The sharp contacts between beds without surficial modification by ripples indicate sudden reduction in energy following deposition, and that low velocity redistribution of sediment at the surface did not occur. The channel deposits overlain by mm-scale couplets (Facies 3) indicate a shift in sediment discharge direction or energy. Mutti and Normark (1987) note that small-scale channels (~2 m height) are typical of submarine fan distributary channels, and this probably is the case at Wagendrift.

The overlying interval of Facies 3 (siltstone/mudstone to sandstone/siltstone couplets) represents background sedimentation associated with a distal turbidite setting (Mutti and Normark, 1987). A subtle change from distal to more proximal turbidite deposits is witnessed by the increase in sandstone proportion upsection (Reading and Richards, 1994). The near absence of bioturbation suggests oxygen levels were insufficient to support either infaunal or epifaunal detritivores (Savrda and Bottjer, 1991). While lack of bioturbation is, at times, attributed to rapid sediment influx (Savrda and Bottjer, 1991), the small mm to dm scale beds in this outcrop along with the one escape structure (*Fugichnia*) bears witness to the ability of the detritivores to survive the episodic sediment influx.

The olistoliths and laterally adjacent massive siltstone layer (Facies 2) represent the distal end of a shelf/slope failure with an associated chaotic deposit. The preservation of bedding within olistolith blocks indicates that the sediment was dewatered or semi-lithified at the time of failure. If these sediments possessed a high amount of pore water, bedding would most likely have been disrupted during the failure event. The slope failure may have been due to channel scouring, avulsion, or sediment loading on the shelf. Emery and Meyers (1996) note that deep-water slump blocks, with concave-up failure planes consisting of undeformed bedding that is at an angle to the dominant bedding orientation, represent elastic rotational slumps.

The presence of rippled sandstone with overlying massive siltstone, and ball-and-pillow intervals upsection (Facies 4, 6 and 7) represent individual turbidites on a scale much larger than those found in the top of Facies 3 (dm vs. cm scale). Again, this marks a shift to a more proximal turbidite position formation in the basin. The scale of all these features allows comparison with the standard Bouma (1962) sequence. The rippled and planar beds overlain by laminated siltstone and mudstone are equivalent to Bouma units C and D. Segmented fine-grained turbidite sequence successions (as observed here) reflect the progradation of the sediment fan into a distal environment (Walker, 1984). This interpretation is supported by the eventual migration of a channel within close proximity to the outcrop, as evidenced by the rippled sandstone (Facies 8) that caps the section. These sediments are identical to the basal sandstone, suggesting a repetition of processes upsection, though the bedding characteristics differ between them.

The diagenetic nodules and ball-and-pillow structures in this study and reported by Van Dijk *et al.* (1978) are fossiliferous, and most notably contain *Glossopteris* leaves. The presence of fossil-rich, diagenetically altered nodules was interpreted by previous studies to indicate that the basin was a freshwater environment with low acidity, indicating low bacterial productivity (Woodland and Stenstrom, 1979). The absence of bacterial activity again confirms that bottom conditions in which these sedimentary rocks formed were anoxic. Hence, the presence of a diagenetically altered interval in which iron-rich cements overprint the sedimentary succession is suggestive of influx of organic matter-rich turbidites, which were subsequently subjected to low oxygen conditions.

The one lithology that is not associated with a turbidite depositional regime is Facies 5, a microcrystalline tuff. Best (2003) notes several descriptive and interpretive aspects that should be considered when describing a tuff. These include size of clasts, composition, heritage, and process of fragmentation. Clasts within the Wagendrift bed are sand-sized and composed of individual (unwelded) quartz grains. The angularity of the grains and the homogenous composition indicates that these are juvenile pyroclasts generated at the time of eruption. The sharp bottom and top contacts of this thin, laterally extensive bed reflect a short-lived (days-weeks) ashfall event. Hence, the Wagendrift site was in some proximity to volcanic activity, although the provenance of the ash or its geochronometric date is unknown, to date.

Discussion

Van Dijk *et al.* (1978) and Hobday (1978) refer to the Estcourt Formation, in general, and the Wagendrift section, in particular, as characteristic of interdistributary bay environments within a continental Beaufort setting. The fine sedimentary nature of these rocks is attributed to the result of fluvial processes and overbank flooding. Johnson *et al.* (1997) note that the mudrocks in the Estcourt Formation are different than the rest of the Beaufort Group due to the presence of horizontal lamination. They interpreted them to represent "lacustrine" conditions (Johnson *et al.*, 1997, p. 298) that consist of small prograding deltaic successions (Hobday, 1978). While certain parts of turbidite systems can be confused easily with fluvial and alluvial facies (Walker, 1984), the Wagendrift section is characteristic of deeper (~50 m) water turbidite deposits rather than shallow transitional settings.

The original interpretations of the Wagendrift quarry imply that these deposits are decidedly shallow water (Van Dijk *et al.*, 1978; Hobday, 1978). Mutti and Normark (1987) demonstrated that overbank deposits similar in nature to terrestrial settings occur upstream from and within turbidite systems, and several features are used to distinguish continental from deep-water settings. Shallow water, bay facies and overbank deposits typically consist of highly bioturbated (Smith *et al.*, 1993), graded mudstones (Mutti and Normark, 1987) that are wedge shaped and locally discontinuous (Mutti and Normark, 1987; Emery and Meyers, 1996). Bedding, where preserved, is extensively current laminated (Mutti and Normark, 1987). In contrast, laminated fining-upwards successions in which there are minimal bioturbation, usually restricted to surface tracks and trails, is a feature of deep-water settings.

Typically a 'backstepping' of sand deposition in deep-water settings is represented by a proximal, wedge-shaped sandstone contained within or near the channel that grades laterally into a thin bed (Mutti and Normark, 1987). Abundant slumping and associated chaotic deposits segment sedimentation that result in extensive disconformities (Mutti, 1985; Mutti and Normark, 1987). An argument could be made that the Wagendrift Quarry succession represents prodeltaic deposits in a lacustrine setting. In this interpretation, the olistoliths would have originated from delta-front slumping and the ripple-laminated capping sandstone resulted from the progradation of delta-front deposits. Prodeltaic deposits in many Recent large lakes are characterized as homogenous clay without any discernible lamination (*e.g.*, Caspian Sea – Overeem *et al.*, 2003; Neales Formation, Lake Eyre basin, Australia – Hicks *et al.*, 2001), with similar descriptions found in pull-apart lake basins (*e.g.*, Lake Hazar – Dunne and Hempton, 1984). Where finely laminated sand, silt, and clay are recognized, they are considered to be lacustrine in nature (*e.g.*, Neales Formation – Croke *et al.*, 1998) or, depending upon the climatic regime in which sedimentation occurs, glacially derived (*e.g.*, Leckie and McCann, 1982). The presence of such bedding in glacial-fed lakes has been attributed to interflow and overflow currents. Here, incoming water density is insufficient to create an underflow current but there is enough suspension load sediment to deposit thin (0.5 to 2 mm) laminae. These laminae remain undisturbed and non-bioturbated due to the water chemistry of the lake, particularly the low temperatures at greater depth. Interbedded slump structures are attributed to failure along the delta front, whereas interbedded cross-laminated sand and clayey silt are deposited by the prograding delta (Leckie and McCann, 1982). Small-scale turbidites often are associated laterally with delta-slope failure.

Several features of the Wagendrift Quarry section preclude a prodeltaic interpretation. The near absence of bioturbation within Facies 3 – the interlaminated couplets – would require a continuous, influx of highly turbid waters into the lake from a shoreline source. It is understood that paleocurrents derived from ripples cross beds are highly variable, due to a variety of processes that may affect their genesis, and unreliable (Miall, 1984). But, with a point-source discharge, paleocurrents of all rippled beds in this interval would be expected to be more unidirectional in orientation. Yet, when individual rippled beds are measured (one of the only structures from which vector data can be derived), paleocurrent orientations are diametrically opposite (Figures 5A; B). Additionally, when these vectors are compared to the orientation of ball-and-pillow structures found higher in the section or the capping rippled sandstone facies, there is no concordance (Figures 5C; D). Paleocurrent orientations in Beaufort Group fluvial systems are fairly unidirectional and generally to the North (*e.g.*, Smith, 1990) except in KwaZulu-Natal province where westerly orientations are reported (Johnson *et al.*, 1997, figure 24). Hence, the only paleocurrent data available at Wagendrift do not conform to the overall fluvial trend in the region.

The presence of a concretionary horizon in the middle of Facies 3 indicates a change in bottom-water conditions and early diagenetic alteration. Such concretionary horizons form near the sediment-water interface during periods of sediment starvation (Raiswell, 1987). This laterally continuous horizon implies a time during which macrofauna and meiofauna could have colonized the surface when high sediment yields abated. Yet, there is no evidence for bioturbation associated with this interval. The absence of bioturbation indicates dysaerobic or anoxic bottom-water conditions that are more characteristic of deeper water setting (Savrda, 1995). Overall, the lithological characteristics at the Wagendrift Quarry are more similar to reported deep-water turbidite deposits than shallow bayfill successions.

Although turbidites typically are considered to be the products of a submarine fan, Mutti and Normark (1987) note that restricted basins in tectonically active areas can produce conditions in which turbidite deposits form. To date, there is only one semi-contemporaneous stratigraphic interval in the depositional history of the Karoo Basin in which deep-water turbidite sedimentation is documented (Johnson *et al.*, 2001; Sixsmith *et al.*, 2004); however, there have been some unpublished reports of turbidites within other units (*e.g.*, Molteno Formation – Hancox, 1998). Turbidites are one of the diagnostic sedimentary sequence successions of the Middle-to-Late Permian Ecca Group, which were reconstructed to have formed in the deep water environments adjacent to the rising thrusts (orogenic load) of the Cape Fold Belt (Smith *et al.*, 1993; Johnson *et al.*, 1997; Catuneanu *et al.*, 1998; 2002). In addition, intercalated volcanic ash deposits are more commonly found in the Ecca Group than the Beaufort Group (Smith *et al.*, 1993).

Turbidites in the Ecca Group recently have been studied in detail with the resurgence of interest in hydrocarbon potential of deep water clastic systems (Johnson *et al.*, 2001; Sixsmith *et al.*, 2004). Johnson *et al.* (2001) and Sixsmith *et al.* (2004) characterized a number of turbidites and identified relationships in various parts of the Karoo Basin that show an overall progradational trend in the Skoorsteenberg and

Laingsburg Formations. These authors describe fine-grained sedimentary successions virtually identical to the features found at the Wagendrift Quarry. Hemipelagic suspension and low-concentration turbidity current deposits in the Skoorsteenberg Formation consist of parallel laminated siltstone and claystone, in which starved ripple lamination occurs, in addition to volcanic ash and concretionary horizons (Johnson *et al.*, 2001). Thin-bedded turbidites consist of interbedded millimeter-to-centimeter thick, very fine sandstone and siltstone in which trace fossils are common, although bioturbation is absent in the fine-grained, interlaminated intervals of the Laingsburg Formation (Sixsmith *et al.*, 2004). These deposits may be up to 10 m in thickness and show an overall coarsening upwards trend. These successions are attributed to deposition from low- to medium-density turbidity currents. Johnson et al. (2001) also report a slump facies association similar in character to Wagendrift Quarry. Sixsmith *et al.* (2004) characterize channel-fill successions as consisting of erosionally based, thick bedded fine-grained sandstones, and overbank deposits as dominated by stacked beds of ripple cross-laminated sandstone and siltstone.

Pollen preparations from Wagendrift consist of a low diversity assemblage of moderate to well-preserved palynomorphs in only one of twelve samples processed (Cindy Looy, personal communication, 2004). Many of the multitaeniate forms are torn, making identification to generic and species level difficult. The flora is characterized by multitaeniate bisaccate pollen grains (~55%) and the multitaeniate non-saccage genus *Weylandites* (~20%). The most common saccate pollen are assigned to *Protohaploxypinus* and *Lunatisporites*, with *Striatopodocarpites* and *Striatoabieties* rare. These forms are known from the Middle Permian (Krassilov et al., 1999). Non-taeniate bisaccate forms are less abundant, whereas acavate trilete spores occur frequently (Figures 5D; G). The significant element in the assemblage is the presence of cf. *Lueckisporites*, a biostratigraphic indicator of the Late Permian (Figure 5F).

Aitken (1998) characterized Permian palynological biozones in the northern Karoo basin from analyses of boreholes in the Highveld Coalfield and the Free State. Biozones VI and VII were characterized by a high abundance (55=70%) of 'striatiti' in which both bisaccate taeniate (*e.g., Protohaploxypinus* and *Lunatisporites*) and multitaeniate pollen (*e.g., Weylandites*) occur. Other palynomorph taxa in the Wagendrift assemblage are not useful biostratigraphically. Some are thought to have terminated in older biozones (*i.e., Chordasporites australensis* and *Horriditriletes ramosus* [III], *Apiculatisporis* and *Deltoidospora directa* [V]), while others begin in succeeding biozones (*e.g., Falcisporites stabilis* [VII]). Therefore, a partial canonical correspondence analysis (CCA) was conducted (Cindy Looy, personal communication, 2005) using one variable, sample depth (stratigraphic level within the boreholes), on the data of Aitken (1998). The Wagendrift assemblage was included as a supplementary sample in the analysis, with its' resultant position in ordination space based on its' similarity to the borehole data. This analysis places the Wagendrift assemblage in the lower part of Zone VI (*Guttulapollenites hannonicus* - *Protohaplozypinus rugatus* zone), which is characteristic of the Volkrust Formation (Tatarian = Wujiapingian). Hence, although the stratigraphy is reminiscent of Middle Permian rocks noted throughout the basin, the palynology indicates that these rocks are of a younger age.

Summary and Conclusions

Van Dijk *et al.* (1978) and Hobday (1978) interpreted Wagendrift as a succession of interdistributary bay overbank deposits based on what they thought were key features within a shallowing basin model. Although the coarse-grained portions of shallow-water overbank facies may resemble those of turbidite deposits (Walker, 1984), many of the key characteristics of overbank deposits are not observed at Wagendrift. Graded sandstones to mudstones occurring in laterally continuous beds nearly devoid of bioturbation are inconsistent with the heavily bioturbated, wedge shaped, current laminated and locally discontinuous graded mudstone beds predicted by an interdistributary bay overbank model. While in Karoo context, turbidite facies are more characteristic of the Ecca Group than shallow water Beaufort deposits (Smith *et al.*, 1993; Johnson *et al.*, 2001; Sixsmith *et al.*, 2004), a Late Permian (Wujiapingian) pollen signature indicates that Wagendrift represents a remnant deep lake that may have occurred synchronously with Beaufort deposition. Hence, the interpreted diacrhonous contact between the Ecca and Beaufort Groups in the Estcourt area (Cateneau *et al.*, 1998; Rubidge *et al.*, 2000; Modesto *et al.*, 2001; Catuneanu *et al.*, 2002) indicates that Ecca-style deposits are consistent with Latest-Permian deposits in the Karoo Basin, thereby establishing the probability for a remnant deep lake to have existed during the fluvially dominated Beaufort.

The misinterpretation of this one outcrop/formation suggests that depositional environments indicated within the literature should be looked at critically, especially because many of the formations within the Karoo Basin were described and looked at in detail for the last time during the 1960s and 1970s (Johnson, 1994). Refinement of published sedimentological studies would not only help to improve the paleogeographic interpretations but also to increase the precision of the stratigraphic correlations within the basin.

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