Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa

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Abstract

The sedimentary rocks of the Karoo Supergroup in the Tuli Basin (South Africa) may be grouped in four stratigraphic units: the basal, middle and upper units, and the Clarens Formation. This paper presents the findings of the sedimentological investigation of the fluvial terrigenous clastic and chemical deposits of the upper unit. Evidence provided by primary sedimentary structures, palaeontological record, borehole data, palaeo-flow measurements and stratigraphic relations resulted in the palaeo-environmental reconstruction of the upper unit.

The dominant facies assemblages are represented by sandstones and finer-grained sediments, which both can be interbedded with subordinate intraformational coarser facies. The facies assemblages of the upper unit are interpreted as deposits of a low-sinuosity, ephemeral stream system with calcretes and silcretes in the dinosaur-inhabited overbank area. During the deposition of the upper unit, the climate was semi-arid with sparse precipitation resulting in high-magnitude, low-frequency devastating flash floods. The current indicators of the palaeo-drainage system suggest flow direction from northwest to southeast, in a dominantly extensional tectonic setting.

Based on sedimentologic and biostratigraphic evidence, the upper unit of the Tuli Basin correlates to the Elliot Formation in the main Karoo Basin to the south.

Keywords: Semi-arid climate; flash floods; ephemeral fluvial system; fluvial deposit; Karoo Supergroup; paleoclimate; paleoenvironment; sandstone; stratigraphy; Tuli Basin; South Africa

1. Introduction

The transfrontier Tuli Basin is situated around the triple junction of the Zimbabwean, Botswanan and South African borders, defined by the Limpopo River (Fig. 1). This basin was filled by sedimentary and igneous rocks of the Karoo Supergroup. This sequence is thinner (estimated max ~450–500 m) and less continuous than that in the main Karoo Basin (Fig. 1), where the age of the Karoo Supergroup is Late Carboniferous-Middle Jurassic. In the South African part of the Tuli Basin, the Karoo sedimentary rocks occupy an area of about 1000 km^2 (Fig. 2). The available geological information and the lack of proper age indicators allow only a tentative application of the formal stratigraphic nomenclature used for the Karoo Supergroup in the Limpopo area. Four lithologically and genetically distinctive lithostratigraphic units are differentiated in the study area, namely the basal, middle and upper units, and Clarens Formation (Bordy, 2000). The basal, middle and upper units are not recognized by South African Committee of Stratigraphy (SACS), and therefore the use of their names here must be regarded as informal.

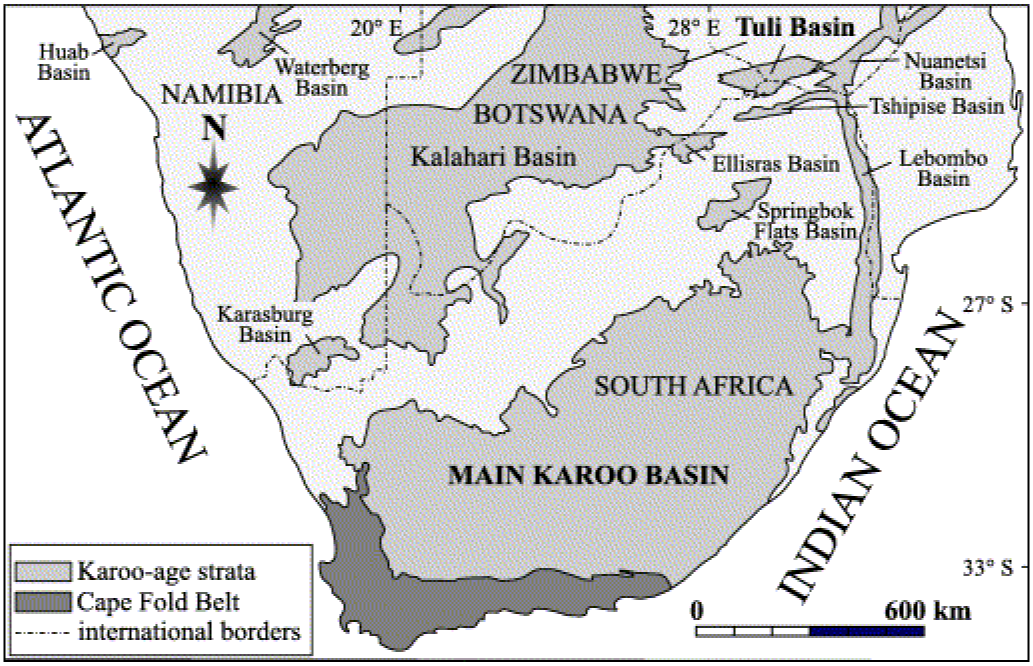


Fig. 1. The Karoo Supergroup in southern Africa and the Tuli Basin (modified after Johnson et al., 1996).

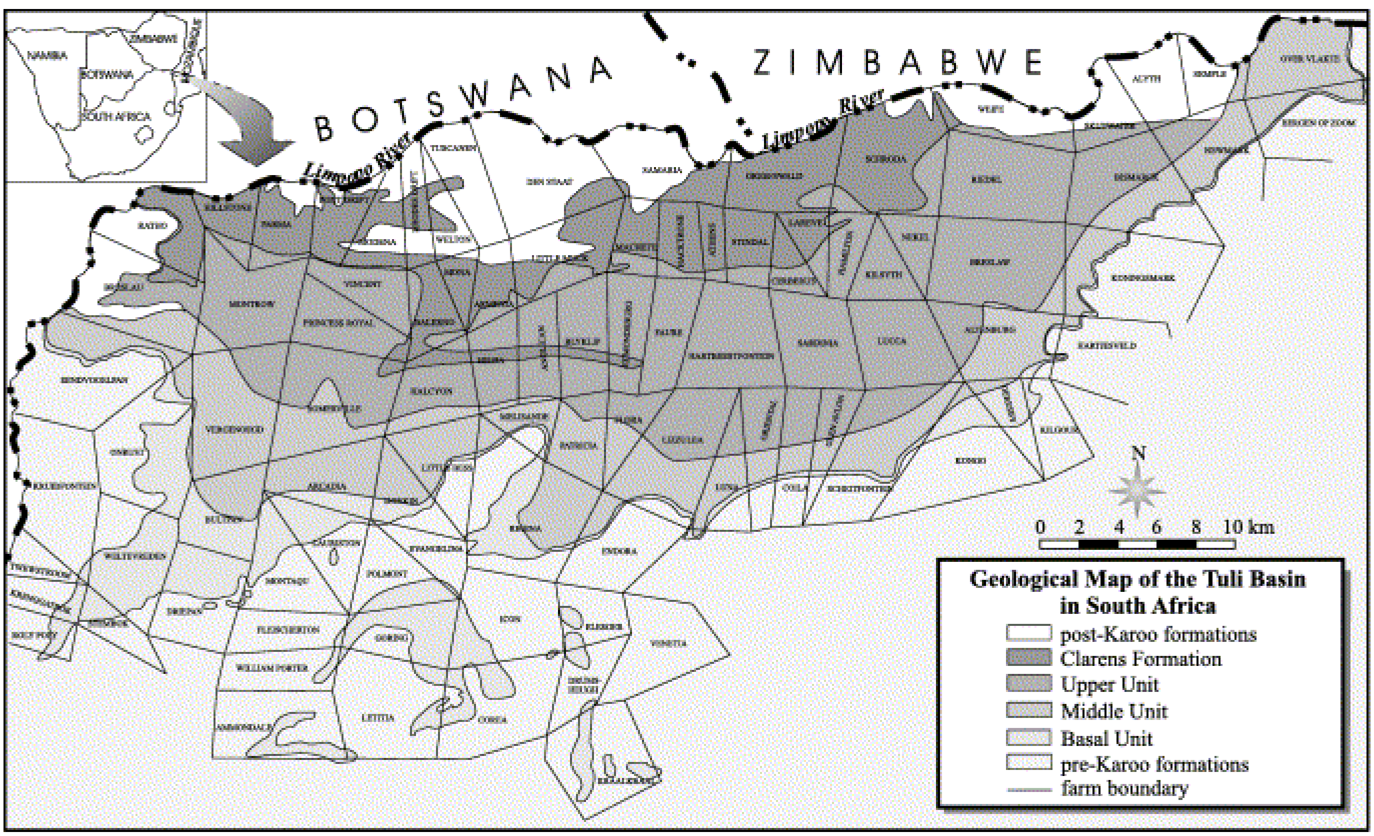


Fig. 2. Geological map of the southern part of the Tuli Basin (modified after Geological Map, Beit Bridge (1957) of 1:250 000).

The purpose of this paper is to present the sedimentology of the fluvial upper unit and its potential relation to the Karoo Supergroup strata in the main Karoo Basin. Furthermore, the tectonic setting of the Tuli Basin during the deposition of the upper unit is briefly discussed. To date, there is only one brief, unpublished report by Chidley (1985) describing the Karoo Supergroup in the South African part of the Tuli Basin.

2. Geological background

2.1. Tectonic setting

In southern Africa, the deposition of the Karoo Supergroup occurred in two broadly different tectonic settings (Rust, 1975). According to Catuneanu et al. (1998), the sedimentary rocks of the main Karoo Basin are retroarc foreland fills. North of the main Karoo Basin, the formations are preserved in separate, fault-bounded depositories which are interpreted either as rift basins or intracratonic thermal sag basins (Watkeys and Sweeney, 1988; Groenewald et al., 1991; Johnson et al., 1996).

The Tuli Basin, together with the Tshipise (South Africa, partly Zimbabwe) and Nuanetsi (Zimbabwe) basins represent the so-called Limpopo area Karoo-age basins. It has been proposed that the Limpopo area forms the western arm of a failed rift triple junction, which later extended in a north–south direction, from the Save Basin (Zimbabwe) to the Lebombo ‘Monocline' (South Africa, Mozambique) (Vail et al., 1969; Burke and Dewey, 1973). The genesis of the rift was associated with the Gondwana break-up (Burke and Dewey, 1973; Duguid, 1975).

A half-graben structure for the Tuli Basin is suggested by the general gentle (<5°) northward dips of the Karoo Supergroup beds and the northern boundary fault which is a major, ENE trending tectonic line (Smith, 1984). According to Watkeys and Sweeney (1988), the Tuli Basin is a pull-apart rhombochasm. In the light of the observations made by the present authors, new ideas are added to the tectonic development of the Tuli Basin (see Section 8).

2.2. Stratigraphy

Although the southern African basins containing Karoo Supergroup strata appear in different tectonic settings, the overall climatic overprinting resulted in similar vertical lithological profiles (Groenewald et al., 1991; Johnson et al., 1996). The progressive climatic shift from glacial to cool, moist conditions, then to warm, semi-arid, and finally to hot, arid conditions is recorded in all Karoo rocks, and it is attributed to Africa's latitudinal drift from cold/glacial to desert climatic belts.

Earlier palaeo-environmental reconstructions of the Karoo Supergroup in the Tuli Basin show a clear transition from non-glacial, cold climate to semi-arid then to arid environments. Because of the geographical position of the Tuli Basin (i.e., transfrontier), there are three previous Karoo Supergroup descriptions for the Tuli Basin, each developed in different countries (Table 1). Due to the fact that the stratigraphic and palaeontological records are not sufficiently well known, accurate correlations across the basin and with the main Karoo Basin are difficult. Thus the correlation given in the Table 1 should be considered as only tentative.

Summary of the lithostratigraphic nomenclature and tentative correlation of the Karoo supergroup strata of the transfrontier Tuli basin and main Karoo Basin (* there are two possible correlations of the middle unit. See Bordy (2000) for details)

<table>
<tr><th colspan="2">Main Karoo Basin (Johnson et al., 1996)</th><th colspan="2">Tuli Basin (South African part) (Bordy, 2000)</th><th colspan="2">Tuli Basin (South African part) (Chidley, 1985)</th><th>Tuli Basin (Zimbabwean part) (Thompson, 1975)</th><th colspan="2">Tuli Basin (Botswanan part) (Smith, 1984)</th></tr>
<tr><td rowspan="7">‘Stormberg Group’</td><td rowspan="2">Clarens Formation</td><td colspan="2" rowspan="2">Clarens Formation</td><td rowspan="3">Clarens Formation</td><td rowspan="2">Tshipise Sandstone member</td><td rowspan="2">‘Forest Sandstone’</td><td rowspan="6">Lebung Group</td><td>Tsheung Sandstone Formation</td></tr>
<tr><td>Thune Formation</td></tr>
<tr><td rowspan="2">Elliot Formation</td><td colspan="2" rowspan="2">Upper Unit</td><td>Red rock member</td><td rowspan="3">Red Beds</td><td rowspan="4">Korebo Formation</td></tr>
<tr><td colspan="2" rowspan="3">Bosbokpoort Formation</td></tr>
<tr><td rowspan="3">Molteno Formation</td><td rowspan="3"></td><td rowspan="3">Middle Unit*</td></tr>
<tr><td rowspan="2">‘Escarpment Grit’</td></tr>
<tr><td colspan="2">Klopperfontein Formation</td><td colspan="2"></td></tr>
<tr><td colspan="2">Beaufort Group</td><td>Middle Unit*</td><td></td><td colspan="2">Solitude Formation</td><td></td><td colspan="2"></td></tr>
<tr><td colspan="2" rowspan="3">Ecca Group</td><td colspan="2" rowspan="4">Basal Unit (undifferentiated)</td><td colspan="2">Fripp Formation</td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="3">Basal Beds</td><td>Mikambeni Formation</td><td rowspan="2">Fulton’s Drift Mudstones</td><td colspan="2">Seswe Formation</td></tr>
<tr><td>MadzarIndwe Formation</td><td colspan="2">Mofdiahogolo Formation</td></tr>
<tr><td colspan="2">Dwyka Group</td><td>Diamictites</td><td>Basal Beds (undifferentiated)</td><td colspan="2">??</td></tr>
</table>

The outcrop belt of the upper unit runs in a roughly E to W direction through the northern–central part of the study area (Fig. 2). In the geological cross-sections, the estimated thickness of the unit varies from ~200 to 280 m and the maximum exposed thickness is 30 m (covered lower boundary). The predominantly red coloured sedimentary rocks and dinosaur bone remains of the upper unit reflect deposition under generally oxidizing conditions in a fluvial milieu.

The investigated stratigraphic unit (Fig. 3) is developed in the upper part of the Karoo Supergroup of the Tuli Basin, and it has conformable boundaries with the underlying conglomeratic unit (middle unit) and overlying aeolian sandstones (Clarens Formation). The exact delineation of the lower contact is difficult as the red–green–purple mudstones of the middle unit are lithologically similar to the mudstones of the lower part of the upper unit. Therefore, the lower boundary was established in boreholes at the first occurrence of uniformly red, calcrete glaebule-bearing mudstones, even though this assumption can lead to chronostratigraphic misinterpretations. The upper boundary of the unit is clearly detectable, especially in those outcrops where the yellow-creamy, large-scale cross-bedded sandstones of the Clarens Formation overlie a laterally continuous, white silcrete horizon which shows a clear genetic relation to the upper unit.

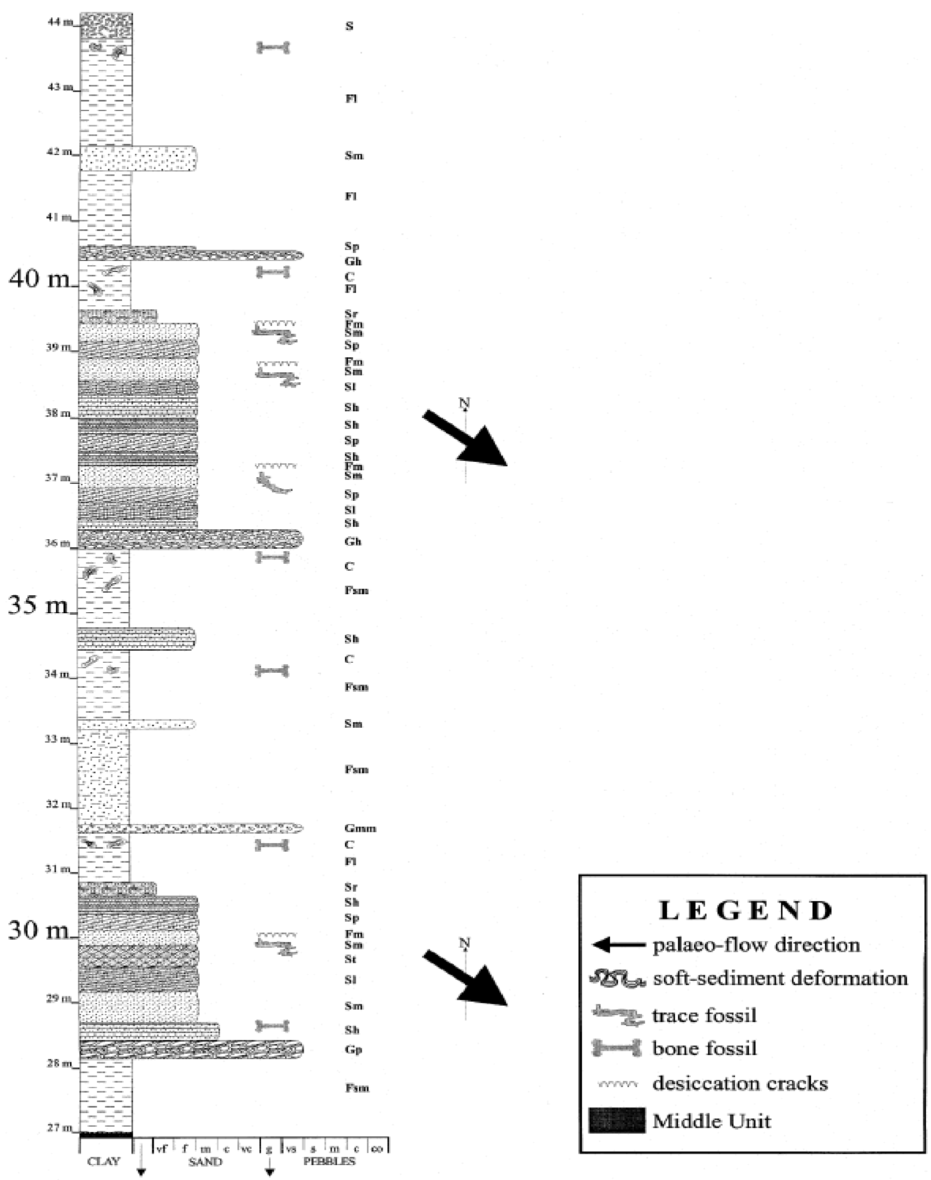


Fig. 3. General vertical profile of the upper unit in the southern Tuli Basin, South Africa. Forlithofacies codes, descriptions and interpretations, refer to Table 2. Thicknesses are approximate.

Chidley (1985) reported two red coloured rock formations from the South African part of the Tuli Basin. Firstly, he mentioned the Bosbokpoort Formation (Table 1) which is a 60 m thick brick-red, purplish mudstone and siltstone unit with calcareous nodules and concretions. Small bone fragments were noted from beds containing poorly sorted calcareous conglomerates (Chidley, 1985). This formation was interpreted as floodplain deposits formed under semi-arid conditions. The second red coloured association described by Chidley (1985) is the red rock member of the Clarens Formation. This is about 60 m thick and consists of argillaceous, very fine- to fine-grained pinkish to red sandstones (Chidley, 1985). Irregular calcareous nodules and concretions are abundant, reptilian remains and occasionally shell fragments have been found (Chidley, 1985). The beds were interpreted as deposits of a distal overbank floodplain in arid climatic conditions (Chidley, 1985).

In Zimbabwe, there is a 300 m thick succession of red to purple mudstones, fine-grained sandstones and marls, frequently with scattered, very fine-grained red sandstone pebbles and calcareous nodules (Thompson, 1975; Cooper, 1980). There are occasional pebbly, very coarse sandstones and partly silicified limestones (Watkeys, 1979). Bedding is rare in the sandstones (Watkeys, 1979). Reptilian fossils have been found in this widespread formation, and the remains of an *Euskelosaurus* cf. *browni* allow a direct correlation with the lower part of the Elliot Formation in the main Karoo Basin (Cooper, 1980).

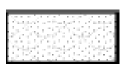
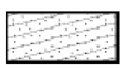
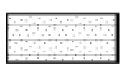
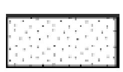
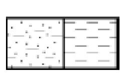
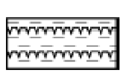
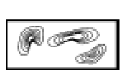
In Botswana, the Thune Formation is a transitional unit between the more argillaceous Korebo and the typical aeolian dune-bedded Tsheung Sandstone Formation (Table 1) (Smith, 1984). The Thune Formation ($\sim$65 m) contains fine-grained sandstones and siltstones with some cross-bedded sandstone intercalations (Smith, 1984). Due to its small fining-upward cyclothems, the formation was interpreted to be fluvial in origin (Smith, 1984).

3. Facies description

3.1. Outcrop sections

The internal structure of the upper unit was examined during outcrop-based sedimentological field work along natural exposures. Facies analysis of the unit was carried out and resulted in numerous sedimentary logs, field sketches and photomosaics. Applying Miall's, 1978 and Miall, 1996 lithofacies classification scheme, 18 lithofacies types were identified (Table 2). These were grouped into facies assemblages. Finally, the three-dimensional relationships of the architectural elements were then used to interpret the depositional palaeo-environment.

Table 2. The fluvial lithofacies of the upper unit, Tuli Basin (modified after Miall, 1996)

Facies code and symbol		Facies	Sedimentary structures	Interpretation
Gmm		Matrix-supported, massive gravel	Weak grading	Plastic debris flow (high-strength, viscous)
Gcm		Clast-supported massive gravel	–	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gh		Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits
Gt		Gravel, stratified	Trough cross-beds	Minor channel fills
Gp		Gravel, stratified	Planar cross-beds	Transverse bedforms, deltaic growths from older bar remnants
St		Sand, fine to very coarse, may be pebbly	Solitary or grouped trough cross-beds	Sinous-crested and linguoid (3-D dunes)
Sp		Sand, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Transverse and linguoid bedforms (2-D dunes)
Sr		Sand, very fine to coarse	Ripple cross-lamination	Ripples (lower flow regime)
Sh		Sand, very fine to coarse, may be pebbly	Horizontal lamination, parting or streaming lineation	Plane-bed flow (critical flow)
Sl		Sand, very fine to coarse, may be pebbly	Low-angle (<15°) cross-beds	Scour fills, humpback or washed-out dunes, antidunes
Sm		Sand, fine to coarse	Massive or faint lamination	Sediment-gravity flow deposits/very high deposition rates
Sc		Sand, silt rich intraformational clasts	Massive	Sediment-gravity flow deposits
Fl		Sand, silt, mud	Fine lamination, very small ripples	Overbank, abandoned channel, or waning flood deposits
Fsm		Silt, mud	Massive	Backswamp or abandoned channel deposits
Fs		Mud with sand, fine to coarse	Massive, may be laminated	Sediment-gravity flow deposits
Fm		Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
C		Calcrete glaebule	Pedogenic features: glaebules, filaments	Soil with chemical precipitation
S		Silcrete	Pedogenic features: nodules, filaments	Chemical precipitation in soil

The upper unit is composed of two sedimentary facies assemblages:

1. *Sandstone facies assemblage*, dominated by sandstones (Sm, Sh, Sl, St, Sp, Sr) with subordinate (~1%) intraformational conglomerates (Gcm, Gh, Gp, Gt) and desiccated mud drapes (Fm).
2. *Fine-grained facies assemblage*, dominated by overbank facies (Fsm, Fs, Fl) containing pedogenic glaebular calcretes (C); a silcrete horizon (S); subordinate sheet-like sandstones (Sm, Sh, Sp ~5%); intraformational breccias (Gmm <0.25%; Gcm <0.25%; Sc ~3%) and conglomerates (Gh <0.25%).

The outcrops of the two facies assemblages are confined to clearly distinguishable zones, but there are certain outcrops where the simple twofold subdivision is inadequate to identify the complex of facies shown. For instance, some of the mudstones, either as mud drapes (Fm) or as <2 m thick beds (Fl, Fsm), are locally interbedded with thicker sequences of sandstones.

3.1.1. Sandstone facies assemblage

3.1.1.1. Sandstones

The sand-grained sedimentary rocks of this facies assemblage comprise angular to subrounded, medium-well sorted, relatively clean, predominantly very fine- to fine- or medium-grained, largely red-coloured quartz, feldspar and calcite particles.

The sandstone beds exhibit the following internal bedding features (Fig. 4 and Fig. 5): massive beds (Sm) (~70%); horizontal lamination (Sh) (20%); trough cross-bedding (St) (5%); low angle (Sl) and planar cross-bedding (Sp) (2.5%); ripple cross-lamination (Sr) (2.5%). No preferential arrangement of these structures was clearly detectable in the coarse unit, although ripple cross-lamination (Sr) was more commonly found capping repetitive semi-sequences of Sh–St–Sp, Sh–St(Sp) and Sh–Sm (Fig. 6). Penecontemporaneous soft-sediment deformation was observed in the form of convolute bedding.

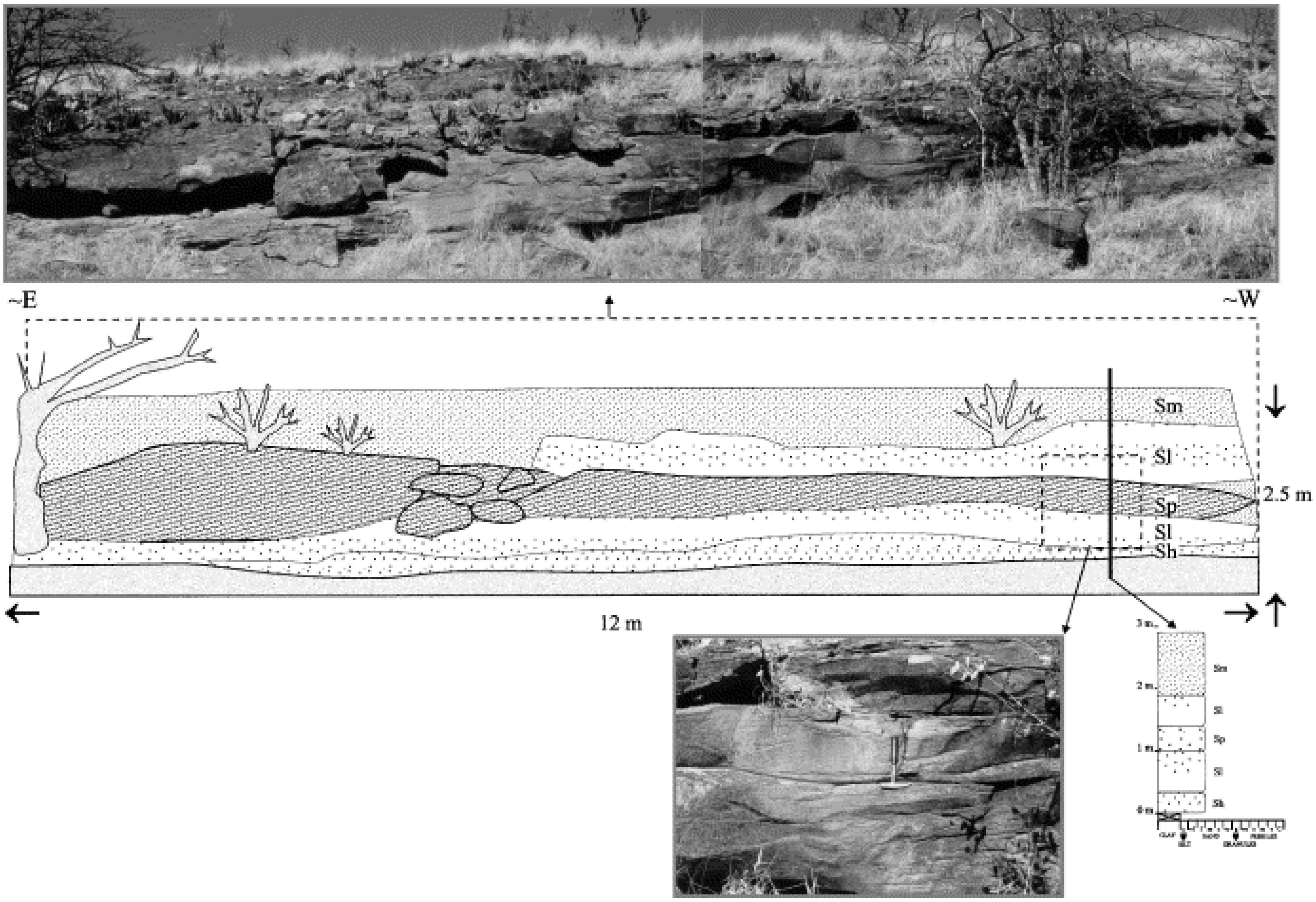


Fig. 4. Outcrop dominated by lithofacies Sl and Sp (farm Somerville; Fig. 2).

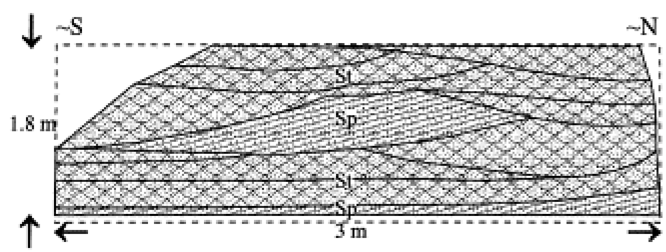


Fig. 5. Lithofacies Sp (farm Nekel; Fig. 2). Note the changing geometry of the foreset from tangential to angular and then back to more tangential. Flow direction from right to left.

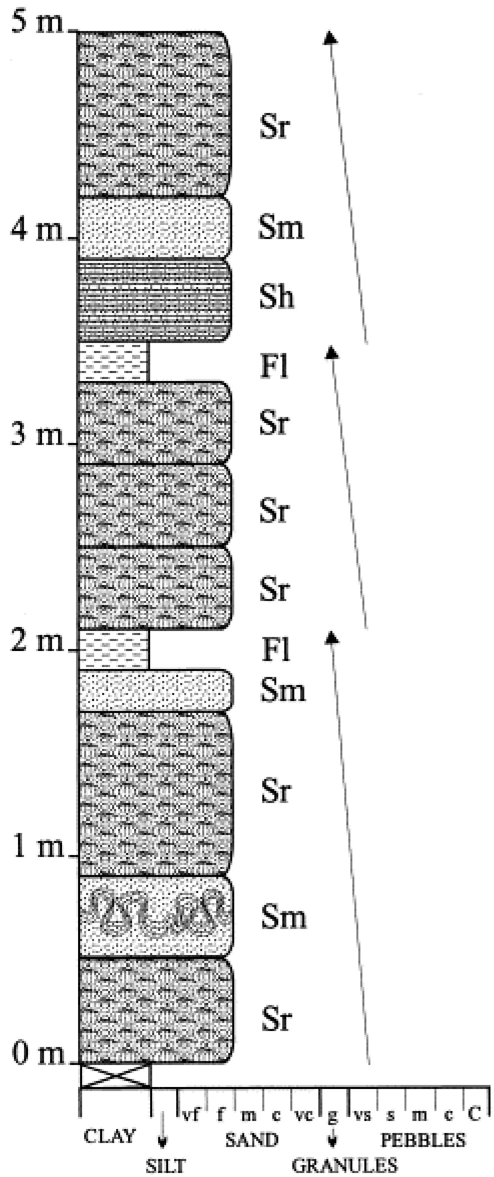


Fig. 6. Sedimentological log of three fining-upward cyclothems. The third cyclothem shows a common semi-sequence type consisting of Sh–Sm–Sr (farm Lizzulea; Fig. 2). See Fig. 3 and Table 2 for legend.

The sandstones are often draped with mud films less than 0.5 cm thick, displaying desiccation features (Fm). Fig. 7 and Fig. 8 show the delicate concave-up mud curls, and the semi-orthogonal pattern of the mudcracks on the bedding planes. Apart from the desiccation cracks, the bedding planes also display abundant burrowing features (Fig. 9) and rare vertebrate footprints (Fig. 10). In the sandstones, broken bone fragments were observed only at two localities.

Fig. 7. Concave-up mud curls related to dessication processes (farm Weipe; Fig. 2).

Fig. 8. Semi-orthogonal pattern of mudcracks on the bedding surface (farm Weipe; Fig. 2).

Fig. 9. Trace fossil of a burrowing organism (farm Ratho; Fig. 2).

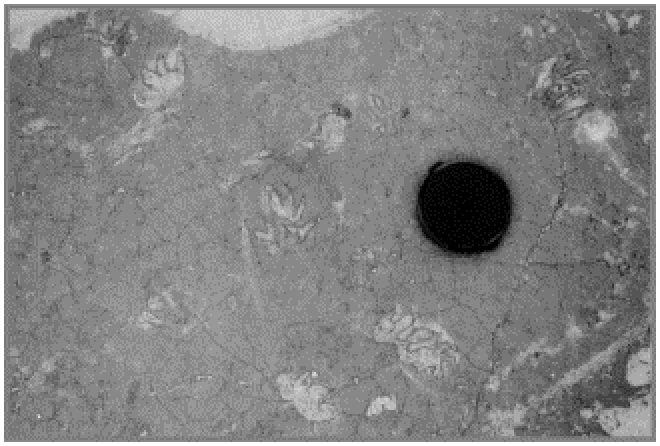


Fig. 10. Vertebrate tracks (farm Schroda; Fig. 2). The footprints are, on average, 3.5 cm long, and appear to have been made by a small four-toed animal(s). One of the footprints shows that the digits clearly ended in claws, but in the rest of the tracks the digits just thin towards the toe tip. The minimum distance between two adjacent prints is 3 cm, while the maximum distance is about 6 cm.

The outcrops of the sandstone facies assemblage have lateral extents in the order of less than a few tens to more than one hundred meters. The 10–30 cm, rarely more than 40 cm thick beds have generally tabular geometry, although lenticular bedforms were also noticed. The sandstones form multistoried, stacked, slightly upward-fining cyclothems capped by laminated or massive, 0.05 to about 1.5 m thick red siltstones and mudstones (Fm, Fl, Fsm). In outcrop, these cyclothems are rarely thicker than 10 m. The cyclothems are characterized by sharp, non-channelized bases and truncated upper contacts (Fig. 11). Very rarely, the individual, erosively based cyclothems commence with basal lag horizons of 0.5 m thick intraformational conglomerates or breccias of rip-up sandstone and mudstone clasts (Fig. 12); however, in most cases basal lag deposits are absent. Within the cyclothems, shallow scour-and-fill structures were observed. Most of the bedding surfaces within sandstones are erosive. Although the bedding planes in the fine-grained beds are rather smooth, sharp and continuous, the coarser-grained beds are often bounded by shallow scour surfaces (Fig. 13). Commonly, the cyclothems do not show grain size variation, but the bed thickness and the scale of the sedimentary structures decreases upwards. No evidence of lateral- or downstream-accretion nor channel-cutbanks have been found in any of the deposits.

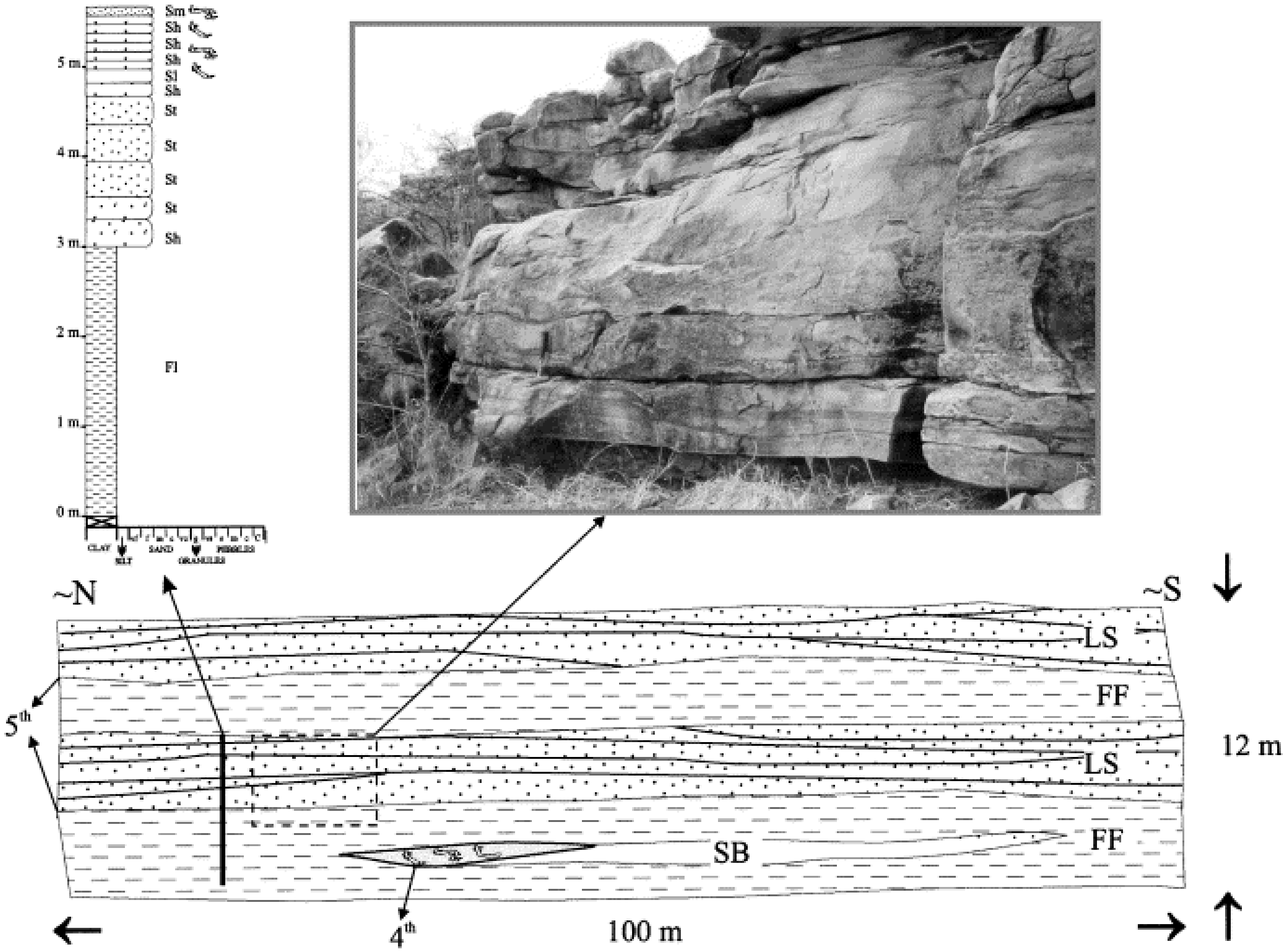


Fig. 11. The fully developed fining-upward cyclothem (in the middle of the outcrop outline) shows the sharp, non-channelized base and truncated upper contact of the architectural element LS. The truncated upper cyclothem is partly eroded. Other elements are overbank fines (FF) with a minor SB (lower part). Photo shows the sharp, straight, non-channeled base of the architectural element LS (farm Weipe; Fig. 2). Fourth and fifth represent hierarchical orders of fluvial surfaces (Miall, 1996). Fourth-order surfaces represent macroform boundaries. Fifth-order surfaces are isolated channel bases.

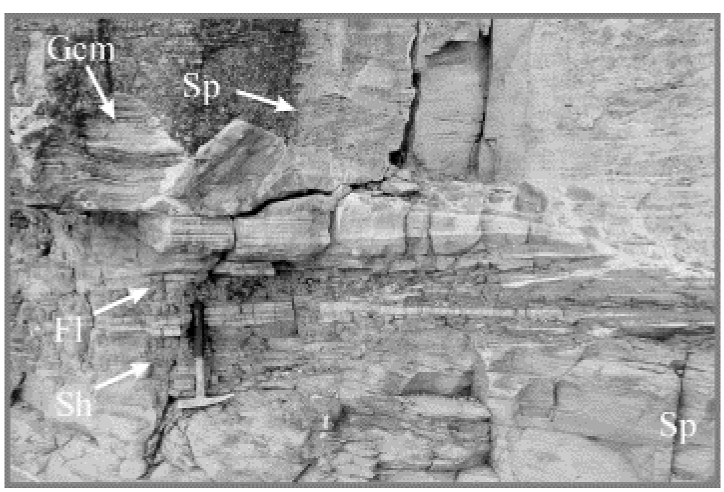


Fig. 12. Base of a fining-upward cyclothem commencing with a shallow scour and very fine, rip-up sandstone and mudstone clasts (Gcm). The size, roundness as well as the identical lithologies of the clast and the underlying laminated bed (Fl) indicates that the clasts were torn up and transported from the immediate vicinity (farm Edmondsburg; Fig. 2).

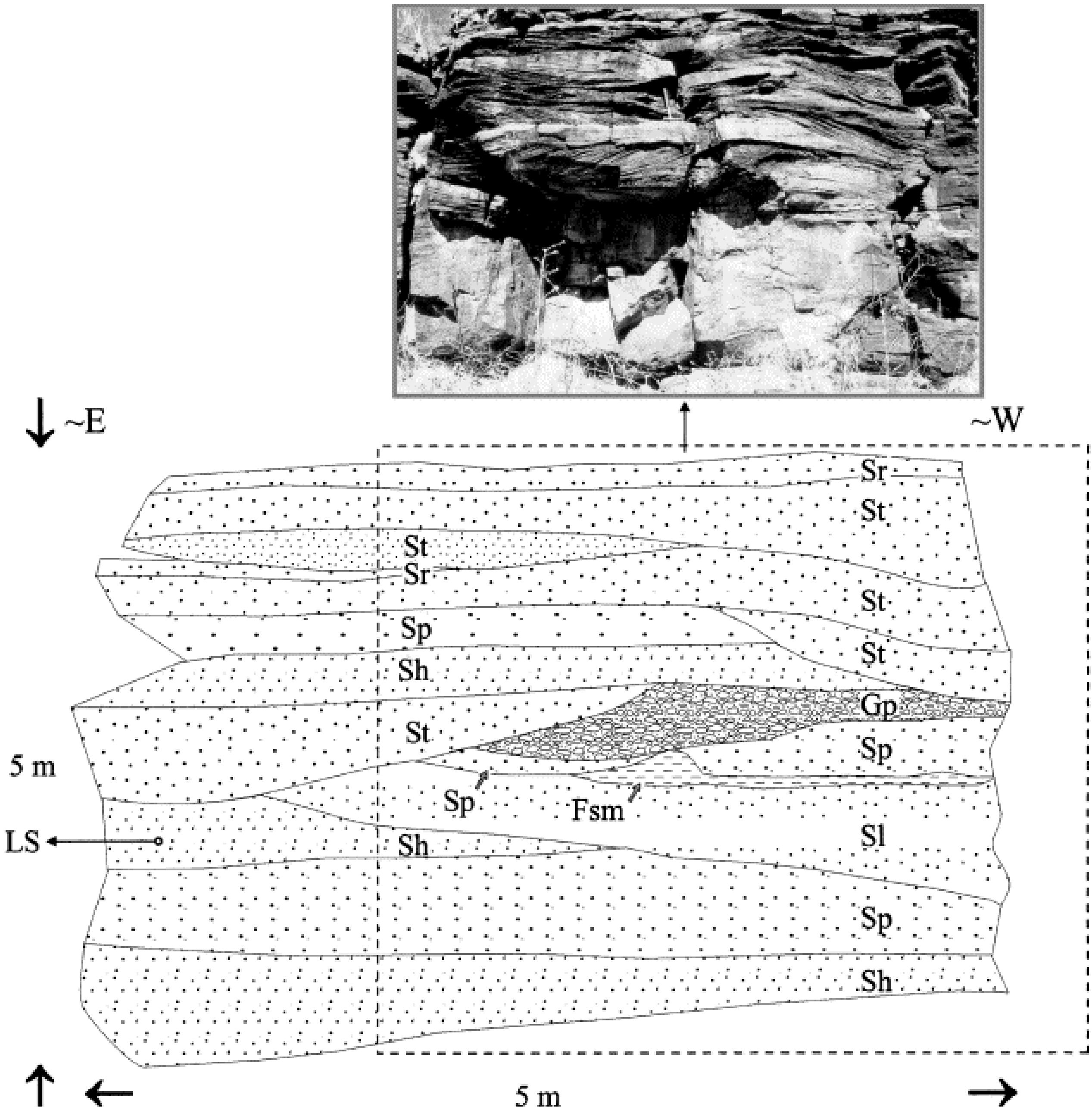


Fig. 13. Coarser grained beds bounded by shallow scour surfaces (third order). Note the slight fining-upward trend (element LS) (farm Lizzulea; Fig. 2).

3.1.1.2. Intraformational conglomerates

The reddish–greyish intraformational conglomerates form only about 1% of the sandstone facies assemblage and range in thickness from <0.1 to 1 m. They consist of granule- to pebble-grade white, well-rounded carbonate concretions, septaria and nodules (~80%); white to reddish, subangular to subrounded mudstone clasts (~10%); red, subangular to subrounded sandstone clasts (~10%); reddish, subangular to subrounded isolated, broken and abraded bone fragments (<1%), and red to white, subrounded to rounded quartz pebbles (<1%). The average clast size in poorly sorted and clast-supported conglomerates is ~2.5 cm, while the maximum diameter is 25 cm. The matrix is a red very fine sandstone, occasionally with coarse, rounded reddish quartz grains scattered throughout. The cement is uniformly carbonate, which indicates that the conglomerates are the most calcareous deposits in the unit. Most conglomerates lack stratification

(Gcm), though some display slight horizontal layering (Gh) or cross-bedding (Gp, Gt). The horizontal layering as well as the foresets of the planar cross-stratified conglomerates are often defined by normally graded single pebble layers with clasts ranging in size from large pebbles (6.4 cm) to granules (0.4 cm) (Fig. 14).

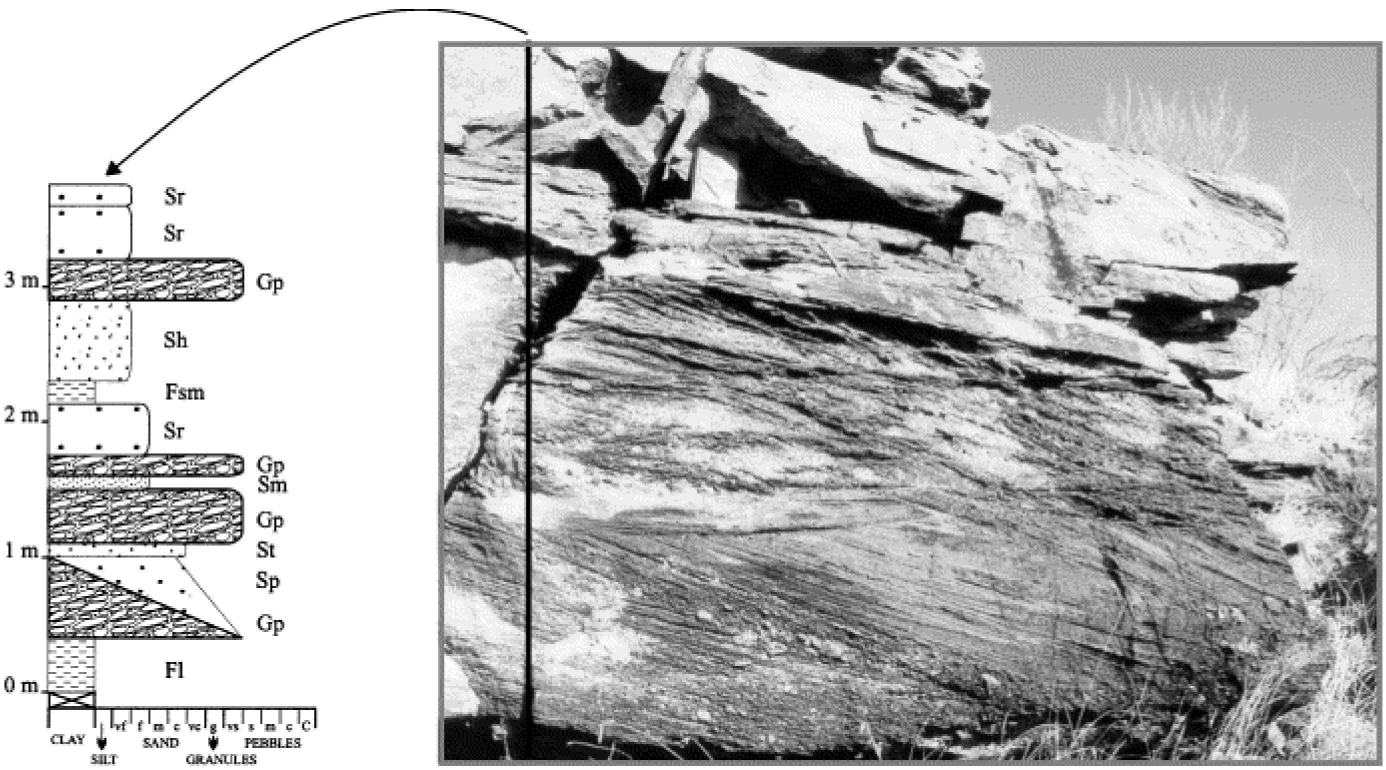


Fig. 14. A ~0.6 m Gp bed with foresets consisting of normally graded, single-pebble layers ranging in size from granule (0.4 cm) to large pebble (6.4 cm). Note that within the same bed, from left to right, the inclination of the foresets gradually changes from low angle to high angle and back again to low angle (sandier) foresets. The photograph illustrates a major fining-upward cyclothem with several internal truncation surfaces and conglomerate lenses (farm Lizzulea; Fig. 2).

The intraformational conglomerates are often found at the base (Fig. 14) and/or in the middle part of the slightly fining-upward cyclothems (Fig. 15). The conglomerates are invariably topped by, or interbedded with, sandstone units. In places, the conglomerates are directly overlain by ripple cross-laminated (Sr) very fine sandstones.

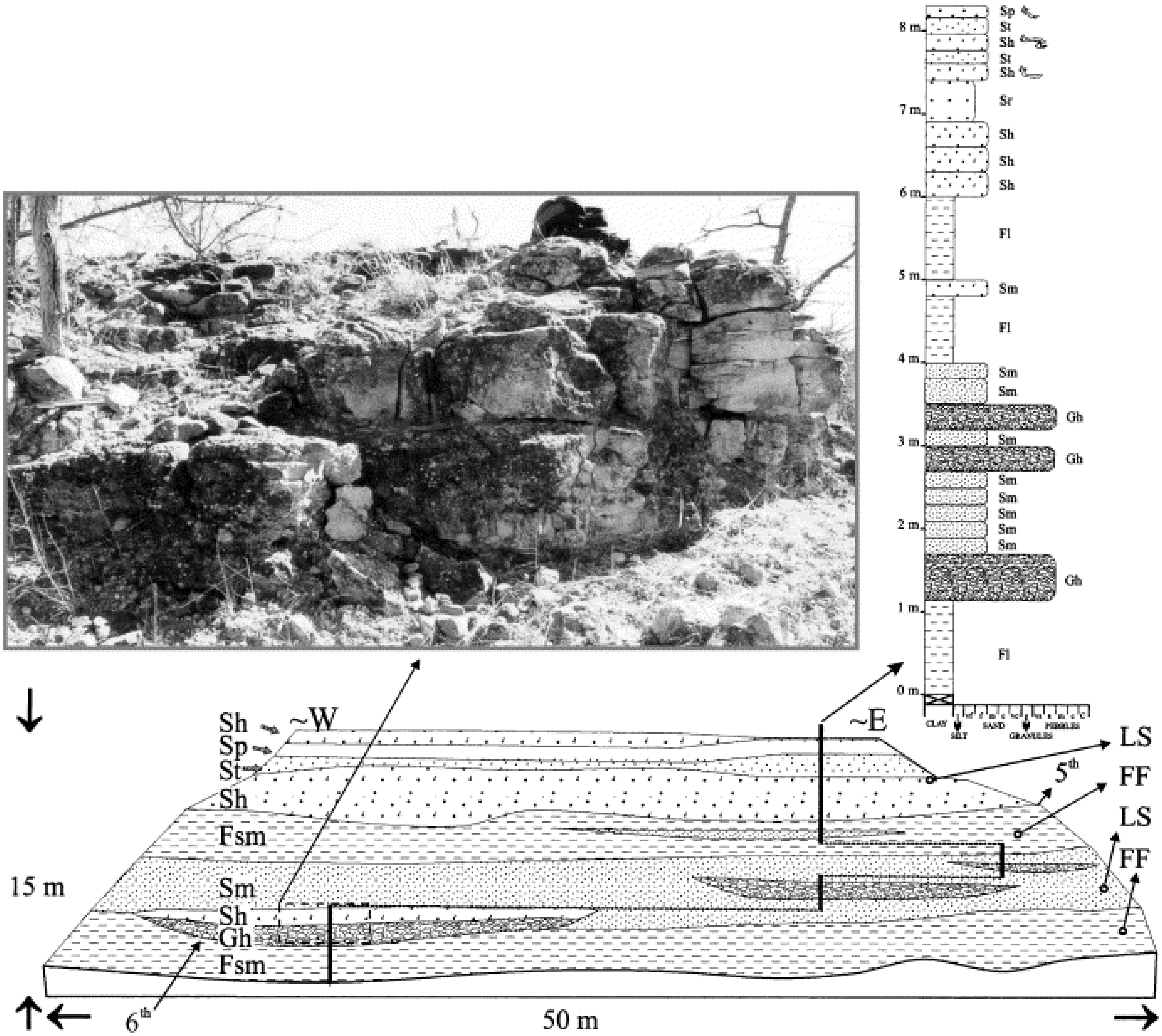


Fig. 15. Intraformational conglomerates are often found both at the base and in the middle section of the slightly fining-upward cyclothems (farm Nekel; Fig. 2). Fifth and sixth represent hierarchical orders of fluvial surfaces (Miall, 1996). Fifth-order surfaces are isolated channel bases. Sixth-order surfaces represent the base of amalgamated channels.

In the field, the lowermost occurrence of intraformational conglomerates was observed 40 m above the lower boundary of the upper unit. The thickness of the unit is estimated to be ±200 m in this area. The conglomerates seem not to be confined to one stratigraphic level, being present in various positions within the unit.

The upward-fining cyclothems of the sandstone facies assemblage are identified as laminated sand sheets (LS) architectural elements, based on: (1) dominance of the lithofacies Sm, Sh with minor St, Sp, Sr, very rare (∼1%) Gcm, Gh Gp, Gt, (2) desiccated mud drapes on bedding planes, (3) flat erosion surfaces, and (4) absence of channel-shape geometries.

3.1.2. Fine-grained facies assemblage

3.1.2.1. Argillaceous strata

All argillaceous lithofacies types presented in this section belong to the overbank fines (FF) architectural element. The fine-grained deposits that are found within the previously described LS architectural element are relatively thinly bedded (<2 m), red, massive or laminated (Fm, Fsm, Fl) mudstones or siltstones. In contrast, argillaceous rocks that occur at certain lateral distances from the above-mentioned sandstones and associated thinly bedded, fine-grained strata, are thickly bedded (>2 m). Their colour varies from greenish to reddish. These rocks display intense colour and grain size mottling, sometimes showing a blotchy appearance (Fig. 16). In composition, the argillaceous sediments range from pure mudstone to muddy fine sandstone or siltstones (greywacke). Most of the beds are massive (Fsm, Fs) with very rare relict lamination (Fl) (Fig. 17). The best outcrops of the argillaceous sediments seem to be preserved only in those areas where a conspicuous 1–1.5 m thick silicrete (S) horizon underlies the succeeding Clarens Formation. The maximum outcrop thickness of the facies assemblage is 20–25 m.

Fig. 16. Blotchy colour mottling in massive, thickly bedded argillaceous rocks (farm Hilda; Fig. 2).

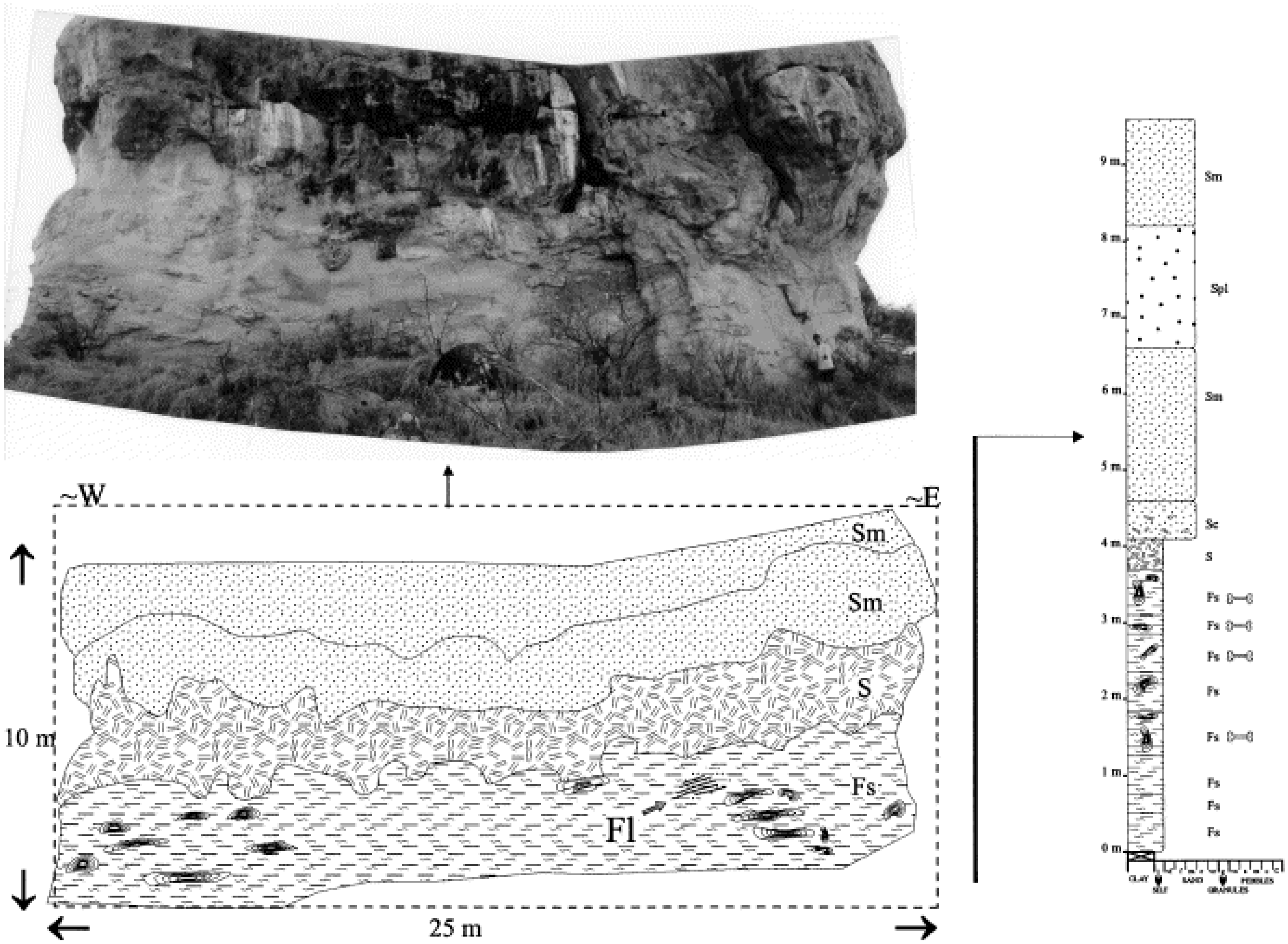


Fig. 17. Relict lamination (Fl) in otherwise massive, muddy-silty-sandy argillaceous rocks (Fs). The laminated blotch has a purplish colour and lacks carbonaceous cement. The concentration of the carbonate glaebules is higher toward the top of the argillaceous beds (see log). Note the sharp upper and gradational lower boundary of the silcrete layer (right centre of photomosaic) (farm Breslau—Show of Rhodes koppie; Fig. 2). See Table 2 for legend.

Based on differences in the frequency, thickness and grain size of the sedimentary rocks observed in boreholes, the argillaceous deposits were subdivided into the following three major groups:

(a) *Fine-grained strata interbedded with thicker coarse beds* of the sandstone facies assemblage. These fine-grained deposits are relatively thinly (<2 m) bedded mudstones or siltstones.
(b) *Argillaceous strata without or with single, isolated sandbodies*. These argillaceous rocks are generally 10–30 m thick. The single, isolated sandbodies are generally 2–6 m thick.
(c) *Multiple sandbodies and mudstones*. These consist of alternating relatively thin sandstone and mudstone beds. The sandstone beds are generally 3 m thick, whereas the mudstone beds are generally 3–5 m thick. The sand versus mud ratio in the multiple sandbodies and mudstones is approximately 1:1.

In most places, the distinctive feature of the argillaceous sediments is the presence of isolated, hard carbonate glaebules (C) in the form of nodules (Fig. 18), concretions and septaria. These range in size from a few centimetres to decimetres, and are concentrated in the upper part of the individual argillaceous beds (see log in Fig. 17).

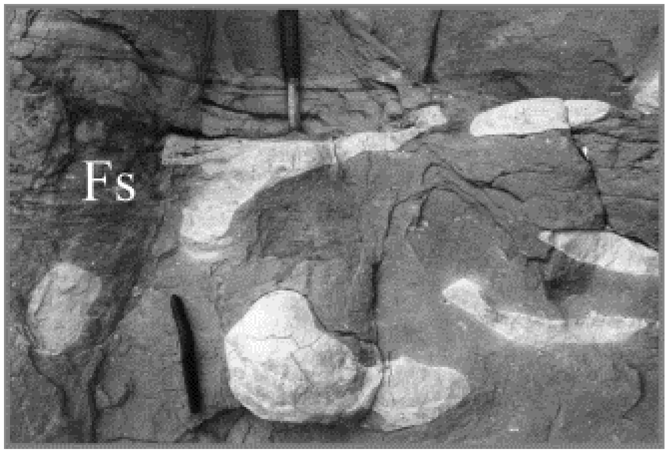


Fig. 18. Irregular and crudely cylindrical and spherical carbonate glaebules in horizontal and sub-horizontal position. The hammer is 28 cm long. The host rock is red, carbonaceous, massive muddy siltstone (Fs) with very fine sand grains (farm Parma—Tsolwe; Fig. 2).

Besides the carbonate and silcrete accumulations, a significant number of vertebrate fossils was also found towards the top of the argillite beds. The lowermost in situ bone fossil (overlain by bone-bearing conglomerates) was found in an outcrop which is situated only 40 m above the lower boundary of the upper unit. Most of the vertebrate remains are disarticulated. The fossils show little or no abrasion, but there are a few fragmented bones as well.

3.1.2.2. Sheet sandstones

In some of the outcrops, sheet-like sandbodies were recognized within relatively thick argillaceous deposits (lower part of Fig. 19) (see Groups (a) and (b) in previous section). These beds form less than 5% of the fine-grained facies assemblage. The internally massive (Sm) and very rarely horizontal laminated (Sh) (Fig. 20) or planar cross-laminated (Sp), very fine- to fine-grained sandstone beds have sharp lower and less definite, but planar upper surfaces, grading into laminated or bioturbated mudstone. Often the sandstones are also bioturbated and may contain scattered angular mud pellets as well as very fine sandstone clasts (<5%).

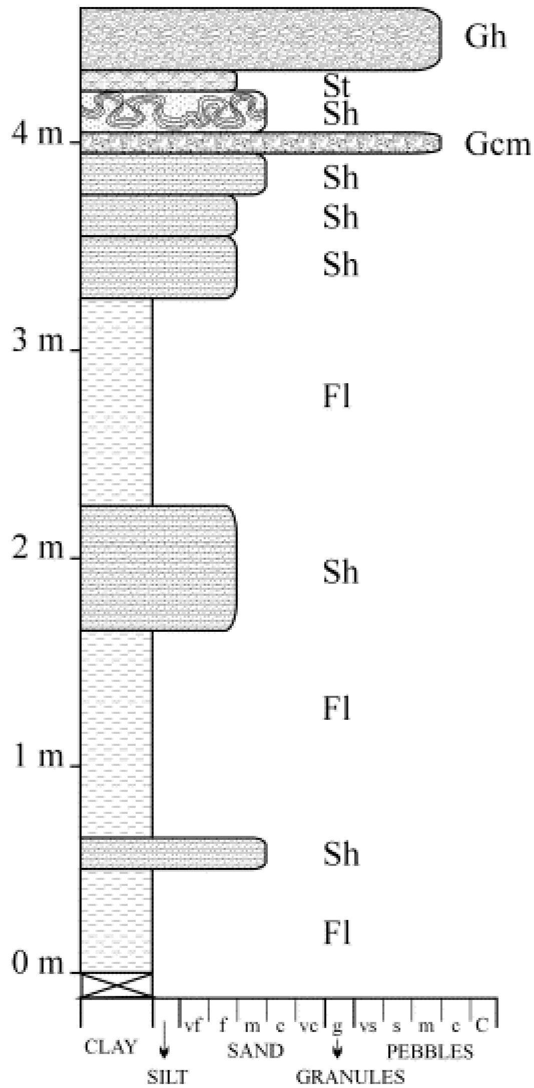


Fig. 19. Thick and thin sheet-like, single sandbodies within thick argillaceous deposits.

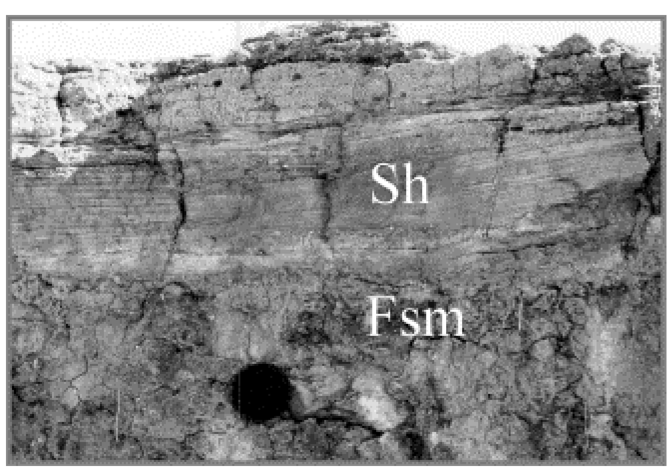


Fig. 20. Lithofacies Sh in sheet-like sandbodies within bioturbated mudstones (farm Lizzulea; Fig. 2).

Two types of sandbodies were differentiated, according to their frequency of occurrence within the argillaceous deposits:

(a) *Single, tabular sandbodies* (~1 m) showing lateral continuity without any thinning for well over 50–80 m. Thinner (<0.5 m), narrower (<3 m) but also single, isolated sandstone beds with a lenticular or wedge shape also fall in this category.
(b) *Multiple sandbodies and mudstones* are perhaps the outcrop equivalent of rocks presented in Group *c*. These superimposed sheets of sandstones and mudstones show great lateral continuity, generally in the vicinity of major sand facies assemblage exposures.

These isolated, sheet-like sandstones were identified as sandy bedforms (architectural element SB) because of their internal structures, overall geometries and relations to the surrounding rock formations.

3.1.2.3. Intraformational breccias and conglomerates

Red intraformational breccias form <0.5% of the fine-grained facies assemblage. These lens- or irregularly-shaped, narrow (0.2–2 m), isolated bodies range in thickness from <0.1 to 0.5 m and consist of red sandy siltstone and mudstone clasts, but lack carbonate glaebules. These granule- to large pebble-sized particles are angular, have a red clay-film coat and are set randomly in the mud-rich matrix forming either a matrix- or clast-supported fabric (Fig. 21). In addition, intraclast-bearing very fine sandstones and siltstones (Sc) (Fig. 21) were also observed. The intraclasts also consist of red sandy siltstone and mudstone clasts. This lithofacies (and its code) was introduced because the very fine, randomly scattered, angular sandstone clasts (1–2 cm) usually represent about 5% of the rock type, so the matrix-supported breccia (Gmm) term would not be applicable in this case. In addition, the relative abundance of the clast-rich sandstones (3% of the total fine-grained facies assemblage) as compared to the matrix-supported breccias makes clearer the necessity of this separation, even though there is a gradational boundary between one type and the other. Based on internal structures, bed geometries and stratigraphic position, the intraformational breccias and the clast-rich sandstones were identified as sediment gravity (SG architectural element) flow deposits.

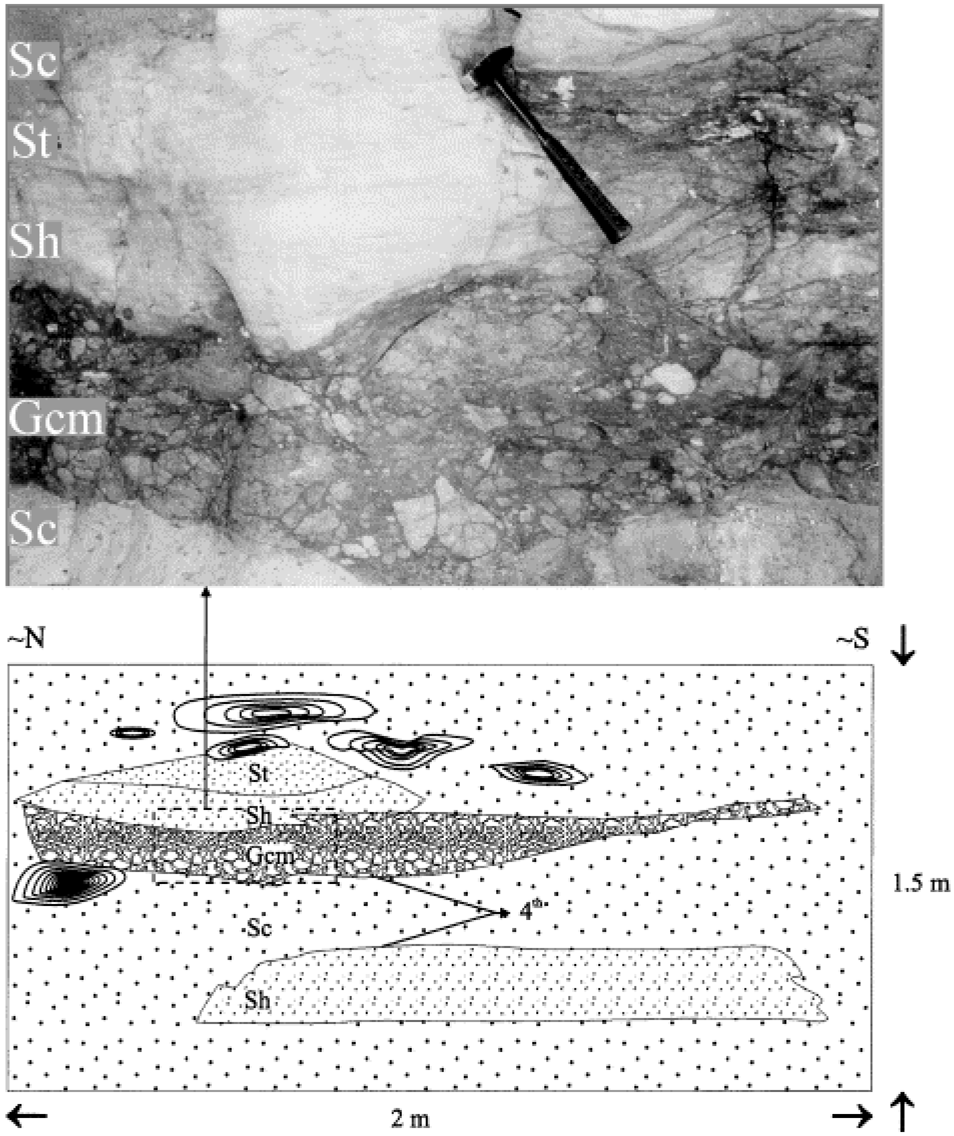


Fig. 21. Lithofacies Gcm is overlain by lithofacies Sh and St. Note the lenticular bedforms and the lack of erosive boundaries. The beds are surrounded by lithofacies Sc containing large carbonate concretions as well. Note the clay coating of the breccia clasts (farm Balerno—Tolwe; Fig. 2). Fourth-order surfaces (fourth) represent macroform boundaries (see the hierarchy of fluvial surfaces in Miall, 1996). See Table 2 for legend.

At one locality, two successive 0.3 m thick and 3 m wide, sheet-like layers of intraformational conglomerates occur in laminated, carbonate glaebular red mudstones. These clast-supported, poorly sorted conglomerates consist of granule to pebble (3 cm) grade, mostly well-rounded carbonate glaebules with a minor amount of quartz granules (1%). The beds show ill-defined normal grading and display slight horizontal layering (Gh). The matrix is red muddy, very fine sandstone, the cement is uniformly carbonate. At the top of the first Gh layer, a well-preserved fossil bone was encountered. On top of the second Gh layer, a small 8 cm thick, 1 m wide, planar (sigmoidal) cross-laminated very fine sandstone stratum was found. Such thin, cross-laminated sandstone sheets were also observed at other localities. The intraformational conglomerates were identified as gravel bedforms (GB architectural elements).

3.2. Borehole data

Because the Karoo Supergroup was affected by post-Karoo denudation events, the precise lateral thickness variation of the unit could not be determined from the outcrops. Fifty nine drill hole sections served to bridge this information gap. The computer processing of the borehole data produced the thickness map of the upper unit (Fig. 22). The borehole records show that the average thickness of the unit is ~60 m (max ~207 m), that the arenaceous facies form 40% (average thickness ~12 m) of the unit, whereas the argillaceous facies form 60% (average thickness ~20 m) of the unit. However it must be emphasized that figures based on borehole data should be treated with caution, bearing in mind that firstly, the boreholes were unevenly spaced within the basin; secondly, the boreholes were sunk in the southern, eroded edge of the basin and, thirdly, the map-plotting computer program performed extrapolation while producing the thickness figures. For instance, the northward thickening of the unit is rather uncertain, because only one borehole was drilled in the northern part of the basin (Fig. 22).

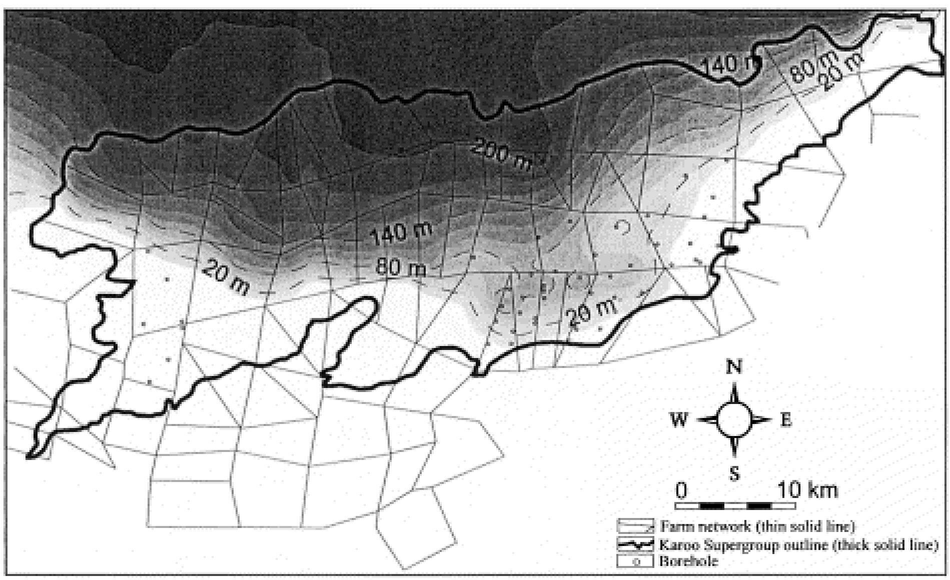


Fig. 22. Thickness map of the upper unit for the South African part of the Tuli Basin.

3.3. Palaeo-current data

The collection of palaeo-current data was carried out in order to determine possible denudation trends and sediment dispersal patters within the upper unit. The calculated statistical values and generated palaeo-current rose diagrams were based only on the orientation data derived from the foreset dip direction of the medium- and large-scale planar cross-stratified beds. The 156 palaeo-current measurements reveal unidirectional current patterns (Fig. 23). The spatial distribution of the mean vectors are indicated in Fig. 24. This map displays that the regional mean current direction was from NNW to SSE (~156°) during the deposition of the unit.

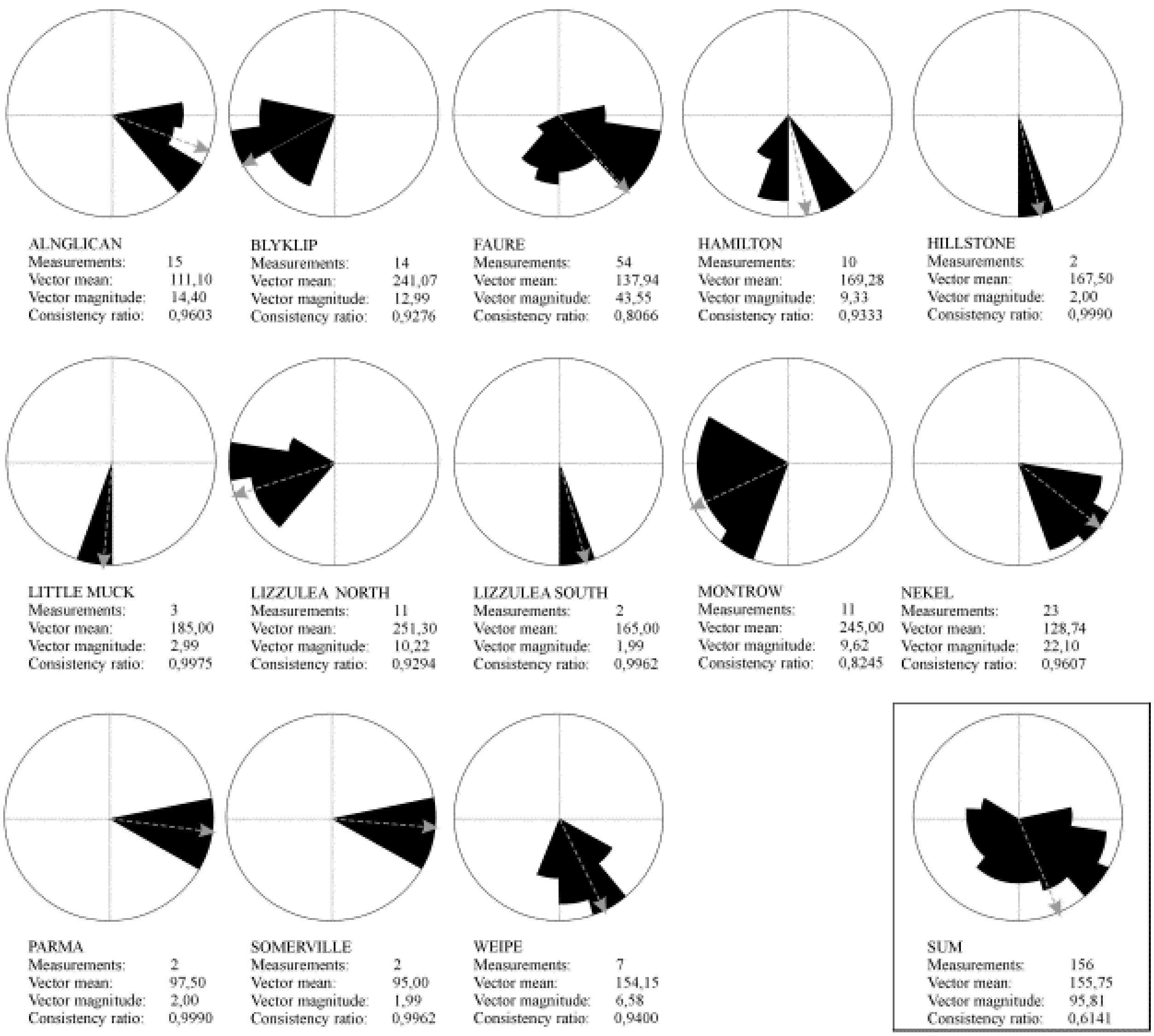


Fig. 23. Palaeo-current rose diagrams for planar cross-bedded sandstones in the upper unit.

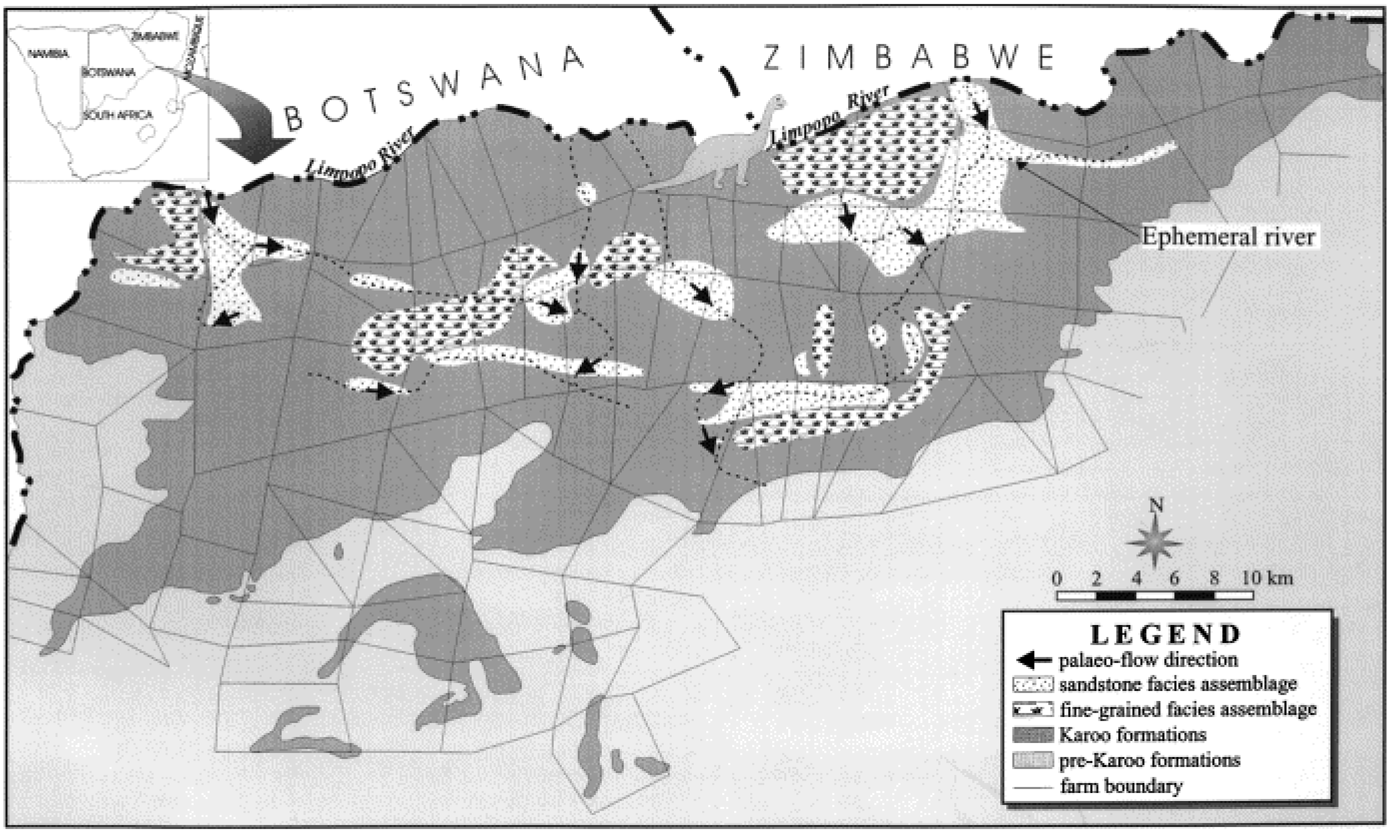


Fig. 24. Map showing the palaeo-environmental reconstruction inferred for the upper unit. Distribution of the facies assemblages is based on outcrop and borehole data. The arrows correspond to the mean vector of the palaeo-current measurements obtained from the outcrops adjacent to the arrow.

4. Facies interpretation

4.1. Sandstone facies assemblage

The suite of the lithofacies found in the laterally continuous, thinly bedded sandstone facies assemblage not only resembles upper flow-regime sedimentary structures, but also records wide energy fluctuations of the transporting agent, as indicated by the presence of intraformational conglomerates sometimes overlain by ripple cross-laminated sandstones. On the other hand, the desiccated mud drapes that often separate the predominantly tabular bedforms are indicative of erratic sedimentation. This evidence suggests a high energy but ephemeral depositional milieu. In continental settings, such episodically vigorous environments exist in the flash-flood dominated ephemeral stream/river systems of semi-arid/arid climates. Therefore the relatively thinly bedded, upward-fining, multistoried cyclothems of the sandstone facies assemblage are thought to have formed in wide, shallow channels of an ephemeral stream/river environment.

4.1.1. Sandstones

Hot, arid areas are characterized by influent stream systems with downstream decreasing discharge due to water losses, caused mainly by seepage into the alluvium towards the ground water table and by evaporation. Seepage into the alluvium largely depends on the permeability and thickness of the channel substratum (Knighton and Nanson, 1997). The short-lived nature of the floods as well as the transmission losses caused by evaporation and infiltration into the sandy channel substrate could be responsible for the formation and predominance of the massive sandstones (Sm). As bioturbation is common in the unit, a significant proportion of the Sm sandstones may also have resulted from the burrowing activity of living organisms disrupting internal sedimentary structures. Apart from the fact that flashy, ephemeral systems are dominated by short-lived, high-energy currents that mainly generate horizontal lamination and/or massive beds, the paucity of the cross-bedding may also be explained by the predominant very fine and fine grain size of the sandstones. In shallow water streams, the development of cross-bedded strata in very fine- or fine-grained sands is limited, with a decrease in water velocity, the upper flow regime horizontal lamination is abruptly followed by ripple cross-lamination (Ashley, 1990). In this case study, the ripple cross-laminated sandstone is thought to have been formed during the waning phase of floods. Low angle cross-bedded (Sl) sandstones that are often found in association with horizontal-laminated sandstones are thought to represent flow velocities transitional to upper flow-regime current conditions (Miall, 1996).

The repeated semi-sequences of Sh–St–Sp–Sr and Sh–Sm–Sr are attributed to velocity fluctuations, perhaps even within a single flood event. In addition, the frequent scour surfaces and intraformational conglomerates, not only as basal lags but also within the sandstone beds, confirm the pulsating hydrodynamic conditions. The boulder-sized intraclasts within the basal-lag deposits may indicate the intensity of the intrachannel flows which caused underscouring and collapse of the river banks into the channel. An unsteady flow pattern is a distinctive characteristic of ephemeral streams with multiple-peak discharges. During a vigorous storm the overland flow is generated within minutes, with the water reaching the channels from several entry points. As a result, the intrachannel discharge has unpredictable, forceful wave-like pulses (at least two), which are thought to be generated mainly by widely separated storm cells with fluctuating intensities (Lucchitta and Suneson, 1981; Reid and Frostick, 1997).

Along with the common bedding surface features (desiccated and bioturbated mud drapes, etc.), the soft sediment deformation structures provide a record of the processes that occurred shortly after the flood water receded. Therefore, the convolute beds may be attributed to quicksand conditions which commonly develop in water-saturated and disturbed sands through water expulsion in late flood stages (Turner, 1984). These contorted beds suggest rapid deposition from suspension and plastic deformation of partially liquefied sediments produced by shear stress on the bed.

The mud drapes with desiccation cracks, bioturbation and vertebrate footprints argue for repeated non-deposition and subaerial exposure of the intrachannel deposits. The mud drapes may be used as measures of the palaeo-channel bathymetry, assuming that each set of sandstone-mud drape units is the result of a single dynamic flood event. In this way, the thinly bedded (<0.5 m), mud draped, laterally continuous sandstones suggest rather shallow and wide courses. The internal structures (massive, horizontal- and (rarely) planar-cross bedding, ripple cross-lamination) of the sandstones and their organization in sequences imply high-stage flows succeeded by minor low-stage conditions. Wide, shallow channels and poorly connected drainage networks are characteristic of the ephemeral river/stream systems in semi-arid/arid zones (Knighton and Nanson, 1997).

Accepting that the multistoried, mud-draped sandstone beds are the result of several flood events, it can be concluded that the slightly upward-fining arenaceous units without channel cutbank surfaces may comprise many palaeo-channel fills superimposed one upon the other. The thinner beds towards the top of the cyclothems may indicate progressive filling of channels resulting in shallower channels (Friend, 1978). The general absence of waning flood-phase sedimentary rocks (lithofacies Sr) within the multistoried sandstone beds and their rare presence in the upper part of these stacked sandstone beds are explained by the fact that the waning flood-phase deposits (lithofacies Sr) of earlier floods were eroded in subsequent rain storms. Possibly the absence of the Sr lithofacies within fining-upward cyclothems was not caused only by subsequent erosion, but by non-deposition because the water level dropped too rapidly. The possibility of sudden water level falls may be indicated by the presence of massive beds (Sm). All these features show that deposition took place in short time intervals.

The fine-grained mudstone and siltstone (Fm, Fsm, Fl) interbeds in arenaceous deposits are interpreted as thick mud drapes which settled from suspension in intrachannel stagnant pools that dried out in time. The soft and delicately laminated mud dried out as a massive, bioturbated mud unit. These intrachannel mud deposits are excellent sources of intraformational mud clasts, as subsequent floods often remove the fine-grained deposits from the channels.

4.1.2. Intraformational conglomerates

The carbonate glaebules, mud- and sandstone clasts and bone fragments of intraformational conglomerates (Gcm, Gh, Gp, Gt) originate from a nearby source as they display low abrasion effects and poor sorting. These gravel beds, together with the other sedimentary structures of the sandstone facies assemblage, indicate the high strength of the floods.

The gravel lithofacies (Gcm, Gh, Gp, Gt) are thought to have been formed in traction currents with constantly changing strength and sediment yields. They likely represent channel-bottom lag deposits in the form of gravel sheets, straight (2-D) and sinuously (3-D) crested gravel dunes. The normal graded foresets resulted from the segregation of gravel–sand mixtures on the avalanche slope of the forward-accreting foreset aprons in large gravel dunes (Allen and Williams, 1979; Miall, 1996).

The presence of the locally derived intraformational conglomerates and the lack of distinct paleosol horizons can be taken as an indication of a depositional system in which the streams/rivers often deserted their channels, eroding the paleosols up to their carbonate-bearing horizons and occasionally even the older channel deposits. Yet, the absence of LA macroforms indicates that the rivers/streams did not wander frequently on their floodplain. It is believed that periodic but significant overbank erosion was generated by powerful overland flows during exceptional cloud bursts. These overland flows were competent to wash away the relatively thin topsoil of the calcisols (sensu Mack et al., 1993), remove the resistant calcrete glaebules from the calcic horizon and transport them to the larger channels.

4.2. Fine-grained facies assemblage

In arid climates where intermittent heavy rainfalls deliver high water volumes exceeding the rate of infiltration into the floodplain deposits, overland flows and pluvial water ponding are important factors in both landscape formation and sedimentary processes (Baird, 1997). Therefore, the sediment transportation in the overbank area is dominated by forceful overland (Hortonian) flows rather than by overspilling flows from major channels.

In flash-flood environments, the sediment-transport capacities of the overland flows are controlled by the rainfall intensity, exposed lithology types, vegetation and geomorphology (Frostick et al., 1983). The extremely flashy regimes, generated by high intensity storms, easily mobilize the otherwise dry, loose surface sediments, especially after prolonged dry periods. The development of current structures is often prevented because of the short-lived nature of the storms and by the rapid dissipation/evaporation of the floodwater (Tunbridge, 1984; Tirsgaard and Øxnevad, 1998).

4.2.1. Argillaceous strata

The highly argillaceous strata of the overbank area imply low surface-infiltration capacities, and therefore intense overland flows with mixed sediment load (Frostick et al., 1983). In turn, these rapid Hortonian flows probably speeded up the beginning of the intrachannel processes. On the other hand, the muddy deposits with reduced permeability may also have enhanced the subsequent deposition from ponded pluvial waters. Thus the argillaceous strata dominated by homogenous mudstones and siltstones (Fsm, Fs) possibly settled out from mixed Hortonian flows of the interchannel area. The laminated argillaceous deposits reflect subsequent deposition from ponded pluvial waters (ephemeral lakes).

The common clay-rich sandstones (greywackes) (Fs) within the fine-grained facies assemblage may originally have been deposited from mixed load Hortonian flows, but due to the mechanical infiltration of clays through influent seepage of muddy pluvial water ponds, the initial low mud:sand ratio was increased.

The rounded, silt-sized quartz grains of the argillaceous rocks may be indicative of aeolian dust or loess derived within the unit or from neighbouring desert environments via dust storms. Aeolian material is thought to be a significant contributor to the sediment supply in semi-arid floodplain settings (Smith and Kitching, 1997).

The calcretes and silcretes are evidence of duricrust formation in arid climate soil. The calcretes indicate calcisols (sensu Mack et al., 1993), whereas the blocky structures and the clay coated clasts are interpreted as peds and argillans, being hints of vertisol formation (Talbot et al., 1994). The abundance of massive, structureless, colour-mottled argillaceous rocks may also be indicative of floral bioturbation within paleosol profiles. Besides, the trace and vertebrate bone fossils indicate that the fine-grained facies assemblage accumulated on surfaces that most probably supported different forms of life, including vegetation.

The distribution and abundance of disarticulated dinosaur bone fossils and the absence of whole articulated skeletons may be suggestive of rare but powerful floods that punctuated extended non-depositional periods when the desiccation of the ligaments could take place (Smith, 1995). On the other hand, the preservation of some articulated and unbroken fossil bones suggests that the fine-grained sediments accumulated in an area dominated by less vigorous depositional processes than those of the channel subenvironment. Palaeosol features (calcrete; silcrete; silicified rootlets; soil peds; clay coated argillans; massive, colour-mottled deposits) indicate that the landscape was stable over relatively extended periods (i.e., no clastic deposition).

4.2.2. Sheet sandstones

The tabular bedforms and the internal structures of the single, sheet-like sandstones enclosed by fine overbank rocks indicate non-channelized, high-energy currents away from the main, ephemeral channels. Thus the isolated, sheet-like thickly and thinly bedded sandbodies (element SB) are interpreted as massive overland wash deposits of short-lived, unconfined, major or minor sheet floods, respectively. Such ephemeral, sediment-laden, sheet-like flows are common features of the very slightly elevated interfluvial areas of flash flood stream/channel systems. Sandy, blanket-like flood deposits formed in sheet floods over ephemeral, muddy flood plains are well-documented in the literature of semi-arid sedimentary systems (van Dijk et al., 1978; Allen and Williams, 1979; Tunbridge, 1984; Demicco and Kordesch, 1986, etc.).

The superimposed sheets of sandstone and mudstone that show great lateral continuity are explained here as rare, preserved examples of well-developed ‘rhythmites' formed by cyclic sedimentation in natural levees (Farrell, 1987). The multiple sandstones and mudstones are extremely rare and are exclusively found adjacent or proximal to major exposures of the channel sandstones (element LS).

4.2.3. Intraformational breccias and conglomerates

The locally derived sandstone and siltstone clasts, the poor sorting, the very angular fabric, the uncommon bedding in the intraformational breccias (Gmm, Gcm) and clast-rich sandstones (Sc), all suggest that the strata were deposited after short transportation distances. The red clay coating of the angular and relatively soft intraclasts resemble blocky structures (peds) with clay coatings (argillans) of aridisols (Talbot et al., 1994); thus the breccias might be seen as local accumulations of redeposited soil peds. The initial brecciation may have taken place within the soil profile, where during pedogenesis the original sandstone and siltstone had been cracked, and later on coated by illuviated clays. This process seems to be relatively common in modern semi-arid mud playa/pan environments (Demicco and Kordesch, 1986).

The poor sorting, the lack of bedding structures and the general absence of erosional surfaces indicates that the intraformational breccias (Gmm, Gcm), clast-rich sandstones (Sc) and accompanying laminated sandstones were formed in a higher viscosity medium than the normal stream traction currents (Steel, 1974). While matrix-supported breccias (Gmm) and clast-rich sandstones (Sc) are formed as debris flow deposits, perhaps the clast-supported massive breccias (Gcm) were high-density flood flow deposits which represent transition between stream flow and debris flow conditions (Hartley, 1993). Accordingly, the horizontally laminated and trough cross-bedded sandstone sequence overlying the clast-supported breccia, shown in Fig. 21, may point to the coexistence of stream flow currents and debris flows. This indicates that both the energy and sediment load of the transporting medium fluctuated.

5. The model and analogues

Supported by outcrop and subsurface observations, the spatial relationships of the lithofacies assemblages suggest that the stacked palaeo-channel deposits form laterally and vertically isolated zones within the fine, overbank sedimentary rocks. These indicate periodically confined, multichannel alluvial systems with well-developed channel and overbank subenvironments. The abrupt termination of the multistoried, tabular palaeo-channel sandbodies against the surrounding fine-grained strata may invoke the picture of former wide arroyos (Dreyer, 1993) cut into the cohesive muddy deposits which inhibited the lateral migration of the channels. In the absence of syn-sedimentary faults, the initial incision of the river valley together with the generation of the intraformational conglomerates perhaps took place during severe torrential floods, following extended dry periods when the regional base-level (i.e., groundwater level) dropped below the equilibrium profiles of the ephemeral stream system (Smith and Kitching, 1997). Such base-level lowering could have been generated by prolonged droughts.

The fluvial system under investigation is equally dominated by stacked sequences of two architectural elements, LS and floodplain fines (FF). While the former represents the channel subenvironment, the latter element is testimony of overbank areas where, during major flooding, minor amounts of sandy bedforms (SB), gravel bars (GB) and sediment gravity flow (SG) architectural elements also accumulated. The genetic model of the area is illustrated in Fig. 24. According to this figure, the sandy and fine-grained facies assemblages were deposited simultaneously in different parts of the depositional system. None of the available semi-arid/arid climate fluvial facies models (Miall, 1996) can be applied without modifications. This is partly because each fluvial system is unique, and partly because the processes dominating in semi-arid/arid areas are still insufficiently known—mainly because of the hazardous, infrequent and unpredictable character of the floods (Reid and Frostick, 1997). Classic descriptions of sedimentary structures from modern and ancient ephemeral streams are provided by the work of Williams (1971), Picard and High (1973), Karcz (1972), Stear (1985) and Tunbridge (1984).

6. Ancient analogues

Most of the architectural characteristics listed for the flashy, ephemeral sheetflood (‘Bijou Creek type') river style are pertinent for the present study, although the ‘criteria' of sand predominance and lack of well-developed floodplain areas are not met here (Miall, 1996). On the other hand, the characteristics described in the terminal fan (middle part) model of Kelly and Olsen (1993) seem to be partially applicable to the present study as well, although there is insufficient palaeo-current data to support the fan-shaped geomorphology and the radially divergent nature of the distributary system. The other major difference in the case of the upper unit is that there are no consistent downstream trends in the various sedimentary parameters (downward decrease in grain size and increase in the proportion of fine-grained sediment). In other words, the sandstone and fine-grained facies assemblages cannot be separated into only two discrete zones because they are laterally interspersed.

The facies assemblages of the studied deposits correspond in some respects with the ephemeral stream system and clay-playa model of Tunbridge (1984). Although there are some major differences, the medial to distal transitional sequences from this model (distributary-channel, sheet-flood and clay-playa deposits) may be comparable to the succession of the upper unit.

In addition, the fine-grained facies assemblage shows similarities with the confined and the terminal floodplain sequences described by Sneh (1984) from Wadi El Arish, northern Sinai. The confined floodplain deposits occur as mud draped sandstones forming upward-fining units of horizontal and cross-bedded strata capped by climbing ripples. Scour-and-fill structures are common and pebble-sized particles may be present. Terminal floodplain deposits are characterized by laminated and massive mudstones alternating with minor cross-laminated sandstones (Sneh, 1984).

Regarding the overbank area sedimentation processes in the Tuli Basin, the clay-floored pan/playa depositional model of Rosen (1994) seems to be applicable. Such pans usually develop in flat-lying areas, over sandy clay and/or clay surfaces, and are relatively vegetated (Shaw and Thomas, 1997). In addition, the clay-floored pans (sensu Rosen, 1994) are characterized by low salt and high carbonate inputs and a low-lying groundwater table (Rosen, 1994). Pans of this type and adjacent areas are the sites of non-groundwater duricrust accumulations (calcrete and silcrete). The sediments of the overbank area, including the clay-floored pans, are supplied by episodic inundations and aeolian inputs (Shaw and Thomas, 1997).

7. Recent analogues

The present day climate, landscape and sedimentary processes of the study area seem to be reasonably contemporary analogues of the sedimentary dynamics that most likely prevailed during the deposition of the upper unit. Generally speaking, the present-day semi-arid climatic conditions (average annual rainfall 339–400 mm) are characterized by prolonged dryness punctuated by rare, but intense rainstorms. The relatively flat, barren terrain is dominated by an ephemeral stream system, draining into the Limpopo River, which itself flows only during major thunderstorms.

The 5–25 m wide, shallow, mostly straight sandy river beds have relatively low banks and flat floors, and are virtually dry through the year. Water courses along them for only a few hours, may be a few days, depending on the rainfall intensities. Water in the riverbeds starts flowing after the runoff from the overbank area reaches the channels. Because the discharge in the channels is not steady, but depends on storm intensity, storm cell density, tributary network, catchment area size and vegetation, wave-like pulses of discharge may be observed. Such waves have great and unpredictable energy, even in 0.5 m deep and 15 m wide channels. During medium storms, the flowing water partially occupies the wide river bed, so bank-full channel stages are only seen in the low gradient reaches where the water spreads over a wide area, forming either numerous smaller braids or wide, shallow sheetflows. Otherwise, the flood waters subside very rapidly in the thick sandy channel substratum, resulting in a downward decrease in the river discharge. Flash floods with high sediment-transport capacities are followed by hot desiccation periods, with decreased sedimentation rates. During the dry season, sunbaked, cracked mud drapes or layers are formed.

The fairly well-developed floodplain area is relatively flat and covered by loose alluvial sands/silts, thin topsoils of sandy and/or calcareous soils and other regoliths with isolated inselbergs rising above it. Depending on the storm magnitude and frequency, the flash floods may generate shallow, ephemeral ponds and lakes as well as blanket-like sandy-silty sheets over the flat interchannel area. The sandy/calcareous soils sustain a sparse vegetation and a relatively rich fauna. The soils of the overbank area are fragile: at some places the soil erosion rate is high, and gully and rill formation processes are active. Aeolian processes, mainly in the form of dust storms, occur primarily during the dry period. Wind-blown sand and silt are often trapped by the scrub-like vegetation. Contemporaneous calcrete occurrences are relatively common in the near surface deposits, and evaporites (NaCl and $CaSO_4 \cdot 2H_2O$) were occasionally observed (farms Weltevreden, Regina).

8. Discussion

The thinner (estimated max ~450–500 m) and less continuous Karoo-age sequence of the Tuli Basin presents difficulties when attempting to correlate the beds with the Karoo supergroup in the main Karoo Basin.

The red, maroon and green ephemeral stream and floodplain deposits of the upper unit are very similar to the alternating sequences of fine- to medium-grained sandstones and argillaceous beds of the Elliot Formation in the main Karoo Basin. The following features, which are common in both stratigraphic units, highlight strong lithological similarities: predominance of upper-flow regime sedimentary structures (horizontal lamination, massive beds); trough cross-bedding; small-scale slumping; intraformational breccias/conglomerates; desiccation cracks; mud drapes; carbonate concretions; bioturbation; vertebrate footprints; multistoried sandbodies (Botha, 1968; Visser and Botha, 1980; Kitching and Raath, 1984; Eriksson, 1985).

Numerous medium sized prosauropod dinosaur remains have been collected throughout the upper unit, but these could not be identified at genera level. The other reported dinosaur fossils from the Tuli Basin appear to be of *Massospondylus,* and there is one controversial *Euskelosaurus* specimen. Kitching and Raath (1984) proposed two biozones in the Elliot Formation in the main Karoo Basin: a lower *Euskelosaurus* Range Zone, and an upper *Massospondylus* Range Zone. Because of the uncertainties mentioned above, it is debatable whether the fossil fauna of the upper unit represents only the upper biozone or whether it belongs to both of them. Nevertheless, the presence of the prosauropod dinosaur remains, in conjunction with the lithological similarities presented above, support an unambiguous correspondence between the upper unit and the Elliot Formation.

It has been proposed that the sedimentary rocks of the middle and upper units, and the Clarens Formation represent syn-rift deposits which were accumulated in the E–W trending rift system comprising the Tuli and Tshipise Basins (Fig. 25) (Bordy, 2000). The contrasting palaeo-current directions of the middle and upper units (i.e. from ~SE to ~NW in the middle unit and from ~NW to ~SE in the upper unit) indicate that the dip direction of the regional palaeo-slopes varied with time due to the evolution of the major faults within the rift system. In other words, the master fault of the rift system (i.e. the northern boundary of the Tuli Basin) was the major active fault during the accumulation of the middle unit and its equivalents. This structural framework would have generated a northerly inclined palaeo-slope stretching from the southern rift shoulder to the northern master border fault. The similar palaeo-current directions of the middle unit in the Tuli

Basin and its equivalent (Fripp and Joan formations —van der Berg, 1980) in the Tshipise Basin may imply that both areas formed part of the same ∼E–W trending depository. By the time of the accumulation of the upper unit, the rift system reached the stage when due to intrabasin fault activity individual, ∼E–W trending sub-basins were created (Fig. 25). This model would explain why the palaeo-drainage pattern in the Tuli Basin is opposite to that of the north–easterly inclined depositional ramp of the neighbouring Tshipise Basin. If during the deposition of the upper unit, the Tuli and Tshipise Basins were two individual sub-basins parallel to each other and within the E–W trending rift system, these two depocentres may have been supplied with sediment from different sources: the Tuli Basin mainly from north, and the Tshipise Basin mostly from south.

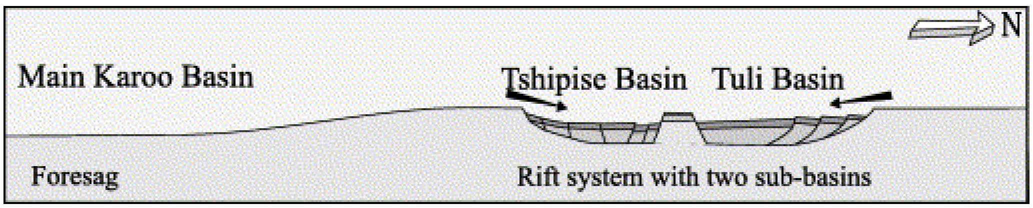


Fig. 25. Summary of the tectonic setting during deposition of the upper unit in the Tuli and Tshipise Basins (not to scale).

To summarize, the reason for the various regional palaeo-slope directions that prevailed during the deposition of the Karoo Supergroup in the Tuli Basin remains uncertain for the time being. It is tentatively suggested that incipient continental extension occurred shortly before the deposition of the middle unit, or during the accumulation of the upper unit. However, this study shows that the tectonic model of Watkeys and Sweeney (1988) is subject to modification as extensional rift tectonics did not occur during the deposition of the basal unit, which was formed in the back-bulge basin setting of the Karoo foreland system (Catuneanu et al., 1999; Bordy, 2000).

9. Conclusions

The sedimentary fill of the Tuli Basin consists of a succession of four main lithostratigraphic units, namely the basal, middle and upper units, and the Clarens Formation. The sedimentology of the upper unit is dominated by two main facies assemblages, i.e. sandstones and finer-grained sediments, both of which can be interbedded with subordinate intraformational coarser facies.

Palaeo-environmental reconstructions indicate that the upper unit was deposited by ephemeral fluvial systems. The climate was semi-arid with sparse precipitation resulting in high-magnitude, low-frequency devastating flash floods. These transported mainly fine-grained arenaceous and argillaceous sediment from a weathered, quartz-rich craton interior and other sedimentary source rocks located NNW of the study area. The fining-upward channel-fill sequences were built up by numerous flooding events as indicated by the desiccated mud drapes and internal erosion surfaces. The overbank area supported both flora and fauna as evidenced by indicators of soil-forming processes (e.g., pedogenic calcrete and silcrete) and palaeontological findings (e.g., ichnofossils and prosauropod dinosaur remains).

Based on sedimentologic and biostratigraphic evidence, the upper unit of the Tuli Basin correlates with the Elliot Formation of the main Karoo Basin. During the accumulation of the upper unit, the Tuli Basin seems to have undergone significant extensional tectonics, which finally led to the preserved half-graben geometry of the sedimentary fill.

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