Sedimentology and Ichnology of Floodplain Paleosurfaces in the Beaufort Group (Late Permian), Karoo Sequence, South Africa

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Floodplain paleosurfaces are depositional surfaces that were exposed on ancient floodplains and have been preserved in the rock record. Three types of floodplain paleosurfaces have been recognised in the Late Permian Beaufort Group strata of the southwestern Karoo Basin of South Africa. They occur in sedimentary sequences which represent point bar, proximal floodplain, and distal floodplain facies.

The distribution of paleosurfaces in the Beaufort strata was ultimately controlled by flash-floods which transported sand out of the large meandering river channels into the floodplains. Preservation of the vertebrate and invertebrate traces was enhanced by a silty-clay veneer that accumulated on the sand surfaces during waning flood. The surfaces were buried without significant modification in parts of the floodplain where water became ponded. These were most commonly in crevasse splay channels, on distal crevasse splay lobes prograding into axial floodbasin lakes and in swales on the downstream portion of point bars. Ichnotaxa that appear to be environmentally specific include arthropod trackways of Umfolozia *type on proximal crevasse splays, algal matted textures on distal crevasse splays and large 'septate' traces of* Beaconites *type on point bar ridges.*

Trackways of synapsid reptiles are present on many of the paleosurfaces and do not appear to be environmentally specific. Cross-cutting relationships of the ichnofossils and desiccation features are compared with those of modern flash-flood deposits to reconstruct some time constraints on the formation, exposure, and burial of these surfaces.

INTRODUCTION

Paleosurfaes are the surfaces of ancient depositional landforms that are preserved in the rock record with their original topography and surface sculpture intact. They display a suite of sedimentary bedforms which are commonly overprinted with run-off and desiccation structures as well as a variety of trace fossils. This study investigates the sedimentation and biological colonization of paleosurfaces in the fluvio-lacustrine strata of the Late Permian Beaufort Group in the southern Karoo Basin of South Africa. The Lower Beaufort (Adelaide Subgroup) is a 1000-m-thick succession of alternating siltstone, mudstone, and fine-grained sandstone beds with fining-upward textures interpreted as the overbank and channel deposits of mixed-load meandering rivers (Kubler, 1977; Turner, 1975; Smith, 1981, 1987; Stear, 1983, 1985) that flowed generally northwards (Theron, 1975) across an expansive semi-arid alluvial plain (Keyser, 1966). Grey, greenish-grey, and reddish-brown siltstone dominated floodplain sequences contain numerous fossils of therapsid vertebrates. Calcareous paleosols occur in abundance in these rocks and indicate warm to hot semi-arid climatic conditions with strongly seasonal rainfall of 50–80 cm per annum (Smith, 1990).

Mild basinal tectonism within the large E-W trending foreland trough (Tankard et al., 1982) maintained equilibrium between subsidence and floodplain aggradation over extended periods (Rust, 1975). Seasonal downpours in the Gondwanide mountain catchment (Du Toit, 1954) caused overtopping and crevassing of the cohesive channel banks and inundation of the flanking floodplains (Smith, 1987). It was the rapidly fluctuating hydrodynamic regime of these rivers (Stear, 1978, 1985) that promoted the formation and preservation of the floodplain paleosurfaces described in this report. Within the major channels the

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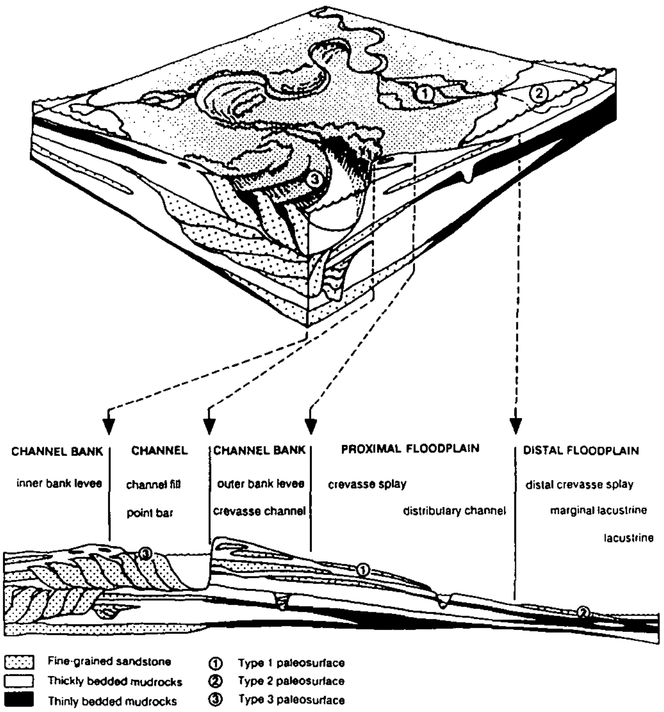

FIGURE 1—Schematic cross section through a Lower Beaufort floodplain showing the distribution of paleosurfaces amongst the various depositional environments and their general stratigraphic relationships.

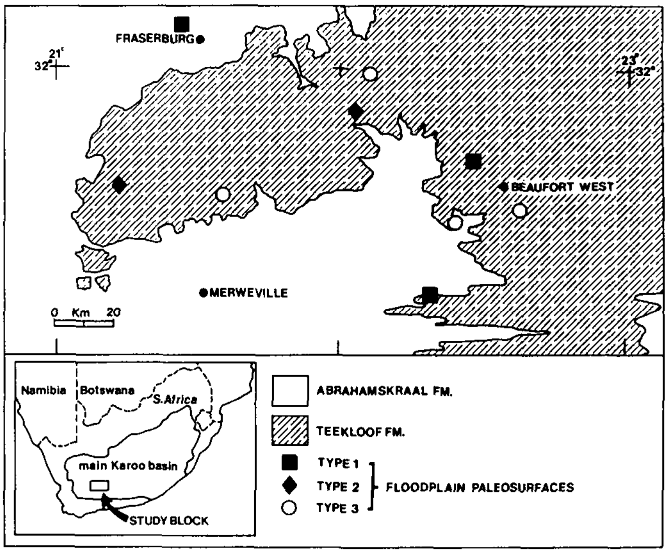

FIGURE 2—Location of Beaufort Group paleosurfaces described in this report.

erratic discharge led to irregular accretion on point bars as is clearly demonstrated by the pattern of accretion ridges on exhumed sandstones in the study area (Smith, 1987). Flourishing vegetation on the channel banks supported a complex terrestrial, aquatic, and semi-aquatic fauna of which the therapsids, or so called "mammal-like reptiles," were the largest in size and the most abundant.

Considering the abundance of therapsids that have been collected from the southwestern Karoo over the past 150 years it is unlikely that their tracks would have been overlooked. It appears that the general paucity of vertebrate tracks is due to their non-preservation. Only six vertebrate trackway surfaces have been described from the southwestern Karoo to date (Seeley, 1904; Watson, 1960; Smith, 1980; Fountain, 1985; De Beer, 1987; MacRae, 1990). In all cases it was concluded that they were preserved within floodplain deposits.

Paleosurfaces are difficult to find in the Lower Beaufort outcrops because the sedimentary environments in which they formed were originally of limited area and the sequence of depositional events necessary to ensure their preservation occurred infrequently. Furthermore, under the semi-arid climate of the present-day Karoo region, mechanical weathering rapidly destroys the delicate sculpture of the surfaces soon after they are exposed. Thus paleosurfaces are found in areas where the sandstones are being rapidly denuded such as ephemeral stream beds and reservoir overflow spillways, and unfortunately, in these settings, they are most susceptible to removal.

Stear (1978) studied the sedimentological aspects of some sandstone paleosurfaces from the Lower Beaufort and clearly demonstrated emergence features, interpreting them as having formed on the surface of crevasse splays. Similar surfaces, which contain vertebrate tracks, were attributed by Smith (1980) to algal-matted distal crevasse splay lobes issuing into an axial floodbasin lake. Sedimentological and ichnological features of a well-preserved paleosurface near Fraserburg were later described by De Beer (1987) who interpreted them as having formed through ponding of floodwaters in the distal parts of a meandering river floodplain. Sandstones in the overbank sequences may be generally described as medium- to well-sorted, fine- to very fine-grained arkosic wackes (Kubler, 1977). The original cement was probably calcite but it has been subjected to weak silicification. The framework grains are composed of quartz and feldspar with isolated rock fragments of igneous origin and rare volcaniclastic glass shards (Martini, 1974).

In this study, differences in host sequences, sandstone geometries, surficial topography, bedforms and ichnofossils all provide a means of distinguishing three types of paleosurface and assigning them to different sub-environments of the Lower Beaufort floodplains. These are: Type 1 paleosurfaces of proximal crevasse splays, Type 2 paleosurfaces of distal crevasse splay deposits, and Type 3 paleosurfaces of point-bar ridges and swales (Fig. 1).

Three paleosurfaces, one of each type, are documented in detail in this report and reference is made to at least 10 others in the Lower Beaufort strata of the southwestern Karoo (Fig. 2). Planimetric mapping of the sedimentary structures and trace fossils provided data for reconstructing the sequence of events that led to the deposition and preservation of these paleosurfaces. In addition, the numerous trace fossils give an almost day-by-day documentation of the movements of a variety of reptiles, fishes, and arthropods.

PALEOSURFACE TYPE 1 (PROXIMAL CREVASSE SPLAY)

Sedimentology

Type 1 paleosurfaces occur on undulating upper surfaces of thin (<1.5 m thick) sheet-like tabular sandstone bodies with sharp non-erosive bases and sharp upper contacts. The sandstones, interpreted as proximal crevasse splay deposits (Smith, 1980), occur within 2–10-m-thick sequences of greenish-grey/purple-mottled siltstone with abundant pedogenic carbonate nodules (Smith, 1990) and numerous vertebrate fossils. Sedimentological, pedalogical and taphonomic characteristics of these sequences have been previously investigated (Smith, 1980, 1989, 1990) and interpreted as indicative of deposition on the proximal floodplain at the base of the meanderbelt slope on and between prograding crevasse splay lobes (Fig. 3).

The proximal crevasse splay sandstones have a wedge-shaped geometry and are normally less than 2 m thick, extending laterally for up to 500 m. They are characterized by flat, non-erosive bases and undulating surface topography. Type 1 paleosurfaces occur on and between these undulations which are in the order of 50 m wide and 150 m long, resembling erosively bound braid-bars (Fig. 3). The wide shallow channels between the bars are commonly floored with a succession of elongate spoon-shaped depressions or pools; these are conformably filled with thin beds of fine-grained sandstone separated by millimeter-thick mudstone veneers. These depressions are interpreted as pool and riffle surfaces formed by streaming vortices that scoured the sandy stream bed during rising flood stage (Harms and Fahnestock, 1965; Bridge and Jarvis, 1982). The scour-pools on these surfaces are approximately 8–10 m long, 2–5 m wide and from 50 to 75 cm deep (Fig. 4a). Some have a concave bottom profile whereas others are flat-bottomed and covered with large straight-crested symmetrical ripples. The bar tops and narrow ridges of sandstone that separate the depressions have a chaotic surface texture that appears to have resulted from excessive trampling (Fig. 4b) by large vertebrates (similar to the 'dinoturbation' of Dodson et al., 1980) with footprint diameters between 24 and 30 cm. It is possible that, as the splay channels gradually dried up, the interpool ridges provided walkways for the vertebrate fauna to cross from one bar to another and were thus subjected to repeated trampling.

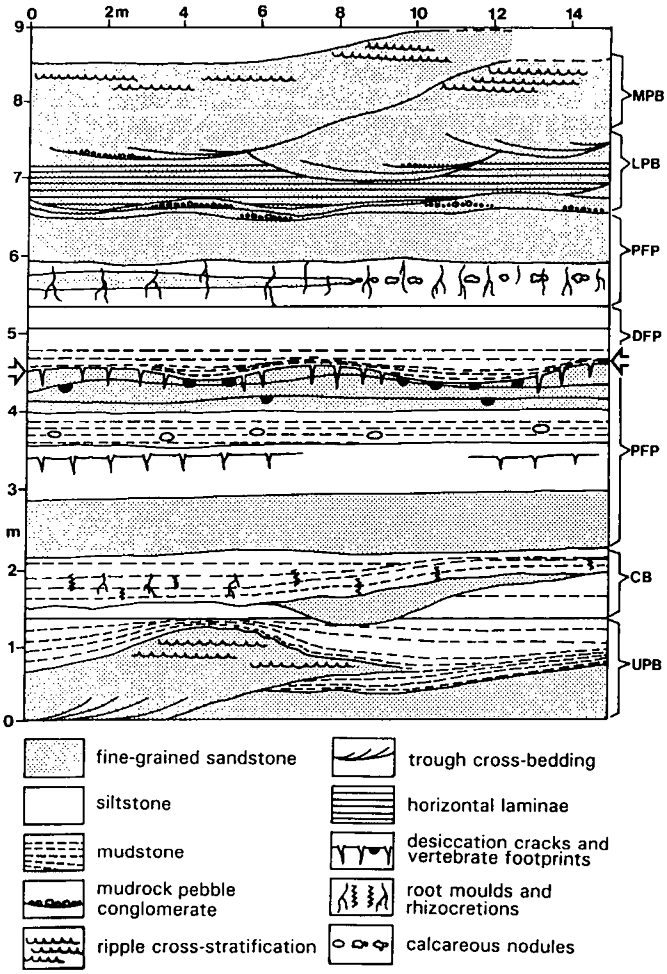

FIGURE 3—Panel section of the sedimentary sequence containing Type 1 paleosurfaces (arrowed) that are exposed on the farm Gansfontein near Fraserburg (see Fig. 2). LPB = lower point bar, MPB = middle point bar, UPB = upper point bar, CB = channel bank, PFP = proximal floodplain, DFB = distal floodplain.

High-up on the pool sides a sequence of 'emergence' structures is commonly encountered which was clearly formed during the progressive lowering of water level in the pool. This sequence begins at the upper rim of the pool with a narrow zone of parallel adhesion ripples that gives way to a zone of falling water-level marks (Fig. 5) which, in plan view, delimit the former water's edge and in profile define the former horizontal plane. These millimeter-scale terraces are commonly well-preserved only around one side of the pools and were formed by small wind-generated waves lapping against the downwind sides of the pools as the water level gradually dropped. Lower down the pool sides the water-level marks give way to a concentric zone of adhesion warts which become gradually smaller and more closely spaced downslope to form a sharp boundary with the zone of run-off rills below. Adhesion "warts" are the result of wind shear on wet sand surfaces (Reineck and Singh, 1975) and indicate that while the sand was exposed, the interstitial water remained for some time.

Below the adhesion "warts" there is commonly a zone of dendritic run-off rills fringing the scour-pools. Individual rill networks are in the order of 15–20 cm wide, up to 60 cm long and very evenly spaced every 30–50 cm along the slope. Each rill network coalesces downslope into a single gulley but rarely do the gulleys converge (Fig. 6). The rill spacing is in some cases controlled by primary

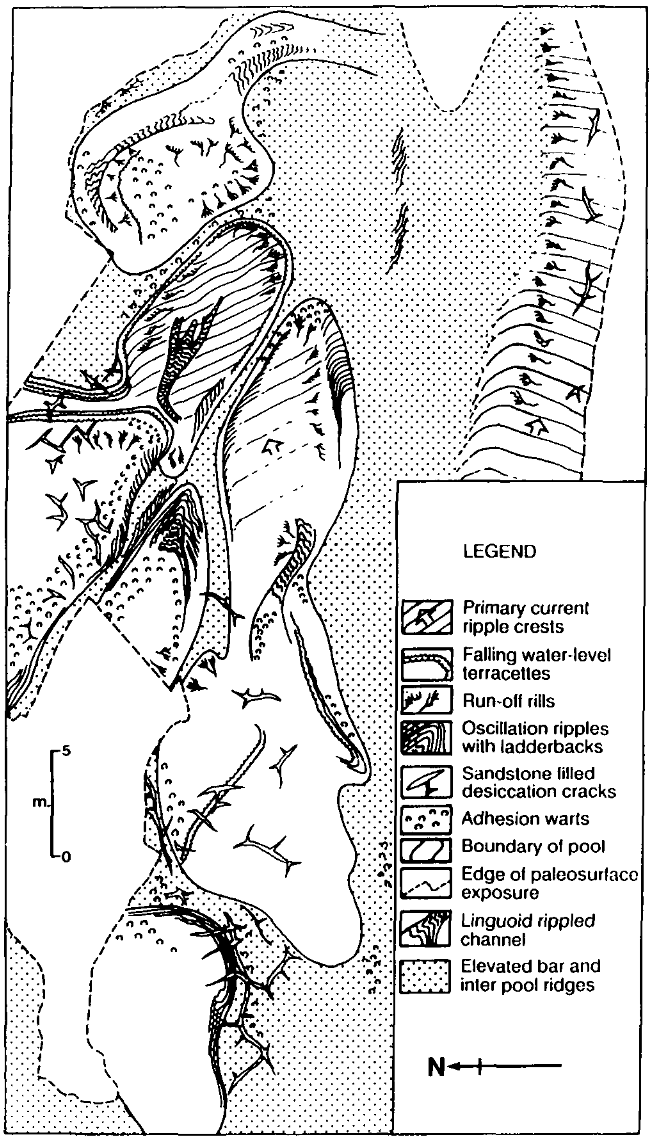

FIGURE 4a—Planimetric map of the topography and sedimentary structures of a proximal crevasse slay paleosurface exposed near Fraserburg.

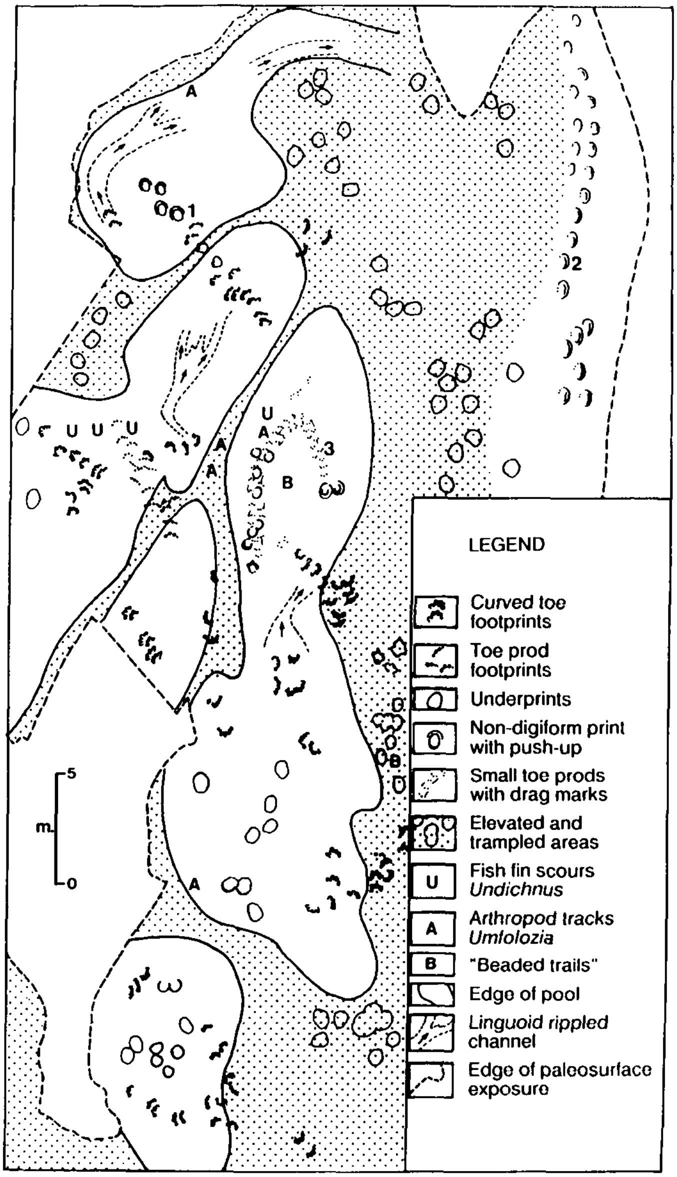

FIGURE 4b—Plan of the trace fossils on the Type 1 paleosurface shown in Figure 3b taken from a proximal crevasse splay paleosurface exposed near Fraserburg.

ripple troughs but is regular even on smooth-sided depressions.

The flat bottoms of some of the shallower pools are covered in a complex of small symmetrical oscillation ripples, the crests of which clearly deflect along the pool sides and show ladderback-type reworking on the troughs (Fig. 7). In some places the pools are linked by narrow (<1 m-wide) run-off channels with flat bottoms covered in linguoid ripples (Fig. 8). Distinctive near-vertical walls of these channels, up to 10 cm high, are an indication that the sand was partially consolidated before being cut, suggesting that they are post-emergence features. The courses of these small low-sinuosity channels are clearly influenced by the pool topography yet they all tend to flow in the same direction (Fig. 4a) corresponding to the long axes of the pools and presumably the paleoslope into the floodbasin. The interpretation of these as run-off channels (De Beer, 1987) is problematical as they were formed after emergence and must have carried a continuous stream of shallow, fast-flowing water that could not have been locally supplied by groundwater seepage. It is more likely that the linguoid-rippled channels were incised through the mud veneer, into the sand surface, at the onset of the succeeding flood event.

Sandstone-filled desiccation cracks are common on the intervening ridges between the pools and across the convex

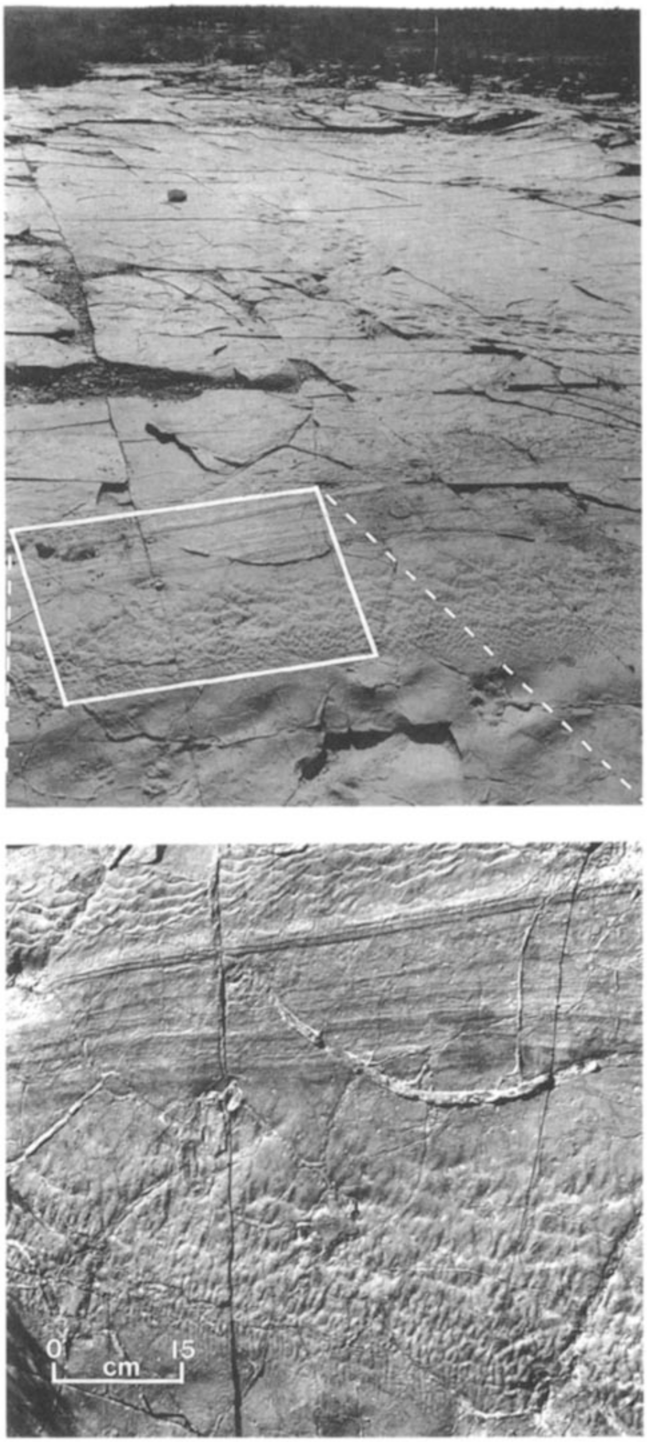

FIGURE 5—Emergence structures at the edge of a pool on the paleosurface shown in Figure 4a. The surface slopes towards the viewer with adhesion ripples, falling water-level marks, adhesion "warts," giving way to the smooth bottom surface of the pool. The larger sand-filled shrinkage cracks have penetrated down from an overlying bed.

FIGURE 6—Part of a pool and interpool ridge on the surface shown in Figure 4a. Note the fringe of run-off rills below the zone of adhesion "warts" along the edge of the pool and the curved-toe underprints in the foreground.

bar surfaces. Only rarely do these cracks disrupt the finely sculptured sandstone surfaces within the pools. Arcuate fissures up to 15 cm wide intersect each other to form crude polygonal patterns. It is evident from the manner in which the sandstone infill protrudes above the palaeosurface (Fig. 12) that many of the larger cracks penetrated down from a higher level and must have opened after the surface had been buried beneath a centimeter-thick layer of mud.

Discussion

The wedge-shaped geometry and undulating or "swaley" surface topography of these sandstones are similar to some modern crevasse splay lobes described by Smith et al. (1989) from the Cumberland Marshes in Saskatchewan. A distinctive feature of the Type 1 (proximal crevasse splay) paleosurfaces is the preservation of low-energy run-off channels and rills on the high-energy scoured bed. This reflects the essentially ephemeral nature of flow in the splay channels caused by a rapid rise to peak velocities as floodwaters spilled through a breach or crevasse in the

FIGURE 7—Oscillation and interference ripples in the bottom of a pool on the proximal crevasse splay paleosurface of Figure 4a.

FIGURE 8—Linguoid-rippled channel eroded into the bottom of a pool on a Type 1 paleosurface near Fraserburg (see Fig. 4a). Scale rule = 1 meter.

banks of the main meandering river and spread out over the floodplain surface, rapidly dumping its bedload in an anastomosis of small sand-bed channels (Smith et al., 1989). This was followed by an abrupt decline in flow velocities and abandonment of many of the splay channels as waning floodwaters were again confined to the main channel. After the flood episode the abandoned splay channels were left filled with standing water for sufficient time to allow a thin veneer of suspended fines to settle onto the sandy bed. The scoured bed topography of the splay channels was thus only slightly modified during the waning flood phase by run-off and emergence features.

The style and spacing of the rills suggests that local seepage from a temporarily 'perched' watertable was the most likely source of run-off water. Rainfall is ruled out as a source because raindrop impressions are lacking and because on exposed paleosurfaces, fine details are preserved that would otherwise have been obliterated by rainsplash.

Ichnology

Trace fossils on the proximal crevasse splay surfaces have, in most cases, imprinted through the millimeter-thick mudstone veneer to be preserved as epireliefs in fine-grained sandstone beneath. Soft-bodied worm-like organisms have exploited the sandstone mudrock contact leaving sinuous *Planolites*-like backfilled burrows. Unusual epichnial "beaded scribble trails" (Fig. 9), consisting of a series of small (1 mm diameter) conical pits linked by narrow grooves, bear a superficial resemblance to the trails of some modern nematode worms (Chamberlain, 1975). However, the characteristic "scribble" pattern is very similar to that of some shallow endichnial tunnels of mole crickets (Ratcliffe and Fagerstrom, 1980). Various arthropod tracks of '*Diplichnites* type' belonging to the ichnogenus *Umfolozia* (Anderson, 1975; Fig. 10) are a testament to the fact that, although no body fossils have been found, freshwater crustaceans were present on the ancient floodplains. Meandering septate grooves, 2–3 cm wide, in some of the smooth-bottomed pools, may reflect the subaqueous furrowing activity of gastropods. Intertwined pairs of sinuous grooves (*Undichnus* sp., Fig. 23) along the margins of some of the pools are interpreted as marks made by the caudal and pectoral fins of freshwater fish as they swam in the shallows (Anderson, 1975).

Five types of quadruped tracks have been recorded on the crevasse splay paleosurfaces in the Beaufort Group,

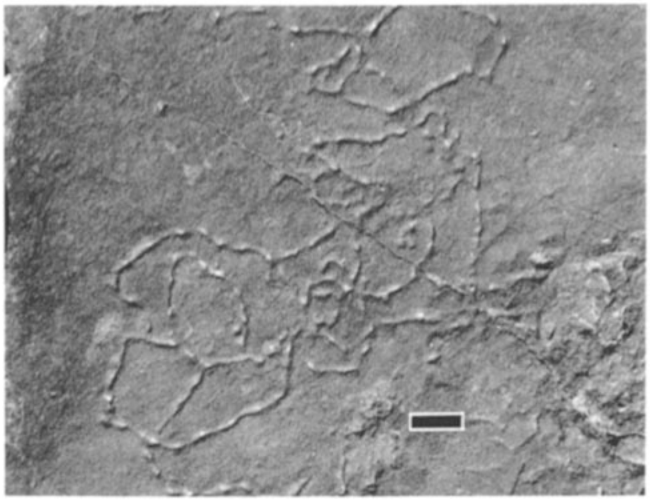

FIGURE 9—Scribble-shaped 'beaded trail' on the bottom of a pool on a Type 1 paleosurface. Scale bar = 1 cm.

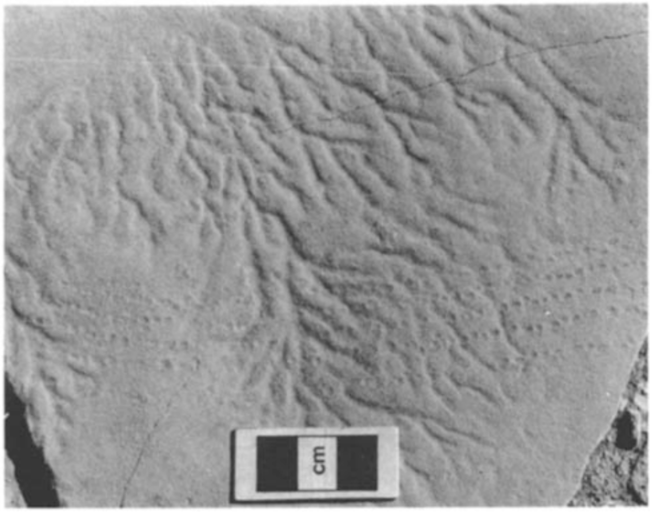

FIGURE 10—Arthropod trackway of unknown affinity (possibly decapod) impressed on dendritic rills along the edge of a pool on the Type 1 paleosurface shown in Figure 4b.

mainly preserved as concave epichnia (Martinsson, 1970). These include: (1) curved-toed with small palm print; (2) straight-toed with large palm print (both 1 and 2 are commonly underlain by non-digitiform transmitted prints); (3) circular depressions with push-up ridges; (4) individual toe-prods with claw scrapes and (5) randomly trampled 'squelch' marks. Large curved-toed tracks (trackway 1 of Fig. 4b and Fig. 11) have been attributed to adult dinocephalians (De Beer, 1987), these being the most likely candidates among the fossil fauna found in these strata. The pentadactyl manus and pes prints (Fig. 11) are equal in size (0.25 m wide) and shape with pace lengths of 65–70 cm and stride lengths of 1.25–1.30 m. Pace angulation of the pes (150 degrees) is larger than that of the manus (130 degrees) resulting in a slightly smaller separation of right and left pes prints (18 cm) than manus prints (27 cm). The separation of 88 cm between the reconstructed positions of mid-glenoid and mid-acetabulum is a rough estimate of trunk length (Padian and Olsen, 1984). This is similar to that measured from articulated fossils of adult dinocephalians such as *Tapinocephalus* and *Struthiocephalus*.

The curved-toed imprints have a distinctive inward curvature of the first 4 digits. The imprint of digit V is straight and has a slightly greater interdigital angle (55°) in contrast to the other digits which diverge about 40° from each other. Digits II, III, IV, and V are imprinted deeper than digit I indicating that they were the principal load-bearing digits. The toes of adult dinocephalians are slender and straight with digit I considerably smaller than the rest. The inward curve on the distal ends of digits I–IV probably resulted from an outward rotation of the feet as weight was transferred to them halfway through the step cycle.

Analysis of several trackways on the Gansfontein surface has led to the recognition of three stages in the implantation of these footprints (Fig. 11): (1) positive rotation of the foot as it was carried forward in a lateral arc and lowered onto the substrate with toes I–IV being grounded in sequence; (2) slight outward rotation, splaying and flattening of the planted digits as weight was transferred to them and the imprinting of the outermost digit V into the substrate; (3) overdeepening of the distal ends of digit impressions II–V as the foot was raised. This would suggest that the tracemaker had an elbows-out, 'rolling' gait with limited tarsal rotation (Padian and Olsen, 1984) on both fore and hind limbs and a certain amount of lateral flexure of the vertebral column. This resulted in a slight overlap of manus and pes prints and the inward curve on the toe prints.

Straight-toed footprints with large circular palm impressions and no overlap of manus and pes are attributed to the robust, barrel-shaped pareiasaurian, *Bradysaurus* (De Beer, 1987). This is based on similarities in the size and shape of the digit impressions with the fossil skeletons that occur in this stratigraphic interval. Accepting this association, it seems that the pareiasaurian gait differed from dinocephalians in that the latter were fully plantigrade and there was no rotation of the planted foot in spite of their elbows-out stance. This suggests that the tarsal and carpal joints were more flexible and able to accommodate the rotation created as the body moved forward through its step cycle (Padian and Olsen, 1984).

At the edge of one of the mapped exposures, a half trackway (trackway 2 of Fig. 4b) of non-digitiform footprints has penetrated the dried crust of a sloping bar surface forming "knife-edged" push-up ridges on the downslope side of each print (Fig. 12). Only the right side of the trackway was impressed through the crust, the left being on firmer substrate higher up the slope. The circular depressions disrupt run-off rills in the sandstone and provide a locus for the initiation of desiccation cracks indicating that they post-date emergence and crust formation yet pre-date complete desiccation. The sandstone casts in

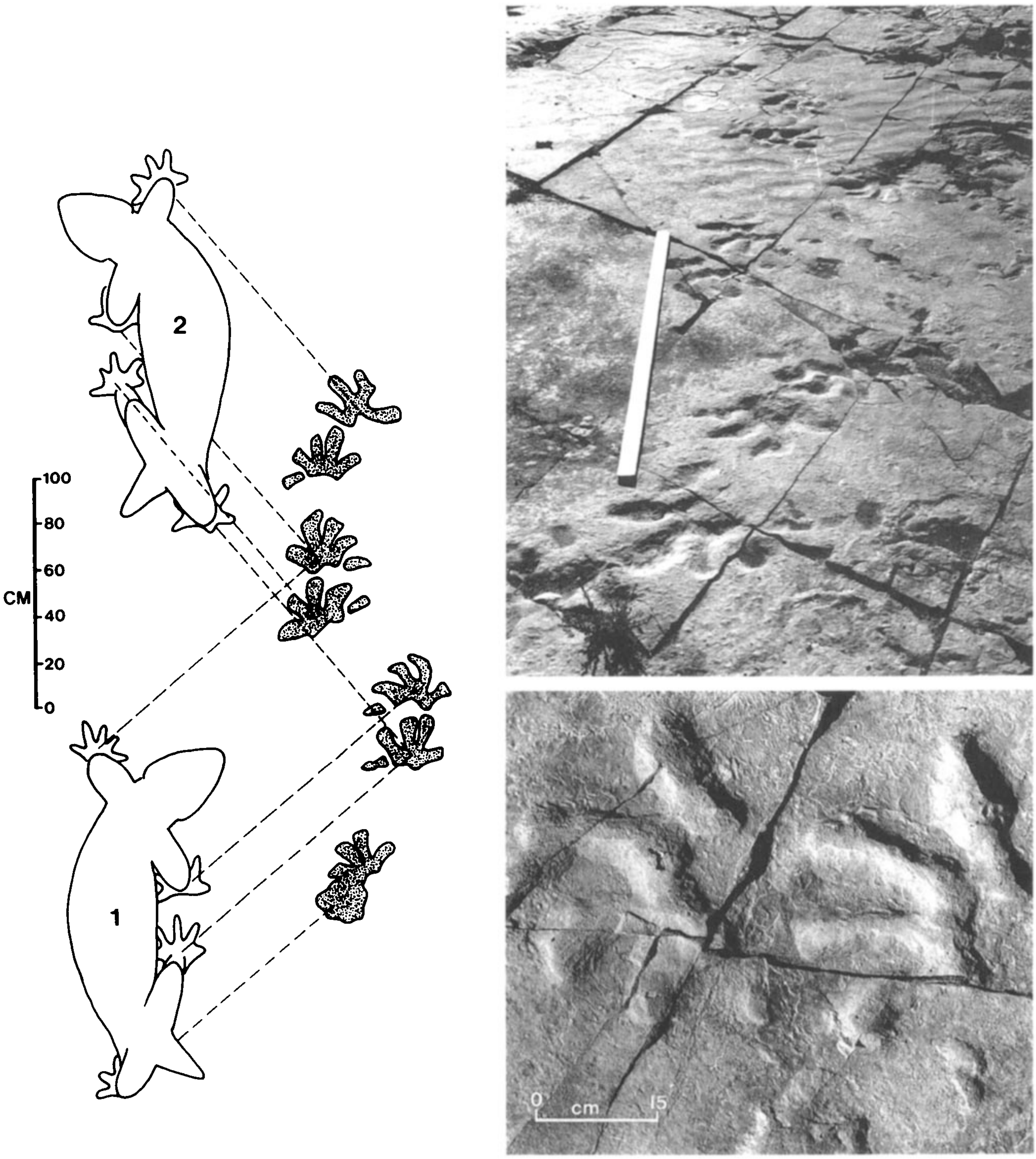

FIGURE 11—Field view and close-up of curved-toe footprints possibly made by a dinocephalian walking out of a pool on the Fraserburg paleosurface of Figure 4b. Scale rule = 1 m. A plan of the trackway shows a reconstruction of the possible trace-maker in two stages of its step cycle.

FIGURE 12—Trackway 2 of Figure 4b with non-digitiform footprints along a sloping bar surface of a proximal crevasse splay paleosurface. Knife-edged push-up ridges have been preserved on the downslope side of each print. Note the radiating pattern of sand-filled shrinkage cracks within the footprints suggesting that the surface was draped with mud before being imprinted and desiccated. Scale rule = 1 m.

these mudcracks protrude above the rilled surface indicating that after a short period of exposure, during which time the sun-baked rilled surface was trampled, the water level rose again and a cm-thick layer of fines was deposited on the surface. Subsequently the surface dried out completely causing desiccation cracks which penetrated into the underlying sand bar then became filled with eolian sand. The irregular topography of the footprints clearly affected the pattern of shrinkage cracks that developed in the clay veneer. Similar footprint-controlled desiccation crack patterns are described by Thulborn (1990). Some of the poorly defined non-digitiform footprints seen on these surfaces are, in fact, transmitted prints (Thulborn, 1990) of digitiform prints made in the overlying sediments. The transmitted or ghost prints are considerably larger than their surface prints and they commonly have smooth, unfissured raised rims with overhanging margins (Fig. 13).

One of the pools in Fig. 4b was skirted by three smaller quadrupedal animals (or the same animal on three occasions), leaving well-preserved toeprints with distinctive forwardly directed claw scrapes (trackway 3 of Fig. 4b and Fig. 14). The size, pace length and pace angulation of these tracks closely match those reconstructed from skeletons of the small, 50-cm-long, dicynodont *Diictodon.* Some of the manus prints display a slight inward curve indicative of some inward rotation of the planted foot suggesting an elbows-out gait. Many of the pes prints simply consist of a row of four small dimples left by the toes. In laboratory studies, Brand (1979) observed that similar toe-print dimples were made by salamanders walking on damp rather than wet sand. Toe prods and claw scrapes of similar style, described by Coombs (1980), are attributed to theropod dinosaurs walking in water deep enough to buoy the animal. The unusual claw scrapes, the lack of desiccation features and their association with the edge of a pool support the subaqueous origin for these tracks. Claw scrapes were made by both manus and pes and clearly indicate an outward swing of the foot as it was being raised from the substrate. This confirms that they carried the feet forward in a lateral arc, in the manner of a reptilian sprawling gait rather than the upright gait of mammals. Accepting that these are subaqueously imprinted *Diictodon* footprints, then the route around the edge of the pool was probably determined by the depth of water in the pool, which prevented the reptiles from taking a short-cut across the middle. This would indicate a maximum water depth above the tracks of 10–12 cm at the time of their formation.

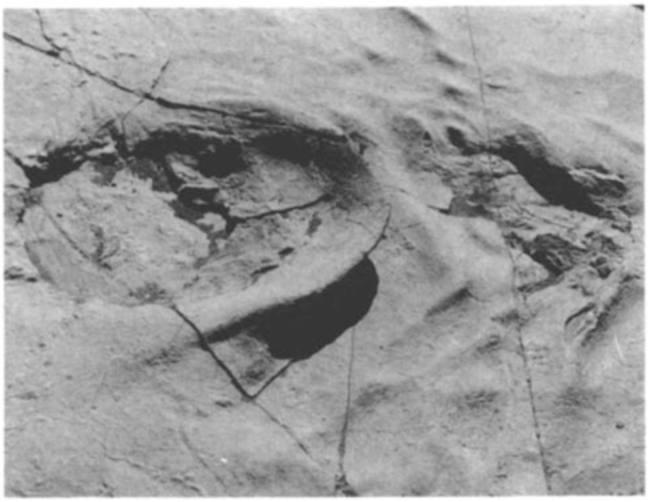

FIGURE 13—Transmitted prints or underprints of large non-digitiform footprints on the bottom of a pool on the Fraserburg paleosurface (see Fig. 4b). Note the overhanging tongue of sandstone that formed inside a push-up ridge as the foot was lifted from the substrate. Scale bar = 5 cm.

Large areas of poorly defined 'squelch marks' (Tucker and Burchette, 1977; Fig. 4b) that occur along the bar tops and interpool ridges on some Type 1 paleosurfaces are difficult to assign to specific tracemakers but judging from their size and depth they appear to have been made by dinocephalians or pareiasaurians walking on a saturated muddy-sand substrate. Figure 4b shows the distribution of vertebrate footprints on the mapped surface relative to

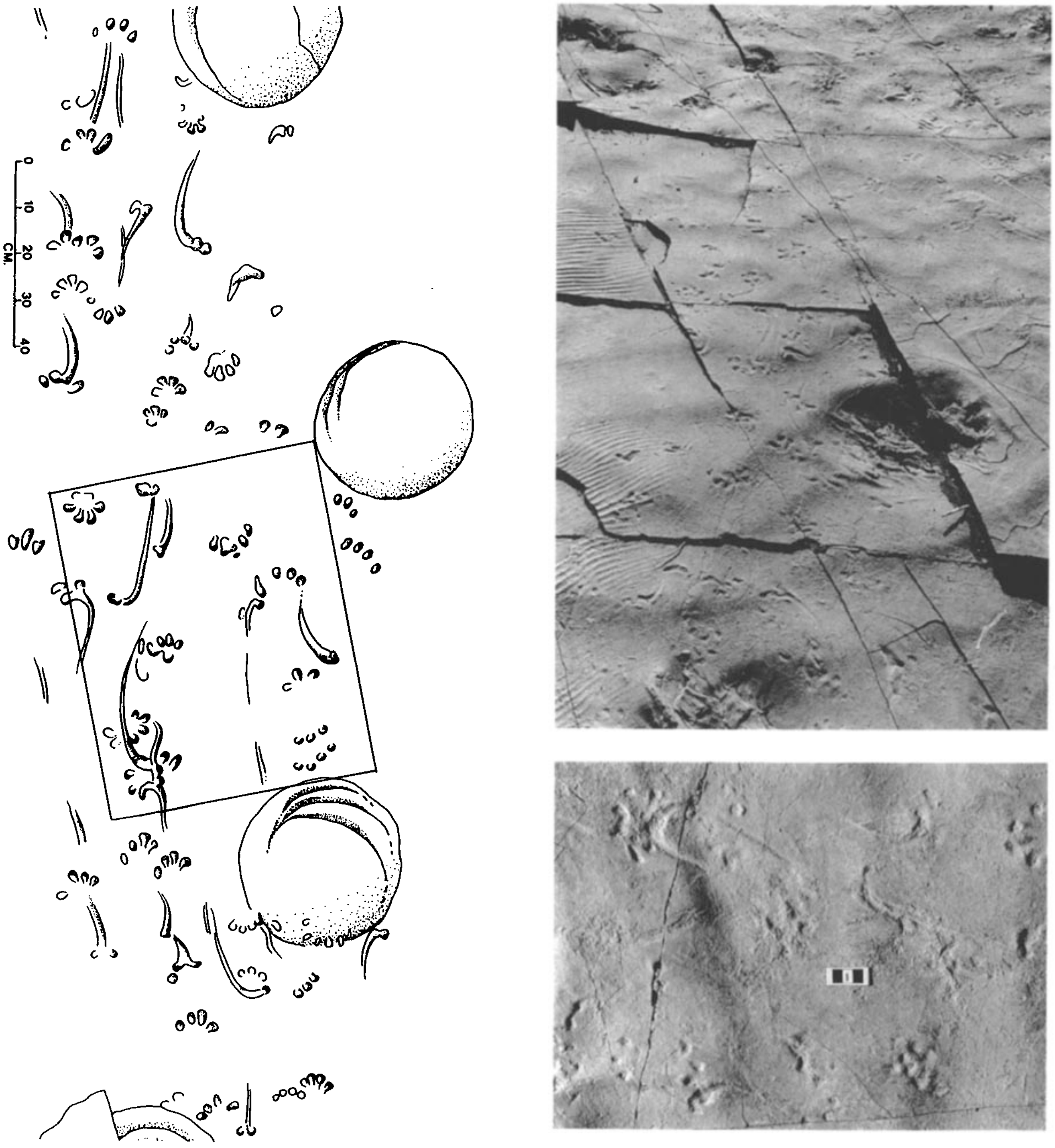

FIGURE 14—Field view and close-up of part of trackway 3 of Figure 4b comprising three small toe-prod trackways skirting the edge of a smooth-bottomed pool on a proximal crevasse splay paleosurface. A plan of this part of the trackway illustrates the arcuate claw scrapes that emanate from the anterior edge of toe prints on the ripple crests and taper in the direction of locomotion. These tracks were probably made subaqueously by *Diictodon*. The large circular depressions that disrupt the trackway are underprints of non-digitiform tracks on the overlying bed.

the pool and bar topography. There is no preferred direction of vertebrate movement although locally the topography and substrate consistency have influenced the routes as well as the preservation of tracks. Trackway 1 is a good example of the variations in print morphology that resulted from changes in slope and substrate consistency along a single trackway. Well-defined curved-toed prints are preserved as moulds in rippled sandstone on the flat-bottom of the first pool. On the up-slope, the metapodial prints are more prominent while a single print on top of

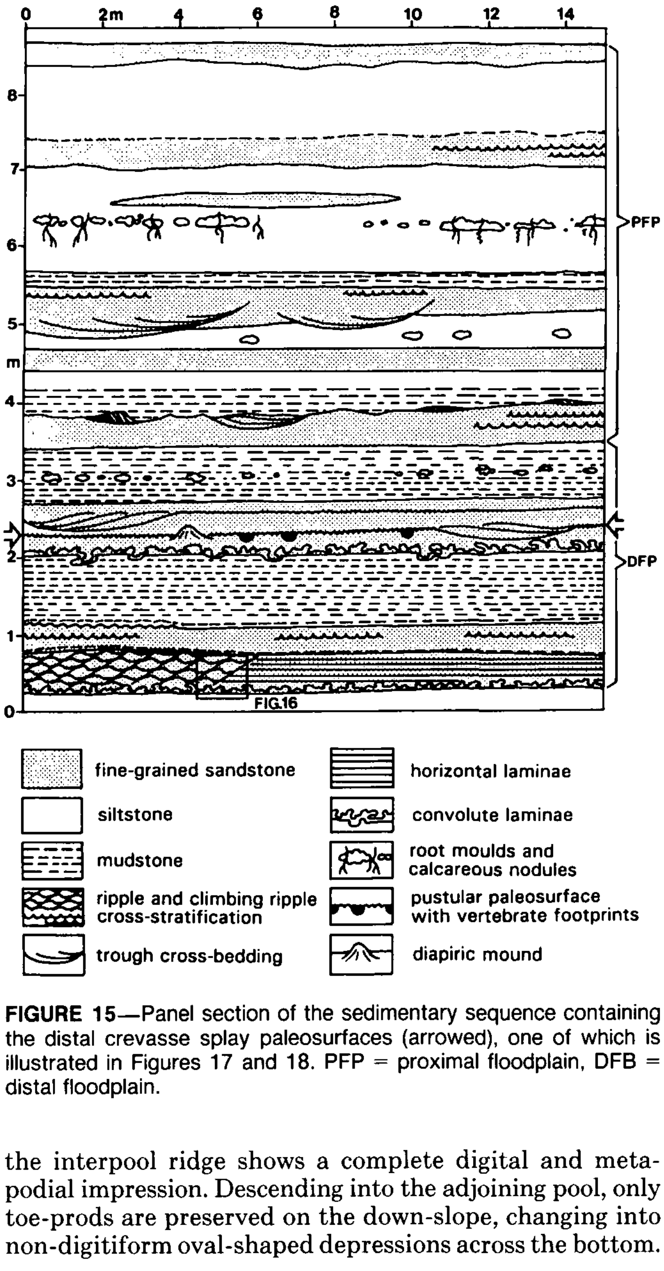

FIGURE 15—Panel section of the sedimentary sequence containing the distal crevasse splay paleosurfaces (arrowed), one of which is illustrated in Figures 17 and 18. PFP = proximal floodplain, DFB = distal floodplain.

the interpool ridge shows a complete digital and metapodial impression. Descending into the adjoining pool, only toe-prods are preserved on the down-slope, changing into non-digitiform oval-shaped depressions across the bottom.

PALEOSURFACE TYPE 2 (DISTAL CREVASSE SPLAY)

Sedimentology

Distal floodplain deposits comprise 0.5–5-m-thick sequences of thinly bedded sandstone/mudrock couplets interbedded with sharply bounded sandstones with paleosurfaces preserved on their upper contact. Within the interchannel or overbank strata, these sequences are most commonly encountered in the middle and upper parts of the section, bounded by proximal floodplain deposits (Figs. 3, 15). Type 2 paleosurfaces occur on the tops of thin, sharply-bounded, tabular fine-grained sandstone beds that commonly occur closely stacked on top of each other within the fissile dark green and grey siltstone (Fig. 15). The mudrocks are commonly overprinted with dark reddish brown mottles and contain horizons of calcretized desiccation cracks and fossil 'desert rose' gypsum crystals which are interpreted as distal floodplain hydromorphic paleosols (Smith, 1990). Therapsid body fossils are generally scarce in this facies, being mostly disarticulated post-cranial bones. The Type 2 paleosurfaces are generally flat and commonly have "pustular" or "woven" surface textures which are attributed to the growth of algal mats. Circular mounds of structureless fine-grained sandstone up to 1 m in diameter and 25 cm high with smooth surface textures are present on some of these surfaces. These are interpreted as diapiric mounds formed during dewatering of saturated muds below the sand bed.

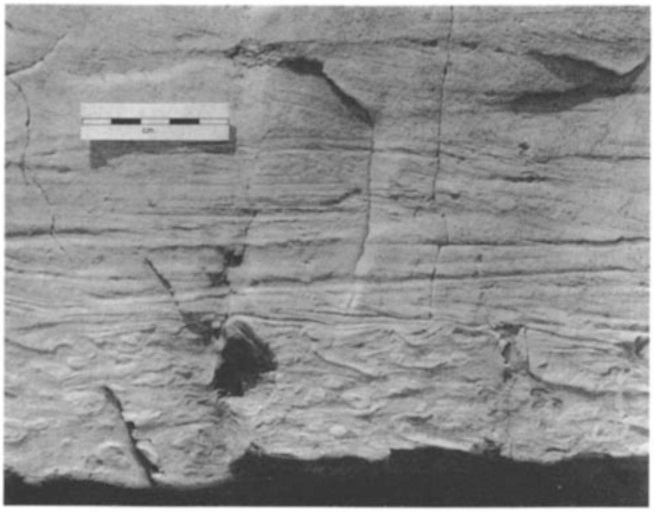

FIGURE 16—Vertical section of a distal crevasse splay sandstone showing a Bouma-like sequence of structures indicative of rapid deposition from unconfined sediment-laden flow. The convoluted bedding at the base may be caused by load-casting of ripples.

The tabular sandstones commonly display a 0.3–0.5 m vertical sequence of sedimentary structures that resembles a truncated Bouma sequence (Bouma, 1962) of turdidites (Fig. 16). The upward transitions are sharp flat base/ wavy lamination/ convoluted laminae caused by load casted ripples/ climbing ripple cross-laminae/ ripple cross-laminae/ mudstone veneered paleosurface. These structures are interpreted as having formed during a single flood event as sediment-laden floodwaters issued from the mouth of a floodplain distributary channel into an axial floodbasin lake. The presence of adhesion ripples, algal matted textures and vertebrate footprints on these sandstones suggests that they accumulated in a shallow water, marginal lacustrine setting on the surface of a distal crevasse splay fan (Lockley, 1986; Van Dijk et al., 1978). Vertical stacking of several of these distal crevasse splay sandstones, separated by thin veneers of clay-rich fines, is an indication of episodic surges in sediment supply; this is characteristic of ephemeral stream discharge in semi-arid terrains (Williams, 1971; Rust, 1981).

Discussion

The fissile green and dark grey mudstones that commonly overlie and preserve the Type 2 paleosurfaces are interpreted as clay-rich fines that were deposited from suspension during the period of lake high stand following a major flood. Most of the suspended fines entered the lake during overbank events; however, this would have been supplemented by local run-off from the lake margins during downpours as well as eolian influx. Rosette-shaped (Stear, 1978) and desert-rose-shaped (Keyser, 1966) quartz pseudomorphs after gypsum commonly occur in horizons in these mudstones. Recent studies of gypsum crystallization by Cody and Cody (1988) found such clusters to be formed only under high temperatures in the presence of organic colloids. Such conditions may be produced in marginal areas of a semi-arid floodplain lake that is periodically replenished by streams flowing off a well-vegetated meanderbelt ridge.

Hyperpycnal flows spread out across the distal crevasse splay lobes on the margins of a shallow freshwater lake and deposited sequences similar to those of unconfined turbidity currents (Mutti and Ricci Lucci, 1975). Diapiric mounds resulted from fluid escape through the saturated sand. The preservation potential of paleosurfaces on these sandstones was increased by the synchronous expansion of the lake margin as overbank flows discharged into the axial floodbasin lake. Consequently, as the lake waters deepened over the prograding distal crevasse splay lobes suspension fall-out resulted in the accumulation of a mud drape over the paleosurfaces.

Ichnology

Type 2 paleosurfaces are characteristically flat or gently hummocky with a pustular or matted surface texture (Fig. 17). The matted textures are imparted by the impressions of numerous randomly criss-crossing fibers. These are interpreted as having formed beneath *Spirogyra*-like algal mats. Unlike Type 1 paleosurfaces, these matted surfaces show no evidence of desiccation. They do, however, display a few well-preserved vertebrate trackways of the smaller, curved-toed *Diictodon* type (Fig. 18). These tracks were probably imprinted through a thin algal mat growing on the surface of a distal crevasse splay fan that was in very shallow water or temporarily exposed along the margin of a floodplain pond or lake. It may be significant that, to date, no tracks of the larger therapsids have been found on Type 2 paleosurfaces suggesting that this was not their preferred habitat. Rarely, Type 2 paleosurfaces are carpeted with the finely sculptured impressions of small (15–20 cm long) *Glossopteris* leaves. They are interpreted as a strand-line accumulation on the downwind margin of a pond or lake during autumnal leaf fall (Rayner, 1992).

To summarize, the distal crevasse splay paleosurfaces were deposited in the margins of axial floodplain playa-type lakes by episodic, flood-generated turbidity currents that interrupted the slow steady settling of suspension fines. Periodic shrinking and expansion of the lake margins allowed the algal-matted sand surfaces to be briefly exposed or at least covered by water depths shallow enough for *Diictodon* to wade through without drowning.

TYPE 3 PALEOSURFACES (UPPER POINT-BAR RIDGES AND SWALES)

Sedimentology

These surfaces occur within the complicated interdigitation of sandstone and mudrock that characterize the gradual vertical transition from upper point-bar deposits into inner-bank levee deposits (Smith, 1989; Fig. 19). The sequences consist of undulating beds of dark greenish grey siltstone interbedded with thin sheets of fine-grained, ripple cross-laminated sandstone which are commonly bedded at a high angle (up to 20°). These standstone sheets are the uppermost extension of lateral accretion units in the underlying point-bar sandstone (Smith, 1987) and are interpreted as the coarse member of upper point-bar accretion ridges and swales.

Mapping of an extensive planimetric exposure of an exhumed meanderbelt sandstone in the Lower Beaufort (Smith, 1987) showed that the eroded stubs of the accretion ridges were best preserved on the downstream portion of the 3-km-wide point bars where they tended to converge with each other. Unfortunately denudation has removed most of the paleosurfaces on these ridges, their destruction being facilitated by the fact that the thin sandstones dip gently (16–20°) toward the channel and are supported only by easily erodable mudrocks. However, nearby riverbed exposures show the complicated stratigraphic relationship of scroll bar paleosurfaces with the laterally equivalent fine-grained swale-fill deposits (Fig. 19). Here the flanks of three point-bar ridges display rippled surfaces. One of the swale floor surfaces displays numerous sand volcanoes of variable diameter but all of the same height (Fig. 20). The volcanoes have been gently scoured by a 1-cm-deep unidirectional sheet flow forming distinctive terracettes and tails of sand tapering downstream from each mound.

The convex upper surfaces of the scroll bar sandstones commonly display well preserved sinuous and straight-crested current ripples which in places have planed-off crests, double-crests and ladderbacked troughs. Current directions on any surface are relatively consistent but may differ as much as 90° from the underlying surface. Ripple crests tend to strike tangentially up the slope of the scroll bar but this too is highly variable. The uppermost convex surfaces of the scroll bar sandstone sheets are smooth and show emergence features such as run-off rills, wrinkle marks, desiccation cracks and rarely vertebrate tracks (Stear, 1980).

Surface markings of a scroll bar sandstone exposed in the Beaufort West townlands are shown in Figure 21. This 15-cm-thick sandstone is bedded at an angle of approximately 20° from horizontal and occurs within a sequence

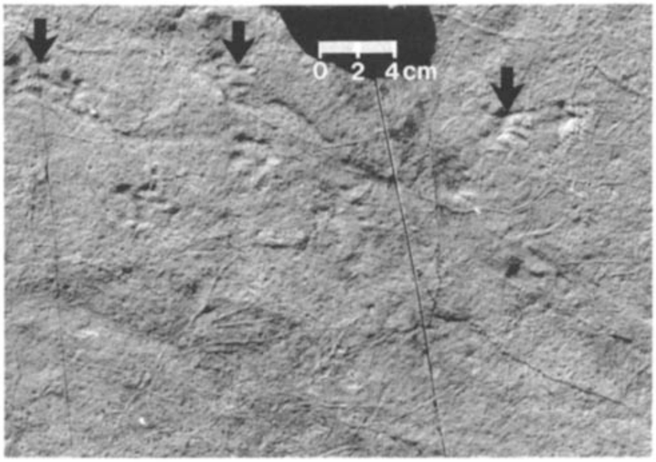

FIGURE 17—Distal crevasse splay paleosurface with filamentous matted texture interpreted as of algal origin. A trackway of small digitiform footprints (arrowed) was probably impressed through the algal mat.

of alternating sandstone and siltstone wedges about 70 cm above a 2-m-thick channel sandstone. The obliquity of the straight-crested current ripple crests on this surface confirms that this sandstone was deposited by unidirectional flow tangential to the curved linear axis of the bar. In several places the ripple crests have been cut, brushed and prodded (Fig. 22) most probably by floating plant debris (or possibly animal carcasses) to form a series of toolmarks, most of which are parallel to the primary flow direction. As flow waned the water level dropped, slowly at first, allowing a series of oscillation ripples to form at the water's edge with crests parallel to the strike of the scroll bar. As the water level dropped further, the primary ripple troughs became the favored path for expelled interstitial water to drain away. This resulted in a series of equally spaced dendritic rill networks in the troughs. At several points along each of the more obliquely orientated ripples, the run-off flow became strong enough to overtop the retaining ripple crest and continue down the adjacent trough (Fig. 23). The absence of desiccation cracks on this surface indicates that its emergence was relatively short-lived, possibly only a matter of days before another flood surge filled the adjacent swale trough with water again.

Discussion

Under a flash-flood hydrological regime, at peak discharge, sinuous dunes may become stranded in the upper mid-bar position (Jackson, 1976). During waning flood, the thalweg reverts back to its normal position on the outside of the meander leaving the stranded dune surface to be modified by the waning currents. The angle of obliquity (Edwards et al., 1983) of the scroll bar surface to the prevailing current determines the direction of the surface ripples. Modern studies show a tendency for the ripple trends on either side of point-bar ridges to converge on the downstream end (Jackson, 1976; Deitrich et al., 1979; Nanson, 1980). These have been termed "swept ripples" by Allen (1968). The paleosurfaces were probably preserved by upward and bankward building of the sandy point-bar ridges into the intervening slough during successive bankfull flows (Nanson, 1980).

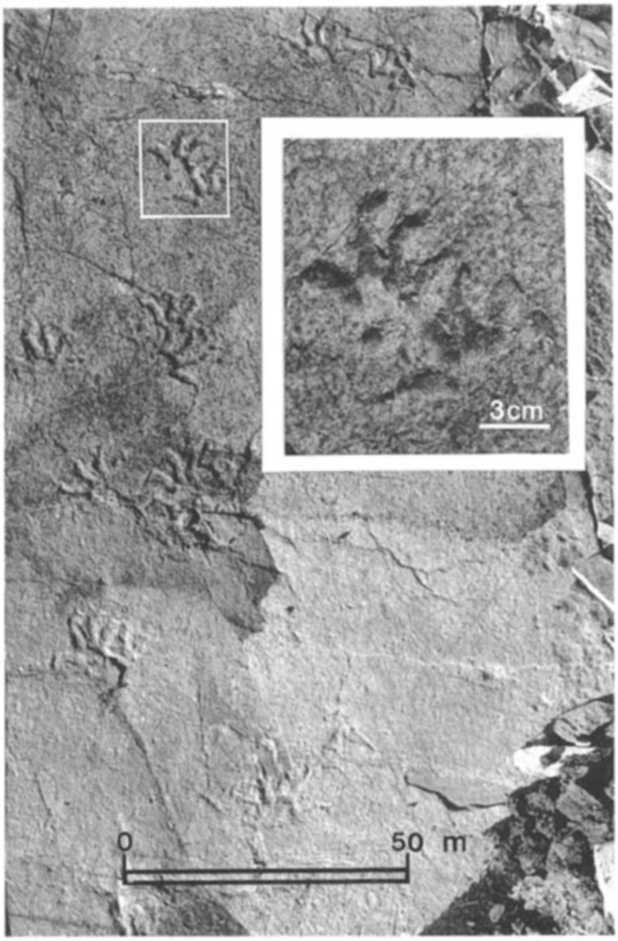

FIGURE 18—Vertebrate trackway interpreted as having been made by the small dicynodont *Diictodon* on the same distal crevasse splay surface as in Figure 17. Note the similarity of footprint shape and progression with the much larger dinocephalian trackway of Figure 11.

Fisk (1944) noted that floating plant debris was invariably trapped in the Mississippi River swales after major floods. The occurrence of tool marks on the scroll bar surfaces and sand volcanoes on the swale-fill paleosurfaces may reflect a similar setting. Floating plant material accumulated in the slack-water ditches and was buried by the bankward migration of the scroll bar. Gases produced as the plant matter decomposed within the bottom sediments escaped through the overlying waterlogged sand forming sand volcanoes on the surface.

Ichnology

Planolites is the most common trace fossil on the Type 3 paleosurfaces. These are straight to slightly sinuous elon-

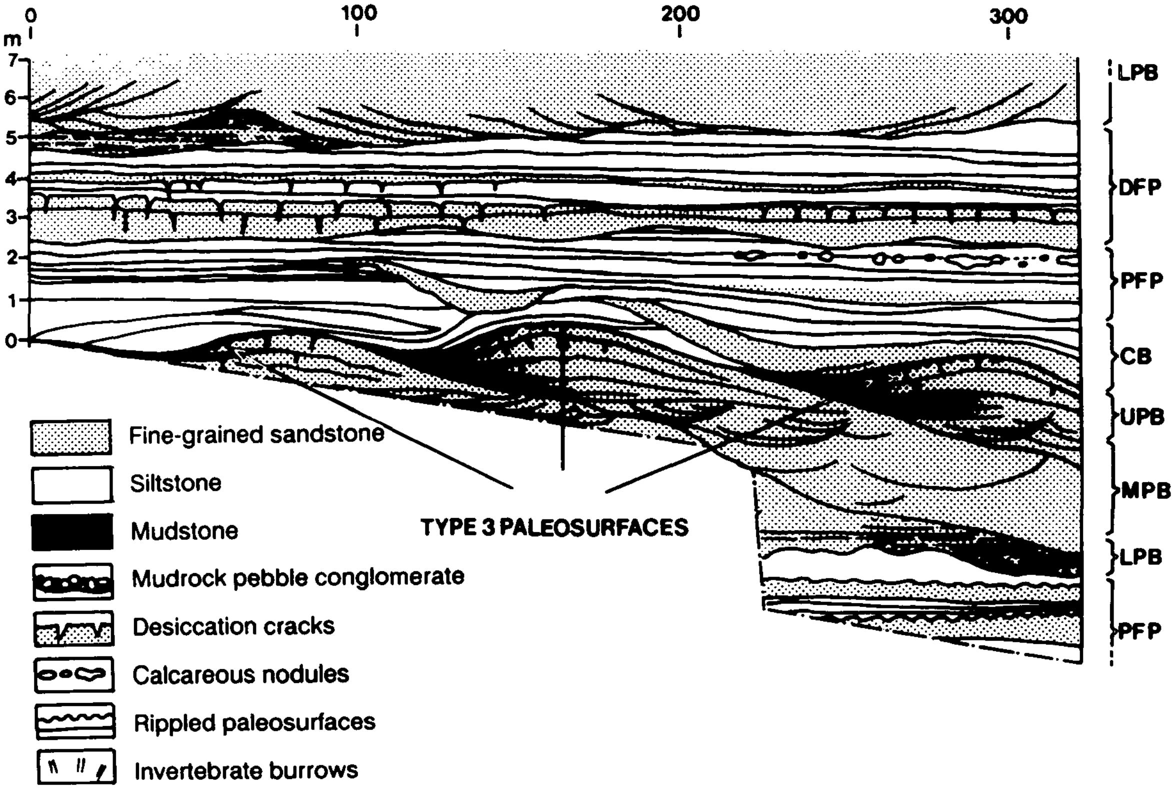

FIGURE 19—Field sketch showing the vertical transition of a single storied high sinuosity channel sandstone into the overlying floodplain sequences. Note the intricate interdigitation of the upper portion of lateral accretion units (UPB) with the inner bank levee deposits (CB). Type 3 paleosurfaces are preserved on the inner bank side of scroll bars and on the adjacent swale floor. LPB = lower point bar, MPB = middle point bar, UPB = upper point bar, CB = channel bank, PFP = proximal floodplain, DFB = distal floodplain.

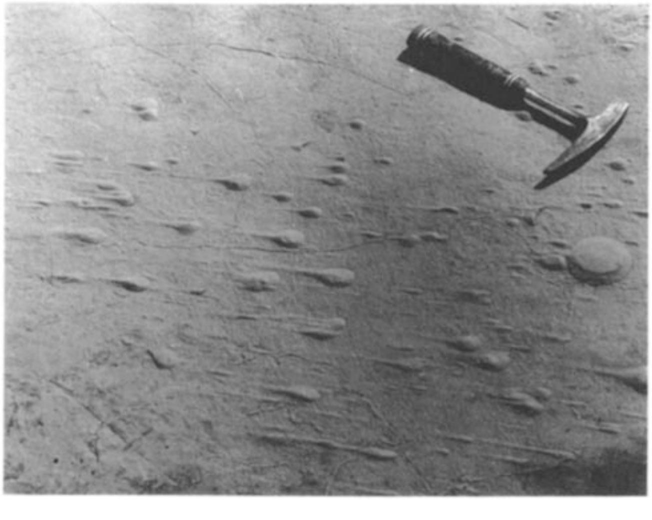

FIGURE 20—Sand volcanoes on a Type 3 paleosurface interpreted as having been deposited on the floor of a swale. Note the eroded teracettes and downstream 'tails' of sand indicating that a 1-cm-deep sheetflow occurred here after formation of the volcanoes and some of the invertebrate trails.

gate cylinders of 'clean' sand, penetrating the sandstone in all directions and interpreted as unlined burrows of a sediment-ingesting worm-like organism. On some of the rippled surfaces it is apparent that the *Planolites* organism preferentially followed the thickest mudstone veneer in the buried ripple troughs suggesting that the veneer was rich in organic fines. Sinuous *Undichnus* trails occur on the ripple crests (Fig. 23) probably made by the fins of palaeoniscid fish.

Unusual 'septate' trails or burrows traverse some of the rippled Type 3 paleosurfaces. These 2–3-m-long traces consist of a regular series of partially overlapping inclined crescent-shaped laminae, 6–9 cm wide, composed of a very fine-grained sandstone with slightly coarser interlayers (Fig. 24). The trace has no side burrows or 'arms' (Basan and Scott, 1979) which excludes it from the *Rhizocorallium* group in spite of its similarity in other respects. The trace may possibly be *Beaconites,* which has been described from Devonian strata in the Beacon Supergroup of Antarctica (Gevers et al., 1971) and from the Old Red Sandstone of Wales (Allen and Williams, 1981). It is tentatively attributed to a burrowing vertebrate and bears a striking resemblance to the surface expression of modern Golden Mole burrows in unconsolidated sands of the Namib Desert and the fossil mole burrows that have recently been

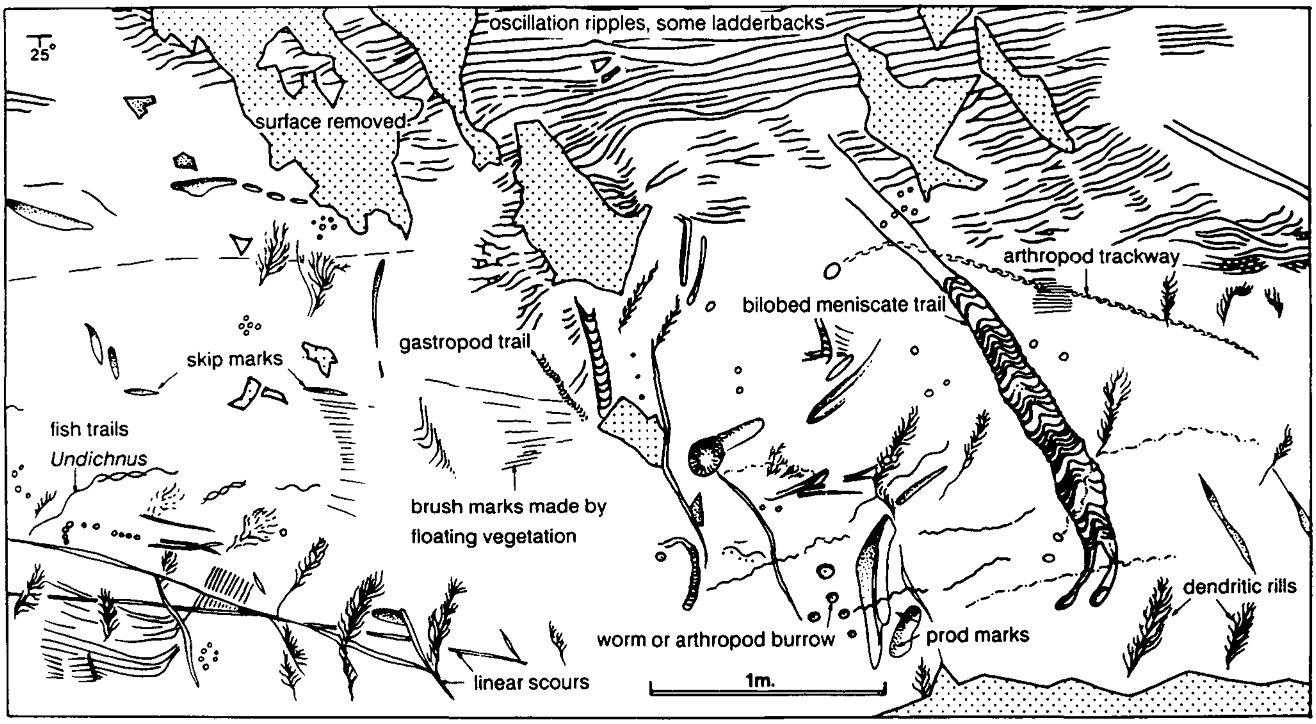

FIGURE 21—Detailed mapping of a Type 3 paleosurface on the Beaufort West townlands. The primary ripples have been ommitted but their trend may be inferred from the dendritic rills which follow the primary ripple troughs. The surface is bedded an angle of 25 degrees from horizontal sloping from top to bottom of the map.

described from Cretaceous sandstones of Namibia (Ward, 1984). It is possible that the septate traces on Type 3 paleosurfaces were made by mole-like vertebrates burrowing just beneath the surface.

Another unusual bilobed septate trail on the paleosurface in Figures 21 and 22 appears to have been made by a bilaterally symmetrical animal crawling or 'ploughing' up the bar surface. The lateral continuity between the overlapping lobes of sand across the medial high suggests that they were formed simultaneously possibly by the paired pectoral fins of a lungfish or by the *Beaconites* burrower on surface.

TIME CONSTRAINTS ON THE PRESERVATION OF PALEOSURFACES IN FLOODPLAIN DEPOSITS

The three types of paleosurface recorded in the Lower Beaufort floodplain deposits have a number of similarities in their mode of sedimentation and burial; these are:

1. Episodic and rapid sedimentation of fine-grained sand under fluctuating flow conditions.
2. Bedload sedimentation terminated under rapidly decelerating flow during which sand surfaces were sealed by claystone veneer.
3. Emergence and drying out of part or all of the surface.
4. Sun baking of veneer and development of shrinkage cracks.

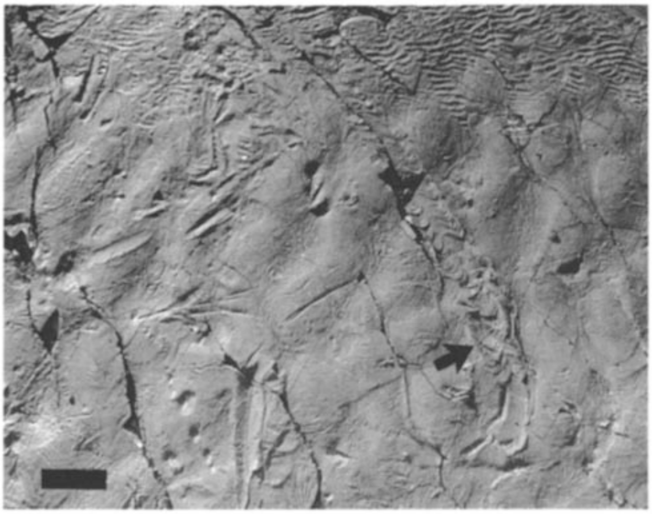

FIGURE 22—Part of the scroll bar paleosurface on the Beaufort West townlands (see Fig. 21) showing tool-marked primary ripples with dendritic rills in the troughs. An unusual bilobed septate trail (arrowed) climbs up the slope towards the oscillation ripples at the top of the scroll bar. Scale bar = 25 cm.

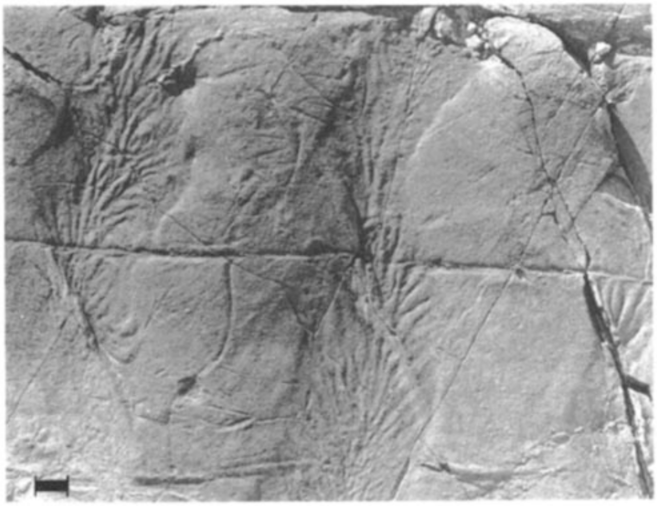

FIGURE 23—Clse up of run-off rills on a scroll bar paleosurface. The rills are eroded into the primary ripple troughs. As the rills coalesced, the resultant scour built small sand bars that caused the flow to overtop the ripple crest. The linear groove that bisects the rills is interpreted as a tool mark made by floating vegetation during a subsequent flood. The sinuous groove is interpreted as a fish trail (*Undichnus*). Scale bar = 2 cm.

5. Burial soon after emergence beneath a similar sequence of flood deposits or, more commonly, beneath clay-rich, lacustrine or palustrine deposits.

The duration of sub-aerial exposure is critical in this sequence of events. After a period of desiccation the veneered surfaces begin to break up due to the compounded effects of trampling, shrinkage cracking and wind deflation. Observations of flash-flood deposits in the bed of the arid-zone Kuiseb River in Namibia are useful in putting some time constraints on the emergence sequences recorded on the Lower Beaufort paleosurfaces. The climates are not considered to be closely analogous in that the present-day central Namib is hot and hyperarid as opposed to the warm semi-arid conditions interpreted for the Lower Beaufort. However because both are distal mixed-load fluvial systems which are sourced in a wetter climatic region and flow into a comparatively drier region, there are similarities in the discharge patterns and floodplain hydrodynamics.

During waning flood the entire sand bed of the Kuiseb River is draped with a uniform 0.01–0.05-m-thick layer of silt (Ward, 1987). The low stage flow bedforms are very similar to those of Type 1 paleosurfaces. They consist of linguoid rippled channels, interference rippled pools and smooth-topped longitudinal bars, all draped with silt. Within 24 hours after the bar tops are exposed, the silt drape becomes hardened. At this stage the bar tops are already subjected to trampling because they provide a preferential route for animals crossing the river. The pools, however, take up to 2 months to lose their water, mainly through evaporation, during which time a mm-thick clay veneer is deposited on the silt drape on the bottoms of the pools. Concentrically disposed falling water-level marks, identical to those of the Type 1 paleosurfaces, are a ubiquitous feature on the upper side walls of the pools.

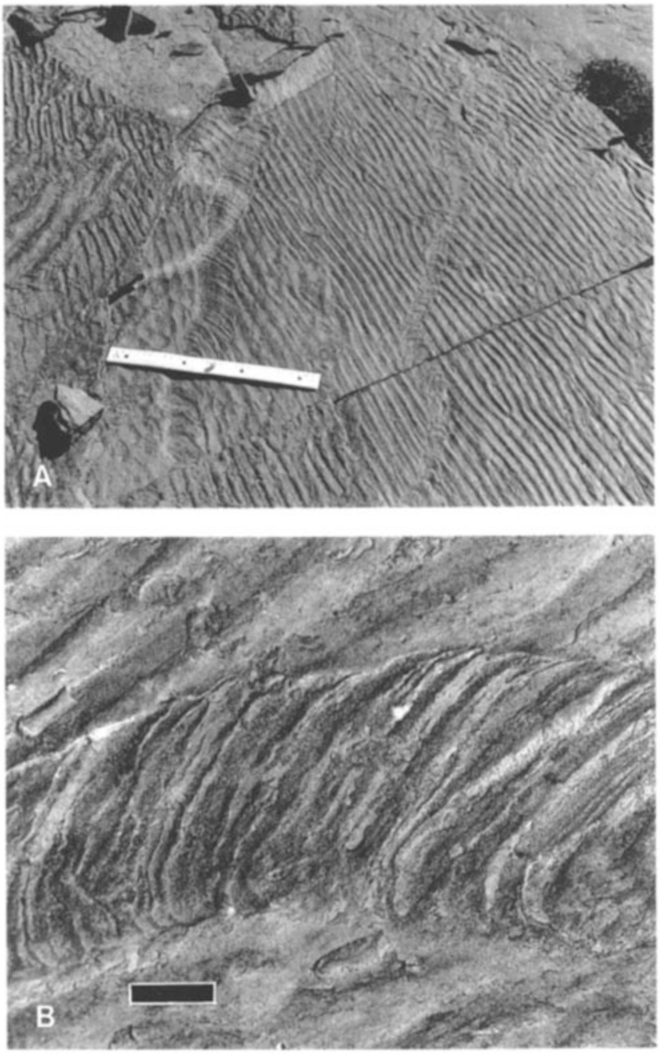

FIGURE 24—(**a**) Two 'septate' trails or burrows of *Beaconites* type on an oscillation rippled Type 3 paleosurface (Scale rule = 30 cm), (**b**) Close-up of one of the *Beaconites* 'septate' traces showing the overlapping lobes of sandstone indicating movement of the trace maker from left to right (Scale bar = 2 cm).

About 2–3 days after emergence of the bar tops a polygonal network of small-scale shrinkage cracks begins to form in the silt drape. As the sand bar continues to dry out many of them become wider and deeper and form a much larger superimposed polygonal pattern. When the bottom sediments of the pools begin to dry out the muddy veneer rapidly shrinks, cracks and curls-up into small cylinders. A week later large arcuate mudcracks open up on the deepest part of the depression gradually narrowing towards the sides. During the following dry season these mudcracks become filled with windblown mud curls and eolian sand. The distribution, planimetric shapes and infill of desiccation cracks in the Kuiseb River bed are very similar to those on Type 1 paleosurfaces in the Lower Beaufort (having ignored those that were superimposed after burial).

It is therefore possible to interpret minimum periods of sub-aerial exposure from the distribution of mudcracks on the Type 1 paleosurfaces (Fig. 3). This would be in the order of 2–3 days for the bar tops and 0–7 days for bottoms of deeper pools. From the degree of trampling, the maximum duration of subaerial exposure is estimated to be 1–2 months. Perhaps more significant are the smooth-bottomed pools that display run-off rills but no shrinkage cracks. Having lost their standing water, the bottom sediments must have retained sufficient moisture to prevent shrinkage. This suggests that the deeper pools intersected a perched water table which was about 1 m below the bar tops and for a few months they would have provided a convenient source of drinking water. This may account for the high degree of trampling along the bar tops.

SUMMARY

Sandstone paleosurfaces in the fluvio-lacustrine Beaufort Group strata of the southwestern Karoo Basin represent small remnants of the ancient landscape surface. They display an array of sedimentary structures and trace fossils that record details of the paleoenvironments and biological activity in different parts of the floodplains. Three different types of paleosurface, informally labelled Types 1, 2, and 3, are interpreted as having formed on proximal crevasse splay sand sheet, distal crevasse splay lobes, and upper point-bar ridges respectively. The diagnostic sedimentary structures and trace fossil assemblages of each paleosurface type are summarized in Table 1.

The formation of paleosurfaces in the Beaufort rocks was mainly controlled by the pulsatory discharge of large Mississippi-sized meandering rivers that flowed into the subsiding foreland trough from the southern Gondwanide mountains (Du Toit, 1954). During peak floods the channel banks were breached and overtopped causing sandy bedload to be transported onto the flanking floodplains. Much of this sand was rapidly deposited in the proximal floodplain on crevasse splay lobes. Short periods of emergence allowed the damp sand surface to become sculptured by run-off rills and the biological activity of terrestrial organisms. Preservation of the delicate traces was enhanced by a silty-clay veneer that accumulated on the sand surface during waning flood. Burial of the sculptured surfaces beneath a layer of fines most commonly occurred in parts of the floodplain that frequently contained ponded water. Consequently the distribution of preserved paleosurfaces in the Beaufort fluvial strata reflects those fairly restricted areas of the ancient floodplains where episodic floods transported sand into or alongside a standing water body. These were most commonly in crevasse splay channels, on the surfaces of distal crevasse splay lobes prograding into margins of distal floodplain lakes, and within ridge and swale topography on the downstream portion of point-bars.

TABLE 1—Summary of the sedimentology and ichnology of floodplain paleosurfaces in the Lower Beaufort.

Paleosurface:	Type 1	Type 2	Type 3
Interpreted depositional environment:	Proximal crevasse splay	Distal crevasse splay	Upper point bar
Sedimentary sequence	tabular sheet sandstone within pedogenically modified siltstone	stacked tabular sheet sandstones showing "Bouma" sequences	sandstone wedges bedded at high angle on top of high sinuosity channel sandstones
Original substrate	fine-grained sand	fine-grained sand	fine-grained sand
Surface topography	wide shallow channels and elongate erosively-bound bars	flat surfaces with isolated diapiric mounds	arcuate scroll bar surfaces dipping up to 20° towards the paleochannel
Tool marks	rare	absent	common
Rill marks	common	rare	common
Current ripples	common	rare	common
Oscillation ripples	common	rare	common
Linguoid ripples	common	absent	absent
Pustular ?algal mats	absent	common	absent
Falling water level marks	common	rare	common
Desiccation cracks	common	rare	absent
Arthropod tracks	common	rare	rare
Septate trails	rare	absent	common
Fish trails	common	rare	common
Beaded trails	common	rare	absent
Digitiform footprints	common	rare	rare
Non-digitiform footprints	common	rare	rare
Trampled areas	common	absent	absent

The trace fossil assemblages on each type of paleosurface show some ichnofossils that are specific to those surfaces. The substrates of all three paleosurfaces are essentially the same being fine-grained sandstone with a thin veneer of mudrock. It is possible therefore that the following ichnotaxa may be useful paleoenvironmental indicators—(1) Arthropod trackways (*Umfolozia* sp.) are associated with proximal crevasse splay sands, (2) algal-matted textures are most commonly found on distal crevasse splay paleosurfaces and (3) large septate trails (*Beaconites* sp.), possibly of burrowing or crawling vertebrates, are restricted to paleosurfaces on the point-bar ridges.

Type 1 paleosurfaces in the Beaufort Group are similar to stream bed surfaces in modern flash-flood deposits in the Kuiseb River, Namibia. Observations of the time that elapsed before shrinkage cracks developed in the mud-draped sand on the modern river bed are useful in putting some time constraints on the ancient surfaces. It is concluded that the mudcracked bar tops of Type 1 paleosurfaces were exposed for more than 2–3 days, and up to a maximum of 2 months. The pools retained water for most of this time and remained damp even after the water had drained. It is likely, therefore, that the pools were used as watering holes by the resident therapsid fauna resulting in excessive trampling of the bar tops and pool margins.

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