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LATERAL-ACCRETION DEPOSITION IN BRAIDED FLUVIAL SYSTEMS: A CASE-STUDY FROM THE KAROO SEQUENCE, SOUTH AFRICA

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by

A.B. CADLE[1] and B. CAIRNCROSS[2]
([1]Department of Geology, University of the Witwatersrand,
Private Bag 3, WITS 2050, South Africa.
[2]Department of Geology, Rand Afrikaans University,
P.O. Box 524, Auckland Park 2006, South Africa)

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ABSTRACT

A Lower Permian fluvial channel sandstone has been studied from the Karoo Sequence, South Africa. Drill hole core data supplemented by studies of the vertical and lateral facies associations obtained from outcrop have delineated the channel geometry and channel-fill associations.

The channel has an average width of between 2 and 5km, a width to depth ratio of $\pm$ 420 and can be traced in the subsurface for 60km. Vertical profiles of channel-fill associations were defined and these include:

1. large-scale fining-upward sequences;

2. large-scale coarsening-upward sequences; and

3. a fining-/coarsening-upward sequence.

The dominant sedimentary structure of these sequences is tabular cross-stratification. The analysis of photomosaics of the channel sandstone revealed the existence of channel-fill sequences comprising a second-order scour surface overlain by large-scale tabular cross-stratification and compound cross-stratification. The upper parts of the channel-fill sequences are structured by small-scale tabular cross-stratified sets.

The channel-fill sequences represent the deposition of a sandy, bed-load dominated/braided fluvial system. Palaeocurrent data derived from the sedimentary structures show a transport direction to the southwest which is oblique to the south-southwest trend of channel geometry. A conceptual model of channel-fill sedimentation and progressive lateral migration of the fluvial system in a westerly direction is presented. The migration of dunes and sand waves over braid and compound bars in an oblique downstream direction permits formation of large-scale tabular and compound cross-stratification on the side and downstream ends of these bars. The lateral migration of first-order channels in a westerly direction causes the development of new compound bars lateral to, and downstream of, earlier formed compound bars. With continued lateral migration of the first-order channel, abandonment of both the trailing second-order channel and initially formed compound bar takes place. In this model, lateral accretion deposits, formed from the oblique downstream migration of compound bars, are preferentially preserved in the rock record.

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CONTENTS

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INTRODUCTION

The Permian coal deposits of the Karoo Sequence in the southeastern Transvaal Province of the Republic of South Africa (Fig. 1, inset B), have been the subject of several sedimentologically based investigations (see Cadle *et al.*, in press and Cairncross, 1989 for reviews). Most of these investigations have focussed on subsurface facies analysis using diamond drill hole core and records. Several widespread facies types have been documented and the spatial and three-dimensional relationships of facies associations have been used to interpret environments of deposition of the coal and associated clastic strata. Le Blanc Smith (1980), Cairncross (1979, 1986), Winter (1985), and Stavrakis (1989) are some of the workers who have collectively used several thousand borehole records to formulate these palaeoenvironmental models. These facies models constitute an overall fluviodeltaic depositional setting for the coal-bearing Vryheid Formation in the Witbank Coalfield (Fig. 1, inset B). Refinement of this model has led to the recognition of additional subenvironments including back-barrier settings (Winter, 1985) and glacigenic deposits (varved shales, glaciolacustrine and glaciodeltaic sediments), particularly in the lower portion of the sequence (Le Blanc Smith and Eriksson, 1979).

Fluvial depositional palaeoenvironments have featured prominently in all of the models. The predominant fluvial deposystem was one dominated by bed-load transport of medium to coarse sand, and granule-grade gravel with minor amounts of coarser, pebbly gravel. These braided/bed-load channel systems are particularly common below the No. 1 coal seam and above the No. 3 and No. 4 coal seams (Fig. 2). These channels have been defined and delineated from isopach maps and subsurface cross-sections of the sandy facies. Mapping of the thicker (>5 m) sandstone bodies has revealed relatively unconfined (2-5 km wide) linear to sublinear (low-sinuosity) sand tracts which are dip oriented and which define major loci of coarse clastic sediment transport and deposition within palaeochannels. Comparisons with existing river systems and facies models (for example, Coleman, 1969; Collinson, 1970; Smith, 1970, 1971; Miall, 1977) led to the conclusion that the palaeochannel systems are almost exclusively braided and, using vertical facies assemblages as comparison, resemble most closely the "Platte-type" model described by Miall (1977, 1978).

Jackson (1978) and Miall (1985) have questioned the validity of fluvial facies models, in particular the "braided/meandering" end-member concept. This criticism is relevant when the models are applied to ancient fluvial deposits, particularly if drill holes are widely spaced and/or outcrop is not continuous and does not facilitate detailed lateral facies correlation. If the required three-dimensional delineation of channels cannot be achieved, then Miall (1985) states that "vertical profile analysis is of limited use in interpreting channel morphology". The diverse in-channel behaviour of sediment movement within a single channel system blurs the braided/meandering classification and this has been noted by Jackson (1978) and Allen (1983). Bristow (1987) has documented braided, meandering and anastomosing channel morphologies in the braided reach of the Brahmaputra River which illustrate the complexity of interpreting fluvial systems in the rock record. For some time, the authors have suspected that drill hole core was not revealing large-scale sedimentary structures which should have been present within the large (5 km wide) palaeochannels that have been defined from the

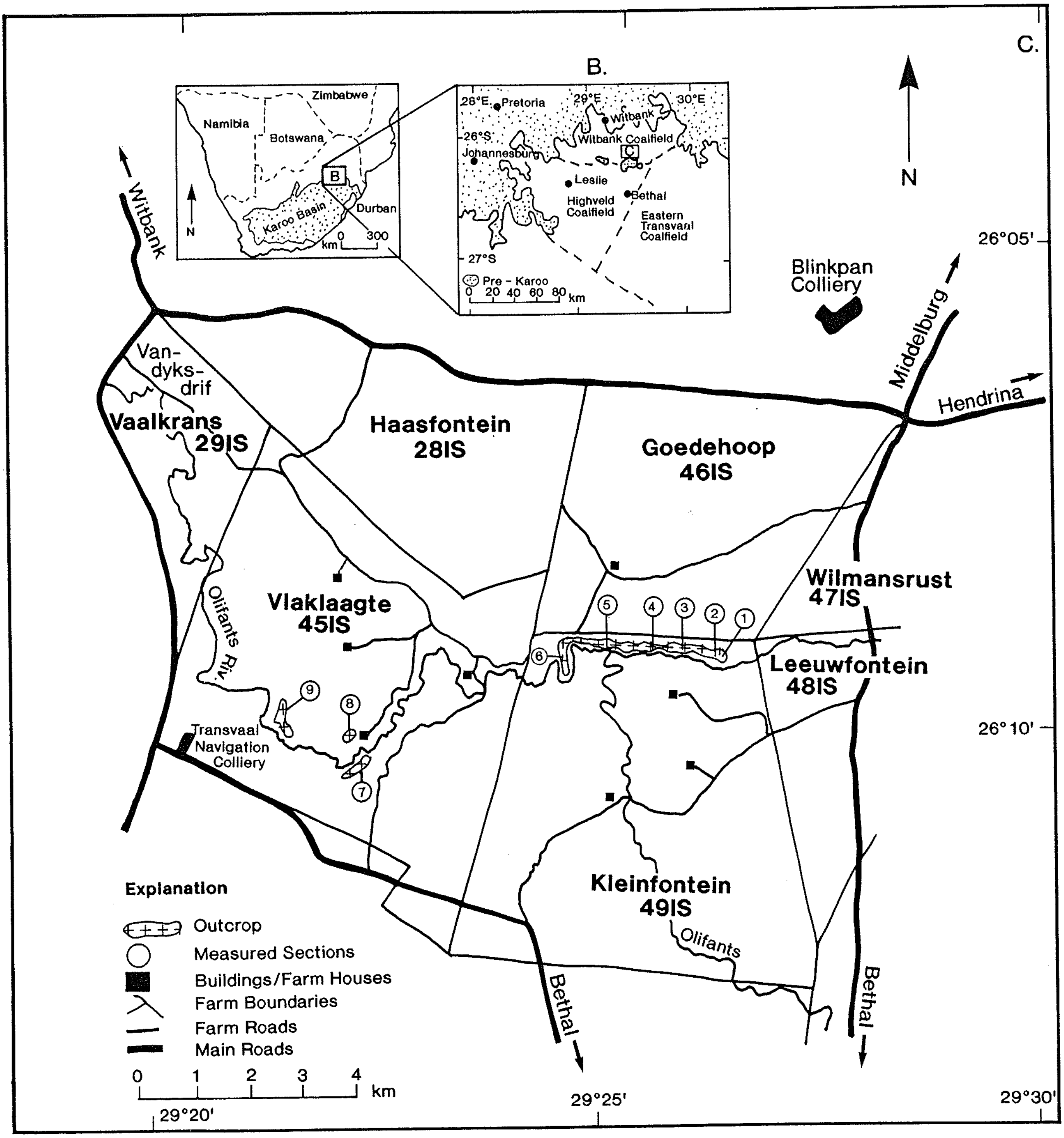

Figure 1: Locality of the study area, Karoo Sequence, South Africa. Sections 1-9 represent the positions of measured vertical profiles.

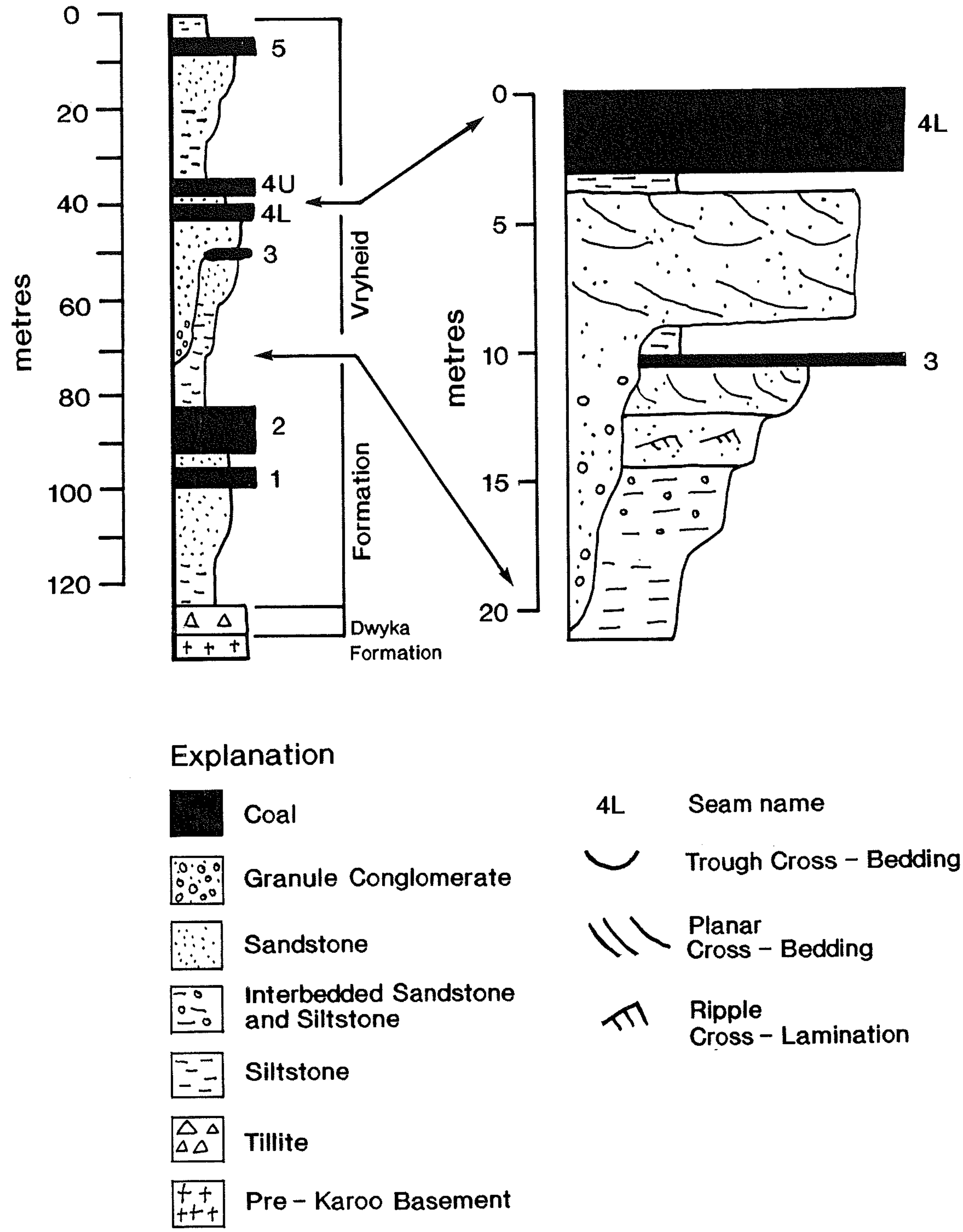

Figure 2: Stratigraphic column of the Dwyka and Vryheid Formations illustrating the stratigraphic relationship of the channel sandstone studied. Note the incision of the channel into the underlying deltaic sedimentary sequence present between the No. 2 and No. 3 coal seams.

Witbank Coalfield. Similarly, a hierarchy of channels and bedforms (e.g., Allen, 1983) could also not be observed, reinforcing Miall's (1985) criticism of vertical facies analysis. The presence of large-scale, "giant cross-beds" (sets up to 500 m long and 20 m thick) were documented from the deltaic component above the No. 4 coal seam (Fig. 2) only once these became visible from large opencast coal mine high-wall exposures (Cairncross and Winter, 1984) although these deltaic deposits had previously been interpreted from their three-dimensional subsurface geometry. The writers therefore searched for, and found, excellent outcrop of one of the "braided" channels described by Le Blanc Smith (1980) and Winter (1985) from their subsurface data. This outcrop is located 35 km southeast of Witbank on the farms Kleinfontein and Vlaklaagte where the Olifants River has eroded through the succession (Fig. 1C). A relatively continuous outcrop of the sandstone between the No. 3 and No. 4 coal seam (Fig. 2) is preserved at this locality. This exposure was used to measure detailed vertical sections and these data were then combined with those previously obtained from drill holes and mine exposures. More importantly, the lateral extent and distribution of sedimentary structures has for the first time been recorded in detail. These data are collectively presented in this paper in support of a braided/bed-load, low-sinuosity palaeochannel associated with the coal seams in this region.

STRATIGRAPHY

The coal seams and associated clastic sedimentary strata of the Witbank Coalfield are Lower Permian in age and most likely fall within the Artinskian-Kungarian (Langford *et al.*, 1991). In the present study area, the entire coal-bearing sequence attains a maximum thickness of 200m (Le Blanc Smith, 1980) and consists of 5 coal seams interbedded with mudstone, siltstone, sandstone and minor amounts of thin conglomerate. Reworked glacial tillite and other glacigenic material is present below the lowermost coal seam and these sediments attest to the existence of the widespread Late Carboniferous glaciation which preceded the coal-forming period.

The detailed stratigraphy of the study site is shown in Figure 2. The strata below the No. 3 coal seam consist of an upward-coarsening grain-size succession consisting of siltstone, gradationally overlain by interlaminated siltstone and fine-grained sandstone. This, in turn, is overlain by fine-grained cross-laminated sandstone followed by planar and trough cross-bedded medium-grained sandstone capped by the thin (<50 cm) No. 3 coal seam. This sequence has been interpreted as representing a prograding deltaic succession which subsequently became abandoned and overlain by peat which constitutes the No. 3 coal seam (Le Blanc Smith, 1980; Winter, 1985). Between the No. 3 and No. 4 seams, an arkosic medium- to coarse-grained sandstone and granule-grade conglomerate is present (Fig. 2) and this sandbody is the focus of attention for this paper. In one opencast coal mine in the coalfields, this sandstone body is seen to incise through the underlying No. 3 seam and into the strata below and may rest close to or directly on the roof of the No. 2 coal seam. On the basis of subsurface facies analysis, vertical-profile measurement (borehole core) and three-dimensional reconstruction, this sandstone is interpreted as a braided/bed-load channel system. However, the detailed internal sedimentary structures and hierarchical relationship of bedding surfaces and bedforms has never been described in detail. The channel system is known to originate to the north of the study area (Fig. 3) and its confinement to the interval between the No. 3 and No. 4 seam is clearly established from borehole cross-

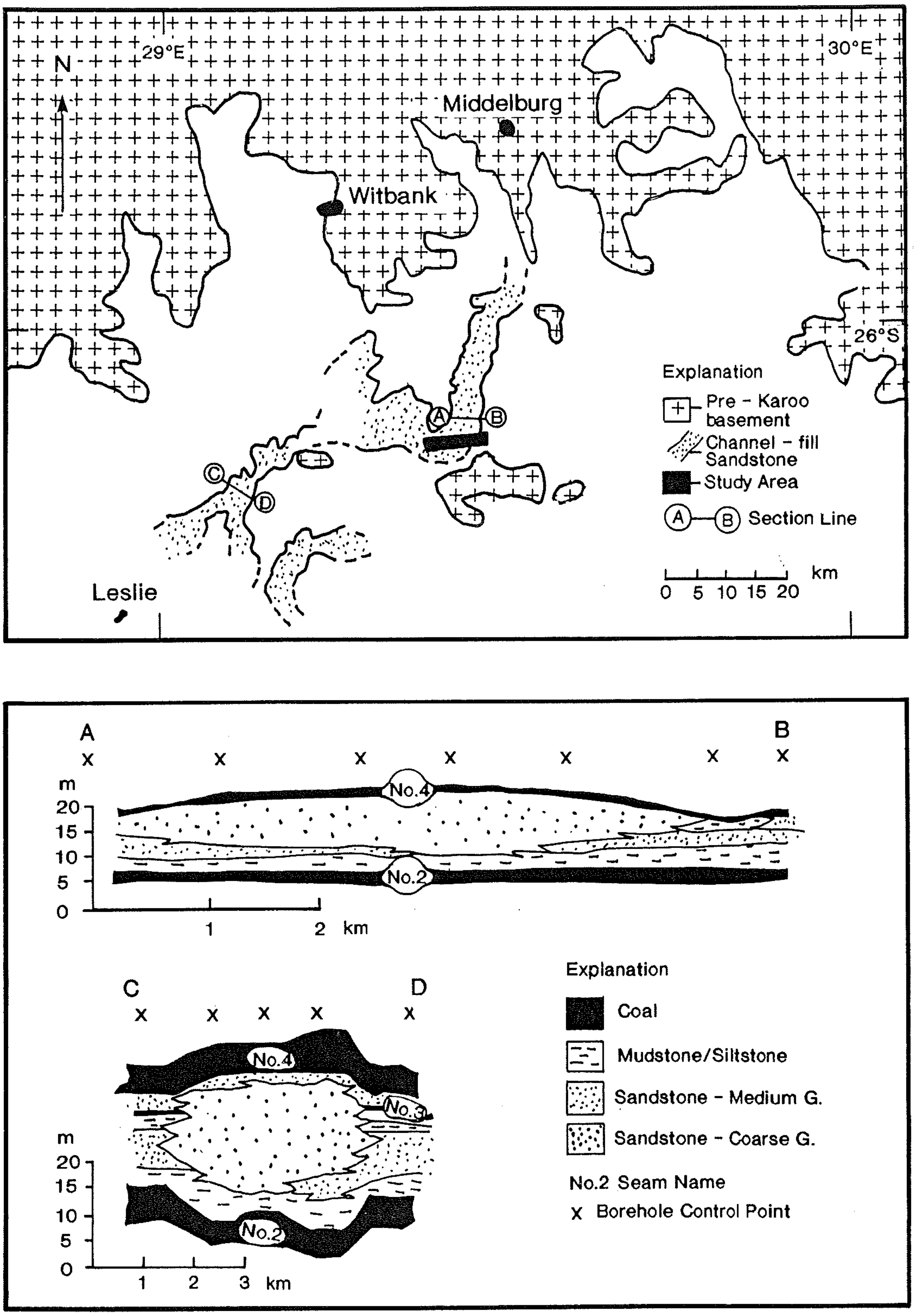

Figure 3: Position of the channel sandstone as mapped out from drill hole data. Channel width averages between 2-5km and minimum channel length is in the order of 60km. Sections A-B and C-D are shown in the lower illustration.

sections (Fig. 3).

SANDBODY GEOMETRY

The No. 3 to No. 4 seam channel-sandstone sequence has a linear to sublinear geometry which is traced in the subsurface over tens of kilometres. Subsurface drilling to assess the economic potential of the No. 2 and No. 4 coal seams have provided data for the delineation of the channel geometry as shown in Figure 3. The channel is traced for 60km in the subsurface from the present edge of the basin margin in a basinward direction. The width of the channel sandstone varies between 1-12km and over much its length averages between 2-5km. Cross-sections through the channel illustrate a lenticular geometry with the channel displaying thicknesses ranging between 12m to 22m. Although the channel orientation can swing through 90° (Fig. 3) due to deflections away from Pre-Karoo basement highs, the channel displays a linear geometry. The fact that the channel width to depth ratio varies between 40 and 1000 and is commonly $\pm$ 420 implies that in cross-section the sandstone has a sheet-like geometry. The base of the channel, where documented from field exposures, is to flat convex-down over short distances. Where the base of the channel is convex-down, up to 2m of underlying lithologies are removed. Where the channel base is relatively flat, local scours 50cm deep by 50cm wide are present and erode into underlying lithologies. Borehole intersections show that the channel sandstone can locally scour and remove up to 20m of lithologies below the No. 3 coal seam (Figs. 2 and 3). Thinning of the No. 4 coal seam over the channel apex may imply that the top of the channel sandstone had a slightly convex upward profile at the time of deposition (Le Blanc Smith, 1980; Winter, 1985).

VERTICAL PROFILE CHANNEL-FILL ASSOCIATIONS

The measurement of detailed vertical profiles through the exposed channel sandstone over a distance of 9km, has led to the recognition of a number of channel-fill associations (Fig. 1). Due to present-day erosion, the uppermost 3-5m of the channel sandstone is removed. Consequently, this part of the channel sequence was not described. Data obtained from nine profiles are synthesised into three channel-fill associations based upon the overall grain-size motif:

1. large-scale fining-upward sequences, comprising between two and four vertically stacked fining-upward sequences;

2. large-scale coarsening-upward sequences, comprising between two and four vertically stacked fining-upward sequences; and

3. a sequence which first fines then coarsens upward. The sequence comprises a small-scale fining-upward sequence overlain by lithologies that coarsen-upward in grain-size.

These three channel-fill associations and their respective types of channel fill are described below.

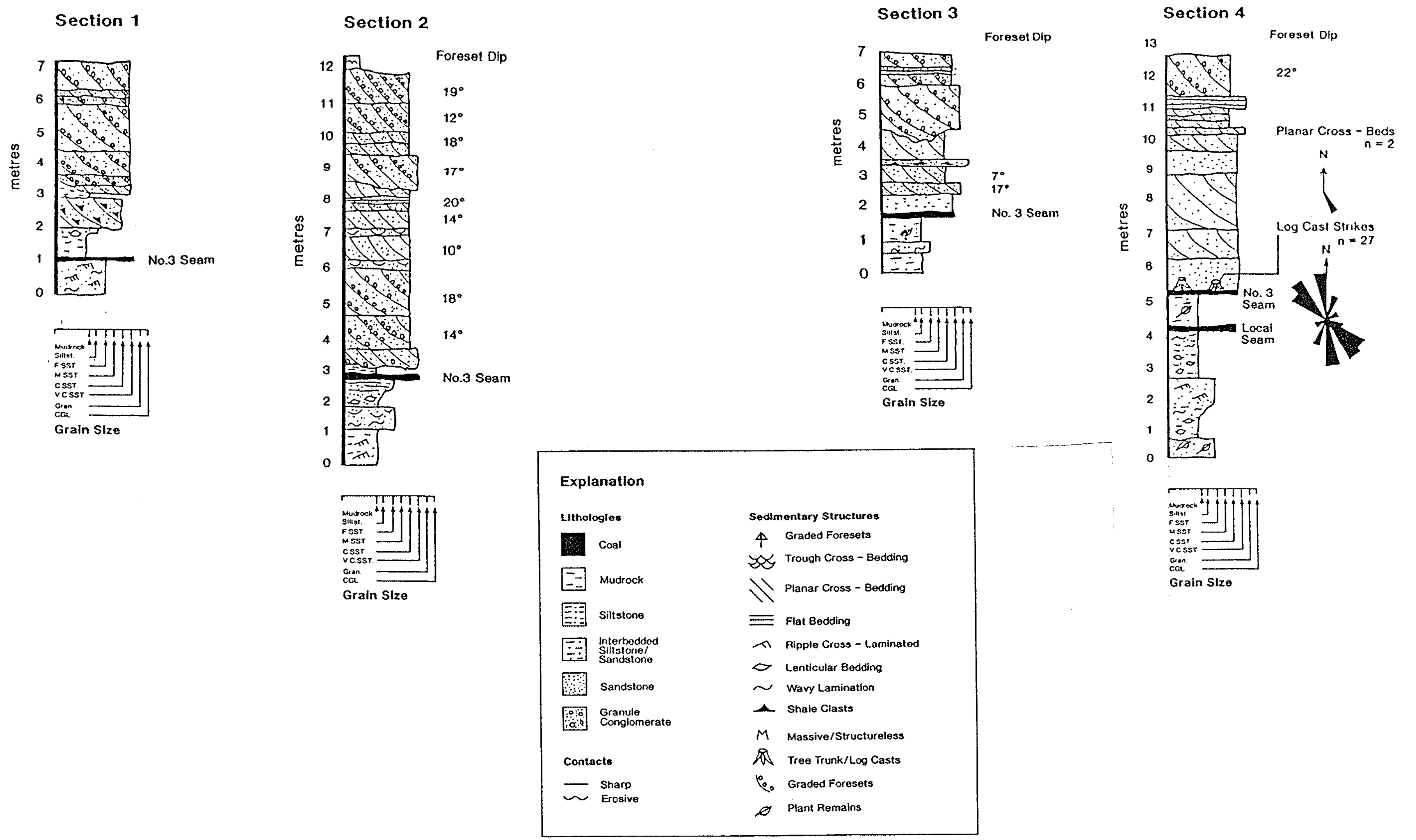

Figure 4: Vertical profiles and palaeocurrent data of the channel sandstone for sections 1-4 (see Fig. 1 for geographic locations of sections).

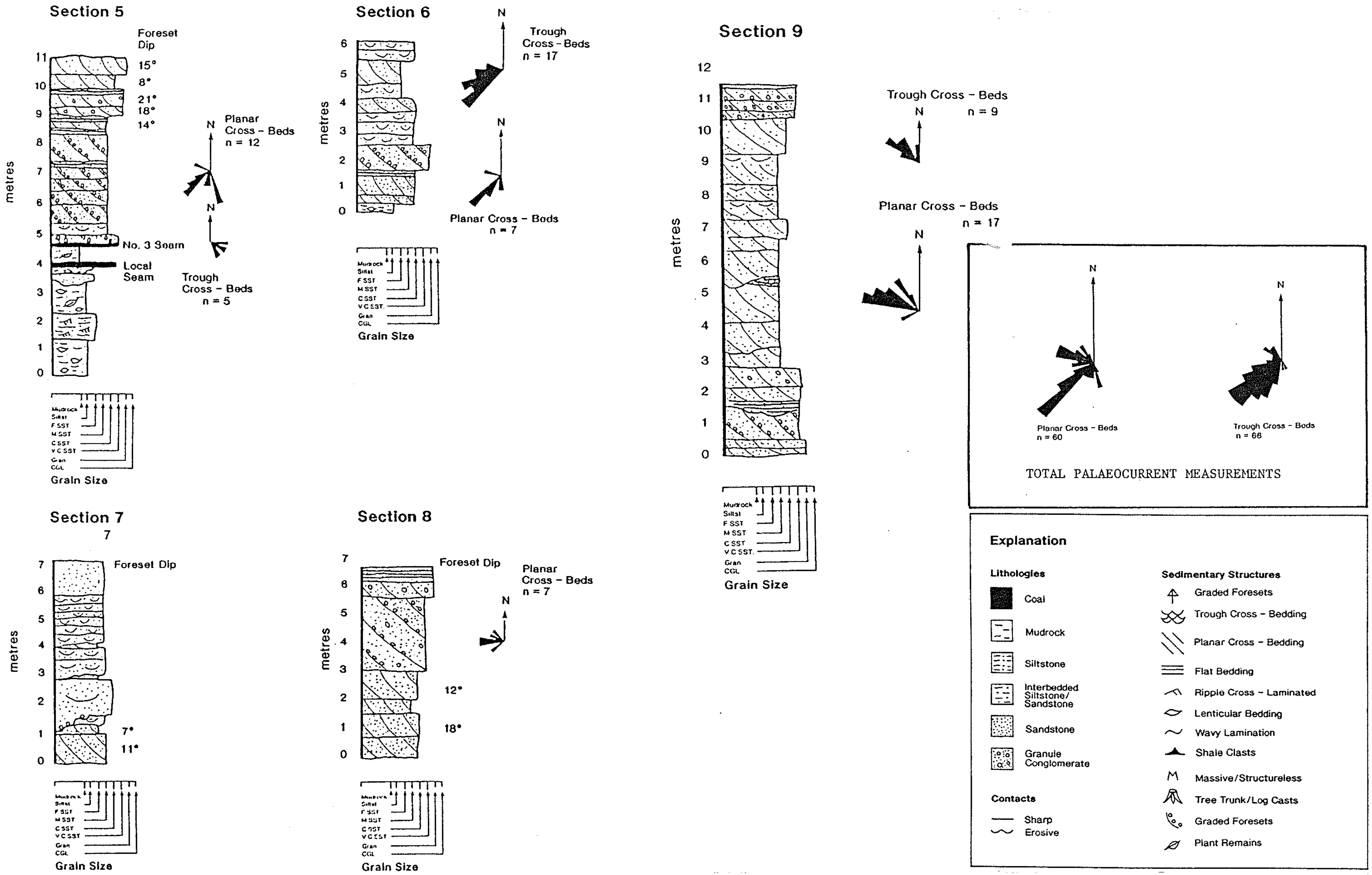

Figure 5: Vertical profiles and palaeocurrent data of the channel sandstone for sections 5-9 (see Fig. 1 for geographic locations of sections). See inset for all palaeocurrent data.

Large-scale fining-upward channel-fill sequences

Based upon stratification type, three large-scale fining-upward channel-fill sequences are differentiated. The three dominant stratification types are; tabular cross-stratification, mixed tabular and trough cross-stratification, and trough cross-stratification.

Tabular cross-stratified sequences

Fining-upward sequences dominated by tabular cross-stratification are a common channel-fill type (Fig. 4; sections 2, and 4). Small-scale fining-upward sequences are defined by a change in lithologies from conglomerate to sandstone and the presence of low-angle erosional surfaces. The sequences commence with flat to erosive bases with the basal tabular cross-stratified set containing mudstone intraclasts or displaying fossilised tree-trunk casts. In plan view, foresets are up to 60m in width and display a sinuous outline. Cross-sets, which vary in thickness between 20cm and 1.8m, are traced for up to 100m in length in outcrop and are stacked in cosets up to 4m in thickness. Foresets are well defined due to grain size variation. The foresets of sand-dominated sets grade upwards from very coarse-and coarse-grained sandstone to coarse- and medium-grained sandstone. Foresets comprising conglomerate and sandstone lithologies are also well defined. The base of these foresets comprise granule conglomerate which grades upwards into very coarse-grained and coarse-grained sandstone. Despite the dominance of tabular cross-stratification in these sequences, trough cross-stratification and plane bedding are documented. Trough cross-stratification is present in sandstones which are coarse and medium grained and display set thicknesses between 20cm and 30cm (Fig. 4, section 2). The trough cross-stratified sandstones are under- and overlain by tabular cross-stratification. Plane-bedded coarse- to very coarse-grained sandstone or granule conglomerate 10cm to 30cm thick are an important stratification type as they are present close to or define the tops of small-scale fining-upward sequences. With respect to the measured vertical profiles, tabular cross-stratified lithologies comprise 93% of the stratification type, trough cross-stratified lithologies 3% and plane-bedded lithologies 4%.

Tabular and trough cross-stratified sequence

One measured vertical profile (Fig. 5; section 6) displays two small-scale fining-upward sequences, the uppermost of which comprises interbedded tabular and trough cross-stratified granule conglomerate and sandstone. The sequence commences with two sets of tabular cross-stratified coarse-grained sandstone overlain by a bed of plane-bedded sandstone. The uppermost fining-upward sequence commences with a set of tabular cross-stratified granule conglomerate displaying graded foresets which is, in turn, overlain by alternating sets of trough and tabular cross-stratification. The trough cross-stratified sets are 20-40cm thick and cosets are up to 1m thick. There is an overall vertical grain size decrease of this sequence from granule-conglomerate to medium-grained sandstone.

Trough cross-stratified sequence

A profile, comprising four small-scale fining-upward sequences and dominated by outcrop area (Figs. 1 and 5; section 7). The lowermost small-scale fining-upward sequence is dominated by tabular cross-stratification. Three further fining-upward sequences structured by trough cross-stratification overlie the tabular cross-stratified sequence. Within these fining-upward sequences there is a decrease in the set size, from 1.8m to 20cm, and grain size from coarse- to medium-grained sandstone. Cosets of trough cross-stratified sandstone, up to 2m thick, are present in this sequence which is dominated by trough cross-stratified sandstone. The sequence is exposed over a 20m-wide interval and is defined by a large-scale erosive base.

Large-scale coarsening-upward channel-fill sequences

Large-scale coarsening-upward sequences are defined by an overall coarsening upward in grain size from sandstone to granule conglomerate (Figs. 4 and 5; sections 1, 3, 5, and 8). The base of these sequences is defined by a flat to undulating basal scour surface which is in places overlain by a laterally impersistent small-pebble conglomerate which is, in turn, overlain by a tabular cross-stratified sandstone. With the exception of section 8 (Fig. 5), the coarsening-upward sequences comprise between two and four small-scale fining-upward sequences. Between one and three sandstone-dominated fining-upward sequences are overlain by a fining-upward sequence dominated by granule conglomerate. The abundant stratification type is tabular cross-stratification displaying well-defined graded foresets. Set sizes vary between 20cm and 1.5m and maximum coset thickness within fining-upward sequences is 2.8m. Plane-bedded sandstones and granule conglomerates, about 20cm thick, frequently overlie tabular cross-stratified lithologies and terminate small-scale fining-upward sequences. Trough cross-stratification is only present as one 20cm-thick isolated set in section 8 (Fig. 5). Only at the top of the first fining-upward sequence in section 1 (Fig. 4) is the rare occurrence of mudrock preserved.

Section 8 (Fig. 5) differs from sections 1, 3, and 5 (Figs. 4 and 5) as it comprises a basal fining-upward sequence overlain by sandstones that coarsen-upward in grain size. The top 1m of the sequence consists of granule conglomerate. Almost the entire lithological succession is structured by tabular cross-stratification displaying graded-bedded foresets and having a coset thickness of 6m. The uppermost 50cm of the sequence is structured by plane-bedded granule conglomerate. Trough cross-stratification is not a dominant sedimentary structure in large-scale coarsening-upward channel-fill sequences (Figs. 4 and 5).

Large-scale fining/coarsening-upward channel-fill sequence

Section 9 (Fig. 5) is a section through the channel sandstone in the extreme west of the outcrop area. In this section the grain size motif of the sequence first fines and then coarsens upward in grain size. There is a fining upward in grain size from conglomerate at the base of the section to medium-grained sandstone in the middle of the section which, in turn, coarsens upward to very coarse-grained sandstone at the top of the section. In detail, the large-scale sequence comprises five small-scale fining-upward sequences overlain by a coarsening-upward sequence. The small-scale fining-upward sequences consist of an erosive scour overlain by either, sets of tabular cross-stratified sandstone or, infrequently by plane-bedded sandstone. Tabular cross-stratified sets vary between 30cm and 1m and in places they are mantled by plane-bedded and trough cross-stratified sandstone. The uppermost 2.5m of the sequence comprises flat-based sets of tabular cross-stratified sandstone which coarsen upward in grain size.

LATERAL CONTINUITY OF FACIES AND SEDIMENTARY STRUCTURES

A series of three mosaic photographs were compiled so as to illustrate the lateral continuity of the lithologies, and, particularly, the hierarchical arrangement of sedimentary structures along the length of the outcrop (Figs. 6, 7, 8). In places, weathering has eroded the outcrop face and destroyed some of the surface detail. For this reason, tracings were made of the mosaics so as to highlight the features that are preserved. These are shown below each of the photomosaics (Figs. 6, 7, 8).

Sedimentary structures: tabular cross-stratified sets

A feature recorded in all of the vertical profiles (Figs. 4 and 5) is the abundance of tabular cross-stratified sets. The lateral continuity of these is best illustrated in Figure 9 (location: section 1, Fig. 1C). The thickness of individual sets varies from 30 cm to 1 m (Fig. 10). A prominent characteristic is that the individual sets comprising the stacked cosets maintain their thickness with the upper and lower bounding surfaces remaining essentially parallel to one another for the length of the outcrop (> 20 m) as shown in Figure 9. The base of each set is non-erosive. The angle of contact of the foresets with the lower bedding surface is sharp, indicating little reworking of the toesets by reverse flow eddies (Collinson and Thompson, 1989). A similar, laterally continuous set is shown near the top of the outcrop in Figure 6 where the set is present for over 50 m along strike. In both Figures 6 and 9, the exposure is approximately parallel to the direction of migration of the sand waves. In plan view, as seen on the upper surface of the outcrop, the foresets are exposed as relatively linear features, extending over 15 m in length (Fig. 11). Some display slightly undulatory, sinuous outlines. The bar forms that produced these particular structures were therefore essentially two-dimensional (Harms *et al.*, 1982) and migrated downstream under lower-flow regime conditions. They were perhaps similar to the transverse bedforms described by Smith (1971) or the cross-channel bars described by Cant and Walker (1978). The movement of these bedforms was relatively passive as they have no basal scour surfaces and bar thickness remained constant throughout.

Sedimentary structures: trough cross-stratified sets

Trough cross-stratification is relatively uncommon in the outcrop, except within specific levels. When present, the sets occur virtually isolated such as at the top of Figure 7 (immediately to the right of the bush), and in the lower right-hand side of Figure 6. Some surfaces expose the troughs approximately parallel to the palaeoflow, and these sets resemble asymptotically based planar cross-stratified foresets, except that in the case of the trough cross-stratification, the lower bedding surface is either undulating or partly concave due to scouring.

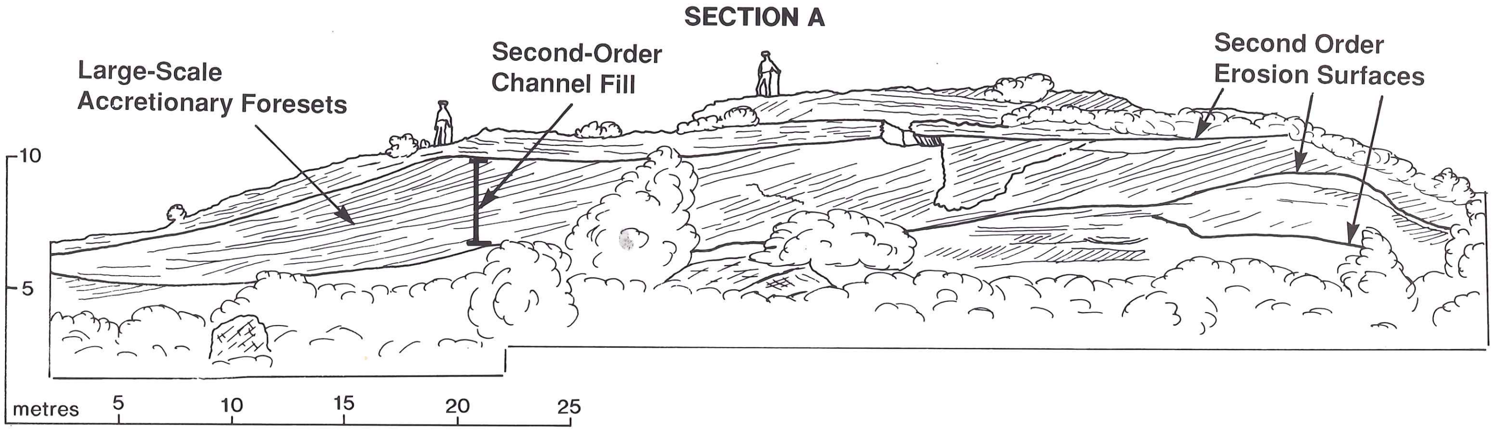

Figure 6: Photomosaic of the channel sandstone between sections 2 and 3 (see Fig. 1). Lower diagram is a sketch of the photomosaic illustrating major sedimentary structures and second-order erosion surfaces. Note the large-scale accretionary foresets bounded by second-order erosion surfaces.

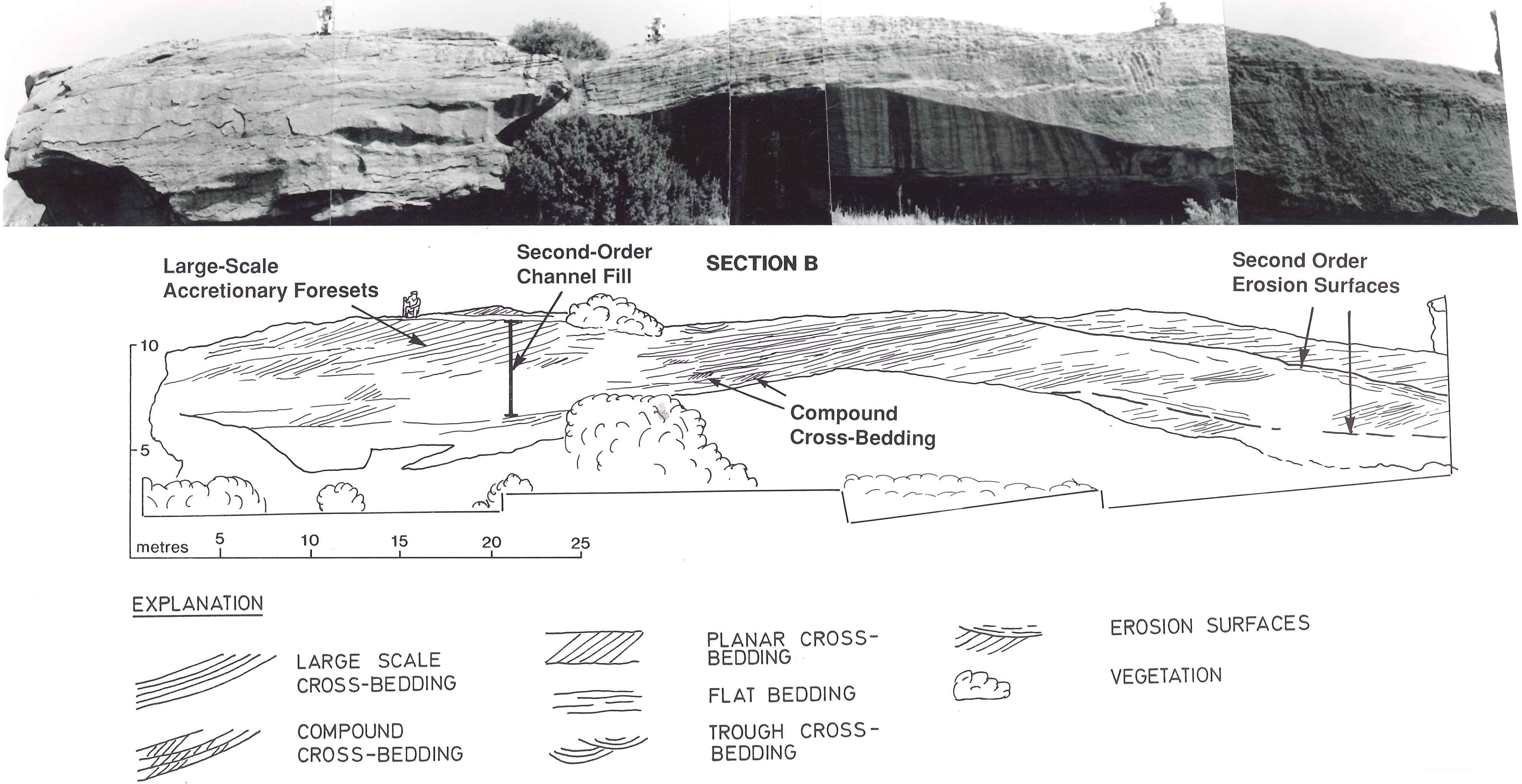

Figure 7: Photomosaic of the channel sandstone between sections 1 and 2 (see Fig. 1). Lower diagram is a sketch of the photomosaic illustrating major sedimentary structures and second-order erosion surfaces. Note the compound cross-stratification and lateral-accretion channel fills.

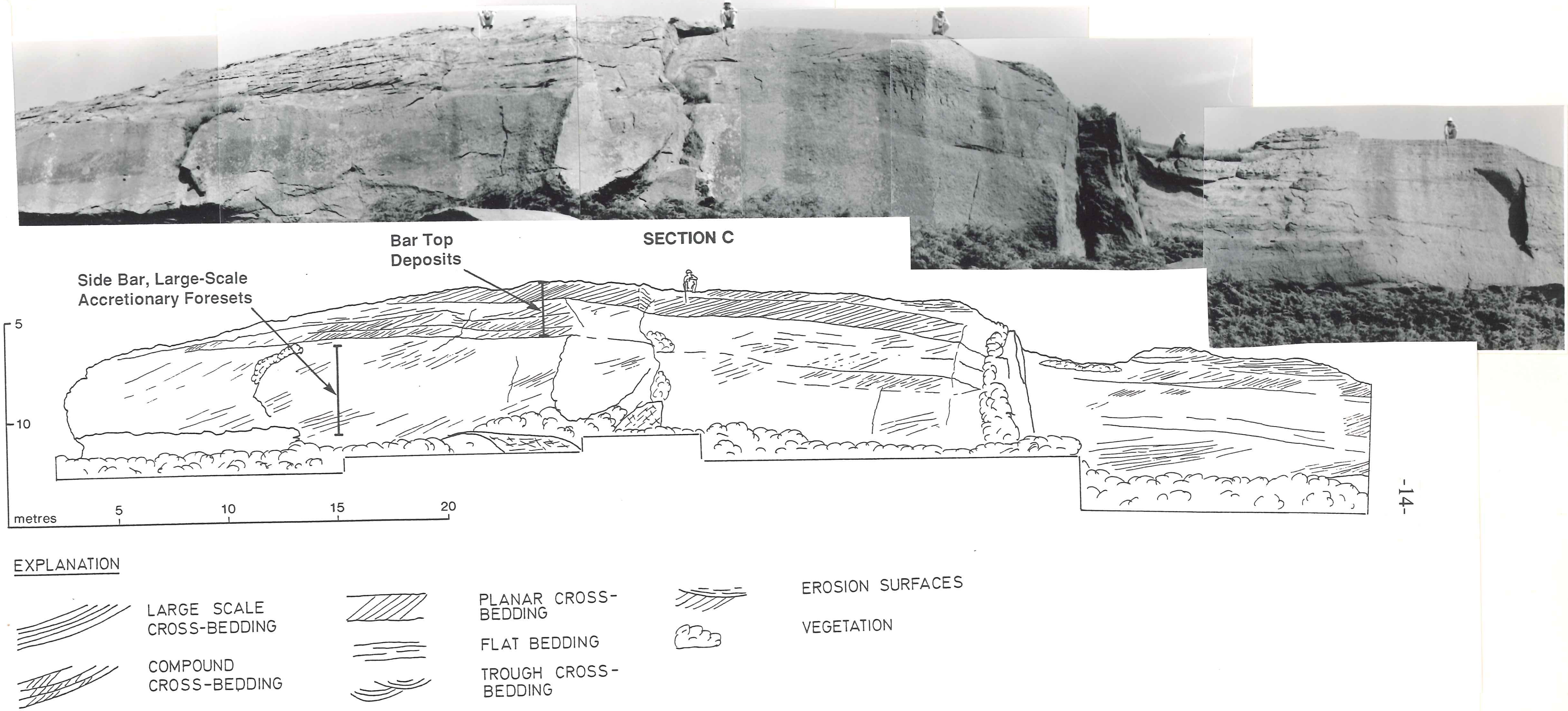

Figure 8: Photomosaic of the channel sandstone east of section 1 (see Fig. 1). Lower diagram is a sketch of the photomosaic illustrating major sedimentary structures. Note the large-scale accretionary foresets and cosets of small-scale tabular cross-stratified sandstone interpreted as bar-top deposits.

Sedimentary structures: large-scale accretionary cross-stratification

A prominent sedimentary structure, particularly well illustrated in Figures 6 and 7, occurs in the form of large-scale (>5m thick, >65m long), relatively low-angled cross-stratification, although the angle of dip on the foresets can be variable. These foresets typically comprise an upper section consisting of steeply dipping foresets which then become progressively more shallow angled relative to the lower bedding surface as they toe-out. The large-scale set shown in Figure 7 has an erosional basal scour, immediately overlain by several tens of centimetres of plane-bedded sandstone. The latter represents upper flow regime sedimentation following the scour event (Fig. 7, lower right hand section). Another important feature of this large-scale cross-bedding is that sets exhibit compound cross-stratification (Collinson and Thompson, 1989). The foresets are themselves internally stratified by smaller-scale tabular cross-stratified sets which dip in the same direction as the enclosing master bedding (see Fig. 7, lower central section). The upper surfaces of the large cross-bedded sets can be erosively truncated as shown in Figure 6.

Sedimentary structures: plane bedding

Plane-bedded sandstone is present as relatively thin (1-2 m) sets (Fig. 10). This structure is seen in the upper portion of Figure 6, and in the central section of Figure 9. The sandstone containing this structure is coarse to very coarse-grained.

The plane-bedded and trough cross-stratified cosets described above were observed in the detailed vertical sections, but other sedimentary features, including scour surfaces and the large-scale cross-stratification, only became apparent when the photographic mosaics were examined. A definite hierarchy of structures, similar to those described by Allen (1983, Fig. 8) exist at the Olifants River exposure. Both first-order contacts, which erosively separate cosets and second-order contacts which cut a variety of stratification types, are illustrated in Figures 6 and 7. The foresets composing the large-scale cross-stratification are enclosed by second-order surfaces (Figs. 6 and 7).

CHANNEL-FILL FACIES INTERPRETATIONS

The linear geometry of the deposit, striking approximately perpendicular to the basin margin, the coarseness of lithology (granule-grade conglomerate and coarse- to very coarse-grained sandstone), the composition of the rock (arkosic), the sedimentary structures and their palaeodirection (the dominance of tabular cross-stratification to the southwest) and the stratigraphic position of the deposit between coals of the No. 3 and No. 4 coal seams (Fig. 2) indicate that the channel-fill associations were deposited by a low-sinuosity, bed-load-dominated fluvial system.

The channel-fill associations comprise granule-grade conglomerate and sandstone and rarely, occasional siltstone beds. The conglomerate and sandstones are structured dominantly by tabular cross-stratification and to a minor extent by trough cross-stratification and plane bedding. The channel-fill associations either coarsen or fine upwards in grain size and at one locality (Fig. 5; section 9) the sequence first fines upward then coarsens upward in grain

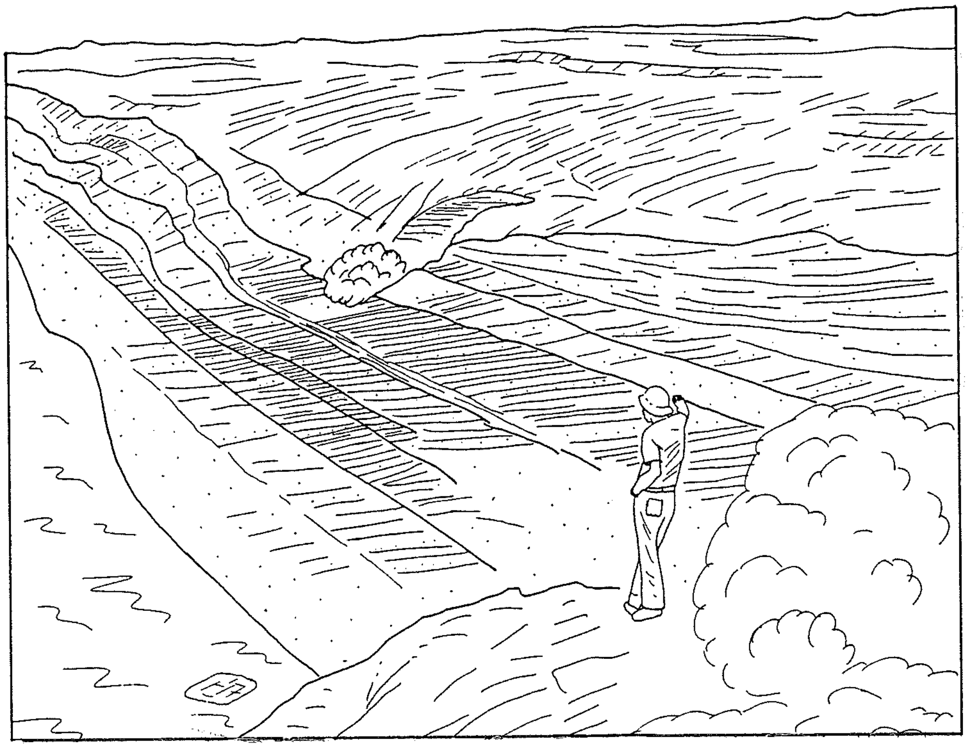

Figure 9: Sketch illustrating the lateral continuity of tabular cross-stratified sets. Locality, section 1 (see Fig. 1). Person in sketch is 1.8m.

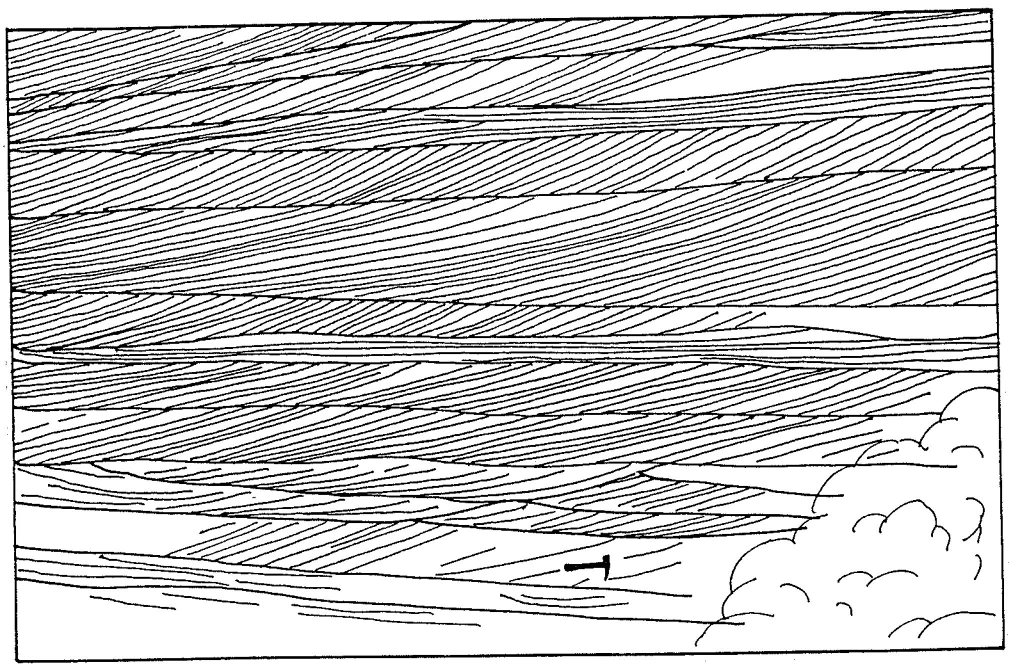

Figure 10: Sketch illustrating both tabular cross-stratified and plane-bedded sets. Note how the plane-bedded sets become low angle tabular cross-stratified sets when traced in a downcurrent direction. Hammer for scale is 30cm.

Pebble and granule-grade conglomerates overlying an erosional scour surface containing siltstone intraclasts represent bed-load material concentrated at the base of laterally migrating channels during initial sedimentation of the fluvial system. The scour surfaces would represent 1st, 2nd and 3rd order contacts, after Allen (1983). In section 1 (Fig. 4) a horizontally laminated siltstone, defining the top of the first fining-upward sequence, records channel abandonment and the deposition of fine suspended-load material. The general lack of fines in the deposit can be interpreted in a number of ways:

1. renewed flood events removed, through erosion, previously deposited fine-grained material;

2. that velocities were sufficiently high to flush silt and clay through this part of the fluvial system; and

3. a high bed-load to suspended-load ratio of sediment derived from the source area.

The dominant sedimentary structure of the fluvial system is tabular cross-stratification and sets between 20cm and 1.8m represent the migration of sand waves as unit bars (Harms *et al.*, 1975, Collinson and Thompson, 1989). The bar foresets are exposed in plan view on the upper surface of the outcrop (Fig. 11). Limited exposure of the foresets in plan view indicate that they have sinuous crests and a minimum lateral dimension transverse to flow of 100m. Many of the foresets fine upward from granule-grade to sand-grade material. These fining-upward foresets are explained by Smith (1972) as resulting from the segregation of gravel and sand by small-scale bedforms (dunes, Harms *et al.*, 1975) which move along the top of the bar. The gravel is segregated into the lee of the bedform which comprises sand. Avalanching of the gravel pocket in the lee of the dune followed by the sandy material constituting the bedform results in the fining of grain size of the foresets. The general lack of plane bedding and or trough cross-stratification overlying the tabular cross-stratified sets suggests that the tops of these bars were subject to periods of erosion either, during falling water stage or, during periods of high discharge. Alternatively, the small-scale bed forms such as plane beds and dunes acted as transporters of sediment to larger bed forms rather than depositors of sediment. Consequently, their preservation potential in the rock record would be small.

Larger compound tabular cross-stratification is attributed to the avalanching of sediment over the slip faces of compound bars (Bluck, 1974, 1976; Crowley, 1983; Haszeldine, 1983). The mechanism of migration is by lateral accretion similar to point bar migration (Jackson, 1976). Cross-bed data (Figs. 4, 5, 12) illustrate an overall southwesterly transport direction and the photomosaics of the compound cross-stratification complement these data and illustrate an apparent westerly transport direction. The direction of bar migration is to the southwest which is oblique to the overall sandbody length which, in turn, is south-southwesterly.

Figure 11: Photograph illustrating foresets in plan view on bar top.

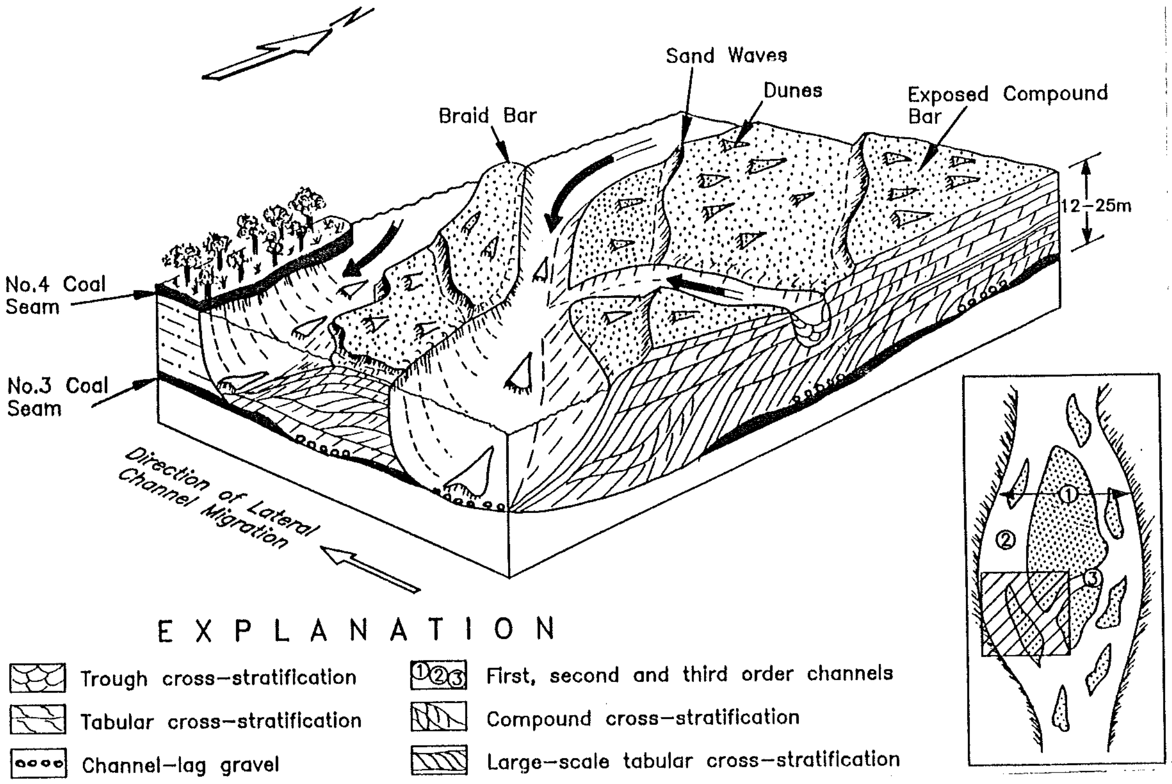

Figure 12: Block model of portion of a compound bar and braid bar illustrating hypothetical internal stratification. Direction of first-order channel migration is to the left. Orientation of sand waves and dunes is oblique to bar morphology. First- second- and third-order channels and position of block diagram is shown in inset sketch plan.

Trough cross-stratified granule conglomerate and sandstone sets vary in thickness between 20-40cm and are 40cm to 1.5 m in width. This structure represents the migration of sinuous crested dunes in unidirectional flows (Harms *et al.*, 1975; Collinson and Thompson, 1989). The presence of this stratification type overlying tabular cross-stratification suggests the presence of small-scale dunes migrating over sand waves or bars. Section 7 (Fig. 5) illustrates a channel-fill sequence comprising cosets of trough cross-stratification which fine upwards in grain size. This sequence of sedimentary structures is interpreted as representing the fill of a small-scale sinuous channel $\pm$ 20m wide and about 6m deep. The channel probably experienced fairly high and constant velocities which enabled these small-scale bed forms to migrate through the channel and deposit sediment.

Sets of plane-bedded (Harms *et al.*, 1982) granule-grade conglomerate and sandstone are interbedded with sets of tabular cross-stratification (Figs. 4, 5, and 10). The plane bedding is either parallel to or forms low-angle discordances with the tops of underlying tabular cross-stratified sets. In addition, the individual laminae of planar-laminated sets when traced out downcurrent, vary from parallel to discordant and certain sets grade downcurrent into low-angled tabular cross-stratification. These relationships are well illustrated in Figure 10. The plane-bedded granule conglomerates and sandstones represent either the migration of upper flow regime plane beds or the transport of coarse-grained sands and granule-grade gravel under conditions of weak current velocities (Harms *et al.*, 1982). The presence of plane-bedded sets 10-20cm thick overlying tabular cross-stratified sets 20cm to 1.8m thick implies that these sediments are deposited on bar tops by plane beds. The plane-bedded sandstones and conglomerates are interpreted as upper flow regime deposits which formed either during periods of high discharge or waning flow when water depth is reduced over sand waves. Lateral gradation from plane bedding into tabular cross-stratification possibly results from increasing water depth caused by undulations on the bar surface. Increasing water depth causes a reduction in water velocity and sediment is deposited to form a low-angle foreset. Subsequent sedimentation and vertical aggradation of the plane bed results in the downstream termination of the plane bed which develops a slip face. Thereafter, sediment avalanches down the slip face initiating low-angle tabular cross-stratification (Fig. 10).

The fining-upward and coarsening-upward grain size motifs determined from detailed vertical profile measurements are cut by second-order surfaces (Allen, 1983) defined by erosive scours. The fining- and coarsening-upward grain-size profiles thus represent the net result of periods of sedimentation separated by a period of erosion and non-deposition. Consequently, the coarsening-upward channel-fill sequences represent a period of sedimentation dominated by sand deposition terminated by a second-order erosion surface which was followed by a period of renewed sedimentation dominated by granule-grade gravel deposition.

DISCUSSION

The classification of fluvial deposits as braided (Miall, 1977; Rust, 1978) or bed-load dominated (Schumm, 1977, Galloway, 1981) follows an evolutionary trend which is based upon the study of modern braided river systems (Williams and Rust, 1969; Coleman, 1969; Collinson, 1970; Smith, 1970; Cant and Walker, 1978; Bristow, 1987), and the synthesis of these data led to the formulation of braided-stream models which explain braided-stream processes and postulated vertical facies arrangements (Miall, 1977, 1978; Cant and Walker, 1978; Rust, 1978). The classification of a number of braided-stream models is evidence that braided streams or bed-load-dominated fluvial systems deposit variable channel-fill sediments which, in turn, imply that variable processes operate within these fluvial systems. The variability of channel-fill lithologies and sedimentary structures has led to studies utilizing both two- and three-dimensional channel-fill geometry as further criteria to identify bed-load (braided) from suspended-load (meandering) fluvial systems (Galloway, 1981; Friend, 1983). More recently, studies have documented the facies architecture (Allen, 1983; Miall, 1985) of two-dimensional cross-sections to determine the complex channel-fills of fluvial systems and thereby quantify mechanisms and processes of channel-fill sedimentation (Allen and Williams, 1982; Allen, 1983; Haszeldine, 1983a; Okolo, 1983).

Galloway (1981) combined both three-dimensional geometries of fluvial systems together with detailed two-dimensional cross-sections in order to distinguish bed-load, mixed-load and suspended-load channels and channel-fill sequences of the late Quaternary and Oligo-Miocene fluvial systems of the Texas Coastal plain. More recently, the study of the Brahmaputra River by Bristow (1987) described a hierarchical approach to channel identification and the documentation of first-, second- and third-order channels and their movements through time. In addition, the relative amounts of deposition within the braided reach of the river was recorded over a six year period. The recognition of lateral and downstream accretion of existing bar forms and lateral bank accretion being the most important sites of deposition has applicability to the present study.

This study, using both comprehensive subsurface data and excellent two-dimensional data obtained from both vertical profile measurements and the mapping of macroforms from photomosaics, has recorded complex channel-fills leading to the postulation of a model for channel-fill sedimentation.

Channel-fill sedimentation

The interpretation of sedimentary sequences present between second-order contacts (Figs. 6 and 7) revealed that the sand body represents both a multistory and multilateral channel-fill fluvial sequence dominated by both lateral and vertical accretion of sediment. The second-order surfaces are erosional and reflect a high discharge event during which scouring of channels and pre-existing braid bars takes place. The sediment fill occurred via the successive deposition of sand waves over topographically elevated areas which would represent pre-existing braid bars, compound bars and sand flats (Fig. 12; Cant and Walker, 1978). Vertical accretion is the style of sedimentation that results from the migration of sand waves and the deposition of tabular cross-stratified medium- to very coarse-grained sand and granule-grade gravel. Large-scale tabular cross-stratification and compound cross-stratification results from lateral accretion of the side or downstream ends of braid bars or sand flats. Figure 6 illustrates how a tabular cross-stratified set can be traced downcurrent to become a large-scale tabular cross-stratified set. In addition, these large-scale tabular cross-stratified sets can be traced down current to become large-scale compound cross-stratified sets (Fig. 7). It appears that towards the base of the large-scale foresets where the angle of the foreset becomes less steep, smaller scale unit bars deposit tabular cross-stratified sediments on the foreset surface. Similar compound cross-stratification is documented by Coleman (1969) from a large sand wave in the Brahmaputra River and by Haszeldine (1983b) from an Upper Carboniferous fluvial channel sequence. Certain of the small-scale tabular cross-stratified sets, present as compound cross-stratification at the base of the large-scale foresets, evolve into larger tabular cross-stratified sets upon which large-scale foresets accrete. This mechanism of channel filling is well illustrated in Figure 7. An important point to note is that the mechanism of lateral accretion, and not vertical aggradation, of braid bars was the dominant form of sedimentation in the two-dimensional sections studied (Figs. 6, 7, 8).

Scour and fill sequences are also well documented. Figure 7 illustrates two large-scale scour features overlain by plane-bedded sandstones and gravel which parallel the scour surface. The plane-bedded units are, in turn, overlain by large-scale tabular cross-stratified foresets which dip westwards. The uppermost scour has a depth of at least 5m and most likely represents the base of a 2nd order channel formed through scouring of a pre-existing braid bar during a high discharge event. The plane-bedded very coarse-grained sandstones and granule-grade conglomerates, which parallel the scour surface, represent upper flow regime sedimentation which occurred soon after peak discharge. The overlying large-scale tabular cross-stratified sets represent the lateral migration of the slip face of an adjoining braid bar which has resulted in the amalgamation of braid bars to form a more compound bar. Again, the channel-fill process is through lateral accretion rather than vertical accretion. The mechanism of lateral accretion of braid bars as alluded to here is the dominant form of sedimentation, similar to that documented by both Coleman (1969) and Bristow (1987) for the braided reach of the Brahmaputra River.

The channel-fill associations documented by vertical profile analysis contain tabular cross-stratification as the dominant sedimentary structure. These sequences are interpreted, from two-dimensional analysis of the outcrop, as representing both sedimentation resulting from sand wave deposition and lateral accretion of braid bars. The coarsening-upward channel-fill sequences reflect the multistory nature of the deposit. The change from coarse-grained sandstone to granule-grade gravel occurs along an erosive base interpreted to represent a second-order scour surface. This scour surface separates an initial period of sedimentation which reflects a change in grain size from granule-conglomerate to sandstone from a second period of sedimentation during which granule-grade gravel dominates. The trough cross-stratified fining-upward sequences represent small-scale channel fills. These channel fills represent third-order channels along which dunes migrated (Fig. 12). Sedimentation took place during a period of waning flow in relatively shallow water. Vertical accretion is the dominant mechanism of channel-fill in third-order channels. Volumetrically, this is an insignificant type of channel-fill for this particular channel deposit.

Channel migration

From the study of channel-fill sedimentation and the analysis of palaeocurrent readings, the direction of first-order channel migration is considered to represent the controlling factor which dictated the direction of second-order channel migration and consequently, the internal stratigraphy of the deposit. Mechanisms of first-order channel migration are postulated and include autocyclic channel migration either towards or away from the margin of a floodplain or intrabasin high (Bluck, 1980) and preferential migration of the channels in response to tectonic tilting of the floodplain (Leeder and Alexander, 1987). These mechanisms of channel migration are conceptual in origin, apply largely to meandering river systems, and are not based upon the study of modern river deposits. An exception, however, is the study of the Brahmaputra River by Coleman (1969) and Bristow (1987) who documented between 1830 and 1984, a net westward migration of the river of 10km over a period of about 150 years. This westward migration of the river system is counter to the regional tectonic slope and it is postulated that the migration direction may be influenced by intrabasinal faults (Bristow, 1987). Todd and Went (1991) proposed the lateral migration of sand-bed rivers to account for the laterally extensive sandbody geometries within the Devonian Formation in southwest Ireland and the Alderney Formation, Channel Islands. In this latter study, tectonic tilting of the floodplain is appealed to as the mechanism by which the channels migrate towards the zone of maximum subsidence. In this study, the orientation of large-scale tabular and compound cross-stratification and cross-bed readings indicate a preferred direction of channel migration in a westerly direction over a first-order channel width which varies between 1km and 12km (Fig. 3).

The mechanism of channel migration does not relate to either basin margin migration or to intrabasinal faulting due to the position of the channel with respect to the basin margin and its location above the stable Kaapvaaal Craton (Fig. 3). Rather, the channel orientation was most likely controlled by the palaeotopography of the basement floor with the channel migrating away from basement highs (Fig. 3). The position of the palaeochannel outcrop is situated immediately north of the Proterozoic felsite ridge which deflected channel pathway towards the west. Despite the rather obvious control in this study of channel migration away from areas of basement elevation, the lateral migration of bed-load-dominated first-order channels, by whatever cause, is considered to have controlled the migration of second-order channels and thereby the detailed channel-fill stratigraphy.

Conceptual model of channel-fill sedimentation

Based upon the data presented in this study, and the recognition of lateral migration within the modern Brahmaputra and ancient sand-bed rivers, a mechanism for channel-fill sedimentation is postulated. Channel-fill sedimentation is achieved through firstly, erosion of previously deposited sediment and secondly, deposition largely by lateral and oblique downstream accretion of side and braid bars in the direction of first- and second-order channel migration. The lateral migration of first-order channels will control the net direction of lateral migration of second-order channels. Second-order channels will, therefore, with time, migrate in the same direction as first order channels. Lateral migration of second-order channels will, with time, cause lateral erosion and deposition of sediment. Therefore, channel migration preferentially preserves sediment which has been deposited through the lateral and oblique downstream accretion of braid bars. It is envisaged that, if second-order channels avulse and migrate in a direction opposite to first-order channel migration, the deposits that result from this second-order migration will constitute only a minor portion of the overall sandbody.

The mechanism of braid bar growth and lateral channel migration is illustrated in Figures 12 and 13. Braid bars originate and develop through the initial deposition of sediment from unit bars (sand waves). Vertical stacking of sediment is accomplished by the repeated deposition of sand waves to form an incipient braid bar. Subsequent evolution of the braid bar is through sediment transport over the braid bar and deposition on the side or downstream end of the braid bar (Fig. 13A). Depending on the amount of vertical aggradation and channel scouring which takes place, sediment moved laterally or obliquely across the bar avalanches down the advancing flank and downstream end of the braid bar to form large-scale tabular cross-stratified or compound cross-stratified sediments (Fig. 12). Concommitant lateral and downstream migration of the bar complex with time, produces braid-bar deposits consisting of a second-order erosion surface overlain by large-scale tabular cross-stratified sediments formed by lateral-accretion. These sediments are overlain, in turn, by small-scale tabular cross-stratified sands and granule-grade gravel representing sand wave deposition on the top of the braid bar. With continued migration of the braid bar in a downstream direction, oblique to channel flow, the initially deposited braid-bar sediments will be eroded and thus the preservation potential of small-scale tabular cross-stratification at the base of the braid-bar deposits would be negligible.

With time, braid bars evolve into compound bars (Fig. 13B). The compound bar increases in size through the oblique accretion of braid bars, within the trailing channel, on to the compound bar. In addition, periods of high discharge cause sediment to be transported obliquely across the compound bar and deposited on the side and downstream end of the bar (Fig. 13B). Flow divergence around the compound bar causes erosion of the first-order channel margins and channel widening (Fig. 13C). The development of a large compound bar causes two second-order channels to become established. Within each second-order channel braid bars will be present. The morphology of the second-order channels around the enlarged compound bar will be that of anastomosed channels (Fig. 13C). Both Coleman (1969) and Bristow (1987) document these anastomosed channel geometries within the Brahmaputra River. Third-order channels develop during the waning stages of a high discharge event and incise into both compound and braid bars (Fig. 13C). Third-order channel-fill sequences composed of trough cross-stratified sands constitute an insignificant proportion of the first-order channel deposit. With continued lateral migration of first-order channels, braid bars amalgamate to form a new compound bar lateral to, and downstream of, the initially formed compound bar (Fig. 13D). The trailing channel of the initially formed compound bar fills and becomes abandoned and the leading channel becomes a single active channel and the entire compound bar becomes abandoned (Fig. 13E). The braid bars, sand waves and dunes present within second-order channels are not depositors of sediment but rather, largely transporters of sediment through the fluvial system. Only compound bars preserved through lateral migration of the fluvial system constitute the bulk of the sediment deposited by the fluvial system. Consequently, these deposits would be preferentially preserved in the rock record.

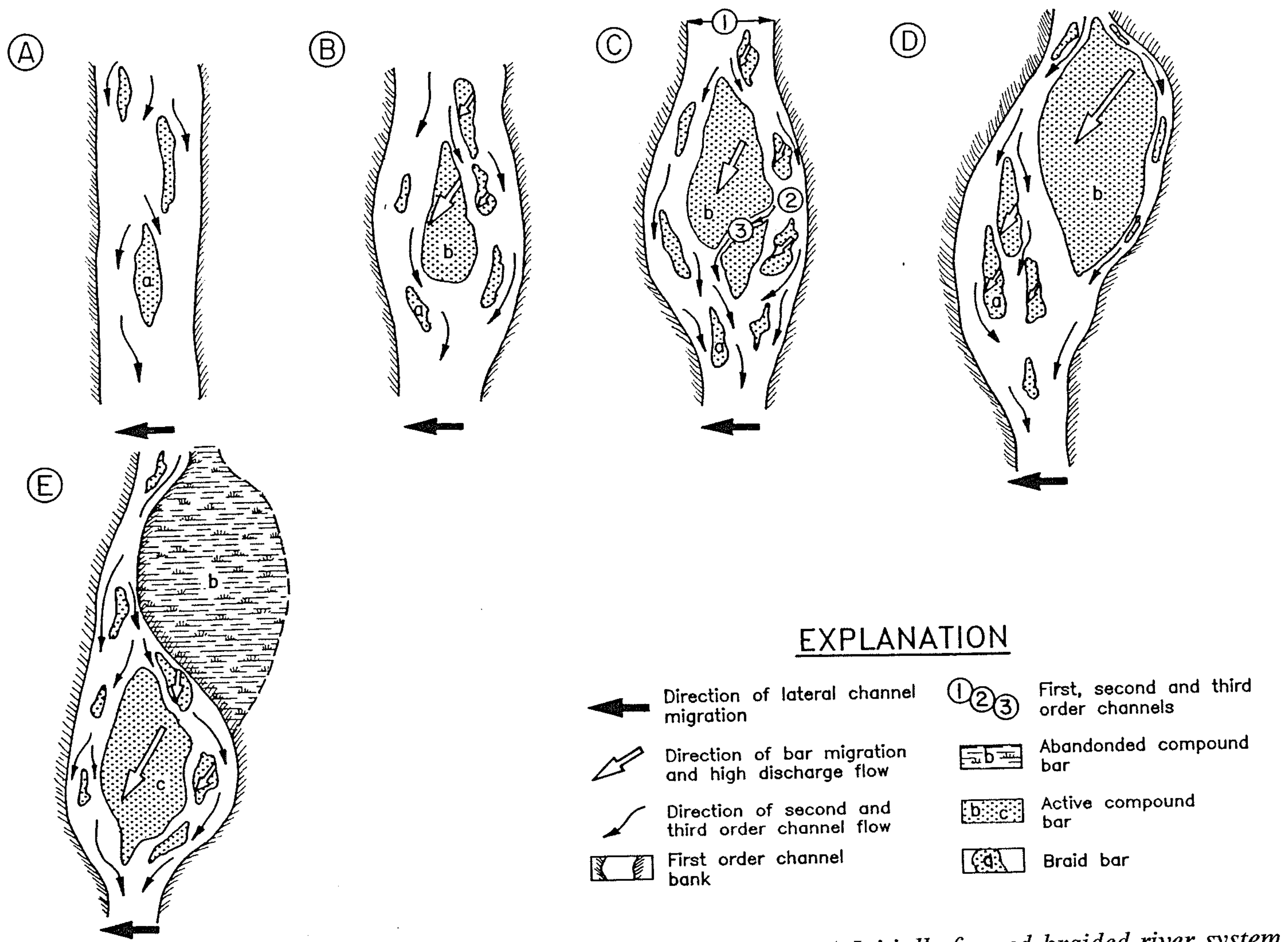

Figure 13: Illustration of lateral migration and evolution of a braided river system. A) Initially formed braided-river system with braid bars. B) Development of a compound bar through braid bar amalgamation. C) Enlargement of the compound bar to form two second-order channels. The morphology of the channels becomes anastomosed. D) New compound bar begins to form lateral to, and downstream of, the initially formed compound bar. E) First-order channel migration causes abandonment of the initially formed compound bar.

SUMMARY AND CONCLUSIONS

The three-dimensional geometry of a bed-load channel sandstone from the Vryheid Formation of the Karoo Sequence, South Africa is delineated from closely spaced drill-hole data. The channel has a linear geometry, a width which varies between 1-12km and a thickness variation between 12 and 22m.

Vertical profile measurements of the sandbody and two-dimensional cross-sectional data determined from photomosaics of outcrop have delineated the detailed stratigraphy of this channel sandstone. These data have led to the postulation as to the mechanism of channel-fill sedimentation in this bed-load dominated fluvial system.

Vertical profiles of the sandbody reveal that the texture of the sandbody is dominated by coarse- to very coarse-grained sandstone and granule-grade conglomerate. The sandbody comprises a sequence of small-scale cosets dominated by tabular cross-stratification which fine-upward in grain size. The cosets, however, fine- but more frequently, coarsen-upward in grain size. A second-order scour surface separates sandstone-dominated lithologies at the base of the sandbody from granule-grade conglomerate lithologies present towards the top of the sandbody. Trough cross-stratification is a minor stratification type present in the sandbody.

Two dimensional analysis of the sandbody documented the internal stratigraphy of the deposit. Second-order scour surfaces (Allen, 1983), delineate channel-fill sequences which comprise both compound and large-scale tabular cross-stratified sets overlain by small-scale tabular cross-stratified sets. The vertical stacking of these units implies that the sequence studied represents both a multilateral and multistory sandbody. The large-scale tabular cross-stratified sets reflect deposition of sediment through the lateral and oblique downstream accretion of braid bars. Small-scale tabular cross-stratified sets reflect deposition by unit bars on the tops of braid bars (macroforms). Both lateral and vertical accretion processes can account for this style of sedimentation.

Lateral migration of second-order channels with time allowed for the preferential preservation of lateral-accretion deposits in the direction of first-order channel migration. The direction of first-order channel migration was towards the west, away from Proterozoic basement topographic highs. This mechanism of channel migration facilitated the accumulation of large-scale tabular cross-stratified sets overlain by small-scale tabular cross-stratified sets and is postulated as representing the internal stratigraphy of both braid and compound bars. The dimensions of the large-scale cross-strata reflect the depth of channel scour and the depth between two second-order scour surfaces therefore gives an indication of the minimum channel-fill depth. Data from this particular study imply that in bed-load dominated systems that undergo lateral channel migration the dominant style of channel-fill sedimentation is by lateral accretion rather than by vertical aggradation. Consequently, the conclusion of Bridge (1985) that the proportion of channel fills relative to lateral-accretion deposits increases with the degree of braiding is the antithesis of the model of channel-fill sedimentation postulated by this study. Vertical profile analysis of outcrops provide data as to the small-scale stratigraphy of the deposit. This deposit would classify in terms of Mialls' (1977) postulated Platte model and serves as a useful technique when applied to subsurface investigations. However, this study documents that only through extensive two-dimensional analysis of outcrop can the large-scale macroform features be recognised and interpreted and the mechanisms of channel-fill sedimentation postulated.

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