GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 27

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BY
R. M. HOCKING

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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Perth 1991

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**Cataloguing-in-publication entry**

Hocking, R.M. (Roger Malcolm) 1952 -
The Silurian Tumblagooda Sandstone, Western Australia

Bibliography
ISBN 0 7309 0987 5

1. Physical geology – Western Australia – Murchison River Region. 2. Murchison River Region (W.A.).
3. Geology, Stratigraphic – Silurian.
I. Geological Survey of Western Australia.
II. Title. (Series : Report (Geological Survey of Western Australia) ; no. 27).

559.413

**ISSN 0508-4741**

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**The Director**
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**100 Plain Street**
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## Abstract

The Tumblagooda Sandstone is a Silurian, fluvial and coastal, redbed sequence and is the oldest known unit in the Perth and Carnarvon Basins. Well-exposed sections are in the type section along the Murchison River gorge (1385 m total thickness, 1210 m stratigraphic thickness) and nearby coastal cliffs south of Kalbarri (about 50 m thick), about 600 km north of Perth.

Five facies associations, FA1 to FA5, are recognized, of which the first four occur (in ascending order) in the type section. Each association has a distinctive depositional setting, and each shows lateral variation in grain size and structures, both across and down the inferred palaeoslope. The facies associations, individually, are both stratigraphically and lithologically distinct. FA1 and FA3 are dominated by trough cross-bedded, coarse-grained sandstone arranged in laterally persistent, but internally scoured, cosets. Palaeocurrent directions are northwestward, unimodal, and show a low scatter. A distinctive pebbly sandstone interval, the Gabba Gabba Member, occurs within FA3. FA2 and FA4 overlie and interfinger with FA1 and FA3, respectively. FA2 consists of medium- to fine-grained, thin-bedded sandstone, which has varied bedforms, dominantly south-southwestward palaeocurrent indicators, and abundant trace fossils (characteristic trace fossil: *Heimdallia* sp.). FA4 consists of interbedded sandstone and siltstone, in part bioturbated (characteristic trace fossil: *Skolithos*). FA5 consists of cross-bedded, interbedded coarse-grained sandstone and conglomerate, and occurs up-palaeoslope from the other associations, 30 to 50 km to the southeast.

FA1 and FA3 were formed by episodic deposition in low-sinuosity, braided-fluvial systems. Both can be regarded as low-relief, high-energy, fluvial-dominated delta systems. Higher energy levels prevailed during FA3 deposition. FA2 was deposited in moderate- to high-energy tidal conditions. FA4 formed in a moderate- to low-energy, paralic, interdistributary area, and is a distal equivalent of FA3. FA5 was deposited in an alluvial-fan complex or on the adjacent proximal braid-plain.

FA1 to FA4 form two depositional megacycles (FA1 and FA2, FA3 and FA4). Each cycle began abruptly with fault-related rejuvenation of the basin hinterland, and was caused by a gradual decrease in sediment influx rather than major eustatic transgression. Sediment influx then gradually diminished, which led to marginal-marine deposition. FA5 could be related to either couplet, or both. The climate was probably arid, based on the nature of the red colouration of the Tumblagooda Sandstone.

The nature of the fluvial deposits in the Tumblagooda Sandstone agrees with the hypothesis that active distributary vs. overbank deposits were not clearly differentiated prior to the evolution and spread of land plants. It does not agree with the extension of the hypothesis, that channelized flow was virtually absent.

Previous workers regarded the Silurian sequence as having formed in a "failed arm" setting in a north-opening gulf, after a rifting and divergence episode from 510 to 570 Ma. This study suggests that a later rifting episode, about 430 to 450 Ma ago, caused deposition of the Tumblagooda Sandstone.


**Keywords:** Tumblagooda Sandstone, facies, Silurian, Carnarvon Basin, Perth Basin.

# Introduction

## History of investigation

Clarke and Teichert (1948) named the Tumblagooda Sandstone and described the sequence in the lower Murchison River area (Plate 1) in detail, but did not recognize the basal Cretaceous unconformity and so considered the Tumblagooda Sandstone to be part of the Cretaceous sequence. They did not designate a type section, but considered Tumblagooda Hill (Plate 1) to be a typical part of the section.

In the early 1950s, as part of regional appraisals of the Carnarvon Basin, geologists from both West Australian Petroleum Pty Ltd (WAPET) and the Bureau of Mineral

Resources (BMR) studied the lower Murchison River area, and recognized the unconformity separating the Tumblagooda Sandstone from younger units. An Ordovician to Silurian age was suggested for the unit because of trace fossils (Opik, 1959) and the discovery of Silurian fossils in Dirk Hartog 17B petroleum-exploration well (Glenister and Glenister, 1957). In an unpublished WAPET report, Johnstone and Playford (1955) proposed the type section, and recognized a "Yalthoo Member", which corresponds to FA4 of this study. The type section was formalized in McWhae et al. (1958, p. 17).

Condon (1965) published a graphic log of the type section. He considered that the Tumblagooda Sandstone was a shallow-marine deposit, which formed as shoals over a topographically positive Northampton Complex. Playford et al. (1976) incorporated the unpublished work of Johnstone and Playford (1955), and suggested fluvial and shallow-marine environments. They assigned the formation a Silurian age.

Three honours projects at the University of Western Australia have dealt with the Tumblagooda Sandstone. Karajas (1969) described some outcrops in the Hutt River–Horrocks area, Mandyczewski (1973) reviewed the whole type section, and Longley (1983) did a detailed study of the Z Bend and Fourways area.

The present study began in 1977, with the mapping of the Ajana 1:250 000 geological sheet (Hocking et al., 1983). Based on this mapping, Hocking (1979) gave a preliminary sedimentological interpretation. This was revised after the type section was remeasured in 1980 (Hocking, 1981a, 1981b). Hocking et al. (1987) summarized early findings of this study. The thesis on which this report is based (Hocking, 1987) was prepared under the joint supervision of Dr B. C. McKelvey (University of New England) and Dr P. E. Playford (Geological Survey of Western Australia), and was accepted in 1987 at the University of New England, Armidale, New South Wales.

## Topographic setting

Outcrops of the Tumblagooda Sandstone occur discontinuously over an area of approximately 7 500 km$^2$ between the Greenough and Murchison Rivers (Plate 1, Figure 1). They extend from near the eastern margin of the Perth Basin to the coast.

The Murchison Gorge is an etch-entrenchment (Finkl and Churchward, 1973), up to 150 m deep, along the lower Murchison River (Plate 1). The gorge extends from the Hardabut Fault downstream to Mount Curious as a subvertically-walled incision, up to 70 m deep, within a broad, gently sloping valley 2 to 4 km wide. Between Mount Curious and Kalbarri, lateral shifting of the

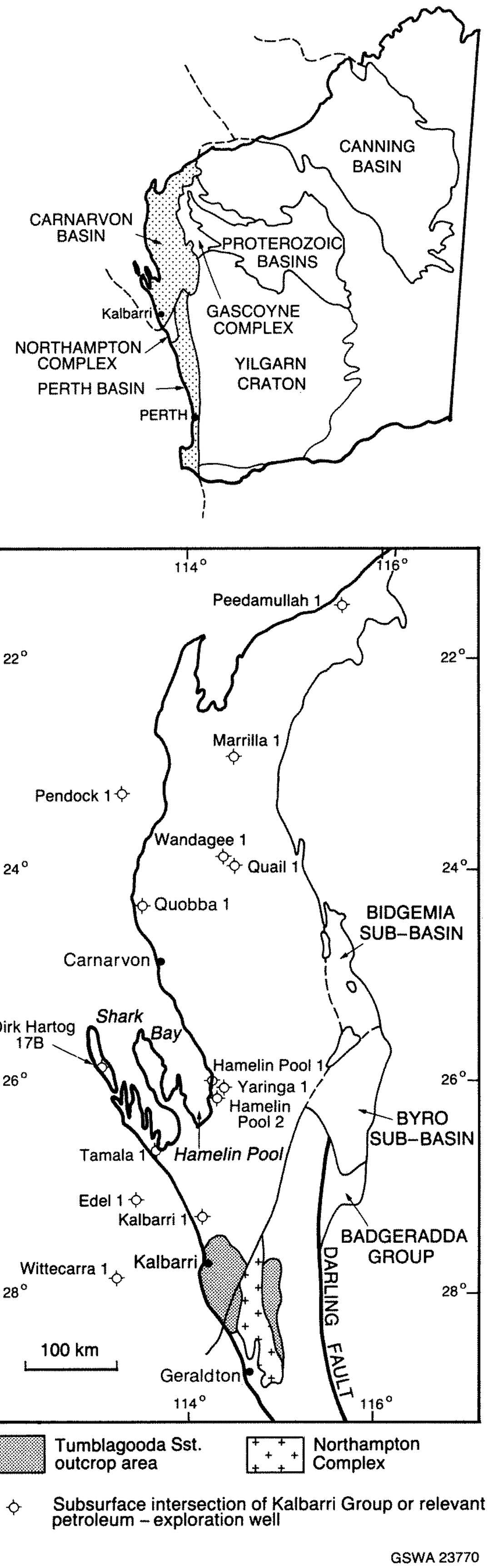


**Figure 1. Regional locality map showing outcrops and subsurface intersections of Tumblagooda Sandstone.**

Murchison River occurred during its incision, and the valley is broader but still rugged and locally precipitous.

Coastal cliffs and gorges extend south of Kalbarri from Red Bluff to Bluff Point, and offer further continuous exposure of Tumblagooda Sandstone. However, they are separated from the Murchison Gorge by approximately 10 km of discontinuous to negligible exposure.

The steeper river gorges and the coastal gorges are partially accessible by formed roads and fire trails (Plate 1). The remainder are part of Murchison House Station, and are accessible from station tracks. Except for tourist lookouts, four-wheel drive vehicles are needed for access. The remainder of the outcrop area lies in mixed grazing and farming country, and is served by a relatively dense and well-established road network (Plate 1).

## Geological setting

The Tumblagooda Sandstone is a thick, well-exposed, sandy "redbed" sequence; the dominant colouring is a hematitic brownish red to purplish brown. Pallid, light-brown to yellowish sediments are present in places; these tints are largely caused by deep weathering. Greenish colouration (due to ferrous rather than ferric iron) is totally absent except in rare mudstone intercalations. There is no clear lithologic control on overall colouration, but on a finer scale, sedimentary structures and prominent joints are highlighted.

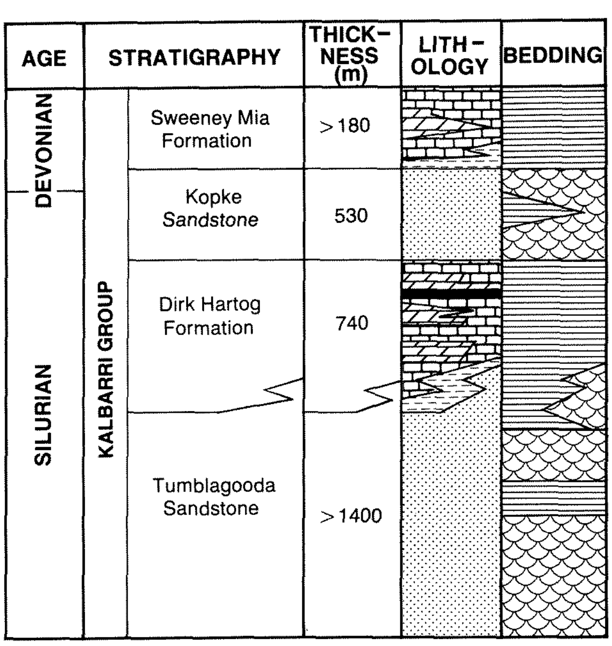


**Figure 2. Silurian to ?Early Devonian stratigraphy in the Carnarvon Basin. Only the Tumblagooda Sandstone is present in the Perth Basin.**

The formation is wholly of Silurian age. This is indicated by rare, poorly preserved microfossils; the conformable relationship between the Tumblagooda Sandstone and the overlying, moderately well-dated, Upper Silurian Dirk Hartog Formation (Philip, 1969); and by radiometric dates of mineralization in the underlying Northampton Complex (434 ± 16 Ma; Richards et al., 1985).

The sandstone is the oldest unit in the Kalbarri Group (Figure 2), and the oldest known sequence in the Perth and Carnarvon Basins. It straddles the boundary between the Perth and Carnarvon Basins in outcrop, and extends through most of the Carnarvon Basin in the subsurface (Figure 1) but does not appear to extend into the Perth Basin much further than the outcrop area.

In the Palaeozoic, the Perth and Carnarvon Basins formed a broad, elongate north-opening trough, and deposition continued uninterrupted across the presently recognized basin boundary. For this reason, the term Perth–Carnarvon Basin is used when referring to the Silurian depositional basin.

## Type section

The type section of the Tumblagooda Sandstone extends for approximately 70 km down the gorge of the lower Murchison River between the Hardabut Fault and Second Gully (Plate 1). It is the only near-complete sequence and is excellently exposed. Consequently, most of the description and analysis in this study is based on the type section. Hocking (1981a) presented a broad sedimentological interpretation of the section, and outlined its limitations.

The true stratigraphic base and top of the Tumblagooda Sandstone are absent in the type section. The oldest strata are in the core of the Hardabut Anticline, adjacent to the Hardabut Fault, and the top of the type section is an eroded surface beneath the Cretaceous Birdrong Sandstone. A conformable contact between the Tumblagooda Sandstone and the overlying Upper Silurian Dirk Hartog Formation is preserved in Kalbarri 1, 30 km northwest of the Murchison River gorge (Figure 1, Plate 1). Comparison of the sequence inferred from electric logs and the sequence in the type section indicates that about 200 m of Tumblagooda Sandstone is absent at the top of the type section.

The type section has been measured as several partial sections because the formation dips west at angles less than 5°. The total exposed thickness is about 1385 m, although the true stratigraphic thickness is probably 1210 m because

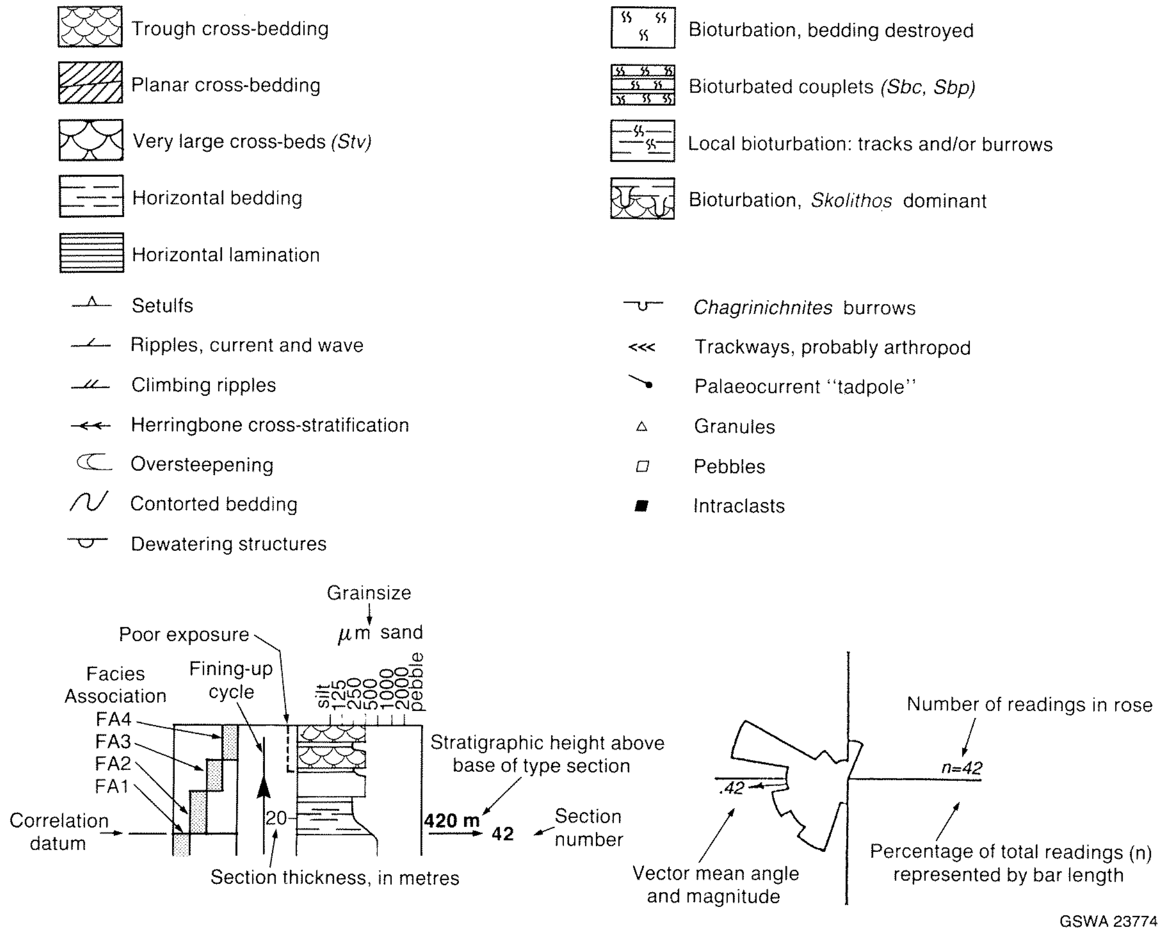


**Figure 3. Legend for palaeocurrent roses and graphic logs of measured sections. Because of the diversity in the numbers of readings, all palaeocurrent roses have been adjusted to one of two sizes. The percentage figure on each rose indicates the length of the bar relative to the total number of readings (n) shown on the rose.**

of fault repetition. Detailed measured sections in the type section and elsewhere are shown in the Appendix and summarized on Plate 1. Figure 3 shows a legend for these sections.

## Facies distribution

Hocking (1981a) proposed three broad facies associations, Facies Associations 1 to 3 (FA1–FA3). A low-energy variant of FA3 was termed FA3a, and is here referred to as FA4. A further association (FA5) is proposed for rocks east of the Northampton Complex.

Each association consists of several facies which commonly occur together in the sequence. An environmental interpretation is not part of the definition of the association. A different environment probably applies for each association, but subjective environmental interpretation is not used in defining each facies association. The facies within each association are primarily single lithotopes, and are based on grain size and/or bedding type (e.g. trough cross-bedded sandstone). They do not have environmental (i.e. interpretive) connotations. In places, two or three similar lithotopes (e.g. laminated and rippled siltstone) are grouped into one facies. For ease of description and reference, the facies are given alphabetic codes, which follow those devised by Miall (1977, 1978) and extended by Le Blanc Smith (1980) and Cole (1980).

In the type section, the facies associations are for the most part stratigraphically and lithologically distinct, and can be regarded as stratigraphic units. They have not been formalized as formations within a "Tumblagooda Subgroup" because they are not mappable units over the outcrop extent of the Tumblagooda Sandstone. The associations and their constituent facies are summarized in Tables 1 and 2. Their distribution and palaeocurrent data are summarized on Plate 1.

## Facies Association 1

Facies Association 1 (FA1) occurs at the base of the type section from the Hardabut Fault to near Ross Graham Lookout (Plate 1), a thickness of about 440 m. It is interbedded with FA2 between Ross Graham Lookout and Fourways (about 150 m stratigraphic thickness), and decreases in abundance to the northwest (up the type section). Away from the type section, sediments similar to FA1 occur in the Bowes River–Hutt River area, for example, south of the turnoff to the Bowes River mouth on the Horrocks Beach road (Figure 4, Plate 1); and east of the Northampton Complex, on Riverside and Yandi Stations and east of Binnu (Plate 1).

## Facies Association 2

Facies Association 2 (FA2) occurs in the central part of the type section between Ross Graham Lookout and Mooliabaanya Pool (Plate 1), in a section about 200 m thick. It is interbedded with FA1 between Ross Graham Lookout and Fourways. FA2 sediments are present in the Hutt River–Bowes River area, for example, on the Horrocks Beach road about 1 km past the turnoff to the Bowes River mouth (Figure 4). It also occurs in low breakaways on Riverside Station, south of Pencell Pool (Plate 1).

## Facies Association 3

Facies Association 3 (FA3) abruptly overlies FA2 near Mooliabaanya Pool, and extends from there to the southernmost coastal cliff exposures. Its maximum thickness in the type section is approximately 260 m. The upper contact is laterally and vertically gradational into FA4. Similar groups of facies to FA3 occur in the Hutt River area (Figure 4) and are regarded as part of FA3, although they probably occur much lower in the sequence than does FA3 in the type section. The upper and lower units exposed at Pencell Pool are both similar to the non-cyclic parts of FA3.

## Facies Association 4

Facies Association 4 (FA4) is present above FA3 and extends to the top of the type section. The maximum exposed thickness is about 45 m, in Tumblagooda Hill and Second Gully (Plate 1). It extends south from Toolonga Hill to the southernmost coastal gorges, but is inaccessible south of Grandstand Rock. The stratigraphic level at which FA4 occurs varies, as does its thickness. The upper boundary of FA4 is not preserved in outcrop due to post-Silurian erosion; Mesozoic sediments rest on a near-peneplained surface of Tumblagooda Sandstone. The central portion of the Pencell Pool sequence is correlated with FA4 because of its trace-fossil assemblage.

## Facies Association 5

Facies Association 5 (FA5) occurs in isolated outcrops east of the Northampton Complex (Figure 5). It has not been seen near other outcrops of Tumblagooda Sandstone. Because the region is highly faulted and outcrops are discontinuous, it is impossible to estimate the thickness of FA5.

# Stratigraphic correlation

## Type section area

At least five high-angle or vertical faults cut the type section. Fault planes or slickensides are not exposed, but the facies sequence is displaced. Correlation across faults is by detailed sequence comparison, and should be regarded as tentative. The possible magnitude of each fault, and thus the extent to which each fault limits stratigraphic correlation and affects environmental interpretation, is discussed here. The names used for the faults are for convenience, and are informal.

### Lockwood Springs fault

The Lockwood Springs fault strikes at approximately 45°, and fault drag is minimal. Sections 11 and 12 are on either side of the fault (Figure 6, Plate 1). Intervals of FA1 in Section 12 resemble the portion of FA1 which is exposed upstream from the stream gauging station — they are coarser grained, more pebbly, and probably thicker than any of the FA1 intercalations between Ross Graham Lookout and the fault immediately to the east (see Appendix, Sections 4 to 11). In contrast, Section 11 is similar to sections which are located some distance downstream. A tentative stratigraphic correlation can be made between Sections 11 and 16 at the 565 m stratigraphic level, based on gross facies distributions (Plate 1). The Lockwood Springs fault is therefore regarded as a down-to-the-east fault which has a probable throw of slightly more than 100 m.

### Fourways fault

The Fourways fault strikes at approximately 30°, and separates Sections 19 and 20. The fault passes through the two major tributary valleys at Fourways, where its position is marked by a ferruginous breccia. The breccia formed by cementation of loose talus by percolation of iron-rich groundwater that seeped from the fault plane. The facies present in FA2 are similar in both blocks, but the section on the east (upstream) block contains more FA1 interbeds. A 30 m thick sequence which is dominated by facies *mSxt* occurs at river level in the west (downstream) block and at the top of the east (upstream) block. This provides a tentative correlation over the fault, and indicates that the west block dropped. Steeper dips either side of the fault, caused by drag, support this sense of movement.

**TABLE 1. KEY TO LITHOFACIES CODES USED FOR THE TUMBLAGOODA SANDSTONE**

| *Prefix (grain size)* | *Major lithotope* | *Suffixes* |
|---|---|---|
| *vf* very fine | *M* mud | *x* cross-bedded |
| *f* fine | *F* silt | *t* trough cross-bedded |
| *m* medium | *S* sand | *p* planar/tabular cross-bedded |
| *c* coarse | *G* gravel (pebble and cobble) | *l* laminated |
| *v* very coarse | *SG* pebbly and granuley sand | *b* bioturbated |
| | *GS* very pebbly sand and granule conglomerate | *v* vertically bioturbated |
| | | *bc* bioturbated couplets |
| | | *bp* bioturbated couplets in planar cross-bedded sand |
| | | *k* *Skolithos*-bearing |
| | | *tv* very large-scale trough cross-bedded |
| | | *tl* large-scale trough cross-bedded |
| | | *tm* medium-scale trough cross-bedded |
| | | *ts* small-scale trough cross-bedded |
| | | *h* horizontally bedded |
| | | *r* rippled |

Note: Codes are modelled on those of Miall (1978), Le Blanc Smith (1980), and Cole (1980).

### The Loop fault

On the northern side of The Loop, an FA1 intercalation within FA2 is juxtaposed with FA2 sediments at river level, and sequences cannot be matched across a 50 m wide valley (Appendix, Sections 25 and 26). This indicates a fault is present along the valley. The valley, and hence the fault, strikes at 45°. When the strike of the fault is extrapolated to the southwest, to a bluff which has 100% exposure, no fault is present, and it cannot be recognized in intermediate exposures around the western side of The Loop. As the fault does not appear to be present on the southwest side of The Loop, and the facies and their proportions are similar in both blocks on the north side of The Loop, the fault is disregarded in terms of its effect on correlation.

### Mooliabaanya Pool faults

Two subparallel faults, striking about 10°, occur along the line of Mooliabaanya Pool and in the ridge immediately west of it, respectively. The western fault is clear on aerial photographs. A small exposure of sandstone on the northeastern side of Mooliabaanya Pool dips 60° east, at approximately the location (from aerial photographs) of the eastern fault. At the south end of Mooliabaanya Pool, dips are not steeper near the fault, but a 10 to 12 m interval of medium- to coarse-grained sandstone of FA1 or FA3 is juxtaposed with facies *mSh* of FA2. Correlation across the faults (Appendix, Sections 28 to 30; Plate 1) is based on the first appearance of FA3 sandstone (facies *cSt*) above a thick interval of FA2 sediments (facies *mSh*, *mShx*, *mSxp*, *Sbv*). Because this transition is below river level in the east block of the east fault, the correlation is taken from the next section upstream, 2.5 km to the southeast. This correlation suggests that both faults have a downthrow to the east of 50 m or less.

## Other areas

### Coastal gorges

The pebbly sandstone marker, the Gabba Gabba Member (*GStS* of FA3), and the first occurrence of facies *Fl* and *Stk* of FA4 can be used to correlate between Sections 35–37 (river gorges) and Sections 41 – 45 (coastal gorges). The relative positions of each suggest that there is no faulting between the two areas, and that the two areas can be correlated stratigraphically.

### West of the Northampton Complex

No marker horizon or major facies change (e.g. FA3 to FA4) is known by which detailed correlation could be extended to scattered outcrops of Tumblagooda Sandstone that lie in the Hutt River valley and further south. Unconformable contacts between Tumblagooda Sandstone and Precambrian rocks can be seen or inferred at several localities, but the facies immediately above the contact varies from locality to locality (Figure 4). Broad stratigraphic correlation may be possible (see "Basin geometry — Southern basin margin").

### Pencell Pool

Correlation of the sequence east of the Northampton Complex at Pencell Pool with the type section appears to be possible (see "Pencell Pool sequence").

### Northern Gully–Nolba area

Outcrops of FA5 in the Northern Gully–Nolba area cannot be correlated with the type section or with each other. They are undoubtedly Tumblagooda Sandstone, but

**TABLE 2. FACIES ASSOCIATIONS, LITHOFACIES, AND LITHOFACIES CODES FOR THE TUMBLAGOODA SANDSTONE**

| *Facies association* | *Code* | *Facies* |
|---|---|---|
| FA1 | *St* | Trough cross-bedded sandstone |
| | *Sp* | Planar cross-bedded sandstone |
| | *Sh* | Horizontally stratified sandstone |
| | *Fl* | Laminated siltstone |
| | *Sb* | Bioturbated sandstone |
| FA2 | *Sh* | Horizontally stratified sandstone |
| | *Shx* | Low-angle cross-bedded sandstone |
| | *Sx* | Medium- to large-scale cross-bedded sandstone |
| | *Sxp* | Planar cross-bedded sandstone, mostly medium to large scale |
| | *Sxt* | Medium- and large-scale, trough cross-bedded sandstone |
| | *Stm* | Small- to medium-scale, trough cross-bedded sandstone |
| | *Sb* | Bioturbated sandstone |
| | *Ss* | Sheet-like sandstone |
| FA3 | *St* | Trough cross-bedded sandstone |
| | *SGt* | Trough cross-bedded sandstone and granule conglomerate |
| | *GSt* | Trough cross-bedded, pebbly sandstone to pebble conglomerate |
| | *Sh* | Horizontally stratified sandstone |
| | *Stv* | Very large-scale cross-bedded sandstone |
| FA4 | *St* | Trough cross-bedded sandstone |
| | *Sp* | Planar cross-bedded sandstone |
| | *Sh* | Horizontally stratified sandstone |
| | *Stk* | Trough cross-bedded sandstone with *Skolithos* |
| | *Spk* | Planar cross-bedded sandstone with *Skolithos* |
| | *Fl* | Laminated and rippled, fine sandstone and siltstone |
| | *Ml* | Laminated mudstone |
| FA5 | *Gt, Gp* | Trough and planar cross-bedded pebble conglomerate |
| | *vSx* | Very coarse-grained sandstone |

Note: Grain-size prefix omitted in most parts of the lower section of the table.

are for the most part dissimilar to the remainder of the formation.

## Palaeoslope

The palaeoslope dipped to the northwest during deposition of the Tumblagooda Sandstone. This is discussed here, rather than later, in order to aid visualization of the regional setting.

Palaeocurrent directions for FA1 and FA3 are strongly unimodal to the northwest (311° and 299°, respectively; Figure 7). As both FA1 and FA3 are low-sinuosity fluvial deposits, these directions indicate that the palaeoslope dipped to the northwest during deposition of FA1 and FA3.

The palaeoslope during deposition of FA2 also dipped to the northwest. This is indicated by the northwestward palaeocurrent directions of intercalated intervals of facies *cSt* (FA1) within the main FA2 sequence, and the southeastward and northwestward palaeocurrent directions of cross-beds in FA2 (facies *mSxt*, *mSxp*, *mStm*). Other palaeocurrent modes in FA2 (Figure 7) are attributed to local undulations in the palaeoslope and longshore currents.

Palaeocurrent directions for FA4 in the river and coastal gorges are northwestward (307°; Figure 7), and indicate that the palaeoslope had the same orientation as for FA3. Directions for the probable FA4 sequence at Pencell Pool (285°; Figure 7) are more scattered, but are not irreconcilable with a northwest-dipping palaeoslope. Reasons for the divergence are discussed in the interpretation of the Pencell Pool sequence.

Palaeocurrent directions for FA5 range from westward to northward (Figures 5, 7), and have a mean of 308°. FA5 is also a fluvial deposit, so that the directions support a broadly northwest-dipping palaeoslope for the most southeasterly outcrops of the Tumblagooda Sandstone.

## Bedform terminology

Megaripples, dunes, and sandwaves are regarded as a continuous gradation of bedforms (Harms et al., 1982, p. 2.10; Allen, 1982a, p. 334–336), rather than as

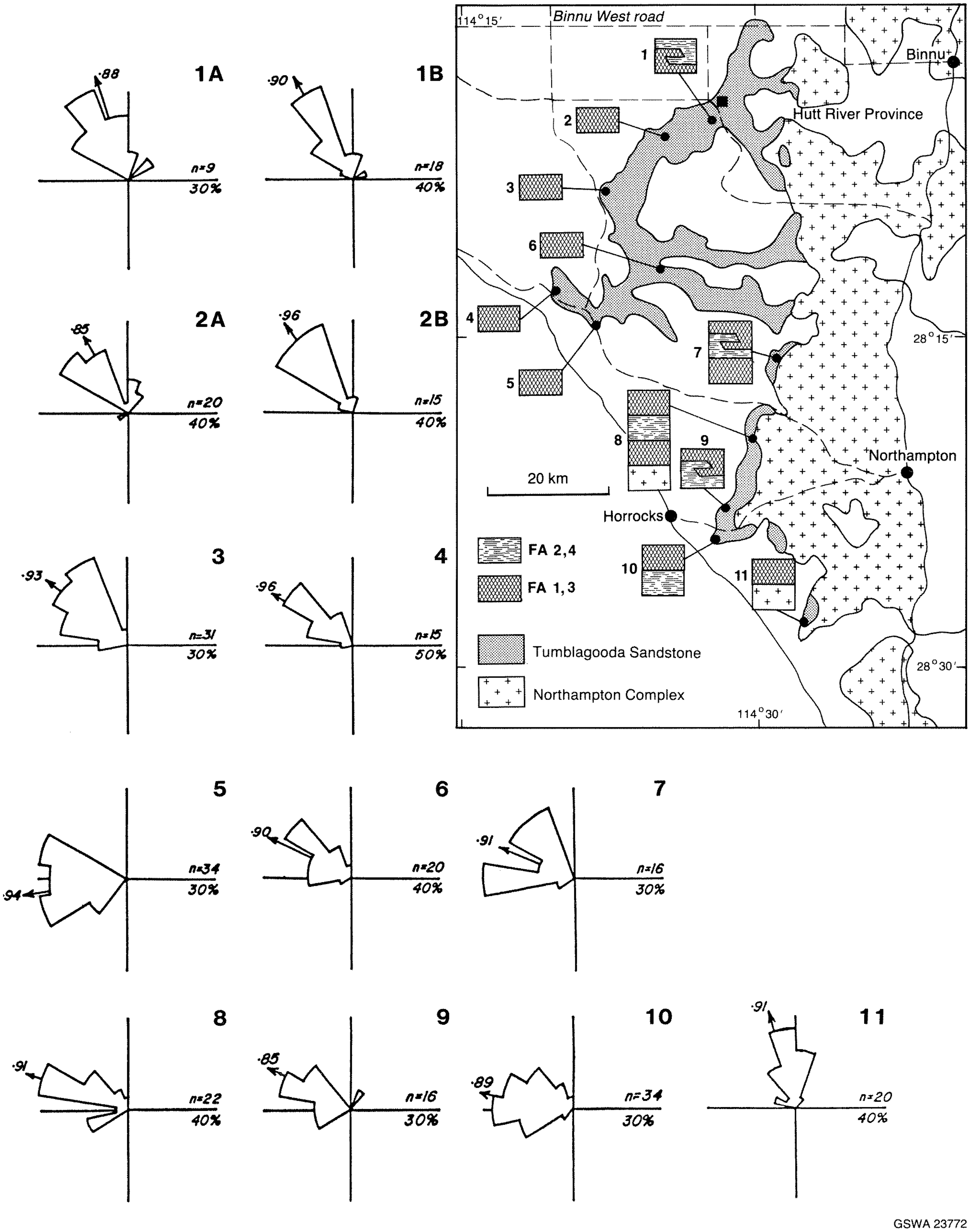


**Figure 4. Distribution, facies, and palaeocurrents for Tumblagooda Sandstone west of the Northampton Complex and south of 28° S. Note the spatial variation in the facies which rests on the Northampton Complex. Palaeocurrent measurements are all from FA1 and FA3; no FA2 exposures contained measurable foresets or ripples. 1A and 1B, and 2A and 2B, are from different cosets at each locality.**

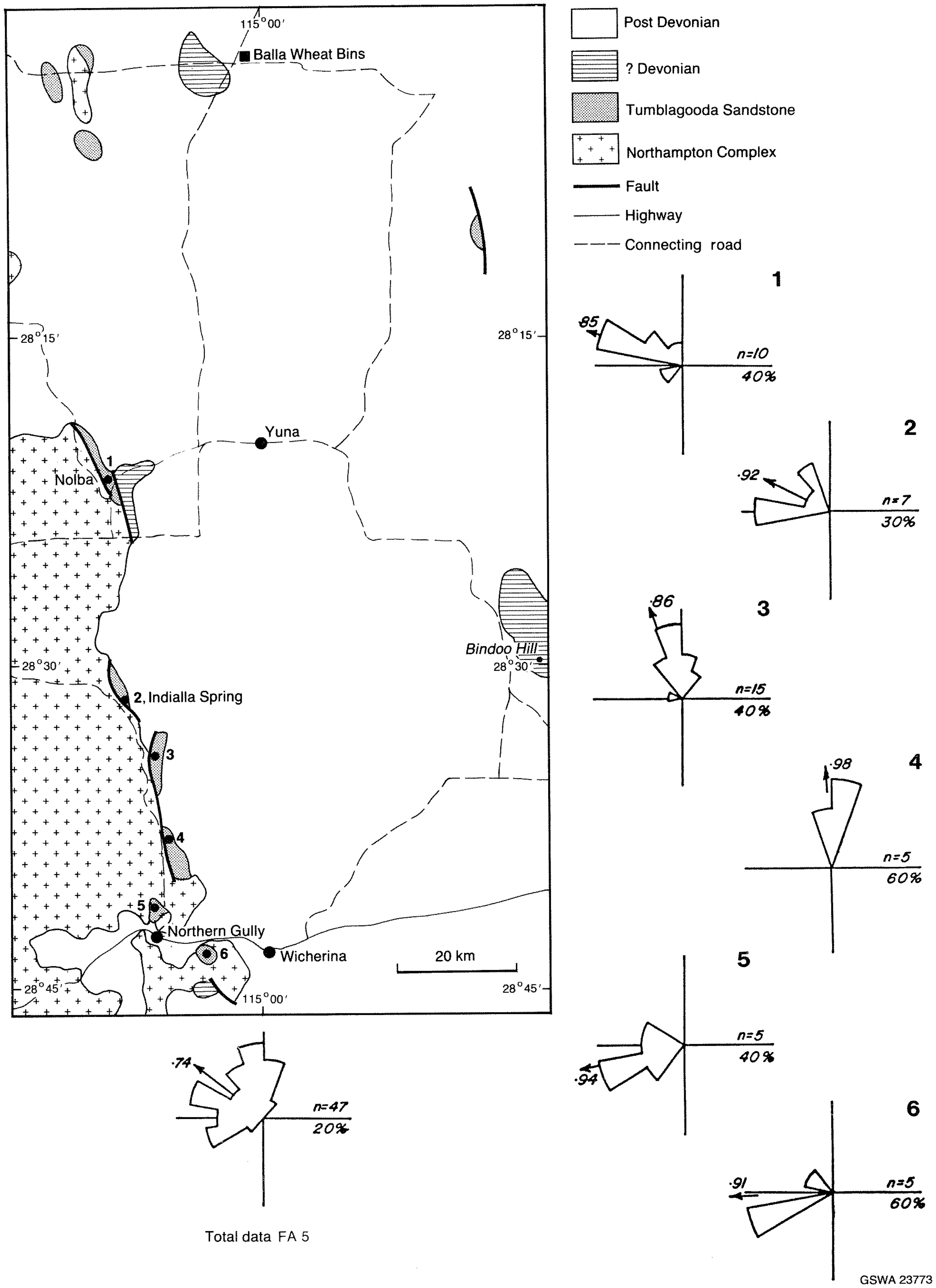


**Figure 5. Distribution and palaeocurrents for the Tumblagooda Sandstone east of the Northampton Complex and south of 28° S. This area covers all FA5 outcrops. The "?Devonian" unit was shown as Tumblagooda Sandstone by Playford and others (1970).**



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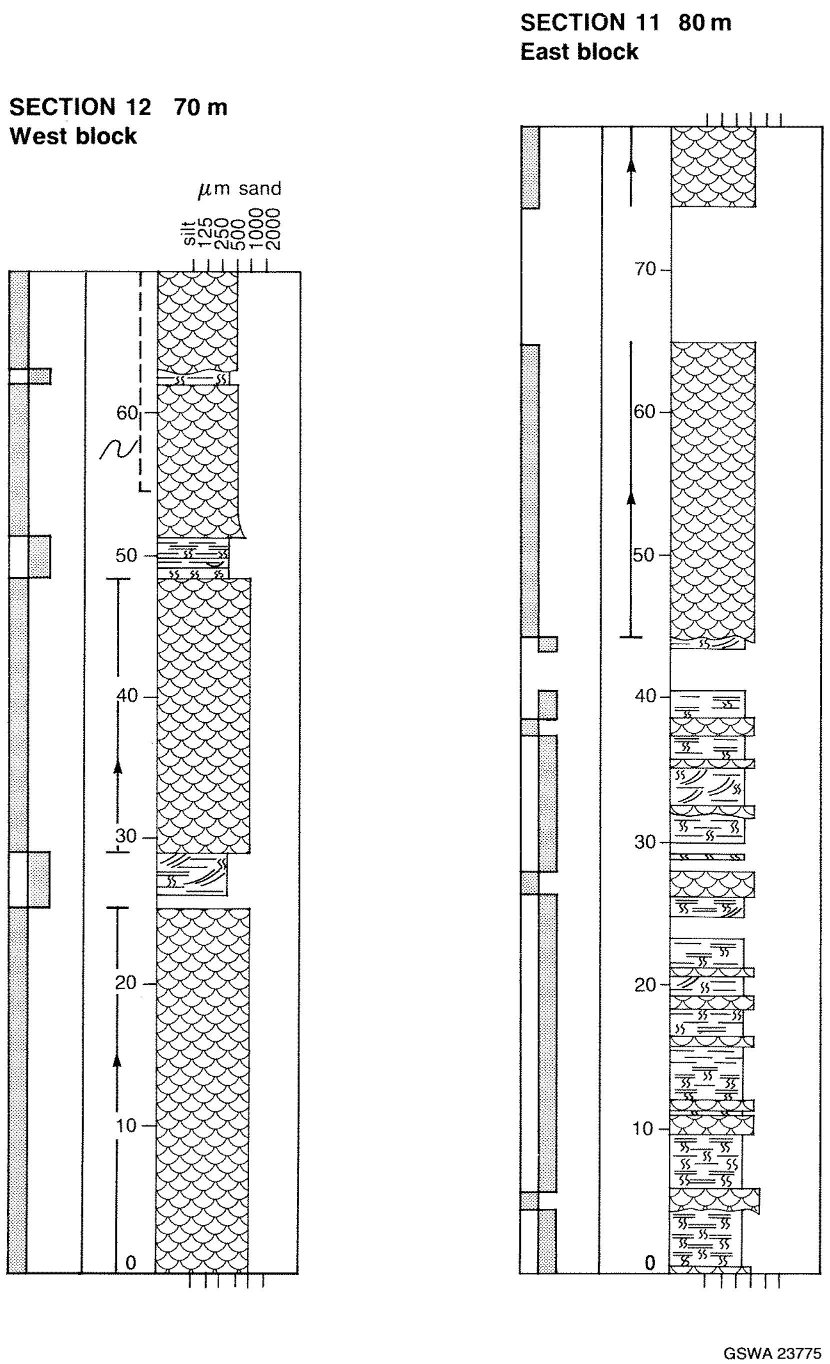



**Figure 6. Sequences exposed on either side of the Lockwood Springs fault. These are Sections 11 and 12 of the Appendix and Plate 1, and their location is shown in Figure 82 (Appendix).**

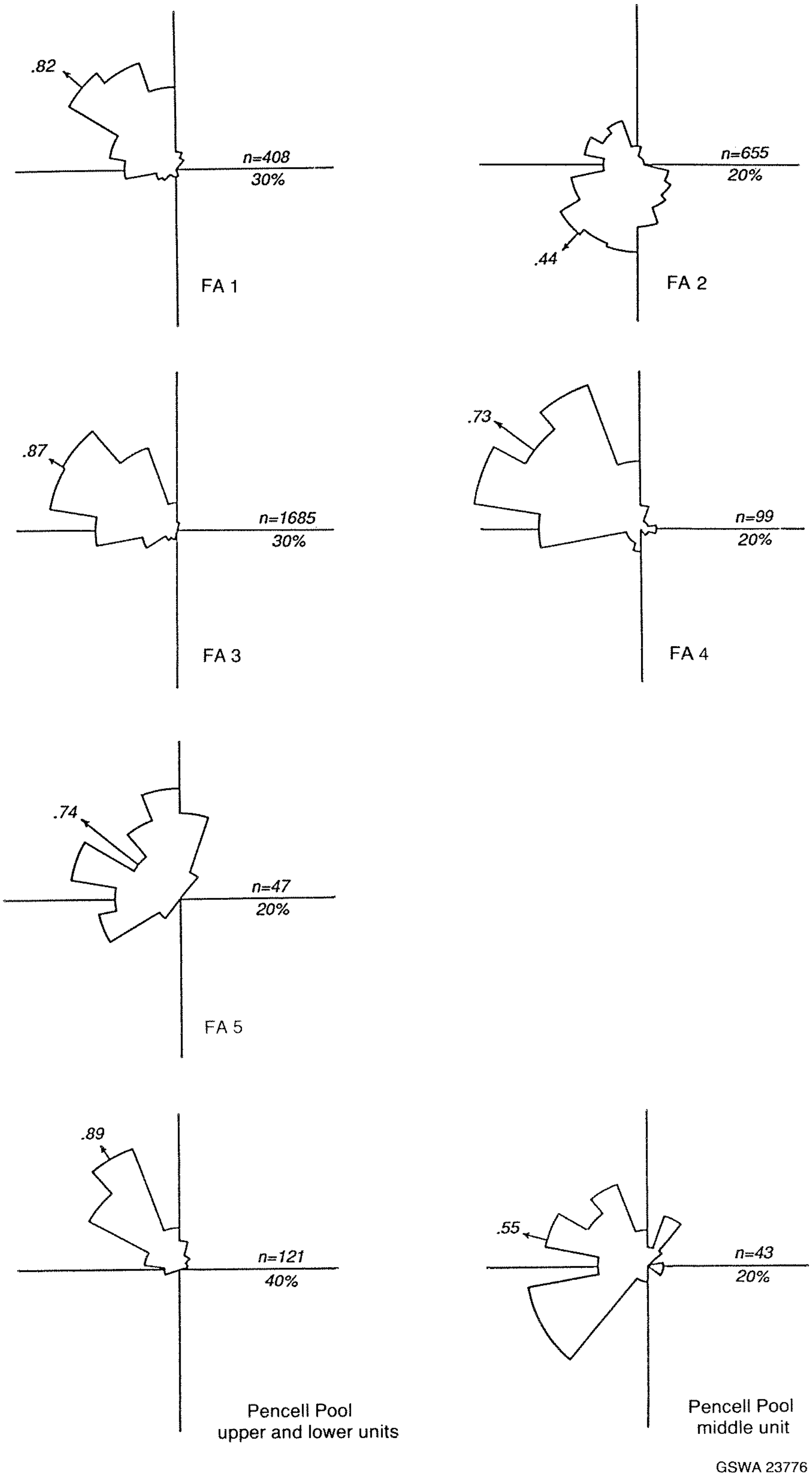



**Figure 7. Total palaeocurrent directions for each facies association and the Pencell Pool sequence. The data for Pencell Pool are grouped into the two main lithofacies groups in that section. Annotations on the roses are explained in Figure 3.**

**TABLE 3. BEDDING SCALE DIVISIONS**

| *General bedding terms* | *Bounding thickness* | *Cross-bedding terms* |
|---|---|---|
| Thinly laminated | | |
| | 2 mm | |
| Laminated | | Laminated |
| | 1 cm | |
| Very thin | | Very small scale |
| | 5 cm | |
| Thin | | Small scale |
| | 20 cm | |
| Medium | | Medium scale |
| | 80 cm | |
| Thick | | Large scale |
| | 120 cm | |
| Very thick | | Very large scale |

Source: McKee and Weir (1953), Table 2.

Note: A "medium" division has been added, to suit bedding in the Tumblagooda Sandstone.

genetically different bedforms, each with a different hydrodynamic threshold. Following Allen's terminology, cross-stratified bedforms larger than ripple size are referred to as two-dimensional (relatively straight) or three-dimensional (strongly curved) dunes. Where used, the terms megaripple, dune, sandwave, and sandridge apply simply to the size of the bedform. "Dune" has no implication of an eolian origin.

Bedding-scale divisions (Table 3) are based on McKee and Weir (1953). Only a two-part division of cross-bedding is made, into trough and planar types. "Planar" is used instead of "tabular" to suit the facies codes. Horizontal stratification, used here, is the same as the flat, planar, plane or parallel stratification, lamination, or bedding of other authors (Harms et al., 1982, p. 3.23; Collinson and Thompson, 1982, p. 97; Allen, 1982a, p. 260).

# Facies Association 1 (FA1)

Facies Association 1 (FA1) consists of mostly coarse-grained (overall range: fine to very coarse), poorly to moderately sorted, quartz sandstone. FA1 extends from Section 1 to Section 30, but only Sections 1 to 3 have thick, continuous sections of the association — elsewhere it is interbedded with FA2.

## Facies description

Facies codes for FA1 are summarized in Table 2. More than 80% of FA1 consists of trough cross-bedded sandstone (*St*). Pebbles are common, both scattered through the sandstone and in discrete stringers. Subordinate facies are horizontally stratified sandstone (*mSh*) and planar cross-bedded sandstone (*cSp*), and (at the tops of some fining-upward cycles) rare bioturbated beds (*Sb*). Laminated siltstone (*Fl* ) has been found in one location. Palaeocurrent data are unimodal to the northwest (311°, vector magnitude 0.82; Figure 8).

Sorting is very poor to moderate and, overall, improves upwards in FA1. Fine- and medium-grained intervals are, in general, better sorted than coarse-grained intervals. There is no obvious correspondence of either sorting or grain size with scale of bedding, except that very coarse-grained, very poorly sorted intervals are generally small- to medium-scale cross-bedded rather than large-scale cross-bedded. Fining-upward and/or thinning-upward cyclicity is clear in some areas (e.g. on the track to the stream gauging-station (Plate 1; Appendix, Section 2); near the station; and in the river bed 400 to 600 m downstream of the station). The cycles are 2 to 10 m thick and commonly appear to be contained within single cosets. They have a facies sequence of (locally *cSGt* →) *cStl* → *cStm* → *mStm* (locally → *f Stm* or *f Sts* and/or *Sb*)).

Cut-and-fill structures are common within cosets (Figures 9, 10), but coset boundaries, although erosive, are laterally persistent and planar to sub-planar. Cosets extend over hundreds of metres, and major bedding planes (at least some of which are coset boundaries) commonly can be traced on 1:40 000 scale aerial photographs with reasonable confidence for several kilometres. No significant erosional relief has been observed.

## Lithofacies

### Trough cross-bedded sandstone (*St*)

Trough cross-bedded sandstone (*St*) ranges from medium-grained sandstone to granule and (uncommonly) pebble conglomerate, but is dominantly coarse to very coarse grained (*cSt*). Bedding ranges from small (cm) to very large (1 m) scale (Figures 9, 10). Troughs have medium-angle (10 –20°) foresets and persist down dip for several times their width. Large-scale rib and furrow pattern is well-developed on bedding plane exposures. Simple parabolic recumbent oversteepening (Doe and Dott, 1980) and more complex contorted bedding are common. Reactivation surfaces are also present. Palaeocurrent data are strongly unimodal to the northwest (vector mean 322°, vector magnitude 0.85; Figure 8). Measurements showed no consistent variation according to bedding scale or grain size, so palaeocurrent data generally have not been subdivided. No eastward palaeocurrent directions were found.

Coarse- to very coarse-grained, trough cross-bedded sandstone (*cSt*) occurs as stacked (multi-storey) sequences, or in the lower portions of fining-upward cycles. Cross-sets are primarily medium-scale sets (*cStm*), 40 to 60 cm thick, and large-scale sets (*cStl* ), more than 60 cm thick. Pebbles and granules are commonly present, especially near the base of the FA1 interval and downstream of the Lockwood Springs fault.

Medium-grained, trough cross-bedded sandstone (*mSt*) occurs mostly near the top of the sequence of FA1. It is generally transitional upwards from larger scale and/or coarser grained, trough cross-bedded sandstones in fining- and/or thinning-upward cycles. Thick, non-cyclic sequences of medium-grained sandstone are uncommon. Cross-sets are small scale (10 – 20 cm) and medium scale (40 – 60 cm). Facies *mSt* is succeeded either by bioturbated sandstone (*Sb*) (near the top of FA1 where cyclicity is present, or where the facies is interbedded with FA2 sediments), or coarse-grained, trough cross-bedded sandstone (*cSt*). Scattered pebbles and granules are locally present.

### Trough cross-bedded sandstone (*cSt*) intervals within FA2

Discrete intervals of coarse-grained, trough cross-bedded sandstone (*cSt*) are interbedded with FA2 sediments between the stream gauging station and The Loop. These intervals are regarded as part of FA1 rather than FA2 because they are less mature texturally and are very similar to the remainder of FA1, and palaeocurrents were northwestward (307°, vector magnitude 0.82; Figure 8), not southward. Their lower contacts are planar or sub-planar (Figure 11), with one exception (see below), but local "stepping" of the contacts indicates they are erosive.

Intervals of this facies have a sheet-like, rather than a channel-like (shoestring), geometry (Plate 1), and range in thickness from less than 1 m to more than 20 m. When traced laterally in the gorges, they are commonly persistent

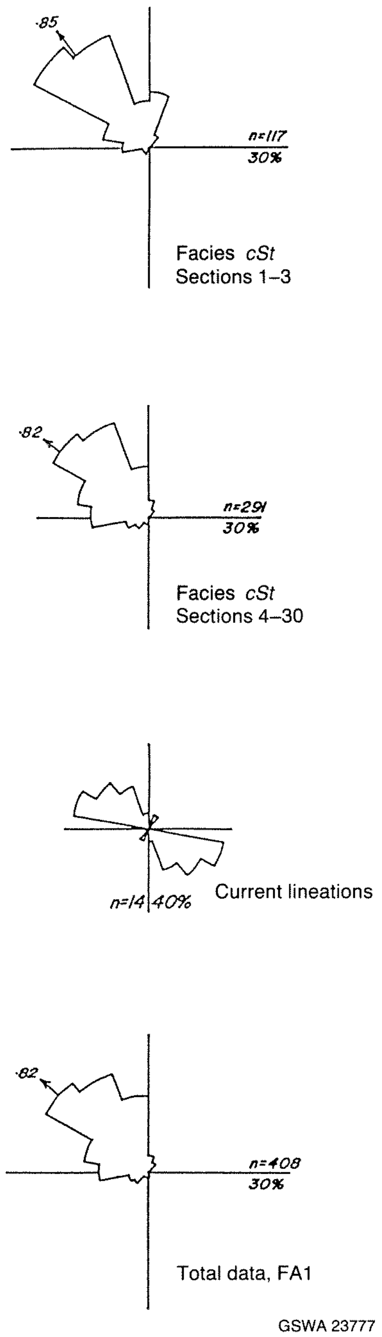



**Figure 8. Palaeocurrent totals for FA1, grouped by facies. Data for planar cross-bedding *(Sp)* is included with trough cross-bedding *(cSt)* because of the small number of readings and the apparent similarity of direction.**

over several kilometres but they do thicken, thin, coalesce, lens out or grade into FA2 facies eventually. This is shown in the Hawks Head–Ross Graham area in Sections 4 to 11. In this area, some thin FA1 intervals grade laterally into FA2 (facies *mSs*, *mStm*, and *mSx*). The cross-beds in FA2 can be distinguished because they have southeastward palaeocurrent directions.

A major FA1 interval is present near the base of the Z Bend, and extends from at least Section 15 (and possibly Section 14) to Fourways. A scoop-shaped channel at the base of the interval cuts into thinly bedded FA2 sediments (Figures 12, 13) at the Z Bend. The channel is 5 m deep, trends northwest, and is capped by a marked diastem. It is filled by a single coset which consists of very large (up to 1.5 m) trough sets. Both the channel fill and the overlying sandstone interval consist of sparsely pebbly, coarse- and medium-grained sandstone which is locally oversteepened or contorted (Figure 14) and has northwestward palaeocurrent directions. The main sandstone interval is 9.8 m thick, and fines upwards slightly. It is overlain by a 40 cm bed of bioturbated sandstone, and then by 1 m interval of small-scale, trough cross-bedded sandstone. The latter is texturally similar to the underlying FA1 sandstone, but has southwestward palaeocurrent directions. These directions indicate short-distance reworking by currents normal to those which infilled the channel. The same pattern occurs at the top of the interval at Fourways.

At most occurrences, coarse-grained sandstone intervals are underlain and overlain by laterally extensive horizons of bioturbated sandstone (*Sb*). Unidentified sinuous trails occur locally on the topmost sandstone of the interval, and symmetrical ripples cap one of the intervals near the foot of Hawks Head Lookout.

### Planar cross-bedded sandstone (*Sp*)

Planar cross-bedded sandstone (*Sp*) is uncommon within FA1, and was not separately discriminated during measurement of sections. It can be seen downstream from the Hardabut Anticline, and is, like the trough cross-bedded sandstones, poorly sorted and dominantly medium to coarse grained. Foresets dip at 10° to 15° to the northwest, and have asymptotic rather than angular bases. Grain-size differentiation down foresets is typical, and scattered pebbles occur. The facies occurs mostly as single, laterally discontinuous sets up to 1 m thick. The sets overlie, underlie, and grade laterally into, trough cross-bedded sandstone.

### Horizontally stratified sandstone (*mSh*)

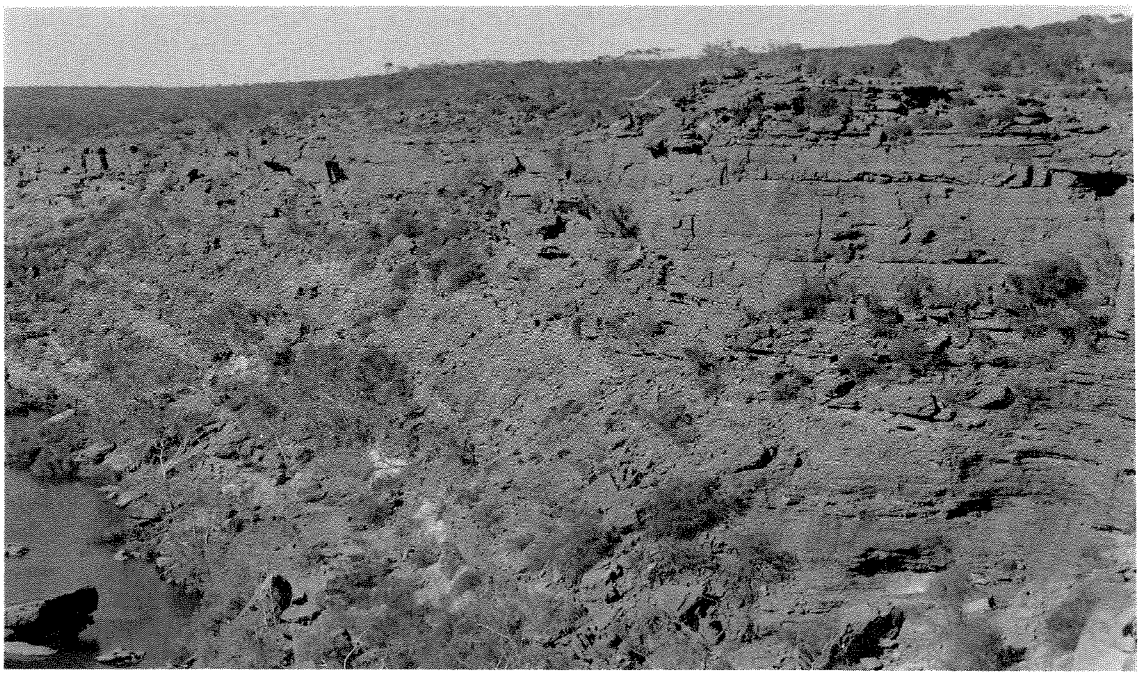
Horizontally stratified, medium-grained, moderately sorted sandstone (*mSh*) is common in FA1 in some areas, as in the Hardabut Anticline. Primary current lineation is uncommonly preserved, and palaeocurrent data are shown

GSWA 23778

Figure 9. FA1: small and medium troughs of *cSt*, showing scooped basal surface and very consistent current direction; 200 m downstream of stream gauging station.

GSWA 23779

Figure 10. FA1: small-scale trough cross-bedded sandstone at stream gauging station. Cut-and-fill is common within sets, but higher order planar bounding surfaces (arrowed) also occur.



GSWA 23780

**Figure 11. FA1 and FA2: FA1 (vertical bluff) overlying FA2 at Hawks Head Lookout. Note the planar coset boundaries within FA1 and the slightly scoured, nearly planar contact between FA1 and FA2.**

in Figure 8. The facies occurs as interbeds a few centimetres thick, and as intervals up to 4 m thick which truncate trough cross-bedded sandstones. In neither form is it laterally persistent.

### Laminated Siltstone (*Fl*)

Dark red to purple-grey, finely horizontally laminated micaceous siltstone (*Fl*) has been found in one small exposure about 2 m across and 30 cm thick. It rests on coarse-grained, trough cross-bedded sandstone (*cStm*), and is erosively overlain and cut out laterally by the same facies. The exposure is on the south side of the river in the Hardabut Anticline, at 27° 52' 39" S, 114° 32' 17" E. It is unlikely that the facies was widespread or thick, because silty or muddy intraclasts are rare in coarser grained facies of FA1. However, sandstones do become silty at the tops of fining-upward cycles in some areas (e.g. on the track into the stream gauging station).

### Bioturbated sandstone (*Sb*)

Bioturbated sandstone (*Sb*) occurs downstream of the stream gauging station, as thin (less than 30 cm) irregularly preserved beds of intensely bioturbated, medium-grained, poorly sorted sandstone which contains scattered granules. It is the only facies in FA1 which contains any indication of biogenic activity. The poor sorting reflects the complete disruption of bedding and (presumed) original stratification. Intervals of bioturbated sandstone cap fining-upward and/or thinning-upward cycles, and are erosively overlaid and cut out by trough cross-bedded sandstone of the next cycle. The facies is identical to the vertically bioturbated sandstone facies (*Sbv*) in FA2, although occurrences are thinner and more laterally restricted in FA1. The burrow pattern resembles *Heimdallia chatwini* (Bradshaw, 1981), but is commonly slightly deeper.

## Facies interpretation

Hocking (1981a) established that FA1 was deposited in a low-sinuosity, braided fluvial environment. This interpretation was based on the unidirectional, low-scatter palaeocurrent directions; the textural immaturity of sandstone within FA1; the predominance of trough cross-bedding; and the lack of bioturbation except in a specific setting.

The amount of detail possible in the interpretation for FA1 is less than for other parts of the Tumblagooda Sandstone because of the limited exposure; only Sections 1 to 3 are composed predominantly of FA1. Lateral facies relationships cannot be determined because these sections overlie each other, and are located almost directly down-palaeoslope from each other; only broad bedding trends can be traced for any distance across the palaeoslope.

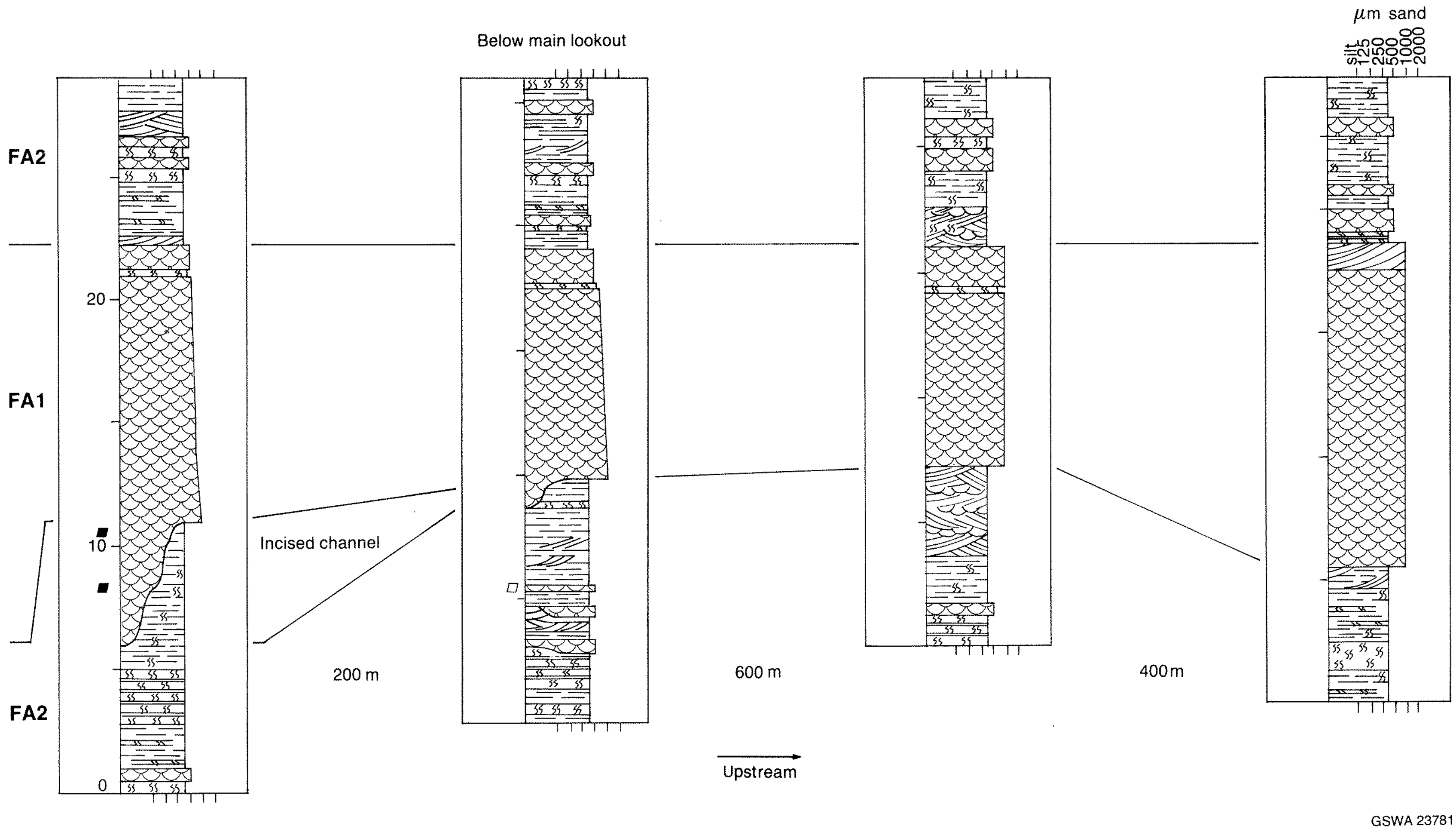



**Figure 12. Measured sections through the FA1 intercalation at the Z Bend. The left-hand section is through the incised channel shown in Figure 13.**

GSWA 23782

Figure 13. FA1 and FA2: FA1 intercalation at the Z Bend (north arm, south face) showing scoured channel of FA1. FA2 is the thinly bedded sediment at the top and base. FA1 is the thicker bedded interval in the centre of the photograph.

GSWA 23783

Figure 14. FA1: contorted bedding within FA1 interval at the Z Bend; located near top of FA1 interval, approximately midway between the two main joint fissures on the western face.

## Lithofacies

### Trough cross-stratified sandstone (*St*)

The trough cross-bedded sandstone facies (*St*) was formed by migrating three-dimensional (curved) dunes (Allen, 1982a, p. 361), at moderate to high current velocities (Harms et al., 1982, table 2.1). The range in scale of trough sets, from small to large, and grain size, from very coarse to medium, over short intervals laterally and vertically, indicate that both current velocities and water depth were variable. Scattered pebbles and poor sorting suggest turbulent flow.

The presence of 2 to 10 m thick, fining-upward cycles suggests that maximum water depth was at least 10 m, and progressively thinner sets were deposited in progressively shallower water. No further attempt at calculating water depth is made because, as Harms et al. (1982, p. 3.20 –3.21) noted, set thickness is generally only a small fraction of original dune thickness.

Oversteepening is formed by current drag on liquidized trough sets (Allen 1982b, p. 392). Liquidization of the sediment may have taken place in response to shocks produced by earthquakes or "local" events, such as sudden flooding (Allen, 1982b, p. 300).

### Planar cross-bedded sandstone (*Sp*)

Planar cross-bedded sandstone (*Sp*) formed in migrating two-dimensional dunes (Harms et al., 1982, p. 3.22). Although such dunes mostly form at lower flow velocities (but not necessarily lesser water depth) than three-dimensional dunes (Harms et al., 1982, p. 3.22; Allen, 1982a, p. 334), the asymptotic bases of sets of planar cross-bedded sandstone indicate higher than average flow velocities for this bedform (see Leeder, 1982, figure 6.39; Jopling, 1965). Grain-size differentiation on foresets indicates that avalanching occurred and provides further evidence of strong flow. The local development of planar cross-sets rather than trough sets is assumed to be related to local bar geometry rather than to markedly different flow conditions or environments.

### Horizontally stratified sandstone (*mSh*)

Primary current lineation (parting lineation) on some exposures of horizontally stratified sandstone (*mSh*) indicates that the facies was deposited at high flow velocities by turbulent, unidirectional currents (Allen, 1982a, p. 264 –265). This is usually referred to as upper flow-regime or upper plane-bed deposition (Leeder, 1982, p. 89; Collinson and Thompson, 1982, p. 97; Harms et al., 1982, p. 2.13 –2.16). More horizontally stratified sandstone may originally have been deposited during periods of high current velocities. However, such accumulations were probably destroyed as velocity lessened and formed dunes.

### Laminated siltstone (*Fl* )

The solitary known occurrence of laminated siltstone (*Fl* ) formed by quiet deposition from suspension in a temporarily protected area.

### Bioturbated sandstone (*Sb*)

Intense bioturbation at the tops of FA1 cycles (facies *Sb*) occurred when deposition ceased in a specific area for a substantial period of time. This was probably between episodic floods. The most likely setting is a fluvial system that prograded onto tidal flats but only flowed intermittently. The development of the bioturbated sandstone facies is discussed in more detail in the interpretation of Facies Association 2.

## Architectural elements

Miall (1983, p. 282–283) proposed a three-dimensional approach for the analysis of fluvial sequences, because of the shortcomings of (essentially) two-dimensional, vertical profile analysis. He used the term "fluvial architecture" to encompass the study of the distinct components which make up an entire fluvial depositional system and of how they are related (Miall, 1983, p. 282).

Miall (1985) argued that there are eight basic architectural, or geometric, elements in fluvial systems. These range from channels (macroforms, which in their broadest form include the entire river "valley") to components of bars (microforms), and they are in part hierarchical (Table 4). In theory, recognition and description of the elements and their relationships to each other, in three dimensions, should lead to reconstruction of the depositional system without distorting the data to fit an existing facies model (Miall, 1985).

Study of FA1 is restricted largely to the mesoforms of Miall (1985, p. 266), because nearly all the accessible exposure extends directly down the palaeoslope, which makes recognition of macroforms difficult. FA1 consists primarily of sandy bedforms (Element SB of Miall's architectural element classification, see Table 4). Lesser amounts of laminated sand-sheets (Element LS) are present (Figure 15), as facies *Sh*, but these are impersistent laterally. Lateral accretion deposits, Element LA, have not been recognized, but this may be due (in part) to limitations of outcrop. Gravel (Element GB) and silt or mud (Element OF) are effectively absent. Gravity flows (Element SG), which would be recognizable by graded bedding or disorganized internal textures (Miall, 1985), are also absent.

TABLE 4. ARCHITECTURAL ELEMENTS FOR FLUVIAL DEPOSITS

| *Code* | *Element* | *Characteristics* |
|---|---|---|
| CH | Channels | Concave-up-base; variable-scale macroform |
| FM | Foreset macroforms | Convex-up bounding surface; macroform composed of multiple smaller elements |
| LA | Lateral accretion deposits | Sigmoidal cross-bedding or other evidence of lateral accretion; macroform composed of multiple smaller elements |
| GB | Gravelly bars and bedforms | Conglomerate-dominated mesoform |
| SB | Sandy bedforms | Sand-dominated mesoform |
| SG | Sediment gravity-flow deposits | Structureless or chaotically bedded gravel, sand, or mixture of both; mesoform |
| LS | Laminated sand sheets | Horizontally stratified sand with sheet-like geometry |
| OF | Overbank fines | Mud and silt; mesoform and/or macroform |

Source: summarized from Miall (1985).

The two larger elements, channels (Element CH) and foreset macroforms (Element FM), are distinguished less easily. Major concave-up or convex-up bedding contacts (channels and foreset macroforms respectively: Miall, 1985, p. 274, 277) have not been seen. A possible foreset macroform is indicated by the fining- and thinning-upward cycles, the downdip extent of cross-sets, and the lateral extent of cosets in FA1. These suggest a broad, large, compound bar. The bar was composed of, at the base, medium to large three-dimensional dunes which formed in relatively deep water along a channel thalweg. They were overlaid and succeeded by progressively smaller, superimposed, bedforms as the bar grew and water depth lessened. The bar may have been capped locally by horizontally stratified layers, where shallow water forced a transition to upper regime flow (Figure 15). Foreset macroforms cannot be distinguished in non-cyclic and indistinctly cyclic parts of FA1. Deposition there and away from the channel thalweg may have been as an extensive field of smaller, simple three-dimensional dunes and, where channel geometry and flow conditions allowed, local two-dimensional dunes.

Indications of channel morphology (Element CH) are provided by the low scatter of palaeocurrent data; the lateral persistence of cosets; their planar contacts; and the absence of concave-up erosional relief at a larger scale than cross-set size, on air photographs or the ground. On the scale of cosets and fining-upward cycles, the width-to-depth ratio exceeds 20:1, which indicates that smaller channel forms are mobile channels, and points to sheet-braiding rather than channel-braiding, under Cotter's (1978) terminology. This agrees with the inherently unstable nature of a sandy substrate on which there were no plants.

## FA1 depositional environment

Palaeocurrent roses for measured sections in FA1 are shown with the sections in the Appendix, and grouped data are shown in Figure 8. Palaeocurrent directions are strongly unimodal to the northwest, with a very low scatter at any one horizon and a low scatter overall.

The unidirectional palaeocurrent data for FA1, the textural immaturity of sandstones within it, and the predominance of trough cross-bedded sandstone (Element SB) indicate that FA1 was deposited in a low-sinuosity fluvial environment in which three-dimensional dunes predominated. The lack of bioturbation, except in the uppermost part of FA1, and its restriction to a specific setting, supports this interpretation. The virtual absence of fine-grained suspension deposits (Element OF), even as intraclasts, indicates that no stable interdistributary areas were present, and makes any form of anastomosing or single-channel model untenable. Fluvial style was therefore braided, using Rust's (1984) terminology. Although horizontally stratified sandstone (Element LS) is common locally, it is not laterally persistent, and is not associated with ripples. This indicates that widespread, upper flow-regime deposition in sheet floods (Miall, 1985) was not common.

The predominance and variable scale of trough cross-bedding indicate that current velocities were mostly medium to high, but quite variable within that range. Parting lineations within horizontally stratified sandstone indicate that high to very high current velocities prevailed at times, possibly at the peaks of floods. Some contortion of bedding also took place then. Successively finer grained and/or thinner trough sets resulted from a combination of both lessening current velocity and water depth, in part during the waning stages of floods. Planar cross-bedded sets probably indicate minor development of transverse bars rather than periods of significantly lower current velocity. Water depths, as deduced from the thickness of fining- and thinning-upward cycles, sometimes exceeded 10 m.

The combination of the interpretation above with architectural element analysis indicate that FA1 was deposited in a major, low-sinuosity, sand-dominated fluvial system (Figure 16) which flowed during

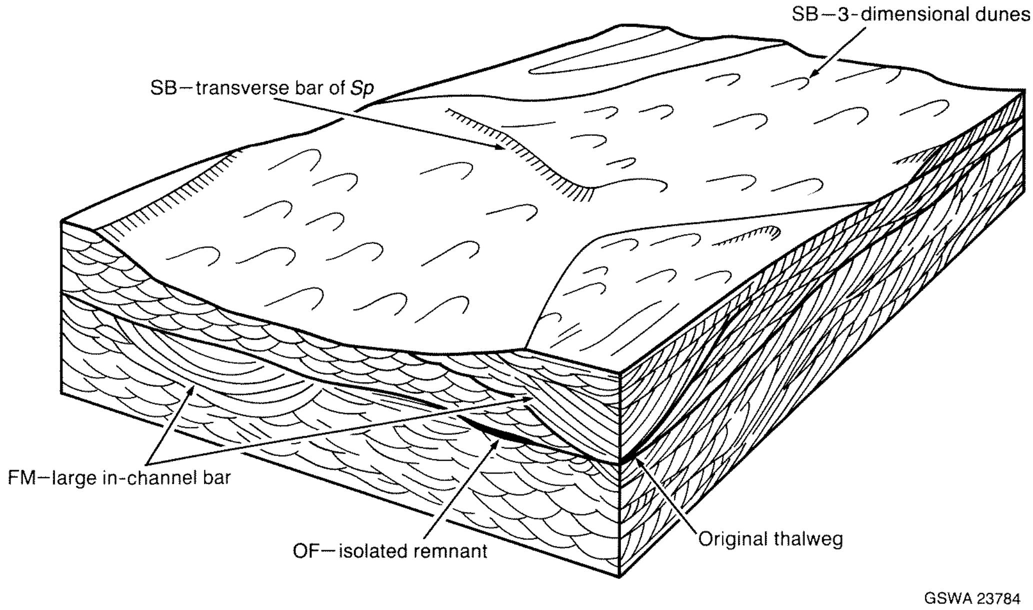



**Figure 15. Architectural elements interpreted for FA1 and FA3. Bedforms are dominated by three-dimensional dunes. Shallow flow occurs over top of a large, gradationally bounded, in-channel bar; the bar now diverts flow, but it originally developed in the channel thalweg. Scale varies for FA1 and FA3, because the depth of flow was different, but the elements are similar.**

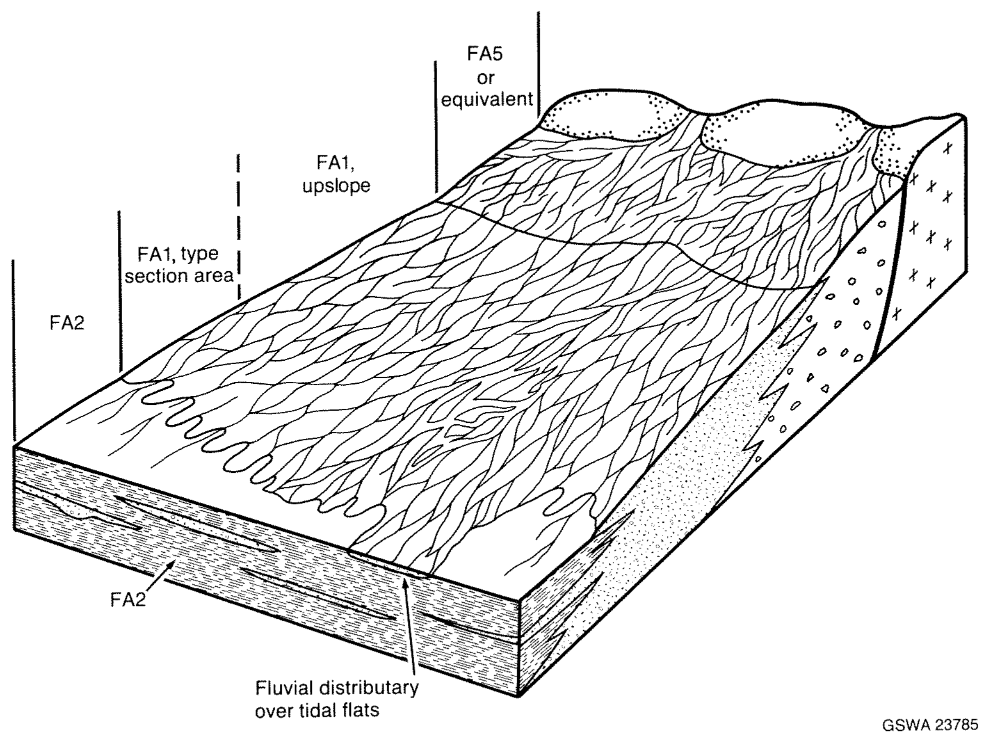



**Figure 16. Depositional model for FA1. There is severe compression of scale from front to back; the braiding is diagrammatic only. Movement along the bounding fault generated abundant terrigenous sediment supply from the basin hinterland. When rivers were not flowing, marine waters could enter the lower fluvial distributaries, and sediments were bioturbated. At other times, the fluvial system prograded over the tidal flats, as shown.**

intermittent floods. Channels were up to 10 m deep, broad, had very gently sloping or stepped banks, and migrated rapidly. Large compound bars, composed of superimposed sets of progressively smaller three-dimensional dunes, first grew in the channels and then diverted flow, while fields of smaller three-dimensional dunes formed between the bars. Compared to the twelve models, or examples, given by Miall (1985), the FA1 fluvial system is closest to Model 10: a deep, low-sinuousity river containing sand flats or shoals with isolated linguoid transverse bars.

Palaeocurrent data for FA1 indicate a source to the southeast. The Northampton Complex was not a source, because palaeocurrents were not deflected around the complex and the Tumblagooda Sandstone is not, and has not been, garnet-rich (as is the Northampton Complex; Peers, 1971). The principal source was the Yilgarn Craton, approximately 120 km southeast of the type section. Uplift of the craton, by movement on the Darling Fault at the western margin of the craton, could generate the volume of sediment necessary for FA1. Lesser sediment input may have been derived from intervening Precambrian areas such as the Mullingarra Inlier. An overall fining-upward trend in FA1 could be due to either gradually decreasing palaeoslope, or to decreasing movement on the Darling Fault and consequent lesser relief on the Yilgarn Craton.

Deposition of the distal parts of FA1, where it is interbedded with and subordinate to FA2, is discussed in the next section, under "FA1–FA2 transition".

# Facies Association 2 (FA2)

Facies Association 2 (FA2) contains the most varied and potentially largest collection of facies of any association in the Tumblagooda Sandstone, and five broad facies have been distinguished. All five are predominantly fine- to medium-grained sandstone. The association is present in Sections 3 to 31. Palaeocurrents are summarized in Figure 17.

Between Section 15 (near Lockwood Springs) and The Loop (Sections 23 to 26), the gorge progresses obliquely down the palaeoslope at about 30° to palaeoslope strike (determined from FA1 and FA3), and up-section by about 200 m total. From this area, lateral and vertical variation within FA2 can be assessed over about 20 km down-palaeoslope and about 35 km across palaeoslope. There is pronounced down-palaeoslope change in the abundance of the various facies which constitute FA2, from dominance by bioturbated sandstone (*Sb*) near Hawks Head Lookout, through a mixed area near Z Bend–Fourways, to dominance by horizontally stratified sandstone (*mSh*) in The Loop area (Figure 18). Different facies also change in abundance within individual sections. For example, cross-bedded sandstone (*mSx*) increases in abundance up-section at The Loop (Figure 18). However, there is no obvious cyclicity or repeated association of facies, except for bioturbated sandstone (*Sb*), which commonly occurs immediately above FA1 intercalations.

## Facies description

Bedding within FA2 is dominantly small to medium scale, and is highlighted by red and white striping, mottling and streaking. This colouring is commonly delicate enough to outline internal structures in ripples and burrows. Five (mostly) broad facies are recognized: horizontally stratified sandstone (*mSh*); intensely bioturbated sandstone (*Sb*); medium- to large-scale cross-bedded sandstone (*mSx*); small- to medium-scale, trough cross-bedded sandstone (*mStm*), and thin, sheet sandstone (*mSs*). The first three facies are both broader in scope and more abundant than the last two. Tracks, trails and lateral and vertical burrows are common in much of FA2. Except for intensely bioturbated sandstone (*Sb*), trace fossils have not been used to differentiate facies, although different forms are in part facies dependent.

Palaeocurrent directions are varied (Figure 17). Two principal modes, southeastward and southwestward, and a lesser northwestward mode are present. These are more apparent on the facies total roses (*mSxp*, *mSxt*, *mStm*) than on the FA2 total rose, because the greater number of readings for facies *mStm* masks the directions gleaned from other facies. Ripple forms are varied, and because of their lack of relationship to a particular facies (except as a transitional bedding type) they are discussed and analysed separately.

### Lithofacies

#### Horizontally stratified sandstone (*mSh*)

Facies *mSh* (Figures 19, 20) is dominated by horizontally stratified sandstone *sensu stricto* (*mSh*). Red and white colouration, mica veneers, and slight grain-size variations (from fine to medium) define bedding. Much of the internal structure consists of small, low-angle ripple cross-lamination. Primary current lineation is seen mainly on loose talus blocks rather than *in situ*. At Hawks Head Lookout, bedding in facies *mSh* undulates over the top surface of a cross-bedded interval (*mSx*), but this has not been noted elsewhere. In some good, laterally extensive exposures (more than about 50 m), horizontal stratification grades laterally into low- to very low-angle (<10°, commonly <3°) cross-bedded sandstone (*mShx*). The cross-sets are solitary, up to 1 m thick and have an asymptotic base extending several metres before merging into horizontal stratification (Figure 19). Both the horizontal and the low-angle stratification are mostly 2 to 5 cm scale; beds rarely reach 20 cm thickness. Palaeocurrent data from *mShx* are grouped with *mSxp*, because of the small number of readings.

Sedimentary structures in facies *mSh* include dewatering structures (Figure 21), desiccation cracks (Figure 22), contorted and syndepositionally faulted bedding (Figure 23), rippled surfaces, ripple washouts (Figure 24), and setulfs. All of the above are locally enhanced by clay drapes. Intervals of subcritically to supercritically climbing ripples up to 40 cm thick (mostly less than 15 cm) occur throughout the facies (Figure 25). Contorted bedding, due to dewatering, is also locally present on a large scale. On the platform below the lower carpark on the downstream side of The Loop (base of Section 23), disrupted bedding extends through at least 3 m vertically and, as irregular hollows, over more than 50 $m^2$ laterally. Adhesion ripples, adhesion warts and adhesion lamination (Kocurek and Fielder, 1982) are particularly common, and locally grade into setulfs (see below).

Some medium-angle (10–20°) planar cross-stratification is included within facies *mSh*, when exposures are two-dimensional and do not show the foresets. Bioturbated beds up to 20 cm thick are also included locally. Over several metres stratigraphic thickness, such interbedded intervals comprise up to 30% of the section (see Figure 19).

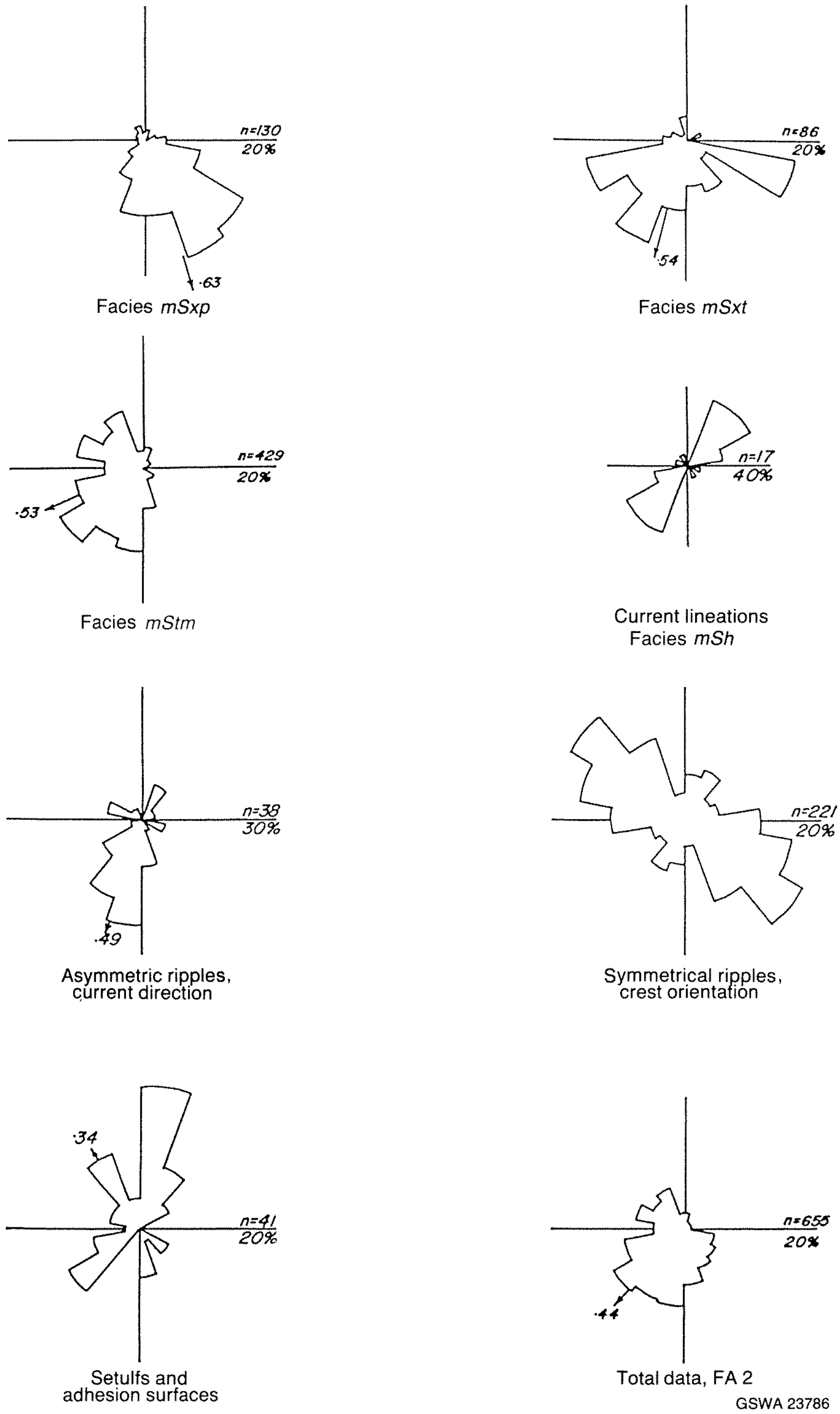



**Figure 17. Palaeocurrent totals for FA2, grouped by facies. Facies *mShx* measurements are included with facies *mSxp* because of the paucity of readings.**

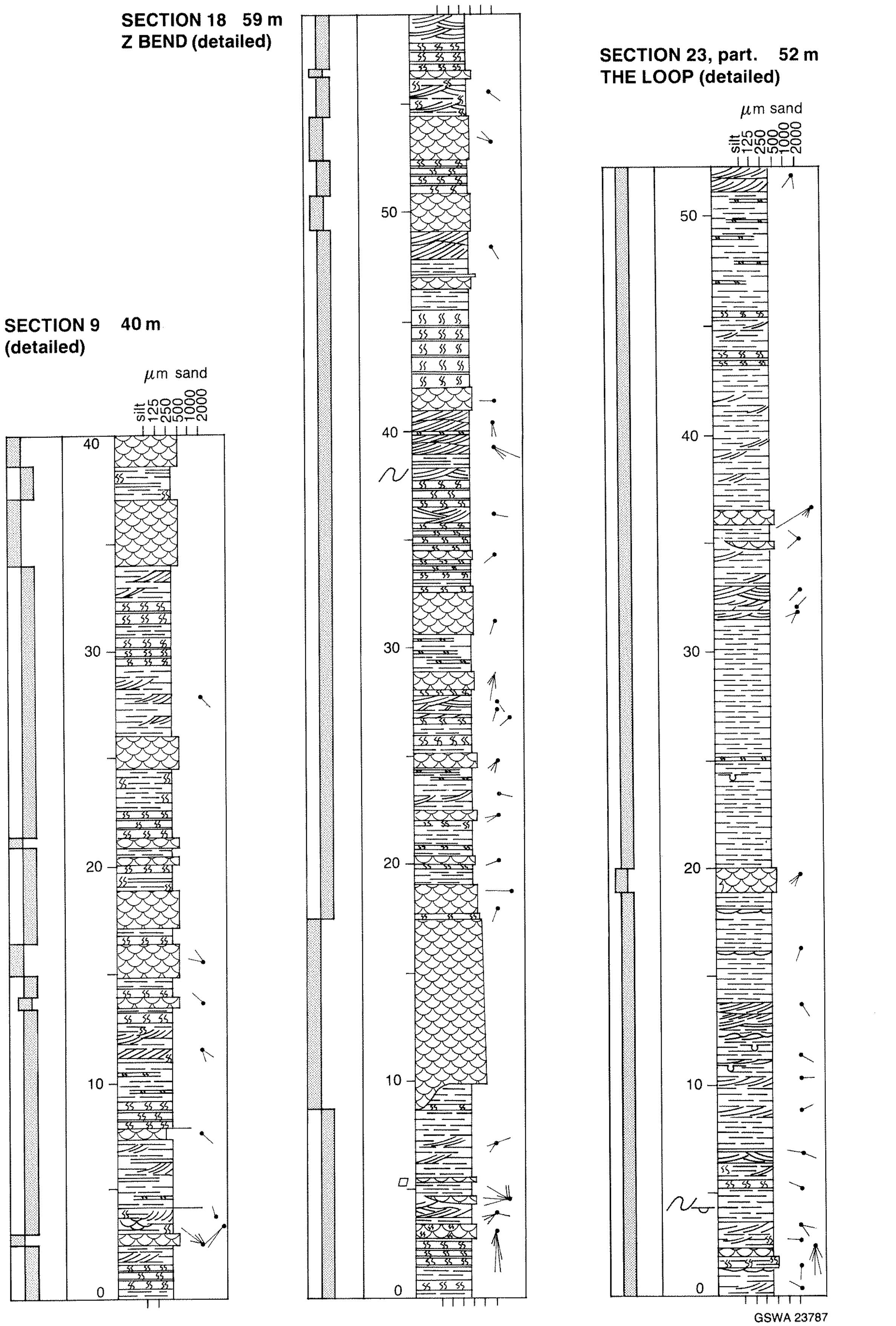



**Figure 18. Detailed measured sections of FA2 at Hawks Head lookout (Section 9), the Z Bend (Section 18), and The Loop (Section 23). The sections show the variation in facies abundance within the association along the palaeoslope.**


GSWA 23788

**Figure 19.** FA2: horizontal stratification *(mSh)*, small scours, superficial channels, low- to medium-angle asymptotically based cross-bedding *(mShx)*, burrowed beds *(Sbv)*, lack of obvious cyclicity, and erosively capped megaripples *(mSxt)*; 1 km upstream from Natures Window, The Loop.

GSWA 23789

**Figure 20.** FA2: reactivated megaripple *(mSxt)* with eroded top and later sub-horizontal infill by *mSh*: 300 m northwest of Natures Window, The Loop. This is included in facies *mSxt*, though it would not be distinguished from the surrounding *mSh* in section logs due to scale.

GSWA 23790

**Figure 21. FA2: dewatering pit, western side of The Loop below bottom car park. Such pits are common in FA2, and are locally associated with large escape burrows.**

Setulfs occur mainly in facies *mSh*, and range in size from less than 1 cm high, 1 cm wide and 2 to 3 cm long, to about 2 cm high and wide, and 6 to 7 cm long (Figures 26 –28). They occur commonly in subparallel lines, and are closely associated with adhesion surfaces and adhesion ripples (Figures 28, 29). Mandyczewsky (1973) recognized "wind structures" in The Loop area, but it is not clear whether he was referring to adhesion structures or setulfs.

The trace fossil in intensely bioturbated intercalations is mostly *Heimdallia* sp. Other trace fossils include arthropod walking tracks (Figure 30), escape burrows and ?resting hollows (Figures 31–33), and various less specific trails, tracks and burrows (Figure 34). Many trackways, ranging in width from about 1 cm to more than 35 cm, appear to have been made by eurypterids (K. McNamara, pers. comm.).

### Bioturbated sandstone (*Sb*)

The bioturbated sandstone facies (*Sb*) increases in abundance down-section and up-palaeoslope from the Z Bend. It includes massive, vertically bioturbated beds in which there is no relict primary bedding (*Sbv*) (Figures 35, 36); laminated to burrowed couplets with horizontal lamination preserved at the base of each couplet (*Sbc*) (Figure 37); and laminated to burrowed couplets where the original bedding was low angle planar cross-bedding (*Sbp*). Bioturbated intervals commonly appear coarser grained and grittier (scattered coarse grains) than surrounding sediments.

The principal burrow type is *Heimdallia* sp. (Figures 38, 39). *Heimdallia chatwini* was initially described from the Devonian–?Silurian Taylor Group of Antarctica by Bradshaw (1981), and identified in the Tumblagooda Sandstone by Longley (1983). *Heimdallia* as described by Bradshaw had a maximum depth of 13 cm, whereas the burrows in the Tumblagooda Sandstone average 20 cm, and may be better considered as a separate species. Round clumps (in plan) of 1 to 2 cm diameter burrows (Figure 40) are also present. Other trace fossils include plugs and grooves (some of which may be *Beaconites* and *Chagrinichnites*, Figures 31–33, 36) amidst bioturbated sandstone.

Massive bioturbated beds (*Sbv*) are generally 20 to 30 cm thick, and locally up to 80 cm thick. Upper contacts are sharp and erosive, while lower contacts range from clearly defined and relatively sharp, to transitional over 5 to 15 cm into underlying beds (Figure 35). Individual beds cover hundreds of square metres (Figure 36), and locally can be traced laterally for several tens of metres before they grade into facies *mSh* or *mSx*. Well-defined, sharp non-erosive lateral contacts also occur.

GSWA 23791

**Figure 22. FA2: desiccation cracks; 1 km upstream of Natures Window, The Loop. Cracks in a clay-draped surface were infilled by sand; the clay has since been eroded.**

Laminated to burrowed couplets (*Sbc* and *Sbp*) consist of a sharp-based laminated sand overlaid by progressively more bioturbated sand. There is no relict primary bedding for most of the couplet. The only difference between *Sbv* and *Sbc* or *Sbp* is that, in the latter two, bioturbation has not totally destroyed bedding. Couplets are up to 60 cm thick but more commonly 20 to 30 cm thick, and persist laterally for tens of metres. Couplets occur singly and in stacked sequences. *Sbp* consists of low-angle, intersecting couplets which grade laterally into facies *mSh* and *mSx*, and is less common than *Sbc*.

### Medium- to large-scale cross-bedded sandstone (*mSx*)

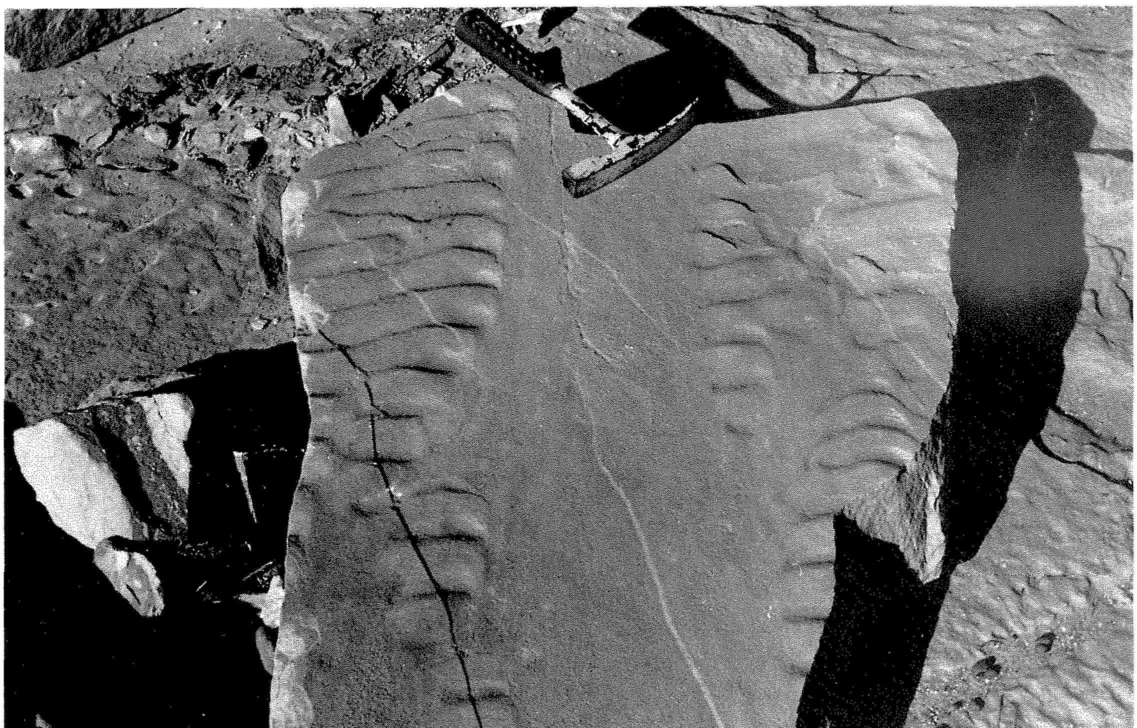
Medium- and large-scale (20 to 60 cm, and 60 cm respectively), trough (*mSxt*) and planar (*mSxp*) cross-bedded, fine- to medium-grained sandstone are grouped in one facies (*mSx*). There is a continuous gradation between these two bedding types, and the facies is transitional into low- to very low-angle cross-bedded sandstone (*mShx*). In places, cross-bedded intervals begin as several thin cross-sets separated by facies *mSh*. Laterally, the cross-sets gradually cut down, thicken and coalesce into larger cross-sets (Figure 41). Rippled surfaces occur as topsets, and were included in the facies by Longley (1983). Palaeocurrent roses are shown in Figure 17.

Trough cross-bedding (*mSxt*) ranges from small to large scale, but most sets are between 20 and 60 cm thick (Figures 19, 20, 42). The cross-bedding is characterized by multiple closely spaced erosion and reactivation surfaces in sets and foresets respectively. Sets commonly climb slightly, show sideways-filling as well as down-channel progradation, and are in places sigmoidal. Basal contacts vary from relatively planar surfaces, through channels less than 2 m across which have gently sloping banks, to scoop-shaped scours. Upper contacts are generally planar due to erosion by the overlying unit, generally facies *mSh* or *Sbc* (Figure 19), although exhumed megaripples occur near river level northwest of Natures Window (Figure 20). Bundle sequences have not been recognized. Apparent herringbone cross-stratification is present at several localities but commonly it does not fulfil the criteria given by Klein (1977); it is largely complex trough filling. Bioturbation is rare except on topsets.

Planar cross-bedded sandstone (*mSxp*) occurs in solitary and multiple sets. Sets are mostly tabular and, less commonly, attenuated wedges. Foresets dip at up to about 20°, and have asymptotic bases which can locally be traced via low-angle cross-beds (*mShx*) into horizontally stratified sandstone (*mSh*) (Figure 19). Solitary sets range in height from less than 10 cm (these are normally grouped with facies *mSh*) to 1.8 m. Intervals of *mSxp* persist for several hundred metres laterally, and foresets show repeated slight changes in direction every 20 to 50 m. Exposures parallel to palaeostrike appear as intersecting, low angle planar cross-stratification dipping at 5 or 6°, and are superficially similar to swash cross-stratification

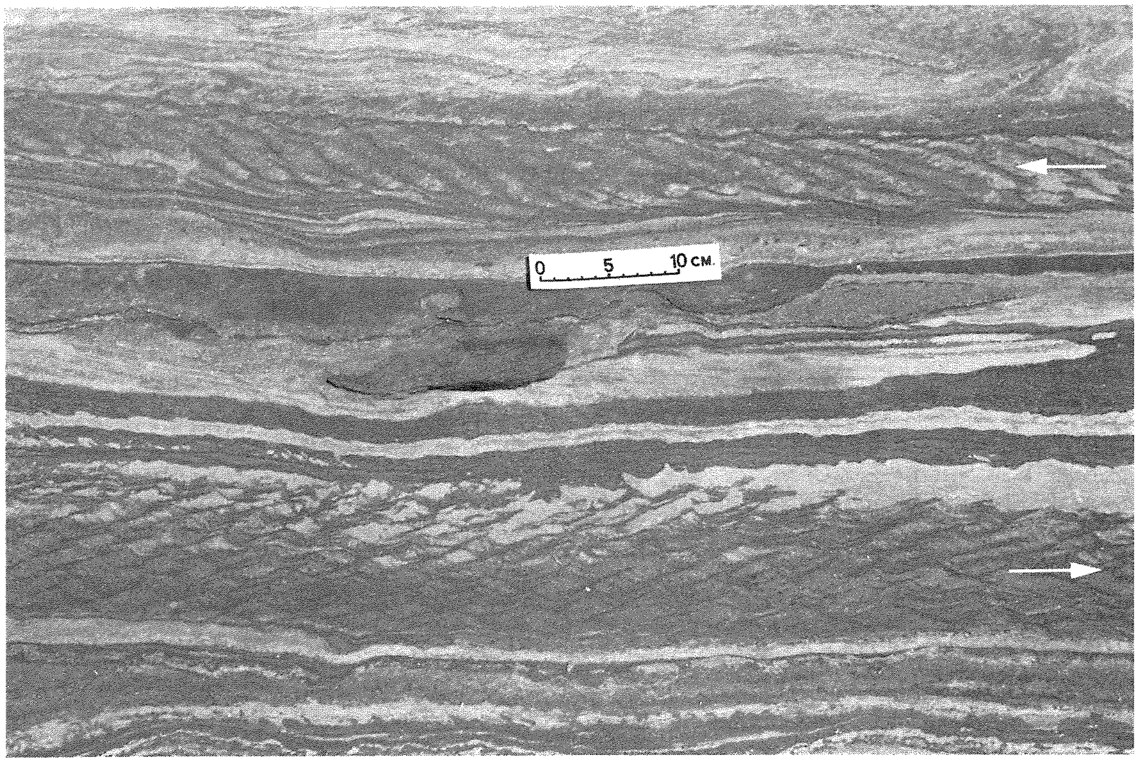
GSWA 23792

Figure 23. FA2: syndepositionally oversteepened, contorted, and faulted bedding; between The Loop and Fourways at Section 21. The contortion is confined to a 3 m thick zone of *mSxp* within *mSh*, and persists for about 100 m laterally. It was probably caused by high velocity flow shortly after deposition. Contorted horizons are laterally truncated at the top of the layer.



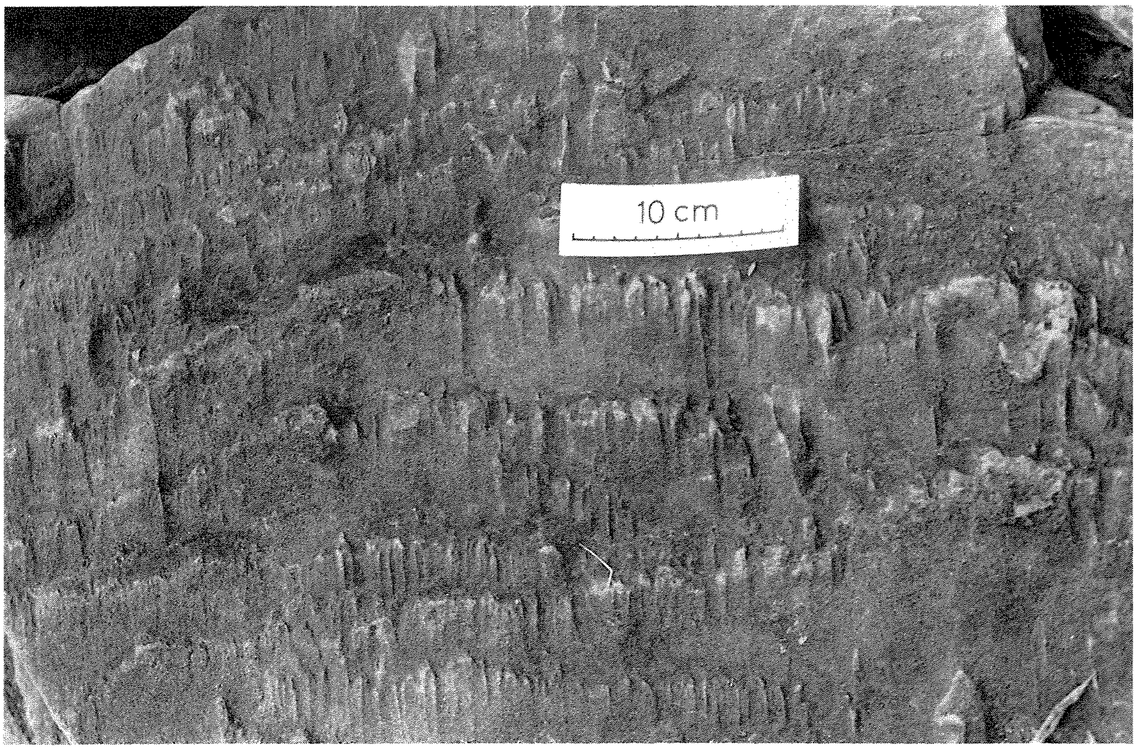
GSWA 23793

Figure 24. FA2: ripple washout; west side of The Loop, near river level below bottom carpark. The washout formed by sheet flow during late stage emergence.




GSWA 23794

**Figure 25.** **FA2: three sets of climbing ripples with opposing current directions (highlighted) within facies *mSh;* base of The Loop below top carpark. The sets formed under conditions of continual high sediment influx when there were opposing currents of similar strength.**




GSWA 23795

**Figure 26.** **FA2: lines of setulfs; fallen block below bottom carpark, The Loop. These setulfs clearly originated as blown-out ripples.**

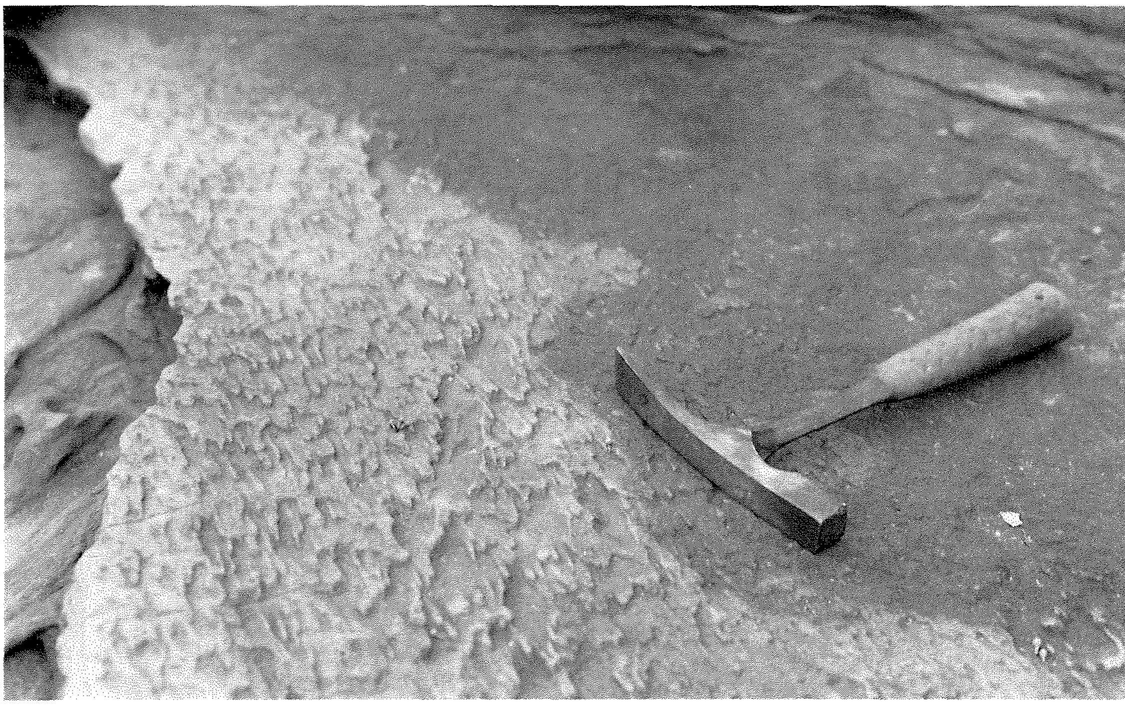



**Figure 27. FA2: field of setulfs; base of Z Bend near Section 18. A thin clay drape has enhanced preservation. These setulfs probably did not originate through erosion of current ripples; they may have formed in very shallow, subaqueous conditions.**

(Harms et al., 1982, p. 7.6). Oversteepening and syndepositional faulting are present but not common (Figure 23). Bioturbation is uncommon. Tracks are present on topsets, but only extend down foresets at one locality, where the animals making the tracks appear to have slid down a foreset.

### Small- to medium-scale, trough cross-bedded sandstone (*mStm*)

Small- to medium-scale, trough cross-bedded sandstone (*mStm*) generally occurs in thin, laterally persistent intervals which are only one or two sets thick. The cross-sets cut into underlying units rather than rest on them (Figure 35). Troughs are scoop-shaped, mostly about 20 cm deep and 1 m wide. The size and shape of the troughs differentiate the facies from facies *mSx*. At each occurrence, palaeocurrent data are moderately to strongly unimodal. Grouped data from all occurrences show a very broad southwestward trend, to 247° (Figure 17). Rare reactivation surfaces are present at Fourways (Longley, 1983), but these have not been observed elsewhere.

Sandstone in the facies is fine- to medium-grained, shows moderate to good sorting, and commonly has a grey, smooth appearance due to silicification. In undercut exposures where facies *mStm* is not silicified (such as at Ross Graham Lookout), it could easily be confused with or included in facies *mSx*. It decreases in abundance markedly northwest from Fourways, down-palaeoslope.

Facies *mStm* is distinguished from superficially similar sandstones of FA1 by palaeocurrent pattern (south to southwest, as opposed to northwest to west), sorting (generally better), and the uniformity of trough size (facies *St* of FA1 has very variable scale troughs). In areas of poor to moderate exposure, the assignation of many thin (<1 m) cross-bedded horizons is doubtful; they could belong to either FA1 or FA2.

### Sheet sandstones (*mSs*)

Sheet sandstones (*mSs*) are thin, laterally persistent, apparently structureless, sheets of medium-grained, commonly silicified sandstone. The sandstone is coarser grained than underlying and overlying units (facies *mSh*). Scattered coarse grains impart a gritty appearance. The sheets are generally less than 20 cm thick, commonly only 1 or 2 cm thick, and can be traced laterally as far as outcrop permits (up to 100 m) with no apparent change.

### Rippled surfaces

Rippled surfaces (Figures 30, 43 – 46) are common in FA2. They occur within or on the uppermost bedding plane of all facies, and represent modification of the underlying bed rather than a depositional facies. They are thus analogous to a scoured surface or an armoured lag. Because they do not appear to be related to a particular facies, they are described separately here. Significant thicknesses of ripple laminated sandstone occur only as intervals of subcritically to supercritically climbing ripples (Allen,

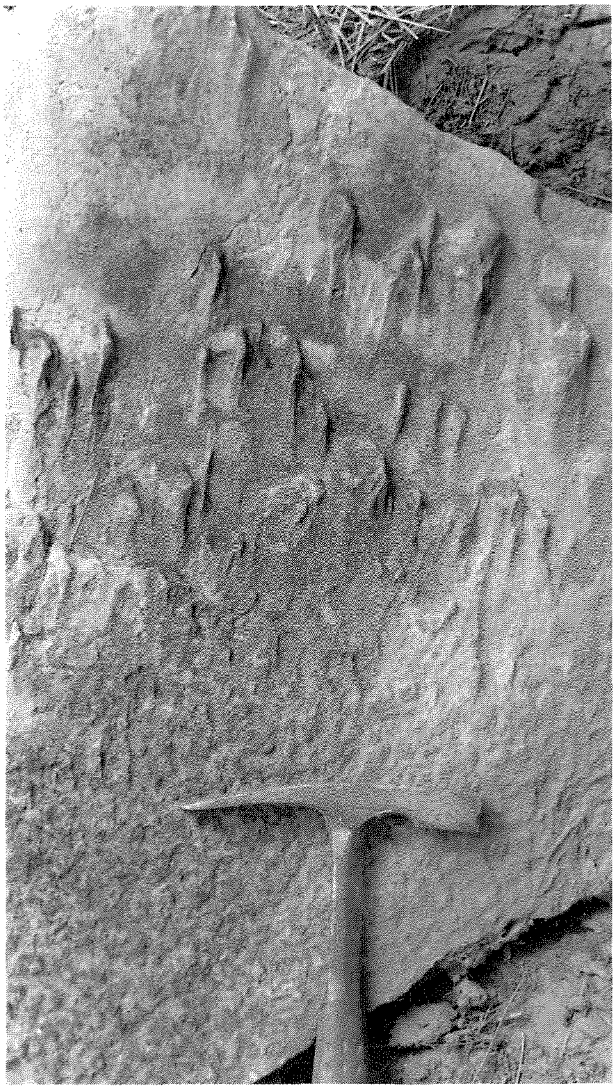



**Figure 28. FA2: large setulfs grading into wind adhesion surface; loose block 60 m below bottom carpark, The Loop. The wind direction was from from top to bottom of photo.**

1982a, p. 353), up to 40 cm thick but mostly less than 15 cm thick (Figure 25). The angle of climb generally increases upwards. Preservation of rippled surfaces is commonly enhanced by clay drapes.

Ripple wavelength is mostly between 2.5 and 9.0 cm, and ripple height (trough base to crest) is mostly between 0.3 and 1 cm. The mean wavelength and height are 4.2 cm and 0.5 cm respectively. Ripples are mostly symmetric to slightly asymmetric in profile, and have ripple symmetry indices (RSI = length long side/length short side; Tanner, 1967, p. 95) mostly between 1 and 2.5. Highly asymmetric forms (RSI > 5) are present but far less common (Table 5). In plan view, ripples range from straight, non-bifurcating forms through relatively straight, bifurcating forms to highly sinuous, non-bifurcating forms. The first two are dominant.

Modification of the simple ripple form is common. Double-crested, flat-topped, interference and ladder ripples occur in many localities (Figures 24, 44 – 46). They are all readily accessible at The Loop, on terraces near river level northwest of Natures Window, as are parasitic ripples on larger bedforms. Several well-preserved rippled surfaces, primarily of straight asymmetric ripples, are present at Natures Window.

Crest orientations indicate a dominant current orientation of south-southwest to north-northeast and a lesser east-southeast to west-northwest influence (Figure 17). Inferred current direction from asymmetric ripples (RSI > 2) is southwards.

# Facies interpretation

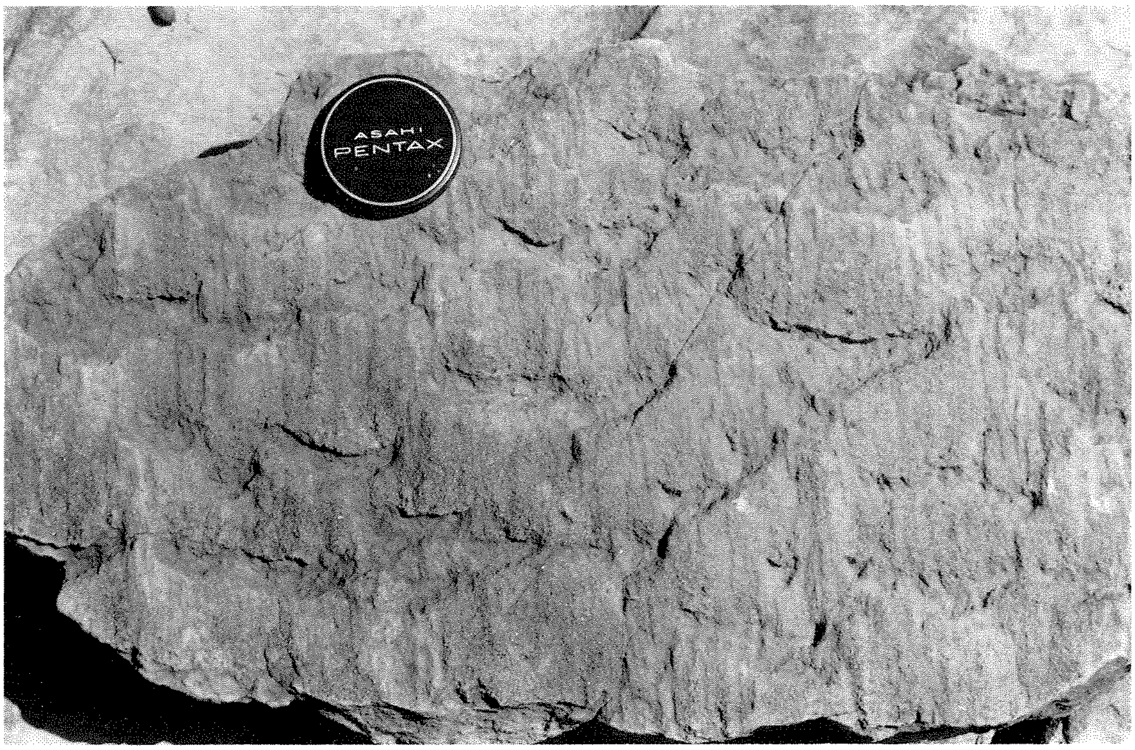
Trimodal palaeocurrent data, the presence of abundant bioturbation, primary sedimentary structures (ripple forms, wind adhesion surfaces, setulfs, reactivation surfaces, herringbone cross-bedding), and the intercalation of FA2 with FA1 between Ross Graham Lookout and Fourways indicate that, in the type section, FA2 was deposited largely in intertidal (i.e. between mean low water and mean high water) environments. This is a refinement of the shallow subtidal (i.e. below mean low water, but still dominated by tidal processes) to intertidal interpretation made by Hocking (1981a).

## Lithofacies

### Horizontally stratified sandstone (*mSh*)

Intermittent subaerial emergence occurred during deposition of facies *mSh*; this is indicated by scattered mud flakes, desiccated mud surfaces, flat-topped ripples, ladder ripples, and wind adhesion surfaces (Figures 22, 24, 26 –29, 44 – 46). Double-crested ripples within the facies formed when water depth decreased rapidly. Reversals in flow direction are locally apparent from opposing foresets and ripples (Figure 25). These features suggest an intertidal setting. The presence of thick intervals of weakly bioturbated or non-bioturbated, horizontally stratified sandstone suggests that there was constant reworking.

The low-angle discordances which characterize swash cross-stratification (Harms et al., 1982, p. 7– 6 and figure 7.5) do not occur in facies *mSh* (Figures 19, 25). This rules out an origin by swash and backwash in a foreshore environment, as was proposed by Longley (1983). The presence of primary current lineation indicates that some intervals were deposited in upper flow-regime conditions by high-velocity currents (for explanation, see facies *Sh* of FA1, above). Rippled surfaces and intervals of cross-bedding preserve transitions to lower flow-regime velocities. Sediment supply was generally low to




GSWA 23798

Figure 29. FA2: low-relief adhesion ripples; base of Section 17 (5 km south of Z Bend). The surface may have been almost dry, so that ripples were partially eroded by further wind action. Lens cap 52 mm.

GSWA 23799

Figure 30. FA2: partially washed-out trackways on rippled surface at the base of Fourways. The width of tracks similar to these ranges from about 1 cm to 34 cm, and individual impressions range from almost totally washed out to very distinct. The type of preservation locally indicates that the surface was emergent, although damp, when the tracks were made. Many were probably made by eurypterids (K. J. McNamara, pers. comm.).

GSWA 23800

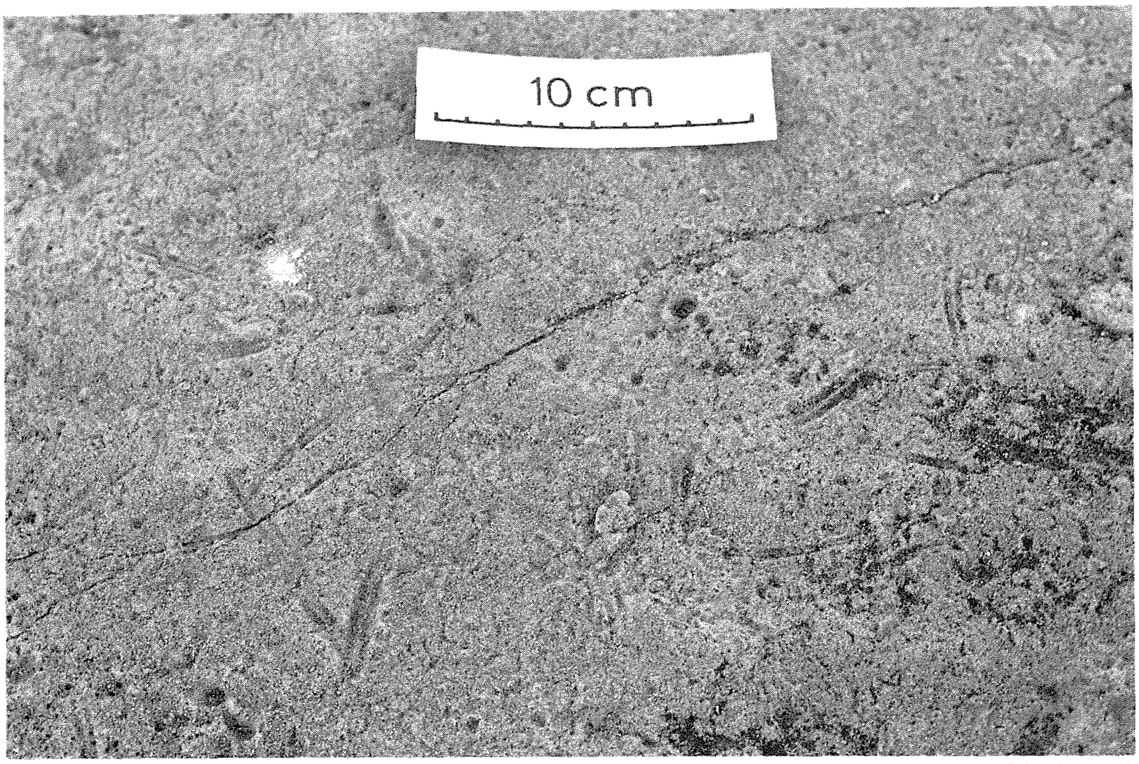
Figure 31. FA2: concave epichnial, bilobate groove with central ridge and virtually featureless infill; terraces near river level at Fourways. The central ridge is absent in some specimens, which are otherwise identical. The trace bears some similarity to *Beaconites barretti*, and differs mainly because it lacks distinct curved backfill. Backfill can be seen locally in some traces. These and other occurrences, in plan and section view, are very similar to *Chagrinichnites osgoodi* (Hannibal and Feldmann, 1983) but are markedly larger.

GSWA 23801

Figure 32. FA2: large round vertical burrow curving at base to horizontal orientation; 150 m north of Natures Window, The Loop. Burrow fill appears to have flowed down into burrow; laminae on left-hand side of burrow are sharply truncated and bent upwards slightly; laminae on right-hand side have ragged edges and appear to have collapsed into burrow. These features suggest the burrowing organism escaped upwards, and used the right-hand side of the burrow for purchase, pushing material from the right-hand side under its body. Lens cap 52 mm.

GSWA 23802

**Figure 33.** FA2: concave epichnial burrow with very slight medial ridge (directly above stem of hammer); Mooliabaanya Pool, base of Section 29. Overlying sediment has collapsed into burrow, and there is a layer of non-bedded sand (speckled appearance) at the base of the burrow.




GSWA 23803

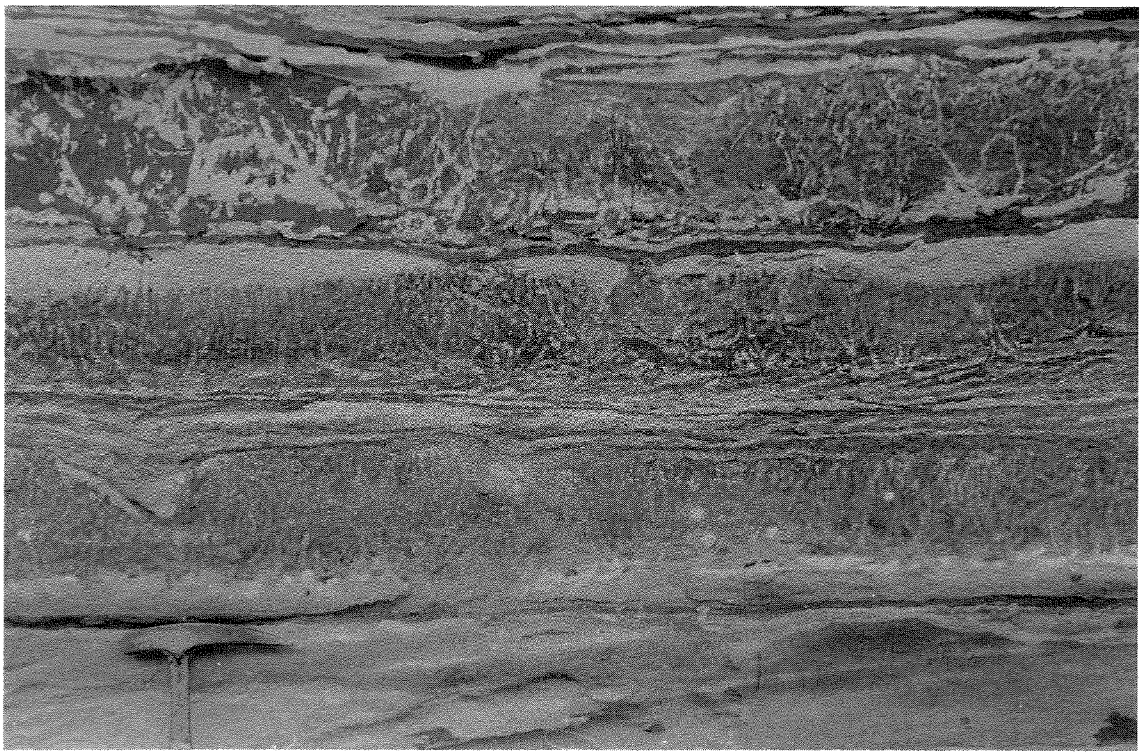
**Figure 34.** FA2: poorly preserved, small, straight double epichnial furrows; from 20 m north of Natures Window at The Loop. These may be *Didymaulichnus lyelli*, a juvenile arthropod burrow. The oblique scratch pattern noted by Bradshaw (1981, p. 635) is absent, possibly because of poor preservation.


GSWA 23804

Figure 35. FA2: thick bioturbated beds *(Sbv)* above and below facies *mStm*; below Hawks Head Lookout, in Section 8. Bioturbated beds are thinner at The Loop (compare with Figure 37), and are far less common in the Z Bend area.

GSWA 23805

Figure 36. FA2: plugs and deep grooves of structureless sandstone amidst *Heimdallia*; from terraces near river level, 500 m northwest of Natures Window, The Loop. Note the truncated *Heimdallia* at the edge of the plug in front of the hammer, and the *Heimdallia* rims around the plug immediately to the left. The plugs and grooves are the feeding or escape burrow of a large organism (?arthropod), and are possibly related to *Chagrinichnites*, although larger. The grooves are similar in broad outline to *Beaconites barretti* (Bradshaw, 1981) but lack well-developed backfill structure. The plugs may be analogous to the short vertical sections mentioned by Bradshaw (p. 631).



GSWA 23806

**Figure 37. FA2: 15 to 20 cm thick couplets of facies *Sbc;* The Loop, near Natures Window ("Painted Wall"). The dominant burrow is *Heimdallia* sp. A single example of *Chagrinichnites* sp., in oblique view, is present directly above the hammer.**

GSWA 23807

**Figure 38. FA2: scattered sinuous upper surfaces of *Heimdallia;* Z Bend, 400 m upstream from lookout, north bank. In this and the following figure, close inspection of the bedding surface – trace fossil contact, and examination of vertical sections (not seen here) shows that the burrow is a laterally migrating vertical trace rather than a convex epichnial trail.**

GSWA 23808

**Figure 39. FA2: top view of part of a sinuous *Heimdallia* trace; same locality as previous figure. Burrowing organism moved from right to left. Lens cap 52 mm.**

GSWA 23809

**Figure 40. FA2: unidentified arcuate tubular burrows; 400 m north of Hawks Head Lookout. These form round clumps of burrows, and are part of a burrowed bed (*Sbv* ) but are not *Heimdallia*.**

moderate, although intervals of climbing ripples indicate periods of higher supply.

The internal ripple lamination suggests that most of the facies was formed by shallow, probably turbulent, lower regime flow on a very broad, level surface. Symmetrical and asymmetrical ripples in the facies (see "Rippled surfaces" below) indicate both wave and current effects. The currents often were generated by winds blowing above a shallow sheet of water, because adhesion surfaces are also present. Winds could also form small waves. The internal structure of facies *mSh* is similar to the wind ripples shown by Kocurek (1981; figures 8, 12 and 13), which he interpreted as interdune features. However, eolian dunes have not been recognized in FA2, which makes eolian deposition (at best) a small component of the facies. Deposition is therefore assumed to have been caused by a combination of tidal currents, wind-driven currents, and small wind-driven waves. These operated over a thin sheet of water in intertidal conditions. When the sediment was fully emergent, winds formed adhesion ripples and adhesion surfaces, and blew out some subaqueously formed ripples.

At relatively high current velocities and with increasing water-depth, planar foresets develop asymptotic bases which have a very extended toeset and bottomset. Increasing proportions of grains are carried in suspension beyond the topset–foreset contact, and eventually settle to

GSWA 23810

**Figure 41.** **FA2: facies *mSxp;* below Hawks Head Lookout near Section 8. Two main sets of *mSxp,* each of which climbs at a low angle, are separated by thin interval of *mSh.* To the left, the upper set cuts down and replaces facies *mSh;* only a thin set of *mSxp* is present at the extreme left of the photograph. Facies *mSh* and *Sbc* overlie and underlie *mSxp.***

GSWA 23811

**Figure 42.** **FA2: facies *mSxt*; 150 m upstream from Section 19 at Fourways. Most of the view is of medium-scale trough cross-bedded, fine- to medium-grained sandstone.**

GSWA 23812

Figure 43. FA2: typical rippled surface, Fourways. Ripples are relatively straight, slightly asymmetrical, and bifurcate occasionally. Crests persist for more than a metre. The ripples formed by oscillation, probably wind waves, in shallow water. Clay drapes locally enhance preservation.

GSWA 23813

Figure 44. FA2: reworked symmetrical ripples; northwest side of The Loop near river level. The first set of ripples (crests aligned from top to bottom of the figure) has been progressively reworked to form the set with crests aligned across photo. At the right-hand side of the photograph, reworking has simply sculpted the crests of the ripples. At the left-hand side, the first ripple set is totally reworked. The rippled surface formed by two perpendicularly oriented, successive currents. The first may have been wave-surge direction, and the second, wind direction. Lens cap 52 mm.


GSWA 23814

Figure 45. FA2: flat-topped ripples; at the saddle below Natures Window, The Loop. Such ripples are caused by a rapid decrease in water depth, which planes the tops from the ripples. Lens cap 52 mm.

GSWA 23815

Figure 46. FA2: ladder ripples; north side of The Loop. These formed during late stage emergence, when water remained in the troughs of large ripples but did not cover the crests. Wind agitated the water, and small ladder-like ripples developed in the troughs. Lens cap 52 mm.

form an extended toeset and bottomset (Reineck and Singh, 1975, p. 21; Jopling, 1965). Gozalo et al. (1985, figure 13) referred to this as flow expansion. Low- to very low-angle cross-bedding (facies *mShx*) formed in this manner, at the margins of sand ridges composed of low- to medium-angle cross-bedded sandstone (*mSxp*, *mSxt*).

These processes (high-velocity, upper and lower flow-regime deposition) adequately explain the horizontally stratified facies. Intermediate, lower flow-regime, velocities formed rippled surfaces and, in conditions of high sediment supply, intervals of climbing ripples. Disrupted bedding was formed either by negative density gradients (associated with submergence of an interval after partial drying; see van den Berg et al., 1983, figure 6.16), or by overpressuring of saturated sediment by later layers of sediment, and subsequent expulsion of water.

In summary, facies *mSh* developed in very shallow, intermittently emergent conditions. There was a low to moderate sediment influx at most times, onto a relatively flat depositional surface, and sediment was constantly reworked. These conditions originated on a tidal flat area, either between channels or where there were few channels. The latter alternative is preferred because tidal flat deposits have a low preservation potential if migrating tidal channels form a significant part of the tidal zone (de Jong, 1977; van den Berg et al., 1983). The lack of bioturbation, attributed to constant reworking, suggests a lower intertidal environment. Facies *mSh* is therefore interpreted as a lower intertidal sandflat deposit.

### Bioturbated sandstone (*Sb*)

Intense bioturbation can occur in two settings. The first is where there are long periods of non-deposition or slow deposition (Howard, 1975, p. 134–135), so that there is sufficient time for suspension-feeding organisms to fully bioturbate each sediment layer. The second is where there are active deposit feeders within sediment (Miller, 1984, p. 207–208); Miller found that a 30 cm bed could be completely bioturbated in little more than a month. *Heimdallia* shows little indication of being made by a deposit feeder (Bradshaw, 1981, p. 641) like those envisaged by Miller, so slow or discontinuous deposition probably prevailed during formation of facies *Sb*.

Massive bioturbated beds (*Sbv*) represent either very slow continuous deposition in the manner described by Howard (1975, p. 134), or intermittent periods of deposition (Howard, 1975, p. 137) separated by slow deposition or non-deposition. *Heimdallia* burrows mostly penetrate about 20 cm into the sediment, so that complete bioturbation of the sediment could occur if less than about 20 cm of sediment resulted from each depositional event, and the events were sufficiently separated in time. Continued, but very slow, deposition between major depositional events could form thicker bioturbated layers, as could episodic deposition of thin ( <5 cm, for example) layers. Vague stratification, at intervals ranging from 5 to 40 cm, in some massive bioturbated sandstone horizons supports the suggestion that intermittent deposition was dominant. The stratification may be partly truncated burrow tops, and partly the base-level of *Heimdallia* burrows where a horizon was fully bioturbated prior to further deposition.

Laminated to burrowed, erosively based couplets (*Sbc* and *Sbp*) formed under conditions of episodic rapid deposition. Two scenarios are possible. The first is erosion, suspension and redeposition of sediment during storms (see Howard, 1975, p. 138). The second is abrupt, but infrequent, deposition (possibly by storms) of a layer of sediment thicker than the depth to which bioturbation penetrated. The second process is preferred because arthropod escape-burrows (?*Beaconites*, *Chagrinichnites osgoodi*) occur within and on bioturbated intervals — if significant erosion and resuspension of sediment occurred, the arthropod would be within a suspension cloud, rather than having to escape through a layer of sediment.

Tidal flats are characterized by an abundant, but not diverse, fauna (Reineck, 1972; Reineck and Singh, 1975, p. 359). On modern intertidal flats, bioturbation is most intense in the middle to upper intertidal zones (Evans, 1975; Reineck, 1975; Weimer et al., 1982, p. 197) because of lesser reworking and lower energy levels than in the lower intertidal zone. Facies *Sb* is interpreted as the product of an upper intertidal environment because it increases in abundance up-palaeoslope (towards Ross Graham lookout), and the limited variety of burrow types within the facies suggests that the fauna was of limited diversity.

Facies *Sb* differs substantially from normal upper intertidal deposits, as described by Klein (1977) or Weimer et al. (1982). The upper intertidal zone is normally dominated by low-energy, suspension deposition of muddy sediments, which are absent in FA2. In FA2, deposition in the upper intertidal zone only took place during abnormal events, such as the highest of spring tides and storms. At that time, sandy sediment was deposited, in layers up to about 60 cm thick. Between depositional events, these layers were reworked by organisms into massive bioturbated sandstone (*Sbv*) or laminated to burrowed couplets (*Sbc*, *Sbp*).

### Medium- to large-scale cross-bedded sandstone (*mSx*)

Reactivation surfaces and current reversals in facies *mSxt* (see the composite palaeocurrent rose for *mSxt*, Figure 17) indicate influence by currents of variable strength and direction. These were sufficiently strong at times to first liquidize and then deform cross-sets, and also to form primary current lineation on top of cross-sets. Decreasing water depth and probable temporary emergence are indicated by double-crested ripples, rare mud-cracked surfaces, and parasitic interference and ladder ripples. The latter occur both on megaripples and in the troughs between them. Temporary emergence is also supported by the presence of both washed-out or blurred and well-preserved tracks in close juxtaposition on topsets where there is no appreciable difference in the degree of clay draping. From personal observation, tracks made subaqueously in similar sediments are always blurred, while those made subaerially are much better preserved, even after further emergence, if the sediment surface was still damp. These aspects (variable current strength and orientation, decreasing water depth, and emergence), together with a maximum cross-set size of about 2 m, suggest deposition in a tidal, at times intertidal, setting.

Facies *mSx* was deposited as two-dimensional (planar cross-bedded units, *mSxp*) and three-dimensional (trough cross-bedded units, *mSxt*) dunes. The intermixing of the two bedding types in many areas indicates that these bedforms graded into each other with no clear distinction. They formed both as infills of scoured depressions (broad channels, smaller steeper sided channels, and local scour depressions) and, where persistent for hundreds of metres laterally with planar bases, as positive-relief bedforms (migrating dunes, or sandridges). Trough cross-sets are more common where basal scouring is present, while planar cross-sets commonly exhibit little scouring and can be traced for hundreds of metres. This indicates that in general, two-dimensional dunes formed migrating sand ridges, while three-dimensional dunes infilled channels.

Large (up to 2 m) planar cross-sets indicate that some of the larger sandridges had relatively simple internal structure. The gradation from medium-angle planar cross-bedding (*mSxp*), through low-angle cross-bedding (*mShx*), to horizontal stratification (*mSh*) indicates that the ridges graded laterally into sand-flat deposits, and supports the hypothesis that facies *mSxp* formed as ridges resting on the sand flats. Trackways on some planar cross-beds indicate the ridges formed subaqueously (although they were emergent intermittently) rather than as subaerial eolian dunes.

Palaeocurrent directions (Figure 17) show that planar cross-beds mostly migrated southeast, directly up the palaeoslope (determined from palaeocurrent data in FA1 and FA3); there was lesser southward (longshore) migration. In contrast, trough cross-beds migrated mostly to the east-southeast and southwest, but also to the south and southeast. Together, the palaeocurrent directions and the south-southwestward direction of wave translation (from ripple orientations) suggest that tidal currents operated normal to the shore, and that the flood tide was dominant. Large tabular foresets formed in uppermost subtidal or lower intertidal, shoreward-moving sand-ridges. Such ridges occur in the macrotidal (4 m tidal range) Bay of Fundy in Canada (Klein, 1977, p. 87; Weimer et al., 1982, p. 209, figure 29; Dalrymple, 1984). Units which can be traced hundreds of metres parallel to palaeoslope strike (northeast–southwest) are presumably transverse ridges, oriented normal to palaeoslope. Units which can be traced up palaeoslope but not across palaeoslope are probably longitudinal ridges, oriented parallel to palaeoslope.

Channelized flow was ebb-dominated rather than flood-dominated, as trough cross-beds and complex cross-beds are mainly southwestward (longshore) and northwestward (offshore) rather than southeastward (onshore). The southward-directed trough sets suggest transverse channels, which drained lower tidal flats and fed into larger northwest-oriented channels. These southward channels may have developed because of subaqueous, but not markedly subaerial, barring by the transverse subtidal to intertidal sand ridges suggested above. Waves oriented north–south (resulting from prevailing winds, which were to the north, based on setulf orientation) would emphasize such a trend.

### Small- to medium-scale, trough cross-bedded sandstone (*mStm*)

Interpretation of facies *mStm* as tidal-dominated, rather than fluvial, is based on its moderate to good sorting, fine to medium grain-size, variation in palaeocurrents, and its intimate association with other tidal deposits (the remainder of FA2).

The thinness of intervals of this facies, the slight scouring at the bases of troughs (by the development of scour pools in front of foresets), and the lateral persistence of each occurrence suggest that facies *mStm* formed in shallow, rapidly migrating channels. Palaeocurrent directions range from northward to southward but are dominantly to the southwest, and indicate that flow was primarily across the palaeoslope rather than down it. These points, and the increase in abundance of the facies up the palaeoslope, suggests the channels were ephemeral, surface runoff features analogous to the channels described by Clifton (1982). Both reactivation surfaces and palaeocurrent reversals are rare, and suggest that flow was either ebb or flood dominated in each interval of the facies.

Much of the sediment contained in facies *mStm* may be reworked fluvial sands, either from abandoned fluvial distributaries or from tidal invasion of fluvial distributaries — the common intercalations of FA1 in the Lockwood Springs–Hawks Head area indicate that the fluvial system was still active in that area. The small channels infilled by *mStm* presumably drained into the larger channels infilled by facies *mSxt*, but this cannot be verified from the available outcrop.

**TABLE 5. MEASURED AND CALCULATED PARAMETERS FOR RIPPLED SURFACES IN FA2**

| *Wavelength* | *Height* | *RI(a)* | RSI(b) | CI(c) | SI(d) | BI()e) | PI1(f) | PI2(f) |
|---|---|---|---|---|---|---|---|---|
| Base of The Loop | | | | | | | | |
| 3.4 | 0.7 | 4.9 | 1.5 | 17.4 (g) | 16.0 | 13.4 | 1.33 | 1.45 |
| 3.1 | 0.3 | 10.2 | 1.8 | 18.2 (g) | 7.3 | 3.9 | 5.12 | 0.33 |
| 8.3 | 1.2 | 6.9 | 2.9 | 12.1 (g) | 13.3 | 5.4 (g) | 1.48 | 1.08 |
| 1.9 | 0.4 | 4.8 | 1.5 | 55.2 (g) | 10.0 | 14.7 | 3.34 | 0.40 |
| 2.6 | 0.5 | 5.2 | 2.8 | 18.5 (g) | 100 (g) | 20 (g) | 12 (g) | 0.31 |
| 8.8 | 0.9 | 9.8 | 2.6 | 6.9 | 6.25 | 7 (g) | 1.69 | 0.51 |
| 3.8 | 0.4 | 9.5 | 2.6 | 19.6 (g) | 12.0 | 5.7 | 1.7 | 0.65 |
| 5.2 | 0.6 | 8.7 | 3.0 | 32.7 (g) | — | — | — | 0.30 |
| Natures Window | | | | | | | | |
| 3.8 | 0.6 | 6.7 | 1.81 | 21.1 (g) | 25 (g) | 13.0 | 8.8 (g) | 0.39 |
| 3.2 | 0.4 | 7.5 | 2.7 | 18.8 (g) | 5.0 | 18.8 (g) | 4.11 | 0.40 |
| 6.2 | 1.0 | 6.5 | 1.8 | 16.2 (g) | 9.8 | 6.2 | 3.8 | 0.48 |
| 2.5 | 0.4 | 6.8 | 1.0 | 20.2 (g) | 10.0 | 5.24 | 2.40 | 0.48 |
| 2.9 | 0.3 | 10.1 | 2.1 | 15.5 (g) | 10 (g) | 6.9 | 2.45 | 0.48 |
| 3.6 | 0.6 | 6.0 | 1.7 | 14.6 (g) | 53 (g) | 3.8 | 5.8 (g) | 0.82 |
| 4.9 | 0.9 | 6.1 | 1.5 | 13.0 (g) | 8.0 | 2.2 | 5.16 | 0.45 |
| 2.0 | 0.3 | 5.7 | 2.4 | 27.3 (g) | 30 (g) | 6.7 | 17.9 (g) | 0.45 |
| Hawks Head lookout | | | | | | | | |
| 10.0 | 1.0 | 10.0 | 2.5 | 3.0 (g) | 5.0 | — | — | — |
| 3.5 | 0.4 | 10.0 | 3.7 | 8.5 | 2.5 | 7.7 | 0.77 | 0.64 |
| 4.1 | 0.8 | 5.1 | 2.3 | 7.4 (g) | 30.0 | 8 (g) | 5.7 | 029 |
| Z Bend | | | | | | | | |
| 1.8 | 0.2 | 7.2 | 2.0 | 27 (g) | 15 (g) | 10.5 | 4.6 (g) | 0.56 |
| 1.2 | 0.3 | 27.0 | 9.4 (g) | 17.1 (g) | 6.0 | 18 (g) | 4.6 (g) | 0.47 |
| 1.0 | 0.2 | 4.8 | 1.0 | 22 (g) | 5.0 | 1.4 | 1.4 | 0.73 |
| 6.1 | 0.5 | 10.0 | 1.0 | 23.9 (g) | 18.0 | 10 (g) | 7.8 | 0.66 |

(a) RI Ripple index, wavelength/weight
(b) RSI Ripple symmetry index
(c) CI Continuity index
(d) SI Straightness index
(e) BI Bifurcation index
(f) PI1, PI2 Parallelism indices
(g) Indicates minimum value

## Sheet sandstone (*mSs*)

Sandstone sheets (*mSs*) contain no internal structures from which the water depth during deposition can be estimated. There are no sedimentological data from which the flow regime could be interpreted. It is coarser grained and grittier than facies *mSh*. The grain size is closer to that of facies *mStm* or *mSx*. From this, the facies may represent abnormal storm events, which "smeared" coarser sand across the tidal flat. Bioturbation is absent, which suggests that further sediment was deposited as the storm waned, so that facies *mSs* was protected from bioturbation. Alternatively, the facies may have formed during brief, fluvially sourced sheet floods.

## Rippled surfaces

Ripple parameters for symmetrical and near symmetrical ripples indicate they are wave-formed (Table 5). Orientations of ripple crests (Figure 17) indicate wave translation was north-northeasterly (primary) and west-northwesterly (secondary).

Near-symmetrical ripples (ripple symmetry index from 2 to 5) are grouped with current ripples as palaeocurrent indicators, following Reineck and Singh (1975, p. 23). Palaeocurrent directions from these and current ripples are predominantly longshore (south-southwestward), with a lesser offshore (northwestward) mode, and indicate that wave translation was southwards. The northwestward mode is due to ebb-tidal flow.

The short wavelength of wave ripples (mean wavelength 4.2 cm) suggests that the waves had very limited fetch (Tanner, 1971). Calculations using Tanner's simple method give a water depth of about 24 cm, a wave height of about 6 cm, and a wave fetch of about 1 km.

## Origin of setulfs

Friedman and Sanders (1974) described setulfs from the upper intertidal zone of the Abu Dhabi tidal flats (Persian Gulf). Their specimens were 4 to 5 cm long, 2 to 3 cm wide, and about 1 cm high. They were uniformly and closely spaced, and were not clustered into longitudinal, transverse or diagonal groups. They were formed by the incoming tide, but Friedman and Sanders could not determine whether they were constructional features built up above the sediment surface, or destructional features resulting from erosion of nearly all of a sediment layer.

The setulfs in the Tumblagooda Sandstone are clearly a degraded form of asymmetric ripple. A complete gradation from barely eroded asymmetric ripples to discrete setulfs can be seen in different localities (Figures 26 –29), and a partial gradation can be seen in some individual outcrops. Subparallel lines of setulfs reflect the erosion of subparallel asymmetric ripples (Figure 26). Where erosion of the ripples is minor, the ripples are sufficiently asymmetric for a current origin to be confidently assigned. Because of the setting of the setulfs in FA2, the currents that formed the ripples were presumably ebb- or flood-tide currents. The agent of erosion which degraded the ripples into setulfs mostly acted in the opposite direction to the ripple-forming current.

Friedman and Sanders (1974) suggested that setulfs formed subaqueously, by a complex but otherwise unspecified flow pattern. In contrast, most setulfs in the Tumblagooda Sandstone are ripples which have been modified by wind erosion. The ripples were initially generated by flood- or ebb-tide currents, or winds. Figure 29 shows incipient ripples which could be described as adhesion ripples, based on descriptions and figures by Collinson and Thompson (1982, p. 72 and figure 6.23) and Kocurek and Fielder (1982). During emergence, marginally drier parts of ripple crests were blown out. For setulfs to form this way, adhesion ripples first formed on a damp surface (base of Figure 28). As the surface dried so that grains no longer adhered, ripples were blown out, as in Figure 29. The common adhesion surfaces in FA2, and their locally intimate association with setulfs, support an eolian origin for setulfs.

A further point in favour of a wind-generated origin is that the dominant setulf direction (steep to tapered end) is northward (Figure 17), a direction not dominant in any current-generated palaeocurrents. This northward mode is significant because the two current-dominated modes, northwest and south, are also present in setulf orientations. If the northern mode was random (a sampling artifact), the other two modes should not be so clear.

Although wind formed most of the setulfs in the Tumblagooda Sandstone, some may have formed by ebb-tidal runoff, although wind possibly modified and smoothed the initial shape. Irregular setulfs with no clear pattern of distribution, no pronounced linearity, and a clay drape (Figure 27) may well be better explained as late-stage runoff (ebb-tide current) features. Either method implies emergence, either before formation of the setulf or shortly thereafter.

## FA2 depositional environment

FA2 was deposited in a shallow subtidal and intertidal setting on a northwest-dipping palaeoslope. The association contains abundant indicators of tidal currents, decreasing water depth, shallow-water waves, and emergence. Reactivation surfaces, gross palaeocurrent pattern, and local reversals of palaeocurrent direction indicate tidal currents. Double-crested ripples, complex ripples, and parasitic ripples on larger bedforms developed under conditions of decreasing water depth; and ripple morphology and the "Tanner parameters" are suggestive of shallow-water waves. Desiccation cracks, adhesion surfaces, setulfs, ladder ripples, flat-topped ripples, and mud flakes indicate emergence. Each of the facies grouped into FA2 can be assigned a setting within the overall tidal environment (Figure 47). Tidal bundle sequences (the only single sedimentary structure which reliably indicates deposition in tidal conditions; Visser, 1980; Nio et al., 1981) have not been recognized, which suggests that subtidal deposits are absent.

Palaeocurrent directions show that the dominant sediment transport directions were onshore (southeastwards), offshore (northwestwards), and longshore (south- to southwest-wards). There are virtually no northeastward palaeocurrent measurements, which indicates that the longshore currents were unidirectional, to the south–southwest.

Between the Lockwood Springs–Ross Graham area and The Loop, the type section progresses obliquely down-palaeoslope and up-section by about 200 m. Interpretation is based largely on changes over that section, using three principal areas: The Loop area (Sections 23 to 26), the Z Bend–Fourways area (Sections 18 to 20), and the Lockwood Springs–Ross Graham area (Section 15 and Sections 4 to 11). No clear, cyclic pattern of facies superposition is apparent.

Facies *mSh* dominates the sequence in The Loop area. The facies was deposited on lower intertidal sand-flats, where there was a low to moderate sediment influx at most times, a relatively flat depositional surface, and constant reworking of sediment. The ridges composed of facies *mSxp* were probably irregular features which moved over a tidal flat, rather than a barrier system, because of their irregular occurrence, the lack of swash cross-stratification (an indicator of a foreshore environment), and the lack of fine-grained lagoonal deposits. Bioturbated sandstone is not markedly associated with facies *mSxp*, and therefore cannot be interpreted as a back-barrier lagoonal deposit.

The lack of tidal channel deposits in FA2 in The Loop area, where they could be expected, suggests that coastal barriers were not significant. This is because the barriers channelize flow; channels are minor when barriers are not significant (de Jong, 1977). Both are best developed on mesotidal (2– 4 m tidal range) coastlines, and are poorly developed on macrotidal (4 m tidal range) coastlines (Elliott, 1986a, p. 155).

The sequence exposed at The Loop is therefore interpreted as a dominantly lower intertidal deposit. There was little fluvial influx, extensive reworking under conditions of low sediment supply, and few deep channels cutting the flats.

Small- to medium-scale, trough cross-bedded sandstone (*mStm*), bioturbated sandstone (*Sb*), and coarse-grained intercalations (*cSt* of FA1) all increase in abundance up-palaeoslope, towards Ross Graham Lookout), and FA2 is dominated by bioturbated sandstone (*Sb*) in the Hawks Head–Ross Graham area. These features suggest that the Ross Graham–Hawks Head area was located in the upper intertidal zone. In that zone, deposition was infrequent (which allowed formation of facies *Sb*), fluvial progradation was common (intercalations of facies *cSt* of FA1), and ephemeral shallow channels (facies *mStm*) drained the flats.

From Section 15 to the Z Bend, there is a decrease in the number of FA1 intercalations and a corresponding increase in the abundance and interval thickness of facies *mSxt*. This is attributed to lesser fluvial influx, which allowed subaqueous channels at the coast to be dominated by tidal rather than fluvial processes. A secondary reason is relative position on the palaeoslope: the dominance of upper intertidal deposition at Hawks Head Lookout, and lower intertidal deposition at The Loop, suggests that the Z Bend area may have been dominantly middle intertidal. This is supported by the decrease in the number and thickness of bioturbated sandstone intervals up-section.

Normally, deposition in the middle intertidal zone alternates between traction and suspension deposition (Reineck and Singh, 1975; Klein, 1977; Weimer et al., 1982). As noted above, suspension-deposited mud is absent in FA2. An alternative indicator of the middle intertidal zone might be the scale of runoff channels. These begin in the upper tidal zone, coalesce and deepen in the middle intertidal zone, and reach base level (the subtidal–intertidal boundary) in the lower intertidal zone (Clifton, 1982). Between the Z Bend to The Loop, facies *mSxt* (which originated largely through the infilling of tidal channels) decreases in abundance and thickness. This may be due to a change from dominantly middle intertidal deposition (Z Bend) to dominantly lower intertidal deposition (The Loop).

Cross-bedding directions in FA2 indicate that tidal currents were normal to the shoreline, and the crestal orientations of wave ripples indicate that wave translation was primarily along the shoreline. Combined with the probable shallow water depths during ripple generation, and the short fetch of waves (see interpretation of rippled surfaces above), these features suggest that the waves were generated by northerly (longshore) winds during the

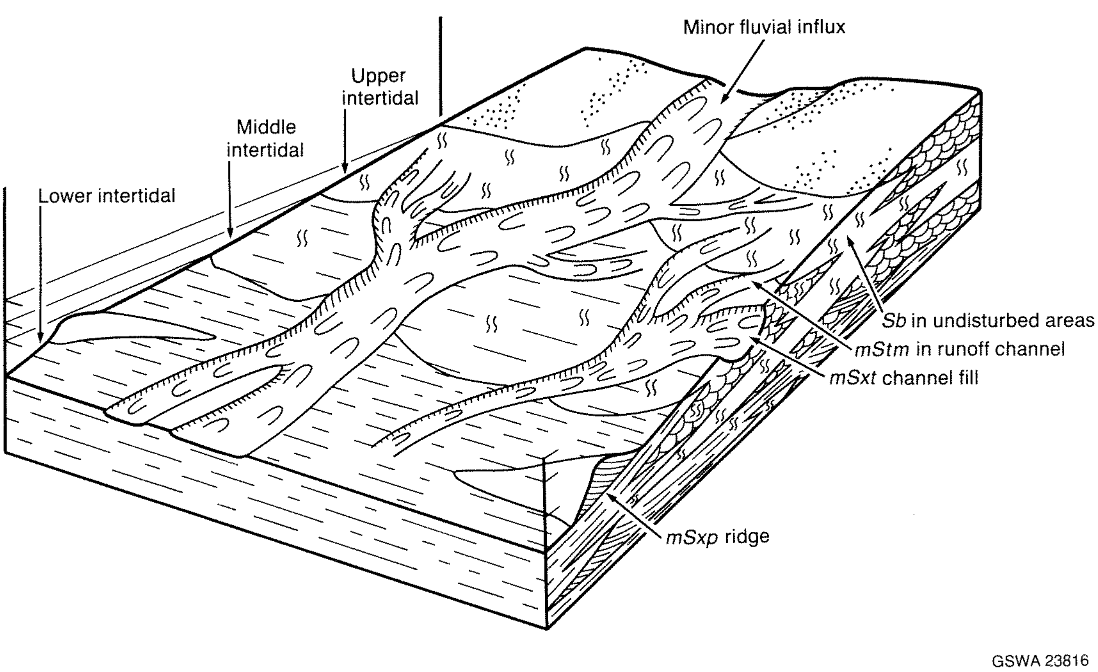



**Figure 47. Depositional model for FA2. The model is diagrammatic only, and not to scale. In the middle intertidal zone, bioturbated sediment and horizontally stratified sediment interfinger, and there is more channelized flow than in either the upper or the lower intertidal zones. The lower intertidal zone is dominated by horizontally stratified sediment, and there are scattered sand ridges and shallow channels. The upper intertidal zone is dominated by bioturbated sediment between channels.**

middle to high-tide period in the restricted area between the sandridges (*mSxp*) and the shoreline (nearest to *Sbv*). The lateral extent of FA2 for about 40 km down-palaeoslope argues against the ripples having formed in an areally restricted, lacustrine environment where waves would necessarily have a short fetch.

In summary, the portion of the type section between Ross Graham and The Loop represents a transition from a dominantly upper-intertidal area which was adjacent to a waning fluvial system (in the Ross Graham–Lockwood Springs area), to a dominantly lower-intertidal area in which there was only minor fluvial influence, at The Loop. Surface runoff channels (*mStm*) traversed the upper intertidal zone, and coalesced into larger runoff channels (*mSxt*) on the middle and ?upper intertidal flats.

Initially, channels were dominated by fluvial processes (Hawks Head area), but tidal processes became increasingly dominant as fluvial influx waned (Z Bend area). Few channels appear to have extended into the subtidal zone, based on exposure in The Loop area; shallow surface-runoff channels were more abundant in the lower intertidal zone. Deep channels were absent because there was insufficient barring of the coastline. Migrating sandridges (*mSxp*, some *mSxt*) caused ponding on the lower intertidal flats, and small wind-waves were generated in the ponds.

## Tidal range

A quantitative estimate of palaeotidal range for FA2 has not been made. The sequence shows no clear cyclicity from which an intertidal B – C sequence (Klein, 1977) could be derived. Subtidal bundle sequences have not been recognized, so Allen's (1981) or Yang and Nio's (1985) mathematical techniques cannot be applied.

The suite of coastal features shown by Hayes (1979) and Elliott (1986a, figure 7.1) allows a qualitative estimate of tidal range. Barrier islands and wave effects are absent, so the coastline was not microtidal (<2 m tidal range). The lateral extent of tidal deposits in FA2 also rules out a microtidal setting. Deep tidal channels, with which tidal deltas and tidal inlets would be associated, are absent. While tidal flats are clearly well developed, there is no indication of the presence of estuaries. From these features, FA2 could have been deposited in either a mesotidal (2– 4 m range) or a macrotidal setting (4 m range). The broad extent of intertidal deposits favours a macrotidal setting, because intertidal flats are best developed on moderate to low wave-energy, macrotidal coastlines; they are present to a lesser extent on mesotidal coasts, and are poorly developed on microtidal coasts.

## FA1–FA2 transition

FA1 grades upwards into FA2, by intercalations of FA1 in FA2, over approximately 150 m of section between Lockwood Springs and Fourways. The intercalations of FA1 diminish in thickness down palaeoslope, and there are more intercalations of FA1 up-palaeoslope near Lockwood Springs and Ross Graham lookout than in the Z Bend area. Generally, the percentage of FA1 also decreases up each measured section. In addition to the many minor intercalations, there are two major intercalations — one at the top of Sections 4 to 11, and one near the bottom of the gorge in the Z Bend area (Sections 15 to 19).

The Murchison River gorge is oriented such that each intercalation of FA1 can only be viewed parallel to palaeoslope strike, except in minor deviations such as the Z Bend. When viewed thus, they have a sheet-like appearance. Each intercalation is erosively based, laterally persistent, and undergoes only minor changes in thickness. The base and top of each remain at a similar stratigraphic level within FA2, and do not migrate up or down section appreciably over 1 or 2 km (the scale visible at the Z Bend–Fourways). This suggests that channels were broad and flat-based, rather than noticeably concave-up. The steps which occur at the bases of intercalations in places record migration or avulsion; only minimal changes of base level occurred.

The geometry of the intercalations indicates that they formed by rapid sheet-like progradation over the tidal flats. The rate of progradation overwhelmed marine influences, and channelized flow was also dominated by fluvial processes. The common occurrence of bioturbated sandstone (facies *Sb*) above FA1 intercalations suggests that the fluvial sediments were protected from tidal processes for a short period after they became inactive, probably by further progradation downstream.

It is unreasonable to expect FA1 intercalations to diminish in thickness from more than 10 m to zero over a distance of about 10 km (the distance from the Z Bend to The Loop). This indicates that the FA1–FA2 sequence in the type section is a depositionally regressive sequence; there was a gradual diminution of sediment supply from continental areas, which resulted in progressively greater marine influence as the fluvial system waned. Marine water depth did not increase significantly, because there is no marked vertical change in the facies abundance within each measured section of FA2.

# Facies Association 3 (FA3)

Facies Association 3 (FA3) is similar to FA1; both consist predominantly of medium- to very coarse-grained, trough cross-bedded sandstone. Major bedforms are laterally persistent and show little evidence of major scouring or channelling. FA3 generally is coarser grained, more pebbly, and less sorted than FA1.

Sections 27 to 45 include parts of FA3. The association is divided into two by a marker horizon of distinctive, laterally persistent, small-scale trough cross-bedded, pebble conglomerate to very pebbly sandstone (*GSts*), which is here named the Gabba Gabba Member of the Tumblagooda Sandstone. Bioturbation, mostly *Skolithos* and *Cylindricum*, generally is present only above the member.

## Facies description

Facies grouped into FA3 are: small- to large-scale, trough cross-bedded sandstone (*cSt*); small- to medium-scale, trough cross-bedded, sandy, granule conglomerate to very coarse-grained sandstone (*SGtm*); the Gabba Gabba Member (*GSts*); very large-scale cross-bedded sandstone (*cStv*); and horizontally stratified sandstone (*Sh*). The first facies (*cSt*) constitutes at least 70% of FA3. Planar cross-bedding is not common, and is included in facies *cSt*. The presence of *Skolithos* or *Cylindricum* in a facies is denoted by the suffix "*k*" on the facies code.

Palaeocurrent directions, as for FA1, are strongly unimodal to the northwest (299°, vector magnitude 0.88; Figure 48), and have little scatter in individual horizons. Measurements are plotted on each section, and facies totals are in Figure 48. Most measurements are from fine-grained *cSt*, the dominant facies. The only vertical variation in the palaeocurrent pattern is a local switch to the southwest immediately above the Gabba Gabba Member. Possible lateral variation in palaeocurrents was checked by measuring palaeocurrents at several localities at river level between Second Gully and Red Bluff. These lie approximately along strike, and are thus at approximately the same stratigraphic level. There is no consistent variation in the palaeocurrents (Figure 49).

Most of the lower part of FA3 (the section below the Gabba Gabba Member in the river gorges) consists of fining-upward cycles, each 10 to 15 m thick, that have the facies sequence (*SGtm* →) *cStv* → (*SGtm* →) *cStm* → *cSts* (→ *mSts* → *Sh*). Above the member, FA3 appears to be non-cyclic, or subtly cyclic. Cyclicity is also more pronounced in the river gorges than in the coastal gorges (Figures 50 – 52). The basal part of FA3, near Mount Yooadda Darlinoo, is dominated by very coarse-grained conglomeratic sandstone. The association fines upward, and sparsely pebbly coarse-grained sandstone is dominant at the level of the Gabba Gabba Member. Above the member, FA3 is dominantly very coarse to coarse grained and does not fine upwards.

### Lithofacies

#### Small- to large-scale trough cross-bedded sandstone (*cSt*)

Trough cross-bedded sandstone in FA3 (*cSt*) includes troughs which vary in scale from small (<20 cm, *cSts*, lesser *mSts*) through medium (20 to 60 cm, *cStm*, some *mStm*) to large (60 cm to 1 m, *cStl*) (Figures 53, 54). Isolated planar cross-sets are also included. The sandstone is poorly sorted overall but has local moderately sorted intervals, and it ranges from medium grained to very coarse grained and pebbly, especially near the bases of foresets. Coarse-grained sandstone is dominant, and constitutes most of the sequence in the river gorges and the upper Hutt River area. Moderately sorted, medium-grained sandstone is virtually restricted to the top 1 or 2 m of fining-upward cycles. In the coastal gorges, very coarse-grained sandstone is more common and bedding scale is smaller than in the river gorges. Foreset laminae are 10 to 20 mm thick, show marked grain-size differentiation, and grade both within and up foresets from coarse to very coarse sand (which commonly has pebbles up to 3 cm diameter) to medium sand. Smaller descending foresets are locally superimposed on each foreset. Fine-grained intraclasts, oversteepening and contortion of bedding are locally common.

#### Trough cross-bedded, granule conglomerate to very coarse-grained sandstone (*SGtm*)

Facies *SGtm* is a coarse-grained variant of facies *cSt*. Diagnostic features of the facies are very coarse grain size, medium- to small-scale trough cross-bedding, and very poor sorting. Pebbles and granules are common either scattered through the sediment, as stringers down foresets, or as armoured lag surfaces separating sets. Siltstone intraclasts occur locally (e.g. Bracken Point). The long axes of the intraclasts are commonly about 10 cm, and the largest known intraclast is 25 cm long and 5 cm thick. They are mostly subangular, although exceptions occur (Figure 55). The parent sediment has not been found in outcrop except in the stratigraphically lowest outcrops of FA3.

In the river gorges (e.g. Bracken Point) facies *SGtm* is present at the base of some fining-upward and thinning-upward cycles, and is less than a metre thick at each occurrence. The basal contact ranges over short

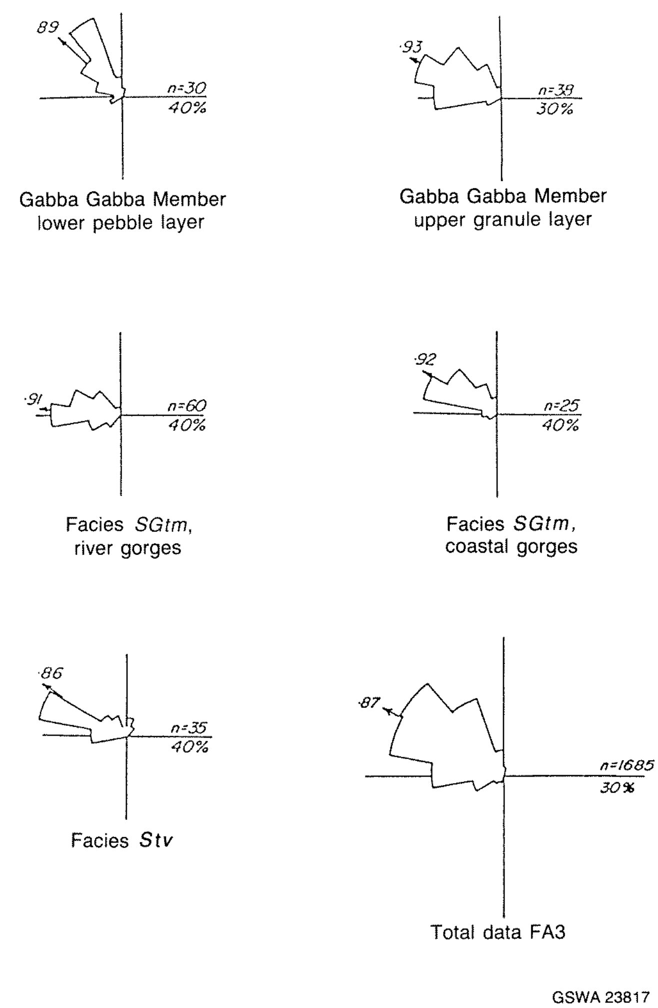



**Figure 48. Palaeocurrent totals for FA3, grouped by facies. Facies *cSt* is not shown on a separate rose because more than 90% of the readings in the total data rose for FA3 are from facies *cSt*.**

distances from erosive but planar, to scoured and even undercut (Figures 53, 55, 56). The facies is erosively overlaid by very large cross-beds (*cStv*) or medium to large cross-beds (*cStm*). In the coastal gorges, facies *SGtm* occurs in intervals up to 20 m thick (e.g. Red Bluff).

### Pebbly sandstone (Gabba Gabba Member) (*GSts*)

A lithologically distinctive interval of pebbly sandstone (*GSts*), here named the Gabba Gabba Member, occurs in the coastal gorges and river gorges, south of Wonong Gully. The latter is approximately 35 km north of Grandstand Rock, the southernmost accessible exposure. At Second Gully and Tumblagooda Hill, the member is below or at river level. It is between 0.4 m and 1.2 m thick, and has its type section immediately in front of Red Bluff, where it is 1.2 m thick (Figures 52, 57). It is named after Gabba Gabba Gully, a small gully near Kalbarri.

The Gabba Gabba Member consists of a lower interval, 20 to 80 cm thick, of very poorly sorted sandy pebble conglomerate to very pebbly sandstone, and an upper interval, about the same thickness, of granule conglomerate and scattered pebbles (Figure 57). The same lithofacies do not occur anywhere else in the FA3 sequence in the coastal or river gorges. Further north, at Bracken Point, the conglomerate is absent but sandstones coarsen abruptly at the same stratigraphic level. Most of the member is very small- to small-scale, trough cross-bedded (5–20 cm set thickness); the remainder is massive to poorly plane-bedded. The troughs indicate westward palaeocurrents (Figure 48), and there is a noticeable difference in directions between the pebble and granule layers. Pebbles are resistant rock types (mainly quartz), sub-angular to rounded, mostly 10 to 15 mm diameter but up to 30 mm diameter, and are supported in a coarse sand to granule matrix.

Poorly defined, 10 to 15 cm long, 1 to 2 cm diameter, vertical burrows (Figure 58) occur in the facies south of Toolonga Hill and in the coastal gorges. They could be either *Skolithos* or *Cylindricum*, which Bradshaw (1981) described and figured from lower Beacon Supergroup

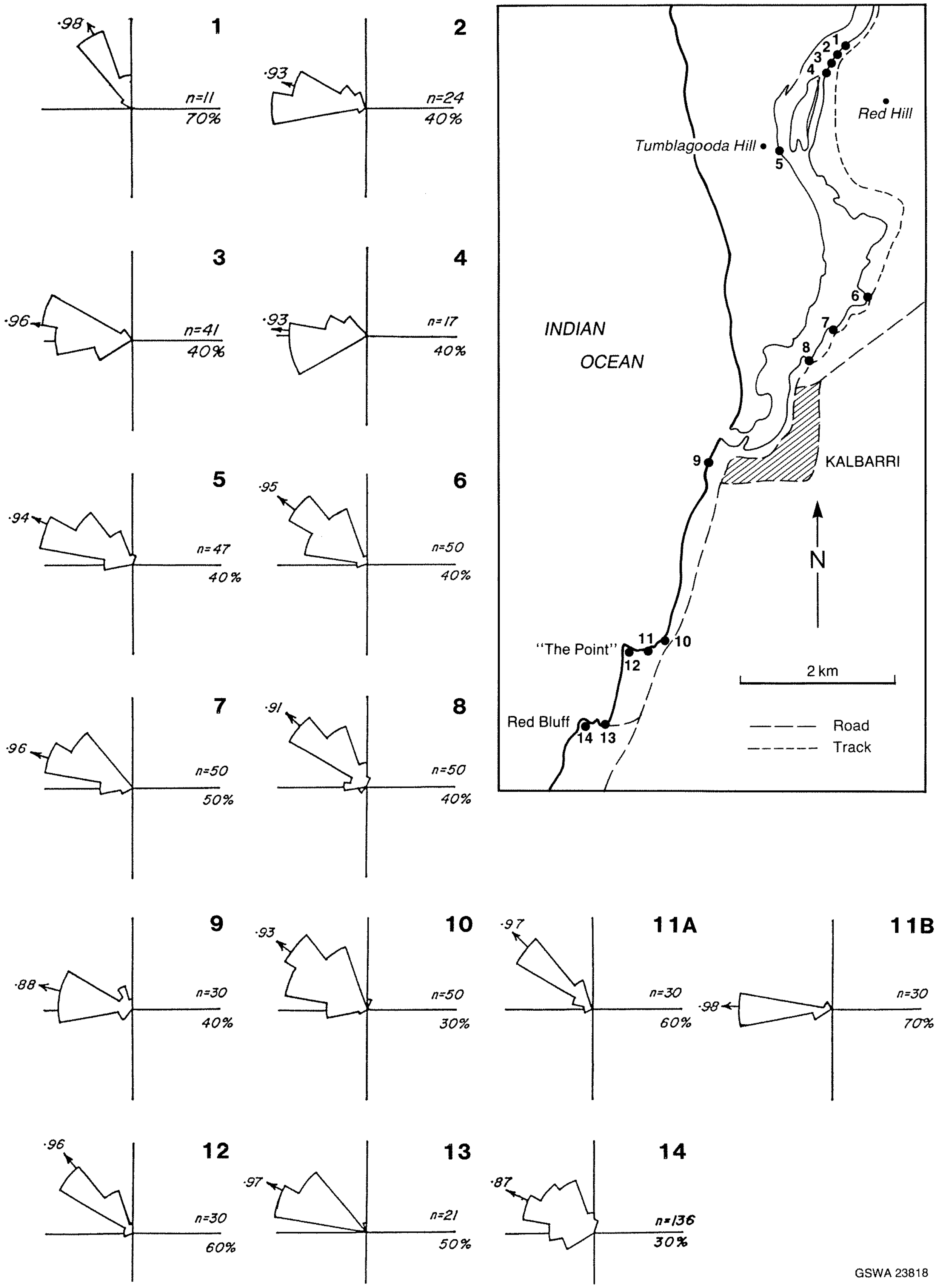



**Figure 49. Palaeocurrent measurements from FA3 between Red Hill and Red Bluff lower car park. All stations are at sea level or river level, and sample approximately the same stratigraphic level of FA3. Note the lack of any consistent variation in direction.**

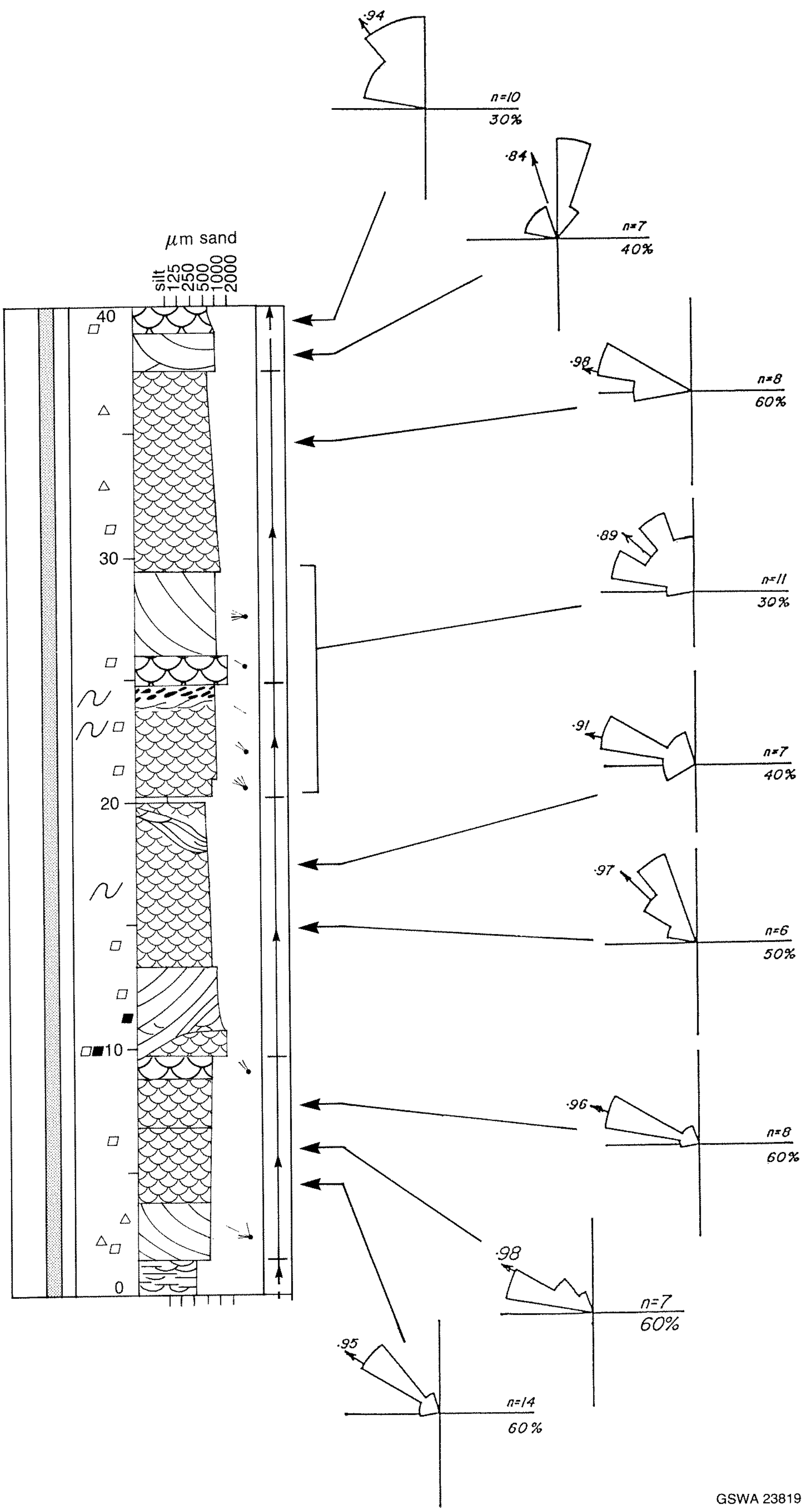



**Figure 50. Detailed measured section in FA3 at Bracken Point (lower part of Section 33). Fining-upward cycles occur throughout the section.**

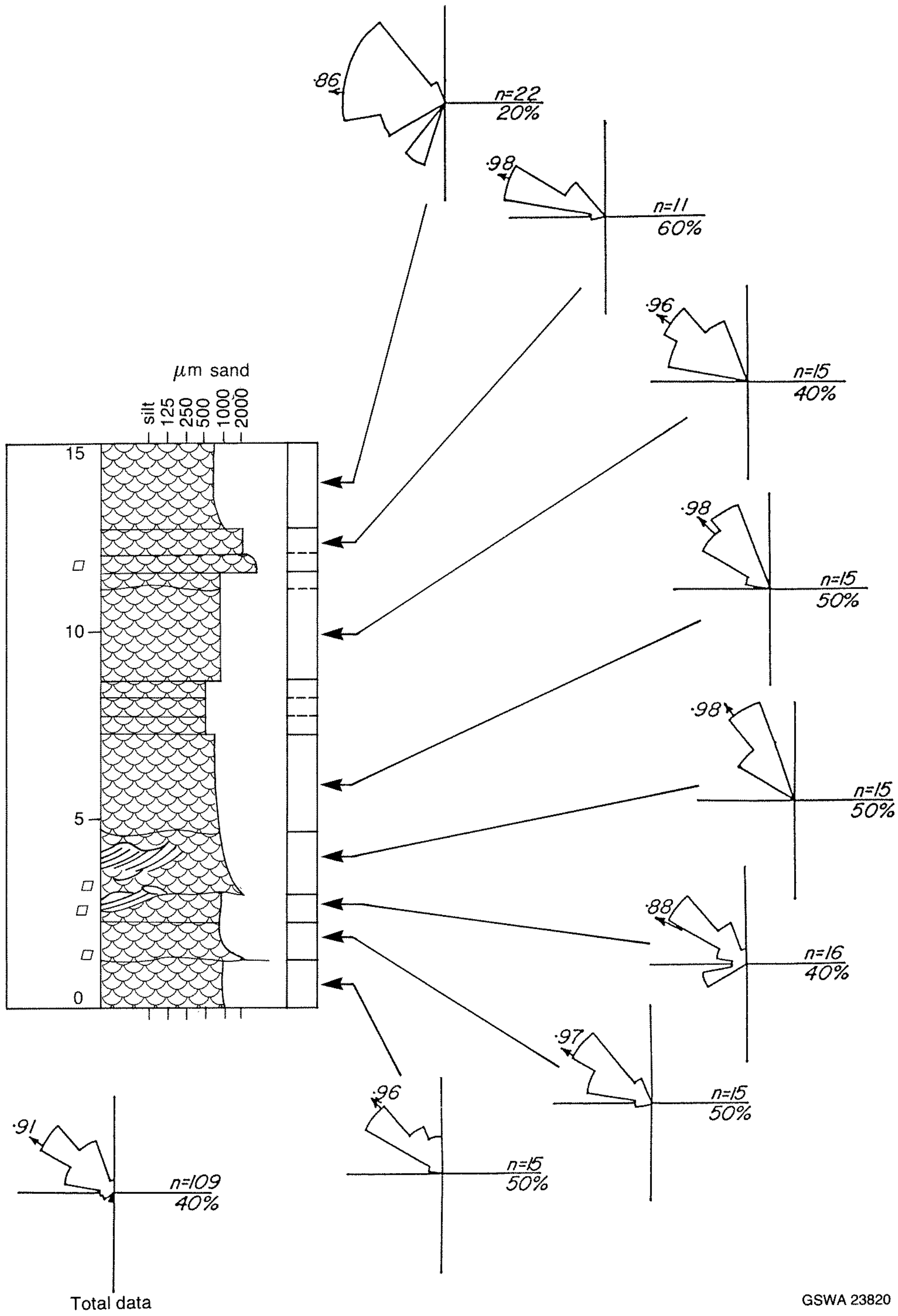



**Figure 51. Detailed measured section in FA3, 150 m north of the base of Red Bluff. The Gabba Gabba Member is at 12 m. No fining-upwards cycles are apparent, cross-bedding is mostly small to medium scale, and there is no apparent bioturbation.**

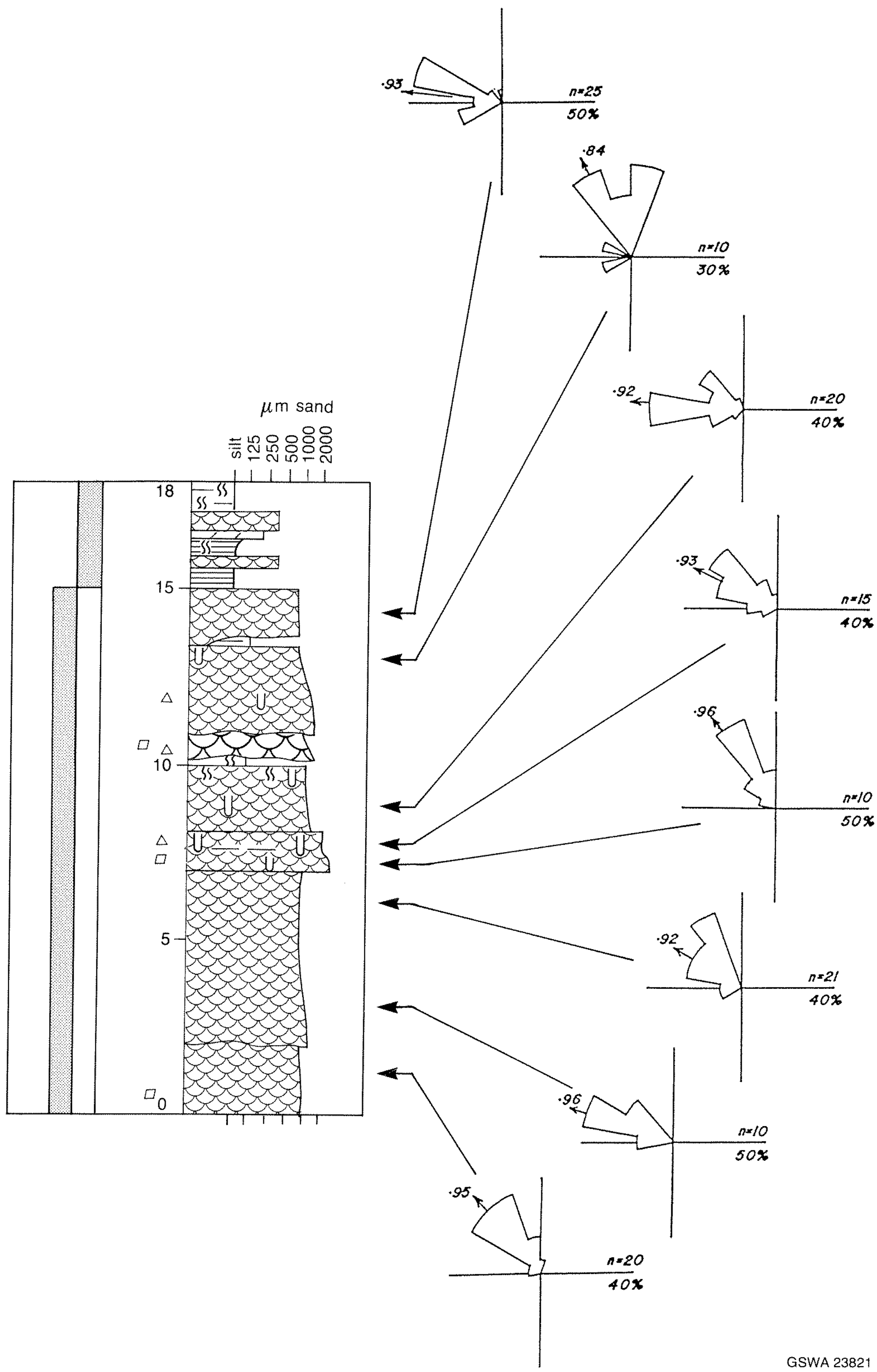
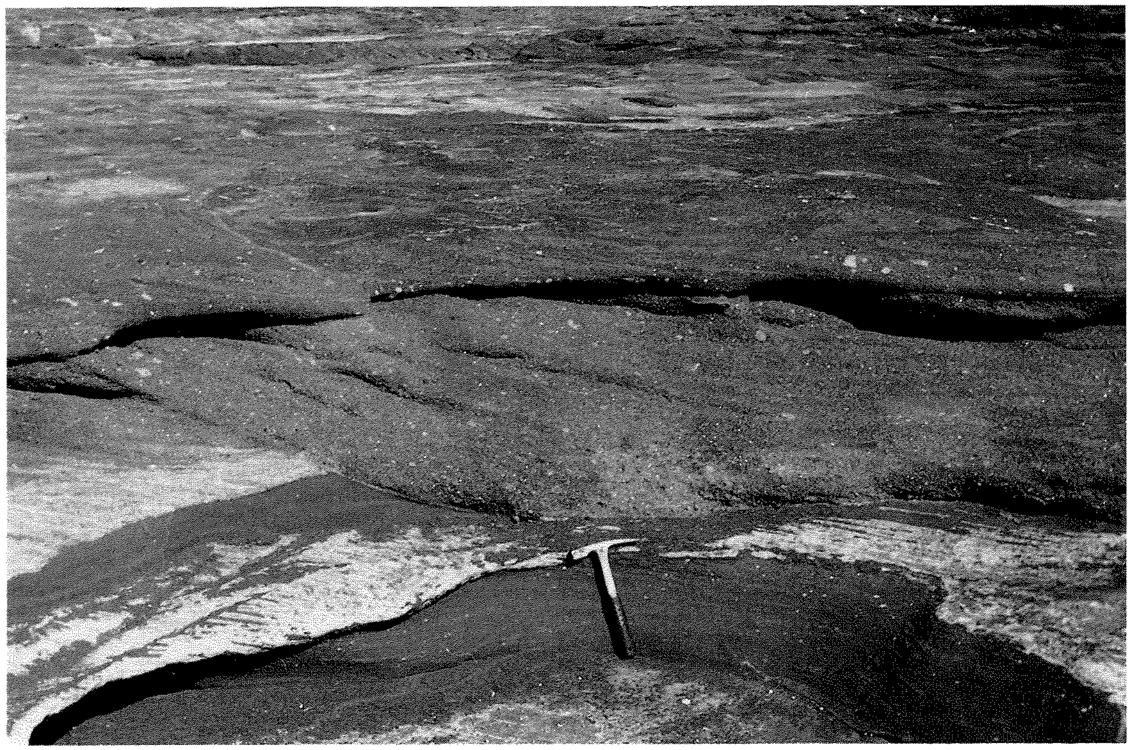



**Figure 52. Detailed measured section in FA3 at the base of Red Bluff (lower part of Section 41). No fining-upwards cycles are apparent. The type section of the Gabba Gabba Member is at 8 m. Bioturbation occurs above the member, and palaeocurrent directions are more variable above the member.**



GSWA 23822

**Figure 53. FA3: facies *cSt*, terraces below Red Bluff. Medium-scale cross-bedded, very coarse-grained sandstone (at the base of a fining-upward cycle) overlies small-scale cross-bedded, coarse-grained sandstone (at the top of a cycle). Mottling of colour such as occurs here is common near cycle tops.**

GSWA 23823

**Figure 54. FA3: medium-scale, trough cross-bedding in pebbly coarse-grained sandstone *(SGtm)*, Section 9, Red Bluff.**

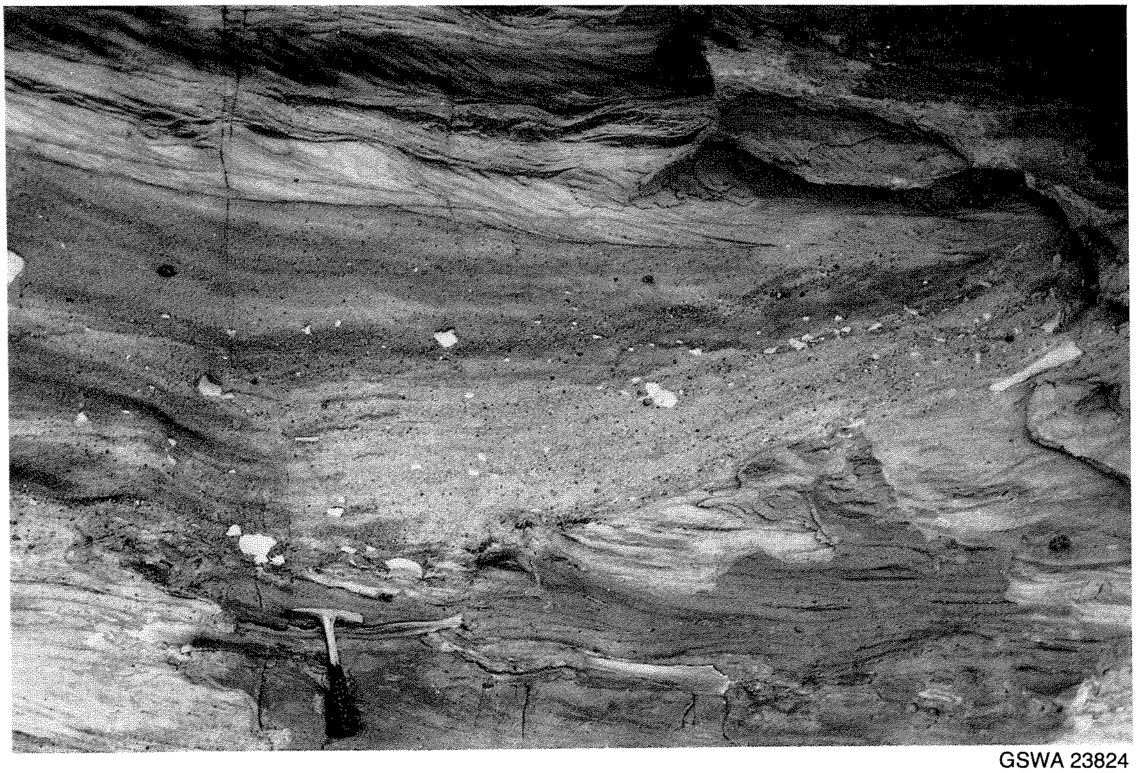



Figure 55. FA3: claystone intraclasts in very coarse-grained pebbly sandstone (*SGt*) at the base of a fining-upward cycle, Section 27 (5 km downstream from The Loop). Note the variety of intraclast shapes, and the scattered pebbles and granules.


Figure 56. FA3: top of fining-upward cycle in basal FA3, Section 27. The sequence below the armoured pebble layer (at level of hammer head) has northwestward palaeocurrents. The sequence above the armoured layer is typical of FA2; it contains horizontally stratified sandstone (*mSh*), southeastward-climbing ripples (30 to 50 cm above armoured layer), and low-angle cross-bedded sandstone (*mShx*). The base of the succeeding cycle is at the top of the figure. More commonly, there is only a thin horizontally stratified interval which occasionally is bioturbated.

sediments in Antarctica. The burrows clearly predate lithification.

A palaeomagnetic reversal coincides with the Gabba Gabba Member between Red Bluff and Grandstand Rock, a distance of about 8 km. Together with the lack of other discrete pebbly horizons, this confirms that it is a single, valid marker horizon in the coastal gorges. Between Thirindine Point and Stone Wall, the same magnetic reversal occurs in or just below the member (Schmidt and Hamilton, 1990; Schmidt and Embleton, in press). This indicates that only a single stratigraphic unit is present, and that more erosion occurred below the horizon in the coastal gorges than in the river gorges.

The Gabba Gabba Member divides FA3 in several respects. With few exceptions, it marks the stratigraphically lowest appearance of trace fossils in FA3 (see Sections 32– 45), except for the basal interval above FA2. Palaeocurrents locally show a marked southerly shift immediately above it, and cross-bedding above the member is primarily medium- to small-scale, rather than the varied very large- to small-scale cross-bedding beneath it. Lastly, the sandstone is coarser grained and compositionally less mature above the member.

### Very large-scale cross-bedded sandstone (*cStv*)

Single sets between 1.5 m and 4 m high of very large-scale trough or (less commonly) planar cross-bedded sandstone (*cStv*) are present at or near the base of many fining-upward cycles in the river gorges (Figure 59). The best exposures are in the breakaways west of Bracken Point and at Nats Mia. The very large cross-sets erosively overlie either facies *SGtm* or the preceding fining-upward cycle, and are overlaid by facies *cSt*, from which they are distinguished by the size of the crossbeds. The foresets are mostly broad, deep, moderate- to high-angle (20°) troughs. Cross-beds persist laterally for tens of metres before grading into medium- to large-scale (40 cm to 1 m) texturally identical trough cross-bedded sandstone. The lateral contacts are gradational rather than eroded. Texturally, the sandstone in the large foresets is similar to facies *cSt*.

### Horizontally stratified sandstone (*Sh*)

Horizontally and subhorizontally stratified sandstone (*Sh*) is present at the tops of some fining-upward cycles. It is well exposed in the breakaways west of Bracken Point. The facies consists of medium-grained, in places partly fine-grained and/or silty, moderately sorted sandstone; pebbles, granules, and intraclasts are rare. Bedding is on a 1 to 3 cm scale and is horizontal to gently undulating. The facies overlies, and grades vertically from, small- to medium-scale trough cross-bedded sandstone. In one place, horizontal bedding is associated with an intraclast breccia in which the intraclasts show distinct upstream-directed imbrication (Figure 60).

Up-section (downstream) of Mount Curious, facies *Sh* is invariably overlaid erosively by trough cross-bedded sandstone. In the sections at Mooliabaanya Pool and between Mooliabaanya Pool and The Loop, it is overlaid by cross-bedded sandstone that contains abundant intraclasts of facies *Sh*, or by intervals of FA2 generally less than 30 cm thick (Figure 56). An armoured surface of granules, the result from winnowing (Levell, 1980), underlies horizontally stratified sandstone at the locality in Figure 56.

## Bioturbation in FA3

With the exception of two localities, Bettie Crossing and "The Point" (1.5 km north of Red Bluff, informal local name), trace fossils in FA3 are restricted to the portion of FA3 above, or less than 5 m below, the Gabba Gabba Member.

*Skolithos* and *Cylindricum* (Figures 58, 61) increase in abundance southwards, from scattered occurrences at Stone Wall to abundant traces in the Second Gully area. They do not show a preference for a particular bedding scale, and occur in sandstone that ranges in grain size from medium to very coarse and pebbly. At one locality near the mouth of Second Gully, vertical burrows penetrate contorted bedding, which indicates that they postdate deposition and contortion, but not lithification. Although previously interpreted solely as *Skolithos* (Hocking, 1981a), comparison with descriptions and figures by Bradshaw (1981) suggests more northerly occurrences may be *Cylindricum*.

Near Bettie Crossing, north of Bracken Point, poorly preserved grooves about 1 cm wide, some of which may be bilobate, occur on a small bedding plane exposure near river level. The traces show a slight star-like aspect (Figure 62). The exposure is about 40 m below the Gabba Gabba Member, and is within the interval of facies *cSt* where fining-upward cycles are pronounced. The traces look similar to unidentified grooves shown by Gevers and Twomey (1982), and could be weathered specimens of either *Aulichnites*, a possible gastropod trail (Zawiskie et al., 1983), or *Agrichnium* ichnosp. B (Bradshaw, 1981).

On bedding plane exposures at "The Point", slightly sinuous, intersecting, bilobate epichnial trails, 1 to 2 cm wide and more than a metre long, occur on trough cross-bedded, coarse-grained sandstone (Figure 63). The trails resemble *Aulichnites*, as described by Zawiskie et al. (1983), although Hantzschel (1975) described *Aulichnites* as commonly strongly curved. Alternatively, the trails match the description by Hantzschel of *Didymaulichnus*.

## Facies interpretation

Hocking (1981a) suggested that FA3 is a low sinuosity, high-energy braided-fluvial sequence. This interpretation is confirmed here, on the bases of the tightly constrained, unidirectional, palaeocurrent directions; the coarse grain size; poor sorting; abundant intraclasts and pebbles; paucity of trace fossils; dominance of trough cross-bedding; and lack of fine-grained sediment.

## Lithofacies

### Small- to large-scale trough cross-bedded sandstone (*cSt*)

Trough cross-bedded sand formed the major component of large longitudinal bars in a northwestward-flowing braided fluvial environment. Each set of *cSt* formed in the same way as facies *cSt* of FA1, as three-dimensional dunes under conditions of turbulent, moderate to high velocity, unidirectional currents and varying water depth. Grain-size differentiation on foresets indicates that progradation was by avalanching down the dune face, rather than by constant flow (Allen, 1982b, p. 148). Upward thinning of cross-sets over 5 to 10 m intervals, from large to medium or small scale, is due to decreasing water depth (Figures 50, 53, 56, 59). Where very coarse-grained sandstone underlies thicker-bedded, coarse-grained sandstone, it is generally cross-bedded on a smaller scale than the coarse-grained sandstones. This indicates that bedding scale was controlled to some degree by grain size of the sediment load, as well as by water depth.

The presence of probable marine indicators (*Skolithos* and *Cylindricum* burrows) in this facies is discussed separately below, in "Bioturbation in FA3".

### Trough cross-bedded, granule conglomerate to very coarse-grained sandstone (*SGtm*)

The size of the trough cross-bedding in facies *SGtm* indicates that it formed as migrating, small- to medium-size, three-dimensional dunes. The poor sorting and coarse grain size indicates that the dunes formed at high current velocities (but still in the lower flow regime) when there was very agitated flow, possibly in the rising stages of floods. The surface over which they travelled and scoured into was sufficiently consolidated for sizeable intraclasts to be ripped up.

### Pebbly sandstone (Gabba Gabba Member) (*GSts*)

The following features need to be accounted for in any explanation of how the Gabba Gabba Member (*GSts*) formed:

(a) It appears to be unique in the Tumblagooda Sandstone.

(b) All palaeocurrents flowed to the west or northwest. There were no eastward palaeocurrents.

(c) Although less than 1.5 m thick, it extends for more than 35 km laterally. Sections in which the member occurs lie approximately along the strike of the palaeoslope. There is no information on the possible persistence of the member either up or down the palaeoslope.

(d) It marks the beginning of widespread bioturbation in FA3. Only minor bioturbation occurs more than 5 m beneath the member.

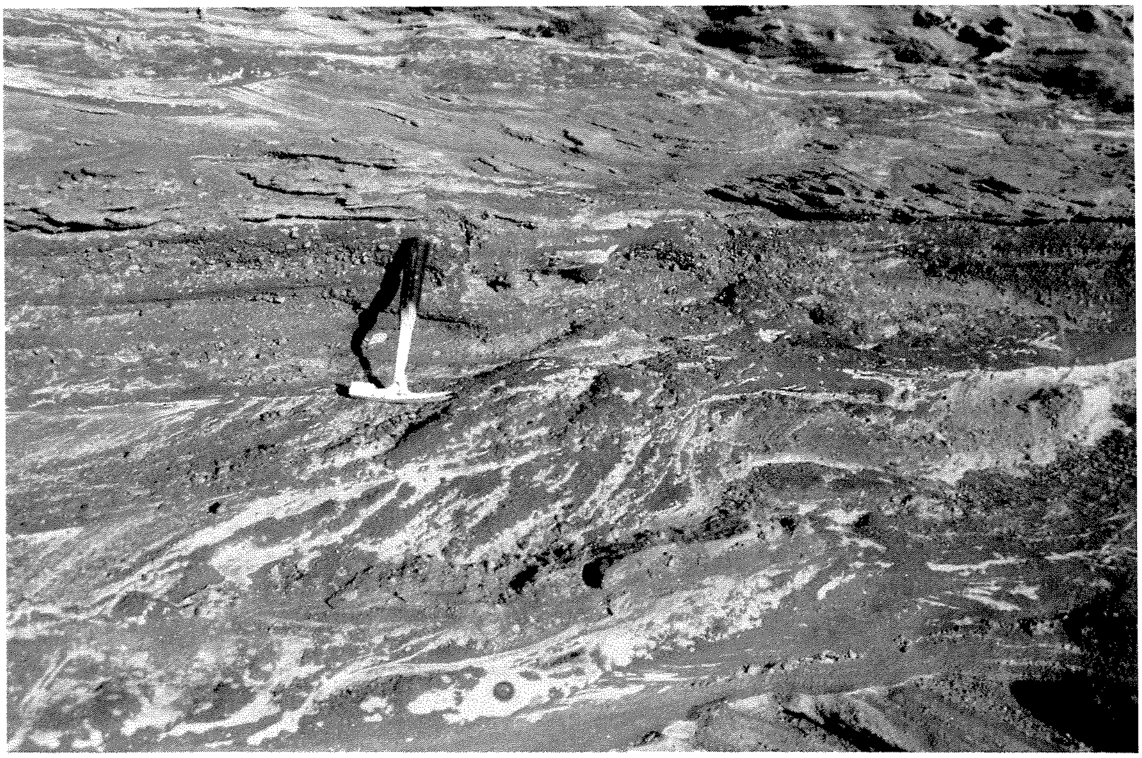
(e) Sandstones above the member show an abrupt decrease in textural maturity and, locally, a switch of about 40° in palaeocurrent directions. The change in palaeocurrent direction is best seen on the "tadpole" plots alongside each section in the Appendix.

Two ways that a thin, laterally persistent pebbly horizon could form are:

(1) Coarse-grained pebbly detritus accumulated in the wave breaker-zone or on a storm beach, and subsequently was totally reworked by fluvial processes. Either a minor transgression or cessation of supply could allow reworking by waves, and either sea-level regression (to a point where fluvial processes became dominant once more) or renewed fluvial progradation could cause reworking. The main weakness of the explanation is the need to totally rework all marine deposits, as eastward (onshore) palaeocurrent directions and winnowed marine sandstone are both absent.

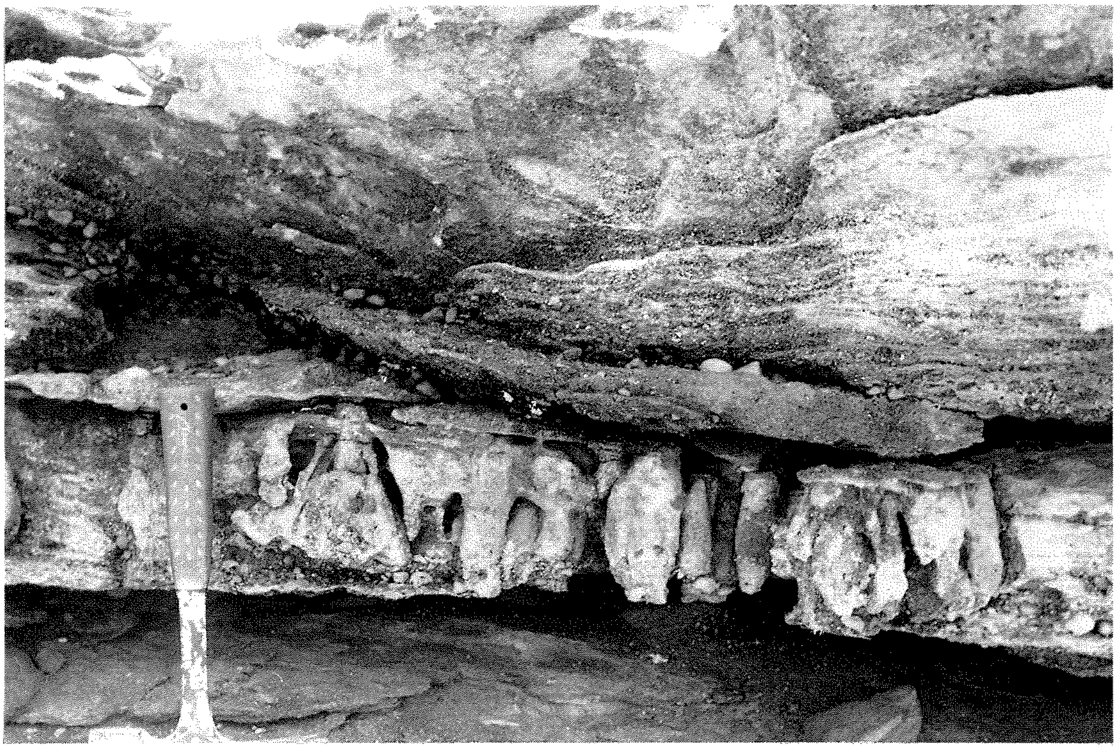
(2) A major fluvial lobe was abandoned and partially reworked. Progradation of another major lobe followed. Basinal subsidence continued at a steady rate throughout. Partial reworking of the surface of the abandoned lobe, by winnowing of finer sediments, would result in a lag deposit and form the Gabba Gabba Member. Subsidence of the basin and sediment compaction during reworking would lower the outcrop area to sea level, where bioturbation could occur. The increase in bioturbation to the south, both within the member and just below it, suggests a centre of subsidence to the southwest. Formation of the lag deposit would have ended when the depositional regime switched back to the area of outcrop.

The sequence of events outlined in the second point allows the Gabba Gabba Member to be explained solely in terms of internal basin processes, without the need to invoke external processes, such as tectonism either at the basin margin or within the basin. It is not possible, from the data in this study, to state definitely that reworking was either subaerial (continental, point 2) or subaqueous (marine, point 1). Reworking by both marine and continental processes may have occurred. In either case, abandonment of a fluvial lobe is implied.



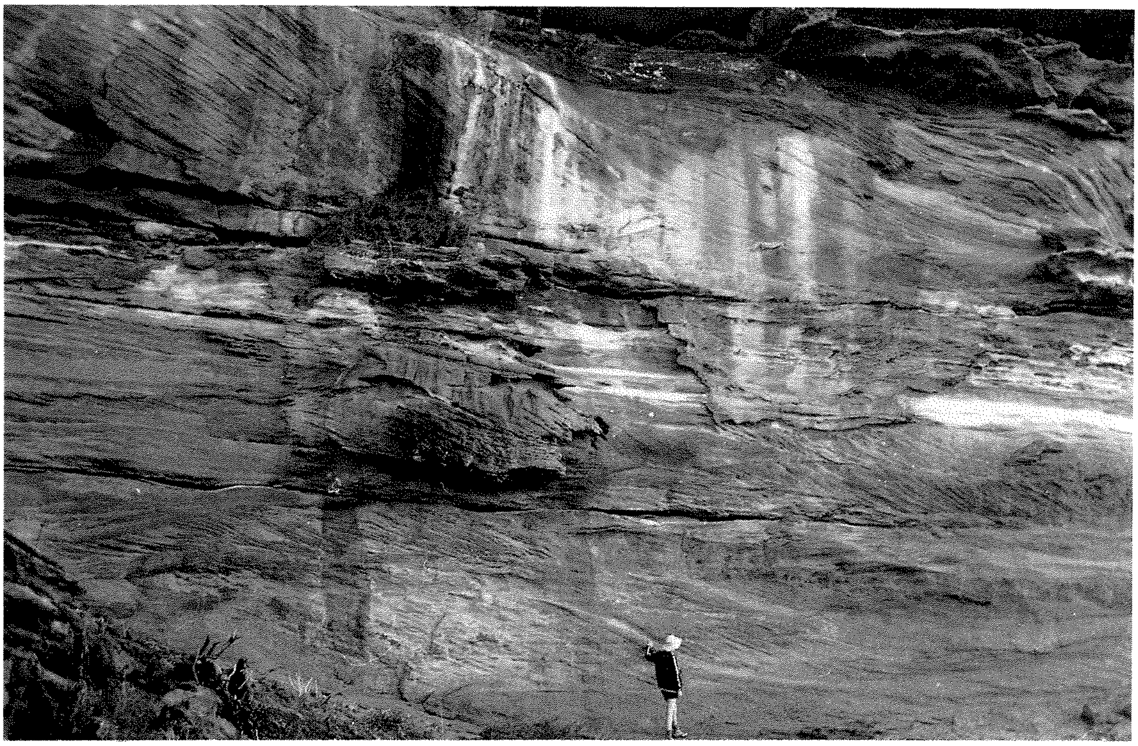
GSWA 23826

**Figure 57. FA3: Gabba Gabba Member (*GSts*) near the base of Red Bluff.**



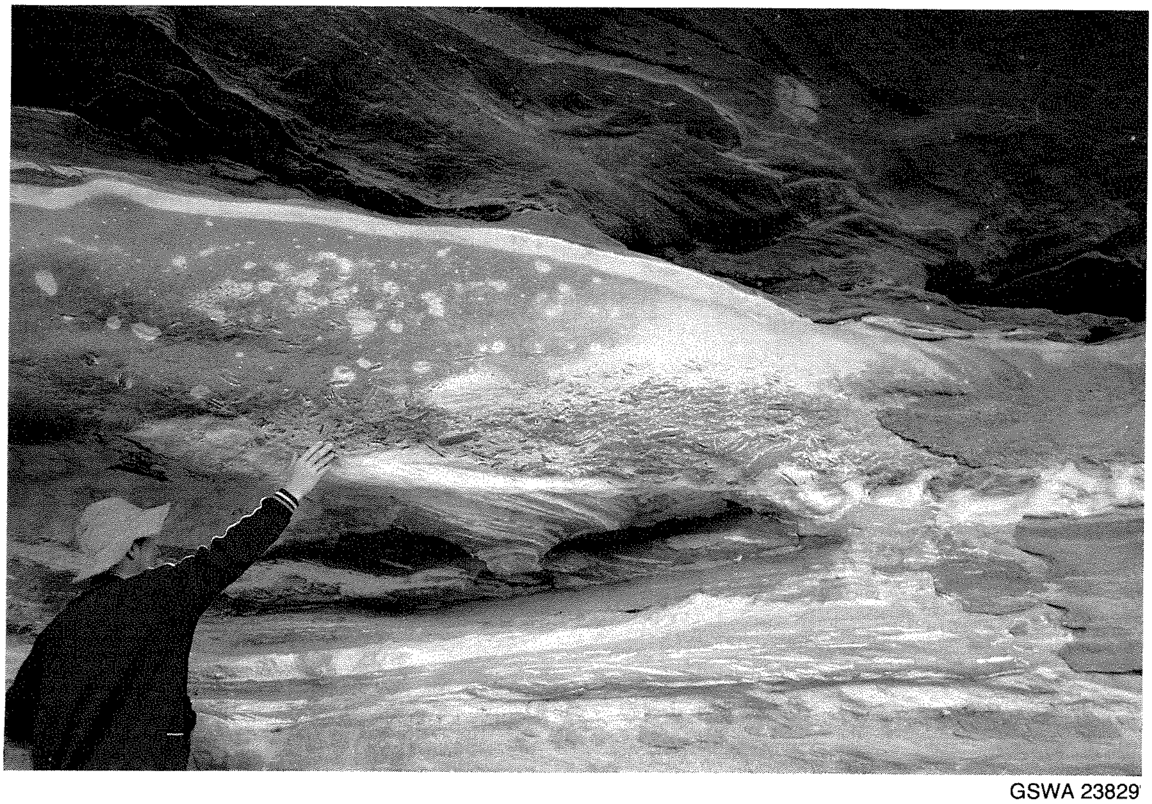
GSWA 23827

**Figure 58. FA3: base of Gabba Gabba Member, about 0.5 km north of Section 36 at Stone Wall. The trace fossil is *Cylindricum*.**



GSWA 23828

**Figure 59. FA3: fining-upwards cycles at Bracken Point (Section 33, base). A single cycle extends from the person's feet to the shrubbery on the rock face. Facies *cStv, cSt, Sh, cSts*, and *mSts* occur in sequence from base to top of the cycle.**



GSWA 23829

**Figure 60. FA3: brecciated and structureless sandstone at the top of a fining-upward cycle, Bracken Point.**

### Very large-scale cross-bedded sandstone (*cStv*)

Foresets in facies *cStv* formed by avalanching (grainflow) and grainfall down a slip face rather than by lateral accretion, because of their high dip and the compound cross-stratification on some foresets. The poor sorting, coarse grain size, and pebble and intraclast content negate an eolian origin as barchan or transverse dunes. Because the very large cross-beds grade laterally into smaller (<1 m) cross-beds, they probably developed as a part of internally complex subaqueous dunes rather than as internally simple, large migrating dunes.

A 20 to 30° difference in palaeocurrent directions between very large foresets (*cStv*) and other foresets in FA3 (*cSt* and *SGtm*) is locally apparent (see "tadpole" plots on graphic logs, and Figures 48, 50–52). This suggests that some very large foresets prograded obliquely across the palaeoslope rather than directly down it. Such cross-beds could have formed in large side-attached bars (alternate bars), similar in concept to those proposed by McCabe (1977), or by progradation down either side of diamond-shaped longitudinal braid-bars, like those described by Coleman (1969) from the Brahmaputra River. The first possibility is unlikely for the Tumblagooda Sandstone because there are no indications of channelling such as McCabe described (i.e. undulatory-bedded sandstones, massive sandstones, or clear large deep scours). Migration of large bars by avalanching down a forward face during the high stages of floods, as described by Coleman, is a more plausible explanation for facies *cStv*.

### Horizontally stratified sandstone (*Sh*)

The occurrence of horizontally stratified sandstone (*Sh*) at the tops of fining-upward and/or thinning-upward cycles, and its association with very small- to small-scale trough cross-beds, almost ripples, indicate that facies *Sh* formed at shallow water depths by high velocity flow (upper flow regime), probably on the tops of bars. Slight undulations may be incipient antidunes. These and the intraclast breccia shown in Figure 60 may have been produced by an upstream-travelling water wave, or hydraulic jump (Allen, 1982a, p. 409–417).

## Bioturbation in FA3

There are two possible hypotheses for the presence of *Skolithos*, *Cylindricum*, and other trace fossils in the texturally immature, apparently fluvial, sequence of FA3:

GSWA 23830

**Figure 61. FA3:** *Skolithos* **in very coarse-grained sandstone, base of Tumblagooda Hill. Lens cap 52 mm.**


GSWA 23831

**Figure 62. FA3: trails on bedding plane of FA3, 1.5 km north of Red Bluff ("The Point"). The trails are either** *Aulichnites* **or** *Didymaulichnus.*

(1) FA3 was deposited in a wholly continental, fluvial setting, and the trace fossils are also continental.

(2) The fluvial sediments of FA3 were subject to marine influence, by incursion of marine waters before lithification.

The first hypothesis is discounted, because *Skolithos* is almost universally regarded as a marine trace (see Seilacher, 1967; Alpert, 1974, 1975; Bradshaw, 1981; Gevers and Twomey, 1982; Hiscott et al., 1984). A continental setting for *Skolithos* has been suggested only by Plume (1982), Maulik and Chaudhuri (1983), Zawiskie et al. (1983), Barrett and Fitzgerald (1985), and Fitzgerald and Barrett (1986).

The rocks described in the latter four papers are of Permian age, about 150 million years younger than the Tumblagooda Sandstone. They were deposited well after the first appearance of invertebrates on land (Rolfe, 1980), and well after the evolution and spread of land plants (Beard, 1989). Vascular land plants were present in the Silurian (Edwards et al., 1979; Edwards and Feehan, 1980) but were certainly not abundant or diverse (Edwards et al., 1979; Niklas et al., 1980), and so could not have offered a major source of nutrition. It is unlikely that the animals which made the traces would venture into a high-energy fluvial environment which had (at best) minimal vegetation. This must have been a far harsher environment than the beach–littoral environment in which most authors consider they lived.

The sequence described by Plume (1982) is the New Mountain Subgroup of the Beacon Supergroup. It is a Devonian and ?Silurian sequence which appears very similar to the Tumblagooda Sandstone (see "Comparison with other sequences"). Bradshaw (1981) and Gevers and Twomey (1982) both suggested a shallow-marine to coastal origin for the New Mountain Subgroup, which indicates that Plume's interpretation is open to doubt.

The second hypothesis, of periodic marine incursion, would result in brackish or marine salinity, and is the hypothesis accepted here. The thickness of the sequence in which trace fossils occur in FA3 indicates the intermittently brackish conditions must have persisted for some time. This could occur if the river system was close to or at sea level, and either flow was seasonal or there were periodic storms. With seasonal flow, sea water would enter fluvial distributaries during dry seasons, and temporarily provide marine or brackish salinity. This was the explanation offered by Selley (1970) for the presence of *Cruziana* in an apparently fluvial sequence, and is equally valid for the Tumblagooda Sandstone. Periodic storms could force saline water up fluvial distributaries to provide temporarily brackish conditions (Cotter, 1983; Hiscott et al., 1984), but is less likely for FA3 because of the absence of both reworked and/or winnowed sediment and southward to southeastward palaeocurrent directions in FA3.

## Architectural elements

Sandy bedforms (Element SB, Table 4) predominate in FA3. Gravel bedforms (GB) occur in facies *GSts* and *SGtm*. Sand sheets (LS) are minimal, in that they occur only at the tops of some fining-upward cycles. Gravity flows (SG) and overbank fines (OF) are absent. Lateral accretion deposits (LA) have not been recognized as such, but the lateral gradation from very large crossbeds (*Stv*) to small- to large-scale crossbeds (part of *cSt*) may record a form of lateral accretion, on the sides of large in-channel bars and at channel sides.

GSWA 23832

**Figure 63. FA3: trails on bedding surface of FA3 near Bettie Crossing. The trails are either** *Aulichnites* **or** *Agrichnium.* **Lens cap 52 mm.**

Channels (Element CH, Table 4) have only been recognized at a local scale. Concave-upward erosion surfaces occur within cosets, which indicates small-scale channelling, metres to perhaps tens of metres across and up to a few metres deep. Larger channels, hundreds of metres to kilometres across, have not been recognized although they must be present — the depth of flow as indicated by fining- and thinning-upward cycles (up to 15 m water depth) is too great for channels to be absent over a significant area in a subaerial environment. At the scale of the outcrops available (generally up to a maximum of 100 or 200 m laterally), bounding surfaces between cycles and cosets appear planar. Major channels may have had very low-angle bounding surfaces and verged on sheet-like (and thus were not recognized), or had stepped margins, as described by Miall (1985, p. 274). Alternatively, they were larger than the scale of outcrop, or the large-scale channel pattern was obscured by medium- and small-scale channel switching and shifting (Miall, 1985, p. 274–275).

Foreset macroforms were large, longitudinally oriented dunes. This is indicated by the lateral gradation from very large crossbeds (*Stv*) to smaller crossbeds (*cSt*); the presence and thickness of fining- and/or thinning-upward cycles; and the presence of cross-bedded, very coarse-grained sandstone to granule conglomerate (*SGtm*) immediately below and above very large foresets (*Stv*). Convex-upward bedding surfaces (a diagnostic feature of the foreset macroform element, Miall, 1985b, table 2) have not been recognized. The bars built up in and migrated down the deepest parts of channels (Figure 15), and their height, as indicated by the maximum size of very large cross-beds (facies *cStv*), exceeded four metres. Migration downstream produced fining- and thinning-upward cycles (Figures 50, 59).

Coleman (1969) described large longitudinal dunes of comparable height in the Brahmaputra River, and found that fining-upward cycles up to 18 m thick could be formed during a single flood cycle, by vertical aggradation and migration of large dunes, or sandwaves. The sequence of events described by Coleman and by Eriksson (1978) can be applied to the fining- and thinning-upward cycles in FA3, as follows:

(a) Formation of large bars occurred during the rising stage of a flood cycle by repeated lateral and vertical accretion of megaripples and dunes (facies *cSt*), as described by Smith (1970, p. 2994). Small dunes of very coarse-grained sandstone to granule conglomerate (facies *SGtm*) preceded the large dunes, migrated between them, and formed upstream behind them. Near to and at the height of the flood (high stage), the large bars migrated over the smaller, simple dunes of facies *SGtm*. Facies *cStv* formed when there was avalanching down the face and sides of the bars.

(b) Aggradation continued during the waning stage of the flood, with the deposition of successively thinner and finer grained sets of facies *cSt* as water depth lessened and competence of the flood waters declined. Horizontally stratified beds (facies *Sh*) formed at the tops of cycles under upper flow regime conditions, in very shallow water depths (analogous to the horizontal stratification recorded by Smith, 1970, p. 2995) or when water depth decreased rapidly (Eriksson, 1978; Boothroyd and Ashley, 1975).

The bars in the Brahmaputra River are wholly continental; there is no marine influence apparent. They are present and very large because the source of the river is the Himalayan ranges. While the provenance for the Tumblagooda Sandstone was a tectonically active hinterland, tectonism on the scale of the Himalayan orogeny need not be invoked. Instead, the scattered occurrences of bioturbation in FA3 indicate a coastal setting, either a major fluvial-dominated, estuary system or a low-relief, high-energy delta. Water depths of 10 to 15 m (necessary to generate the 10–15 m thick, fining- and thinning-upward cycles in FA3) could easily occur in these settings.

Partial fining- and thinning-upward cycles occur between the main belt of cyclic sediments and the stratigraphic level of the Gabba Gabba Member in the Toolonga Point–Bettie Crossing area (Sections 32, 34). They are partial cycles in that the upper part of each cycle is missing, in comparison to the 10 to 15 m cycles below. The grain size and preserved bedding scale is similar to the lower parts of full cycles, which indicates that the grade of the palaeoslope did not decrease. Instead, the subsidence rate of the basin probably decreased, so that the upper portion of each cycle was removed by erosion. This is as outlined by Miall (1980, figure 4 and p. 66). The largest foresets (*cStv*) at the bases of cycles do not exceed 2 m height (as compared to the 4 m maximum height in lower cycles) indicating that maximum water depth may also have been less.

Clear cyclicity and very large foresets are virtually absent in the coastal gorges and above the Gabba Gabba Member, except north of Bracken Point. In general, facies *cSt* is also thinner-bedded above the member. These features suggest that large braid-bars did not develop because of lower water depths at flood peaks, although the coarse grain size indicates that current velocities were still high.

## FA2–FA3 transition

The transition from FA2 to FA3 is present in Sections 27 to 31. It occurs at the very top of the section at The Loop, and near river level in sections at Mooliabaanya Pool. The contact is not a gradual intercalated transition such as occurs between FA1 and FA2. Instead, progradation of FA3 sediments abruptly terminated FA2 deposition. Coarse-grained, high-energy, fluvial sandstone (arranged in 5 to 10 m thick fining-upward cycles) rests abruptly on a lower intertidal sequence of FA2. The latter contains no other significant fluvial intercalations for at least 50 m below the contact.

The only indications that the transition reflects rapid northwestward progradation into the intertidal–subtidal zone, rather than a possibly major disconformity (as Mandyczewsky (1973) suggested), are that the upper 50 cm of some cycles are bioturbated, have south- to southeast-ward palaeocurrent directions, and/or contain typical facies *mSh* (of FA2) intervals. Assuming that each cycle represents deposition during a flood (see FA3 depositional environment), the bioturbation reflects infiltration by marine waters between floods. The southeastward palaeocurrent directions and thin FA2 interbeds indicate that the environmental setting was still coastal, where tidal processes could have a significant effect if fluvial progradation diminished or ceased. Bioturbation and marine reworking at cycle tops diminishes upwards and ceases about 50 m into FA3. This reflects continued progradation and progressive protection from reworking and infiltration by marine waters.

The abrupt change from tidal to fluvial deposition therefore reflects abrupt rejuvenation of the hinterland.

## FA3 depositional environment

The unimodal, low-scatter palaeocurrents, the textural immaturity of sediments within FA3, and the predominance of trough cross-bedded sandstone (Element SB) indicate that the association was deposited in a low-sinuosity, sandy, high-energy fluvial environment which was dominated by three-dimensional dunes (Figure 64). The scattered bioturbation in FA3 indicates that, in the type section, the fluvial system was located in a near-coastal setting. Water of marine salinity entered the lower reaches of the fluvial distributaries when fluvial influx lessened or ceased.

The occurrence of fine-grained interdistributary sediment (Element OF) only as intraclasts and rarely at the tops of fining-upward cycles shows that no stable interdistributary areas were present. Therefore, the fluvial system was braided (terminology of Rust, 1984). Sheet flooding was not significant, because horizontally stratified sandstone occurs only at the tops of some fining-upward cycles, as an integral part of the cycle (see "Architectural elements", above). Instead, flow was in channels, which in places exceeded 15 m depth. The width and complexity of the channels is unknown.

Rippled and/or fine-grained sediments are recorded from the tops of braided-fluvial cycles by most authors (e.g. Eriksson, 1978; Miall, 1978; Cant and Walker, 1976; Cant, 1978). These represent deposition from suspension during the last stages of flow. They are only rarely preserved at the tops of FA3 cycles in the Tumblagooda Sandstone, but the common fine-grained intraclasts (Figure 55) indicate that late stage deposits were eroded by the following period of flow.

Two broad classes of bedforms were present during deposition of FA3. The first class is large, longitudinal, in-channel bars. Their presence is postulated mainly because of the occurrence of very large crossbeds (facies *Stv*) within fining-upward cycles. The bars formed in and migrated down the channel thalweg area in deeper channels (Figure 15). The second class is smaller, simpler three-dimensional dunes (Figure 15). These represent the non-cyclic parts of FA3 (for example, in the coastal gorges, and above the Gabba Gabba Member), and formed in broad

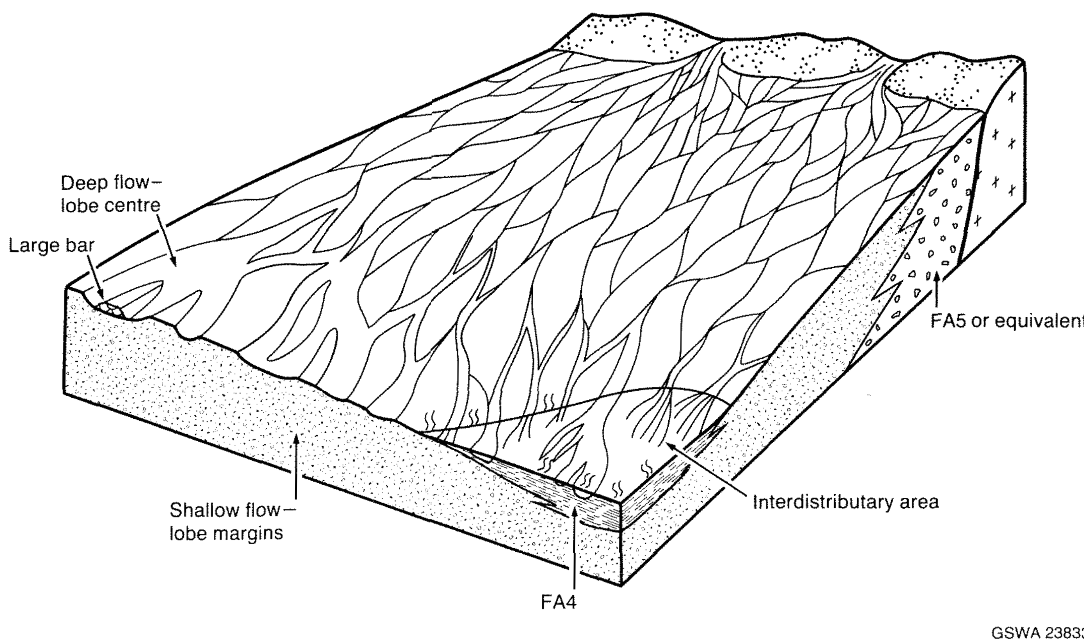



**Figure 64. Depositional model for FA3. The model is diagrammatic only; there is severe compression of scale from front to back, and exaggeration from left to right, at the front. Large bars develop in areas of deep flow. They are absent in areas of shallow flow, where the dominant bedform is a smaller, simpler, three-dimensional dune. The distal portion of lobe, where energy levels are far lower, is shown at the front right.**

ephemeral channels in shallower portions of the fluvial system.

As noted above, flow in the fluvial system was episodic. Periodic floods or seasonal flow are the possible mechanisms. Periodic flooding (which may have been seasonal) readily explains the development of the fining-upward cycles, as rapidly formed bars during a single depositional event.

The fluvial system may have been located in either of two settings, a very large, fluvially dominated estuary or a low-relief, high-energy delta. Both are coastal settings, which would explain the scattered bioturbation in FA3, and flow depths of 15 m could easily occur in either of them. The energy level apparent in FA3 (from grain size, sorting, and bedding scale) suggests that fluvial processes would totally overwhelm marine reworking. The extent and thickness of FA3 would make it a very large estuarine system, but not impossibly large. The alternative setting, in which there are no prodelta deposits (the FA2–FA3 transition is abrupt; there is no coarsening-upward sequence at the base of FA3), could occur if topographic relief was minimal at the coastline.

The transition from cyclic sediments (in the north) to non-cyclic sediments (in the south) occurs approximately along strike of the palaeoslope, and at the same stratigraphic level. The transition also coincides with a southward increase in bioturbation and with a southward decrease in thickness of the interval of FA3 above the Gabba Gabba Member (Sections 35 – 41). Taken with the interpretation of FA3 above, these observations allow the overall development of FA3 fluvial deposits to be deduced, as follows:

(a) FA3 was deposited as large, rapidly aggrading lobes in a flood-dominated, low-sinuosity, sandy fluvial system. The pebbly sandstone marker represents the abandonment and partial erosion of one of these lobes. Possibly only two lobes are present in the type section, one below the Gabba Gabba Member and one above.

(b) Each lobe showed a progression from deep, high-velocity flow in the central portion of the lobe, where large longitudinal bars formed cyclic sequences, to shallower flow at the margins of the lobe, where large bars did not develop and deposition was non-cyclic or poorly cyclic. Aggradation was rapid in the central portion of the lobe, and decreased toward the margins.

(c) The lobes were near to or at sea level, and during dry periods they could be bioturbated.

(d) The depth of flow, the probable size of the largest bedforms, and the presence of minor bioturbation suggest that in the type section area the lobes were either major estuarine systems in which there was almost total dominance by fluvial flow, or high-energy, low-relief deltas that had no development of prodeltaic deposits because of low topographic relief.

(e) Relief on each lobe was sufficiently slight that palaeocurrents were not deflected measurably from a broad down-palaeoslope orientation. Eriksson (1977) and Button and Vos (1977) proposed similar lobes.

(f) The abandonment of one lobe and the subsequent progradation of another lobe can be adequately explained in terms of autocyclic, or internal, processes. Each lobe initially built down a line of greatest slope which, because FA3 is located some 150 km from the basin margin, did not differ significantly from the regional northwest dip of the palaeoslope. As the lobe aggraded, the grade on its surface lessened until, eventually, the loci of floods avulsed and commenced building a new lobe. Subsidence, reworking, and compaction of the abandoned lobe soon reduced its relative elevation so that deposition recoenced over it.

The principal sediment source, as for FA1, must have been the Yilgarn Craton, about 150 km to the southeast of the upper part of the type section (Figure 1, Plate 1). Some reworking of older, consolidated Tumblagooda Sandstone occurred also, at least in the upper Hutt River area where a cobble of red and white blotched, medium-grained Tumblagooda Sandstone (?FA1) is incorporated in pallid, coarse-grained typical FA3 sediments.

# Facies Association 4 (FA4)

Facies Association 4 (FA4) was previously referred to by Hocking (1981a) as Facies Association 3a, because it appeared to be a low-energy variant of FA3. It is now recognized as a separate association because further work on both FA3 and "FA3a" highlighted differences between the two on both descriptive and interpretive bases. The association corresponds to the "Yalthoo Member" of Johnstone and Playford (1955), and Playford et al. (1975). This name is not used here because, while FA4 may be lithologically distinct, its stratigraphic utility is doubtful.

## Facies descriptions

FA4 occurs above FA3, near the top of the type section and along the coastal gorges (Sections 35– 45). In this area, it is less than 25 m thick. The lower boundary of the association varies in its stratigraphic height above the Gabba Gabba Member, as can be seen in Sections 41 to 45, and the association grades laterally into FA3 with no single, clear pattern. The upper boundary in outcrop is an eroded boundary beneath Mesozoic sediments. A conformable contact with the Silurian Dirk Hartog Formation is present in the subsurface in Kalbarri 1.

Three major facies form FA4: laminated and rippled, red and white sandy siltstone to very fine-grained sandstone (*Fl*), parts of which are bioturbated (*Flb*); very fine- to medium-grained sandstone, which is mostly trough cross-bedded (*St*) but locally horizontally stratified (*Sh*) or planar cross-bedded (*Sp*); and medium- to large-scale cross-bedded, *Skolithos*-bearing sandstone (*Stk* & *Spk*). Horizontally stratified sandstone intervals (*Sh*) are uncommon, and grade into facies *Fl*. A volumetrically insignificant facies of laminated mudstone (*Ml* ) can be recognized in some coastal sections.

Palaeocurrent directions were unimodal to the northwest (vector mean of 307°), but show a broader scatter than FA3 (vector magnitude 0.73; Figure 65). The total number of readings is also considerably lower because of the nature of the outcrop.

Detailed interpretation of the association in the type section is hampered by poor exposure. It occurs immediately beneath Cretaceous sediments, and fine-grained intervals are commonly not exposed. Most detail of FA4 is therefore derived from the coastal gorges, and in particular the Red Bluff–Mushroom Rock area (Figures 66, 67).

Fining-upward cyclicity is apparent in much of FA4. Cycles are approximately 1 to 3 m thick, and have the facies sequence *mStm* → *mStf* → *Fl* (→*Flb*). However, in parts of the coastal sequence, sandstone interbeds appear to have been deposited as abrupt, discrete events rather than as part of a cyclic sequence (Figure 66).

### Lithofacies

#### Medium- to fine-grained sandstone (*St*, *Sh*, *Sp*)

Medium- to fine-grained sandstone occurs mostly as single cross-sets which are generally less than 1.5 m thick and commonly less than 50 cm thick.

Trough cross-bedded sandstone (*St*) ranges from fine- to medium-grained, medium- to small-scale cross-bedded sandstone, to very fine- to fine-grained, small-scale cross-bedded sandstone. Planar cross-bedding (*Sp*) occurs but is less abundant and is difficult to recognize in many exposures. Most sandstone is a moderately to well-sorted quartz arenite, although some quartz wacke is present. Scattered coarse grains commonly result in a gritty appearance. Trough sets are between 20 and 60 cm high, are approximately 1 to 1.5 m wide, and have gently scoured bases (Figure 67). Some horizons near Red Bluff appear silty, but this may be in part because they are exposed to intense coastal weathering. *Skolithos* and possibly *Cylindricum* are present at some localities in Second Gully and along the coast, and are locally abundant.

Except for isolated solitary channels less than 1 m wide which occur locally in siltstone (Figure 68), sand bodies are laterally persistent (Figures 66, 67). Detailed section measuring and correlation between Red Bluff and Mushroom Rock shows that they do thicken, thin, coalesce and lens out over distances of 100 to 300 m (Figure 66). In one case (the datum line in Figure 66) a specific horizon changes laterally from 40 cm of trough cross-bedded sandstone to a single 10 cm set of small-scale troughs, then to low-angle planar cross-stratification, and finally to ripple-laminated sandstone over a distance of 20 m, south to north. Further to the north, it again thickens, to 55 cm of cross-bedded sandstone. There is a continuous gradation, both in grain size and bedding scale, from medium-grained, medium-scale cross-bedded sandstone to very fine-grained, small-scale cross-bedded sandstone. Small-scale cross-bedded units occur as small scour and fill structures either at the margins of medium-grained sandstone intervals, or isolated from them but at the same stratigraphic level. Palaeocurrent directions are unimodal to the west (Figure 65).

Horizontally bedded to low-angle cross-bedded, fine- and medium-grained sandstone occurs above cross-bedded sandstone locally, and grades upwards and laterally into laminated siltstone (*Fl* ) or very fine-grained horizontally stratified sandstone (*fSh*). Ripple-laminated sandstone is similarly distributed. Bioturbation, locally with *Skolithos*, occurs in some intervals, generally near the top of the association. Bioturbation is not solely dependent on stratigraphic level, as some intervals grade laterally from bioturbated to non-bioturbated sediment (Figure 66).

Fine- to very fine-grained sandstone (*fSts* and *fSh*) is generally only distinguishable in coastal exposures, because of the constraints of outcrop and weathering.

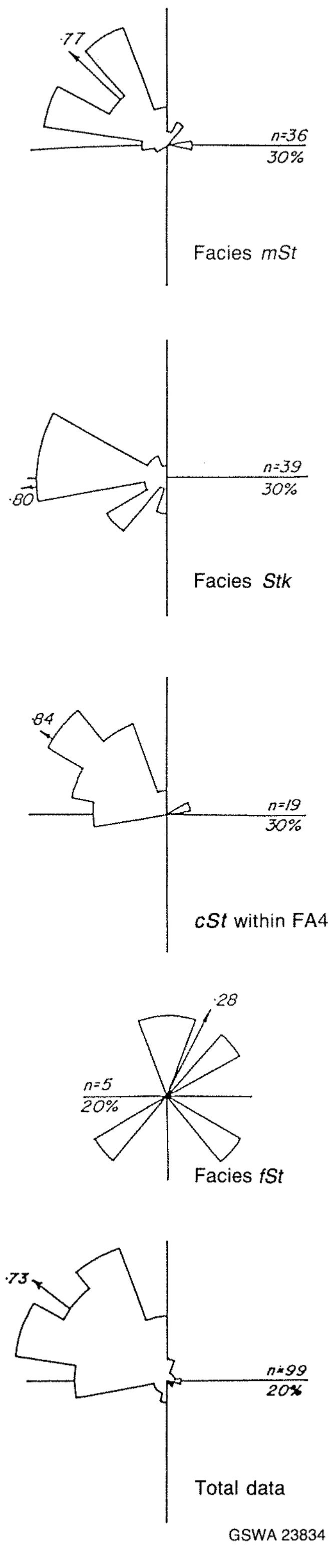



**Figure 65. Palaeocurrent totals for FA4, grouped by facies.**

### Cross-bedded, *Skolithos*-bearing sandstone (*Stk*, *Spk*)

Intervals of cross-bedded sandstone which contain *Skolithos* are both trough (*Stk*) and planar (*Spk*) cross-bedded, and are generally more than one set thick (Figures 67, 69). Trough cross-bedding is dominant. The sandstone is medium- to coarse-grained, poorly to well-sorted, quartz arenite and feldspathic arenite. Scattered coarse grains commonly give a gritty appearance. Small claystone and siltstone flakes are common, and abundant; locally derived intraclasts can be seen at the base of one steep-sided scour at Red Bluff (Figure 70).

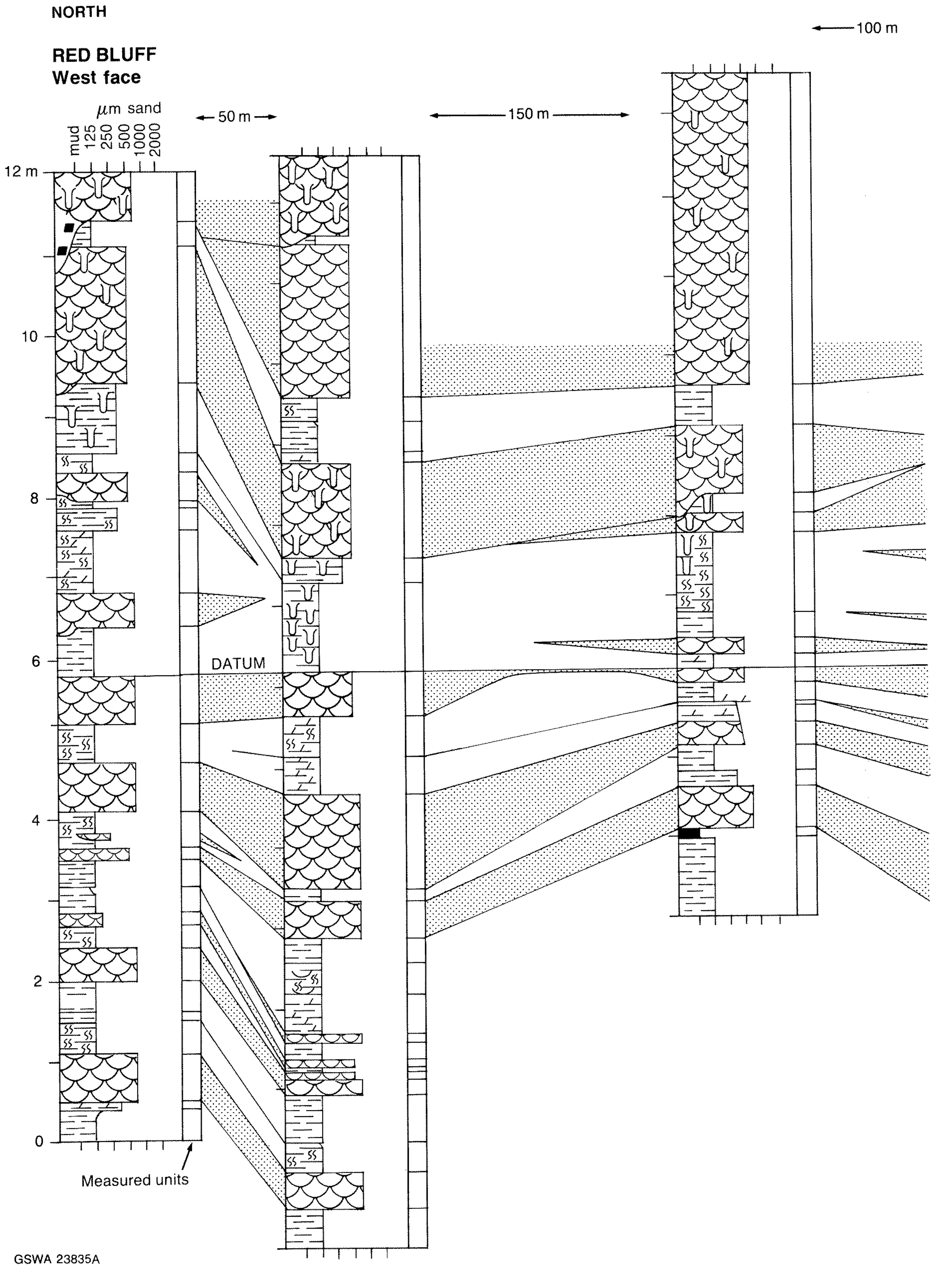
Cross-sets are mostly medium to large (20 cm to 1 m); small and very large sets also occur. They locally show parabolic recumbent (Doe and Dott, 1980) and gently contorted oversteepening. Cross-set bases vary from planar to moderately scoured (Figures 66, 67). Trough infill is both simple and complex, and there are multiple reactivation surfaces. Palaeocurrents were westwards, within a northwest to southwest range (Figure 65).

Planar cross-bedded sandstone (*Spk*) is texturally identical to the trough cross-bedded sandstone (*Stk*). It appears to be considerably less abundant than trough cross-bedded sandstone, and occurs only in single medium- to large-scale erosively based sets. *Skolithos* is less abundant than in trough cross-bedded sandstone.

*Skolithos* pipes are very dense and abundant in some horizons and virtually absent in others. Individual pipes are commonly 30 to 50 cm long and range in length from a few centimetres to more than 1 m (Figure 69). They are commonly truncated by the overlying cross-set, but some pipes extend through more than one set, and in places show morphological changes at the set boundary.

### Laminated and rippled, siltstone and fine-grained sandstone (*Fl*, *Flb*)

Siltstone and very fine-grained silty sandstone (*Fl*, *Flb*) occur in intervals 10 to 20 cm thick (Figure 71), and are characteristically a deep red-brown, locally purple, hematitic colour. Light-yellow to white intercalations highlight bedding and bioturbation, as in FA2. In poorly exposed areas, only a wash of deep red-brown silt and mud


NORTH
RED BLUFF
West face
µm sand
mud
125
250
500
1000
2000
12 m
10
8
6
4
2
0
Measured units
DATUM
50 m
150 m
100 m
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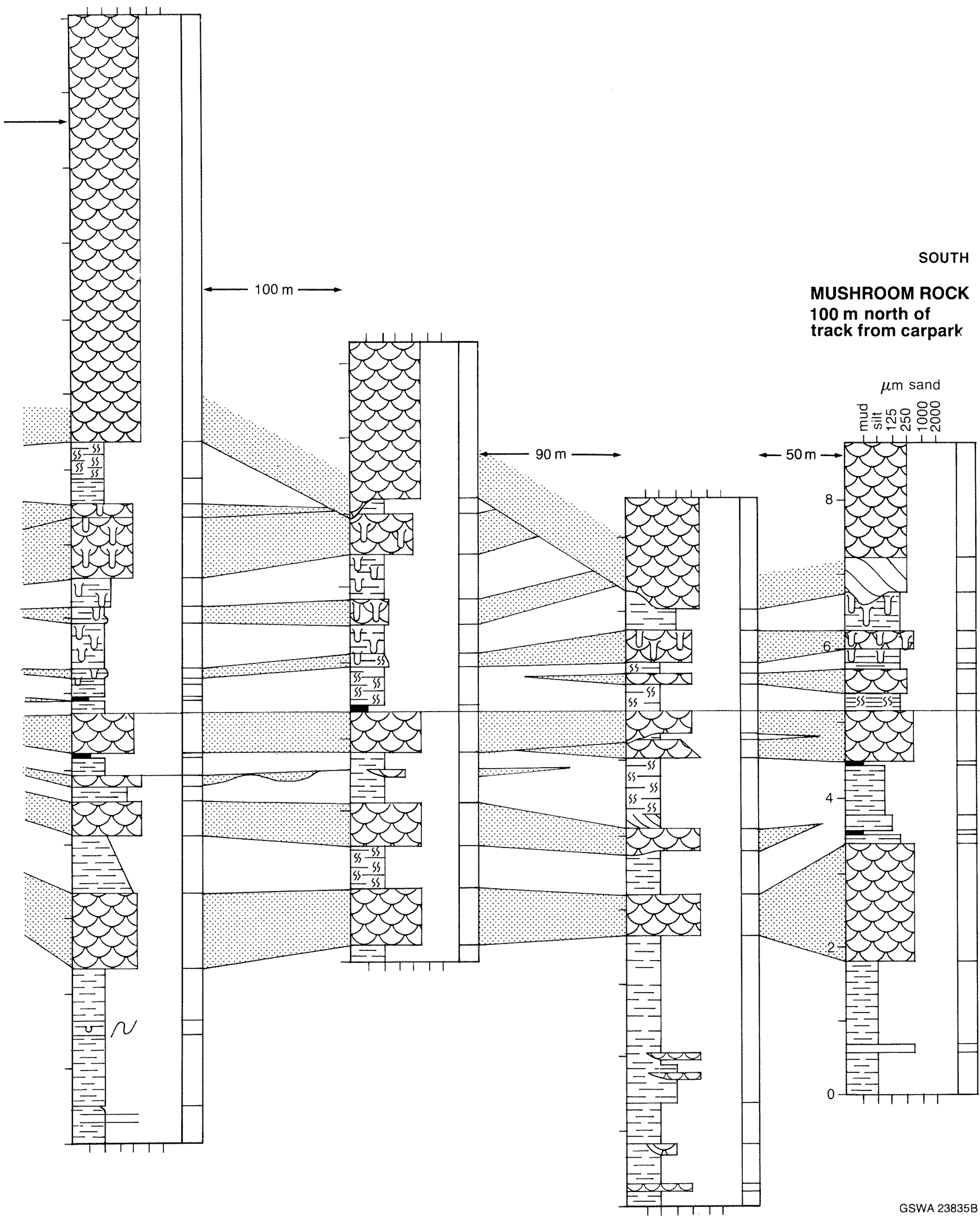


**Figure 66. Detailed sections in FA4 between Red Bluff and Mushroom Rock. Correlations between sections have been verified by walking between sections and by tracing prominent beds by eye. The bar divisions on the right-hand side of each section record individual measured units.**

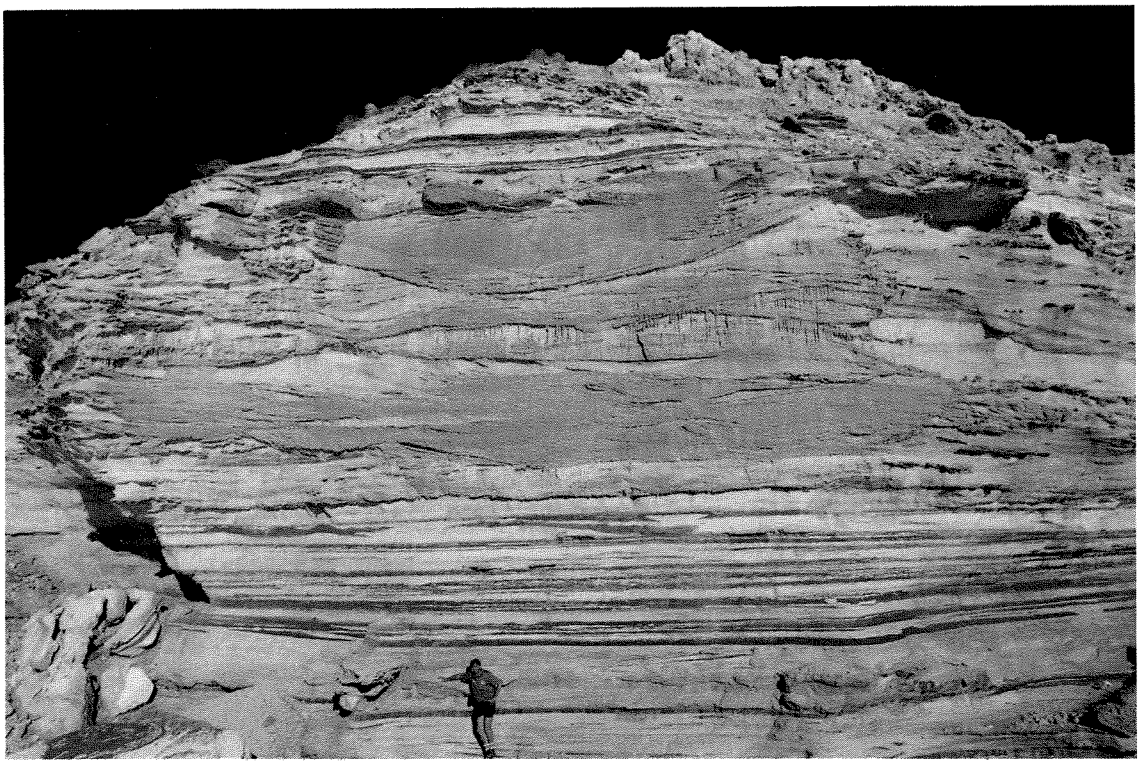

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**Figure 67. FA4: the main face of Red Bluff. The lower part of the face consists of fining-upward cycles or couplets, mostly *St* to *Fl*. The main vertical face is large-scale cross-bedded sandstone; *Skolithos* is abundant in the upper part (*Stk*). More fining-upwards cycles *(Stk to Fl)* are present at the very top of the face. Person for scale at lower left.**

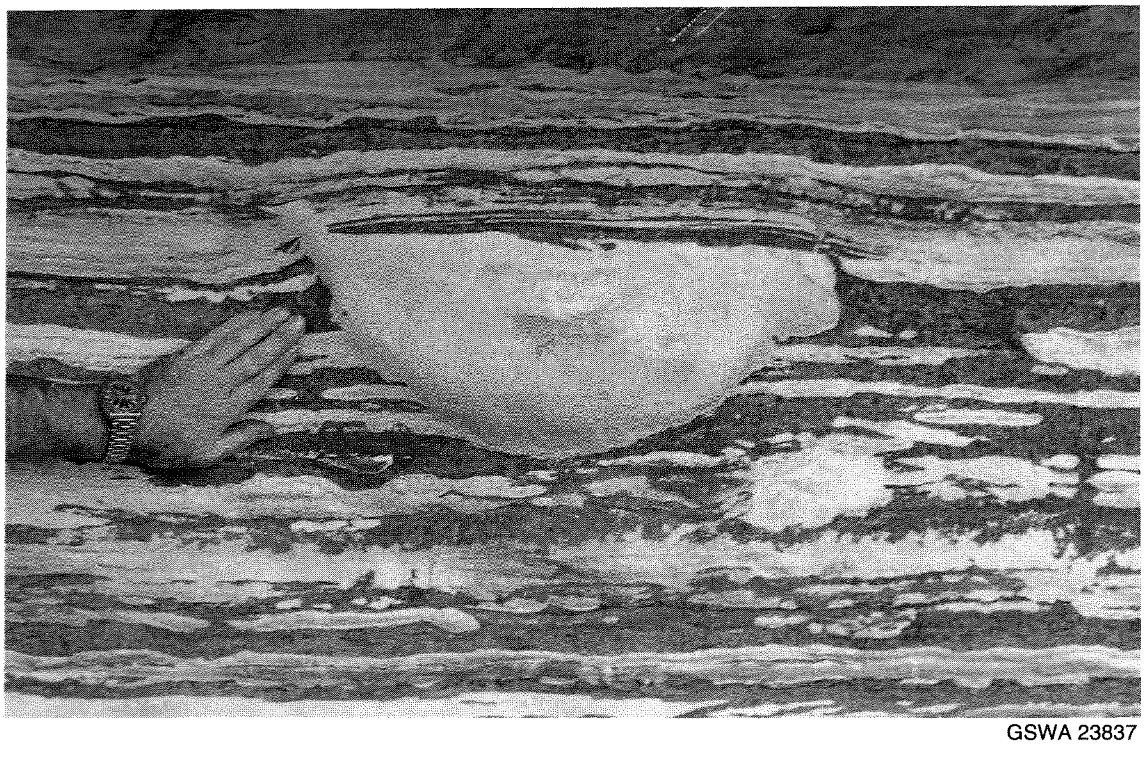

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**Figure 68. FA4: small isolated, steep-sided channel within bioturbated, thinly bedded, very fine-grained sandstone and coarse siltstone; Rainbow Valley, below carpark.**

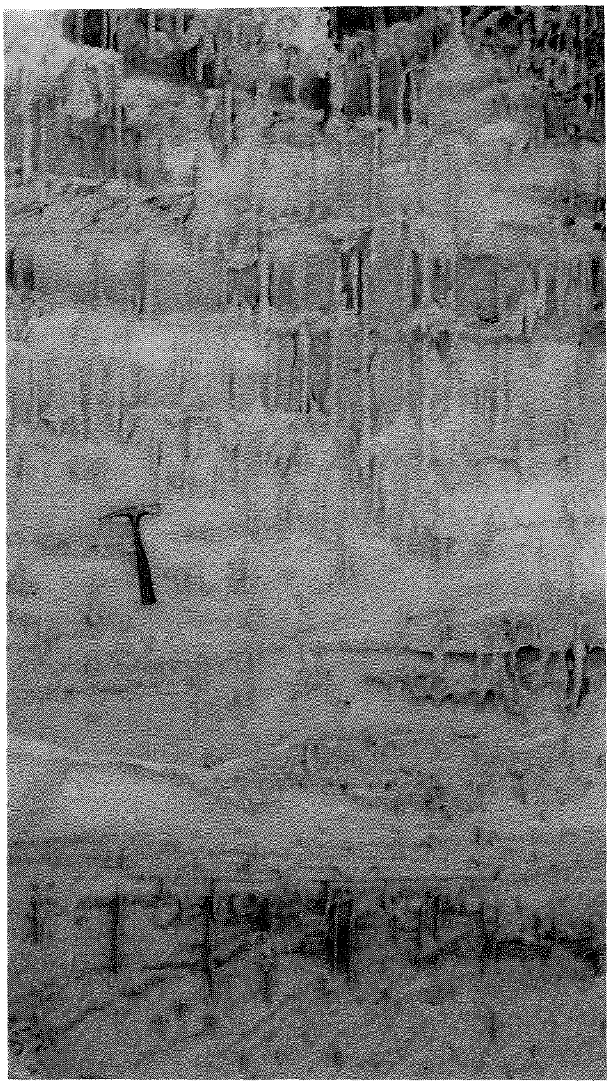


**Figure 69. FA4: very long *Skolithos* below carpark at Rainbow Valley.**

enables the facies to be recognized. Intervals of the facies persist for the width of the outcrop, commonly more than 30 m (Figure 66). Scattered coarse sand laminae and very micaceous laminae are common.

Fine horizontal lamination is dominant, and in places is highlighted by micaceous laminae. This grades laterally into ripple lamination and very low-angle cross-stratification. Ripples are asymmetric current ripples, and locally climb subcritically. Convolute lamination occurs in a well-defined 20 cm thick layer on the southwestern face of Red Bluff. No noticeable grain-size variation occurs below or above the layer, and it is probably the post-depositional convolute lamination of Allen (1982b, p. 351).

Bioturbation occurs intermittently through the facies, and is not related to the stratigraphic level. Collapse structures up to 20 cm across and affecting 10 to 20 cm of sediment are present in the coastal gorges (Figure 71). These are very similar to but much larger than *Chagrinichnites osgoodi* (Hannibal and Feldmann, 1983), an arthropod escape burrow. *Skolithos* is poorly developed in comparison with pipes in fine- and medium-grained sandstone, and occurs mostly in siltstone intervals near the stratigraphic top of FA4.

### Laminated mudstone (*Ml*)

Thin intervals of soft pale-green, laminated mudstone (*Ml*), mostly less than 1 cm thick, can be recognized in some protected overhangs. With few exceptions, they occur immediately beneath, and are cut out laterally by, medium-grained sandstone. The exceptions are interlaminae in laminated sandstone. Chips of the mudstone occur as intraclasts in the basal parts of overlying sandstone intervals.

# Facies interpretation

FA4 was deposited in a protected interdistributary bay setting on interdistributary flats and in subaqueous channels. This is indicated by the presence of bioturbation; the virtual absence of reworking by tides or waves (which implies unidirectional, seaward-directed palaeocurrents, or extremely asymmetrical, ebb-dominant tidal currents); the presence of both suspension and bedload deposits; and the presence of incised scours.

## Lithofacies

### Medium- to fine-grained sandstone (*St, Sp, Sh*)

Small scours infilled by cross-bedded sandstone within laminated siltstone, the scouring at the base of some sandstone intervals, and the lateral variation in thickness of each sandstone interval suggest that both planar and trough cross-bedded sandstone (*St, Sp*) were deposited in rapidly migrating shallow channels and sheets which commonly cut into underlying siltstone intervals. Bedforms were small to medium (<60 cm) three-dimensional dunes and, less commonly, two-dimensional dunes. The westward palaeocurrent directions (Figure 65) indicate that deposition was dominated by continental processes, rather than by marine processes, such as flood tide deltas, barrier bars, or tidal sand ridges.

Horizontally stratified sandstone (*Sh*) was probably deposited from suspension. The absence of primary current lineation and the transitional contacts between horizontally stratified sandstone and laminated siltstone (*Fl*) argue against deposition in high-velocity, upper flow-regime conditions.


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**Figure 70. FA4: scoured base of large trough, at base of main *Stk* interval, Red Bluff. Several large intraclasts are part of the trough infill. The field of view is about 1.5 m high, and is located immediately to right of view in Figure 67.**

### Cross-bedded, *Skolithos*-bearing sandstone (*Stk*, *Spk*)

Trough and planar cross-beds (*Stk* and *Spk*) were deposited in migrating and avulsing channels which flowed westwards in a subaqueous, coastal to nearshore setting. This is indicated by common scours at the base of the facies, as in the face of Red Bluff (Figure 70); the manner in which cosets coalesce laterally (see the left-hand three sections on Figure 66); westward palaeocurrent directions; and the abundant *Skolithos*. The channels were larger and deeper than those in which facies *St* and *Sp* were deposited. Complex channel-fill patterns, reactivation surfaces, and common truncated *Skolithos* (Figures 67, 69, 71) indicate that flow patterns were complex and changeable, rather than uniform. Contorted and oversteepened beds suggest periods of high-velocity turbulent flow during floods (see interpretation of facies *cSt* of FA1), as does the common coarse grain size and gritty appearance of the facies.

Bedforms were primarily three-dimensional dunes, because trough cross-bedding is dominant; two-dimensional dunes occasionally formed planar cross-beds in the deeper parts of channels. *Skolithos* may be less abundant in planar cross-beds because planar cross-sets are generally thicker than trough cross-sets; the organisms responsible for *Skolithos* may not have survived the deposition of the thicker layers of sediment.

There was minimal reworking of the cross-bedded sandstone by waves or tidal currents. Reactivation surfaces in some cross-beds could have been produced either by flood-tide currents which opposed the dominant fluvial currents, or by unidirectional fluvial currents which varied markedly in strength (Mowbray and Visser, 1984, p. 813). Secondly, some cross-bedded horizons are very well-sorted compared with most of the facies. This may have originated by wave or tidal reworking and winnowing, in a temporarily abandoned portion of the fluvial distributary system.

### Laminated and rippled, siltstone and fine-grained sandstone (*Fl*, *Flb*)

The presence of bioturbation in some intervals (*Flb*) but not in others (*Fl* ) suggests that the facies as a whole was deposited in a paralic area which oscillated between marginally marine and terrestrial environments. The gradation of individual horizons from bioturbated to non-bioturbated indicates how fine this oscillation was, and suggests that the sediment surface along palaeostrike undulated slightly rather than being horizontal.

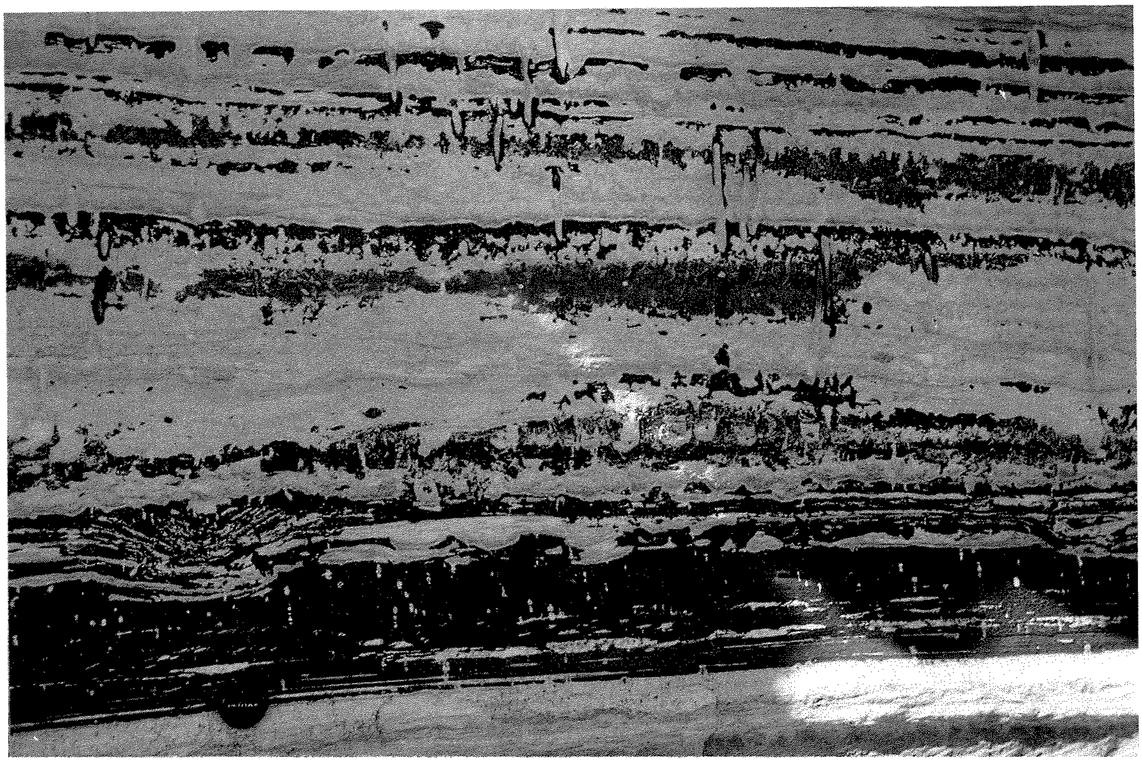

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**Figure 71. FA4:** *Skolithos, Chagrinichnites* **sp. (above lens cap) and unidentified burrows within red and white couplet sequence; south side of Red Bluff. Lens cap 58 mm.**

The facies was deposited from suspension (horizontally laminated horizons) and by low-energy currents (rippled horizons). The presence of climbing ripples indicates that silt to very fine sand was abundant at times. Scattered coarse sand laminae could be armoured surfaces that developed by winnowing during periods of minimal supply. However, given the lack of disseminated coarse sand in facies *Fl*, they are probably indicators of infrequent high-energy events which smeared a small amount of coarse material (derived from adjacent higher energy areas) thinly over a wide area. Bioturbated horizons (*Flb*) probably formed in the same way as facies *Sb* of FA2, by episodic rapid deposition and substantial breaks between each depositional event. The presence of arthropod escape burrows (*Chagrinichnites*) supports this hypothesis.

Distal flood waters, which had previously deposited all sandy material but still carried abundant silt in suspension, could have deposited the necessary thickness of sediment. The depositional setting was coastal, but tidal currents or waves were not the agent of deposition, because there is little evidence of wave activity or tidal currents. In this setting, deposition would be accelerated when the flood waters debouched into the tidal zone. This would abruptly reduce the flood's competence and produce a rapidly settling suspension cloud.

**Laminated mudstone (*Ml*)**

Laminated mud (*Ml*) was deposited in the final stages of suspension settling, in virtually still water conditions after all coarser material had settled. Mudstone intraclasts in sandstone suggest shrinkage cracking of the mudstone occurred, but it is not known whether these were subaerial desiccation cracks or subaqueous syneresis cracks (Collinson and Thompson, 1982, p. 140), since neither have been found in outcrop.

## FA4 depositional environment

The sporadic presence of bioturbation in both silty and sandy facies of FA4 indicates that the association was deposited in paralic conditions, which oscillated between marginally marine and marginally continental. Although evidence of reworking or deposition by waves or tidal currents is minimal, the bioturbation is not considered to be fully continental, for reasons outlined in "Bioturbation in FA3". Instead, FA4 was deposited in an coastal environment protected from marine processes.

Sedimentary structures and the sequence of facies in the lower part of FA4 resulted from deposition by periodic floods, distal effects of which reached to the coastal geographic setting of the FA4 sequence (Figures 64, 72). Each flood deposited most of its sediment load in up-palaeoslope areas, and retained only silt, mud, and lesser medium to fine sand when it reached the coast. This retained load was deposited in three stages. Firstly, medium to fine sand was deposited in sand sheets and shallow channels which cut into earlier flood deposits (facies *St*, *Sp*). The second stage, as flow lessened, was deposition of rippled fine sand to silt (facies *Flr*). This only occurred during some floods. The third stage was the settling of clouds of suspended sediment, to form horizontally laminated horizons (facies *Sh* and *Fl*). Deposition of laminated mud (*Ml* ) occurred at the end of this stage. The flood was followed by bioturbation in marine areas. With this mechanism of deposition, many of the smaller fining-upward cycles could result from a single flood. Larger cycles may reflect gradual diminution of floods on a seasonal or longer term basis, or the migration of channel systems. Such channel systems were probably distributary channels and/or splays from large channels.

The possible tidal influence in facies *Stk* and *Spk* suggests that they were deposited in subaqueous channels which were connected to the open sea. The channels were larger and deeper than those in which facies *St* and *Sp* were deposited. The latter probably formed in distributary channels and/or splays from the large *Stk–Spk* channels. Weak tidal flow extended up the large channels but not into the smaller channels, because of the lesser depth of the smaller channels (Figure 72).

The transition upwards into facies *Stk* and *Spk* is abrupt rather than gradational, and the uppermost exposures in Red Bluff and Rainbow Valley show a change from facies *Stk* and *Spk* back to a silty sequence. These transitions indicate lateral migration, rather than progradation, of a coastally located distributary system. Relative sea level was, if anything, higher in the uppermost exposures, because there is a greater degree of bioturbation therein.

Overall, FA4 is a transgressive sequence deposited in the wake of diminished sediment input. Interdistributary bay sequences, described by Elliott (1974) and summarized by Elliott (1986b) and Coleman and Prior (1982), provide the best analogue for FA4, although some differences between the two are present. Elliott (1974) regarded an interdistributary bay as any area between deltaic distributaries, either open to the sea or closed. He distinguished three processes which introduced sediment to a bay (overbank flooding, crevasse splays, and avulsion) and suggested four stages of development of a bay (overbank flooding, crevasse splay, mouth bar–crevasse channel couplets, and avulsion). Within the bay, deposition is dominated by flood processes. A mixture of sand and mud is deposited, commonly in waning cycles, and the sequence as a whole coarsens up. In closed or semi-closed bays, currents are unidirectional. Based on these characteristics, FA4 could be regarded as a semi-closed

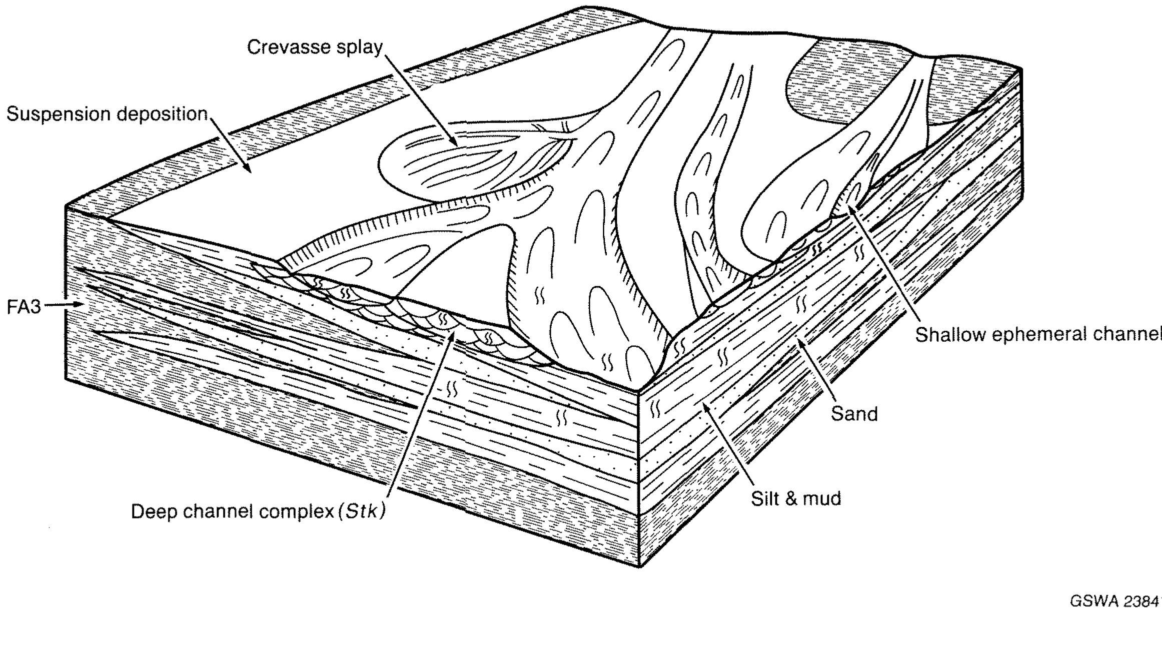


**Figure 72. Depositional model for FA4. This is an enlargement of the front right corner of the FA3 depositional model.**

interdistributary bay sequence which was adjacent to, and later transgressed over, the FA3 distributary lobe.

The fining-upward cycles (from *St* to *Fl*) in the lower part of FA4 are thicker than the crevasse splay–overbank couplets shown by Elliott (1974, figure 1, B –F), although he noted (p. 613) that thick (1–2 m) sand sheets could result from large floods. This may be because deposition in the FA4 outcrop area was by the distal parts of the major floods which deposited FA3, rather than by small, intermittent floods associated with crevassing from channels. A second difference is that the thickness of the couplet sequence in FA4 ($St \rightarrow Fl$) ranges from 10 m (coastal gorges) to 40 m (Section 39), compared to the 2 to 10 m cited by Elliott (1974, figure 1) or the 3 to 15 m stated by Coleman and Prior (1982, p. 150). This may be due to differing rates of subsidence. If subsidence was fast enough, the bay would take correspondingly longer to fill in. Thirdly, no mouth-bar sequence appears to be preserved. Instead, possible crevasse channel or avulsing distributary channel deposits (the thicker intervals of facies *Stk* and *Spk*, as in the main face of Red Bluff) rest on crevasse splay–overbank deposits (the lower part of FA4). This may be because either the interdistributary area was semi-closed or closed and thus protected from waves, or because any mouth-bar deposits were eroded, as in sequence G in Elliott's figure 1. In either case, the central to upper part of FA4 is similar to both sequence G and sequence I of Elliott's figure 1, both in possible scale and sequence of structures.

Within an interdistributary bay framework, FA4 is interpreted as follows. The lowermost parts, where it interfingers with FA3, result from the abandonment of a fluvial distributary system (either a high-energy, fluvially dominated estuary or a low-relief, high-energy delta). Abandonment was probably because of a combination of lessening fluvial input (allocyclic) and northward migration of the distributary lobe (autocyclic). The lower parts of FA4, as in the southwest face of Red Bluff, represent infilling of an interdistributary area under conditions of (relatively) rapid subsidence, so that overall the coastline transgressed slightly. Sand–silt couplets and fining-upward sequences formed by repeated floods, and are analogous to the crevasse-splay sequence of Elliott (1974). Thicker fine-grained intervals (multiple laminated to burrowed couplets) are analogous to Elliott's overbank sequence, and formed when sand was lacking or deposited elsewhere.

Eventually, crevasse channels migrated or avulsed into the outcrop area, and formed facies *Stk* and *Spk* (as in the main face of Red Bluff). Subsidence had continued, so that the channels were subaqueous. The uppermost part of FA4 (exposed at Red Bluff) records abandonment of the distributary–crevasse channel system immediately below, which led to a return to crevasse splay–overbank flood deposition because of continued subsidence.

Indications of wave and tidal current action may be lacking in FA4 because offshore carbonate buildups effectively barred the coastline. The partly calcareous Dirk Hartog Formation is less than 300 m above FA4 stratigraphically, so such buildups may have developed. Alternatively, wave and/or tide effects were overwhelmed by the amount of continental supply, as on a "normal" deltaic coastline.

## FA3–FA4 transition

The transition from FA3 to FA4 can be seen in any of the coastal gorges, and (although poorly exposed) in the river gorges south of Toolonga Point (Sections 35 to 45). FA3 grades upwards into FA4 by progressively thicker intercalations of red siltstone (facies *Fl* of FA4) within facies *cSt* or *vSt* of FA3. The boundary between the two associations is placed at the last coarse- or very coarse-grained sandstone interval below which facies *Fl* is subordinate. Using the Gabba Gabba Member as a stratigraphic datum, the boundary increases in height northward. This suggests that deposition of FA4 in southerly areas was contemporaneous with some FA3 deposition in northern areas.

The FA3–FA4 transition is from deposits of a high-energy fluvial environment to deposits of a medium- to low-energy, interdistributary area. The transition was due to a combination of internal basin processes (northward migration and abandonment of the distributary system, and continued basin subsidence) and external processes (lessened tectonism, which led to diminished sediment influx). Although the FA3–FA4 sequence is depositionally regressive, there was no major transgression by the sea.

# Facies Association 5 (FA5)

Facies Association 5 (FA5) occurs in isolation from the remainder of the Tumblagooda Sandstone, on the eastern side of the Northampton Complex in the Perth Basin (Figure 5, Plate 1). It is included within the Tumblagooda Sandstone for two reasons. Firstly, no other lithologically similar pre-Permian unit is known from the northern Perth Basin to which it could reasonably be assigned. Secondly, if a regional northwest-dipping palaeoslope is accepted for the Tumblagooda Sandstone, the sediments placed in FA5 are a logical upslope extension of the sequence present on the west of the Northampton Complex and at Pencell Pool.

Exposures of FA5 are isolated, mostly poor, complicated by faulting, and are not suitable for measured sections. It is not known if they represent the same stratigraphic level, as there are no obvious marker horizons to allow stratigraphic correlation between exposures. Individual outcrops mostly rest on the Precambrian Northampton Complex on downfaulted terraces, but different outcrops may be on different structural terraces. It is not known which part of the type section correlates with FA5.

Sandstone exposures near Balla Wheat Bins, in strike ridges near Nolba, and at Bindoo Hill were mapped as Tumblagooda Sandstone by Playford et al. (1970). The exposures differ from unequivocal Tumblagooda Sandstone (west of the Northampton Complex and at Pencell Pool) in grain size, sorting, rounding, palaeocurrent directions, and probable environmental setting: when the regional depositional setting of the Tumblagooda Sandstone is considered, they cannot be readily related to it, although they could be derived from the Tumblagooda Sandstone. They are shown as ?Devonian in Figure 5 and on Plate 1.

## Facies descriptions

The characteristic feature of FA5 is the presence of very coarse-grained immature sandstone to conglomerate. Unlike the remainder of the Tumblagooda Sandstone, it is drab coloured. The two facies (conglomerate and sandstone) represent approximate endpoints of a continuous gradation rather than discrete lithofacies.

FA5 shows a similar palaeocurrent distribution to FA1 and FA3 (vector mean of 308° and magnitude of 0.74; Figure 5), although the sample set is far smaller.

### Lithofacies

#### Pebble to cobble conglomerate (*Gt*, *Gp*)

Coarsely cross-bedded, moderately imbricated, matrix-supported pebble to cobble conglomerate (*Gt*, *Gp*) occurs in scattered outcrops near Wicherina and along the Northern Gully road, interbedded with coarse- to very coarse-grained pebbly sandstone. Conglomerate clasts are mostly about 5 cm diameter but range to about 15 cm diameter. They are generally rounded to very well rounded and are all resistant, siliceous rock types. The proportion of clasts ranges upwards from about 5 to 30%, but is commonly only 10 to 15%. Much of the facies is therefore a very pebbly sandstone, by the terminology of Folk (1968). The matrix is coarse- to very coarse-grained, very feldspathic sandstone to granule conglomerate. This is very poorly sorted and poorly rounded.

Both planar cross-bedding (*Gp*) and trough cross-bedding (*Gt*) are present. Planar cross-sets range in thickness from 60 cm to possibly more than 2 m, and trough cross-sets are large (60 cm to 1 m) to very large (1.5 m) and broad. Palaeocurrents were westward to northward.

#### Very coarse-grained sandstone (*vSx*)

The sandstone facies (*vSx*) grades, by abundance of pebbles, into the previous facies. Scattered rounded pebbles and cobbles are common, except at Indialla Spring and near Nolba. The sandstone is very similar to the matrix of the conglomerate facies, and is mostly very coarse-grained. It is less obviously feldspathic and is only coarse-grained near Nolba. The facies is trough and planar cross-bedded; the scale ranges from small (about 20 cm) to large (60 cm to 1 m). Palaeocurrent directions are westward to northward.

## Facies interpretation

The poor sorting; poor rounding; mineralogical immaturity; and unimodal palaeocurrents of sediments in FA5 indicate that they were deposited in either a proximal braided-fluvial or alluvial-fan environment.

### Lithofacies

#### Pebble to cobble conglomerate (*Gt*, *Gp*)

The presence of cross-bedding in the conglomeratic facies (*Gt*, *Gp*) indicates that the depositional process was dune migration rather than sheet flooding or debris flows (Nilsen, 1982, p. 56, 60; Collinson, 1986, p. 33; Miall, 1985). Conglomerate clasts are well rounded, which indicates that either they have undergone prolonged transport or they are inherited from an older unit. The second possibility is realistic because a Proterozoic conglomerate, the Beaconsfield Conglomerate, occurs up-palaeoslope from *Gt* and *Gp* outcrops (Playford et al., 1976, p. 56).

Facies *Gt* and *Gp* were deposited in a gravelly braided-fluvial or an alluvial-fan environment. The facies could be part of either Facies Assemblage G2 or of G3 of Rust (1978), and thus could be either a proximal or distal braided fluvial deposit. Most of the criteria for alluvial fans by Nilsen (1982, p. 65 -67) cannot be applied because of the lack of knowledge about vertical or lateral changes within FA5.

### Very coarse-grained sandstone (*vSx*)

Sandstone (*vSx*) occurs in exposures to the north of facies *Gt* and *Gp*, obliquely down-palaeoslope from them. Its resemblance to the finer grained parts of that facies, both between the sandy matrix and between the interbedded sandstone horizons, suggests it is a down-palaeoslope equivalent to facies *Gt* and *Gp*, and was deposited in a high-energy, fluvial environment.

## FA5 depositional environment

The geometry of the FA5 sequence is largely unknown because of the lack of vertical or lateral control. I assume that facies *Gt* and *Gp* grade northward into facies *vSx*, and that facies *vSx* grades into the sequences at Pencell Pool and in the type section. This is based on the principle that sediments usually fine down the palaeoslope, and agrees with palaeocurrent measurements (vector mean of 308°), but it cannot be verified from outcrop.

Deposition of FA5 was primarily from high-energy streams, because non-bedded, mass-flow deposits are absent. Based on lithology and palaeocurrent directions, the association was deposited on the upslope portion of an alluvial plain and possibly in an alluvial fan. Even a proximal fan environment, using the simple division of Nilsen (1982, p. 54), is possible because conglomerate clasts, while well rounded, may have been recycled from pre-existing Proterozoic conglomerate a short distance upslope. In this case, the basin margin may have been the Urella Fault (Playford et al., 1976) rather than the Darling Fault. The former is approximately 20 km further west.

# Pencell Pool sequence

A sequence of Tumblagooda Sandstone more than 200 m thick is exposed along the western bank of Pencell Pool, on the Murchison River 1 to 2 km east of the Northampton Complex. Most of the sequence is shown in the Appendix and Figures 73 to 76. It is readily divisible into three units: a lower unit of coarse-grained, trough cross-bedded sandstone; a middle unit of fine- to medium-grained sandstone; and an upper unit of coarse-grained, trough cross-bedded sandstone.

## Facies description

### Lower unit

#### Coarse-grained, cross-bedded sandstone (*cSt*)

The lower unit consists of coarse- to very coarse-grained, trough cross-bedded, brown and grey sandstone (*cSt*) which contains abundant granules and common small pebbles. Quartz grains are subrounded to well rounded and poorly sorted, and pebbles are subangular to subrounded. Most troughs are about 20 cm deep and 1 m wide, but some larger troughs up to 80 cm deep and several metres wide are present. These appear to occur at regular intervals, but cyclicity is not obvious because of the nature of the outcrop.

Palaeocurrent directions within it are northwestward. The unit is at least 20 m thick, and is separated from the base of the measured section at the south end of Pencell Pool by about 250 m of superficial cover (about 75 m stratigraphic thickness).

### Middle unit

The middle unit consists of fine- to medium-grained, in part silty, bioturbated sandstone. Bedding within the unit is indistinct because of bioturbation and weathering. Most of the unit is horizontally bedded (*Shb*), but planar (*Spk*) and trough cross-bedding (*Stk*) are also present (Figure 73). Much of the unit is featureless due to bioturbation, which has not left clear burrow outlines, unlike *Heimdallia* in FA2. The dominant recognizable burrow is *Skolithos*, and *Diplocraterion* is present in a few exposures (Figure 74). The *Diplocraterion* and some of the "*Scolithos*" described by Opik (1959) were from this interval. Palaeocurrents directions are broadly southwestward to northwestward, and have a weak vector mean (magnitude 0.55) of 285°.

#### Horizontally bedded, bioturbated sandstone (*Shb*)

Horizontally bedded, bioturbated sandstone (*Shb*) forms about 60% of the middle unit. Bedding ranges from well-preserved horizontal lamination on a 1 to 2 cm scale to vague banding on a 1 to 2 m scale (Figures 73, 75). In the latter, original bedding has been totally obliterated by bioturbation, so that bedding is outlined only by gross changes in grain size or colouration. The facies ranges from sandy siltstone to medium-grained sandstone. Colour ranges from white through yellow to deep red-brown; deeper red intervals are commonly finer grained. *Skolithos* is present in most exposures, and poorly defined *Diplocraterion* occur in some exposures.

Discontinuous thin lenses of medium- and coarse-grained, small-scale (<20 cm) trough cross-bedded sandstone occur in the lower 60 m of the section. *Skolithos* which penetrate below these lenses are commonly infilled by sand from the lenses.

#### Trough cross-bedded, *Skolithos*-bearing sandstone (*Stk*)

Trough cross-bedded, *Skolithos*-bearing sandstone (*Stk*) forms about 30% of the middle unit. Some horizontal bedding occurs between trough sets. The sandstone is dominantly medium grained and moderately to well sorted; a few intervals are coarse- or fine-grained, and coarse sand laminae are common near the base of the middle unit. *Skolithos* is common in most horizons, and sand from this facies commonly infills *Skolithos* pipes which penetrate underlying, finer grained sediment. The facies overlies facies *Shb* sharply at each occurrence, but with little basal scouring. Locally, it grades upwards into facies *Shb*, but the contact is more commonly sharp. Palaeocurrents directions are mostly southward to northwestward; there is a minor northeastward trend.

#### Planar cross-bedded sandstone (*Spk*, *Sp*)

Except for one horizon (*Sp*, at 127 m in the measured section), all intervals of planar cross-bedded sandstone contain abundant *Skolithos* (*Spk*). They are texturally similar to facies *Stk*, and grade laterally into very low-angle cross-bedded sandstone (included in facies *Shb*). Palaeocurrent directions are northeastward and southwestward. The exceptional horizon noted above contains no *Skolithos*, and is a single set of asymptotically based medium- to high-angle planar cross-bedding (Figure 75). It migrated to the northeast and is identical to some larger planar foresets in facies *mSxp* of FA2.

#### Cyclicity in the middle unit

Fining-upward cyclicity can locally be distinguished in the middle unit. Cycles are 3 to 5 m thick, and grade from trough cross-bedded, *Skolithos*-bearing sandstone (*Stk*) at the base; through horizontally bedded, bioturbated, medium- to fine-grained sandstone (*mShb*); to fine- to very

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**Figure 73. Pencell Pool: middle unit, looking north. The lower part shows thick horizontal bedding** *(Shb)*; **some finer bedding detail is locally preserved. The upper part consists of cross-bedded sandstone** *(Stk)* **with laminated red silty sandstone couplets** *(Shb)*. *Skolithos* **occurs throughout.**

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**Figure 74. Pencell Pool:** *Skolithos*, **probable** *Diplocraterion*, **and unidentified vertical burrows in middle unit.**

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**Figure 75. Pencell Pool: middle unit, looking south. A large, asymptotically based, non-bioturbated, planar cross-bed** *(Sp)* **overlies indistinctly bedded and bioturbated sandstone** *(Shb)*. **Note that the person is only approximately 1.2 m tall.**

GSWA 23845

**Figure 76. Pencell Pool: upper unit, looking northwest; trough cross-bedded sandstone** *(cSt)*.


**Figure 77. Exposure of FA2 lithofacies on Riverside, near South Jaffrey Bore. Facies present include** *mSh, mShx,* **and** *Sbv.*

fine-grained bioturbated silty sandstone to sandy siltstone (*fShb*) at the top. Thick, apparently non-cyclic, sequences are also present, as between 75 and 100 m in the measured section.

## Upper unit

The upper unit consists of coarse- to very coarse-grained, trough cross-bedded sandstone (*cSt*), similar to the lower unit. It coarsens upwards over 40 m into very coarse-grained sandstone to granule conglomerate (*vSt*), and extends up the river valley for several hundred metres beyond the top of the measured section.

The lower 30 m of the upper unit is intercalated with the underlying middle unit of the Pencell Pool sequence. Non-bioturbated, trough cross-bedded sandstone gradually increases in abundance and grain size. The stratigraphically highest, medium-grained, bioturbated interbed is at about 160 m in the measured section.

### Coarse-grained, trough cross-bedded sandstone (*cSt*)

The sandstone is poorly sorted, medium-grained in the lowest horizons, and coarse- to very coarse-grained at the top of the section, which is at the rock bar forming the north end of Pencell Pool (Figure 76). Trough cross-beds are mostly 40 to 50 cm thick in medium-grained intervals, and 20 to 30 cm thick in very coarse-grained intervals. Palaeocurrent directions are northwestward, except in one group of northeast-facing troughs. The sequence appears non-cyclic.

# Facies interpretation

## Lower and upper units

The strongly unimodal palaeocurrents, the poor sorting, and the scale and type of cross-bedding indicate that the lower and upper units were deposited in shallow, high-energy, braided-fluvial environments by low, three-dimensional dunes. This environment is the same as that for non-cyclic parts of FA1 and FA3.

## Middle unit

The presence of abundant bioturbation (particularly *Skolithos*) and the interfingering relationship with the upper unit indicate that the middle unit was deposited in marginal marine to nearshore conditions. The intense bioturbation of much of the horizontally bedded facies (*Shb*), in which bedding has commonly been obliterated, probably arose through relatively continuous slow deposition or discontinuous deposition (Howard, 1975,

p. 134, 137). This regime was interrupted by more energetic events which deposited the less-bioturbated intervals, facies *Stk* and *Spk*. These two facies probably formed in subaqueous channels, but may have been migrating shoals like those described by de Raaf et al. (1977).

The palaeocurrents suggest a similar setting to FA4, a protected coastline. The marked southwestward component could be in part longshore currents (as in FA2), but may also be due to sediment being shed from the side of a fluvial lobe which lay to the north. It is not given great emphasis because of the relatively low number of readings; these are few enough that the southwestward mode could be in part an artifact of sampling.

## Correlation with type section

Of the facies associations in the river and coastal gorges, FA4 is most similar to the middle unit at Pencell Pool. Both are characterized by abundant *Skolithos*, and both show regular interbedding of trough cross-bedded sandstone and finer, bioturbated sediments. Neither contain *Heimdallia* sp., the most abundant trace fossil in FA2. Sedimentologically, the upper and lower units at Pencell Pool could be part of either FA1 or the virtually non-cyclic, upper part of FA3. A stratigraphic correlation of the lower unit with FA3 is preferred because of the following reason.

Structural dips on the east side of the Northampton Complex are easterly to northeasterly. Strike varies with proximity to the Yandi Fault, the bounding fault between the Northampton Complex and the Tumblagooda Sandstone east of the Northampton Complex. Although outcrop is not continuous, outcrops of Tumblagooda Sandstone on Riverside Station between South Jaffrey Bore and New Bore (Figure 77) clearly underlie the Pencell Pool sequence because of regional tectonic dip. These outcrops, 2 to 3 km south-southwest of the south end of Pencell Pool, are identical to FA2 (facies *mSh*, *mShx*, *mSxp*, and *Sbv*) in the type section, and contain *Heimdallia*. They overlie coarse-grained, trough cross-bedded sandstone which is readily assigned to either FA1 or FA3.

From the observations above, the best hypothesis is that the same stratigraphic sequence of facies associations occurs both west and east of the Northampton Complex. FA1 and FA2 are present in the exposures on Riverside, FA3 is represented by the lower unit of the Pencell Pool sequence, and FA4 is represented by the middle unit. The trace-fossil assemblages agree with this hypothesis. The upper unit at Pencell Pool is, by this hypothesis, above the top of the type section, and the middle unit is a much expanded section of FA4.

# Basin architecture

Depositional environments for each facies association were proposed earlier, but little consideration was given to the large-scale basin geometry, and other external controls and influences on the depositional basin. These aspects are considered here.

## Basin geometry

This section outlines the nature and dimensions of the depositional basin for the Tumblagooda Sandstone. The basin geometry consists of the orientation of the basin; the location and nature of the basin margins, and any basement inliers in the basin; orientation and magnitude of faulting within the basin and at basin margins; and changes in the basin shape during the Silurian.

The depositional basin for the Tumblagooda Sandstone was a fault-bounded, northward-opening trough. The trough was bounded on the east by the Darling Fault, and shallowed southwards, so that the present-day southernmost exposures were close to the southern basin margin. The western boundary was possibly along the present day continental– oceanic crust boundary. The depth to the Northampton Complex decreased to the south, but the complex was not a discrete, emergent feature or sediment source for the Tumblagooda Sandstone. The bases for this interpretation are discussed below.

### Basin orientation

At the present time, the onshore parts of the Perth and Carnarvon Basins are both north-trending. North of Exmouth Gulf, the northern Carnarvon Basin contains thick Mesozoic and Cainozoic sequences, and trends northeast. It is part of the Westralian Superbasin (Yeates et al., 1987; Bradshaw et al., 1988; Cockbain, 1989), and structural trends within it developed during the breakup of Gondwana. Palaeozoic rocks are inferred at depth, but have only rarely been intersected. Knowledge of the Palaeozoic history in the northern, offshore area is sparse (Hocking, 1988; Bradshaw et al., 1988), so it is not considered further.

From facies distributions in subsurface intersections of the Kalbarri Group (Figure 1), there is no indication that the basin was not oriented approximately north–south in the Silurian. The northerly trend of the eastern basin margin (see below) is the most convincing evidence of the gross north–south orientation of the depositional basin.

### Eastern basin margin

The Tumblagooda Sandstone depositional basin was probably bounded on the east by the Darling Fault (Figure 1, Plate 1). There has been several thousand metres of movement against the fault during the Phanerozoic, based on the thickness of sediment in the Perth Basin (Playford et al., 1976), and post Permian movement is established south of about 28°S (Playford et al., 1970, 1976).

Between 28°S and about 26°S, the Darling Fault is buried but has a strong gravity expression, which is indicative of substantial displacement. Near Bompas Hill (Plate 1), there is continuous exposure of unfaulted Lower Permian sediments across the gravity trace of the fault (Hocking et al., 1982). This indicates that the displacement occurred prior to the Permian. Given that the Tumblagooda Sandstone occurs to the west, and that there are no other thick, extensive, pre-Permian sequences known from the southern Carnarvon Basin or northern Perth Basin, the simplest scenario is that the Darling Fault moved during the Silurian. This would uplift the Yilgarn Craton, and provide a source of granitic detritus for the Tumblagooda Sandstone. Accepting the Darling Fault as the eastern basin margin also explains the lack of Tumblagooda Sandstone in the Byro and Bidgemia Sub-basins of the Carnarvon Basin, which lie east of the line of the Darling Fault (Figure 1).

Hocking et al. (1987) proposed that the Darling Fault extended north of 26°S as a buried, pre-Permian fault, based on lineations and linear contacts, magnetic intensity profiles, and indications of pre-Permian tectonism. This extension would provide a tectonically active basin margin for the Tumblagooda Sandstone throughout virtually all of the Carnarvon Basin. Repeated movements on the fault maintained the pronounced topographic relief necessary to generate the volume of sediment in the Tumblagooda Sandstone, and major rejuvenation of the hinterland provided sediment initially for FA3 and later for the Kopke Sandstone.

### Western basin margin

Prior to the breakup of Gondwana, the Carnarvon and Perth Basins formed an elongate, intracratonic trough (Playford et al., 1976; Veevers et al., 1982), which opened northward into the Tethys Sea (Veevers, 1984, p. 189 and figure 237). The location and nature of the western margin of this trough cannot be determined from outcrop, and apparent indications from subcrop are invalid, as outlined below.

Hocking (1981a, 1987) and Hocking et al. (1982, 1987) assigned the sequence in Edel 1 (Figure 1) between 354 and 2750 m (total depth) to the Tumblagooda Sandstone, and Hocking (1987) used dipmeter data from that sequence to infer the location of the western margin of the basin. However, Smith and Cowley (1987) established that the sequence is Permian and Triassic, through comparisons with Wittecarra 1 to the south. This negates the conclusions drawn by Hocking (1987).

Further north, data from deep wells in the Shark Bay area are inconclusive. The Yaringa Evaporite Member of the Dirk Hartog Formation was deposited in a restricted, possibly closed, basin (Wells, 1980), but closure may not have been due to the proximity of the western margin. It may have been caused by local tectonics (cross-cutting graben and horst structures within the basin), or barring of the evaporite basin by carbonate sills, as occurred during deposition of the correlative Carribuddy Group in the Canning Basin to the northeast (Lehmann, 1984). Dirk Hartog 17B, the westernmost well around Shark Bay (Figure 1), gives no obvious indication that the western margin was any nearer than the eastern margin.

Despite the lack of data, it is still considered probable that the western boundary of the basin lay along the present continental–oceanic crust boundary, prior to the breakup of Gondwana in the Jurassic.

## Northern basin margin

The two northernmost intersections of Silurian sediments are in Marrilla 1 and Peedamullah 1 (Figure 1). Those in Marrilla 1 are transitional between the Tumblagooda Sandstone and Dirk Hartog Formation. The lowermost core in Peedamullah 1 (northeast of Marrilla 1) is from near the well's total depth, is undated, and consists of red–white mottled, bioturbated, medium- to fine-grained sandstone. It is typical of FA2, and is dissimilar to the overlying core, a light-green, Upper Devonian, sandy dolomite. The basal part of the sequence intersected by Peedamullah 1 is therefore regarded as Silurian. From these two intersections, deposition may have extended around the northern margin of the Pilbara Craton, to the correlative Carribuddy Group of the onshore Canning Basin (see Forman and Wales, 1981; Lehmann, 1984). This agrees with Veevers et al. (1982) and Veevers (1984), who believed that the basin opened to the north in the Silurian.

## Southern basin margin

The most southerly exposures of Tumblagooda Sandstone lie near Wicherina (on the eastern side of the Northampton Complex) and 14 km southwest of Northampton (western side of the Northampton Complex; Plate 1). The relationship of the Tumblagooda Sandstone to the eastern margin of the Northampton Complex was discussed under "Pencell Pool sequence" and "Facies Association 5". The western side of the complex is onlapped by the Tumblagooda Sandstone south of the Hutt River valley. *Cylindricum* occur in the southernmost exposure (Figure 4, locality 11), less than 20 m above the basal unconformity. The sediment is similar to FA3. About 15 km north, FA2 sediments occur within 20 m of the basal unconformity, at localities 7 and 9 on Figure 4. Another 15 km north, in the Hutt River valley, a thick FA1 sequence overlies basement (Figure 4, east from locality 1). If the trace fossils are accepted as reliable stratigraphic indicators (as is implied by the Pencell Pool sequence), then the southernmost exposure correlates with FA3 in the type section; the Hutt River area (Figure 4, east of locality 1) correlates with FA1 in the type section; and the intermediate exposures (Figure 4, localities 7 and 9) correlate with FA2 in the type section. This suggests that there is southward onlap of the Tumblagooda Sandstone onto the Northampton Complex, so that the lowermost exposures young to the south.

Palaeocurrent and mineralogical data from the Murchison River area and FA5 indicate that the Northampton Complex did not deflect palaeocurrents or contribute sediment to the Tumblagooda Sandstone (see below). Therefore, the complex formed a southward-shallowing floor to the basin, but had not developed as a separate topographic entity in the Silurian.

## Possible basement inliers

The Northampton Complex presently divides the area of outcrop of the Tumblagooda Sandstone (Figure 1, Plate 1), and Condon (1965) suggested that it was emergent during deposition of the Tumblagooda Sandstone. This is incorrect in the Murchison River area. Firstly, palaeocurrents were not deflected around the Northampton Complex. Fluvial foresets near the Yandi Fault and throughout FA5 are oriented obliquely into the complex, not away from it as could be expected if the complex was a topographic high. Secondly, the Tumblagooda Sandstone is not (and has not been, from petrographic examination) garnet rich, unlike the Northampton Complex (Peers, 1971). The Northampton Complex therefore did not act as a significant source.

Although the Northampton Complex was not a positive topographic feature in the Murchison River area during sedimentation, rates of sediment accumulation on the complex may have been less than in neighbouring areas east and west of the complex. Gravity data suggest that, in the Hutt River– Gregory area, the sequence west of the Hardabut Fault is thicker than the sequence east of the fault. However, there is no disruption of the Tumblagooda Sandstone over the buried gravity trace of the fault. These observations suggest that there was faulting at depth during deposition of the Tumblagooda Sandstone, but that the faulting did not reach the surface.

From the apparent southward onlap of the base of the Tumblagooda Sandstone, the lack of garnet in the sandstone, and the lack of deflection of palaeocurrents, it is concluded that the Northampton Complex shallowed southwards, but only as part of the main basin floor, not as a separate, emergent basement inlier. Possible growth-faulting at the margins of the block affected only sedimentation rates.

## Other aspects

### Tectonic setting

Veevers (1984), following Warris (1973), Veevers (1976) and Veevers et al. (1982) among others, considered that the Carnarvon–Perth Basin initially developed as a "failed arm" basin that extended south from the Tethys Sea (Veevers, 1984, p. 189 and figures 110, 201, 202, 219). The Silurian to Upper Carboniferous sequence reflects "the subsequent fill of failed arms .... that radiated from nodes initiated during the breakup of an ancestral northwestern margin" (Veevers, 1984, p. 189). He considered that the plate divergence took place between about 510 and 575 Ma (Cambrian). The development of the failed arm, by rifting, presumably accompanied and/or immediately preceded divergence along the margin to the north. If the only episode of rifting was in the Cambrian, by the Late Ordovician and Silurian (100 Ma later) subsidence would be minimal (McKenzie, 1978; Watts, 1981). A second period of rifting, in the Late Ordovician or Silurian, is necessary to explain the deposition of a thick Silurian clastic sequence and the persistent syndepositional faulting.

Volcanism is generally associated with rift-valley sequences (Dickinson, 1974; Morgan and Baker, 1983), although Ziegler (1982) noted that non-volcanic rifts occurred where the radius of thermal doming was narrow. No volcanics occur in the Silurian sequence, but the basin was quite wide. Instead, volcanics may have been extruded just before deposition began, in association with mineralization in the Northampton Complex (434 ± 16 Ma; Richards et al., 1985). Mineralization occurred prior to deposition of the Tumblagooda Sandstone, as the sandstone shows no signs of present or past mineralization.

### Palaeolatitude

From the palaeogeographic base maps of Scotese et al. (1979), Smith et al. (1981), and Scotese et al. (1985), the area of outcrop of the Tumblagooda Sandstone was located 20°S to 30°S in the Silurian. Palaeomagnetic work suggests a tropical to equatorial position (Embleton, *in* Veevers, 1984, figure 10; Schmidt and Hamilton, 1990; Schmidt and Embleton, in press).

### Origin and signifcance of red colouration

The red colouration of the Tumblagooda Sandstone is due to hematite and goethite, and was imparted during deposition or very shortly thereafter, before there was appreciable diagenesis. Two features support this interpretation. Firstly, grains in thin section commonly show a dust rim which predates optically continuous, quartz overgrowths. The rims vary from distinct and dark to faint and indistinct. Later hematite, goethite, and limonite growths occur between grains in some thin sections, and postdate some or all overgrowth. Secondly, a palaeomagnetic reversal can be recognized within the Tumblagooda Sandstone at a specific stratigraphic horizon, the Gabba Gabba Member in FA3 (Schmidt and Embleton, in press). The palaeomagnetic orientation is recorded in the hematite, so the coincidence of the reversal and the member indicates that the hematite is virtually syndepositional.

Detailed environmental interpretation cannot be based on the presence or absence of red colouration. The principal factors needed for redbed development appear to be the presence of percolating groundwater and an oxidizing environment (Turner, 1980; Walker, 1967; Collinson, 1986, p. 44). Turner (1980, Chapter 3) and Winston (1978) applied this mechanism for reddening to coastal environments and sediments similar to FA2 and FA4. Therefore, the red colouration of tidal deposits in the Tumblagooda Sandstone is attributed simply to the presence of percolating groundwater under oxidizing conditions, shortly after deposition.

## Comparison with fluvial models

Miall illustrated and explained 12 examples of fluvial systems to illustrate his concepts of fluvial architecture and emphasized that the models were examples only, part of a far wider range. Several of the models combined aspects of more than one of the traditional meandering, braided, or anastomosing fluvial types. Although the examples were not intended to provide a comprehensive suite of fluvial possibilities, FA1 and FA3 can still be compared to them, and similarities assessed.

Models 1 to 8, 9 and 12 are dissimilar to FA1 and FA3 in major aspects, and need no further discussion. In model 10, channel, bar and bar-top deposits appear to be better differentiated than in FA1 and FA3, and the implied scatter of current directions is greater. However, the macroforms (sand flats or compound bars; Miall, 1985, p. 295) may be comparable to the large bedforms that are implied by the fining-upward cycles in FA3 and, to a lesser extent, FA1. Model 11 may be similar to non-cyclic and poorly cyclic parts of FA3 and FA1, which probably formed as extensive fields of subaqueous dunes. Miall (1985, p. 297) noted sheets, lenses, and wedges of sandy bedforms; these correspond to the widespread, trough cross-bedded, non-cyclic sandstone intervals in FA1 and FA3.

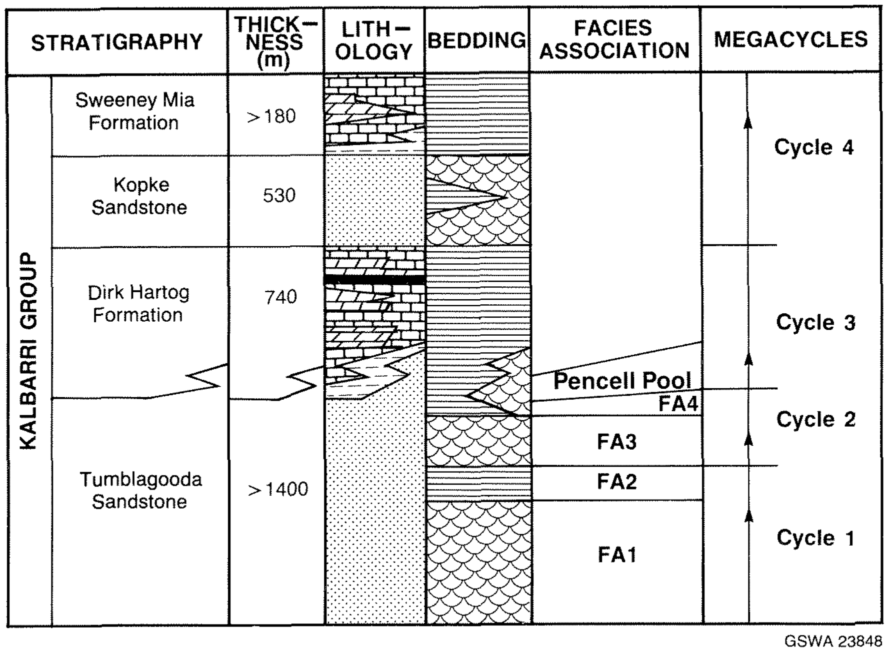


**Figure 78. Megacycles in the Kalbarri Group.**

# Fluvial style

Several authors (Schumm, 1968; Cotter, 1978; Long, 1978; Friend, 1983; Eriksson, 1978; Miall, 1980, 1985) speculated that the presence or absence of vegetation may have affected the nature of fluvial deposition (or fluvial style) over time, so that braided-fluvial systems predominated prior to the evolution and spread of land plants. Cotter (1978) also found that individual genetic units in the pre-Devonian sequence in the Appalachians were laterally persistent and lacked well-developed channels. He referred to "fluvial style" rather than "channel pattern" for river morphology, and subdivided the braided category into "channel-braided" and "sheet-braided". The latter is characterized by extreme lateral persistence of individual or genetic sand bodies, and little or no development of incised channels. Miall (1980) noted that erosion surfaces at the bases of sheet-braided cycles are planar or sub-planar, and that fine-grained intervals are uncommon. He considered that deposition must have been from virtually unconfined flow by sheet runoff. At least some sheet-braided units have an overall lobate shape, which indicates fan-like dispersion of sediment (Miall, 1980).

Both FA1 and FA3 are braided fluvial deposits, but they are not truly sheet-braided, in the sense of Cotter (1978, p. 364–365) or Miall (1980, p. 69). Cotter's figures 2 to 6 and Miall's figures 6 and 7 show strong lateral persistence at the scale of individual bed-sets. Although FA1 and FA3 show pronounced lateral persistence at the scale of cosets and/or fining-upward cycles, they commonly do not show such persistence at the scale of individual cross-sets; scour and fill structures are common within cosets. Secondly, the interpreted depth of flow (up to 15 m) indicates that channels, even if ephemeral, must have been present.

Therefore, the Tumblagooda Sandstone is compatible with the speculations on fluvial style in a general sense, in that fluvial deposits are braided and lack obvious overbank sediments, but does not support Cotter's extension of the speculation, that channels were absent.

# Large-scale cyclicity

Two large-scale cycles, or megacycles, can be recognized in the Tumblagooda Sandstone (Figure 78). The first cycle constitutes FA1 and FA2, and is at least 600 m thick. It could be 700 to 800 m thick, based on the thickness of FA2 in Sections 12 to 27. The second cycle consists of FA3 and FA4, and is more than 340 m thick (from near the base of Section 27 to the top of Section 40). Chow and James (1987) referred to cycles of similar magnitude in the Cambrian of North America as Grand Cycles.

The cycles are too thick to have originated through internal depositional processes — an external cause is necessary. They are allocyclic, not autocyclic, in the sense of Miall (1980). At the start of the second cycle, there is no indication an increase in water depth at, or immediately before, the start of FA3 deposition. Therefore, tectonism did not appreciably lower the basin and thereby increase the palaeoslope. Instead, the second cycle presumably was initiated by tectonic rejuvenation of the basin hinterland. The beginning of the first cycle cannot be observed, but I assume that FA1 rests on Precambrian basement, because gravity data suggest less than 1 km of sediment is present below the base of the type section. The origin of the first cycle is thus less certain, although its later history can be determined from outcrop, as follows.

In FA2 and FA4, there are no major vertical changes in facies abundances (which would suggest a change in water depths) within the 100 to 150 m of vertical section which is present at any one locality in the gorges. Therefore, deposition approximately kept pace with subsidence, and the water depth remained similar for each area. Relative transgression or regression did not occur. The controlling factor on the increasing marine dominance in each megacycle was decreasing fluvial influx into the basin, rather than changes in the rate of basin subsidence. The decrease in influx was presumably due to lessening tectonism along the basin margin.

If stratigraphic correlation of the middle unit at Pencell Pool to FA4 in the coastal gorges and type section is accepted, then a third cycle is represented by the upper fluvial unit at Pencell Pool (Figure 78). This cycle is of lesser magnitude, as it does not extend across the top of the type section to Kalbarri 1. There, sediments similar to FA4 grade upwards into the Dirk Hartog Formation, a shallow-marine unit. The cycle is important because it suggests that deposition of fluvial sandstone proceeded coevally with, but up-palaeoslope from, deposition of the shallow-marine sediments of the Dirk Hartog Formation.

Another megacycle occurs in the subsurface in the Shark Bay area, at a higher stratigraphic elevation (Figure 78). This is the Kopke Sandstone and Sweeney Mia Formation, which are a progression from fluvial and ?tidal sandstone to shallow-marine sediments, analogous to FA1 and FA2, but in a more distal, marine setting.

# Tumblagooda Sandstone depositional model

The depositional models proposed here for the Tumblagooda Sandstone incorporate the known and inferred, internal and external controls on deposition. They are not general models for pre-Devonian fluvial to littoral sedimentation, in the sense that Harms et al. (1982, p. 4.16) used the term "depositional model" and Walker (1979a, 1984) used the term "facies model". The models are applicable specifically to the Tumblagooda Sandstone in outcrop. They probably apply to subsurface intersections of both the Tumblagooda and Kopke Sandstones (Figure 78).

The stratigraphic base of the Tumblagooda Sandstone is not exposed in the type section, but there is probably less than 1 km of sediment below the base of the type section, from geophysical data. For convenience, these unexposed sediments are assumed to be similar to FA1.

Two models are required. Both are of fluvial systems that prograde into a shallow sea. The first, applicable to FA1 and FA2, has a tidally influenced shoreline. The second, applicable to FA3 and FA4, has a shoreline lacking recognizable wave or tide effects.

## FA1–FA2 model

Two Late Ordovician–Early Silurian events are inferred prior to deposition of the Tumblagooda Sandstone. These are uplift of the Yilgarn Craton, and initial subsidence of the area to the west of the craton, by movement on the ancestral Darling Fault. The base of the Tumblagooda Sandstone is not exposed in the type section, but I assume that braided fluvial sediments prograded rapidly northwestward from the scarp of the Darling Fault at the basin margin to the type section area. For the area of outcrop, the sediment was derived primarily from erosion of the Yilgarn Craton. Further north, sediment was derived from the Gascoyne Complex and Proterozoic sedimentary basins (Figure 1).

During deposition of FA1 and FA2, a flood-dominated braided fluvial plain extended west from the basin hinterland to a tidally influenced coastline (Figure 79). The climate was probably arid to semi-arid, and the near surface environment was strongly oxidizing. Alluvial fans were probably present along the basin margin. FA5 represents the upslope portion of the plain and possibly the alluvial fan area, although stratigraphic correlation with FA1 has not been established. FA1 represents only the near-coastal portion of the plain, the environments of which were described in detail in "FA1 depositional environment". They are summarized here.

FA1 was deposited by a large, low-sinuosity, sand-dominated, fluvial system. Flow was episodic, and probably resulted from periodic floods. Successive floods generated rapidly migrating and aggrading three-dimensional dunes in the deeper parts of poorly defined channels, and fields of smaller, simpler three-dimensional dunes in areas of shallower flow. There is no clear record of sedimentation or fluvial activity between floods apart from scattered fine-grained intraclasts and one *in situ* exposure of laminated siltstone. Channel morphology cannot be seen, but the apparent linearity of coset boundaries suggests that they were broad and flat-based, had stepped margins, and may not have persisted between floods. The overall geometry was an interlinked set of large, braided-fluvial lobes which together formed a braid plain. Not all areas on the plain were active simultaneously.

In the area of the type section, bedforms were medium to large dunes, and flow depth was up to 10 m. Very large in-channel bars did not develop. These may have been present at the same time in the Hutt River area, where very large foresets (typical of the lower part of FA3) occur low in the section and may correlate with FA1. The braided lobe in which FA1 was deposited may have had its longitudinal axis south of the type section, if the deductions for FA3 (see "FA3 depositional environment") apply to FA1.

Turner (1983, p. 81–82) considered that the abundance of trough cross-bedding in the Molteno Sandstone of South Africa indicated that deposition was dominated by unidirectional migration of megaripples within channels, so that there was little bar development. This hypothesis is very similar to the origin suggested for non-cyclic parts of FA1 and FA3. He also noted an "overall lack of small internal fining upward sequences" (p. 82), unlike FA1 and FA3, which he attributed to channel shifting and reworking by subsequent floods. In FA3 and FA1, reworking and migration appears to have truncated cycles rather than destroyed them totally.

At the coast, classical deltas (those which contain topset, foreset, and bottomset divisions, and a prodeltaic sequence; e.g. Reineck and Singh, 1975; Elliott, 1986b; Coleman and Prior, 1982) did not develop. Instead, fluvial deposits prograded directly over tidal deposits in sheet-like blankets which only rarely cut distributary

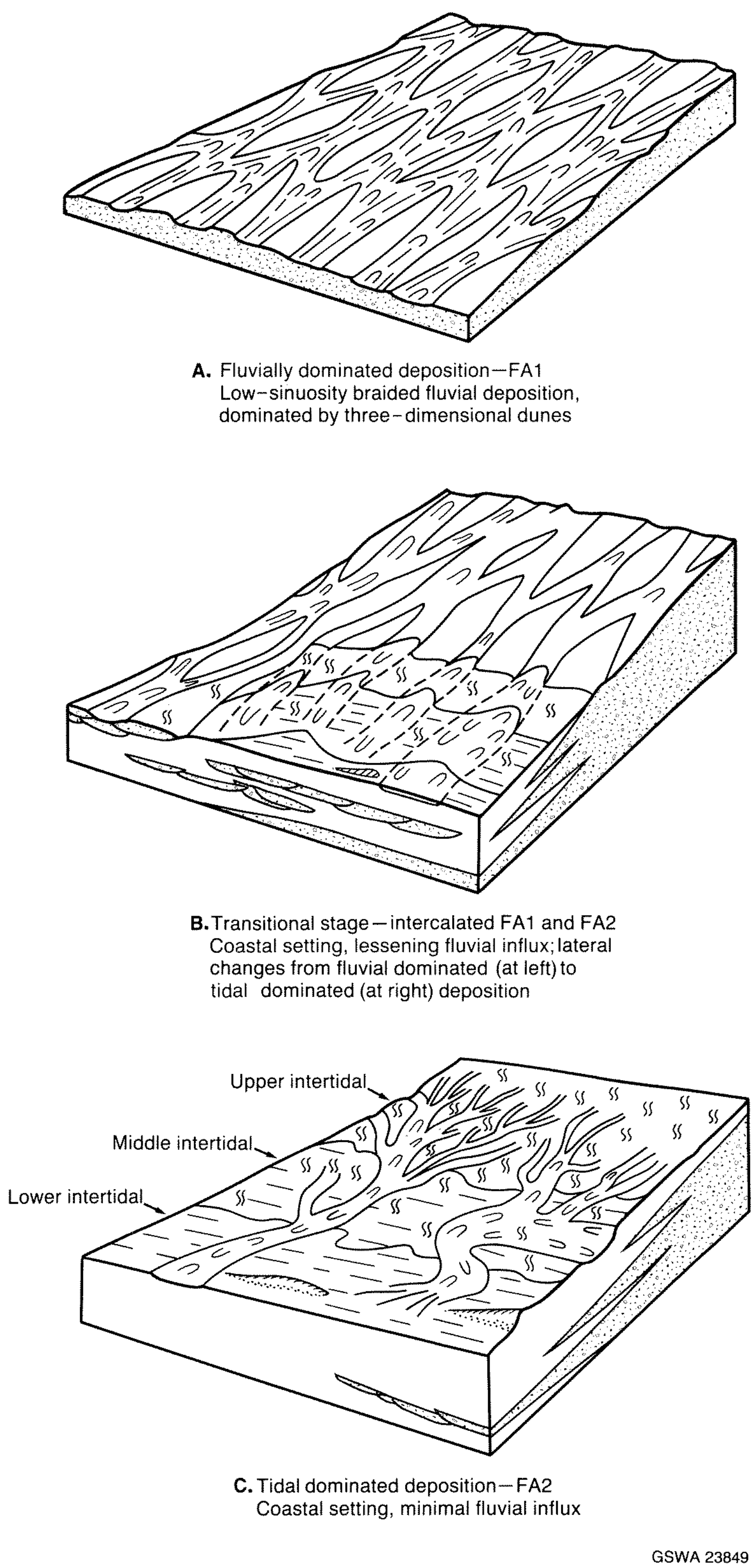


**Figure 79. Depositional model for FA1 and FA2. Refer to Figures 16 and 47 for further details of each stage.**

channels into the tidal deposits. Within those blankets, flow was sufficient to prevent reworking by tidal processes, and occurred in broad, flat-based channels that migrated laterally and avulsed but underwent little net change in base level. Between periods of flow, the lower reaches of fluvial distributaries were infiltrated by brackish to saline water, and bioturbation by marine organisms took place. The marine incursions may have been due to seasonal river flow, or simply have occurred between floods. The setting could be described as a low-relief delta, which had no prodelta sequence due to inadequate topographic relief.

Fluvial influx to the basin gradually waned, and tidal processes became dominant. Diminution in fluvial supply is suggested by the fining-upward trend in FA1, and was probably due to decreasing hinterland relief, as both the basin and its hinterland adjusted to the stresses which had caused the initial basin subsidence and hinterland uplift. Two other interpretations are quite feasible. The first is a eustatic, rather than tectonically caused, transgression. From the coastal onlap curves shown by Ross and Ross (1988), this is quite possible. Sea-level in the Silurian was uniformly high, and second-order transgressions were widely spaced, minor, and (by implication) slow. The gradual transition from FA1 to FA2 could be due to one or more of the Silurian onlap cycles suggested by Ross and Ross (1988). The second interpretation is that deposition maintained its pace, but switched to an area outside the type section, which is also possible from the available data.

Initially, the only marine influence was in the form of bioturbation of the seaward margin of fluvial distributaries. Later, substantial reworking of the lower reaches of distributaries took place (Figure 79). This led to intercalated tidal flat and fluvial sedimentation. The tidal environment was described in detail in "FA2 depositional environment", and is summarized below.

Tidal currents operated both longshore and normal to the shoreline, over a sand-dominated tidal zone. Major tidal channels (deep channels extending into the subtidal area) were largely absent, although ephemeral channels (surface channels extending only to lower intertidal areas) were present (Figure 47). Major barrier bars were also absent, although some sandwaves migrated across the lower to middle intertidal flats. The lower intertidal zone was dominated by deposition of horizontally stratified sandstone; sandwave and dune migration was of minor significance. Due to a lack of mud and silt, deposition on the upper intertidal flat was infrequent. New sediment was only introduced during storms and/or very high tides, and was intensely bioturbated before the next depositional event (Figure 47). The middle intertidal flat was not clearly differentiated, and showed features of both the upper and lower intertidal zones. The most distinctive feature was an increase in the number of ephemeral channels which drained surface water. The tidal flats were inhabited by an abundant, diverse fauna which included both suspension- and deposit-feeding organisms. Only the trails, trackways and burrows made by these organisms were preserved because of intensely oxidizing conditions.

Changes in environment are recorded largely between sections (laterally) rather than within sections (vertically). This indicates that rates of deposition were approximately equal to rates of subsidence throughout deposition of FA1 and FA2; there was no marked transgression or regression.

## FA3–FA4 model

The depositional model for FA3 and FA4 is similar to that for FA1 and FA2. Both are of a fluvial system prograding into a coastal area. The main differences are that energy levels were generally higher during deposition of FA3 than of FA1, and the coastal area was not subject to tidal or wave influences (Figure 80). The difference in energy levels is indicated by the lesser textural maturity of FA3, compared to FA1. The outcrop area may have been closer to a fluvial depocentre during deposition of FA3 than of FA1.

Prior to deposition of FA3, there was renewed tectonic activity which rejuvenated the hinterland and led to the sudden commencement of FA3 deposition. The renewal of fluvial progradation is attributed to allocyclic tectonic processes rather than autocyclic internal basin processes (e.g. depocentre migration) because this pattern is repeated several times in the Kalbarri Group (as discussed in "Large-scale cyclicity"). In the framework of sequence stratigraphy, the progradation of FA3 over FA2 initially appears to be compatible with highstand systems tract and shelf margin systems tract progradational phases (terminology and concepts of van Wagoner et al., 1988; Posamentier et al., 1988; and Posamentier and Vail, 1988). However, if FA3 was a highstand systems tract–shelf margin systems tract deposit, all the Tumblagooda Sandstone would be in the same depositional sequence (as used by van Wagoner et al., 1988, not as by Cockbain, 1989). FA1 would be a proximal part of a transgressive systems tract, and FA2 would have developed during the early, aggradational phase of the following highstand systems tract. This is not feasible, for the following reason. Ross and Ross showed (1988) onlap cycles of 4 to 5 Ma duration in the Silurian, but even these are too short a time span for the deposition of all of the Tumblagooda Sandstone, given that all of the type section is located on a delta plain to alluvial plain area (see figure 5 of Posamentier et al., 1988).

Fluvial deposition again took place on a braided fluvial plain which extended into nearshore marine areas (Figure 64). The geometry was an interlinked set of large prograding lobes, which were probably low-relief,

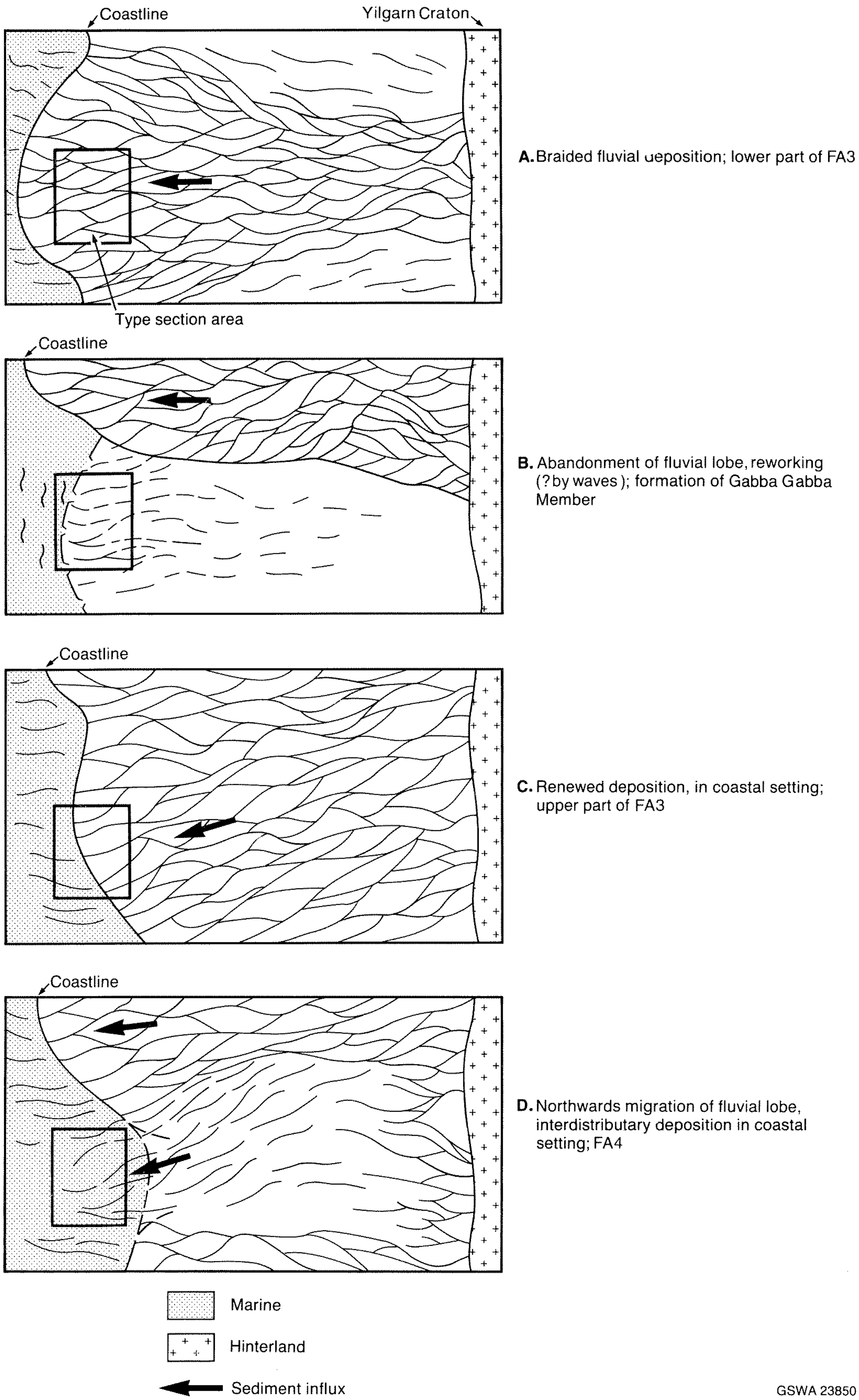


**Figure 80. Depositional model for FA3 and FA4. Refer to Figures 64 and 73 for further details.**

high-energy deltas. Eventually, there was a local decrease in the rate of subsidence, which is indicated by the upward transition within FA3 from reasonably complete cycles to truncated cycles below the Gabba Gabba Member. A fluvial lobe in the type section area was abandoned, and then partially reworked to form the Gabba Gabba Member. Subsequently, another major lobe prograded northwestward, to form another low-relief delta. This was at or near sea-level, and bioturbation occurred between periods of flow.

The transition from FA3 to FA4 occurred when fluvial influx to the outcrop area waned. FA4 was deposited in a protected interdistributary environment. Development of the association was due, in part, to northward migration or avulsion of the fluvial depocentre, but it also reflects overall waning of the FA3 fluvial system, in the same manner that the FA1 system waned.

The interdistributary area gradually sank, so that the degree of bioturbation increased upward. The presence of *Skolithos* through the upper part of FA3 and throughout FA4 indicates that water depth did not increase greatly. Successive floods deposited cross-bedded sand and laminated silt couplets in areas near the distributary system, and laminated fine sand to silt in more distal areas (Figure 72). Depocentres of floods varied, so there is no clear fining or coarsening trend in outcrop. Floods were initially confined by channels (subaqueous examples of which are seen in the upper part of FA4) and later spread into sheet-like flows (seen in the uppermost part of the sequence at Red Bluff and in the lower part of FA4).

The portion of the depositional model which applies to FA4 is more area specific than that for FA2. It applies solely to FA4 in the area of outcrop whereas the FA2 environmental setting is probably applicable as a general transitional, fluvial to marine, model throughout the Kalbarri Group. Similar lithofacies to FA2 occur in the Kopke Sandstone in Yaringa 1 and in the lowermost core in Peedamullah 1, but the sand–silt couplets of FA4 have not been recognized. The FA4 model is dependent on a very specific set of circumstances — abandonment of a large fluvial distributary system and coeval development of a barred coastline.

The final stage of deposition of the Tumblagooda Sandstone was another renewal of fluvial progradation, by tectonic rejuvenation of the hinterland. The only evidence for this is the upper unit of the Pencell Pool sequence. If stratigraphic correlation of the middle unit at Pencell Pool to FA4 is accepted, then the upper unit reflects renewed fluvial progradation. This is a depositional phase which did not extend to the type section, to Kalbarri 1, or to deep exploration wells in the Shark Bay area (Yaringa 1, Hamelin Pool 1, Dirk Hartog 17B). The implications of this were discussed in "Large-scale cyclicity".

# Comparison with other sequences

The Tumblagooda Sandstone and the proposed depositional models show points and broad areas of similarity to several other sequences. Those with the greatest similarity are the New Mountain Subgroup of the Beacon Supergroup (Antarctica), and the Cambrian transgressive sandstones on the North American shield.

## New Mountain Subgroup

The New Mountain Subgroup is a Devonian and possibly Upper Silurian sequence at the base of the Beacon Supergroup, in southern Victoria Land, Antarctica. It contains very similar lithofacies and a very similar sequence of trace fossil assemblages to the Tumblagooda Sandstone (B. C. McKelvey, pers. comm. 1982; Bradshaw, 1981; Plume, 1982; Gevers and Twomey, 1982). The subgroup is about 300 m thick and consists of a lower cross-bedded sandstone unit, the Windy Gully Sandstone (*cf.* FA1); a central thin-bedded siltstone unit, the Terra Cotta Siltstone (cf. FA2); and an upper cross-bedded sandstone unit, the New Mountain Sandstone (*cf.* FA3 and FA4). All three formations contain trace fossils. *Heimdallia–Didymaulichnus* and *Cruziana* assemblages occur in the Terra Cotta Siltstone. In the uppermost part of the New Mountain Sandstone, *Heimdallia* is locally replaced by a monospecific *Skolithos* assemblage (Bradshaw, 1981). This corresponds to the trace-fossil assemblages in the Tumblagooda Sandstone, which are dominated by *Heimdallia* in FA2 and *Skolithos* in FA4.

Differing interpretations of the subgroup were published by Bradshaw (1981) and Plume (1982). Bradshaw considered the subgroup was deposited in nearshore marine to coastal lagoon environments, primarily because of the abundance and nature of trace fossils (Bradshaw, 1981, p. 623 –627). Gevers and Twomey (1982, p. 645, 646) independently reached similar conclusions, also because of the trace fossils. Plume considered that the subgroup formed in braided fluvial and lacustrine environments. He interpreted the Windy Gully and New Mountain Sandstones as braided-fluvial and eolian deposits, based on cross-bedding size and direction (compared to cross-bedding in the Brahmaputra River), and the presence of current lineation (Plume, 1982, p. 573–576). Primarily because of the abundant trace fossils, Bradshaw (1981, p. 624, 626) considered that the Windy Gully and New Mountain Sandstones were deposited in a shallow-marine, tidally affected sandflat setting. Gevers and Twomey (1982, p. 645) considered a fluvial environment which, because of factors such as storms or seasonal river flow, was subject to intermittent marine influence. They drew an analogy with the Ganges–Brahmaputra delta.

For the Terra Cotta Siltstone, Plume's interpretation of its environment as lacustrine was based on carbon-isotope values, the presence of hematite, the lack of body fossils, a network of desiccation cracks at the top of the unit, and the presence of current lineation (Plume, 1982, p. 573, 578, 579). In reference to Keith and Weber's (1964) work (on which Plume's conclusions were based), Bradshaw (1981, p. 625) considered that the carbon-isotope values only indicated proximity to continental areas (lagoons in particular), rather than a fully continental, freshwater setting. The presence of hematite and the lack of body fossils indicates only strongly oxidizing conditions in a setting which could be a shallow, intermittently emergent, marine or tidal environment (Chapter 3 of Turner, 1980), rather than a fully continental environment. Both Bradshaw (1981, p. 625) and Gevers and Twomey (1982, p. 646) suggested that the lack of body fossils was due to high porosity and leaching. This would also allow percolation of hematite-rich water through the sediment. Lastly, desiccation cracks need only temporary emergence to form.

Plume's interpretation of the Terra Cotta Siltstone is not accepted as a significant factor in interpretation of the Tumblagooda Sandstone, despite the similarities of the two sequences, for the reasons set out above. However, his interpretation of the Windy Gully and New Mountain Sandstones is closer to my interpretation of FA1 and FA3 than Bradshaw's interpretation. It differs primarily in the suggestion (made here for the Tumblagooda Sandstone, and for the New Mountain Subgroup by Gevers and Twomey) of intermittent marine influence as a cause of bioturbation.

## Cambrian sandstones, North America

Several Cambrian basal transgressive sandstones in North America are broadly similar to the Tumblagooda Sandstone. These include the Mt Simon Formation (Driese et al., 1981), the Lamotte Sandstone (Houseknecht and Etheridge, 1978), the Tapeats Sandstone (Hereford, 1977), and the Bradore Formation (Hiscott et al., 1984). In all these units, deposition commenced in braided fluvial environments, like FA1 and FA3. Subsequent transgression resulted in interdigitated fluvial and tidal deposits without development of deltas, as in the FA1–FA2 transition and FA4. This was followed by tidal to nearshore marine deposition, as in FA2. The sequences are comparable to the Tumblagooda Sandstone, in that they and the Tumblagooda Sandstone are all the oldest deposits in newly developing basins, and all show a transgressive pattern overall.

Some differences are apparent. Firstly, the North American sequences are much thinner than the Tumblagooda Sandstone. Secondly, the transgressive pattern is not repeated, unlike the Tumblagooda Sandstone. Thirdly, the transgression appears to have been eustatic in origin. The transgressive pattern in the Tumblagooda Sandstone is a relative feature which arose through diminished sediment influx; there was little absolute rise in sea level. These differences are attributed to differences in the tectonic setting. The North American sequences were deposited on a stable craton, whereas the Tumblagooda Sandstone was deposited in a subsiding basin which had a tectonically active, rising hinterland.

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# Appendix

## Graphic logs of measured sections

The appendix contains graphic logs of Sections 1 to 45, which cover the type section and coastal gorges, and of the sequence at Pencell Pool. Section 18 is not included, as a detailed graphic log is part of Figure 18. Palaeocurrent roses for Section 33 are shown in Figure 50. Figure 81 shows detailed locations for the sections. Figure 82 is a legend for the logs.

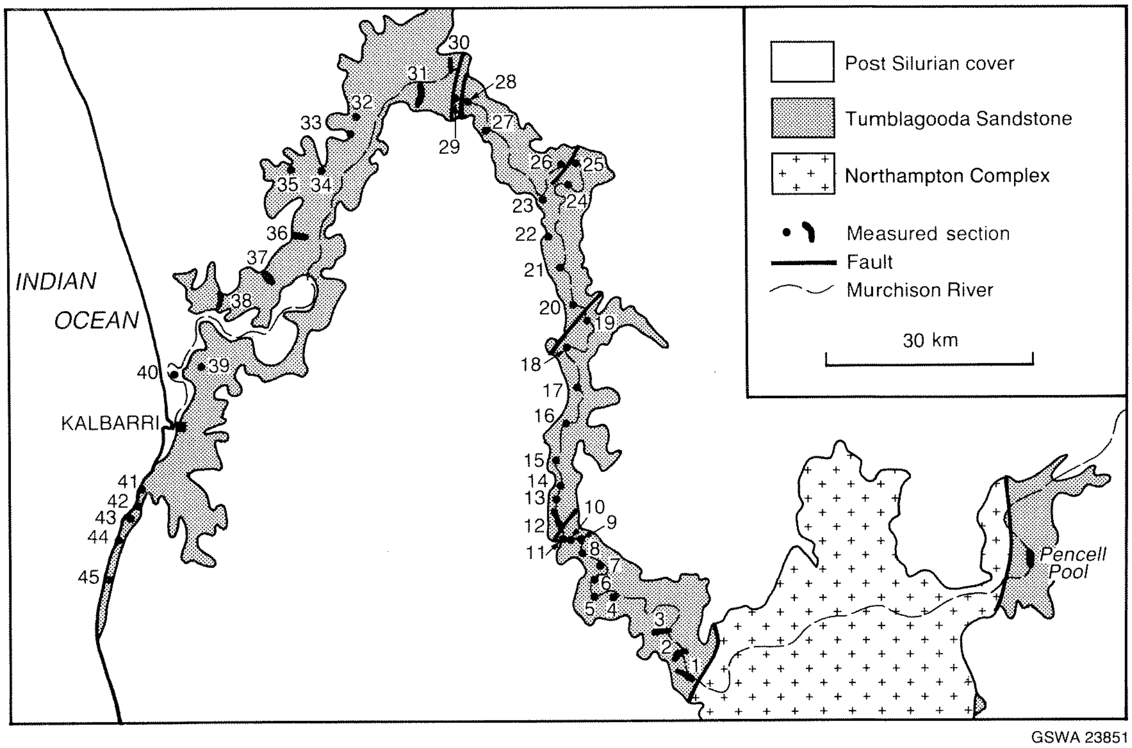



**Figure 81. Locality map for the measured sections, Pencell Pool, type section, and coastal gorges.**

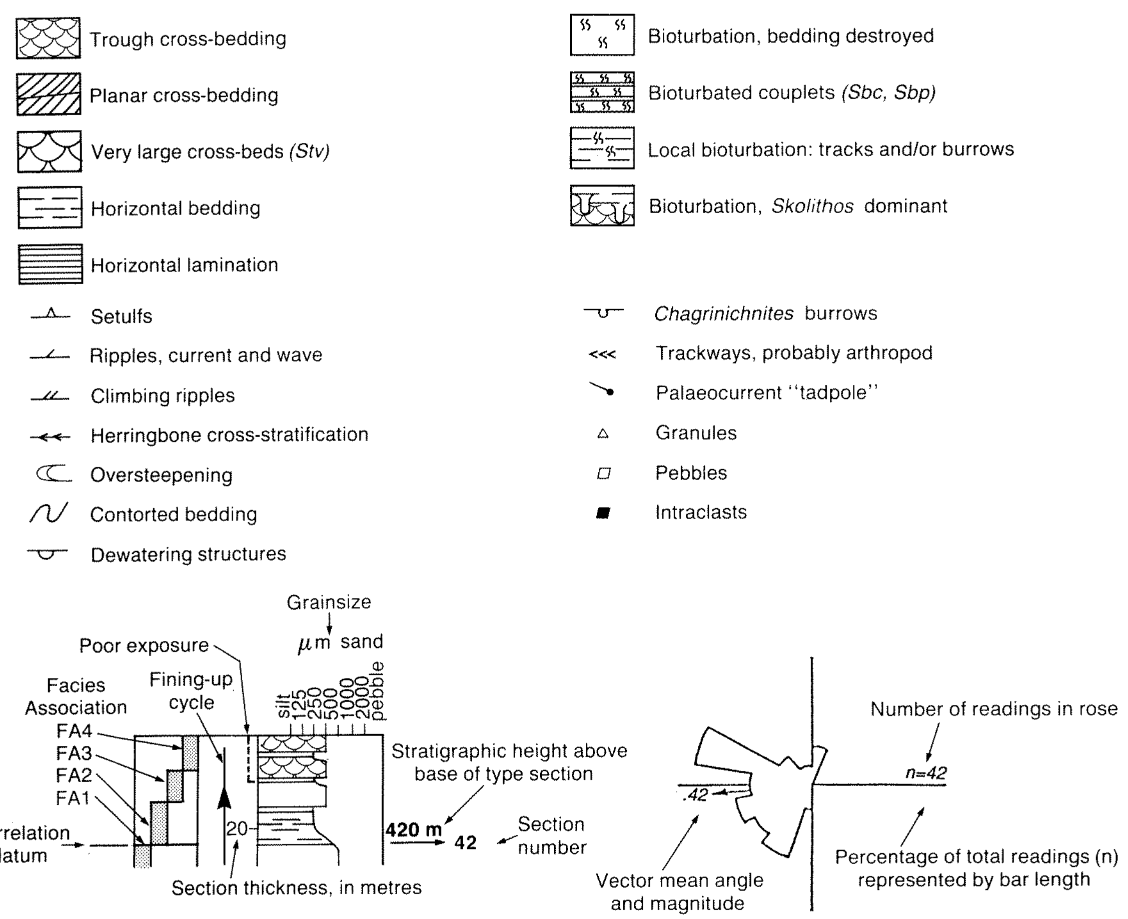



**Figure 82. Legend for palaeocurrent roses and graphic logs of the measured sections.**

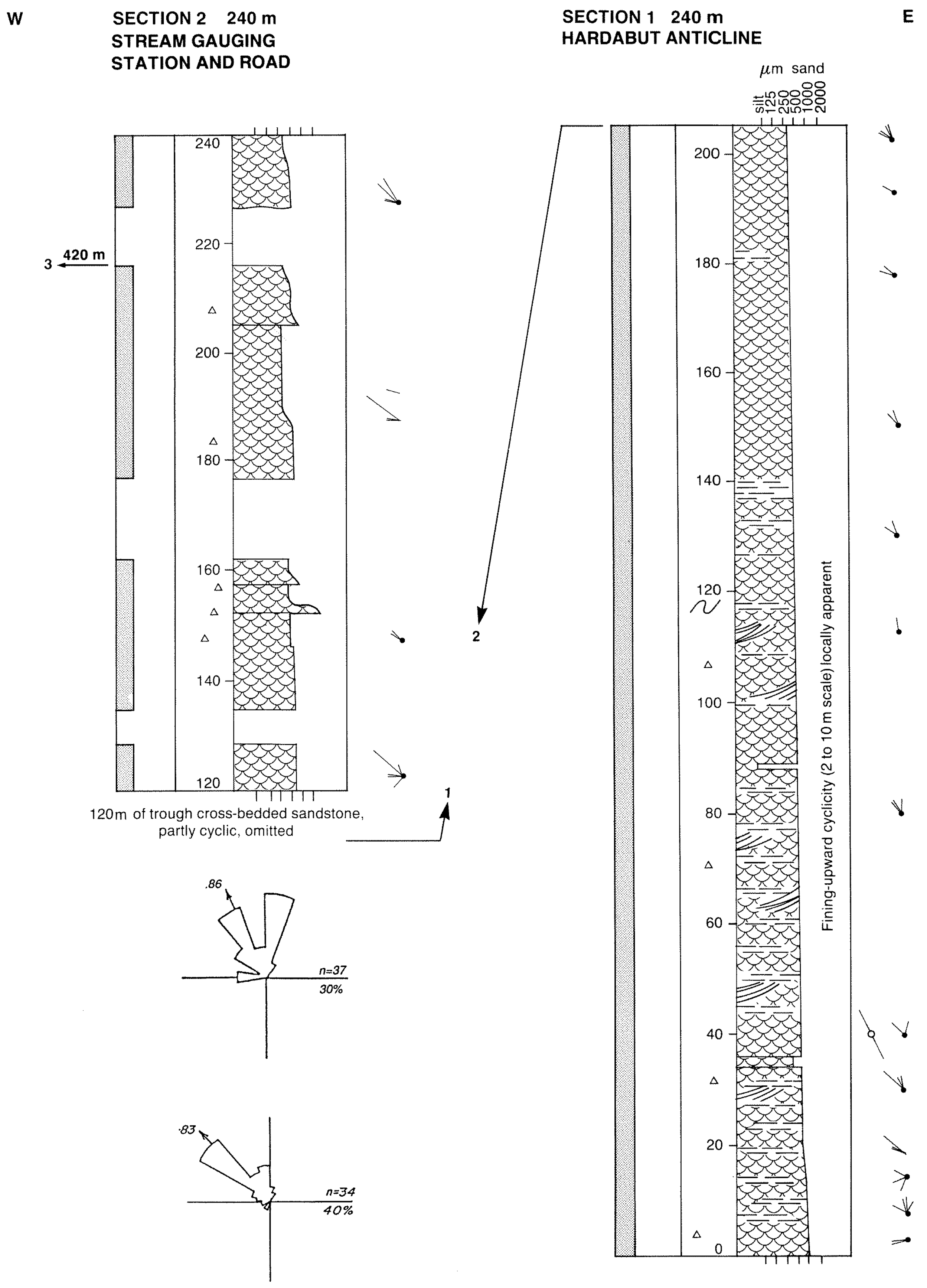



**Figure 83. Graphic logs and palaeocurrent roses for Sections 1 (Hardabut Anticline) and 2 (stream gauging station).**

GSWA 23852

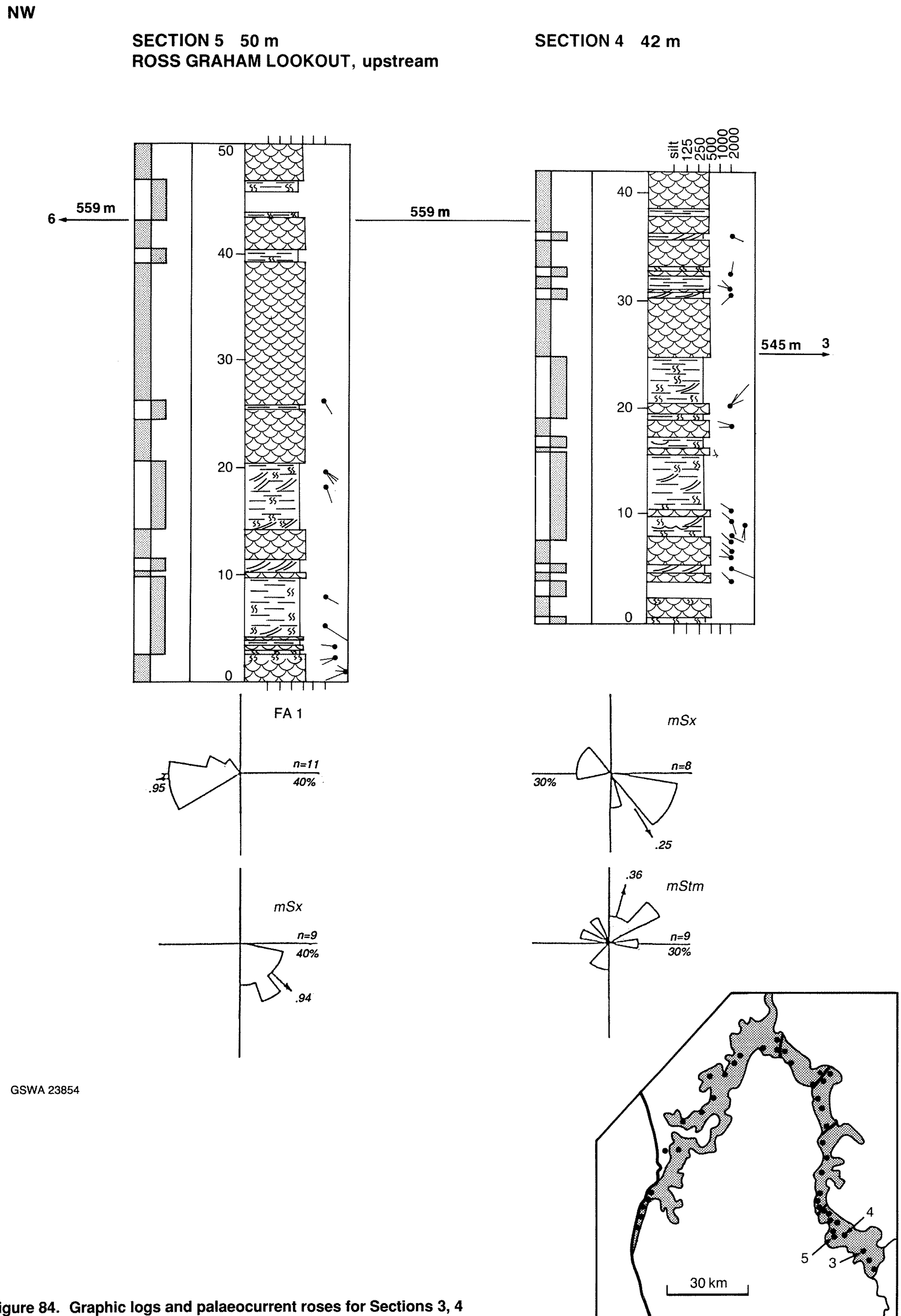
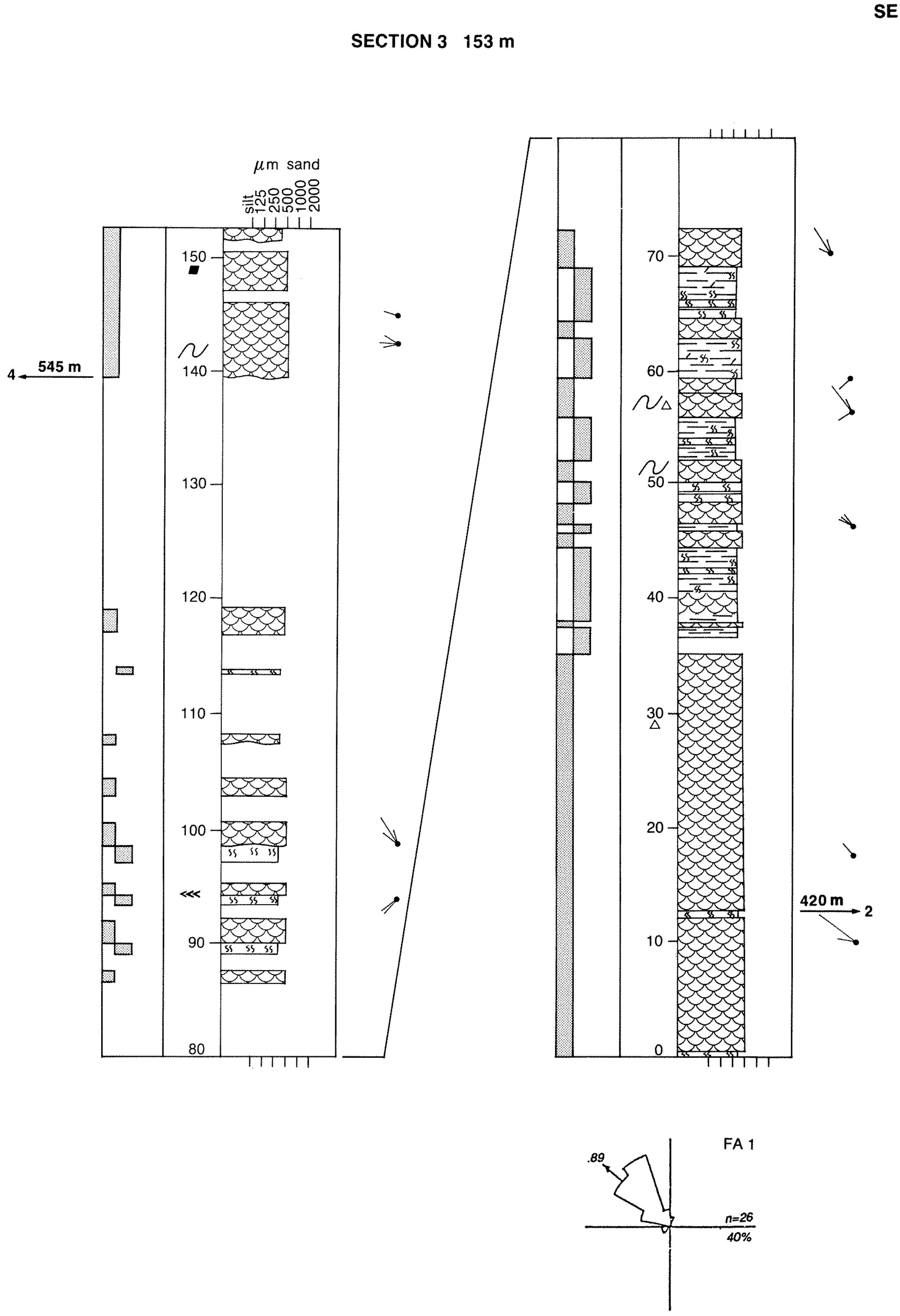


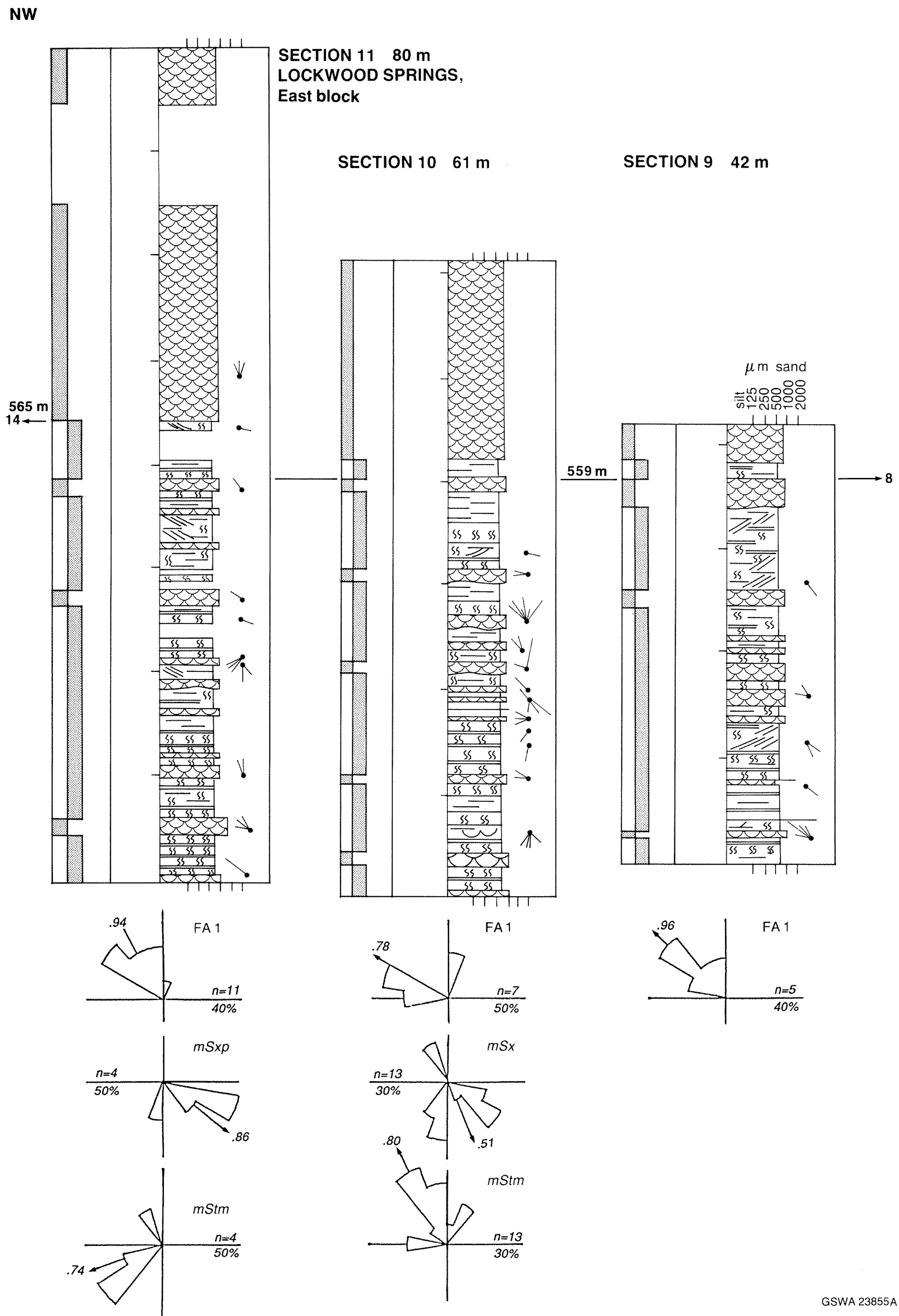

**Figure 84. Graphic logs and palaeocurrent roses for Sections 3, 4 and 5.**

SECTION 3 153 m




GSWA 23853

NW




GSWA 23855A

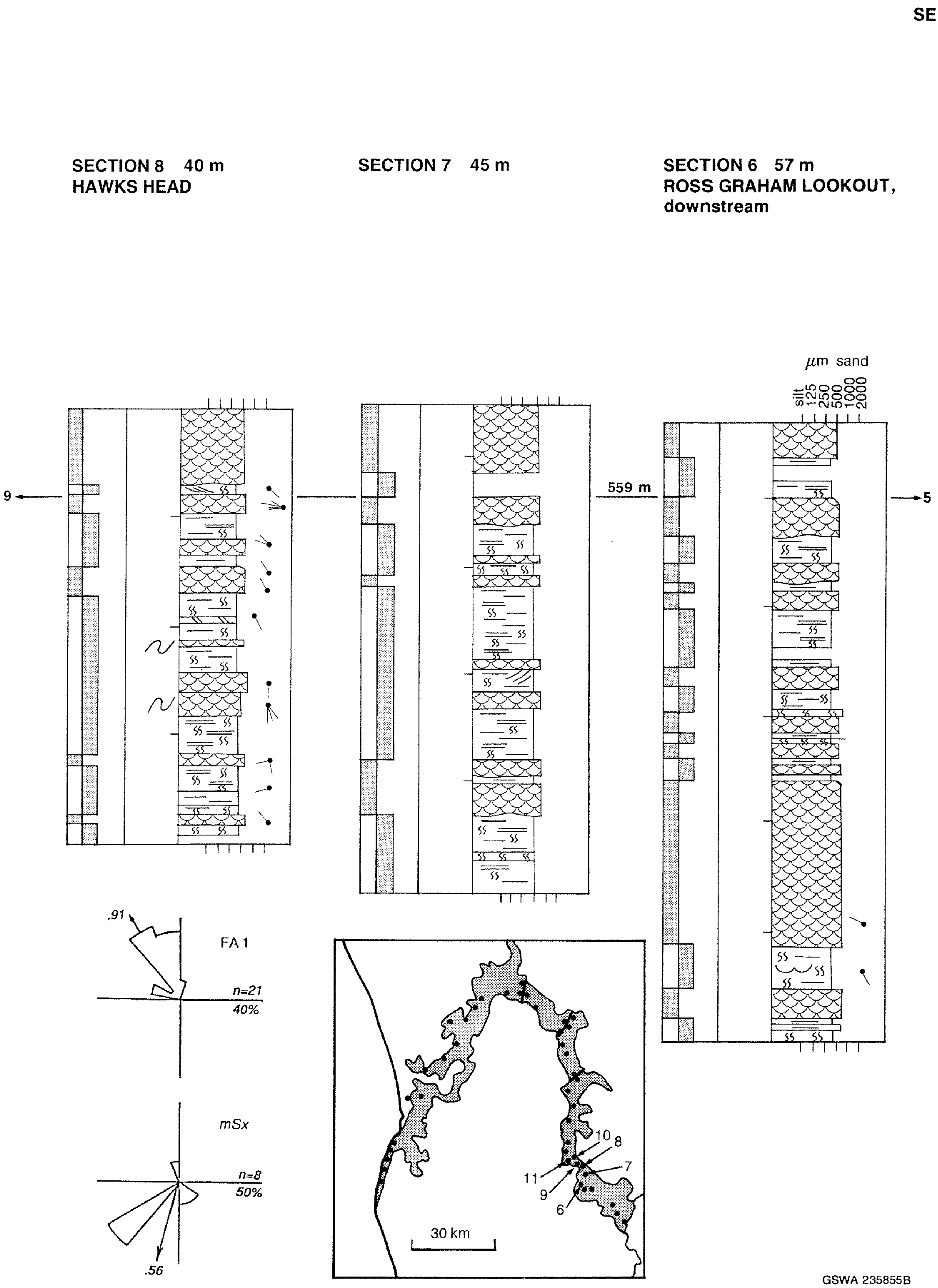



**Figure 85. Graphic logs and palaeocurrent roses for Sections 6 to 11 (Ross Graham and Hawks Head Lookouts, and east fault-block at Lockwood Springs). Figure 18 shows a detailed log of Section 8.**

NW

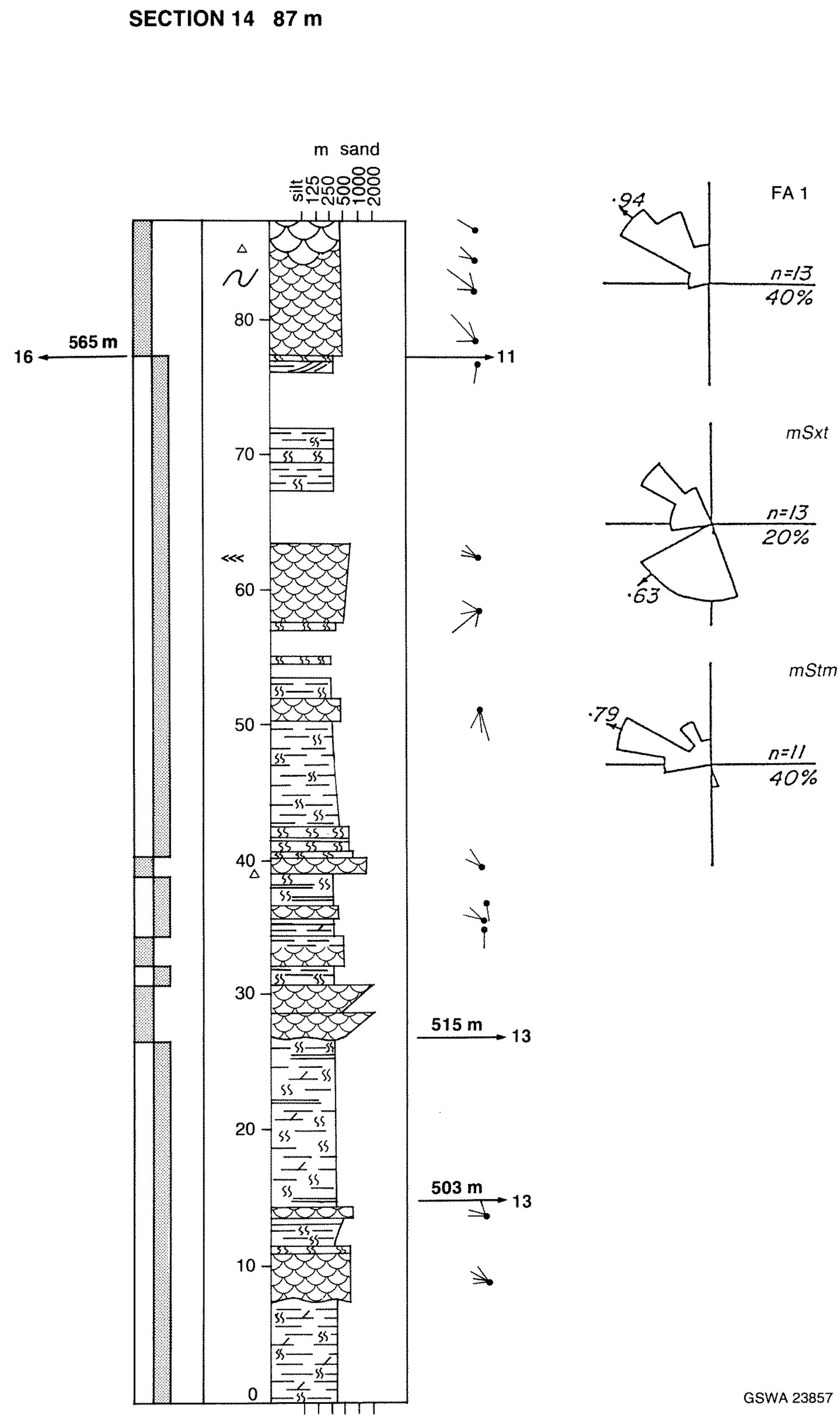
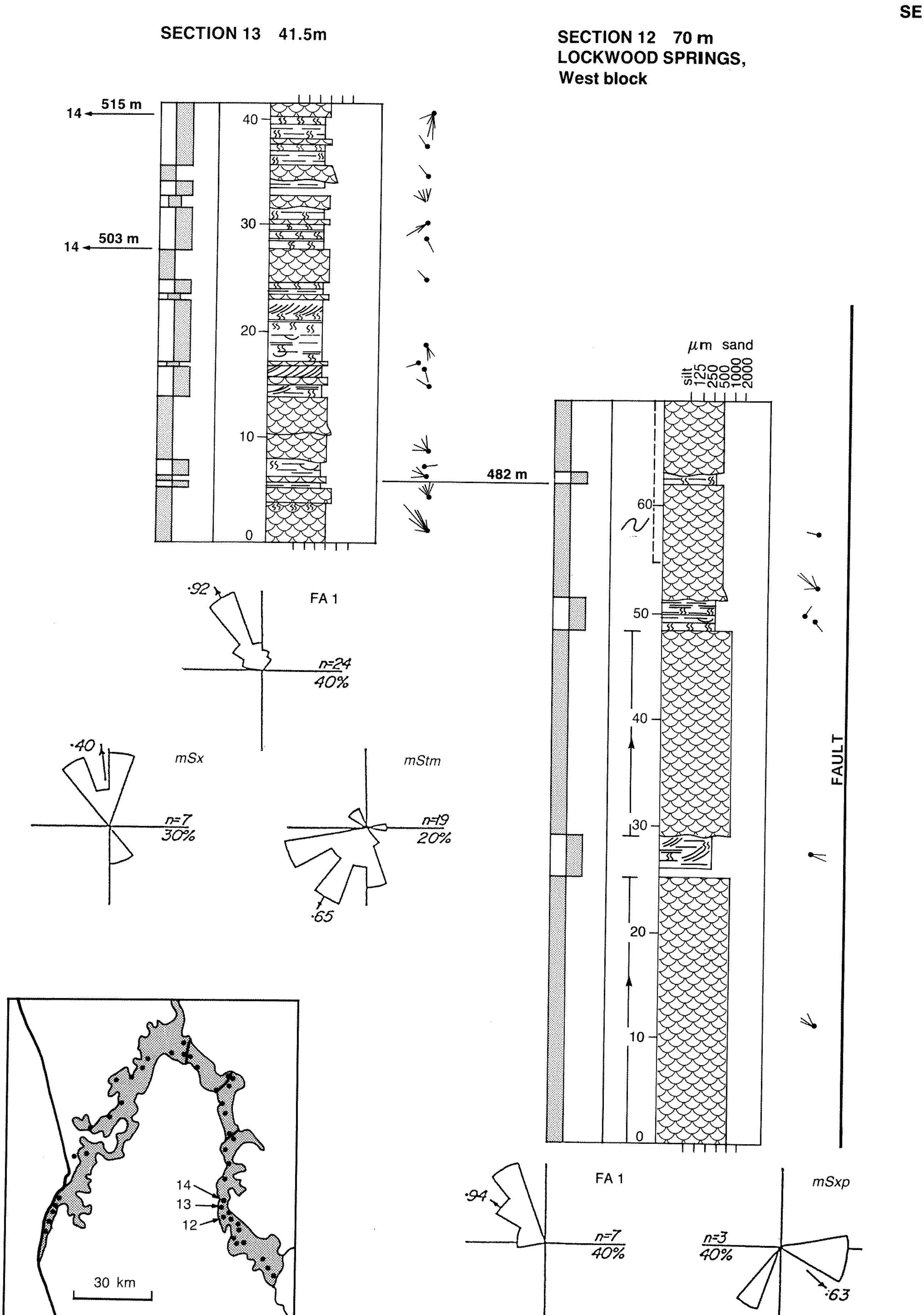
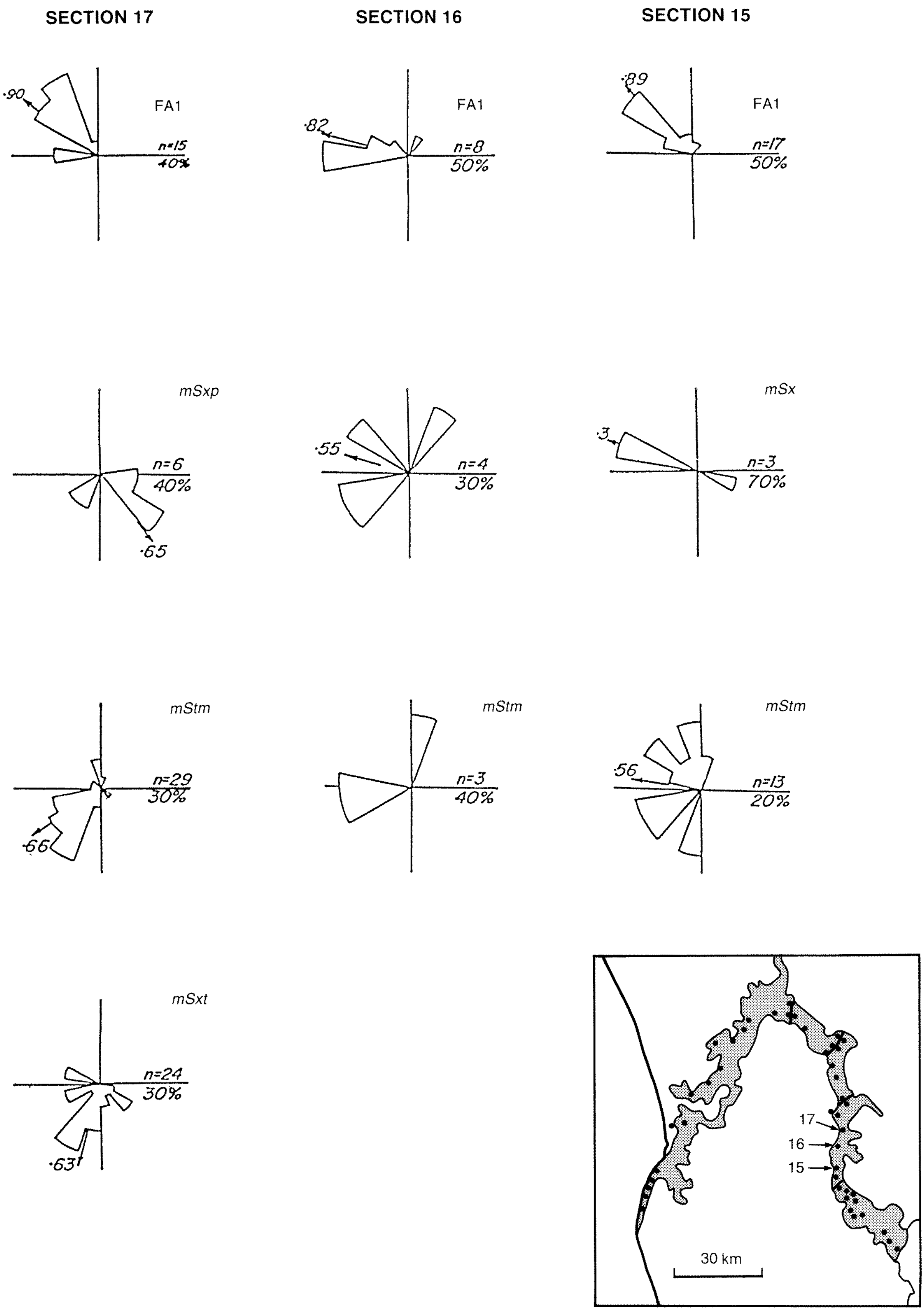



**Figure 86. Graphic logs and palaeocurrent roses for Sections 12 (Lockwood Springs, west block), 13, and 14.**

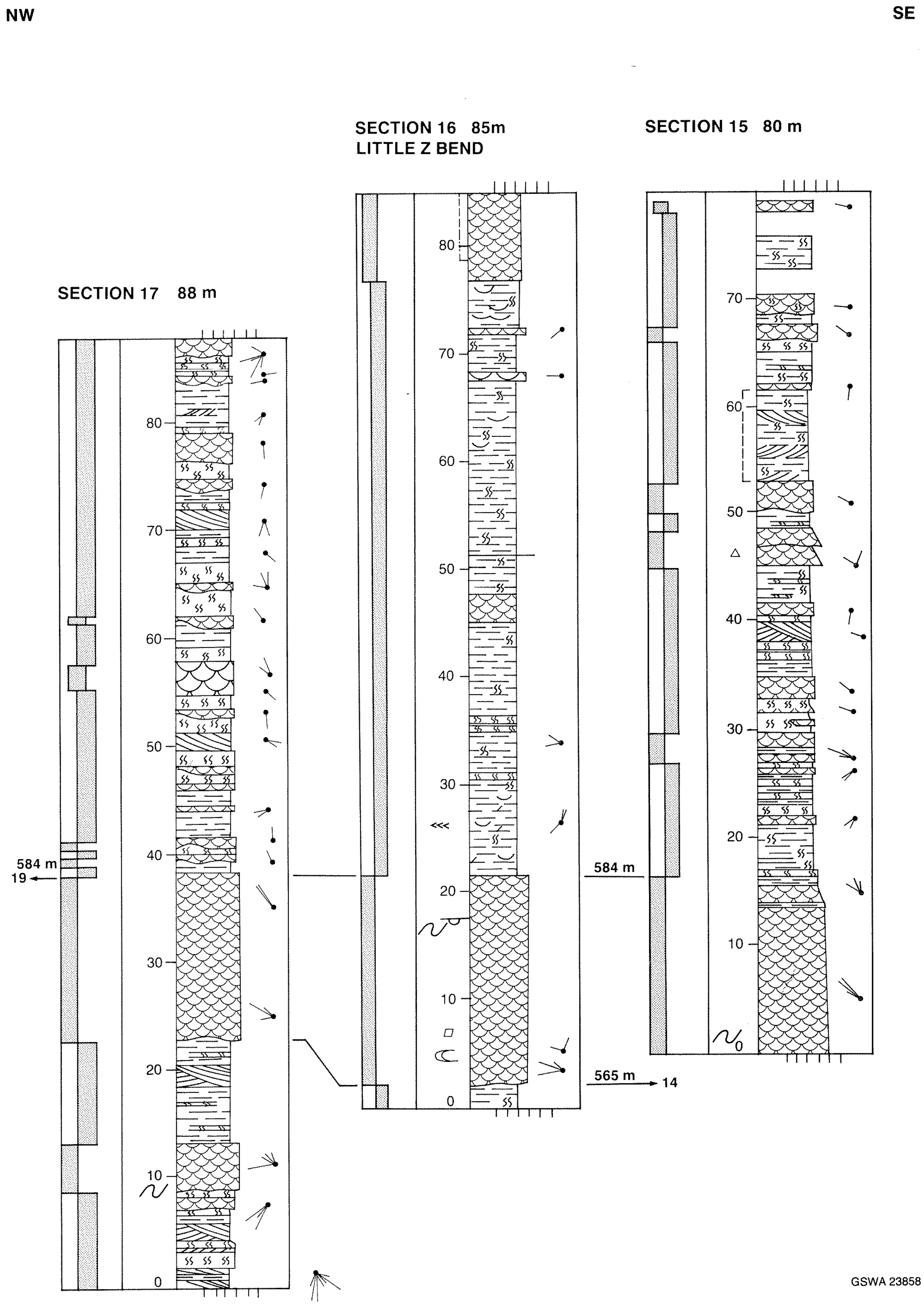

SE
SECTION 13 41.5m
SECTION 12 70 m
LOCKWOOD SPRINGS,
West block
14 515 m
14 503 m
482 m
µm sand
silt
125
250
500
1000
2000
FAULT
FA 1
n=24
40%
·92
·40
mSx
n=7
30%
mStm
n=19
20%
·65
FA 1
n=7
40%
·94
mSxp
n=3
40%
·63
14
13
12
30 km

GSWA 23856




GSWA 23859

**Figure 87. Graphic logs and palaeocurrents for Sections 15, 16 (Little Z Bend), and Section 17.**


NW
SE
SECTION 17 88 m
SECTION 16 85m
LITTLE Z BEND
SECTION 15 80 m
584 m
19
584 m
565 m
14
GSWA 23858



2960-9

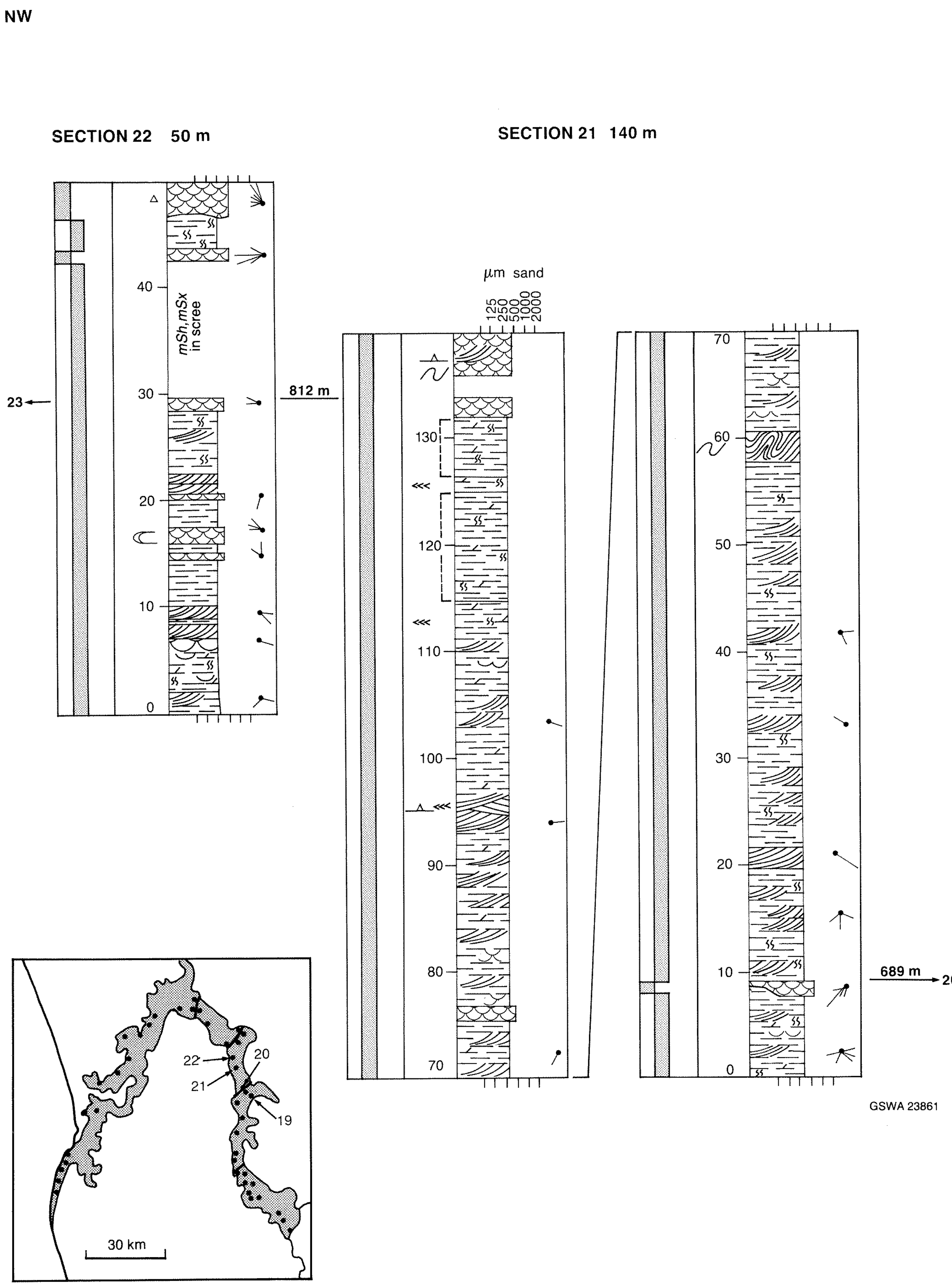
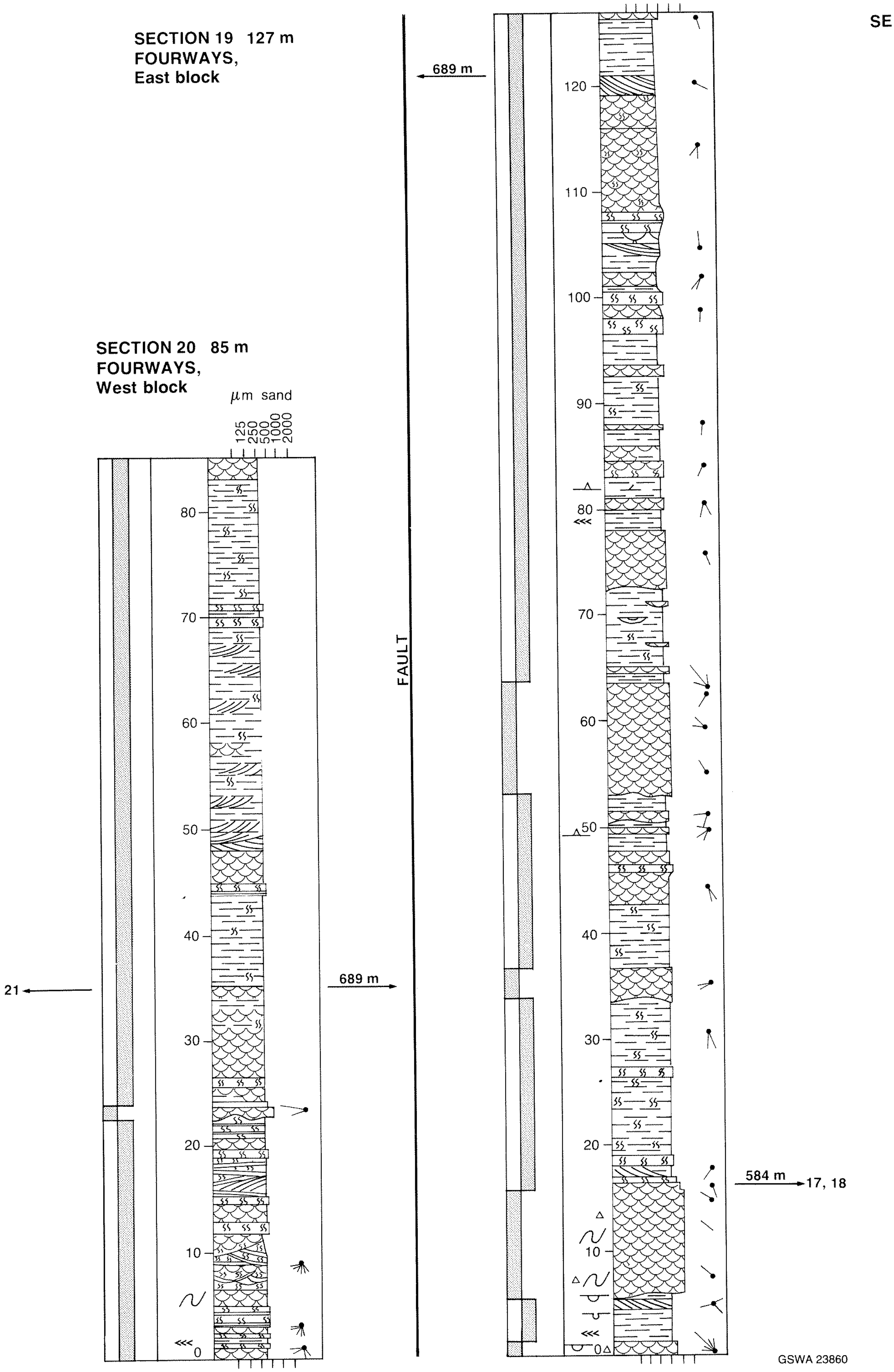
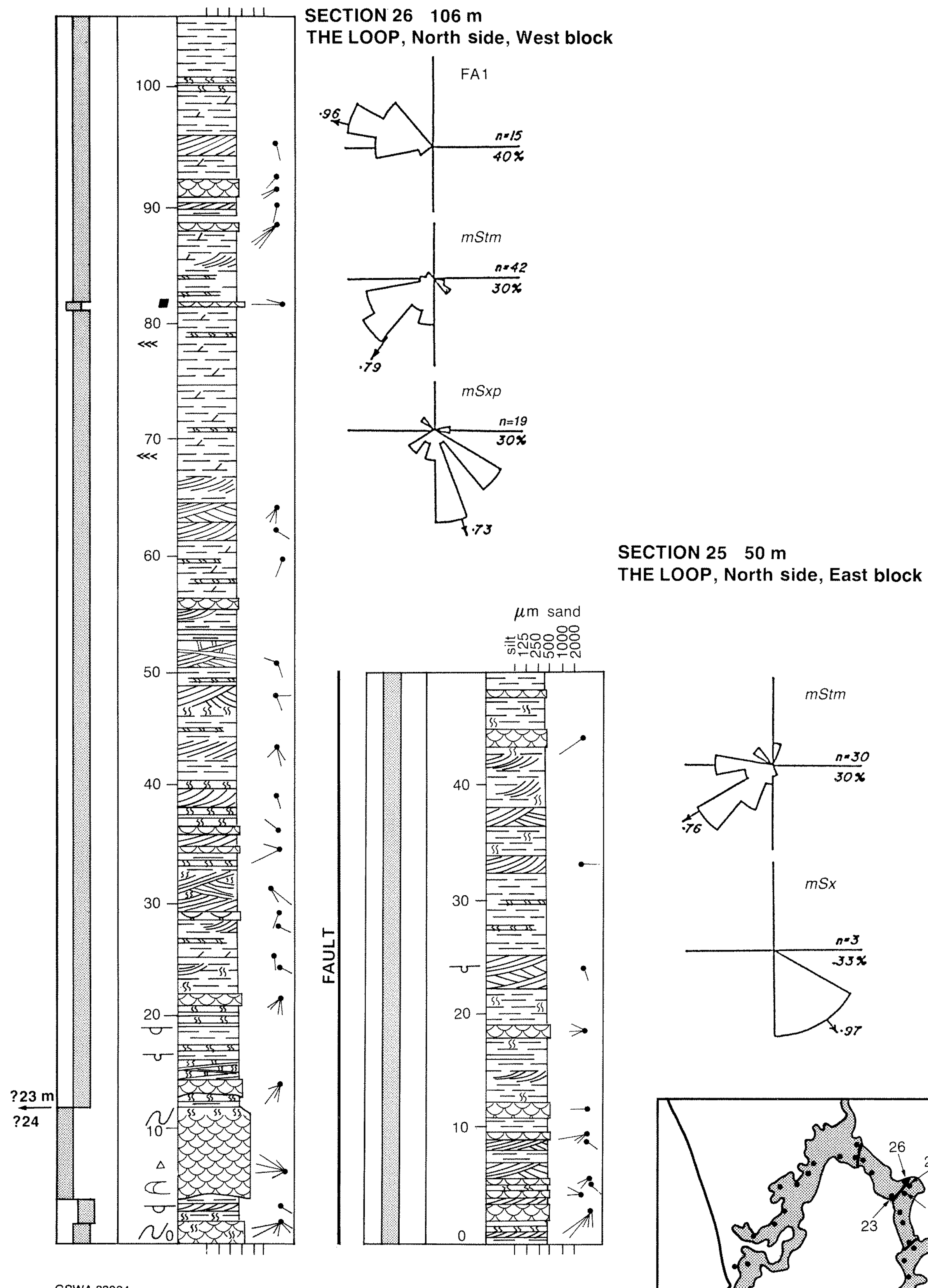



**Figure 88. Graphic logs and palaeocurrent roses for Sections 19 and 20 (Fourways, east and west blocks), 21, and 22. Section 18 is shown in Figure 18.**



SECTION 19 127 m
FOURWAYS,
East block
SECTION 20 85 m
FOURWAYS,
West block
μm sand
125
250
500
1000
2000
SE
FAULT
689 m
689 m
21
584 m
17, 18
GSWA 23860



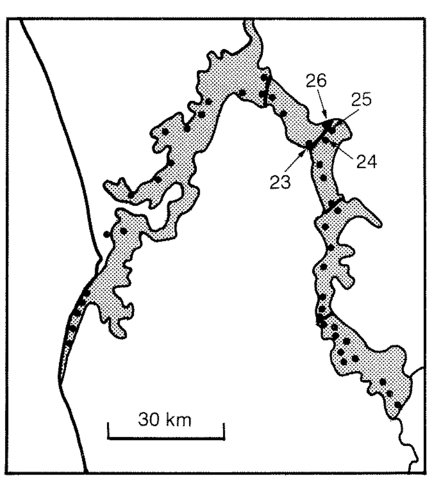
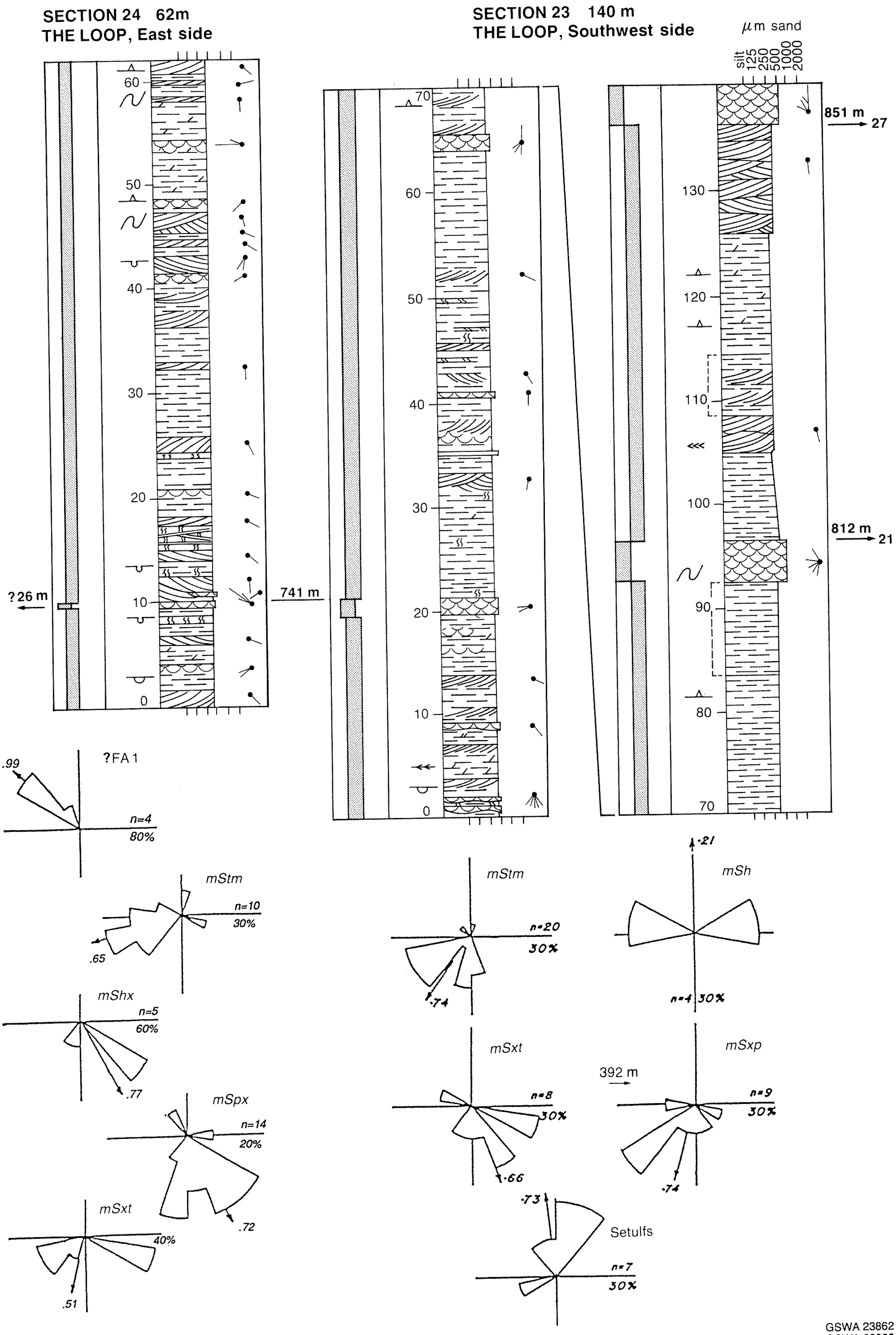




**Figure 89. Graphic logs and palaeocurrent roses for Sections 23 to 26 (The Loop area).**


SECTION 24 62m
THE LOOP, East side
SECTION 23 140 m
THE LOOP, Southwest side
μm sand
silt
125
250
500
1000
2000
?26 m
741 m
851 m
27
812 m
21
392 m
?FA 1
n=4
80%
.99
mStm
n=10
30%
.65
mShx
n=5
60%
.77
mSpx
n=14
20%
.72
mSxt
40%
.51
mStm
n=20
30%
.74
mSh
.21
n=4 30%
mSxt
n=8
30%
.66
mSxp
n=9
30%
.74
Setulfs
.73
n=7
30%
GSWA 23862
GSWA 23863

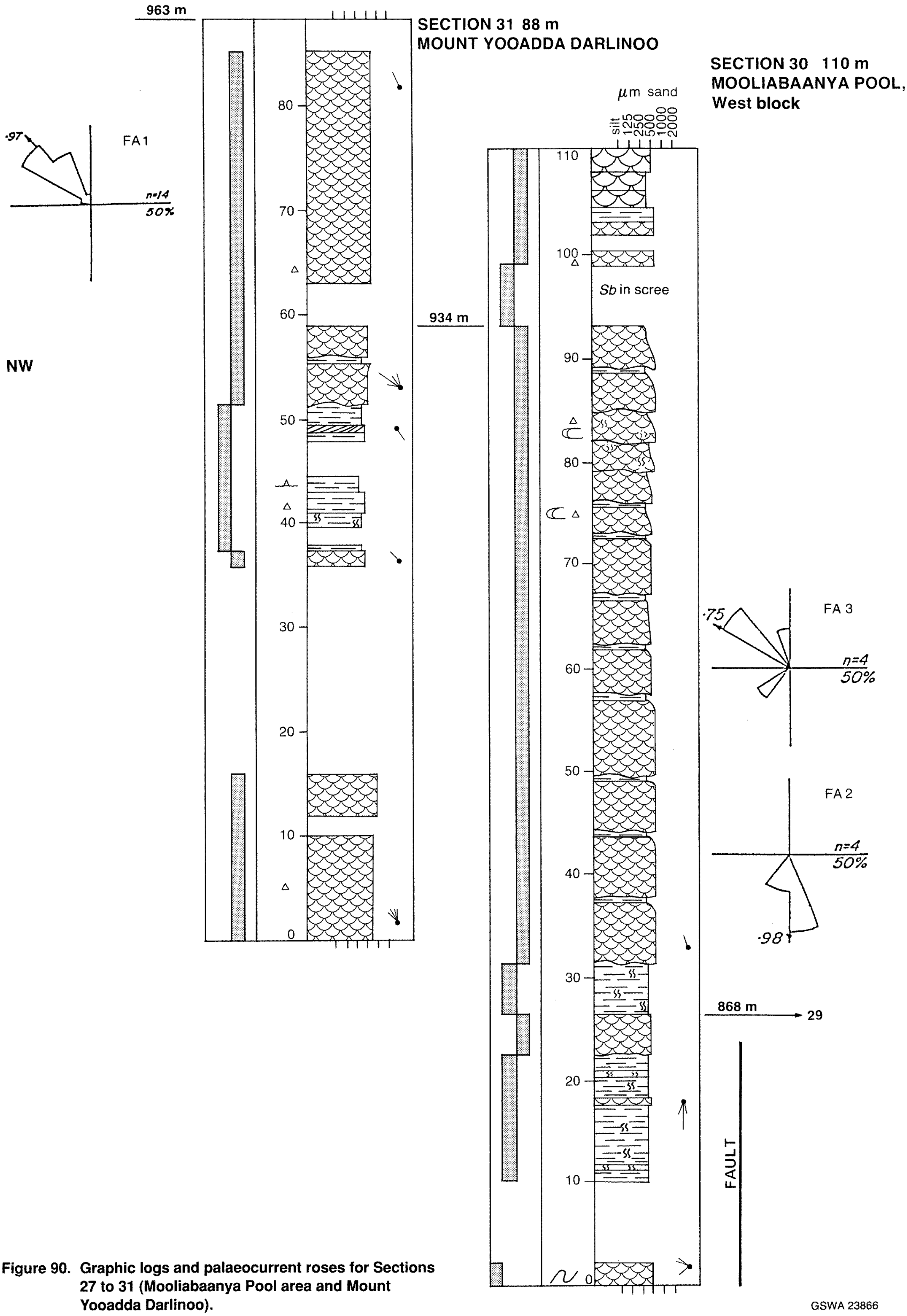
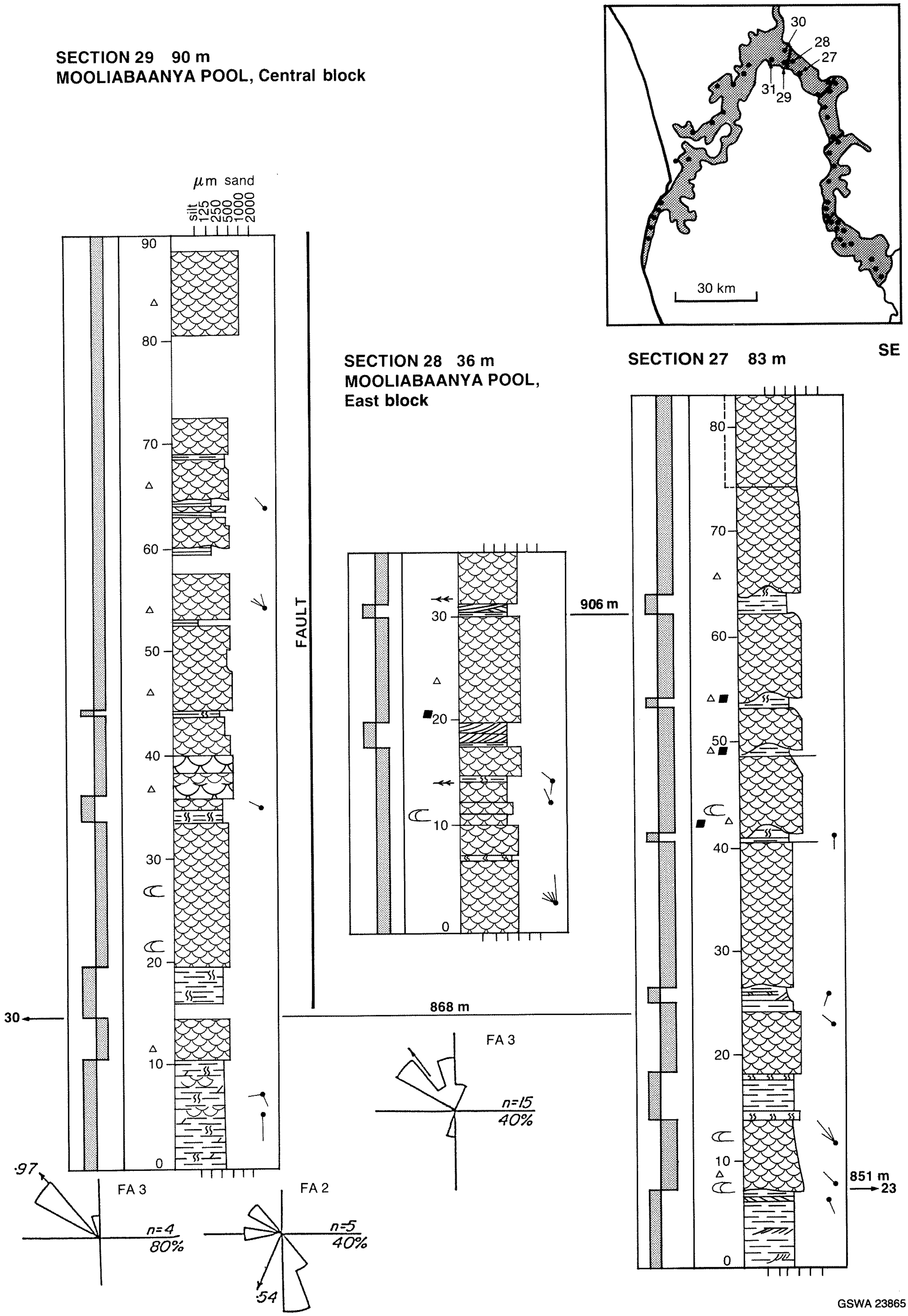



**Figure 90. Graphic logs and palaeocurrent roses for Sections 27 to 31 (Mooliabaanya Pool area and Mount Yooadda Darlinoo).**



SECTION 29 90 m
MOOLIABAANYA POOL, Central block
μm sand
silt
125
250
500
1000
2000
FAULT
SECTION 28 36 m
MOOLIABAANYA POOL, East block
SECTION 27 83 m
SE
906 m
868 m
851 m
23
30
30 km
FA 3
n=4
80%
97
FA 2
n=5
40%
54
FA 3
n=15
40%
GSWA 23865

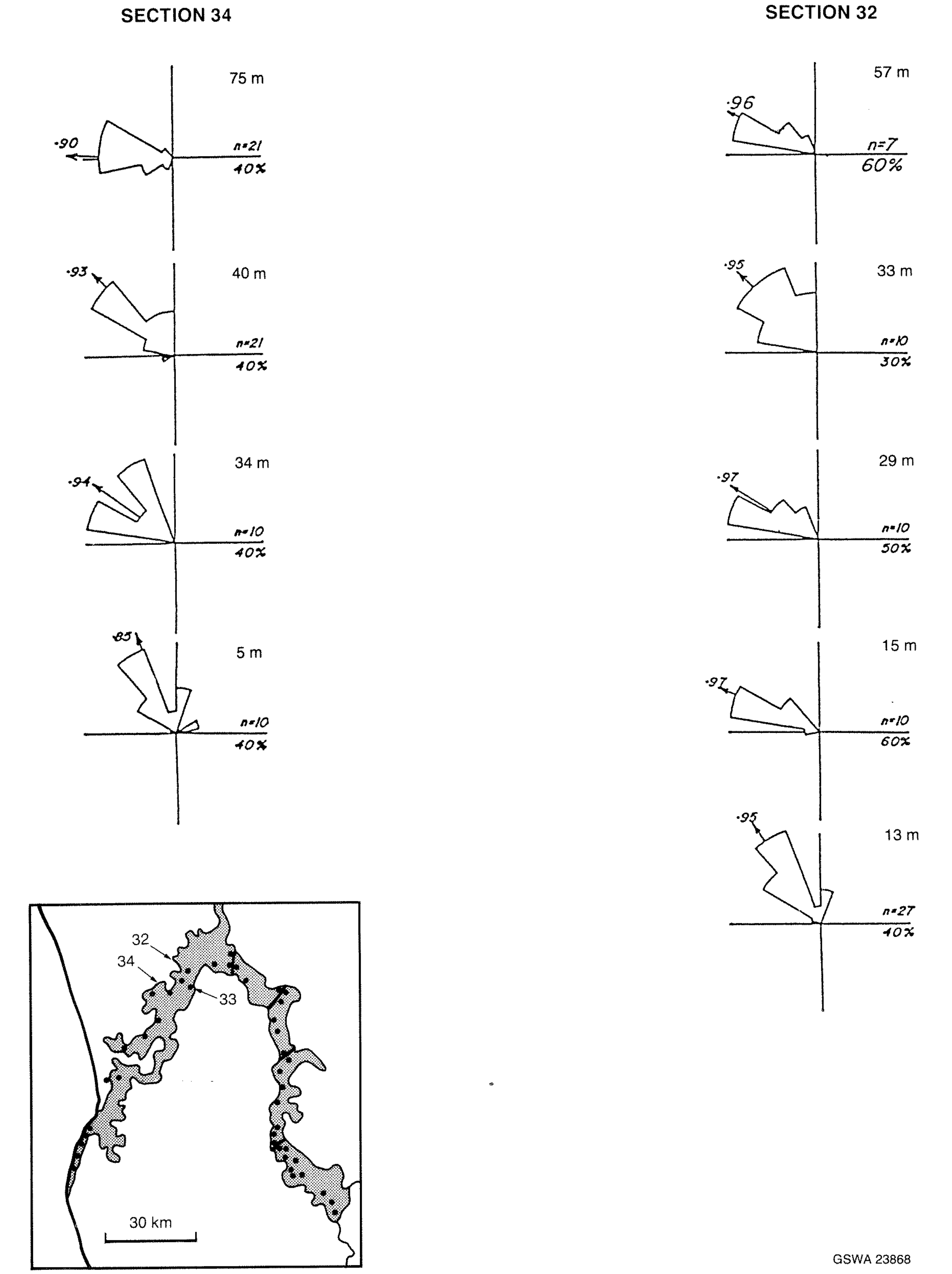
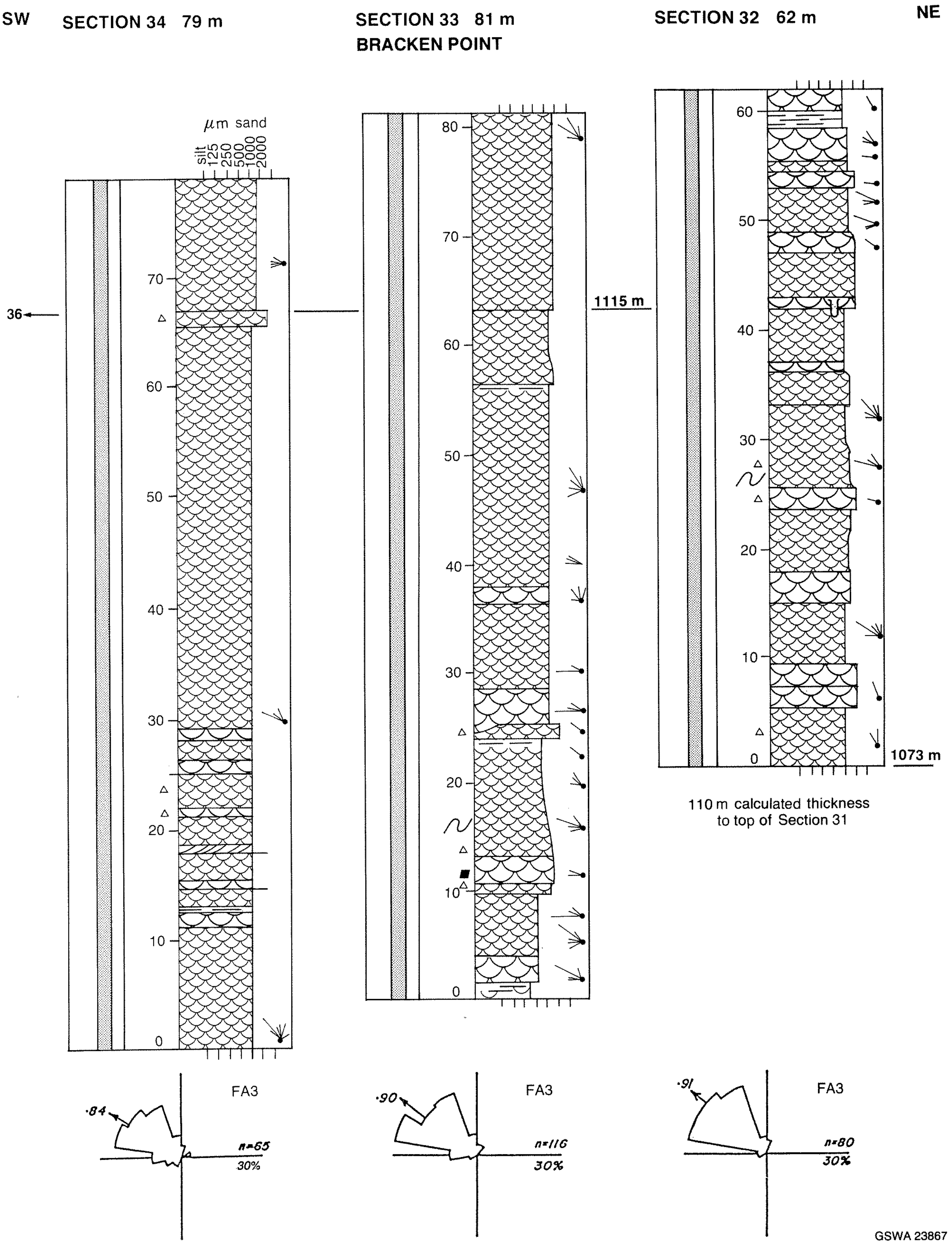



**Figure 91. Graphic logs and palaeocurrent roses for Sections 32, 33 (Bracken Point), and Section 34. Figure 50 shows palaeocurrent roses and a detailed log of the lower part of Section 33.**


SW
SECTION 34 79 m
SECTION 33 81 m
BRACKEN POINT
SECTION 32 62 m
NE
µm sand
silt
125
250
500
1000
2000
36
1115 m
1073 m
110 m calculated thickness to top of Section 31
FA3
·84
n=65
30%
FA3
·90
n=116
30%
FA3
·91
n=80
30%
GSWA 23867

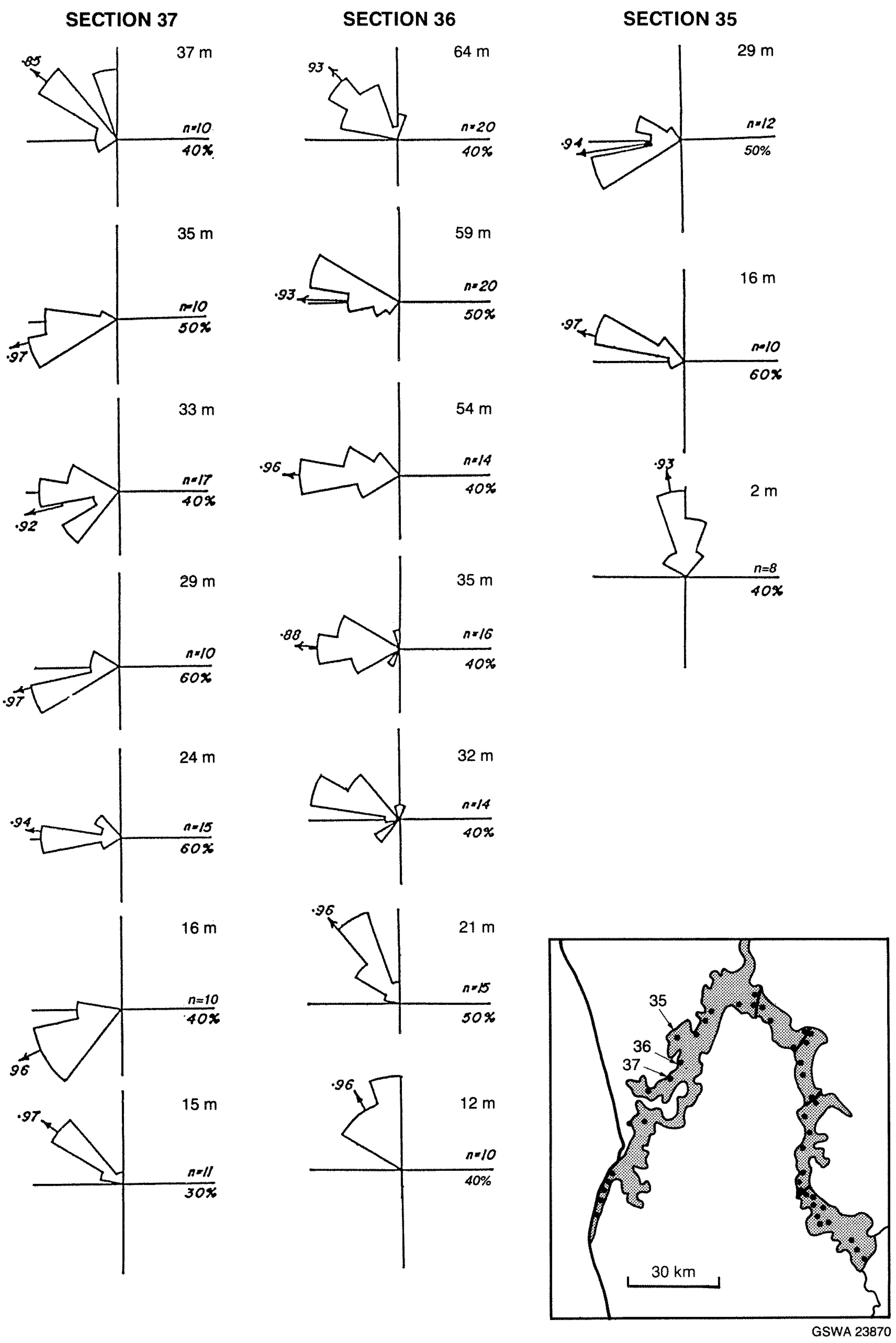
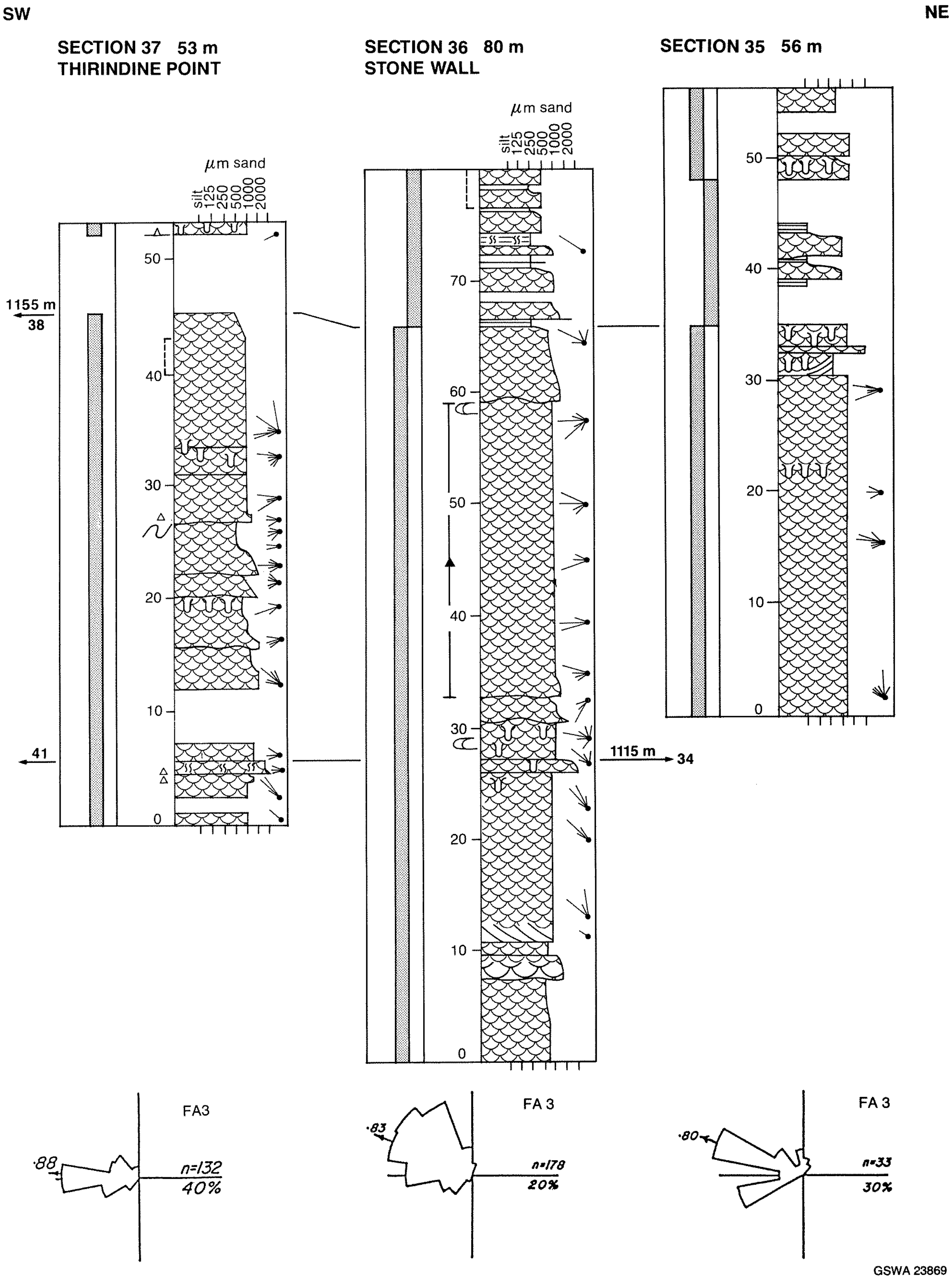



**Figure 92. Graphic logs and palaeocurrent roses for Sections 35, 36 (Stone Wall), and 37 (Thirindine Point).**



SW
NE
SECTION 37 53 m
THIRINDINE POINT
SECTION 36 80 m
STONE WALL
SECTION 35 56 m
μm sand
silt
125
250
500
1000
2000
1155 m
38
41
1115 m
34
FA3
n=132
40%
FA 3
n=178
20%
FA 3
n=33
30%
88
83
80
GSWA 23869

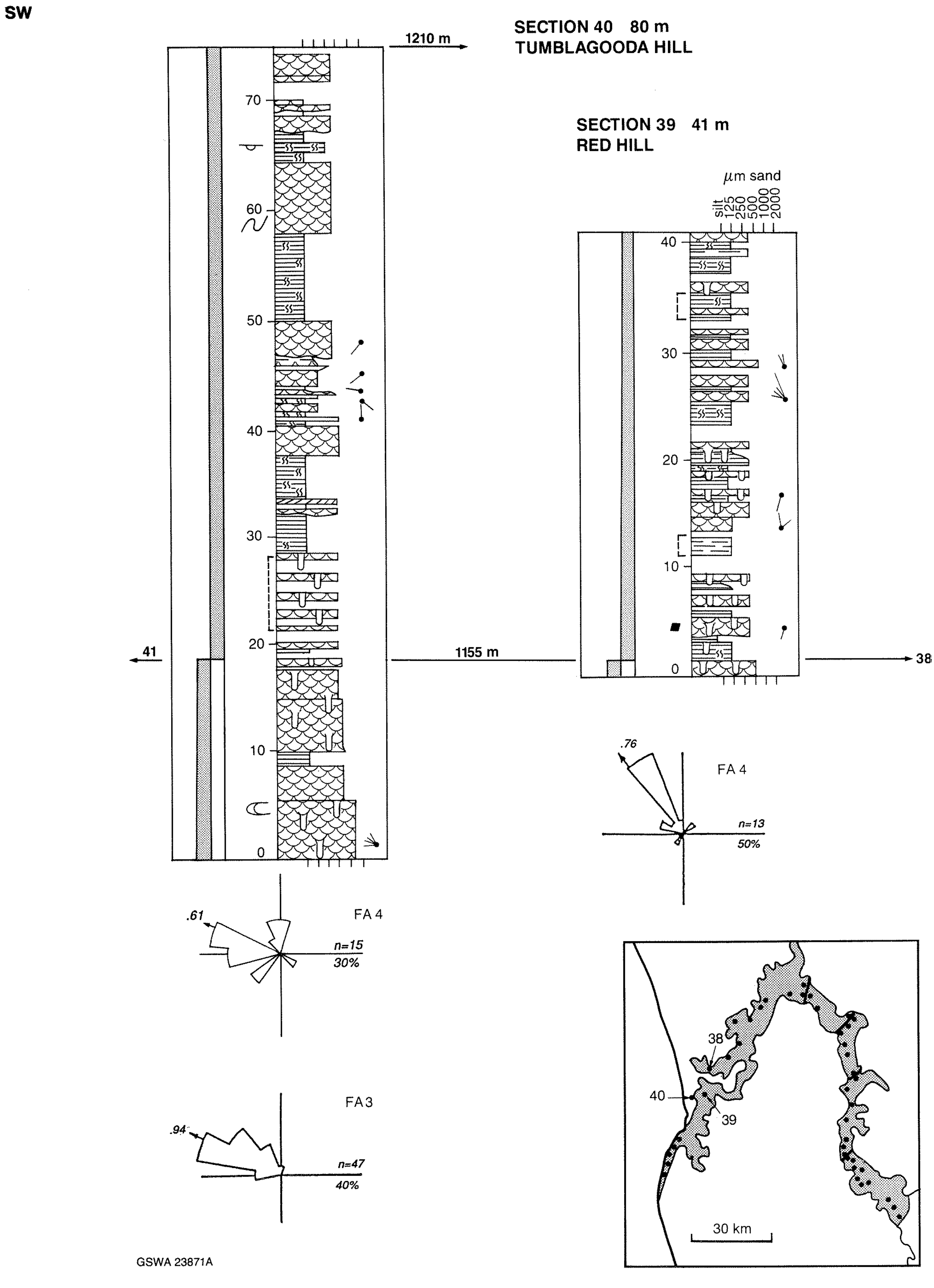
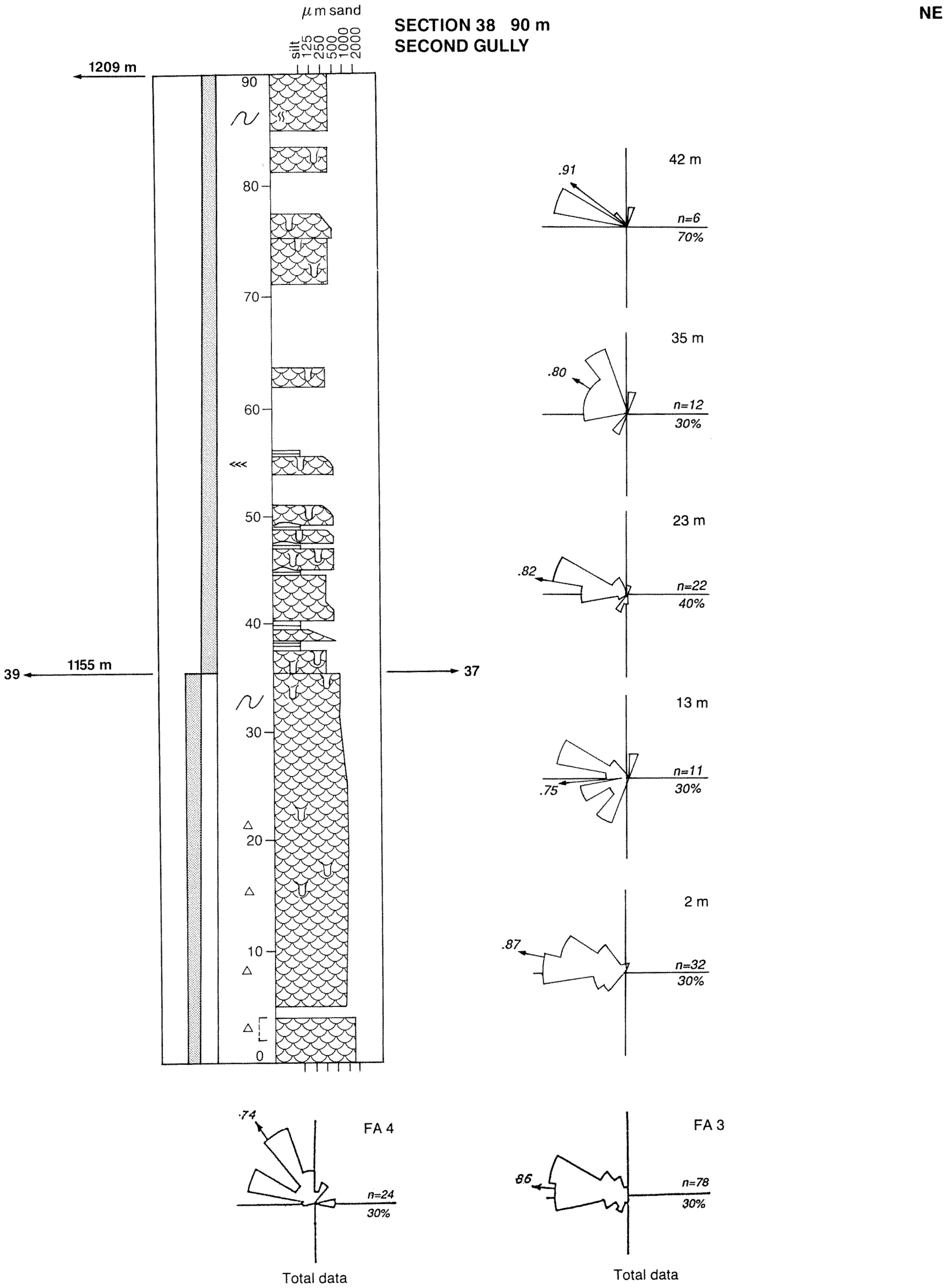



**Figure 93. Graphic logs and palaeocurrent roses for Sections 38 (Second Gully), 39 (Red Hill), and 40 (Tumblagooda Hill).**



μm sand
silt 125 250 500 1000 2000
SECTION 38 90 m
SECOND GULLY
NE
1209 m
39
1155 m
37
90
80
70
60
50
40
30
20
10
0
42 m
.91
n=6
70%
35 m
.80
n=12
30%
23 m
.82
n=22
40%
13 m
.75
n=11
30%
2 m
.87
n=32
30%
.74
FA 4
n=24
30%
Total data
86
FA 3
n=78
30%
Total data
GSWA 23871B

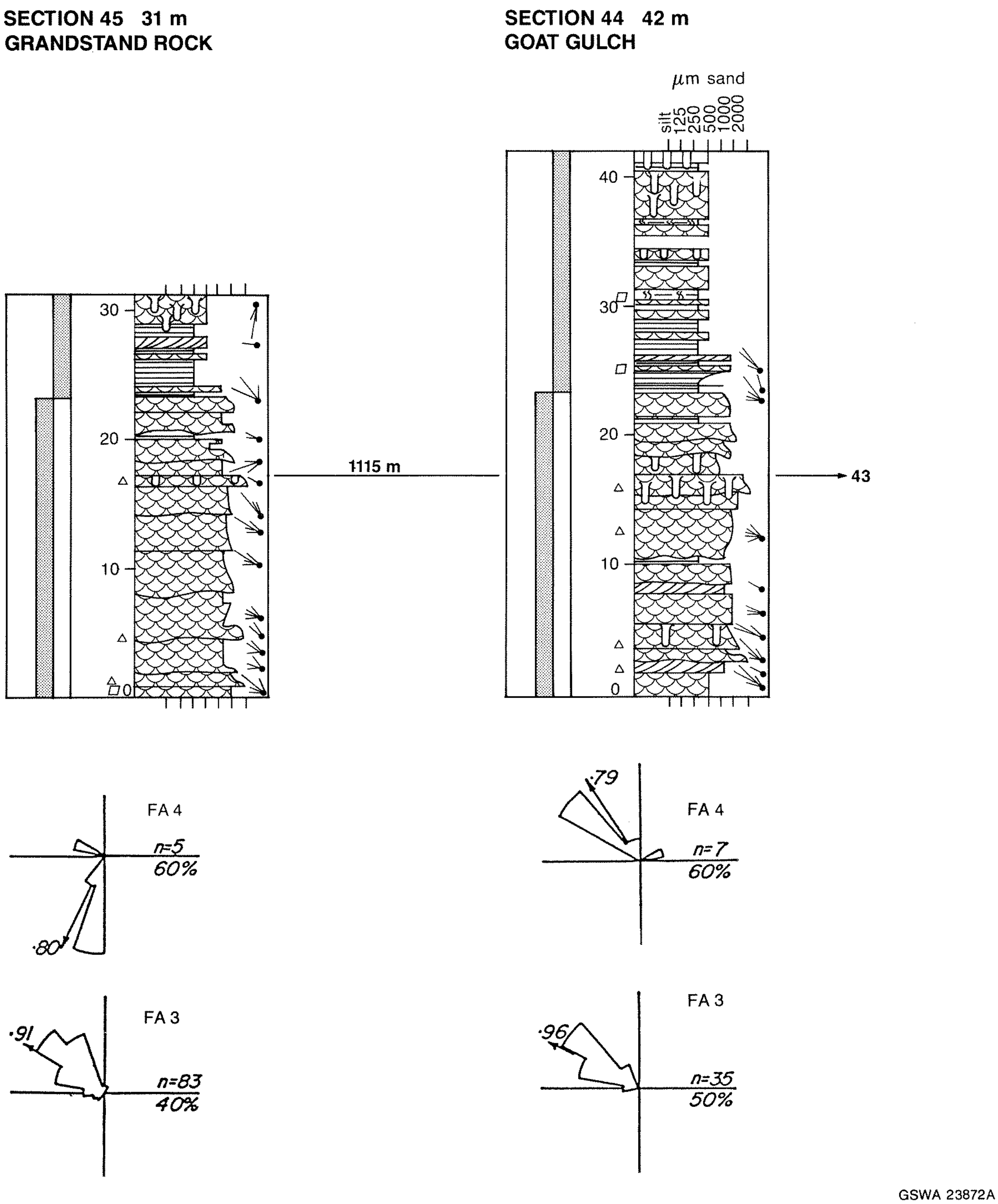
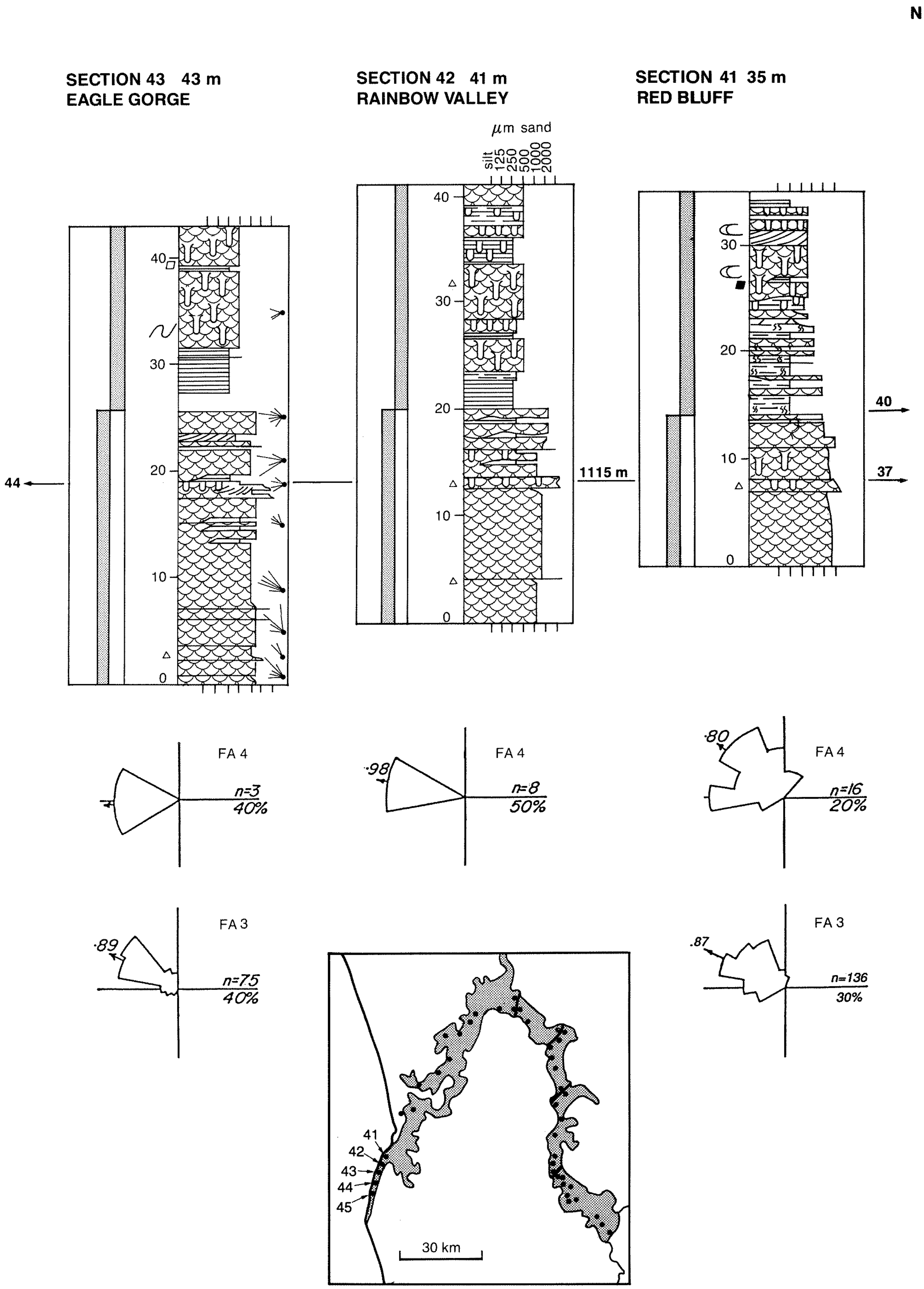



**Figure 94. Graphic logs and palaeocurrent roses for Sections 41 (Red Bluff), 42 (Rainbow Valley), 43 (Eagle Gorge), 44 (Goat Gulch), and 45 (Grandstand Rock). Figure 52 shows a detailed log of the lower part of Section 41.**


N
SECTION 43 43 m
EAGLE GORGE
SECTION 42 41 m
RAINBOW VALLEY
SECTION 41 35 m
RED BLUFF
μm sand
silt
125
250
500
1000
2000
44
1115 m
40
37
FA 4
n=3
40%
FA 4
·98
n=8
50%
FA 4
·80
n=16
20%
FA 3
·89
n=75
40%
FA 3
.87
n=136
30%
41
42
43
44
45
30 km

GSWA 23872B

## PENCELL POOL SECTION

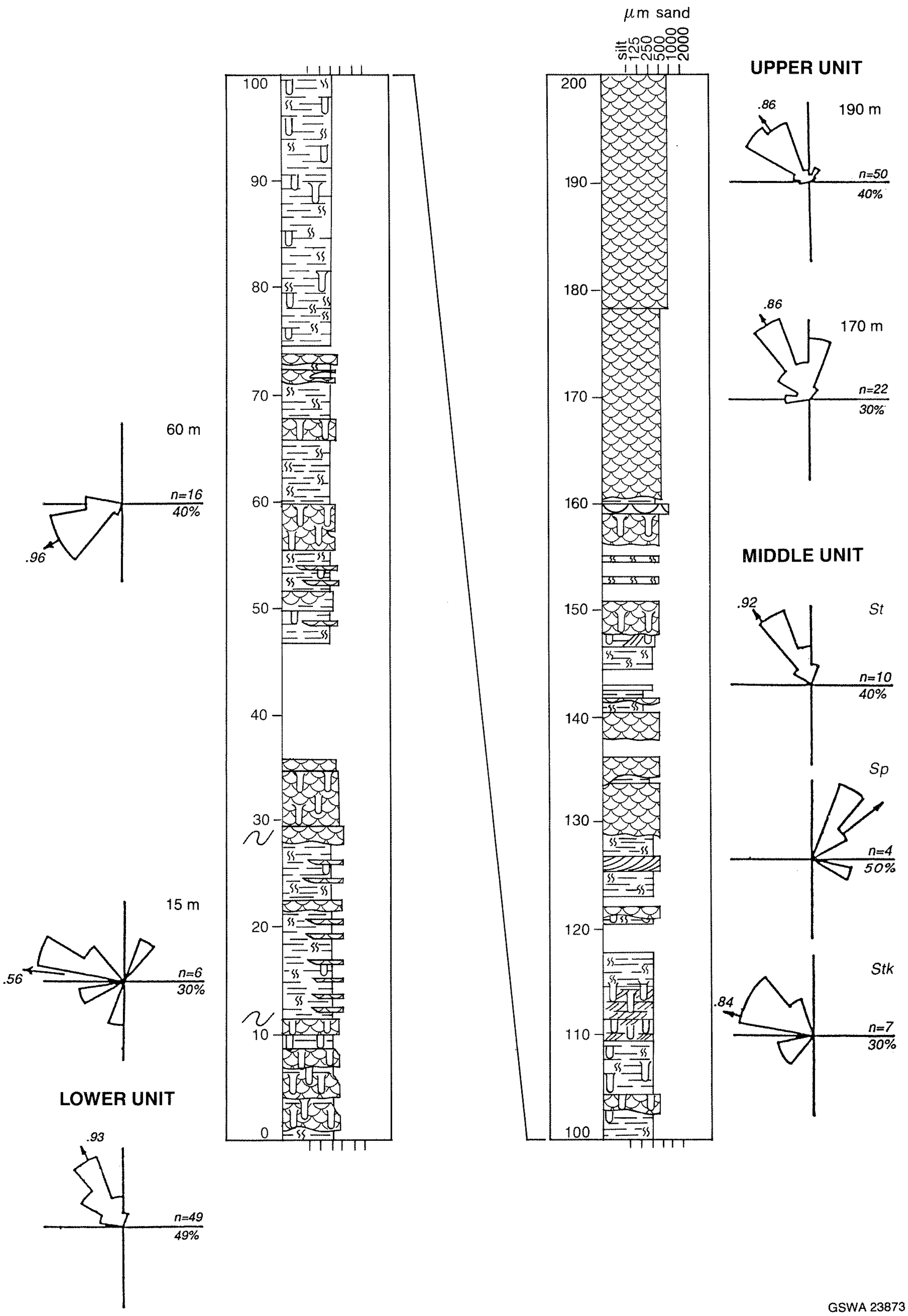



**Figure 95. Graphic logs and palaeocurrent roses for the sequence on the west bank of Pencell Pool.**



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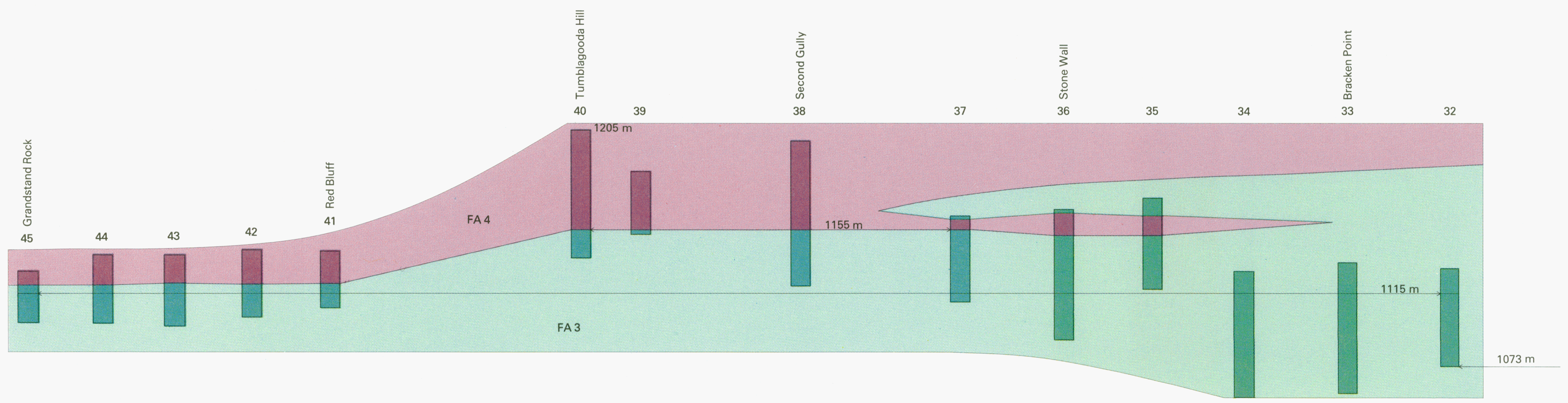
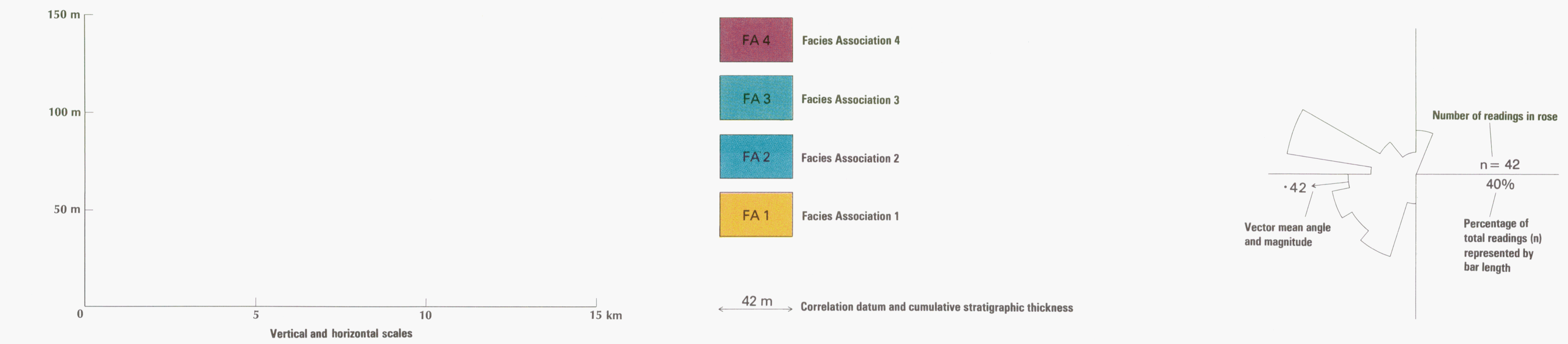
D.R. KELLY, DIRECTOR GENERAL OF MINES

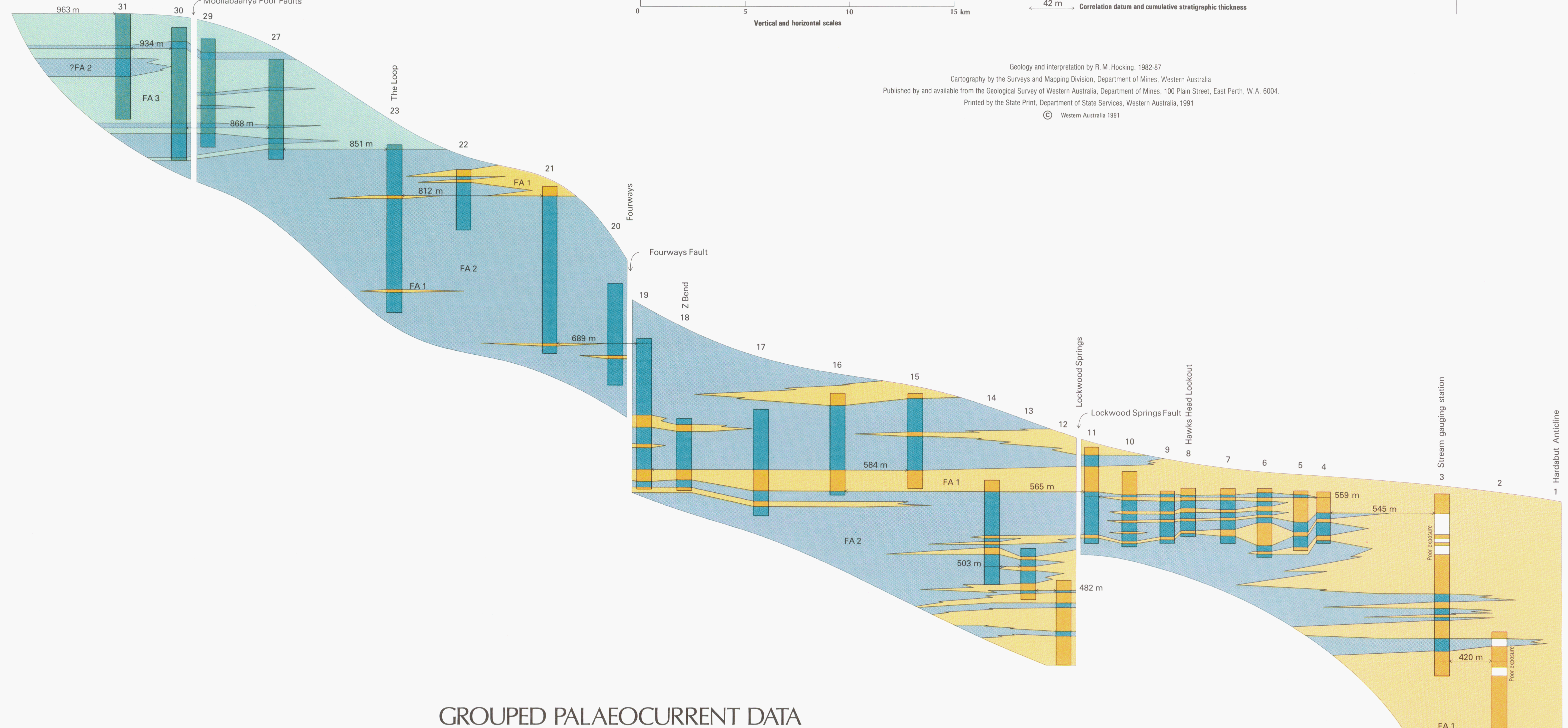
P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

# TUMBLAGOODA SANDSTONE

## TYPE SECTION, OUTCROP DISTRIBUTION, AND GROUPED PALAEOCURRENT DATA





Geology and interpretation by R. M. Hocking, 1982-87
Cartography by the Surveys and Mapping Division, Department of Mines, Western Australia
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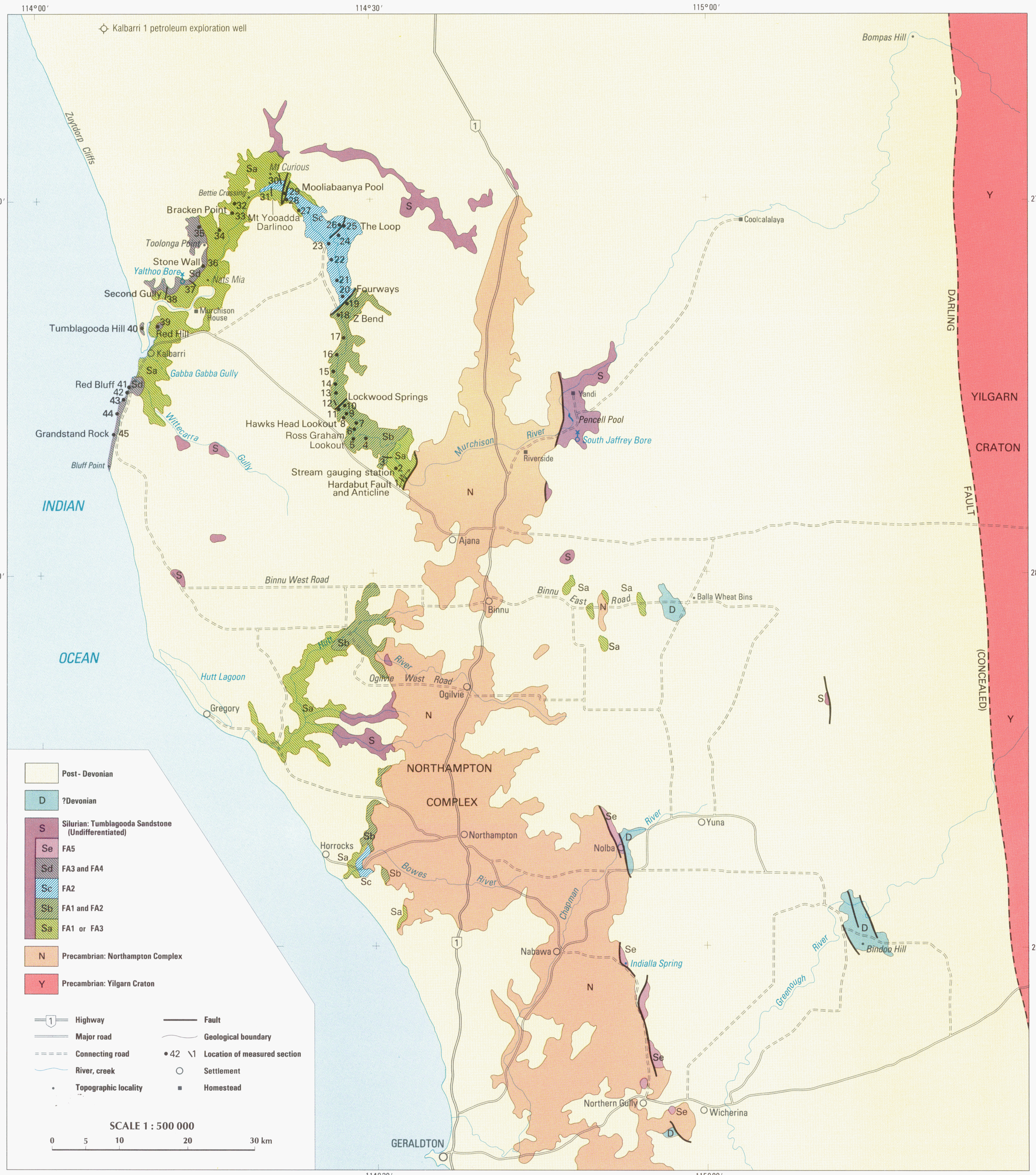
Printed by the State Print, Department of State Services, Western Australia, 1991


## GROUPED PALAEOCURRENT DATA