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# Tectonic and climatic controls on a Mesozoic forearc basin succession, Alexander Island, Antarctica

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**Abstract** – The Cretaceous Fossil Bluff Group on Alexander Island, on the west side of the Antarctic Peninsula, contains a remarkably complete record of the evolution of a forearc basin. The latest (Aptian–Albian) stages in the basin history are recorded in a well-exposed succession at the southern end of the island, where a series of nunataks provide exposure of over a thousand metres of shallow marine and continental deposits. An abrupt facies shift from upper shoreface marine facies to braided fluvial deposits is interpreted as the record of regional uplift in the volcanic arc. This event coincides with the Palmer Land deformation event which may be related to a mid-Cretaceous mantle plume. A gradual reduction in depositional gradient and a return to shallow marine conditions towards the top of the exposed section is interpreted as a consequence of erosion of the arc and subsidence within the basin. Palaeocurrent data and facies distributions indicate that the continental deposits formed a fan-shaped wedge at least 30 km in diameter in the southern part of the forearc basin. Fossil plants indicate that the palaeoclimate was warm and humid throughout the period of deposition. Mapping and facies analysis of the upper part of the Fossil Bluff Group in southern Alexander Island has resulted in a revision of the stratigraphic terminology for the area. The Triton Point Member, formerly part of the Neptune Glacier Formation, has been raised to formation status and two members (the Citadel Bastion Member and the Coal Nunatak Member) and a Bed (the Upper Coal Nunatak Sandstone Bed) are defined here within the formation.

Keywords: Cretaceous, fluvial, sedimentology, Antarctica, fore-arc basins.

## 1. Introduction

### 1.a. Tectonic setting

The Jurassic to Lower Cretaceous Fossil Bluff Group records deposition in a trench-slope and forearc basin setting along the subducting margin of Gondwana (Butterworth *et al.* 1988; Moncrieff & Kelly, 1993; Doubleday, Macdonald & Nell, 1993). Fossil Bluff Group strata are exposed in a 250 km long linear belt, 30 km wide on the eastern side of Alexander Island (Fig. 1). On the western margin, basal units are either in faulted contact with, or rest unconformably on, the LeMay Group, which is the accretionary complex of the arc–trench system (Doubleday, Macdonald & Nell, 1993). To the east of Alexander Island lies the present-day King George VI Sound. This feature is an extensional graben which may be associated with slab roll-back in the Tertiary (McCarron & Larter, 1998), and seismic reflectors imaged within King George VI Sound indicate that Fossil Bluff Group strata lie beneath a thin Cenozoic cover (Bell & King, 1998).

The Fossil Bluff Group forearc basin has a thick sedimentary fill (*c.* 6800 m: Moncrieff & Kelly, 1993) which includes deep marine, shallow marine and continental facies (Butterworth *et al.* 1988; Macdonald *et al.* 1999) (Fig. 2). In Dickinson's (1995) classification of forearc basins it would be considered to be 'overfilled' and either 'shelved' (with the outer ridge formed by the accretionary prism barely emergent) or 'benched' (with the outer ridge wholly emergent). Detritus eroded from the LeMay Group occurs in upper Fossil Bluff Group deposits in the western part of the basin (J. R. Browne, unpub. Ph.D. thesis, Univ. Exeter, 1996), indicating that the accretionary complex was exposed during the later stages of basin fill; the basin may therefore be considered as transitional from 'shelved' to 'benched'. Shelved and benched forearc basin morphologies are host to some of the thickest successions of basin strata. For example, up to 6000 m occurs in the Miocene successions in Alaska (von Huene, Fisher & Bruns, 1987), up to 6500 m of Neogene deposits in parts of the Sunda forearc (Hamilton, 1979) and in excess of 10 000 m of Oligocene strata in Luzon, Philippines (Bachman, Lewis & Schweller, 1983).

The shallow marine and continental deposits which make up the uppermost part of the basin fill exposed in the Fossil Bluff Group provide a record of relative base level change during this stage of evolution of the forearc basin. Analyses of 1000 m of strata in the southernmost part of the area of exposure of the group can be

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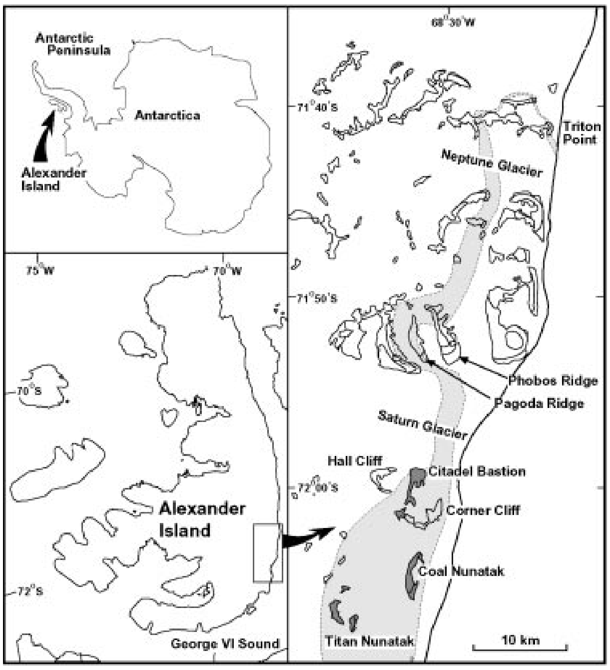


Figure 1. Alexander Island lies on the western side of the Antarctic Peninsula. In the southeastern part of the island the Fossil Bluff Group is exposed in ice-free nunataks and ridges. The shaded area is the outcrop of the Triton Point Formation and this study focuses on the southern part of this area.

| Age | Formation | Member | Environment |
|---|---|---|---|
| Albian | Neptune Glacier (2200 m) | Mars Glacier (>900 m) | Nearshore / paralic |
| | | **Triton Point (>900 m)** | **Fluvial** |
| | | Deimos Ridge (800-1050 m) | Nearshore / paralic |
| Aptian-Albian | Pluto Glacier (1400 m) | | Tidal shallow shelf |
| Valangian-Barremian | Spartan Glacier (1000m) | | Outer shelf to slope |
| Tithonian-Berriasian | Himalia Ridge (2200 m) | | Submarine fan channel complex |
| Kimmeridgian | Ablation Point (440m) | | Slope collapse slump units |

Figure 2. Stratigraphic relationships in the Fossil Bluff Group (from (Butterworth *et al.* 1988; Doubleday, Macdonald & Nell, 1993; Moncrieff & Kelly, 1993). In the present study, the Triton Point Member is raised to the status of formation (see text for discussion).

related to thermal and tectonic events in the adjacent arc and provide a constraint of the magnitude and timing of regional uplift and subsidence events in the arc and forearc.

### 1.b. Stratigraphic setting

Previous studies on the Fossil Bluff Group have recognized seven formations within the basin fill (Butterworth *et al.* 1988; Doubleday, Macdonald & Nell, 1993; Moncrieff & Kelly, 1993) (Fig. 2). This study is concerned with the youngest of these formations, the Neptune Glacier Formation, which was initially divided into three members: Deimos Ridge, Triton Point and Mars Glacier members (Moncrieff & Kelly, 1993). In the type area, the Triton Point Member is no more than 200 m thick, but to the south in the present study area it is substantially thicker (at least 829 m), and includes a greater range of facies than previous studies have indicated. There are a number of distinctive facies associations within this unit which allow it to be mapped quite separately from the rest of the Neptune Glacier Formation. Revision of the stratigraphic nomenclature for the area is suggested and the Triton Point Member is raised to formation status.

## 2. Southern nunataks: structure and correlation

Vertical sections were measured at three areas of exposure in the southeastern part of Alexander Island: Citadel Bastion, Coal Nunatak and Titan Nunatak, field locations KG. 4651 to KG. 4661 (Fig. 3). Exposures in nearby outcrops at Hall Cliff, Corner Cliff and the Hyperion Nunataks were not visited by the authors during the field season for logistical reasons.

The structural dip of the strata in these southern nunataks is variable, but at localities where it could be measured, or estimated, it was found to be between 4° and 10° to the south or southeast. Minor faults or folding are very rare in these exposures, so it is likely that the three nunataks are all part of a single structural block. A geometrical correlation between the three areas of exposure using a regional dip towards the southeast indicates that the sections at Citadel Bastion are at the base of the succession, and these are in turn overlain by the sections at Titan and Coal nunataks respectively (Fig. 3). Comparison between the measured sections (Figs 4, 5, 6) indicates that there is no stratigraphic overlap between the three areas, and this is consistent with a gentle regional dip. The sum of the measured sections of dominantly fluvial deposits (829 m) therefore represents the likely minimum stratigraphic thickness of the Triton Point Formation.

An estimate of the stratigraphic gap between the top of the section at Citadel Bastion and the base of the section at Coal Nunatak can be calculated using the regional dip and the horizontal separation (3.3 km) perpendicular to strike. These two points are at approximately the same elevation, and using a low dip value (4°) the stratigraphic gap is 230 m, which is consistent with the 164 m of section exposed at Titan Nunatak that is considered to fit into this gap. Using a southeasterly dip of 10° the stratigraphic gap would be 570 m. The total thickness of the Triton Point Formation is therefore considered to be between 900 and 1200 m.

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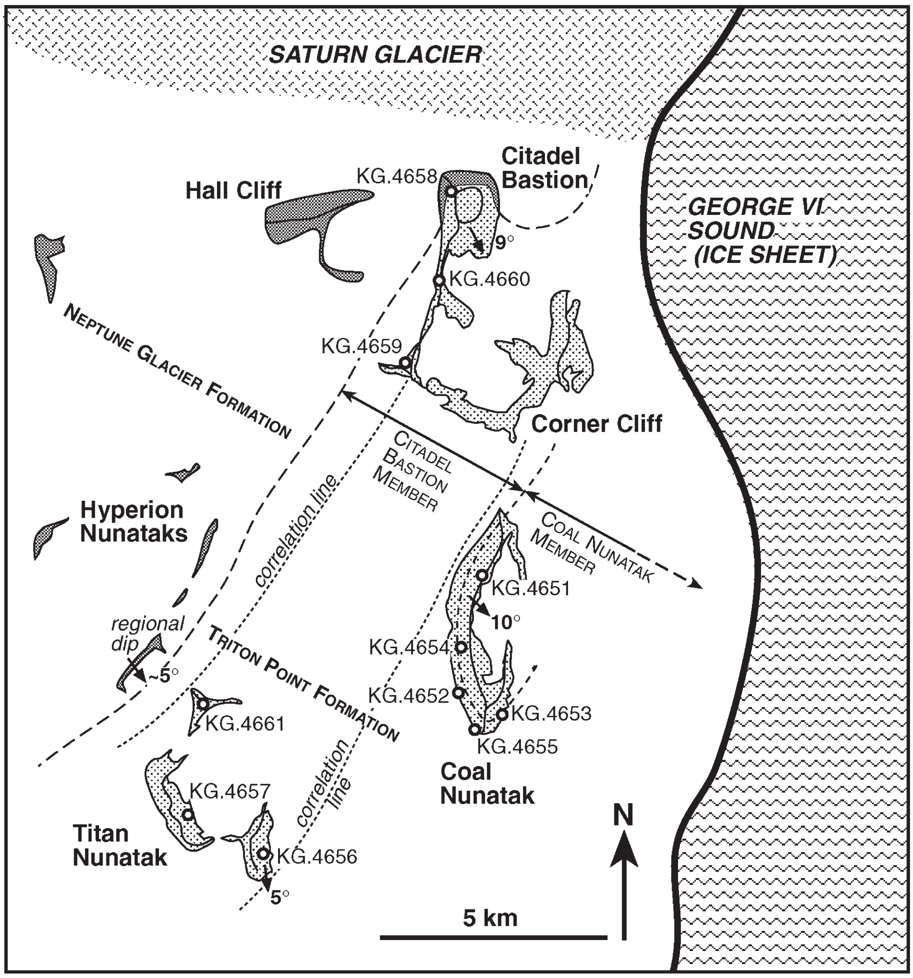


Figure 3. Outcrop map of the Neptune Glacier Formation (dark shading) and Triton Point Formation (light shading) in the southern nunataks on Alexander Island. There is a gentle tectonic dip to the southeast. The lower part of the Citadel Bastion Member is exposed on Citadel Bastion, the middle and upper parts of the member exposed on Titan and Coal nunataks, and the Coal Nunatak Member in the upper part of Coal Nunantak. Lines within the nunataks mark the crests of ridges.

## 3. Sedimentary facies

Excellent exposure in the southern nunataks makes it possible to draw graphic sedimentary logs (Figs 4, 5, 6) which represent nearly 70% of the vertical section exposed in rock faces; the missing sections were covered by scree on gentler slopes and at the bases of the steeper cliffs. The low tectonic dip allows for individual beds and sandstone packages to be traced for the entire length of the outcrop in some places; in the case of Coal Nunatak some packages of beds can be traced laterally over a distance of 4 km along the western side of the ridge (Fig. 7).

The sedimentary rocks exposed in the southern nunataks are mainly sandstones and mudstones with sparse conglomeratic beds; beds of primary volcaniclastic sediments also occur in places. Deposition in a continental environment is suggested (Moncrieff & Kelly, 1993) and hence the principal sandstone and mudstone facies are described in the next sections in terms of fluvial channel and overbank associations (cf. Miall, 1978).

### 3.a. Fluvial channel-fill facies

The following facies (G, $S_{cg}$, $S_{mg}$, $S_{xs}$, $S_{xb}$, $S_u$: Tables 1, 2) occur predominantly within sedimentary bodies which have sharp, scoured bases, a fining-up pattern on a scale of metres, and evidence for unidirectional flow. These bodies are interpreted as the fills of river channels and they are under- and overlain by finer-grained successions containing palaeosol horizons (see below). Other sandy facies ($S_{fg}$, $S_{hl}$, $S_{xl}$) are also found associated with channel-fill deposits, but are more commonly found in the overbank facies associations.

#### *3.a.1. Facies G: Granule and pebble conglomerate*

Fine pebble and granule conglomerate occurs as beds a few tens of centimetres thick with sharp to erosive

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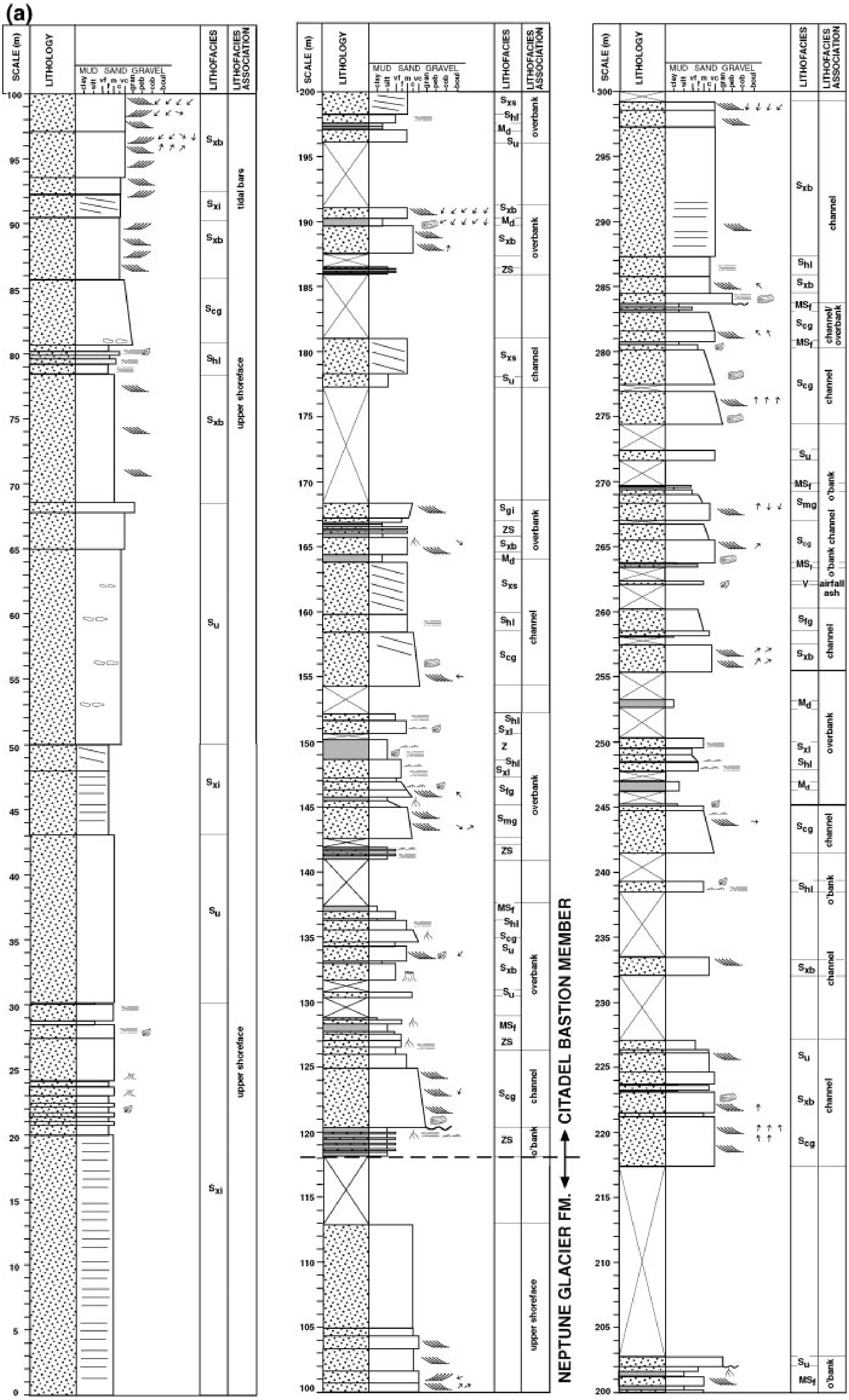


Figure 4. Graphic sedimentary log of exposures at Citadel Bastion (BAS stations KG. 4658, 4659, 4660). For legend see Figure 5.

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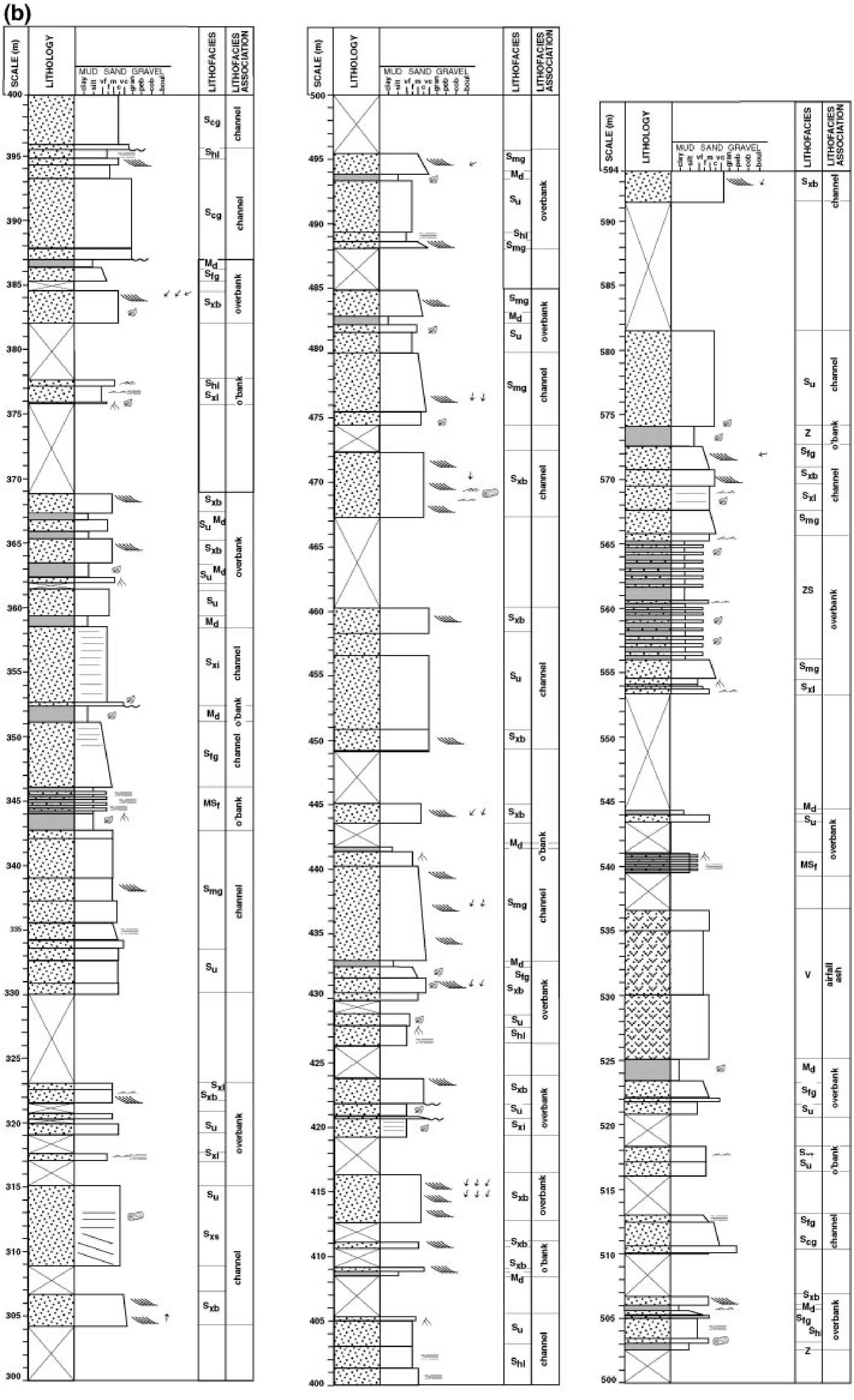

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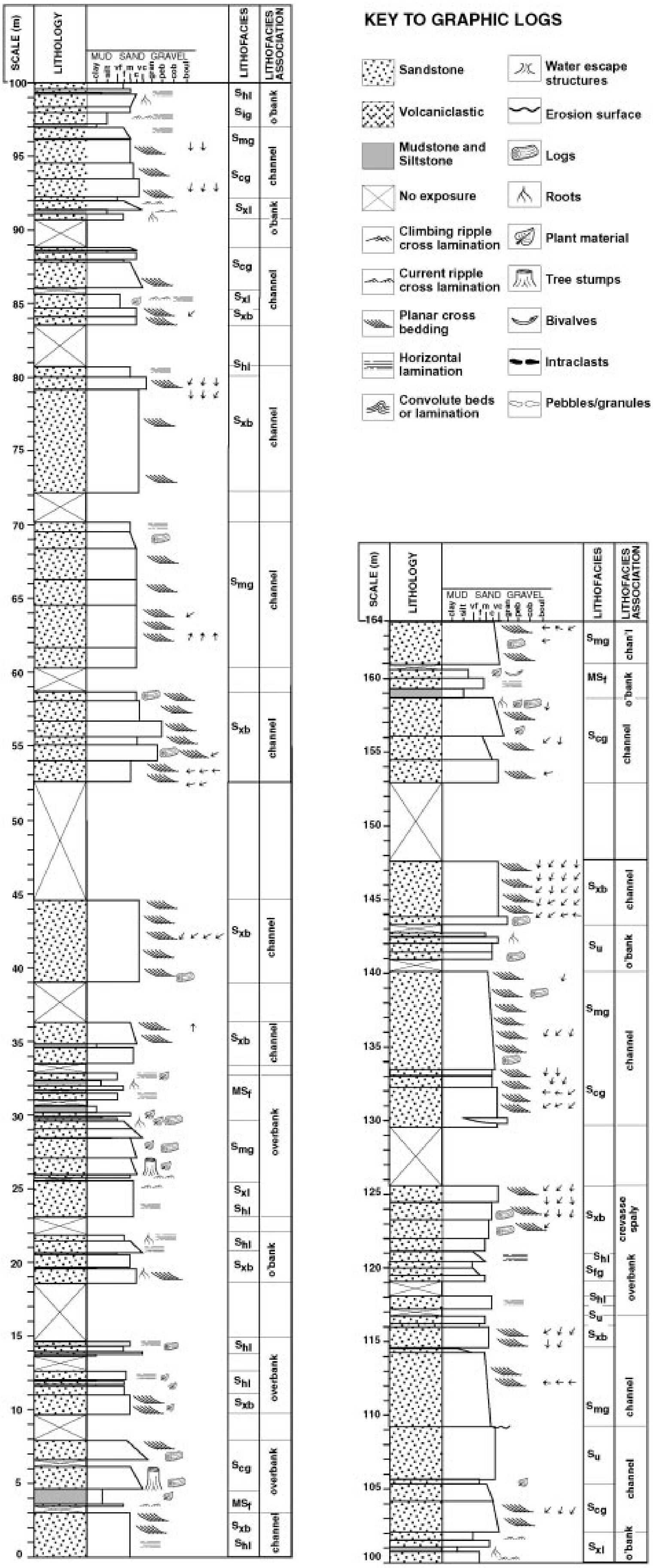


Figure 5. Graphic sedimentary log of exposures at Titan Nunatak (BAS stations KG. 4656, 4657, 4661)

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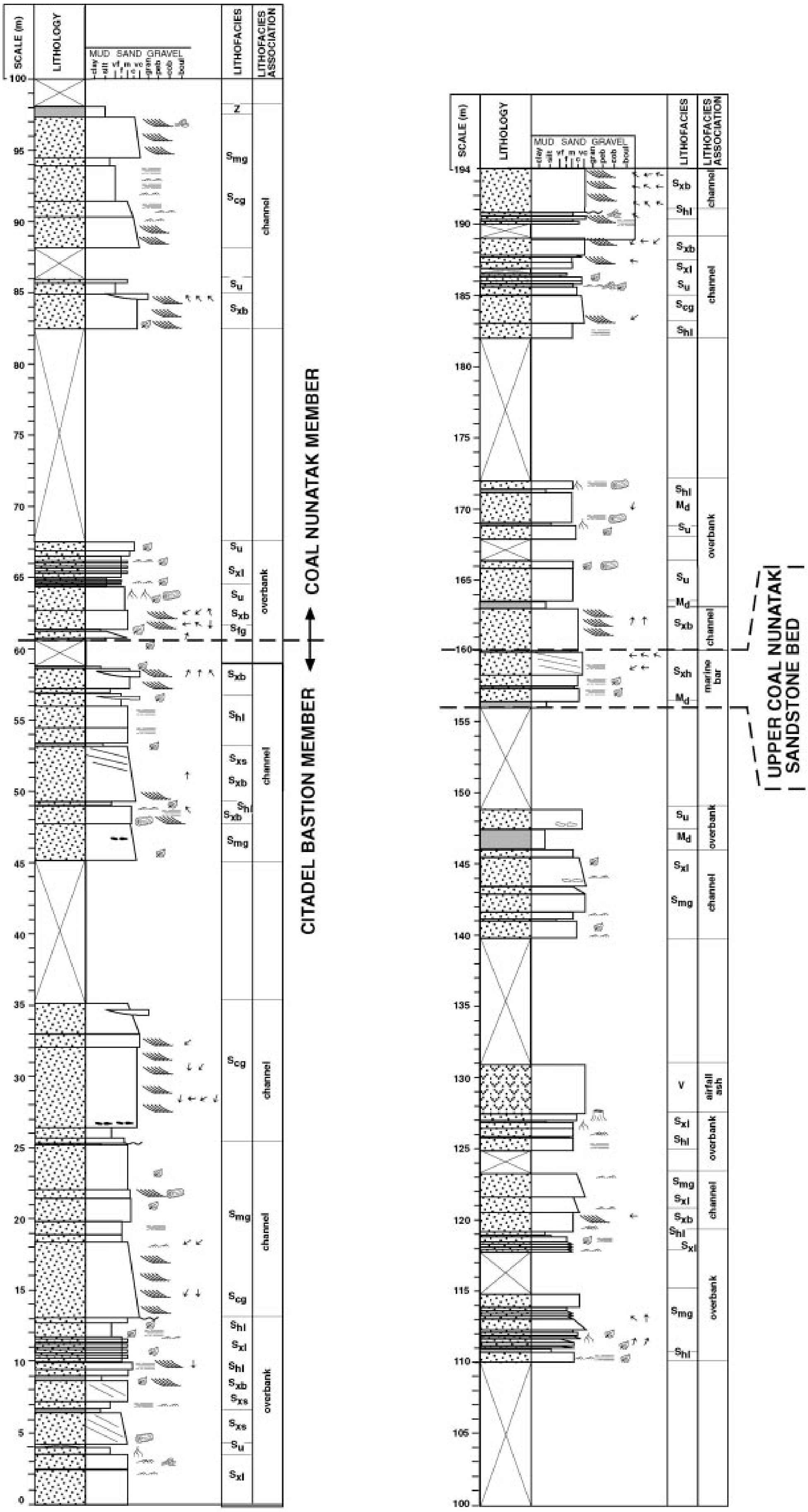

Figure 6. Graphic sedimentary log of exposures at Coal Nunatak (BAS stations KG. 4651, 4652, 4653, 4654, 4655). For legend see Figure 5.

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Table 1. Lithofacies of the Neptune Glacier and Triton Point formations, southern nunataks of Alexander Island

| Code | Facies |
|---|---|
| G | Granule and pebble conglomerate |
| $S_{cg}$ | Very coarse graded sandstone |
| $S_{mg}$ | Medium-coarse graded sandstone |
| $S_{fg}$ | Medium-fine graded sandstone |
| $S_{gi}$ | Inversely graded sandstone |
| $S_{xi}$ | Inclined stratified sandstone |
| $S_{xh}$ | Inclined heterolithic stratified sandstone |
| $S_{xs}$ | Cross-stratified sandstone |
| $S_{xb}$ | Cross-bedded sandstone |
| $S_{xl}$ | Ripple cross laminated sandstone |
| $S_{hl}$ | Horizontally laminated sandstone |
| $S_{u}$ | Structureless sandstone |
| Z | Siltstone |
| ZS | Thinly bedded sandstone and siltstone |
| $MS_{f}$ | Fine sandstone and mudstone |
| $M_{d}$ | Dark grey or black mudstone |
| V | Tuffs |

Table 2. Lithofacies associations of the Neptune Glacier and Triton Point formations, southern nunataks of Alexander Island

| Facies association | Facies |
|---|---|
| Fluvial channel fill (Citadel Bastion Member) | G $S_{cg}$ $S_{mg}$ $S_{xs}$ $S_{xb}$ $S_{u}$ ($S_{fg}$ $S_{hl}$ $S_{xl}$) |
| Fluvial channel fill (Coal Nunatak Member) | $S_{cg}$ $S_{mg}$ $S_{xs}$ $S_{xb}$ $S_{u}$ ($S_{hl}$ $S_{xl}$) |
| Coarse overbank | $S_{gi}$ $S_{hl}$ $S_{xl}$ $S_{fg}$ $S_{xb}$ $S_{u}$ |
| Fine overbank | Z ZS MS $M_{d}$ |
| Marine (Neptune Glacier Formation) | $S_{xi}$ $S_{xb}$ |
| Marine (Upper Coal Nunatak Sandstone Bed) | $S_{xh}$ |
| Volcaniclastic | V |

bases. Clasts are moderately to poorly sorted and show moderate rounding, and the beds are clast-supported in a coarse sandstone matrix. The clasts are principally of basic to intermediate volcanic rocks, many of which have undergone diagenetic zeolitization.

*3.a.2. Facies $S_{cg}$: Very coarse graded sandstone*

This facies is predominantly very coarse sandstone with lenses or beds of granule conglomerate found as a lag above the sharp, erosive basal contacts to the beds. Units are typically 1.0 to 4.5 m thick, normally graded to coarse or medium sandstone and show both planar and trough cross-bedding, the former in sets between 0.3 and 1.5 m thick, the latter in 0.2 to 0.8 m sets. At the bases of these units rip-up clasts of mudrock up to 200 mm across are common, woody debris can be very abundant and standing tree trunks occur (Fig. 5, 5 m).

*3.a.3. Facies $S_{mg}$: Medium–coarse graded sandstone*

Coarse, medium and, in places, fine sandstone occurs in normally-graded beds 1.0 to 1.5 m thick. The lower parts of the beds are commonly trough cross-bedded in sets 0.1 to 0.5 m thick, and ripple cross-lamination occurs in the upper parts of some beds. Standing tree trunks occur (Fig. 5, 26 m) and plant debris is common. Beds of this facies may occur repeated in units several metres thick.

*3.a.4. Facies $S_{xs}$: cross-stratified sandstone*

Medium to coarse sandstone occurs in individual beds 2 to 4 m thick and shows metre-scale, low angle ($< 15°$) cross-stratification which runs through at least half of the bed thickness.

*3.a.5. Facies $S_{xb}$: cross-bedded sandstone*

Decimetre- to metre-thick beds of fine to coarse cross-bedded sandstone occur commonly. The cross-bed sets are typically 0.2–0.5 m in thickness, and the style of cross-bedding is mainly trough, with rare planar, tabular cross-bedding.

*3.a.6. Facies $S_u$: structureless sandstone*

Beds up to 5 m thick of fine to very coarse sandstone displaying no internal sedimentary structures occur throughout the sections examined.

*3.a.7. Interpretation of fluvial channel-fill facies*

These facies occur within normally graded successions of cross-bedded and cross-stratified sandstone with sharp, scoured bases. The scoured bases with mud-clasts and gravel lags (facies G) are interpreted as having formed by channel incision. Where completely exposed, these channel-fill successions are between 4.5 and 14.5 m thick, which suggests that the channels themselves may have been in excess of ten metres deep (e.g. in the middle and upper parts of the Citadel Bastion section at 283 m, 330 m and 449 m, Fig. 4). However, it is possible that some of the thicker sandstone bodies are amalgamated units made up of more than one channel-fill succession (Godin, 1991).

The overall fining-up and successions of cross-stratification and cross-bedding in facies $S_{cg}$, $S_{mg}$, $S_{xs}$ and $S_{xb}$ are characteristic of accretion on bars and sheets within the channels (Godin, 1991; Collinson, 1996). In a number of cases, channel filling appears to have been by accretion on large bar forms several metres thick, overlain by smaller bar features about a metre thick, similar in form but smaller in scale than the giant alternate bar forms described by McCabe (1977). Exposures on the eastern side of Titan Nunatak at KG. 4656 reveal low-angle dipping surfaces separating packages of facies $S_{xb}$ and $S_{cg}$ into lenses a few tens of metres across and two to three metres thick; these are interpreted as bar surfaces preserved within the channel-fill succession (Allen, 1983). Sandstone beds lacking any primary sedimentary structures (facies $S_u$) may be the product of rapid deposition in a channel, or original stratification may have been obscured by

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Figure 7. A view of the exposure on the west flank of Coal Nunatak showing the lateral continuity of exposure of beds approximately parallel to strike. The top of the nunatak is 200 m above the level of the ice in the foreground.

Figure 8. Exposure on the west flank of Coal Nunatak at KG. 4652: the lower part of the exposure consists of braidplain deposits of the Citadel Bastion Member and the upper part, above the sandstone cliff in the centre of the view, is made up of a higher proportion of overbank deposits and more isolated channel-fill sandstone bodies in the Coal Nunatak Member. Approximately 150 m of vertical section is exposed here.

Figure 9. The erosional margin of a channel at KG. 4651 at the northern end of Coal Nunatak viewed from the north.

subsequent slumping and dewatering (Turner & Munro, 1987).

The excellent lateral continuity of exposure in the southern nunataks makes it possible to determine the geometry of the channel-fill sandstone bodies. In the lower part of the formation, exposures on Citadel Bastion provide almost three-dimensional outcrop of the channel bodies. In most cases the channel margins are not seen, but they can be shown to be several hundred metres wide, perpendicular to palaeoflow. An exception is the isolated sandstone body exposed at 177–181 m from the base of the section at Citadel Bastion (Fig. 4), which is clearly lenticular in shape. On Titan Nunatak (Fig. 5) exposure is more fragmented over the irregular topography of the nunatak; some channel bodies can be traced between the three sections of the nunatak, but others apparently pinch out over a few hundred metres between exposures. The continuous exposure along the western flank of Coal Nunatak (Fig. 7) allows individual beds and amalgamated channel-fill sandstone units in the lower 60 m to be traced for four kilometres along the length of the cliff face.

The fluvial channels in all of the section below the 60 m level at Coal Nunatak (Fig. 6) are therefore interpreted as the deposits of braided rivers. Some channels show limited lateral migration, whilst others, especially those in the lower part of Coal Nunatak, evidently spread laterally over a broad braidplain to deposit a sheet-like body (cf. Nemec, 1992).

In the upper part of the exposure at Coal Nunatak (above 60 m, Fig. 6), there is a distinct change in the geometry of the sandstone bodies (Fig. 8). Individual channel-fill bodies are lens-shaped and can be traced for a few tens to hundreds of metres laterally. They have aspect ratios of less than 15 : 1 (width : height) and are classified as ribbon bodies in schemes of fluvial sandstone body geometries (Friend, Slater & Williams, 1979; Friend, Hirst & Nichols, 1986). The margins of the sandstone lenses are generally not well exposed, but at KG. 4651 (Figs 3, 9) there is a distinct, low-angle erosion surface marking the contact between underlying thinly bedded sandstone and mudstone and channel-fill sandstone facies. Within the sandstone body several surfaces can be observed dipping parallel to the channel margin, and these are interpreted as lateral accretion surfaces formed by lateral migration of the river channel (Allen, 1965). This suggests that these ribbon sandstone bodies may have been the deposits of meandering rivers.

### 3.b. Coarse overbank facies

Interbedded with the channel-fill sandstone bodies lie sandstone and mudrock beds that have flat, non-erosive bases and sheet-like geometries. Individual beds are typically a few tens of centimetres thick, but may range up to 2 m in thickness. Carbonaceous debris, mostly leaves, is very abundant in these deposits, and both rootlet horizons and tree stumps are common. Approximately 50% of these overbank deposits are sandstone beds. The coarse facies which occur dominantly or exclusively in these overbank associations are $S_{gi}$, $S_{hl}$, $S_{xl}$ and $S_{fg}$ (Tables 1, 2). In addition, facies $S_{xb}$ and $S_u$, described in the context of channel-fill associations, also commonly occur and there are rare occurrences of facies $S_{mg}$ and $S_{cg}$ within the overbank associations.

#### *3.b.1. Facies $S_{gi}$: Inversely graded sandstone*

Beds of inversely graded, medium to coarse sandstone are uncommon within the studied section. They are up to a metre thick and are crudely to distinctly stratified with sharp bases and tops. A rootlet horizon occurs at the top of such a bed at Titan Nunatak (99 m up section) (Fig. 5).

#### *3.b.2. Facies $S_{hl}$: Horizontally laminated sandstone*

This facies of horizontally stratified coarse or medium sandstone occurs in beds between 0.7 and 2.0 m thick. In places the stratification is sharp and well defined, and in others it is very poorly displayed. The beds are sharp-based, but without evidence of erosion. Mudstone clasts and wisps of siltstone occur in these beds and woody plant debris is common.

#### *3.b.3. Facies $S_{xl}$: Ripple cross-laminated sandstone*

Beds of very fine- to medium-grained sandstone with ripple cross-lamination are commonly associated with horizontally laminated sandstone. The beds range in thickness from 0.1 to 1.2 m and in some cases the thicker beds show normal grading. Standing tree trunks occur associated with this facies (Fig. 6, 127 m).

#### *3.b.4. Facies $S_{fg}$: Medium–fine graded sandstone*

This facies occurs as beds of coarse or medium to fine, normally graded sandstone between 0.3 and 1.0 m thick. The bed bases are flat and non-erosive. The lower parts are trough cross-bedded and the upper parts ripple-cross-laminated or parallel-laminated. Plant debris is common in places.

#### *3.b.5. Interpretation of coarse overbank facies*

Sheets of horizontally stratified sandstone (facies $S_{hl}$) are the most abundant depositional units in the overbank facies association. Where the laminae are sharp and distinct, they are interpreted as the products of plane beds formed under upper-flow regime conditions; less well-marked laminations may have formed under slower flows in coarser sediment (Harms *et al.* 1975). The association of horizontally laminated sandstone with ripple-cross-laminated sandstone (Facies $S_{xl}$) is commonly found in crevasse splay deposits and overbank sheet bodies deposited on the proximal parts of floodplains (Guccione, 1993; Pizzuto, 1987). The inversely graded beds (Facies $S_{gi}$) may also be interpreted as crevasses splay deposits formed during the waxing stage of a flood event and the normally graded beds (Facies $S_{fg}$) during the waning stage. The presence of trough cross-bedded sandstone (Facies $S_{xb}$) in association with these other coarse overbank deposits indicates that flood currents had sufficient strength, depth and longevity on the floodplain to allow the formation and migration of dune bedforms. The apparently structureless sandstone beds (Facies $S_u$) may have either been rapidly deposited in the overbank environment or primary sedimentary structures may have been lost.

In exposures of the same facies in areas further to the north, structureless sandstones occur in units several metres thick which are apparently single event deposits (A. C. M. Moncrieff, unpub. data, 1989). These units contain standing trees that are up to 7 m tall buried within the sand.

### 3.c. Fine overbank facies

Mudrock and very fine sandstone facies (ZS, Z, $MS_f$, $M_d$: Tables 1, 2) occur throughout the succession, but are often poorly exposed because these less resistant lithologies do not form cliffs at any scale and the gentler slopes where they are thought to crop out are generally scree-covered. These fine-grained facies are therefore likely to be under-represented in the graphic logs through the exposures. If it is assumed that all the non-exposed parts of the section are fine-grained facies then at least one-third of the sediment body would consist of fine, overbank deposits.

#### *3.c.1. Facies ZS: Thinly bedded sandstone and siltstone*

Beds of dark grey, centimetre-bedded very fine sandstone and siltstone occur in units a few tens of centimetres thick. Horizontal lamination is common in both lithologies and ripple cross-lamination occurs in some sandstone beds. Carbonaceous debris is abundant.

#### *3.c.2. Facies Z: Siltstone*

Siltstone occurs in structureless or horizontally laminated beds 0.5 to 1.5 m thick. It is typically very dark,

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rich in carbonaceous debris with rootlets preserved in places.

*3.c.3. Facies $MS_f$: Fine sandstone and mudstone*

Very fine, fine and medium sandstone interbedded with siltstone and mudstone occurs in units between 0.1 and 0.8 m thick. Ripple cross-lamination occurs in places, and vertical cracks and rootlets provide evidence of soil formation.

*3.c.4. Facies $M_d$: Dark grey or black mudstone*

Homogeneous, sometimes cherty, dark mudstone occurs in beds 0.2 to 0.3 m thick. Plant debris is abundant, and there is evidence of soil development with common vertical fractures though the beds and preserved rootlets.

*3.c.5. Interpretation of fine overbank facies*

These fine-grained sediments are interpreted as deposits from suspension as flood waters in the overbank area reduced velocity (Guccione, 1993; Pizzuto, 1987) and formed static ponds. *In situ* tree stumps, rootlets and vertical cracks in the beds show that soils developed in these overbank fines.

**3.d. Marine associations**

Strata interpreted as deposits formed in a shallow marine environment occur in two parts of the section: the lower part of the exposure on the northern face of Citadel Bastion at KG. 4658 (the lower 118 m logged, Fig. 4) and between 156 m and 160 m in the Coal Nunatak section (Fig. 6).

*3.d.1. Facies $S_{xi}$: Stratified fine to medium and coarse sandstone*

Coarse, medium and fine-grained sandstone occurs in beds tens of centimetres to tens of metres thick, with thicker beds probably being amalgamated units. Bed bases are sharp to indistinct and are not erosional. Many of the beds show lamination which varies from sharp, fine laminae to indistinct horizontal to gently inclined stratification; dewatering structures are moderately common, disrupting the lamination. Some beds of this facies are structureless, possibly as a result of extensive dewatering. Plant debris occurs in some of the finer-grained beds.

*3.d.2. Facies $S_{xb}$: Cross-bedded coarse and very coarse sandstone*

Trough cross-beds with set thicknesses of 0.3 to 0.5 m occur in sandstone which is coarse, very coarse or slightly granular. The orientation of the cross-bedding is variable (Fig. 10a) with most sets indicating a south-westerly flow, but there are also cross-beds sets indicating flow to the northeast and east or southeast. Beds are generally flat-based and several metres thick.

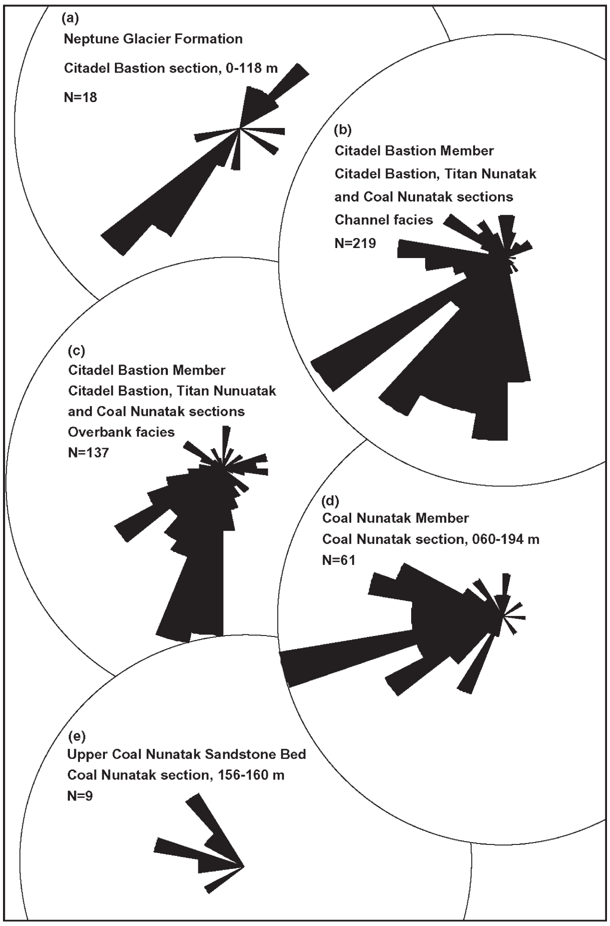


Figure 10. Rose diagrams of palaeocurrent data collected from Citadel Bastion, Titan and Coal nunataks. (a) Cross-bedding from shallow marine facies $S_{xb}$ of the Neptune Glacier Formation from the lower 118 m of section logged at Citadel Bastion (KG. 4658). (b) Cross-bedding from channel-fill sandstone facies in the Citadel Bastion Member at Citadel Bastion, Titan and Coal nunataks. (c) Cross-bedding and ripple cross-lamination from overbank sandstone facies in the Citadel Bastion Member. (d) Cross-bedding from channel-fill sandstone facies in the Coal Nunatak Member. (e) Cross-bedding from Upper Coal Nunatak Sandstone Bed (marine facies).

*3.d.3. Interpretation of facies $S_{xi}$ and $S_{xb}$*

These two facies occur interbedded in the lowest part of the section measured at Citadel Bastion (KG. 4658, 0–113 m, Fig. 4). This logged section represents only a small sample of many hundreds of metres of similar facies that occur stratigraphically below. No marine fossils were found in the logged section, nor was there any clear evidence of bioturbation. However, this association of facies is considered to have been deposited in a shallow marine setting, following the interpretation

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of previous authors (Kelly & Moncrieff, 1992; Moncrieff & Kelly, 1993). The bipolar palaeocurrent directions indicate reversing, probably tidal, currents, and absence of any of the indicators of a continental environment found in abundance higher in the stratigraphy (channelization of the coarser sandstone beds, palaeosols, rootlets and *in situ* tree trunks). The depositional environment is interpreted to be an upper shoreface setting with the development of shoals and bars built up and reworked by tidal currents (Johnson, 1977; Johnson & Baldwin, 1996).

*3.d.4. Facies $S_{xh}$: Inclined heterolithic stratified sandstone*

This facies occurs as a single unit of medium to very coarse sandstone, with centimetre-scale inclined stratification defined by dark, organic-rich partings. The thickness of the organic-rich laminae increases down the dip of the inclined strata, and in the same direction the thickness of the individual beds decreases and the grain size also decreases to medium sand. At the base of the unit the stratification is horizontal and some layers show ripple-cross-lamination. Up-dip along the stratification in the upper part of the unit, the layering angle increases to 30° and is in places oversteepened to vertical or even overturned. The coarsest sand occurs in the upper part of the unit.

This facies association only occurs between 156.1 and 159.9 m from the base of the total stratigraphic section measured at Coal Nunatak (Figs 6, 11). It crops out at the same level across the central and southern parts of the nunatak over a distance of 1.75 km between KG. 4651 and KG. 4654 (Fig. 3). In the north the direction of dip of the foresets is towards the west, whilst further south the dip is more northwesterly.

*3.d.5. Interpretation of facies $S_{xh}$*

With the exception of plant debris along the inclined strata, there are no fossils within this unit. However, there are a number of features that suggest this unit is shallow marine, rather than fluvial in origin. Firstly, the style of stratification is quite different from that seen in the fluvial facies above and below; the heterolithic character suggests a regular variation in the flow strength which may be indicative of tidal currents ('IHS' of Thomas *et al.* 1987). Secondly, there is an overall increase in grain size up through the unit, indicating that there was a decrease in flow strength down through the water body, a situation more likely in an open shelf setting than in a confined channel. Thirdly, the 3.8 m thick unit has an overall sheet-like geometry, with no evidence of channelization or scour at the base. A shallow marine origin is therefore considered the most likely for this facies, probably a tidally influenced upper shoreface setting as a linear tidal sand ridge (Mutti *et al.* 1985).

Oversteepening of the stratification in the upper part of the unit indicates that it was not lithified when it was subject to a flow which sheared the bed surface (Collinson & Thompson, 1982). The overlying bed is a cross-bedded sandstone deposited by a flow which is assumed to be fluvial in origin.

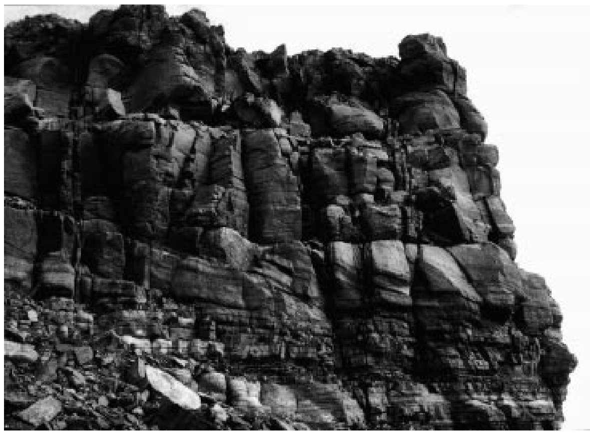

Figure 11. Large-scale heterolithic cross-stratification (facies $S_{xh}$) from the Upper Coal Nunatak Sandstone Bed at KG. 4654 on Coal Nunatak. Approximately 10 m of section are shown in this view from the north.

**3.e. Volcaniclastic facies**

All the sandstone facies in the southern nunataks contain volcanic lithic grains indicating a source area in the volcanic arc on the Antarctic Peninsula to the east (J. R. Browne, unpub. Ph.D. thesis, Univ. Exeter, 1996). Tuff and lapillistone beds interbedded with the sandstone and mudstone facies in the upper part of the Fossil Bluff Group indicate that there was contemporaneous volcanic activity during the period of continental sedimentation in this area.

*3.e.1. Facies V: Tuff*

A unit of medium- to fine-grained tuff 11.5 m thick occurs 525 m up the section at the south end of Citadel Bastion nunatak (KG. 4659) (Fig. 4). The lower two-thirds of the unit is a medium-grained, lithic, crystal tuff, now largely altered to zeolites but with relict pyroxene and feldspar crystals recognizable. The upper part is a finer, white pumiceous tuff. At 127.5 m on Coal Nunatak (Fig. 6) there is a 3.4 m thick unit of coarse tuff and lapillistone with volcanic lithic fragments up to 20 mm in diameter in a matrix of lithic and vitric ash. A paler, more pumiceous layer is again recognizable in the top metre of this unit.

*3.e.2. Interpretation of facies V*

The absence of any internal depositional structures or textural grading suggests that these tuff beds are the deposits of air falls of pyroclastic material. Plinian pyroclastic fall deposits are typically massive or stratified

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(Cas & Wright, 1987). The compositional change from a lithic-rich to a vitric-rich deposit upwards through the ash units may be a consequence of changes in the nature of material being erupted or the slower settling rates of pumiceous material from the ash cloud (Cas & Wright, 1987).

## 4. Stratigraphy

The deposits described form part of the previously defined Triton Point Member of the Neptune Glacier Formation which was originally described by Moncrieff & Kelly (1993) from a section at Triton Point (Fig. 1). The base was defined as the first bed with *in situ* vegetation (standing trees) and the top by the first appearance of marine fauna following the last fossil forest interval. At Triton Point the unit is no more than 75 m thick but it thickens rapidly southwards, cropping out on Pagoda and Phobos ridges (Fig. 1) (*c.* 600 m: Moncrieff & Kelly, 1993) and further south at Coal, Titan and Hyperion nunataks and Citadel Bastion (*c.* 900 m thick: this study). Based on the distinct facies associations within this unit we believe it is best raised to formation status as it is defined by a distinct, correlatable bounding surface at the base. The recognition of two distinct and separate styles of fluvial deposition within the unit allows two members to be defined, and a mappable bed is also recognized. The Triton Point Formation is formally defined and described in the Appendix along with the Citadel Bastion Member, the Coal Nunatak Member and the Upper Coal Nunatak Sandstone Bed.

The lower, Citadel Bastion Member is at least 700 m thick and is exposed on Citadel Bastion, Titan Nunatak and the lower part of Coal Nunatak. The association of coarse-grained overbank facies and channel-fill sandstone facies with sheet-like body geometries indicate that this member is made up of the deposits of a braided river/braidplain system. The Coal Nunatak Member is only exposed at its type locality as a 4 km long, 135 m thick unit of sandstones and mudstones. It is distinguished from the underlying Citadel Bastion Member by a higher proportion of mudrocks of the fine overbank facies association and ribbon sandstone body geometries. A meandering river environment is suggested for this unit. Within this upper member of the Triton Point Formation, a distinctive bed can be mapped across the upper parts of Coal Nunatak. This is referred to as the Upper Coal Nunatak Sandstone Bed and it comprises heterolithic cross-bedded sandstones of facies $S_{xh}$, interpreted as a shallow marine deposit.

## 5. Palaeocurrent analysis

Palaeocurrent measurements were obtained from all facies which showed cross-stratification at all scales (Figs 4, 5, 6). The data were grouped by stratigraphic unit and by depositional facies (Fig. 10). Palaeoflow indicators in the shallow marine facies in the Neptune Glacier Formation at the base of the logged section at Citadel Bastion show a clear bimodal, bipolar pattern which supports the interpretation of this unit as a tidal shoal deposit (Fig. 10a): the dominant currents were towards the southwest and northeast. Data from the Citadel Bastion Member of the Triton Point Formation from all three main study areas have been divided into sets from channel and overbank facies in Figure 10b and 10c respectively. Both sets show a strong cluster of directions in the southwest quadrant, although both include palaeoflow indicators in virtually all quadrants. In the Coal Nunatak Member (Fig. 10d) the mean palaeoflow direction in channel facies is towards the west, with a relatively small number of flow indicators towards other directions. The small data set from the Upper Coal Nunatak Sandstone Bed (Fig. 10f) suggests a west to northwest progradation direction.

There are records (A. C. M. Moncrieff, unpub. data, 1989) of palaeocurrent data from coeval fluvial channel and overbank deposits in the Triton Point Formation on Pagoda Ridge, Phobos Ridge and at Triton Point itself, all localities which lie further to the north (Fig. 1); Moncrieff concluded that there was a pattern of fluvial sediment transport towards the north and northwest. This indicates that there is a divergence of palaeoflow of 90° or more across the line of the Saturn Glacier, which lies between the northern area (A. C. M. Moncrieff, unpub. data, 1989) and the southern nunataks investigated in this study. Fluvial channels in the Triton Point Formation therefore show an approximately radial pattern of flow from a point in the volcanic arc to the east of Saturn Glacier.

## 6. Facies distributions and depositional setting

The facies associations and palaeocurrent data from the Citadel Bastion Member indicate a depositional environment in early Triton Point Formation times dominated by braided rivers flowing in a south to southwesterly direction. The thickness of the channel-fill facies suggests that these rivers may have been ten or more metres deep, and the lateral extent of the sandstone bodies they deposited suggests that they moved across the floodplain to form a broad braidplain environment (cf. Nemec, 1992). The overbank areas received influxes of coarse and fine sediment as sheet flows and crevasse splays, but were sufficiently stable to allow the formation of soils. The vegetation on these soils was dominated by coniferous plants (mainly podocarps) but with the Bennettitales, pteridophytes and liverworts, and to a lesser extent the angiosperms, also being important (Cantrill, 1995, 1996, 1997; Cantrill & Nichols, 1996; Falcon-Lang & Cantrill, 2000; Cantrill & Falcon-Lang, 2001). The source area for the fluvial detritus was the volcanic arc

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of the Antarctic Peninsula to the east, with continued volcanic activity on the arc providing some pyroclastic fall deposits to the area.

A change to a setting with more laterally confined, stable channels in later Triton Point Formation times is recorded in the Coal Nunatak Member, which has a fluvial architecture of isolated channel sandstone bodies. There are some indications that these river channels were meandering and the general palaeoflow is more towards the west. More distal areas of the floodplain developed forests of podocarpaceous conifers with an understorey of ferns and liverworts and rare Bennettitales (*Ptilophyllum* sp. 3). Araucarian conifers became an increasingly important component of the vegetation in this member where they formed open stands interspersed amongst communities of ferns (*Alamatus* and *Aculea*) (Cantrill, 1996). *Ginkgo* appears to be associated with channel margin sediments as does the herbaceous angiosperm *Hydrocotylophyllum alexanderi*. Volcanic activity continued to provide ash layers. An environment of continental deposition close to the shoreline in the Coal Nunatak Member is indicated by the presence of a single, heterolithic, cross-stratified unit, the Upper Coal Nunatak Sandstone Bed which is interpreted as a shallow marine, probably tidal, bar deposit.

In the Triton Point Formation exposures to the north of the Saturn Glacier, braided fluvial channels, coarse and fine overbank and airfall tuff deposits occur, but show a dramatic thinning from around 500 m immediately north of the Saturn Glacier on Pagoda and Phobos ridges to 75 m at Triton Point (A. C. M. Moncrieff, unpub. data, 1989). In addition to this thinning, the proportion of channel-fill deposits decreases northwards, and there is a reduction in maximum grain size from cobbles in the south to small pebbles in the north (A. C. M. Moncrieff, unpub. data, 1989). North of Triton Point there are no continental deposits in the Fossil Bluff Group and the Albian strata are entirely marine facies of the Neptune Glacier Formation (Kelly & Moncrieff, 1992). The overall geometry of the Triton Point Formation is therefore a wedge which thins northwards from at least 900 m to zero north of Triton Point over a distance of around 50 km.

## 7. Palaeoclimate indicators

The fluvial channel facies do not include any indicators of ephemeral flow conditions such as clay layers or evidence of desiccation within the channel-fill deposits (cf. Nichols, 1987). River flow is therefore assumed to have been perennial, but with episodes of high discharge which resulted in overbank flows capable of transporting coarse sand. Periods of stability on the floodplain between flood events were long enough for vegetation to colonize the overbank areas and for soils to develop. On the basis of this sedimentological evidence a relatively humid climate punctuated with high rainfall may be inferred. The change from braidplain deposition in the Citadel Bastion Member to meandering rivers in the Coal Nunatak Member may be associated with an increase in bank stability brought about by a reduced frequency of high-discharge overbank flooding events. It is therefore possible that this represents a minor change in rainfall characteristics, although a reduced depositional gradient may also account for this change in fluvial depositional style.

Qualitative variations in the plant content between members is difficult to interpret as compositional changes in the flora may be influenced by edaphic and hydrological factors rather than climatic change. Nevertheless, the braidplain deposits contain plants generally more xeric adapted (e.g. *Ptilophyllum*) or smaller leaved (e.g. *Ginkgo*) than those seen in the overlying meandering facies. The meandering facies generally have greater abundance of liverworts and ferns (that is, moisture loving forms). These differences may relate to taphonomic biases as the more delicate moisture loving taxa are less likely to survive transport and therefore less likely to be represented in the braidplain facies.

## 8. Base level fluctuations and tectonic implications

The abrupt change in facies at the base of the Triton Point Formation in the lower part of the section at Citadel Bastion indicates a base level fall. An erosion surface marks the base of a braided fluvial channel sandstone body, 5.7 m thick, which overlies a succession dominated by beds of cross-bedded sandstone (facies $S_{xi}$ and $S_{xb}$) which are interpreted as upper shoreface deposits (Fig. 4). The base level change is considered to be in the order of many tens of metres, as a smaller magnitude fall may have been expected to produce a shift to fluvial facies or a coastal plain setting, as seen at the top of the formation at Coal Nunatak (see below). It is noteworthy that the presence of rootlets in the beds below the erosion surface is evidence for subaerial conditions before incision by the fluvial channels. This suggests that uplift occurred and was followed by a period of plant colonization of the sediment surface before river channels incised in this area.

Within the 700 m succession of braidplain deposits which make up the Citadel Bastion Member the only evidence for base level fluctuations is a decrease in the mean thickness of channel-fill facies and an increase in the proportion of channels in the succession (Table 3). The former is not a significant change and may be the product of irregular distribution of channel belt deposits in a broad plain environment, but the increase in channel density up through the section may be attributed to a gradual relative base fall during the deposition of the Citadel Bastion Member (cf. Shanley & McCabe, 1993; Emery & Myers, 1996).

Table 3. Trends in channel thickness and proportions of channel and overbank facies in the Triton Point Formation

| Member | Location | Vertical interval (m) | Number of channels | T channel facies (m) | Mean T channels (m) | T over-bank facies (m) | T other facies (m) | % channels exposed | % channels (whole interval) |
|---|---|---|---|---|---|---|---|---|---|
| Coal Nunatak | Coal Nunatak | 135 | 9 | 36.3 | 4.03 | 32.6 | 7.7 | 47 | 27 |
| Citadel Bastion | All sections | 699 | 45 | 283.6 | 6.30 | 198.3 | 12.1 | 57 | 41 |
| Citadel Bastion | Coal Nunatak | 60 | 6 | 35.2 | 5.87 | 13.1 | 0 | 73 | 59 |
| Citadel Bastion | Titan Nunatak | 165 | 14 | 84 | 6.00 | 43.4 | 0 | 66 | 51 |
| Citadel Bastion | Citadel Bastion | 474 | 25 | 164.4 | 6.58 | 141.8 | 12.1 | 52 | 35 |

Note: 'T' is thickness of facies or channels in metres.

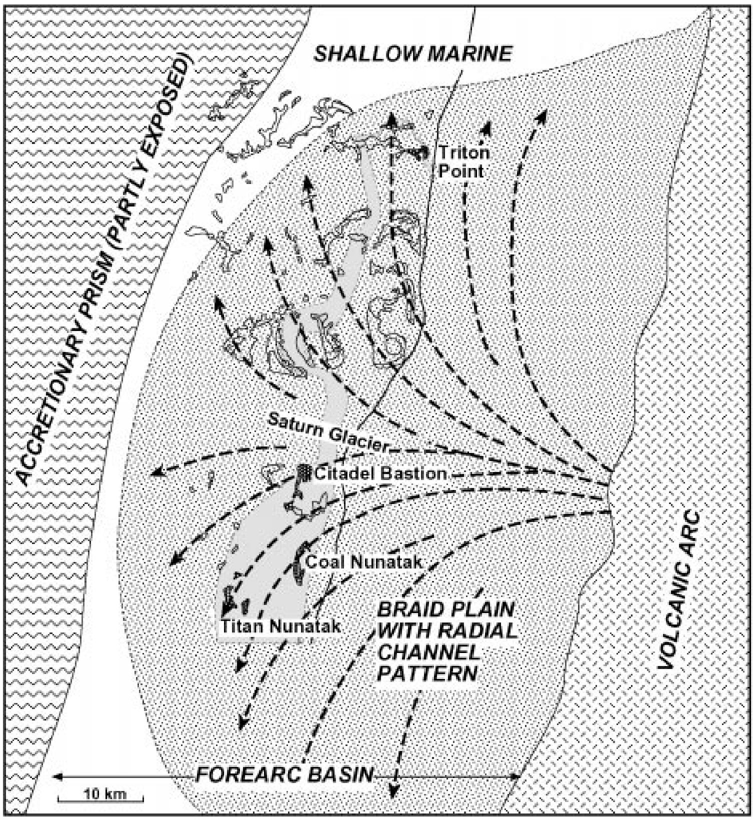


Figure 12. Palaeogeographic reconstruction of the southern part of the Fossil Bluff Group forearc basin at the time of deposition of the Triton Point Formation (Albian). Distribution patterns are based on palaeocurrent data from fluvial channel facies exposed to the south of Saturn Glacier (280 measurements, this study) and a smaller amount of data from exposures of the same stratigraphic unit north of Saturn Glacier (Moncrieff & Kelly, 1993, A. C. M. Moncrieff, unpub. data, 1989).

A reduction in discharge associated with a reduction in depositional gradient is indicated by the change in fluvial style from braidplain deposition to a confined, meandering channel environment in the Coal Nunatak Member (Schumm, 1977; Emery & Myers, 1996). A decrease in the percentage of channels (Table 3) suggests that a relative sea-level rise occurred at the transition from the Citadel Bastion Member to the Coal Nunatak Member (Shanley & McCabe, 1993). This trend is further indicated by the Upper Coal Nunatak Sandstone Bed which provides evidence for a marine incursion in southern Alexander Island during late Triton Point Formation times. The facies shift from channel and floodplain deposition to shallow marine conditions and back again suggests that the area was close to sea-level and the Coal Nunatak Member may be considered to be the deposits of a coastal floodplain setting.

## 9. Discussion and implications

The Fossil Bluff Group forearc basin fill has been the subject of several studies over the last twenty years. Early estimates of the thickness of sediments have been substantially revised and the Fossil Bluff Group is now believed to be in excess of 6800 m thick (Moncrieff & Kelly, 1993). Detailed field mapping has allowed the recognition of the earliest phases of basin development

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and the interplay between sedimentation and tectonics (Doubleday, Macdonald & Nell, 1993; Doubleday & Storey, 1998). Provenance studies of the main sequence indicate a typical arc unroofing sequence (Butterworth, 1985; P. J. Butterworth, unpub. Ph.D. thesis, Council for National Academic Awards, 1988; J. R. Browne, unpub. Ph.D. thesis, Univ. Exeter, 1996).

Tectonic processes have played a major role in sedimentation patterns within the forearc basin. Four main deformation events are recognized within the Antarctic Peninsula (Vaughan & Storey, 1997). Event 1, Late Triassic to Late Jurassic extension, is represented by a hiatus in sedimentation in Alexander Island (Macdonald & Butterworth, 1990). Event 2 in the Late Jurassic–Early Cretaceous broadly coincides with the development of large slump units of the Ablation Point Formation (Macdonald, Moncrieff & Butterworth, 1993; Doubleday & Storey, 1998). Deep marine sedimentation in the Fossil Bluff Group forearc basin continued during Early Cretaceous extension (event 3 of Vaughan & Storey, 1997).

An Antarctic Peninsula-wide compression event has been recognized by Vaughan & Storey (1997) as event 4 and has been inferred as the product of a mid-Cretaceous super-plume (Vaughan, 1995). This mid-Cretaceous deformation event coincides with the deposition of the Triton Point Formation. The abrupt relative sea-level fall at the base of the Citadel Bastion Member and increase in grain size of volcaniclastic detritus derived from the arc at this level may be attributed to regional uplift associated with this event. There is also evidence of uplift in the accretionary prism with an influx of thick conglomerates wholly derived from LeMay Group accretionary complex on the western margin of the basin in the Stephenson Nunatak Beds some 20 km to the west of the study area (J. R. Browne, unpub. Ph.D. thesis, Univ. Exeter, 1996). The bracketing marine faunas indicate that the uplift occurred in mid-Albian times (*c.* 100 Ma). Trends in the fluvial architecture and the return of marine conditions in the upper part of the Triton Point Formation indicate that a base level rise, possibly attributable to regional subsidence, occurred in the late Albian.

The thickness variations, facies distributions and palaeocurrent data from the Triton Point Formation can be used to reconstruct a palaeogeography of the forearc basin in the southern part of Alexander Island during Albian times (Fig. 12). A fan-shaped clast wedge of volcaniclastic detritus built out as a braid-plain delta from a point east of the Saturn Glacier, building out around 30 km to the north into a shallow marine basin, possibly reaching across to the outer ridge of the accretionary complex to the west, and spreading out at least 20 km to the south; the thickness of the fluvial units at the southern end of Alexander island suggests that the wedge built out much further to the south, but Titan Nunatak is the most southerly exposure of the Fossil Bluff Group.

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## Appendix. Definitions of stratigraphic units

### Triton Point Formation

*Nomenclature*. This formation takes its name from the Triton Point Member defined by Moncrieff & Kelly (1993).

*Type section*. The type section was defined by Moncrieff & Kelly (1993) from Triton Point, which lies at 71°41' S, 68°13' W.

*Distribution and thickness*. In the southern nunataks on Alexander Island 829 m of strata belonging to the Triton Point Formation have been measured. This is a minimum thickness and, on the basis of a geometric reconstruction, a thickness of at least 900 m is estimated. Beds equivalent to those exposed at Citadel Bastion, Titan and Coal nunataks have been reported at Triton Point, Pagoda Ridge and Phobos Ridge to the north of this area (Moncrieff & Kelly, 1993).

*Boundary relationships*. The base of the Triton Point Formation is marked by a sharp change from shallow marine sandy facies of the Neptune Glacier Formation. This is exposed on the northern face of Citadel Bastion and is described in the definition of the base of the Citadel Bastion Member below. The top of the formation is not seen in the southern nunataks, but has been described by Moncrieff & Kelly (1993) from Triton Point, Phobos Ridge and station KG. 4112 where the trough cross-bedded, tree-bearing, fluvial sandstones pass into well-sorted cross-bedded sandstone beds with bimodal current indicators.

*Lithology*. Beds of very fine to very coarse, rarely gravelly, sandstone (volcanic lithic arenite) and mudstone dominate the succession with subordinate beds of lithic and vitric tuff.

*Palaeontology and age*. The Triton Point Formation is dominated by terrestrial plant fossils, including large petrified tree trunks, and impressions of leaves and plant reproductive structures. Typically most plant fossils occur at the top of poorly developed soils as leaf litter layers. At least 56 species occur in the sequence and comprise liverworts (Cantrill, 1997), ferns (Cantrill, 1996), conifers (Falcon-Lang & Cantrill, 2000), angiosperms (Cantrill & Nichols, 1996) and other gymnosperms including Ginkgoales, Pentoxylales and rare Bennettitales. Small unioid bivalves occur at one locality (KG. 4656.4) indicating a freshwater environment. Plant fossils found within the Triton Point Formation are consistent with a mid-Cretaceous age, and the abundance of angiosperms indicates that the strata are most likely post-Aptian. This is consistent with invertebrate faunas in bracketing marine units that indicate a Late Albian age for the Triton Point Formation at Triton Point (Moncrieff & Kelly, 1993; Kelly & Moncrieff, 1992).

### Citadel Bastion Member

*Nomenclature*. This member is named from Citadel Bastion (68°32' W, 72°00' S).

*Type section*. The type section was measured at BAS stations KG. 4658, 4660 and 4659 on Citadel Bastion, at KG. 4661, 4657 and 4656 on Titan Nunatak and at KG. 4655 and 4654 on Coal Nunatak.

*Distribution and thickness*. A stratigraphic thickness of 476 m for this member was measured at Citadel Bastion. There is a gap in exposure cutting out an unknown vertical thickness between here and Titan Nunatak, where a further 164 m of section was measured. A further gap in the section lies between exposures at Titan Nunatak and those in the lower part of Coal Nunatak, where a further 60 m of this member is exposed. The total exposed thickness is thus 700 m, but this is a minimum estimate and does not take account of the section unexposed between the three areas of exposure.

*Boundary relationships*. The base of the Citadel Bastion Member is marked by a sharp change from shallow marine sandy facies of the Neptune Glacier Formation exposed on the northern face of Citadel Bastion and continental facies consisting of fluvial channel and overbank deposits including palaeosol horizons. At KG. 4658 a palaeosol horizon occurs beneath the deeply scoured base of a channel-fill unit; the base of the formation is taken as the base of the palaeosol at this locality because this marks the change to continental conditions.

*Lithology*. Beds of very fine to very coarse, rarely gravelly, sandstone (volcanic lithic arenite) and mudstone dominate the succession with beds of lithic and vitric tuff occurring at two horizons.

*Palaeontology*. Fossil wood and standing forests are widespread within this unit. Compositionally the flora is similar in many respects with the overlying Coal Nunatak Member. However, a number of taxa are distinct to this member. Large-leaved Bennettitales (*Ptilophyllum* sp.1 & 2) and *Taeniopteris* sp. 1 (a small leafed form), only occur within the Citadel Bastion Member.

### Coal Nunatak Member

*Nomenclature*. This member is named from Coal Nunatak (68°33' W, 72°04.5' S).

*Type section*. Coal Nunatak (BAS station KG. 4654).

*Distribution and thickness*. This member crops out along the western flank of Coal Nunatak over a lateral distance of 4 km; it is at least 135 m thick.

*Boundary relationships*. At 60 m from the base of the section at Coal Nunatak there is a change in the geometry of the sandstone bodies from a sheet like character seen in the Citadel Bastion Member to an architecture of isolated sandstone lenses in a dominantly fine-grained succession the Coal Nunatak Member. This change is defined as the boundary between these two members.

*Lithology*. Beds of very fine to very coarse, sandstone (volcanic lithic arenite) and mudstone dominate the succession with a bed of lithic and vitric tuff occurring at one horizon.

*Palaeontology and age*. The fossil flora of the Coal Nunatak Member is compositionally different from the underlying Citadel Bastion Member. Amongst the leaf fossils large leafed Bennettites are absent. The wood flora also shows compositional differences from the underlying unit (Falcon-Lang & Cantrill, 2000).

### Upper Coal Nunatak Sandstone Bed

*Nomenclature*. This bed is named from Coal Nunatak (68°33' W, 72°04.5' S).

*Type section*. Coal Nunatak (BAS stations KG. 4654 and 4651).

*Distribution and thickness*. This bed is exposed in the higher parts of the ridge which forms the crest of Coal Nunatak at KG. 4651 and 4654 where it is 4.1 m thick.

*Boundary relationships*. This bed occurs within the Coal Nunatak Member.

*Lithology*. The bed is a single heterolithic unit of coarse sandstone and mudstone.

*Palaeontology and age*. No fossils were recovered from this bed.

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