Mid Cretaceous fossil forests of Alexander Island, Antarctica

Jodie Howe

Submitted in accordance with the requirements for the degree of PhD
The University of Leeds
The School of Earth Sciences
August 2003

Acknowledgements

I would like to thank my primary supervisor Jane Francis (The University of Leeds) for continuous support and guidance throughout the research and preparation of this thesis and my secondary supervisor Dave Cantrill (British Antarctic Survey) for his help and advice. I am extremely grateful for the Ph.D. scholarship from the Natural Environmental Research Council and the additional funding and continual financial and academic support from the British Antarctic Survey.

The three months field work in Antarctica would not have been possible without the tremendous support of many at the British Antarctic Survey, including Crispin Day, my field assistant, the Air Support Unit for safe travel to and from my field area and all the staff at Rothera research base for their support. I would like to thank all of the staff at BAS in Cambridge for their support and advice, particularly Alistar Crame who was always helpful despite my endless questions, Mike Trabecki for the preparation of numerous thin section slides, Chris Gilbert and Pete Bucktrout for their help with photography and finally Prof. Chris Rapley for allowing me to be part of the Antarctic research at BAS.

I am extremely grateful for all the assistance I have received in laboratory work undertaken for this research, including, at The School of Earth Sciences, The University of Leeds, Eric Condliffe for his assistance with the SEM and Probe, Lesley Neve for help with XRD techniques, Neil Cundall for preparation of thin sections and Robert Maeshall for preperation of polished blocks. I would also like to thank Carol Booth (University of Sheffield) for assistance with vitrinite reflectance techniques and Geoff Whitely (The Department of Biology, University of Leeds) for helpful discussion on modern soils.

The quantitative statistical analysis that forms such a fundamental part of this research was made possible by the helpful advice and instruction by many staff at the Botanical Institute, Bergen University, Norway, with particular thanks to John Birks and Einar Heegaard for their endless patience and tutoring. I am very grateful for the Marie Curie Training Site Scholarship that supported this work in Norway.

I would also like to thank the Trans-Antarctic Association and the Palaeontological Association for additional funds to attend international conferences to present this work as well as the British Council for organising the Palaeoclimate Meeting in Paris, which provided useful discussion on climate change. Special thanks also to Steve McLoughlin (The University of Melbourne, Australia) for his guidance on modern Australian conifers and useful discussion. I am

extremely grateful to Robert Nichols (Paleocreations) for providing the visual display of the forests based on all the scientific evidence in this thesis in his fantastic painting of the forests shown on the front cover and discussed in Chapter 7. The original painting was commissioned by the British Antarctic Survey and is displayed at their headquarters in Cambridge.

Finally I would like to give special thanks to my parents, whom this is really all for. They have truly supported me both financially and emotionally throughout my PhD as well as in all the things I choose to do in life, without questions or judgement and for that I am extremely grateful.

Thank you

Jodie

Abstract

Spectacular fossil trees and shrubs are preserved within fossil soils in their original growth positions in mid Cretaceous rocks on Alexander Island, Antarctic Peninsula. These fossils indicate that diverse forest communities grew upon the floodplain areas of Alexander Island during the Albian at a palaeolatitude of 69-75 ° S. The fossil forests are preserved within the fluvial sediments of the Triton Point Formation of the Fossil Bluff Group, which represents the infill of a fore-arc basin.

The fluvial environment matured from a braided river system, with frequent floods and unstable channel banks, to a more mature meandering river system with more stable floodplain areas. Low energy floods preserved plants that grew on the river channel banks in fine muds and silts. Catastrophic floods occurred rarely, possibly as a result of volcanic activity upon the magmatic arc 200 km away. These high-energy floods covered floodplain areas in coarse sands, entombing trees. Well-drained mollisols formed on emergent surfaces becoming rich and fertile and supporting diverse forest communities.

The flora within the forests occurred as well structured communities that occupied different parts of the river floodplain. Open-woodland forests dominated by araucarian conifers, ferns and shrubs, occupied stable areas of the floodplain characterised by low-energy floods. Disturbance vegetation dominated by *Taeniopteris*, liverworts, angiosperms and ferns, occupied river channel banks where frequent floods provided fresh surfaces for these early colonising plants to flourish. Patch forest communities dominated by podocarp conifers, ginkgo trees, cycadophytes and ferns, grew on stable areas of the floodplain distal to the river channel. These mature climax forests were rarely disturbed by catastrophic floods.

Evidence from the palaeosols, sediments and fossil wood of Alexander Island suggest that the climate was warm, temperate, and semi-arid with seasonal precipitation and intermittent wet phases. In structure and composition the Alexander Island forest are very similar to the warm temperate rainforests of New Zealand which experience mean summer temperatures of 16-22 ° C and mean winter temperatures of 3-8 ° C. This study and other palaeobotanical data suggests that the Alexander Island forests are likely to have grown under similar temperatures.

Table of contents

Chapter 1 Introduction **Page**

Chapter 2 Sedimentology **Pages**

Chapter 3 Palaeosols **Pages**

Chapter 4 Fossil plant and fossil tree distribution on forest horizons **Pages**

Chapter 5 Palaeobotany **Pages**

Chapter 6 Quantitative statistical analysis of fossil plant data Pages

Chapter 7 Discussion Pages

List of tables and figures

Chapter 1 Introduction **Pages**

Chapter 2 Sedimentology **Pages**

Chapter 3 Palaeosols **Pages**

Chapter 4 Fossil plant and fossil tree distribution on forests horizons **Pages**

Chapter 5 Palaeobotany **Pages**

Chapter 6 Quantitative statistical analysis of fossil plant data **Pages**

Chapter 7 Discussion **Pages**

Appendix **Pages**

Appendix 2 – Sedimentology

Appendix 3 – Palaeosols

Appendix 4 – Fossil plant and fossil tree distributions on forests horizons

Appendix 6 – Quantitative analysis of fossil plant data

Chapter 1 Introduction

1.1 Introduction

Cretaceous forest floras have been recorded from high latitudes throughout the northern and southern hemispheres. Cretaceous floras grew in areas of Australia, New Zealand and Antarctica at palaeolatitudes of 70-85 ° S and similar floras of Alaska, Asia and Russia grew at palaeolatitudes up to 85 ° N. At this time conifers with understory vegetation of ferns, shrubby and herbaceous plants, liverworts and horsetails dominated the forest communities, with angiosperms becoming more dominant towards the end of the Cretaceous.

These diverse floras were able to flourish at high-latitudes due to the relative warmth of the Cretaceous climate, with high latitudes in particular being much warmer than they are today. Mean annual temperature estimates for the Antarctic, for example, during the Albian are between 10 and 20 ° C (Rees & Smellie 1989; Parrish *et al.* 1998). It is believed that polar forest growth would be possible today if the ambient temperatures were sufficiently raised above their present level to levels that may have existed during the Cretaceous. The other factors required for tree growth at polar latitudes are all within the scope of adaptations such as photoperiodic ecotypes, higher rates of cambial activity during the summer growing season and an appropriate crown structure to optimally intercept the solar radiation from low angles of elevation (Chaloner & Creber 1989).

Polar forests give crucial information about past polar climates allowing a unique snap-shot of the environment rather than a time-averaged parameter, such as the sediments which can sometimes be averaged over millions of years (Spicer *et al.* 2002). Past polar climates are important to study, as they are fundamental to global atmospheric and oceanic conditions; thus understanding the climatic conditions at the poles is a necessary part of understanding the entire global climate system, in the past, present and future. High-latitude Cretaceous forests are of particular importance as they represent vegetation growing under a greenhouse climate and so their study provides a better understanding of how the modern flora may cope with greenhouse conditions in the future. The study of high-latitude forests also provides vital palaeoclimatic data that is needed to further calibrate and improve modern computer climate models, which are used to predict climate change of the future.

The mid Cretaceous fossil forests of Alexander Island, Antarctica are an example of *in situ* high-latitude forests that grew in the Antarctic during a period of increased global warmth. These forests grew at a palaeolatitude of 69-75 ° S during the Albian period (Lawver *et al.* 1985) and were composed of a diverse flora of conifers, ferns, angiosperms and other small shrubs and herbs growing on various parts of a river floodplain. Frequent flooding of the river levees inundated the forest floor with sediment preserving the trees in upright positions and the plants in their growth positions on the forest floor.

Although previous work on these forests has examined the composition of the flora (such as Jefferson 1982a & b; Falcon-Lang *et al.* 2001) and sediments (Nichols & Cantrill 2002) there are many questions that have as yet been unanswered: What was the palaeoenvironment in which these plants and trees grew? What was the nature of the floods that covered them with sediment and how frequently did they occur? What can the fossil soils in which these plants grew tell us about the environment and climate? What are the relationships between different plant types and did they form specific plant communities? Where did the different plant types grow on the floodplain and are there any relationships between the fossil types that occur and the lithology? The aim of this thesis is to investigate these mid Cretaceous fossil forests as an example of high-latitude forests, answering questions such as those above to try and understand their palaeoecology and palaeoenvironment.

1.2 Tectonic setting

Alexander Island is located at 70° S 70° W off the west coast of the Antarctic Peninsula (Figure 1.1). The Peninsula is one of three crustal blocks (along with the Ellsworth Mountains and Thurston Island) that make up West Antarctica. West Antarctic formed part of the super-continent of Gondwana until the Middle Jurassic when it migrated southwards to the polar position it occupies today.

Reconstructions of the palaeogeography of the Southern Hemisphere during the Cretaceous place Alexander Island at ~ 69-75 ° during the Albian (Lawver *et al.* 1985; Smith *et al.* 1994; Figure 1.2) although recent age data from Palmer Land suggest a palaeolatitude closer to the lower estimate may be more likely (Vaughn *et al.* 2002).

The Antarctic Peninsula is largely composed of Late Jurassic to Early Cretaceous calc-alkaline igneous rocks and fore-arc and back-arc volcaniclastic sedimentary sequences (Figure 1.3; Suarez 1976). These were formed by the subduction of the Pacific and proto-Pacific oceanic crust beneath the west coast of the Antarctic Peninsula. Subduction of the sea floor beneath the Antarctic Peninsula and around other margins of the South Pacific has been continuous since the Palaeozoic or early Mesozoic. Deformed metasediments of the LeMay Group are the oldest rocks to crop out on Alexander Island (Figure 1.3). These were formed prior to the break–up of Gondwana during the Middle Jurassic, when West Antarctica was part of the super-continent (Smellie 1981).

Figure 1.1 The Antarctic continent with Alexander Island located off the west coast of the Antarctic Peninsula.

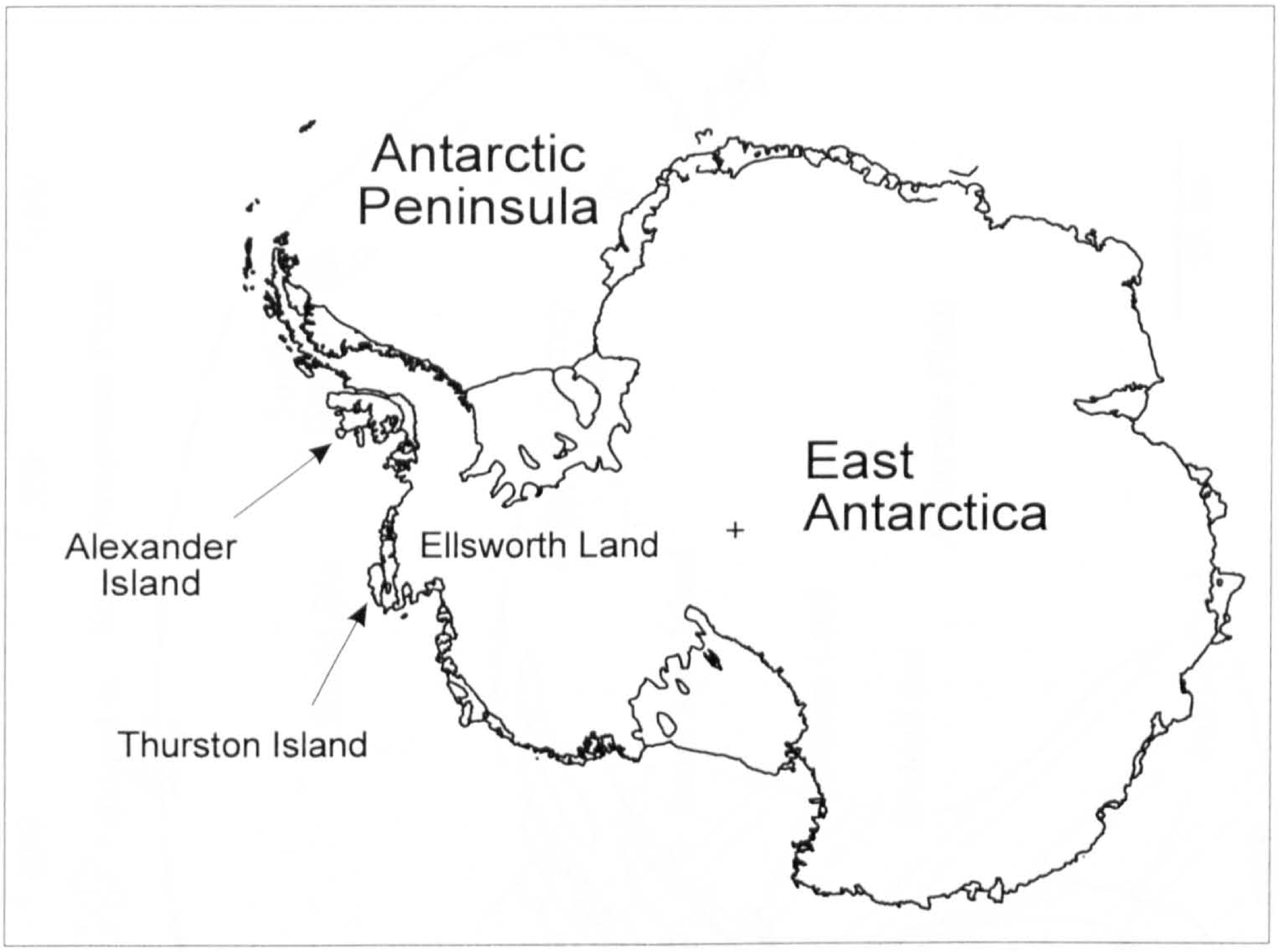


Figure 1.2 Reconstruction of the palaeogeography of the Southern Hemisphere during the Early Cretaceous (119 Ma: after Lawver *et al.* 1985), showing Alexander Island at a palaeolatitude close to 70°S.

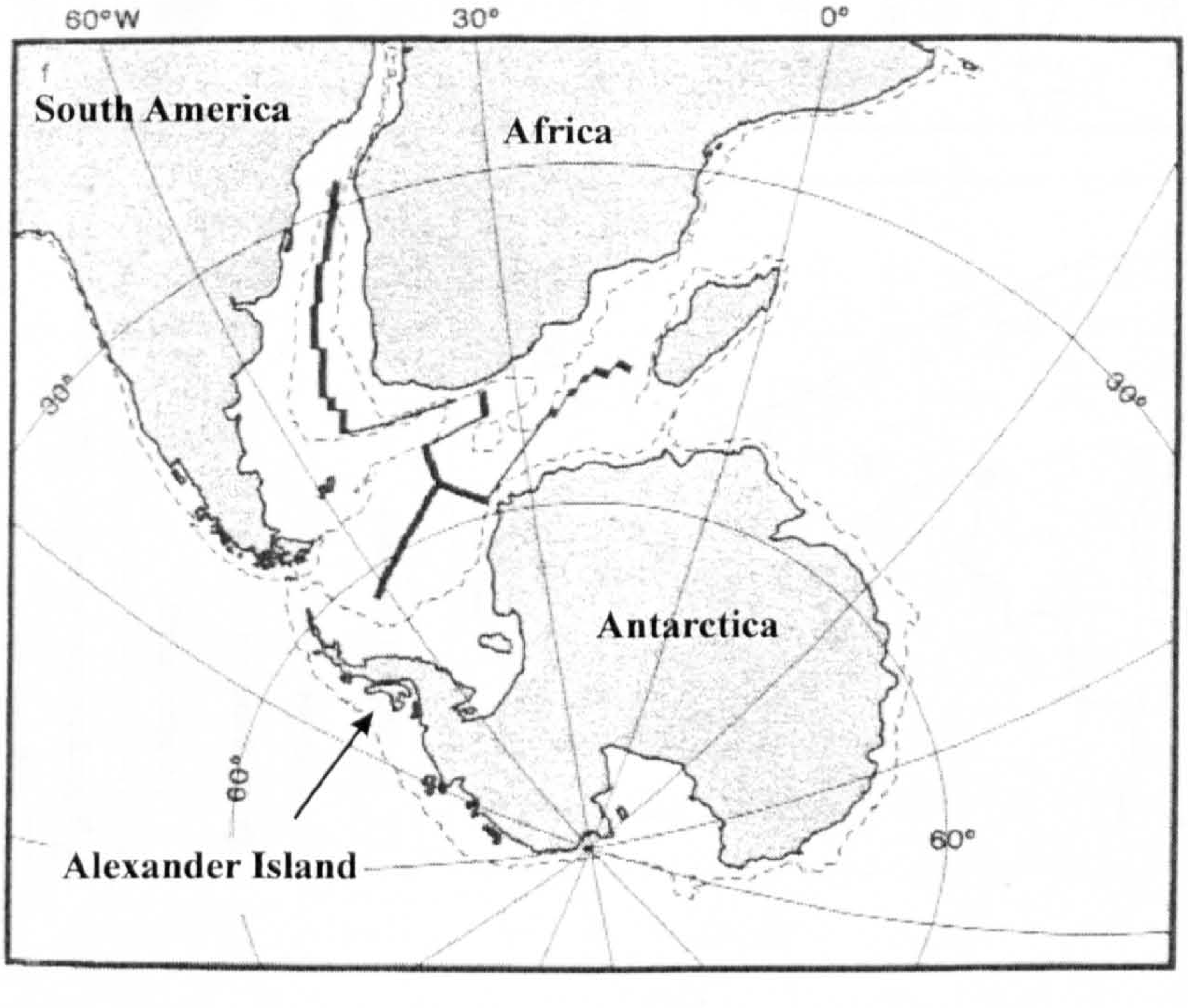
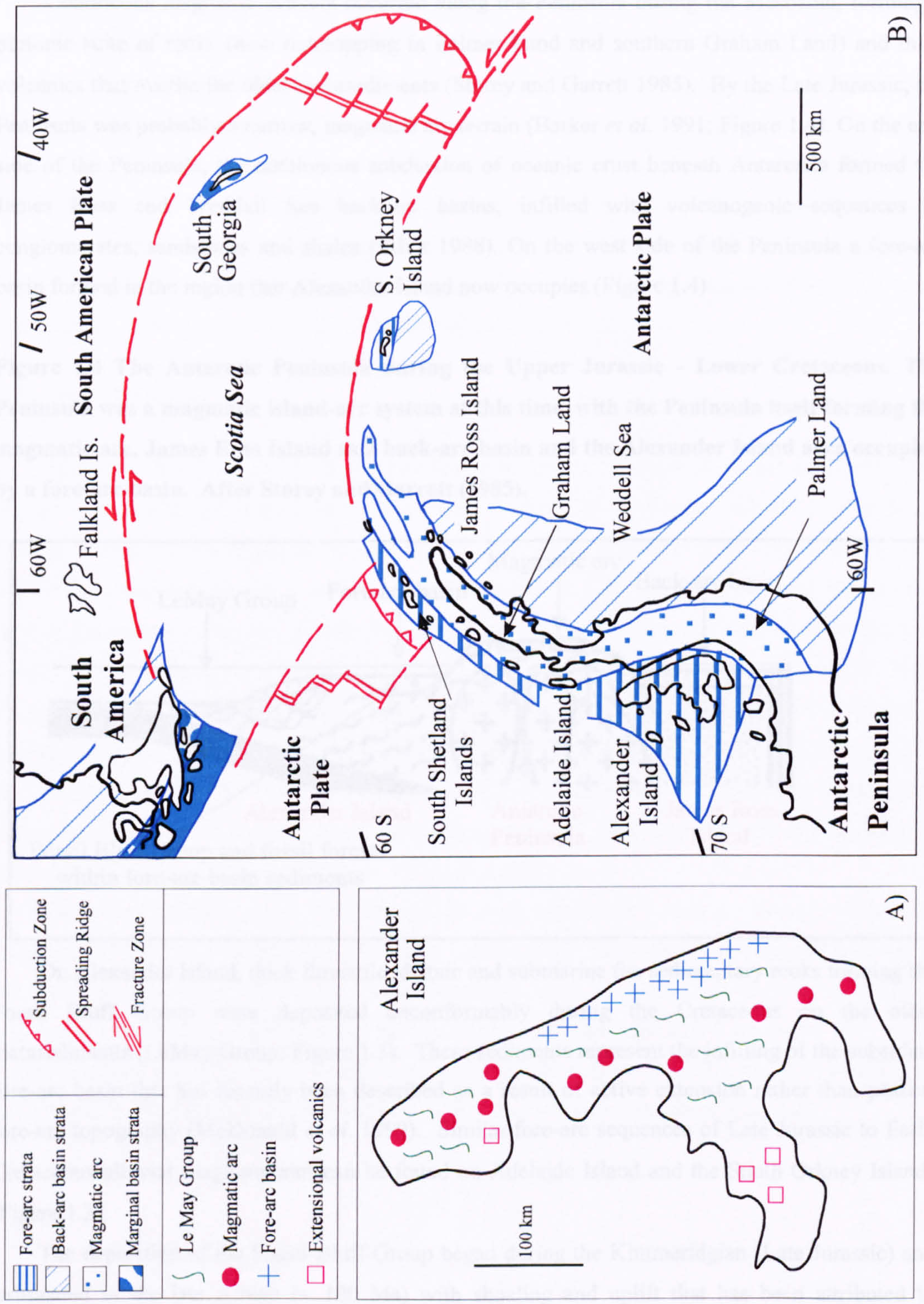
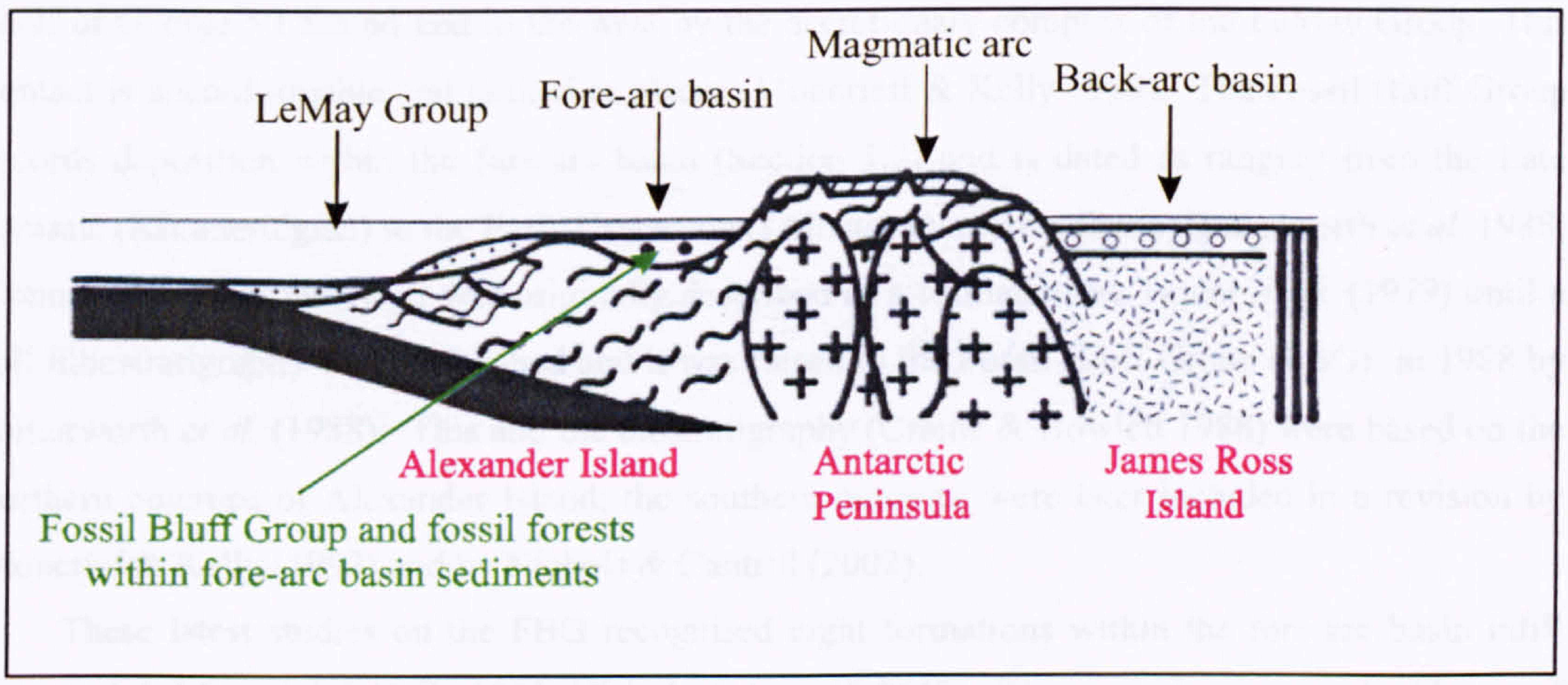


Figure 1.3 A) Tectonic components of Alexander Island. B) Tectonics of the Antarctic Peninsula and surrounding area. After Storey & Garrett (1985).



Continuous magmatic activity occurred along the Peninsula during the Mesozoic, forming a plutonic suite of rocks (now outcropping in Palmer Land and southern Graham Land) and thick volcanics that overlie the older metasediments (Storey and Garrett 1985). By the Late Jurassic, the Peninsula was probably a narrow, magmatic arc terrain (Barker *et al.* 1991; Figure 1.4). On the east side of the Peninsula, the continuous subduction of oceanic crust beneath Antarctica formed the James Ross and Weddall Sea back-arc basins, infilled with volcanogenic sequences of conglomerates, sandstones and shales (Elliot 1988). On the west side of the Peninsula a fore-arc basin formed in the region that Alexander Island now occupies (Figure 1.4).

Figure 1.4 The Antarctic Peninsula during the Upper Jurassic - Lower Cretaceous. The Peninsula was a magmatic island-arc system at this time, with the Peninsula itself forming the magmatic arc, James Ross Island as a back-arc basin and the Alexander Island area occupied by a fore-arc basin. After Storey and Garrett (1985).



On Alexander Island, thick fluviatile, deltaic and submarine fan sedimentary rocks forming the Fossil Bluff Group were deposited unconformably during the Cretaceous on the older metasediments (LeMay Group; Figure 1.3). These sediments represent the infilling of the subsiding fore-arc basin that has recently been described as a result of active extension rather than passive fore-arc topography (McDonald *et al.* 1999). Similar fore-arc sequences of Late Jurassic to Early Cretaceous alluvial fanglomerates can be found on Adelaide Island and the South Orkney Islands (Figure 1.3).

The deposition of the Fossil Bluff Group began during the Kimmeridgian (Late Jurassic) and terminated in the late Albian (~ 100 Ma) with shoaling and uplift that has been attributed to increased ridge-push force at subduction zones triggered by the mid-Cretaceous super plume

(Vaughn 1995). Basin inversion occurred during deposition of the youngest parts of the Fossil Bluff Group and corresponds to a mid-Cretaceous compression event that is thought to be related to the super plume (Doubleday & Storey 1998). This compressional regime also caused the folding of fore-arc sequences of Alexander Island and back-arc volcanic sequences of eastern Palmer Land (Barker *et al.* 1991). From the Late Cretaceous to early Tertiary, magmatic arc activity on the Peninsula migrated westwards onto Alexander Island and formed a volcanic /plutonic belt running through the area that is now the interior of the island (Figure 1.3; Burn 1981). Following the peak of volcanic activity, an extensional regime occurred, forming Tertiary extensional volcanic rocks that outcrop on the western areas of Alexander Island (Figure 1.3).

1.3 Stratigraphy

The Fossil Bluff Group, which contains the fossil forests, outcrops on Alexander Island along the east coast in a strip 250 km long by 30 km wide (Figure 1.5). It is bounded to the east by the ice shelf of George VI Sound and to the west by the accretionary complex of the LeMay Group. This contact is unconformable and faulted in places (Moncrieff & Kelly 1993). The Fossil Bluff Group records deposition within the fore-arc basin (Section 1.2) and is dated as ranging from the Late Jurassic (Kimmeridgian) to the Early Cretaceous (Albian) by marine fauna (Butterworth *et al.* 1988; Crame & Howlett 1988). It was originally described as a formation by Taylor *et al.* (1979) until a full lithostratigraphy was established and it was raised to the Fossil Bluff Group (FBG) in 1988 by Butterworth *et al.* (1988). This and the biostratigraphy (Crame & Howlett 1988) were based on the northern outcrops of Alexander Island; the southern outcrops were later included in a revision by Moncrief & Kelly (1993) and by Nichols & Cantrill (2002).

These latest studies on the FBG recognised eight formations within the fore-arc basin infill (Figure 1.6; Moncrief & Kelly 1993; Nichols & Cantrill 2002). This study is concerned with one of the youngest formations, the Triton Point Formation, as it is within the fluviatile and deltaic sedimentary rocks of this formation that the fossil forests of Alexander Island are found. The Triton Point Formation was raised from member status by Nichols & Cantrill (2002) who also erected two new members, the Citadel Bastion Member and the Coal Nunatak Member (Figure 1.6).

Figure 1.5 A) The location of the Fossil Bluff Group (red shaded area) on Alexander Island. B) A map to show the outcrop of the Triton Point Formation (shaded area) on Alexander Island and all areas mentioned in the text.

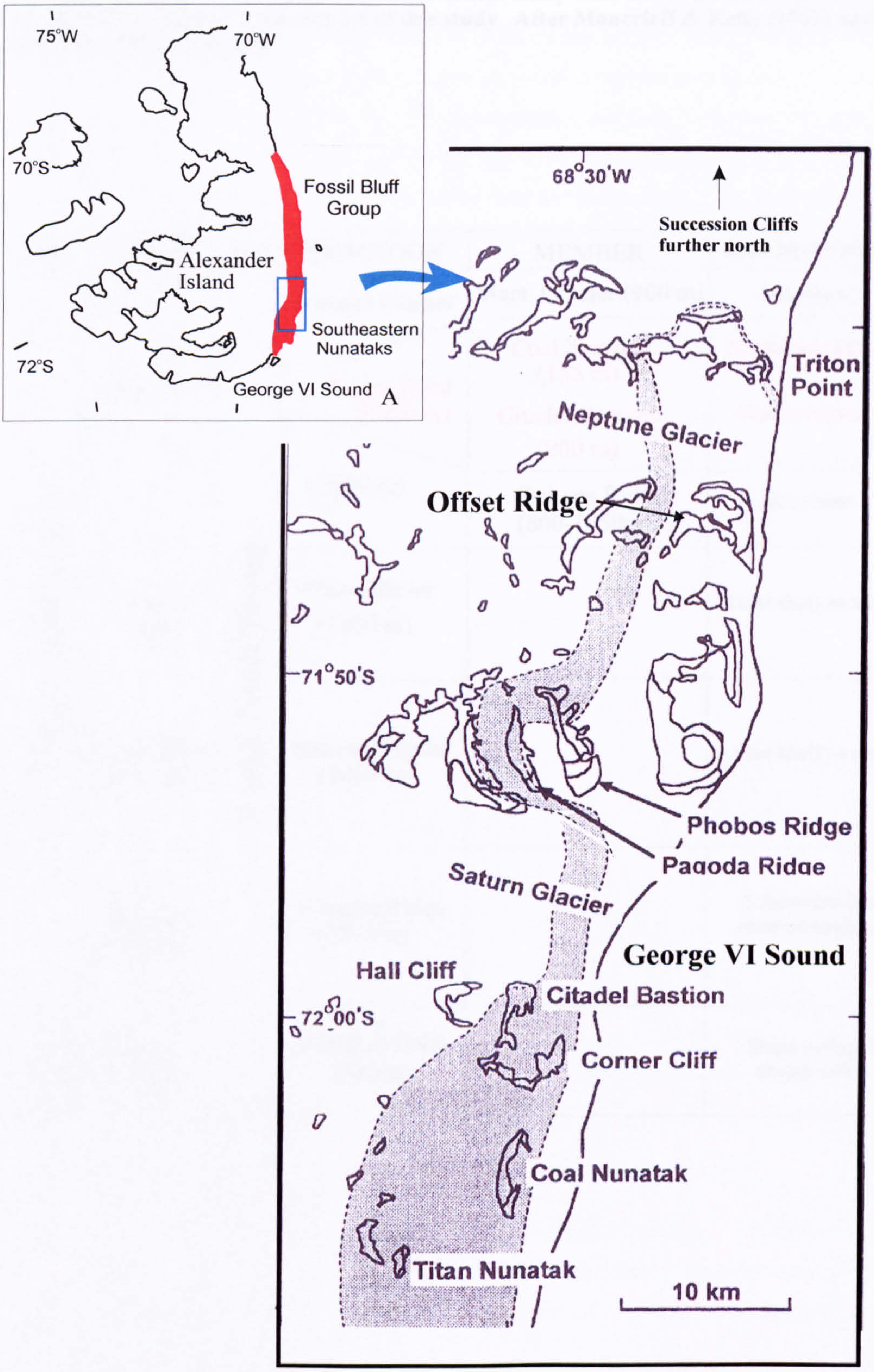
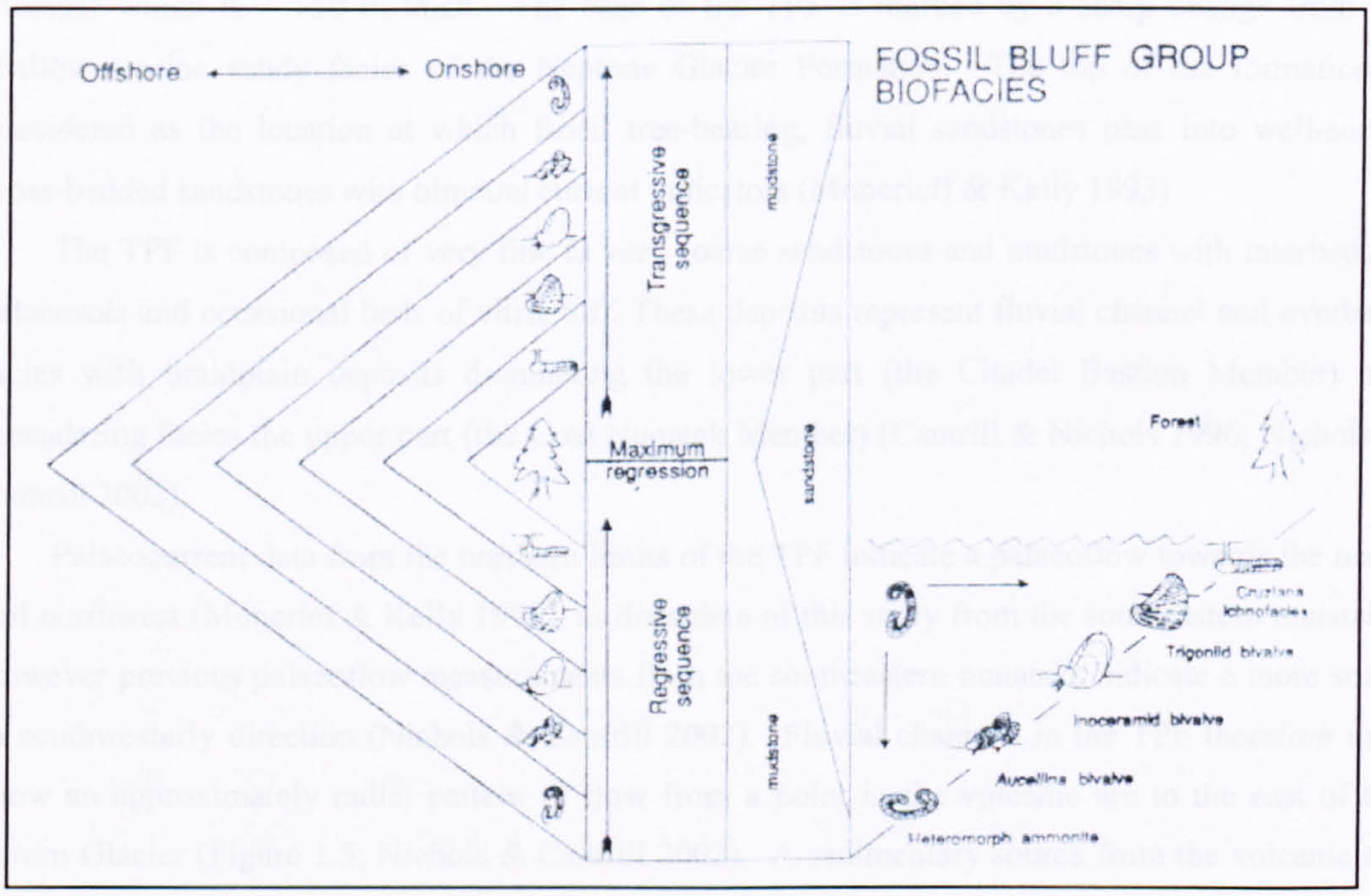


Figure 1.6 Lithostratigraphy of the Fossil Bluff Group, Alexander Island, Antarctica. The red labels identify the sediments discussed in this study with thickness estimates those calculated in Chapter 2, Section 2.6 of this study. After Moncrieff & Kelly (1993) and Nichols & Cantrill (2002).

AGE	STAGE	Gp	FORMATION	MEMBER	ENVIRONMENT
Early Cretaceous	Albian	Fossil Bluff Group	Neptune Glacier (2200 m)	Mars Glacier (900 m)	Nearshore
			Triton Point (1050 m)	Coal Nunatak (155 m)	Fluvial meandering
				Citadel Bastion (900 m)	Fluvial braided
				Deimos Ridge (800-1050m)	Nearshore
	Aptian - Albian		Pluto Glacier (1400 m)		Tidal shallow shelf
	Valanginian - Barremian		Spartan Glacier (1000 m)		Outer shelf to slope
	Tithonian-Berriasian		Himalia Ridge (2200 m)		Submarine fan channel complex
Late Jurassic	Kimmeridgian		Ablation Point (440 m)		Slope collapse slump units

The Triton Point Formation (TPF) is a wedge of sediment that occurs within the marine units of the Neptune Glacier Formation and together they represent a regressive–transgressive cycle from marine to near shore tidal to fluviatile (TPF) environments and then back to marine again. This cycle is marked by lithofacies and biofacies (Kelly 1993) displaying symmetrically paired belts (Figure 1.7). This pattern of symmetrical facies belts has been proposed by Moncrief and Kelly (1993) as a basic model for 'tectonoeustatic' cycles in rapidly subsiding basins.

Figure 1.7 Biofacies of the Neptune Glacier and Triton Point formations. The biofacies identify a regressive-transgressive sequence from off-shore marine (identified by the presence of heteromorph ammonites) through marginal marine (identified by *Aucellina* bivalves to Cruziana ichnofacies) to terrestrial delta top (identified by the presence of fossil trees). The Triton Point Formation represents the maximum stage of regression with the maximum ratio of sandstone to mudstone deposition. After Kelly (1993).



1.3.1 Age Constraints

The Triton Point Formation (TPF) was originally dated as Barremian – Albian from the fossil flora within the forests of the southeastern nunataks (Jefferson 1982a). This date was later revised by Kelly & Moncrieff (1992) using age-significant marine molluscan faunas found directly above and below the fossil forests. The upper sections of the Pluto Glacier Formation below the TPF (Figure 1.6) contain ammonites including *Hypophylloceras* sp., belemnites including *Dimitobelus diptychus* and bivalves including *Birostrina concentrica* gp., which suggest a Late Albian age. Above the TPF, the Mars Glacier Member contains the gastropod ?*Vanikoropsis* and the belemnite *Dimitobelus*, which also suggest a Late Albian age (Kelly & Moncrieff 1992). Thus the age of the TPF and indeed the fossil forests is Late Albian because that is the age of the overlying and underlying marine macrofaunas. Unfortunately palynological samples have proven to be barren due to burial diagenesis or thermal alteration (Kelly & Moncrieff 1992).

1.3.2 Description of the Triton Point Formation

The Triton Point Formation (TPF) thickens southward from ~ 100 m on part of Offset Ridge (the northernmost outcrop; Figure 1.5) to ~ 1050 m at the southern limit of exposure (this study). It contains two members: the Citadel Bastion Member which is ~ 900 m thick and the Coal Nunatak Member which is ~ 150 m thick. The base of the TPF is marked by a sharp change from the shallow marine sandy facies of the Neptune Glacier Formation. The top of the formation is considered as the location at which fossil tree-bearing, fluvial sandstones pass into well-sorted cross-bedded sandstones with bimodal current indicators (Moncrieff & Kelly 1993)

The TPF is composed of very fine to very coarse sandstones and mudstones with interbedded palaeosols and occasional beds of vitric tuff. These deposits represent fluvial channel and overbank facies with braidplain deposits dominating the lower part (the Citadel Bastion Member) and meandering facies the upper part (the Coal Nunatak Member) (Cantrill & Nichols 1996; Nichols & Cantrill 2002).

Palaeocurrent data from the northern limits of the TPF indicate a palaeoflow towards the north and northwest (Moncrief & Kelly 1993), as does data of this study from the southeastern nunataks. However previous palaeoflow measurements from the southeastern nunataks indicate a more south to southwesterly direction (Nichols & Cantrill 2002). Fluvial channels in the TPF therefore may show an approximately radial pattern of flow from a point in the volcanic arc to the east of the Saturn Glacier (Figure 1.5; Nichols & Cantrill 2002). A sedimentary source from the volcanic arc is also indicated from the petrography and whole rock chemistry of the sandstones within the TPF, which show calc-alkaline affinities derived from the magmatic arc (Browne 1996).

1.4 Previous work on the fossil forests of Alexander Island

Plant remains have been known from the Fossil Bluff Group on Alexander Island for over 60 years (Fleming 1938). Horne (1968, 1969) first described plant material within the southeastern nunataks of Alexander Island, where he found a large amount of macerated and carbonised plant remains and lithified fragments of fossil wood within cross-laminated sandstones with thin argillites and conglomerates, which he described as deltaic sequences.

However the first detailed study of the fossil forests of Alexander Island was by Tim Jefferson for his PhD thesis (Jefferson 1981). Jefferson worked on the Triton Point Formation rocks from Triton Point in the north to the Titan Nunataks in the south. He described the rocks as non-marine cross-bedded sandstones, siltstones, conglomerate, marine mudstones and primary volcanic deposits, which he ultimately interpreted as a delta top/alluvial plain environment with marine incursions. He considered vegetated, inter-distributary areas to have been inundated by sediment from crevasse splays or overbank flooding preserving fossil plant and tree remains.

Jefferson (1981, 1982a) recognised 'poorly developed' palaeosols amongst the sandstones of the Triton Point Formation, describing them as poor immature soils with no soil profiles and no differentiation into horizons. He described a moderately diverse forest of conifers, cycadophytes, ginkgophytes and ferns that were preserved as compression fossils with little cuticle material or in the case of the fossil wood, silicified (Jefferson 1982a, b). The dominant leaves were large and entire margined and this, along with the wood anatomy, he attributed to warm equable conditions with abundant light through a long growing season, similar to austral, warm-temperate rainforests today (Jefferson 1983).

Since the early studies of Jefferson (1981, 1982a, b, 1983) the sediments have been re-described. The deposits of Citadel Bastion, Titan Nunataks and the lower units of Coal Nunatak (Citadel Bastion Member) have been described as those of a braided river system which evolved into a lower energy river system, probably meandering, which formed the upper units of Coal Nunatak (Coal Nunatak Member; Cantrill & Nichols 1996; Nichols & Cantrill 2002). Both these river systems had weak banks that led to periodic flooding and preservation of the vegetation that grew on the floodplain.

The wood has been extensively studied and identified as consisting of five different form taxa belonging to the Araucariaceae, Podocarpaceae, and Taxodiaceae families (Falcon-Lang & Cantrill 2000). These studies have also shown that although some species were deciduous in the Cretaceous forests (ginkgo, taxodioid, pentoxylaleans) the majority were evergreen (Falcon-Lang & Cantrill

2001a). Extensive work has been done on the species that occur within the forests by Falcon-Lang *et al.* (2001), who describe a forest made up of a conifer canopy (Falcon-Lang & Cantrill 2001b), with an understorey of ferns (Cantrill 1995, 1996), angiosperms (Cantrill & Nichols 1996) and liverworts (Cantrill 1997a).

1.5 Previous quantitative palaeoecological studies

Most fossil plant studies are concerned with floral composition, determined through fossil plant material of allochthonous plant assemblages. The quantitative study presented here of the *in situ* fossil forests of Alexander Island allows a unique look into not only what grew within the Cretaceous forests but also where the different plants grew and their relationship with each other. The benefits of using quantitative statistical techniques for palaeoecological data have long been recognised (e.g. Shi 1993) but fossil flora studies using these techniques are still rare, possibly due to the rarity of *in situ* fossil plant material.

Ordination statistical techniques similar to those used in this study were used to determine the presence of plant communities within the Carboniferous Secor Coal of Oklahoma (Dimichele *et al.* 1991). The plant material was preserved as fragments within coal balls and allochthonous compression fossils but two distinct plant communities were identified through the statistical method. A similar study based on quadrat sampling of fossil plant material within the Black Creek and Bear Creek Coals used cluster analysis to establish plant groupings (Pryor & Gastaldo 2000). On a larger scale multivariate statistical techniques have been used to try and determine the phytogeography of different fossil plant types across Asia and China (Spicer *et al.* 1993). All of these studies, however, deal with allochthonous fossil plant material and therefore cannot use statistical techniques in the way that they have been used to recreate fossil plant communities within the Cretaceous forests of Alexander Island.

More recently statistical techniques have been used on palaeobotanical data for palaeoclimatic studies (Wolfe 1993; Spicer *et al.* 2002; Kennedy *et al.* 2002). The Climate Analysis Multivariate Program or CLAMP, is a popular technique used to determine temperature estimates from angiosperm leaves by comparing modern leaf characteristics and modern climate information through multivariate analysis and then adding fossil plants to the data set to see how they compare. The rarity of angiosperms within the Albian forest flora, however, prevents the use of this technique within this study.

1.6 Contents of Thesis

The aims of this thesis are to determine the palaeoenvironments of the mid-Cretaceous fossil forests of Alexander Island, Antarctica, using a combination of sedimentology, palaeosol analysis, quantitative palaeoecological analysis, as well as floral composition and biodiversity of the forests, wood anatomy and analysis of forest dynamics such as tree density. This research is based on data collected by the author during a four-month field season on Alexander Island during the austral summer of 1999/2000, and on fossils collected during two previous field seasons from the same field area (Jefferson 1979/1980 and Cantrill 1992/1993), now stored at the British Antarctic Survey in Cambridge.

Chapter 2 looks at the sedimentary setting of the southeastern nunataks of Alexander Island to establish the palaeoenvironments in which the fossil forests grew, as well as information on the frequencies and nature of the flooding events that inundated the forests.

The palaeosols in which the fossil plants and trees grew are analysed fully for the first time in Chapter 3. These palaeosols are exceptionally well preserved and provide evidence for the vegetation within the forests and contain important signals of the prevailing palaeoclimate. In this chapter the occurrence of the palaeosols in the field as well as micro-morphological features are studied.

Chapter 4 looks at the fossil plant and fossil tree spatial distribution data collected in the field in order to gain an understanding of the composition and structure of the Alexander Island forest communities, estimating forest density and productivity and comparing them to modern forests.

In Chapter 5 the plant taxa identified in this study are listed with extended information on the angiosperms and the plant group Pentoxylales, and the taxonomy of the fossil wood is discussed with fossil wood types identified.

Chapter 6 uses statistical techniques to further investigate the structure and composition of the Cretaceous forests and environmental influences on the plants. This chapter looks in detail at plant communities that occurred within the forests and their relationship with their surrounding palaeoenvironment.

In Chapter 7 all information analysed within this study will be summarised and discussed with full descriptions of the fluvial environment and plant communities that occurred during the Albian on Alexander Island and how they evolved through time. Issues associated with forests growing at high latitudes during the Cretaceous will be addressed and the Alexander Island forests will be compared to other Cretaceous floral studies in both the southern and northern hemispheres. Climate estimates for high-latitude areas during the Cretaceous will also be discussed.

Finally in Chapter 8 all research in the above chapters will be summarised and the main conclusions will be outlined.

Chapter 2 Sedimentology

2.1 Introduction

This chapter looks in detail at the sedimentology of the Triton Point Formation, which crops out on the southeastern nunataks (Citadel Bastion, Titan Nunataks and Coal Nunatak) of Alexander Island (Figure 2.1). The Triton Point Formation consists of the Citadel Bastion Member, which crops out on Citadel Bastion, Titan Nunataks and the lower 60 m of Coal Nunatak, and the Coal Nunatak Member, which crops out on the upper 150 m of Coal Nunatak (Nichols & Cantrill 2002). The aim of the sedimentary investigation is to determine the sedimentological environment in which the forests grew. Although some information about the sedimentology of the nunataks has been described previously (Cantrill & Nichols 1996; Nichols & Cantrill 2002), a more detailed sedimentary analysis was required for this project to locate individual plant beds and plant sampling sites and to establish the palaeoenvironments of the individual fossil forests they represent. The Hyperion Nunatak, representing the Neptune Glacier Formation, Fossil Bluff Group, was poorly exposed and visited for one day only due to poor weather conditions and therefore will no longer be mentioned in this study.

Within this chapter, the sediments are assigned to sedimentary facies and then grouped together into environmental facies for convenience; the sedimentology of individual beds is shown on the appendix sedimentary logs (Logs 1-11, Appendix 2). Each facies is described in detail below. Their changing distributions are documented throughout the ~ 1 km section, in order to interpret the nature of the palaeoenvironment of the area as a whole during the Albian period, and any changes in that palaeoenvironment.

In detail this chapter deals with:

1) The assignment of all sedimentary units to sedimentary facies (lithofacies),
2) The establishment of environmental facies associations, and reconstructions of the palaeoenvironments that they represent,
3) Determination of changes in the environmental facies associations throughout the section and therefore changes through time.

The sediments described within this study are fluvial sandstones and siltstones with floodplain deposits forming up to a third of the total section. The commonly used sedimentary facies and facies associations erected by Miall (1977, 1978) tend to emphasise channel processes, as he assumed that overbank deposits are usually of little importance in braided river sediments. The sedimentary facies used in this chapter therefore are based on those lithofacies described by Nichols

& Cantrill (2002), as they reflect the importance that the floodplain deposits play in the sedimentary environment of the southeastern nunataks of Alexander Island. New environmental facies associations were developed to best describe the palaeoenvironments suggested by the sediments.

The structural dip of the strata is shallow and variable and ranges between 4-12 ° to the southeast, forming relatively flat-lying beds. Minor faults are rare and were only seen in the upper sections of Coal Nunatak (Locations KG 4924 & 4926; Figure 2.1) where they had no affect on the stratigraphy. No large-scale faults or folds were evident and so it is possible that the three nunataks that make up the field area of this study (Figure 2.1) are all part of a single structural block. A geometrical correlation of the area using a regional dip towards the southeast suggests Citadel Bastion represents the base of the section, followed by Titan Nunataks and finally Coal Nunatak.

2.2 Summary sedimentary logs

Eleven detailed sedimentary logs were taken in the field covering all three nunataks; these are shown in Appendix 2 and their locations are shown on Figure 2.1. Summary sedimentary logs for all nunataks were compiled and are given here within the text for reference (Figure 2.2, A-D). The correlation of individual location logs to make up the summary log of a whole nunatak was done through dip measurements and bed correlation in the field and cross sections.

Figure 2.1 Location map of Alexander Island. A) The Fossil Bluff Group (red shaded area) that contains the fossil forests on Alexander Island, and the area of this study (blue box). B) The field area of this study with all locations labelled, e.g. KG 4901. Descriptions of all localities can be found in Table A2.1, Appendix 2.

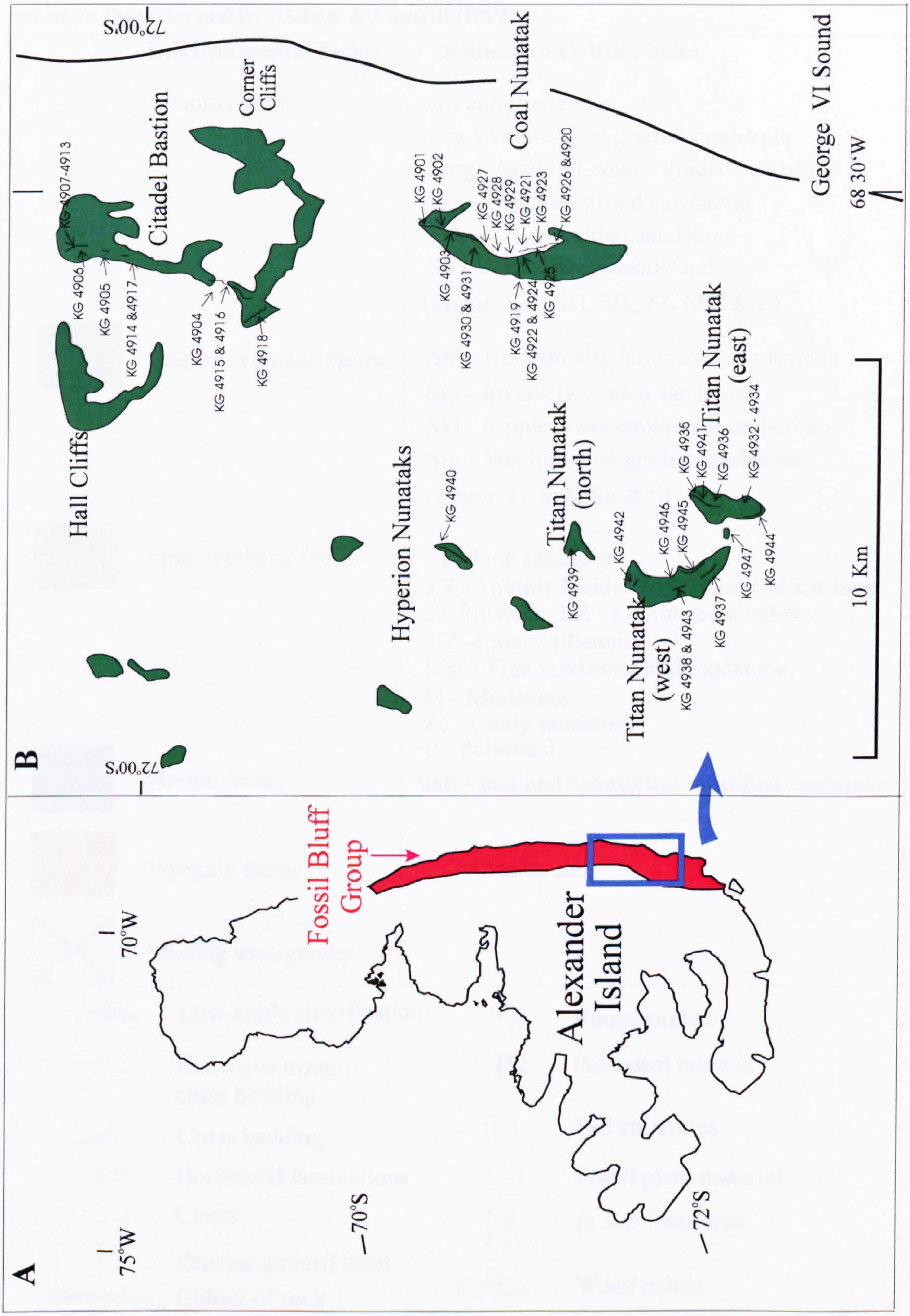


Figure 2.2 Summary sedimentary logs recording the Triton Point Formation on the southeastern nunataks of Alexander Island. Summary logs are based on the full Appendix logs (Logs 1-11, App. 2). A) A key to facies and symbols used on the summary logs. Environmental facies associations devised within this study, sedimentary lithofacies based on those devised by Nichols & Cantrill (2002).

	Environmental facies	Sedimentary lithofacies
🟨	Channel facies	G - conglomerate Scg - Very coarse graded sandstone Smg - Medium-coarse graded sandstone Sxs - Cross-stratified sandstone Sxb - Cross-bedded sandstone Su - Structureless sandstone (minor: Shl, Sxl, Sfg, Sf, Msf & Z)
🟩	Coarse overbank facies	Shl - Horizontally laminated sandstone Sgi - Inversely graded sandstone Sxl - Ripple cross laminated sandstone Sfg - Medium-fine graded sandstone (minor: G, Sxb, Su & Sf)
🟩	Fine overbank facies	Sf - Fine sandstone ZS - Thinnly bedded sandstone and siltstone Z- Siltstone, LZ - Laminated siltstone, CZ -Cherty siltstone Msf - Fine sandstone and mudstone M - Mudstone Zc - Coaly sandstone P - Palaeosol
🟦	Marine facies	Sxh - Inclined heterolithic stratified sandstone
🟥	Volcanic facies	V - Volcanic ash
☒	Missing stratigraphy	

	Low-angle stratification		Roots/rootlets
	Extensive trough cross bedding	Ps	Palaeosol horizon
	Cross bedding		Ped structures
═	Horizontal laminations		Fossil plant material
○◯○	Clasts		*In situ* fossil tree
	Coarser grained band		Wood debris
Sandy/white	Colour of rock		

Figure 2.2 B) Summary sedimentary log for Citadel Bastion, based on the full Appendix logs from locations shown along scale (Logs 1 & 4, App. 2). Key to facies and symbols used shown in Figure 2.2. A, shown previously.

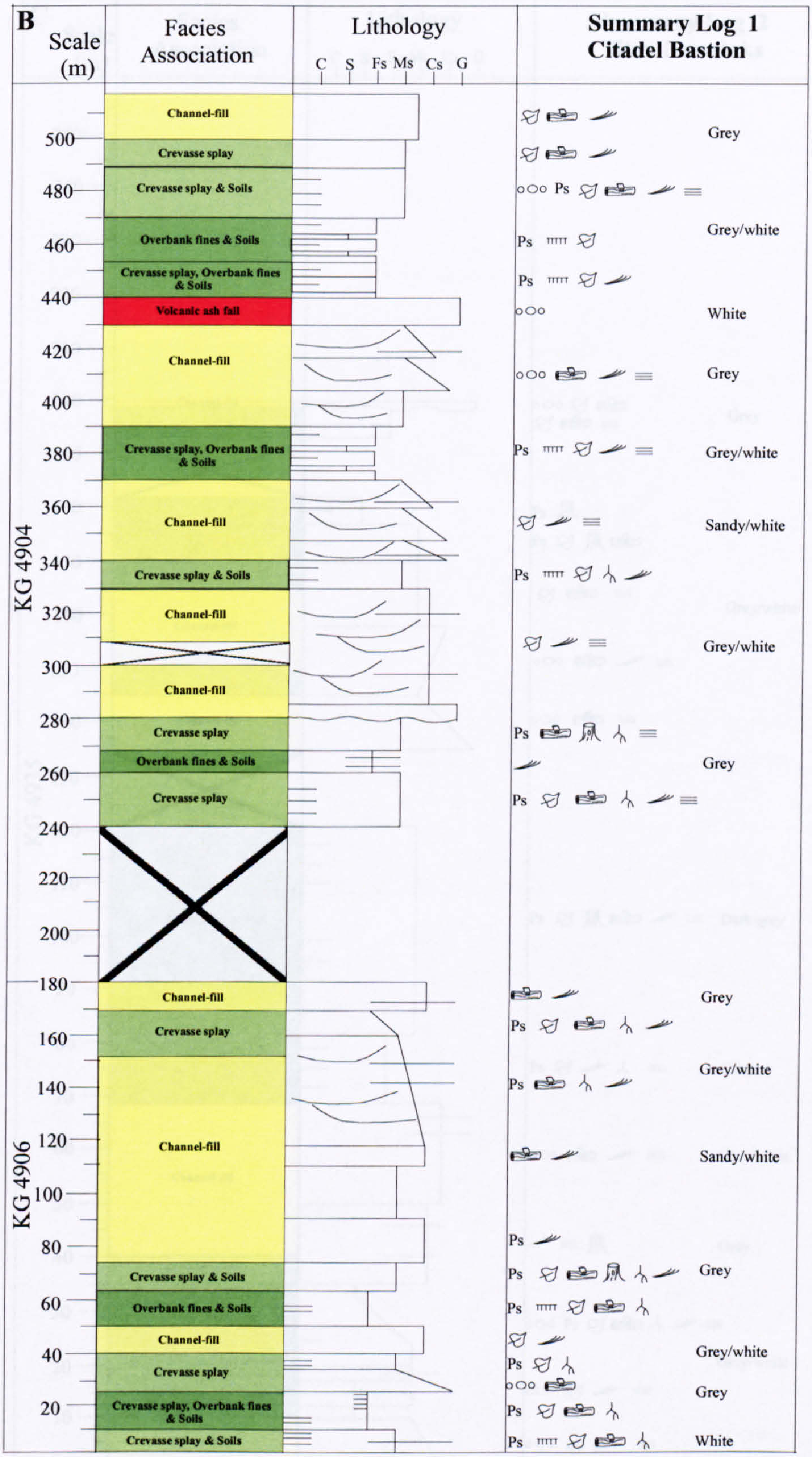


Figure 2.2 C) Summary sedimentary log for Titan Nunataks, based on the full Appendix logs from locations shown along scale (Log 7, App. 2). Key to facies and symbols used shown in Figure 2.2. A, shown previously.

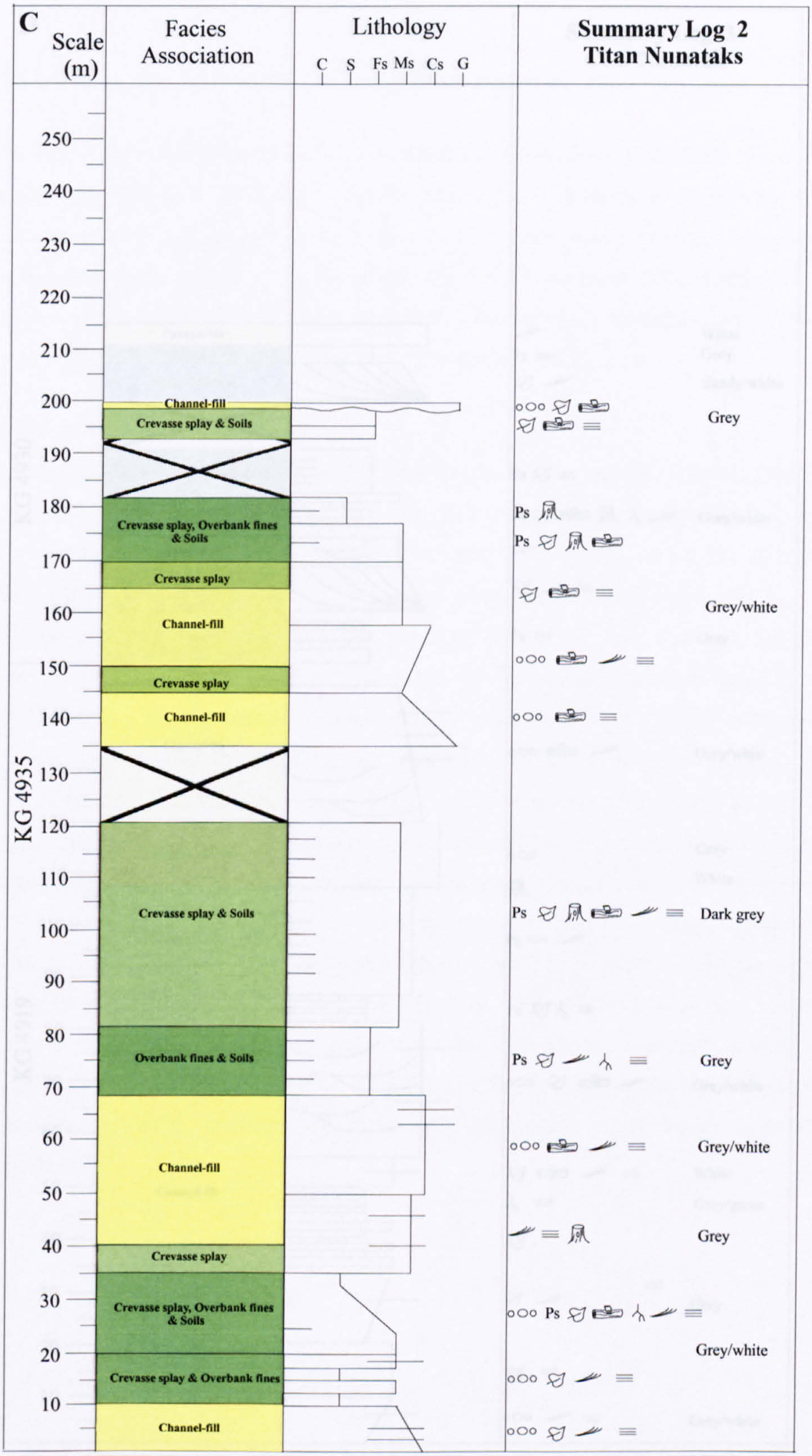
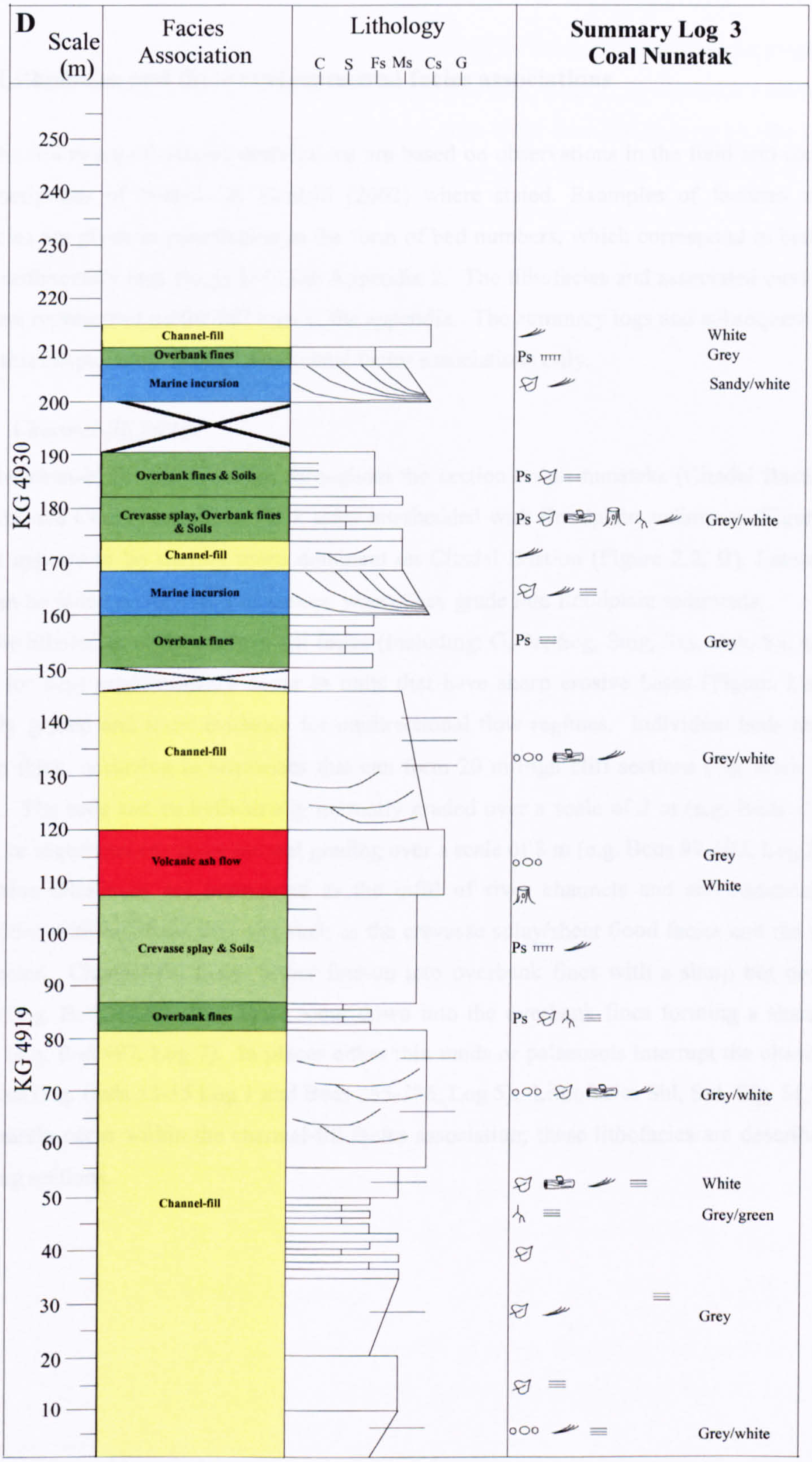


Figure 2.2 D) Summary sedimentary log for Coal Nunatak, based on the full Appendix logs from locations shown along scale (Logs 9 & 10, App. 2). Key to facies and symbols used shown in Figure 2.2. A, shown previously.



2.3 Lithofacies and their environmental facies associations

The following lithofacies descriptions are based on observations in the field and compared to the descriptions of Nichols & Cantrill (2002) where stated. Examples of features within the lithofacies are given in parentheses in the form of bed numbers, which correspond to bed numbers on the sedimentary logs (Logs 1–11) in Appendix 2. The lithofacies and associated environmental facies are represented on the full logs in the appendix. The summary logs and subsequent diagrams within this chapter show the environmental facies associations only.

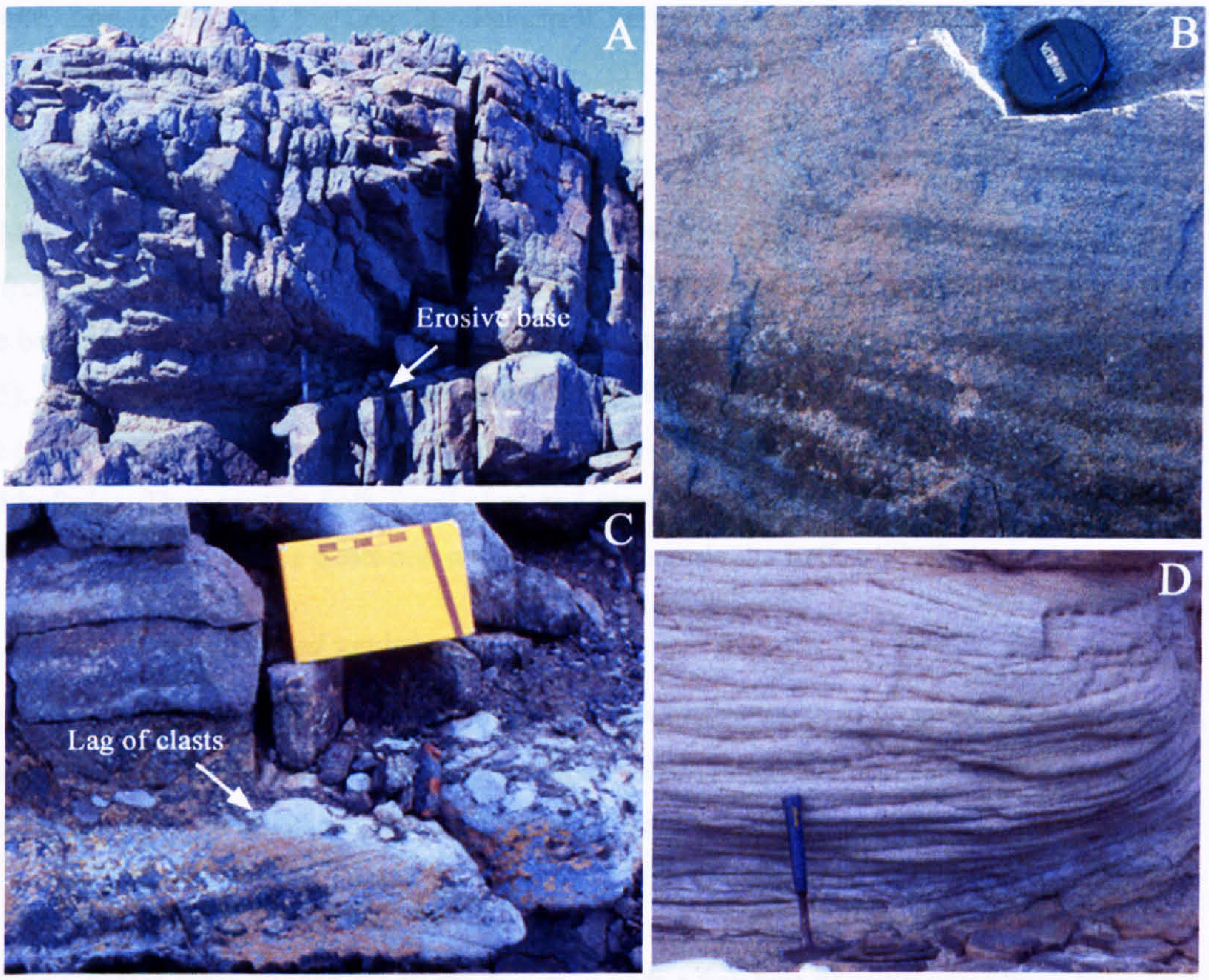
2.3.1 Channel-fill facies

The channel-fill facies occurs throughout the section on all nunataks (Citadel Bastion, Titan Nunataks and Coal Nunatak) as thick units interbedded with floodplain sediments (Figure 2.2, A-D), but appears to be slightly more dominant on Citadel Bastion (Figure 2.2, B). Laterally these units can be followed for 100's of metres, where they grade into floodplain sediments.

The lithofacies of the channel-fill facies (including: G, Sc, Scg, Smg, Sxs, Sxb, Su; see Figure 2.2, A for key) predominantly occur in units that have sharp erosive bases (Figure 2.3, A), are normally graded and show evidence for unidirectional flow regimes. Individual beds range from 0.5-4 m thick, occurring in sequences that can form 20 m high cliff sections (e.g. Beds 600-615, Log 9). The beds can be individually normally graded over a scale of 2 m (e.g. Beds 105 – 108, Log 2), or sequences can show normal grading over a scale of 8 m (e.g. Beds 97-103, Log 2).

These lithofacies are interpreted as the infill of river channels and are commonly found interbedded with overbank deposits such as the crevasse splay/sheet flood facies and the overbank fines facies. Channel-fill facies either fine-up into overbank fines with a sharp but non-erosive contact (e.g. Beds 66-71, Log 1) or scour down into the overbank fines forming a sharp erosive contact (e.g. Bed 487, Log 7). In places either thin muds or palaeosols interrupt the channel facies sequences (e.g. Beds 53-55 Log 1 and Beds 255-256, Log 5). Lithofacies Shl, Sxl, Sfg, Sf, MSf and Z also rarely occur within the channel-fill facies association; these lithofacies are described in the following sections.

Figure 2.3 Features within the channel-fill facies. A) Granular sandstone with a sharp erosive base (arrow). Hammer 35 cm high. KG 4935, Bed 459, Log 7. B) Extensive trough cross-bedding within Scg lithofacies. Lens cap 5.5 cm. KG 4939, Bed 356, Log 6. C) Clasts (arrow) forming a lag at the base of Scg lithofacies. Increments on scale 2 cm. KG 4906, Bed 26, Log 1. D) Trough cross-beds within Sxb lithofacies. Hammer 35 cm high. KG 4902, Bed 667, Log 11.



2.3.1.1 G – Conglomerate

Medium pebble to coarse granule conglomerate occurring in beds tens of centimetres thick, with sharp erosive bases (e.g. Bed 136, Log 4 and Beds 357-359, Log 6). The pebbles are sub-rounded, poorly sorted, and matrix-supported and range from igneous to sandstone and mudstone in composition. In places thicker, homogenous units up to 2 m occur (e.g. Bed 251, Log 5).

2.3.1.2 Scg - Very coarse graded sandstone

Very coarse sandstone beds grade up to medium or coarse sandstone with bands and lenses of conglomerate (G) and fossil plant and wood debris at their erosive bases (e.g. Bed 26, Log 1; Figure

2.3, C). Individual beds range in thickness from 1.5-4 m thick (e.g. Bed 189, Log 4). These beds show both planar and trough cross-beds, which occur in sets between 0.3-1.5 m thick and 0.2-0.8 m thick respectively (Nichols & Cantrill 2002; Figure 2.3, B, D). They are often associated with Smg lithofacies, which commonly occurs above with a sharp but non-erosive contact. This lithofacies commonly has rip-up clasts of mudstone at the base and frequently contains fossil wood debris (e.g. Bed 487, Log 7 and Bed 75, Log 1). Palaeosol horizons occur on the upper surfaces of this lithofacies (e.g. Bed 189, Log 4).

2.3.1.3 Smg - Medium-coarse graded sandstone

Medium–coarse and occasionally fine grained sandstones that are normally graded occur in beds from 0.5 – 3.5 m thick but commonly 1.5 m (e.g. Beds 27 and 63, Log 1 and Bed 271, Log 5). These beds can form sequences up to 10 m thick separated by thin mudstones (e.g. Beds 267 – 271, Log 5). The beds are commonly trough cross-bedded in sets of 0.1-0.7 m thick and occasionally ripple cross-bedded in the upper sections, although they do not always contain cross beds unlike the Sxb lithofacies. They contain both fossil plant and wood debris (e.g. Bed 35, Log 1 and Bed 602, Log 9) and occasionally have clasts and wisps of sandstone similar to Scg lithofacies.

2.3.1.4 Sxs - Cross-stratified sandstone

Medium-coarse sandstone shows metre-scale, low-angle (10–20 °) cross stratification. This facies occurs only rarely within the section studied. Beds range in thickness from 3.5–4 m and laterally grade into Sxb lithofacies (e.g. Bed 623, Log 9 and Log 10).

2.3.1.5 Sxb - Cross-bedded sandstone

Fine – coarse cross-bedded sandstone occurs in beds a few tens of centimetres thick to up to 3 m thick (e.g. Bed 358, Log 6 and Bed 144, Log 4). Cross-beds are predominantly troughs with sets 0.1–0.3 m thick (e.g. Bed 572, Log 6; Figure 2.3, D), but occasionally planar cross-beds occur in the upper sections. The thicker units often have coarse bands that pick out the cross-beds (e.g. Bed 247-249, Log 5). Beds are commonly found associated with Smg and Scg where they normally have sharp but non-erosive bases; however where they overlie overbank fine facies they have scoured erosive contacts (e.g. Bed 564, Log 9 and Bed 419, Log 7). This lithofacies is thinly bedded (e.g. Bed 643, Log 11) in places and contains mudstone rip-up clasts at the base (e.g. Bed 254, Log 5).

2.3.1.6 Su - Structureless sandstone

Fine–coarse sandstone with no internal sedimentary features occurs in beds from a few tens of centimetres to 2-3 m thick. They occur throughout the studied section, commonly as sequences 5.5 m thick (e.g. Beds 548-551, Log 9) interbedded with siltstones (e.g. Bed 630, Log 9). Their upper surfaces often have palaeosol characteristics (e.g. Bed 9, Log 1). They rarely have an erosional contact with the bed below (e.g. Bed 314, Log 5) but commonly have sharp non-erosive bases. They often have fossil wood and plant debris on their upper surfaces (e.g. Bed 22, Log 1) and sometimes are discontinuous (e.g. Bed 536, Log 8 and Bed 100, Log 2).

2.3.2 Interpretation of channel-fill facies

Sandstone units described above occur in sequences of G, Scg and Smg, showing an overall fining upwards sequence and scoured bases. The erosive bases are characterised by gravel, plant and wood debris lags, recording winnowing by strong currents representing the flows in the deepest parts of a river channel and channel incision (Miall 1977; Collinson 1996; Walker & Cant 1984).

The thicker units of conglomerate (G) of poorly sorted pebbles may be a result of deposition within a volcanic basin where volcaniclastic debris and hyperconcentrated flows prevents sorting (Collinson 1996). The change in scale of cross-beds throughout these sequences from trough to ripple and then planar cross-bedding is characteristic of channel floor deposition as water depths decrease (Cant & Walker 1978) and the sandstones here are interpreted as deposits within a fluvial channel. These sequences of channel-fill sediments can be up to 20 m thick (e.g. Beds 509-519, Log 8), indicating a channel depth of more than 10 m or an amalgamation of several channel-fill successions (Nichols & Cantrill 2002).

The sequences of Scg, Smg, Sxs and Sxb represent a fining-upwards sequence of lateral accretion within a river channel (Miall 1992). The low-angle cross-bedding in Sxs, seen clearly on Coal Nunatak (Bed 623, Log 9) represents lateral accretion surfaces with shallow dips forming parallel to the channel margin (Allen 1963). Scg, Smg and Sxb is dominated by trough cross-bedding formed by migrating 3D dunes within the channel. These trough cross-beds fine upwards to ripple and then planar laminations, which form at the tops of the channel sandstones reflecting the relatively weak currents at shallow depths (Collinson 1996).

Upwards in the lateral accretion bar, sandstones can be interbedded with silts (MSf) containing small-scale cross-beds and ripple lamination. The occasional mud drapes separating bedding formed as a result of water stage fluctuations (Collinson 1996). The formation of immature palaeosols between beds indicates a period of channel abandonment and floodplain exposure during low stage (e.g. Beds 255-256, Log 5). Similarly a small sequence of channel sandstones occur interbedded with overbank fines (e.g. Beds 26-28, Log 1) suggesting that a long abandoned channel had been briefly reactivated during very high stage.

Both tabular and lenticular beds of Su lithofacies also occur associated with the channel-fill sandstones. These occur throughout the channel successions and the lack of any sedimentary features suggests rapid deposition from suspension during floods. Where this lithofacies occurs with a lenticular morphology it is likely the result of bank collapse and slumping with liquefaction processes destroying all sedimentary features (Collinson 1996). Shl lithofacies occurs predominately as a crevasse splay sandstone (described in Section 2.3.3) but also occurs rarely amongst the channel-fill sandstones; where it does it is more common towards the top of the channel sandstones (e.g. Bed 154, Log 4), a product of upper stage plane bed transport (Collinson 1996).

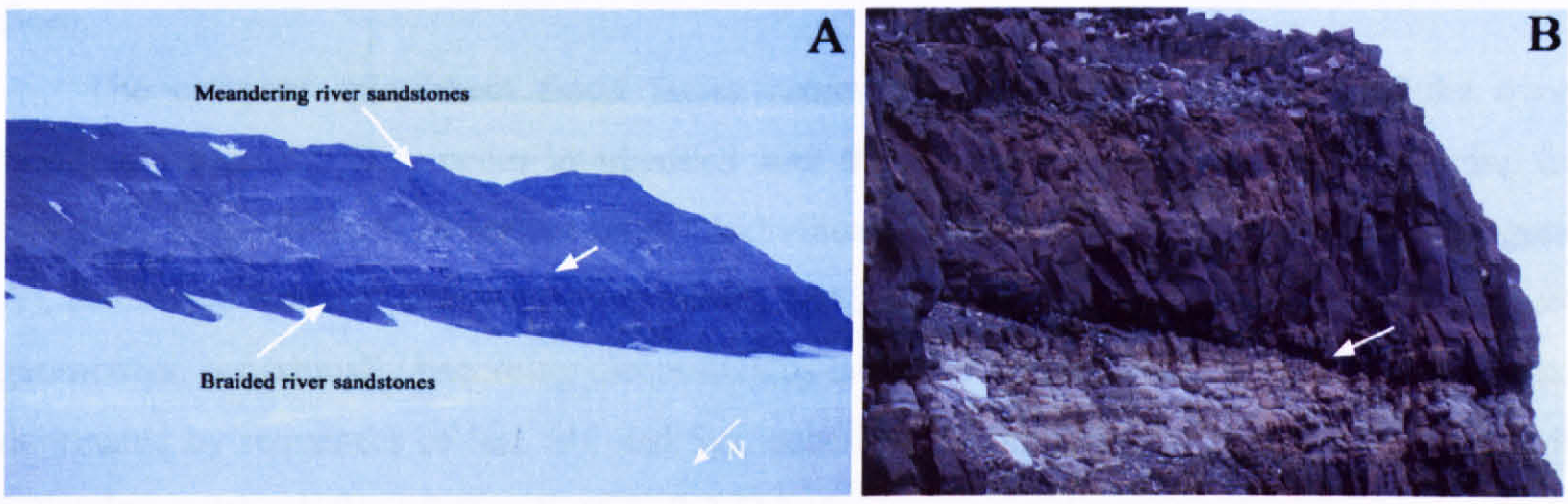
2.3.2.1 Changing channel environment

The nature of these channel-fill sandstone bodies changes within the section on the southeastern nunataks of Alexander Island, as discussed previously by Nichols & Cantrill (2002). On Citadel Bastion, Titan Nunataks and the basal sections of Coal Nunatak (which represent the Citadel Bastion Member; Chapter 1 and Figure 1.6), the channel sandstones form thick and laterally extensive sand bodies extending over many 100's of metres. For example, a channel sandstone body can be traced for nearly 1 km across the southern parts of Citadel Bastion (Beds 179–185, Log 4 correlate to Beds 250–255, Log 5). Although the channel margins are not seen, on Titan Nunataks channel sandstones can be traced across the three nunataks representing an area of 2.5 by 2 km (Beds 355-368, Log 6 correlate to Beds 458-466, Log 7 and Beds 509-519, Log 8).

The continuous exposure within the basal units of Coal Nunatak (Figure 2.4, A) in particular allows channel sandstones to be traced for the whole 4 km length of the nunatak. The lateral extent of the sandstone bodies within the Citadel Bastion Member suggest these sediments were deposited within a braided river channel system with a palaeoflow direction towards the northwest (Section 2.4), with channels frequently migrating laterally to produce the sheet-like bodies (Friend *et al.* 1979; Nichols & Cantrill 2002).

The channel sandstones in the Coal Nunatak Member (the upper 155 m of Coal Nunatak; Chapter 1, Figure 1.6), however, have a very different morphology. Individual channel sandstones are lenticular (e.g. Bed 602, Log 9; Figure 2.4, B) and can be traced for tens of metres laterally, with aspect ratios of 15:1 (width: height) (Nichols & Cantrill 2002).

Figure 2.4 A) The continuous units at the base of Coal Nunatak extend for 2 Km in this photograph. B) A channel sandstone margin with an erosive base (max 1.3 m thick) cutting down into the sandstone below. KG 4919, Bed 602, Log 9.



These sandstone bodies that are commonly found within floodplain fines (e.g. 170 m on Figure 2.2 D) are interpreted as elongate shoestring sands or ribbon sands that are common in meandering and anastomosing river systems (Cant & Walker 1978; Friend *et al.* 1979; Miall 1992; Collinson 1996). Lateral accretion surfaces were described within a channel sandstone body from the Coal Nunatak Member by Nichols & Cantrill (2002), which was used as evidence for a meandering river system as lateral accretion is almost absent from anastomosing rivers (Reid & Frostick 1994).

However evidence for lateral accretion was not seen in any channel sandstone bodies studied here, although tabular cross bedding, which is considered the dominant feature of anastomosing river sandstones (Smith 1983) is fairly rare within the Coal Nunatak Member. Thus, although the possibility of an anastomosing river system cannot be ruled out, it is likely that the Coal Nunatak Member formed in a meandering river system.

The change in channel morphology from sheet-like to shoestring between the sediments of the Citadel Bastion Member to those of the Coal Nunatak Member indicates a change in palaeoenvironment from a braided to meandering river system. This change occurs at the base of Coal Nunatak (arrowed on Figure 2.4, A) and can clearly be seen within the sediments. On Figure 2.4 A, the basal 60 m of Coal Nunatak comprises dark sediments forming thick cliff sections representing deposition by a braided river system. The upper ~150 m of sediment is lighter and predominantly forms slopes with intermittent cliff sections; these sediments represent deposition by a meandering river system.

2.3.3 Crevasse splay/sheet flood facies

Crevasse splay and sheet flood facies sediments interbedded with channel-fill facies and overbank fine sediments (Figure 2.2, A-D) occur throughout the section on Citadel Bastion, Titan

Nunataks and Coal Nunatak but occur more frequently on both Titan Nunataks and Coal Nunatak (Figure 2.2, C & D). They can be followed for 10's metres, sometimes up to 100's metres (e.g. Bed 637 on Logs 9 & 10, ~ 700 m apart) and change laterally into either channel-fill facies or overbank fines.

The crevasse splay/sheet flood facies represents the coarse component of the overbank floodplain deposits. They occur interbedded with the overbank fine facies in beds ranging from a few ten's of centimetres to metres thick. Individual beds have generally non-erosive (Figure 2.5, A), distinctive contacts, occasionally scoured (Bed 284, Log 5 and Bed 314, Log 5) with sheet-like geometries, occasionally becoming discontinuous laterally. The crevasse splay/sheet flood facies is dominated by sequences of Sxl, Shl and Sgi, occasionally fining up to Sfg (or Sf described in the following overbank fines facies, Section 2.3.5) beds.

These sequences can form cliff sections up to 10 m thick (e.g. Beds 122-127, Log 4; Figure 2.5, B) or occur as thin beds interbedded with the overbank fines and palaeosol horizons (e.g. Beds 1-9, Log 1 and Beds 422 – 430, Log 7). Where palaeosols occur above these facies, the upper parts of the units have weathered into the lower horizon of a palaeosol (e.g. Beds 278 and 279, Log 5), and where palaeosols occur they often contain *in situ* fossil upright trees (e.g. Bed 323, Log 6, Bed 433, Log 7, and Bed 542, Log 8).

2.3.3.1 Shl – Horizontally laminated sandstone

Coarse–fine sandstone with horizontal laminae occur in beds between 0.5-2 m thick (e.g. Bed 48, Log 1 and Bed 122, Log 4; Figure 2.6, A). Basal contacts are sharp but non-erosive and laminae are usually well-defined but are occasionally poorly displayed (Nichols & Cantrill 2002). The beds frequently occur as sequences with Sxb and Sfg (e.g. Beds 405-409, Log 7) and are also found as individual beds in between overbanks (e.g. Beds 45-49, Log 1 and Beds 425-431, Log 9). This lithofacies often contains plant and wood debris (e.g. Bed 223, Log 4) and sometimes has large (< 4 cm) mudstone clasts (e.g. Bed 610, Log 9; Figure 2.6, B). These beds also contain bands of granular conglomerate (e.g. Beds 274-276, Log 5; Figure 2.6, C) and wisps of siltstone.

2.3.3.2 Sgi – Inversely graded sandstone

Medium-coarse inversely graded sandstone occurs in beds from 1-3 m thick (e.g. Bed 1, Log 1 and Bed 544, Log 11), as sequences associated with Sxb, Shl and Sfg (e.g. Beds 77-80, Log 1 and Beds 384-387, Log 7) and occasionally as repeated beds grading up over 5 m (e.g. Beds 552-555, Log 9). They commonly show trough cross-bedding and sometimes have horizontal laminations towards the top (e.g. Bed 452, Log 7). They frequently contain fossil plant and wood debris (e.g. Bed 328, Log 6) as well as mudstone clasts (e.g. Bed 386, Log 7 and Bed 543, Log 9).

Figure 2.5 A) The sharp but non-erosive contact (arrow) between a crevasse splay sandstone and an underlying channel sandstone. Hammer 35 cm high. KG 4935, Bed 466, Log 7. B) Thick sequences of crevasse splay sandstones forming a cliff section 7 m high. KG 4935, Bed 454, Log 7.

2.3.3.3 Sxl – Ripple cross laminated sandstone

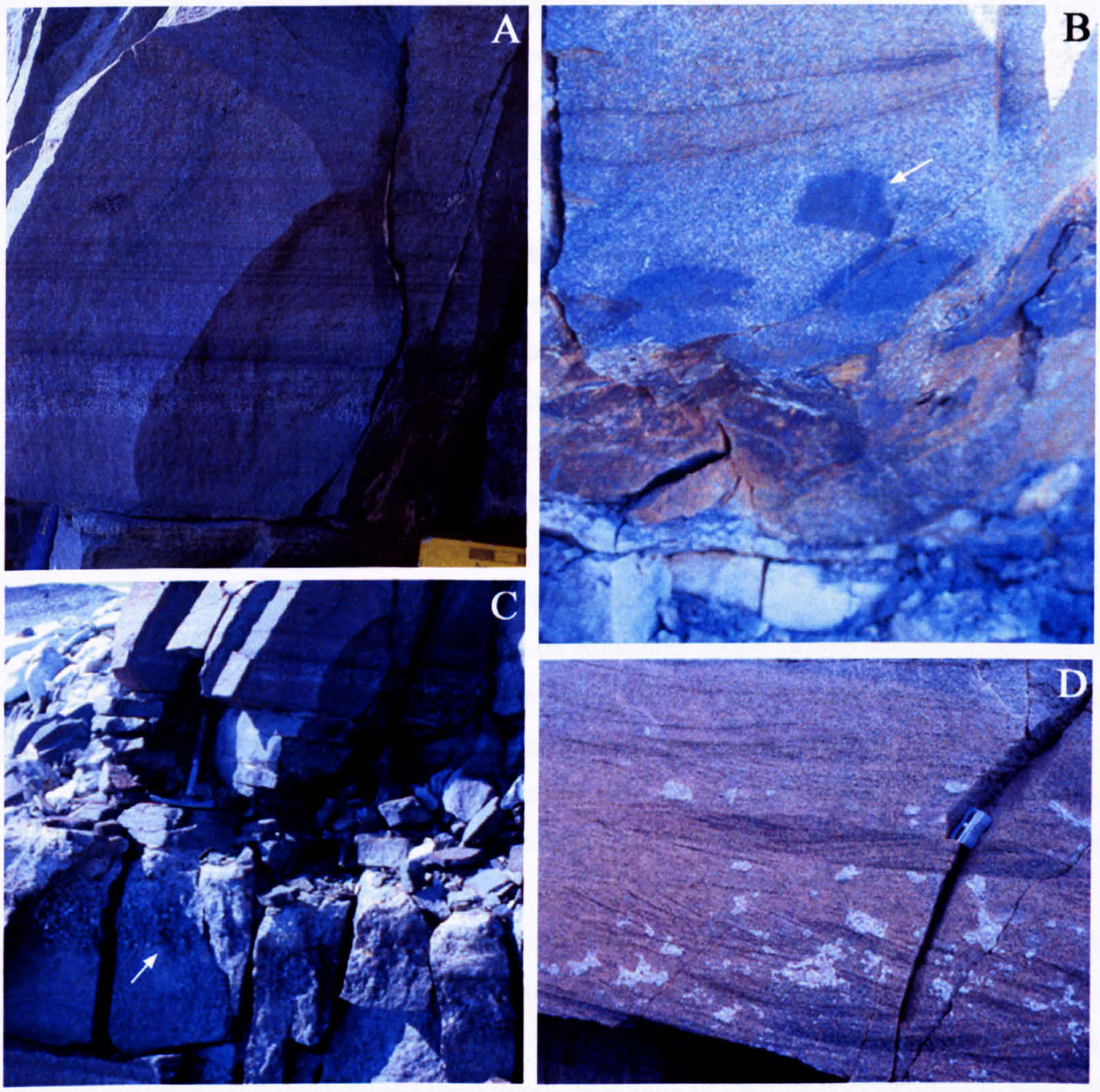
Fine-medium sandstone with ripple cross lamination, often picked out by coarser bands (e.g. Bed 50, Log 1), occur in beds from just a few ten's of centimetres to 2 m in thickness (e.g. Bed 637, Log 9) often forming sequences 6 m thick (e.g. Beds 532-535, Log 8). This lithofacies frequently contains fossil plant and wood debris and occurs as sequences along with Sxb and Shl (e.g. Beds 406-409, Log 7).

2.3.3.4 Sfg – Medium-fine graded sandstone

Coarse or medium–fine sandstone, normally graded, occurs in beds from a few tens of centimetres to 3 m thick (e.g. Bed 243, Log 5). These beds also occur in sequences of 1 m thick beds forming sections 3 m thick (e.g. Beds 131-133, Log 4). They are predominantly trough cross-bedded and occasionally horizontally or ripple laminated towards the top (e.g. Bed 266, Log 5; Figure 2.6, D). They commonly occur above sequences of Sxb, Shl and Sgi (e.g. Bed 80, Log 1) or interbedded within overbank fines such as palaeosols and siltstones (e.g. Beds 583-587, Log 9).

They frequently contain fossil plant and wood debris (e.g. Bed 235, Log 5) and more rarely *in situ* fossil upright trees (e.g. Bed 131, Log 4).

Figure 2.6 Sedimentary features within crevasse splay sandstones. A) Horizontal laminae within Shl lithofacies. Increments on scale 2 cm. KG 4918, Bed 241, Log 5. B) Mudstone clasts (arrow) at the base of a Shl bed. Clasts ~ 3 cm long. KG 4935, Bed 395, Log 7. C) Bands of granular conglomerate (arrow) within Shl lithofacies. Hammer 35 cm high. KG 4918, Bed 241, Log 5. D) Cross-bedding within Sfg lithofacies. Pencil sharpener 2 cm long. KG 4918, Bed 266, Log 5.



2.3.4 Interpretation of crevasse splay/sheet flood facies

The association of these sandstones with floodplain fines, upright *in situ* fossil trees, fossil plants and palaeosol horizons indicates that they are of floodplain origin and not associated with the channel-fill sediments. They occur in sequences of Sxb, Shl, Sgi, Su and Sfg with an overall fining-upwards trend and are interpreted as the result of floods that covered the river floodplain.

The association of graded beds (Sfg) with horizontally laminated (Shl) and ripple laminated (Sxb) beds suggests deposition under waning conditions such as during crevasse splay when the river levees are breached locally during high stage and the load carried by the flood waters is deposited rapidly as the waters spread out over the floodplain (Walker & Cant 1984). Inversely graded sandstones (Sgi) were also found associated with Sfg, Shl and Sxb and may have formed during the initial stages of crevasse splay (Nichols & Cantrill 2002). The sequences of Sxb, Shl and Sfg are often interbedded with overbank fines and can be discontinuous (e.g. Beds 376-380, Log 6), forming lobate sandstone bodies or sand sheets that characteristically form when crevasse splay sands become interbedded with finer deposits of the floodplain (Collinson 1996).

In places these units have scoured bases and show similar features to the crevasse splay channel deposits described by Spicer *et al.* (2002), with unidirectional flow and inter-fingering with floodplain fines. The clasts of mudstone often found at the base of these sandstones may be the result of deeply incised crevasses, which tap the lower levels of the main river channel (Collinson 1996). The lateral extent of the crevasse splay units reaches several 100's m, similar in scale to the modern crevasse deposits of the Brahmaputra (Coleman 1969).

Single beds of crevasse splay sandstones on Alexander Island (which are sometimes 4 m thick; e.g. Bed 241, Log 5) are likely to have been deposited by a single flood event. However thicker sequences of sandstone bodies up to 10 m thick, may be the product of longer-term splay construction over several flood cycles as was the case for the large irregularly shaped sandstone complexes seen in the Upper Triassic, Callide Seam Member of east-central Queensland, Australia (Jorgensen & Fielding 1996).

Structureless sandstones bodies (Su) occur frequently on Alexander Island within the coarse overbank sediments and are often found associated with horizontally laminated sandstones (Shl) and are interpreted as sheet flood deposits. Laminated and structureless sandstones develop by upper flow regime conditions during flash floods especially in seasonally dry climates (Miall 1992). The absence of any structures within these sandstone bodies may be a result of homogenisation by bioturbation of plants and fauna or through rapid deposition; trees and floodplain topography can dramatically reduce the velocity of flow leading to rapid deposition of sediments held in suspension in the flood waters (Miall 1977; Reid & Frostick 1994; Spicer *et al.* 2002).

However, the presence of trough and ripple laminae (Sxb) within the overbank sediments suggests that flows on the floodplain were strong enough to allow the migration of dunes (Nichols & Cantrill 2002). This evidence for fast flow, along with thick individual crevasse splay units, suggests that catastrophic flood events may have characterised the floodplains of southeastern Alexander Island.

2.3.5 Overbank fines facies

Overbank fine facies are found on all three nunataks (Figure 2.2, A-D). They are probably under-represented within the sedimentary logs because they do not form cliff sections like the coarse units and therefore probably outcrop upon the gentle scree slopes in between the cliffs (Nichols & Cantrill 2002; Figure 2.7, A). If it is assumed that all non-exposed parts of the section are overbank fine facies they would represent at least a third of the studied section (Nichols & Cantrill 2002). Laterally the overbank fines commonly change into the coarser sediments of the crevasse splay facies.

The overbank fines comprise sequences of mudstones, siltstones and fine sandstones that occur either above palaeosol horizons, in between crevasse splay sandstones or interbedded with channel-fill deposits. These overbank fines often host fossil plants above, or rootlet horizons beneath them, and on occasions contain *in situ* upright fossil trees (e.g. Bed 480, Log 7). They form thick, up to 3 m, sequences of Sf, ZS and Z (e.g. Beds 299 – 306, Log 5) and all units within this facies have non-erosive flat contacts with under- and overlying units.

2.3.5.1 Sf – Fine sandstone

Fine, often thinly bedded sandstone occurs in beds commonly < 1 m thick but occasionally reaching 4 m thick (e.g. Bed 114, Log 2). These beds are occasionally laterally discontinuous (e.g. Bed 418, Log 7), usually occur interbedded with siltstones (e.g. Beds 299-305, Log 5) but can also occur above palaeosol horizons and above the coarser overbank deposits such as Shl, Sxb and Su (e.g. Bed 355, Log 6). This lithofacies is commonly horizontally laminated (e.g. Bed 3, Log 1) and contains coarser bands (e.g. Bed 380, Log 6). Fossil plant and wood debris is common (e.g. Bed 485, Log 7); *in situ* upright fossil trees occur less frequently (e.g. Bed 480, Log 7).

2.3.5.2 ZS – Thinly bedded sandstone and siltstone

Thinly bedded fine sandstones and siltstones form sequences up to 1 m thick (e.g. Beds 37-41, Log 1), with the sandstones being tens of centimetres thick and the siltstones just a few centimetres thick (Figure 2.7, B). They are frequently horizontally laminated (e.g. Bed 563, Log 9) and contain an abundance of fossil plant debris (e.g. Bed 178, Log 4), sometimes very delicately preserved and on occasions with fossil wood fragments (e.g. Bed 43, Log 1). They are often found interbedded with palaeosol horizons (e.g. Beds 208-212, Log 4) and therefore frequently contain rootlets and often have coarser bands of medium sandstone (e.g. Bed 60, Log 1).

2.3.5.3 Z - Siltstone

Siltstone beds contain an abundance of *in situ*, well-preserved plant fossils (e.g. Bed 298, Log 4) and were frequently sampled for spatial distribution plant data. They are normally interbedded with other overbank fine lithofacies, such as Sf, P and ZS but also occur between channel-fill sandstones (e.g. Bed 85, Log 1) or interbedded with crevasse splay/sheet flood facies units (e.g. Beds 421-430, Log 7). The importance of the siltstone beds in the determination of the palaeoenvironment for plant sampling horizons (Chapters 4 & 6) along with important variations between different siltstone beds justifies subdividing this lithofacies into three sub-lithofacies.

2.3.5.3.1 Zs – Structureless siltstone

Grey siltstones occur in beds from 0.3 – 1 m thick (Bed 525, Log 8) and contain no sedimentary structures. They are always found interbedded with other overbank (Bed 305, Log 5) fines and frequently contain *in situ* upright plants fossilised in their growth position. On occasions, overbank fine sediments below these beds show evidence of soft sediment deformation.

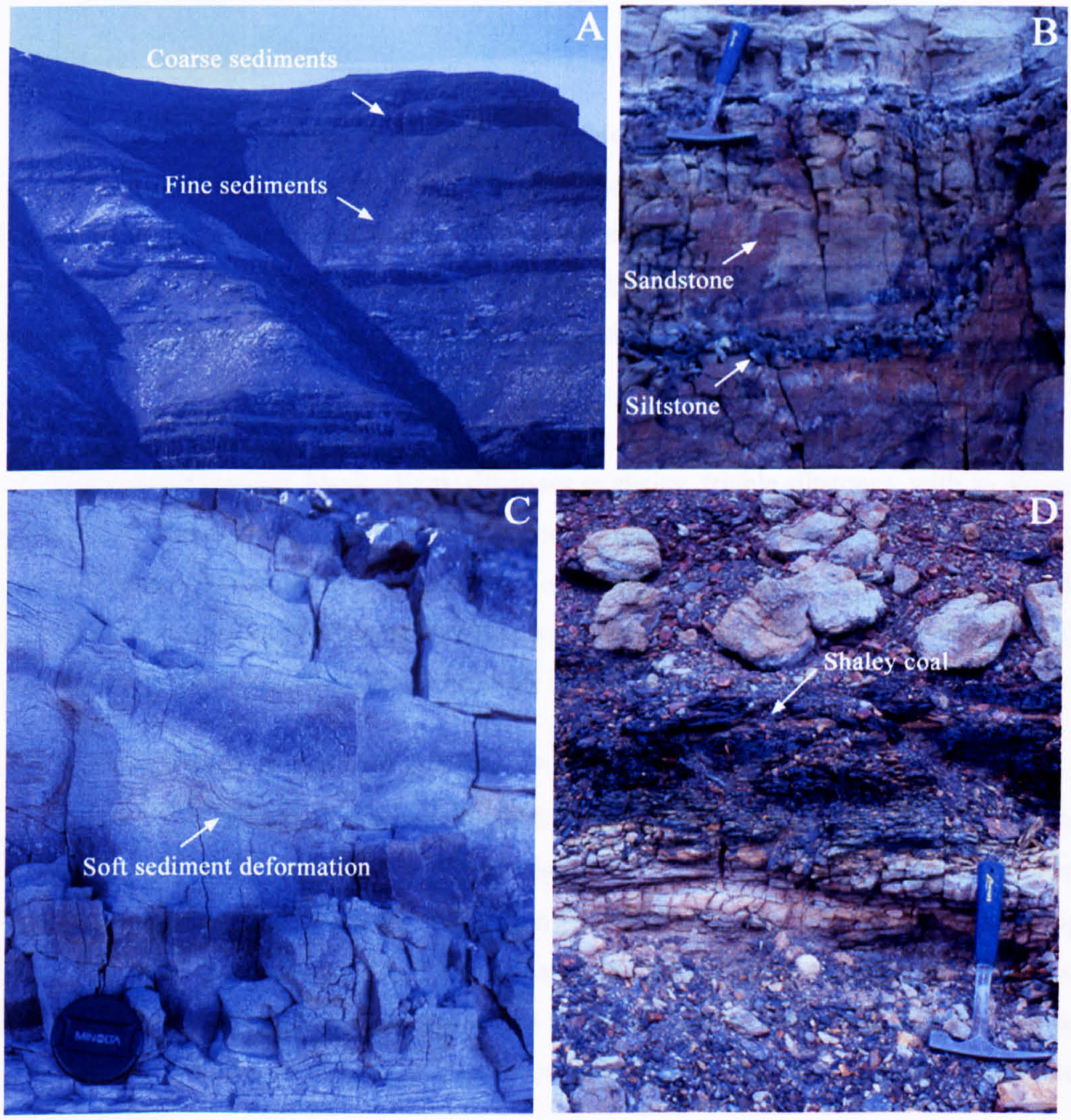
2.3.5.3.2 CZ – Cherty siltstone

Olive green siltstone lithofacies similar to above but very different in colour and finer grained giving it a distinctive cherty appearance. These beds are a lot thicker than the other siltstones with a range in thickness from 1 – 3.5 m (e.g. Beds 280, Log 5 and Bed 118, Log 2) and contain very delicate plant fossils, for example the majority of the small delicate angiosperm leaves were found in these siltstones. On occasions fine laminations (<1 mm) drape around *in situ* plant fossils.

2.3.5.3.3 LZ – laminated siltstone

Grey siltstone lithofacies with fine (< 1 mm) horizontal black laminae of carbonaceous material and thicker laminations of lighter silts. The laminae within these siltstones commonly show distortion around *in situ* plant fossils. These siltstone beds range in thickness from 0.2 – 0.8 m and predominantly occur interbedded with other flood deposits (e.g. Beds 423-430, Log 7).

Figure 2.7 A) Upper ~160 m of Coal Nunatak. Coarse channel and overbank sandstones form the cliff sections clearly seen (arrow). Overbank fines probably make up the bulk of the slope sections covered by scree (arrow). B) Interbedded sandstone (arrow) and siltstone (arrow). Hammer 35 cm high. KG 4922, Bed 634, Log 10. C) Interbedded sandstone and mudstone showing signs of soft sediment deformation (arrow). Lens cap 5.5 cm. KG 4922, Bed 625, Log 10. D) Shaley coal layer. Hammer 35 cm high. KG 4925, Bed 632, Log 9.



2.3.5.4 MSf – Fine sandstone and mudstone

Very fine–medium sandstones interbedded with siltstones and mudstones form beds up to 1.5 m thick (e.g. Bed 601, Log 9 and Bed 669, Log 11). The sandstones are usually the thicker bands within these beds (a few tens of centimetres thick) while the siltstones and mudstones form thinner bands. The mudstones and siltstones are usually black in colour and contain much carbonaceous material (Figure 2.7, C) as well as identifiable fossil plant fragments (e.g. Bed 618, Log 9). They occasionally show signs of soft sediment deformation when overlain by crevasse splay units (Figure 2.7, C). They frequently contain rootlet material and form part of the palaeosol horizon (e.g. Bed 625, Log 9). This lithofacies is predominantly found interbedded with other overbank fine facies, especially above and below palaeosol horizons (e.g. Bed 116, Log 2).

2.3.5.5 M – Mudstone

Mudstone forms very thin beds up to 0.3 m thick that occur interbedded with other overbank fine facies such as Sf, MSf and ZS (e.g. Bed 495, Log 8). They are homogeneous and contain an abundance of carbonaceous material. Thin mudstones also occur interbedded with crevasse splay/sheet flood facies beds where they drape over the sandstones with an undulating contact with the underlying bed and a flat contact with the overlying bed (e.g. Beds 384-386, Log 7).

2.3.5.6 Zc – Coaly siltstone

These are either hard, black, cherty siltstones or shaley, friable siltstones, with an abundance of carbonaceous material and some recognisable fossil plant fragments occur rarely in beds 0.2 – 0.8 m thick (Figure 2.7, D). They predominantly occur on Coal Nunatak (Beds 622, Log 9, Bed 631, Log 10 and Bed 644, Log 11) but one is also present on East Titan Nunatak (Bed 483, Log 7). They occur above crevasse splay/sheet flood deposits and overbank fines such as Sf.

2.3.6 Interpretation of overbank fines facies

These fine sandstones, siltstones and mudstones all occur associated with palaeosol horizons and *in situ* upright fossil trees and fossil plants. They are commonly horizontally laminated, suggesting floodplain deposition by suspension fallout, either from floodwaters or standing water from rising water tables (Collinson 1996; Spicer *et al.* 2002). Interbedded sandstone and siltstone units (ZS & MSf) are often discontinuous and finely laminated, possibly a result of deposition in abandoned river channels with each lamination representing the deposit of a single flood event (Collinson 1996).

Massive structureless siltstones (Zs) up to 1 m thick occur frequently and the lack of structure and evidence of soft sediment deformation beneath them suggest they are a result of rapid deposition by floods, accounting for the delicate fossil plants and *in situ* fossil trees found preserved within them. The occurrence of massive siltstone units within a floodplain sequence has been suggested as evidence for the floodplain being submerged by floodwaters only and not rising water tables (Collinson 1996).

The fine grain size and thickness of individual beds of the cherty siltstones (CZ) however suggests deposition within standing water on the floodplain, possibly from water-table rise, with fine laminae suggesting gentle deposition from suspension fallout of sediments within the water column. The carbonaceous laminae within the laminated siltstones (LZ) also suggest deposition from standing water after flood events, although the occurrence of this sub-lithofacies as sequences interbedded with other flood deposits suggests they are the result of frequent flooding events on the floodplain.

The grey colour of the overbank fines suggests a water-logged environment more indicative of high water tables, however as will be discussed in detail in the following chapter (Chapter 3, Palaeosols) features within the palaeosols agree with the evidence that rising water tables and water-logging were not characteristic of the floodplains on southeastern Alexander Island.

The coarser units that occur within the overbank fines (Sf, Sfg & Zs) with horizontal and occasionally ripple laminae are often associated with the crevasse splay sandstones and laterally change to crevasse splay deposits (e.g. the overbank fines (Sf) of Bed 207, Log 4 correlates with the crevasse splay sandstone (Sxb) of Bed 285, Log 5; Collinson 1996).

Thin coaly layers (Zc) that crop out on Coal Nunatak are the result of thick layers of leaf litter that collected on the floodplain during periods of little clastic deposition by floods. The rarity of these beds elsewhere on the southeastern nunataks suggests that flooding was frequent enough to prevent the formation of thick leaf litter layers. The presence of soft sediment deformation (Figure 2.7, C) suggests the overlying crevasse splay units were deposited very rapidly.

2.3.7 Soil facies

Over ninety palaeosol horizons are recognised within the sections on Citadel Bastion, Titan Nunataks and Coal Nunatak. They occur frequently on all nunataks, interbedded with overbank fines, crevasse splay sandstones and even channel-fill sediments. Laterally they can be traced for 10's, sometimes 100's, of metres although their undulating nature makes correlation between sites difficult. The soil facies will be discussed in great detail in the following chapter (Chapter 3 Palaeosols), therefore only a brief summary is given below.

2.3.7.1 P – Palaeosol

The palaeosols occur either as beds of carbonaceous mudstone, siltstone or fine sandstone up to 0.6 m thick representing the organic-rich upper horizon of a soil (e.g. Bed 115, Log 2), or they occur as weathered sandstones of either channel-fill or crevasse splay/sheet flood facies showing soil characteristics such as peds (Chapter 3, Section 3.4.2), representing the altered lower horizon of a soil (e.g. Bed 166, Log 4). They often contain *in situ* roots, rootlets, fossil plants and fossil upright trees.

2.3.8 Interpretation of soil facies

The palaeosol horizons represent a period of exposure on the floodplain area with enough time for weathering processes to break down the bedrock and form an organic-rich soil. Some palaeosols are thick and have well-formed upper and lower horizons and contain large *in situ* up right fossil trees and plants. The diverse vegetation and the fact that large trees were supported suggest that the soils were fairly mature and were exposed for a long period of time, possibly thousands of years. However immature characteristics of these palaeosols puts a maximum age of no more than tens of thousands of years (Chapter 3, Section 3.6).

Palaeosol horizons that occur interbedded between channel-fill facies indicate that the sandstones were exposed for a period of time, possible an abandoned channel of the river system that was periodically exposed during times of low-stand but reactivated during high-stand periods.

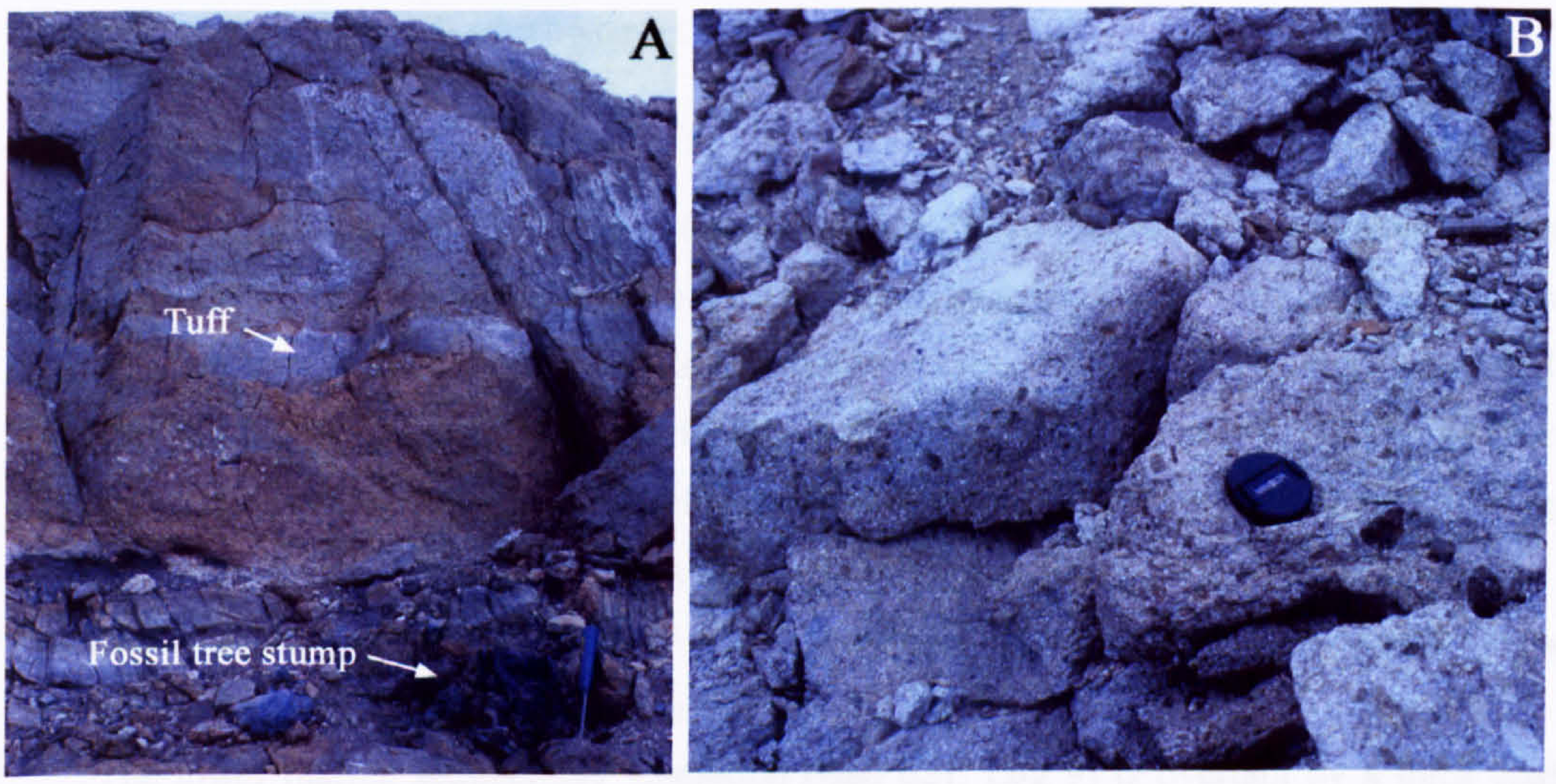
2.3.9 Volcanic ash fall facies

Primary volcanic sediments are only found on Citadel Bastion and Coal Nunatak (Figure 2.2, B & D) where they occur interbedded with channel-fill facies and floodplain sediments. The tuff on Citadel Bastion (Beds 193-197, Log 4) is 11 m thick and is underlain by channel-fill sandstones with a sharp but non-erosive contact and overlain by a thick siltstone bed again with a non-erosive boundary. This tuff bed is discontinuous as it does not outcrop on the log from location KG 4918 (Log 5) which is ~ 1 km away. The tuff beds on Coal Nunatak (Beds 595-599, Log 9) form a total thickness of 13 m (including a scree gap of 3.5 m between beds) and have an undulating contact with the underlying palaeosol horizon, which has rooted *in situ* fossil trees that are preserved within the tuff beds (Figure 2.8, A). Slope scree overlies these tuff beds. This tuff bed appears to be laterally continuous for at least 1.5 km, possibly more.

2.3.9.1 V – Volcanic ash

The tuff on Citadel Bastion grades up from grey, coarse lithic-lapilli tuff containing lapilli up to 30 mm in diameter in an ash matrix, to white, fine pumiceous tuff in the upper sections. The volcanic fragments in the lower sections have been largely altered to zeolites. The tuff on Coal Nunatak is a massive grey coarse lithic- lapilli tuff at the base, changing to a pumiceous ash containing poorly sorted pumice bombs ranging from 10 to 100 mm in diameter (Figure 2.8, B). There is then a gap in the section followed by a grey pumiceous ash with pumice clasts < 10 mm forming clast-wide bands throughout the otherwise massive matrix. Black carbonaceous material is visible throughout all ash beds.

Figure 2.8 Volcanic tuff on Coal Nunatak. A) Basal lithic-lapilli tuff with *in situ* fossil tree (arrow). Hammer is 35 cm high. KG 4919, Bed 595, Log 9. B) Pumice bed. Lens cap 5.5 cm. KG 4919, Bed 598, Log 9.



2.3.10 Interpretation of volcanic ash facies

The grading of grain size within the tuff beds on Citadel Bastion suggests they are ash fall deposits, formed by vertical projections of particles from a volcanic vent (Fisher & Schmincke 1984). Ash fall deposits can cover a wide area and are normally deposited over several hours. The presence of pumice, the relatively thin bed thickness and the combination of lapilli and ash suggests a cataclysmic plinian style of eruption (Bardintzeff 2000).

The massive nature of the tuff beds on Coal Nunatak suggests a very different style of deposition. Thick beds with no internal features, poorly sorted clasts within a fine-grained matrix and lapilli and bomb size fragments are characteristic of ash flows (Fisher & Schmincke 1984). Similarly, alignment bedding (lining up of isolated fragments or bands of fragments within an otherwise structureless bed; Fisher & Schmincke 1984) is also characteristic of ash flows. The alignment bedding seen on Coal Nunatak closely resembles that of the tuffs seen in the Ubehebe Craters, California, which formed from pyroclastic flows (Crowe & Fisher 1973). Ash flow deposits are a result of vertically or laterally directed explosive emissions of gas and solids and the size of the matrix fraction within these tuff beds suggests a St Vincent type of flow (Bardintzeff 2000). The compositional change at the base of these tuff beds from a lithic-rich to pumice-rich deposit may reflect a change in the nature of the material erupted (Nichols & Cantrill 2002).

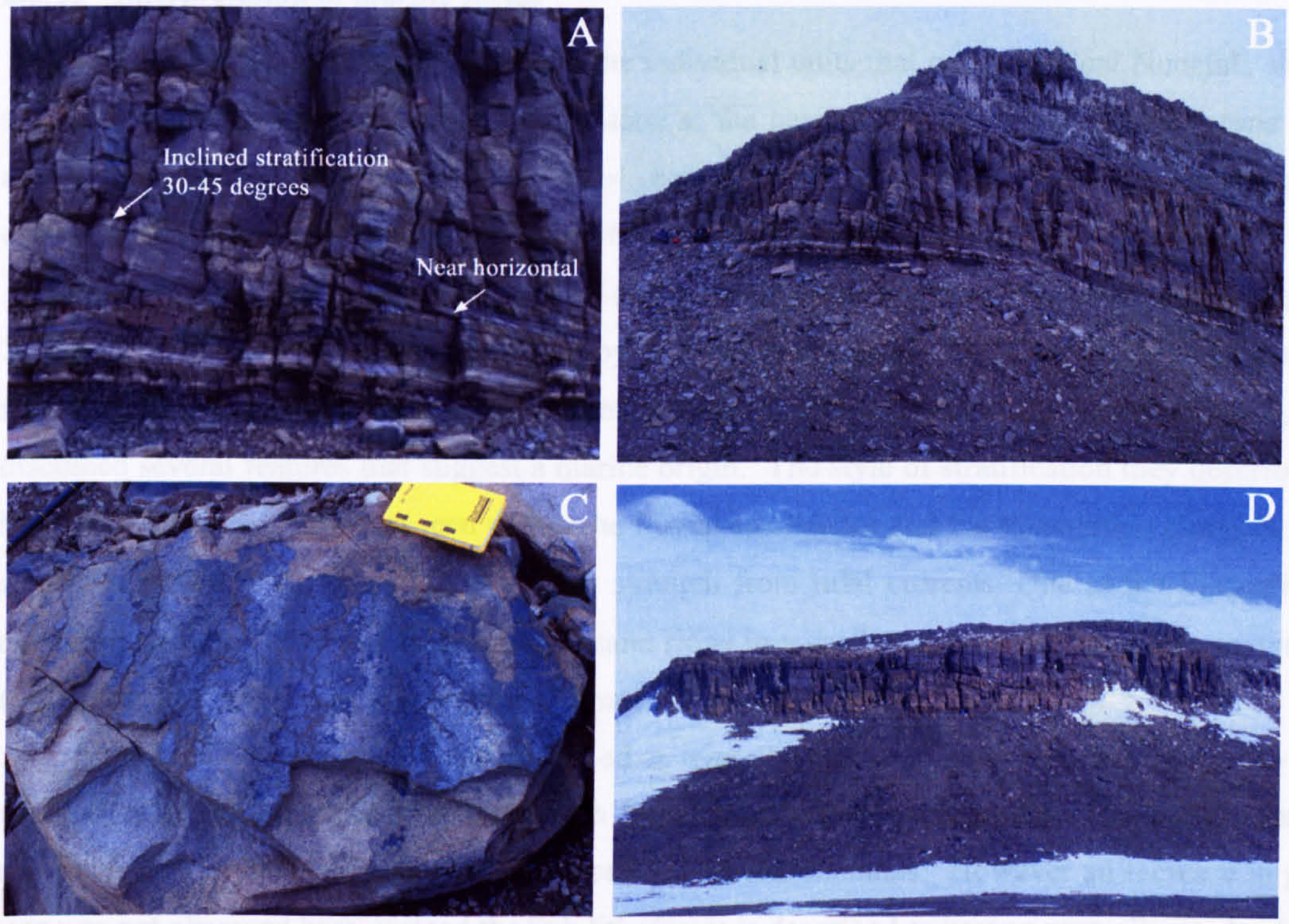
All sandstones within the studied section have a volcaniclastic component within them, but the presence of primary volcanic ash beds containing lapilli and pumice provides evidence for contemporaneous volcanic activity during sedimentation. The source area for the volcanic material within the sandstones and the tuff beds was likely to be the volcanic arc on the Antarctic Peninsula to the east of Alexander Island (Browne 1996).

2.3.11 Marine facies

In the upper units of Coal Nunatak there are two individual sedimentary formations of marine sediments within the Coal Nunatak Member that extend laterally for the full length of exposure (~ 2.2 km). They comprise sequences of Sxh lithofacies interbedded with fluvial sediments (Bed 621, Log 9 and Bed 664, Log 11). Fine interbedded black mudstones and sandstones that show ripple laminations on their upper surface underlie both the marine sedimentary formations. This rippled surface forms an undulating but non-erosive contact with the marine sediments above. Rare fragments of fossil plants and wood within the interbedded mudstones and sandstones at the base of the units were the only fossils found within the marine facies sediments.

The lower marine sedimentary formation (Bed 621, Log 9) is overlain by a thick coalified layer which has a sharp but non erosive base, then by thick channel-fill facies with trough cross-bedding (Figure 2.9 B). The upper marine sedimentary formation (Bed 664, Log 11) is overlain by overbank fines, Sf lithofacies, which also has a sharp but non-erosive contact with the marine sediments below (Figure 2.9 D). The fluvial sediments above and below both marine sedimentary formations suggest a palaeoflow direction towards the northwest.

Figure 2.9 Features within the marine facies. A) Lower marine sedimentary formation on Coal Nunatak with low angle stratification of Sxh lithofacies visible (arrow). See B for scale. KG 4919, Bed 618, Log 9. B) Lower marine sedimentary formation as in A. Rucksack to left for scale. KG 4919, Bed 615, Log 9. C) Symmetrical ripples within the lower marine sedimentary formation on Coal Nunatak. Increments on scale 2 cm. KG 4922, Bed 620, Log 9. D) Upper marine sedimentary formation on Coal Nunatak. 5 m high cliff section. KG 4902, Bed 662-664, Log 11.



2.3.11.1 Sxh – Inclined heterolithic stratified sandstone

Coarse, grading up to medium grained sandstone with beds 0.8–1 m thick, with inclined low-angle stratification defined by dark organic rich muds (Figure 2.9 A). The thickness of the mudstone partings and the sandstones decreases down dip of the inclined strata. The dip of the inclined strata is approximately 30-45 ° in the middle of the unit, shallowing to near horizontal at the base (Figure 2.9 A). The direction of dip of the foresets is towards the northwest, the same as that within the surrounding fluvial sediments. Some thin sandstone beds at the base show ripple–cross-lamination, with symmetrical ripples visible on their exposed upper surface (Figure 2.9 C). These ripples occur with wavelengths from millimetres to centimetres wide.

The lower marine sedimentary formation outcrops at the same level along the southern and middle sections of Coal Nunatak, and can be followed for ~ 2.5 km between locations KG 4930 in the middle and KG 4920 in the south of Coal Nunatak (Figure 2.1). The upper marine sedimentary formation, occurring 40 m above the lower one is less extensive as it first outcrops at location KG 4927 and then is seen to pinch out at location KG 4930 (Figure 2.1), a total length of exposure of 0.5 km (Figure 2.9 D).

2.3.12 Interpretation of marine facies

The marine facies sediments forming the individual units that occur on Coal Nunatak, show a sequence of interbedded mudstone and siltstone at the base, a foreset of inclined sandstone beds, and a top set of fluvial sandstones. This sequence can occur under a Gilbert delta-type of environment where bars are built out into restricted water bodies (Reading & Collinson 1996).

One of the marine sedimentary formations on Coal Nunatak (lower unit described in Section 2.3.11.1) has been interpreted previously by Nichols and Cantrill (2002) as a tidal sand ridge, formed within a tidally-influenced upper shoreface setting. Despite the lack of marine fossils, they discussed several features that suggest a marine origin. The style of stratification they described as being very different from that seen within the fluvial sandstones and the heterolithic character they suggested was a result of variation in flow strength from tidal currents. Due to the inequality of currents that flow either side of an oblique sand ridge in a shallow marine environment, major low angle internal stratification is preserved (Johnson & Baldwin 1996).

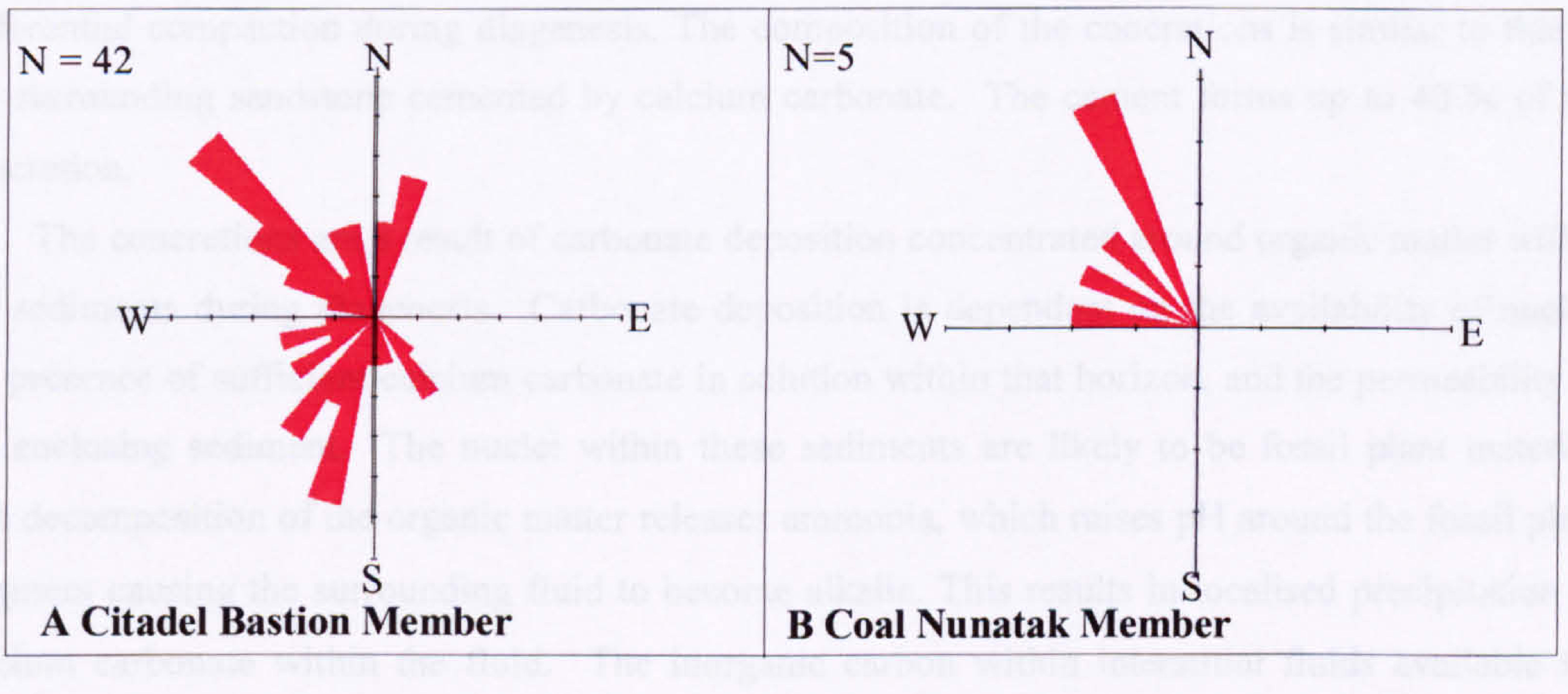
Nichols & Cantrill (2002) also described an overall increase in grain size up through the unit, which they suggested is due to a decrease in flow strength down through the water body, a feature more common in open shelf settings than confined fluvial channels. However an increase in grain size was not observed here, instead the Sxh lithofacies is described as having normally graded beds.

The base of the two units on Coal Nunatak show features which can be characteristic of sand ridge formations: thinly bedded fine sandstones and siltstones with low amplitude symmetrical ripples grading upwards to thicker bedded sandstones with wavy laminations (Johnson 1977). These are deposited in low energy conditions through suspension fallout with wave motions forming ripples during higher energy periods. The marine sedimentary formations that outcrop on Coal Nunatak are likely to have formed as marine tidal sandbars in a shoreface environment.

2.4 Palaeocurrent analysis

Palaeocurrent data were obtained from all units that showed cross-stratification at any scale, within the Triton Point Formation on the southeastern nunataks. Data from both channel sandstones and overbank sandstones were recorded for the Citadel Bastion Member of the Triton Point Formation. The channel sandstones indicate dominant current directions towards the northwest and southwest although they include palaeoflow indicators in all quadrants (Figure 2.10 A) while the overbank sandstones indicate flow to the northwest. Palaeoflow within the channel sandstones of the Coal Nunatak Member was towards the northwest with no indicators in any other quadrants (Figure 2.10 B). The general south-westerly or north-westerly direction of all the palaeoflow data suggests a derivation from the east, undoubtedly off the volcanic arc now represented by the Antarctic Peninsula.

Figure 2.10 Palaeoflow indicators for the Triton Point Formation on the southeastern nunataks of Alexander Island, Antarctica. A) All palaeoflow directions recorded from the channel sandstones of the Citadel Bastion Member (the length of each vector is proportional to the frequency of orientations lying within that sector). B) All palaeoflow directions recorded within the channel sandstones of the Coal Nunatak Member.



A Citadel Bastion Member **B Coal Nunatak Member**

These data are similar with that recorded by Nichols and Cantrill (2002) from the southeastern nunataks, who suggest a mean palaeoflow within the Citadel Bastion Member towards the southwest and within the Coal Nunatak Member towards the west. Earlier data from more northern exposures of the Triton Point Formation (Pagoda Ridge, Phobos Ridge and Triton Point; Figure 1.5) indicate palaeoflow in a north and northwesterly direction (Moncrieff 1989). This 90 ° shift in current direction from northwest to southwest southward was interpreted by Nichols and Cantrill (2002) as a radial pattern of flow of the fluvial channels within the Triton Point Formation. The data presented here suggest that the flow direction was fluctuation across a small area, possibly indicating a fluctuating radial flow pattern.

2.5 Diagenesis and carbonate concretions

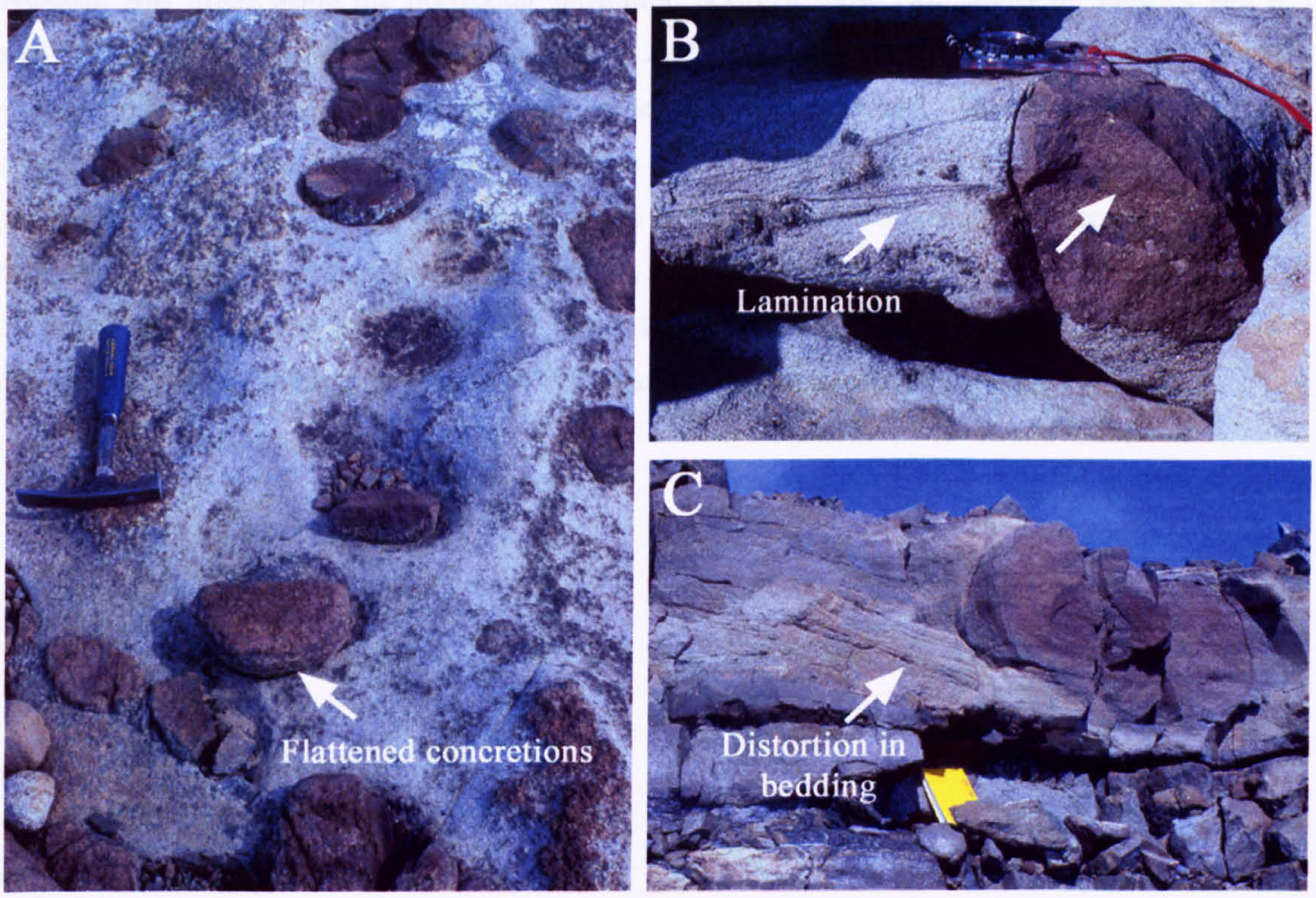
Carbonate concretions are found at seven locations; four within the sediments of the Citadel Bastion Member on Citadel Bastion (Beds 174 & 203, Log 4 and Beds 254 & 313, Log 5) and three within the sediments of the Coal Nunatak Member on Coal Nunatak (Bed 574 & 608, Log 9 and Bed 675, Log 11). The concretions occur within thick (up to 2 m), coarse, white sandstone beds that contain volcanic material and are cross-bedded.

The concretions are predominately ellipsoid in shape, the long axis parallel to bedding (Figure 2.11 A). They range in size from 4 cm thick by 11 cm wide to 76 cm thick by 90 cm wide (Figure 2.11 C). The contact between the concretions is well defined and they are weathered to a distinct orange-brown colour. Laminations within the surrounding sediment continue through the concretion (Figure 2.11 B), suggesting post-depositional formation and in places the bedding within the surrounding sediment shows distortion around the concretion (Figure 2.11 D), indicating differential compaction during diagenesis. The composition of the concretions is similar to that of the surrounding sandstone cemented by calcium carbonate. The cement forms up to 40 % of the concretion.

The concretions are a result of carbonate deposition concentrated around organic matter within the sediments during diagenesis. Carbonate deposition is dependant on the availability of nuclei, the presence of sufficient calcium carbonate in solution within that horizon, and the permeability of the enclosing sediment. The nuclei within these sediments are likely to be fossil plant material. The decomposition of the organic matter releases ammonia, which raises pH around the fossil plant fragment causing the surrounding fluid to become alkalie. This results in localised precipitation of calcium carbonate within the fluid. The inorganic carbon within interstitial fluids available for carbonate precipitation originates from microbial activity, either aerobically through the dissolution of carbonate within the sediments or, in the absence of oxygen, through the formation of bicarbonate (Allison 1990).

Carbonate concretions have been associated with pedogenic diagenesis and are described as characteristic of well-drained soils (Retellack 2001). However, out of the seven localities where concretions were described within this study, only three were associated with a palaeosol horizon. Furthermore, no concretions formed beneath the other 97 palaeosols identified within the section on the southeastern nunataks of Alexander Island. Carbonate concretions have been described previously from the Fossil Bluff Group outcropping further north than this study (Triton Point to Succession Cliffs; Figure 1.5; Horne & Taylor 1969), where no palaeosols have been described. Horne & Taylor (1969) describe diagenetic cannon-ball concretions and coalesced concretions forming continuous stratum. Although some of the carbonate concretions may be due to local pedogenic processes, the majority of the carbonate concretions formed throughout the Fossil Bluff Group are likely to be a result of regional diagenesis rather than localised pedogenic processes.

Figure 2.11 Carbonate concretions within the sediments of the southeastern nunataks, Alexander Island. A-C, concretions within coarse tuffaceous sandstones of the Citadel Bastion Member on Citadel Bastion. A) Flattened concretions (arrow) 11 cm wide by 4 cm thick. Hammer is 35 cm high. KG 4915, Bed 174, Log 4. B) Concretion 7 cm wide by 13 cm thick. Laminations within surrounding sandstone (arrow) continue through concretion (arrow). Compass is 10 cm long. KG 4918, Bed 254, Log 5. C) Concretion 90 cm wide by 76 cm thick. Bedding within sandstone shows distortion (arrow) around concretion. Notebook is 20 cm long. KG 4918, Bed 313, Log 5.



2.6 Correlation of stratigraphy

Comparison between measured sections (Figure 2.2, A-D) using a regional dip of 8 ° towards the southeast indicates that there is no stratigraphic overlap between the three nunataks. Assuming that all three nunataks are part of the same structural block and that there are no faults between them that may cut out or repeat stratigraphy (see Section 2.1), the minimum estimate of the total thickness of the Triton Point Formation in this area, is the sum of all the logs, that is 937 m.

An estimate of the stratigraphic gap between the top of Citadel Bastion and the base of Coal Nunatak was made using the horizontal separation between these two points of 3300 m and a regional dip of 8 ° towards the southeast (Figure 2.12). This dip was found to be the mean of the range of dips within the area as well as the mode of all dips recorded. The separation using this average dip was 321 m, with a maximum estimate of 549 m (dip of 12 °). The minimum estimate of the gap (assuming no faulting) is provided by the 200 m thickness of sediments recorded on Titan Nunataks, which must fit between Citadel Bastion and Coal Nunatak.

The total estimated thickness of the Triton Point Formation within this area is thus 1058 m (Figure 2.13) with a minimum estimate of 937 m and a maximum estimate of 1286 m.

Figure 2.12 Calculation of the stratigraphic gap between Citadel Bastion and Coal Nunatak. A) A map of the two nunataks identifying the points between which the horizontal separation was measured (A & B) and the height above ice level of the two points. B) A sketch to show how the stratigraphic gap was calculated using the regional dip, horizontal separation and trigonometry. C) The calculations of the stratigraphic gap.

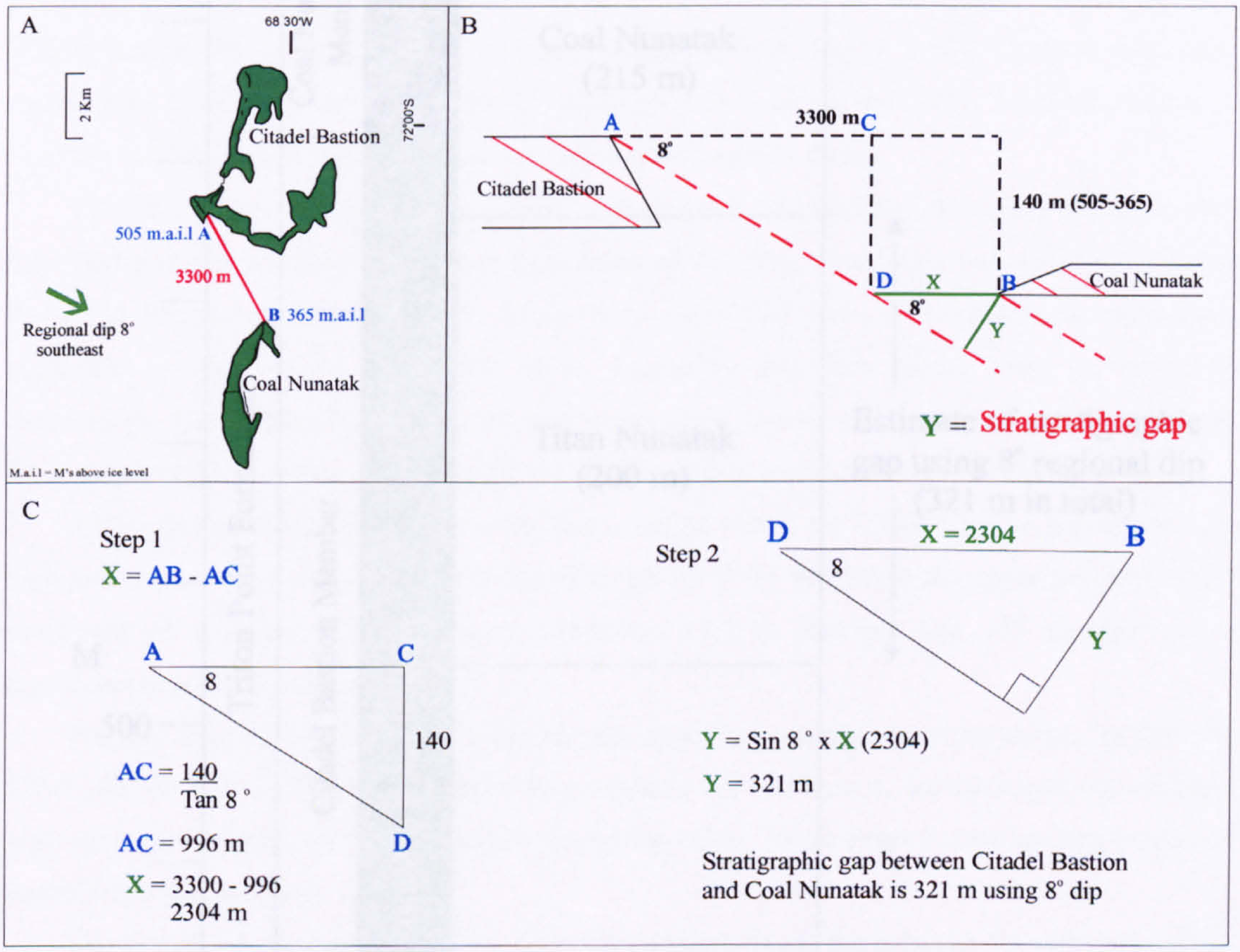
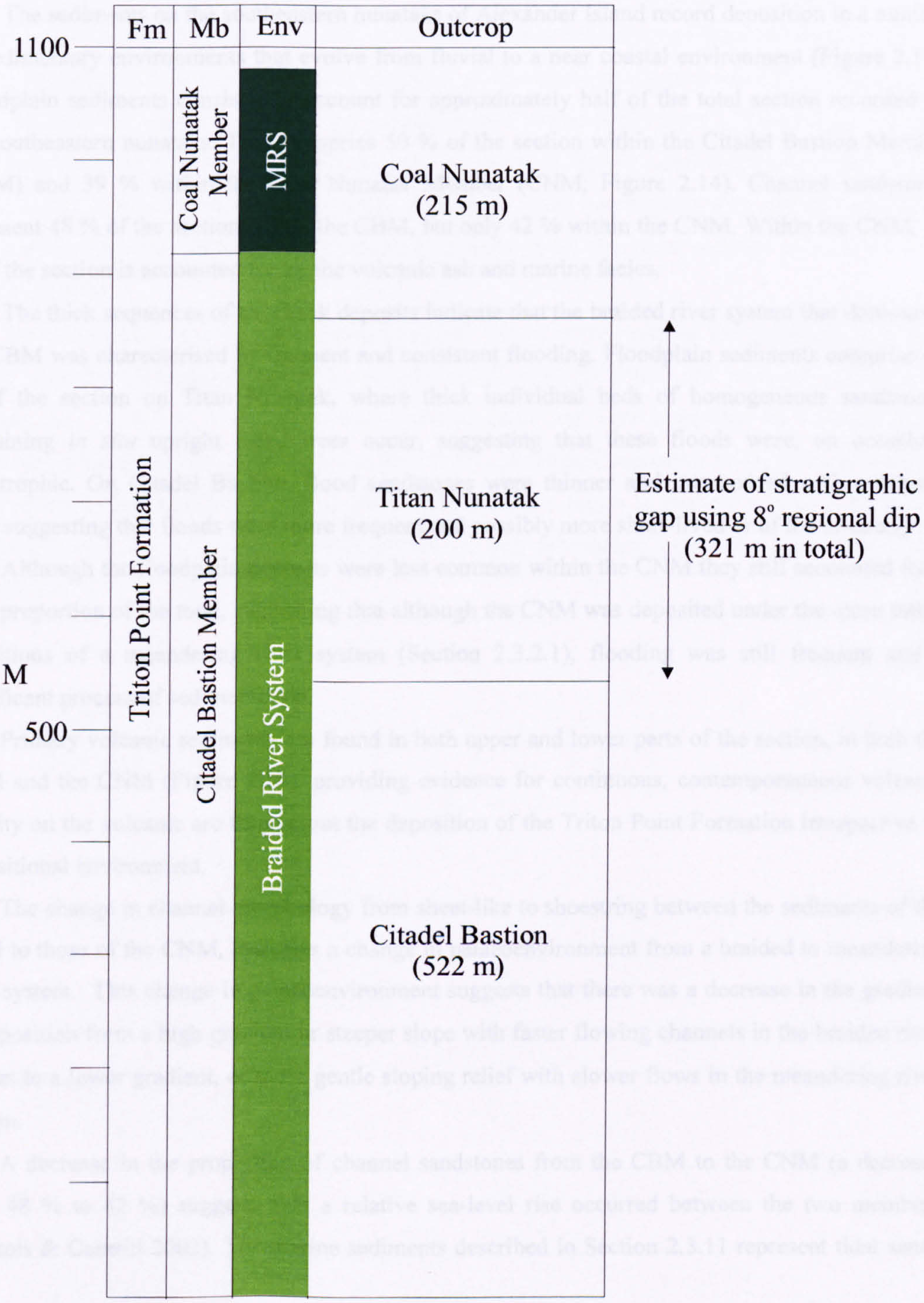


Figure 2.13 A summarised stratigraphy of the Triton Point Formation on the southeastern nunataks of Alexander Island, Antarctica, identifying the thickness of section on individual nunataks and how these correlate with each other. MRS is Meandering River System, Fm is Formation, MB is Member and Env is environment.



2.7 Evolving sedimentary environments

The sediments on the southeastern nunataks of Alexander Island record deposition in a number of sedimentary environments that evolve from fluvial to a near coastal environment (Figure 2.14). Floodplain sediments consistently account for approximately half of the total section recorded on the southeastern nunataks. They comprise 50 % of the section within the Citadel Bastion Member (CBM) and 39 % within the Coal Nunatak Member (CNM; Figure 2.14). Channel sandstones represent 48 % of the section within the CBM, but only 42 % within the CNM. Within the CNM, 17 % of the section is accounted for by the volcanic ash and marine facies.

The thick sequences of overbank deposits indicate that the braided river system that dominated the CBM was characterised by frequent and consistent flooding. Floodplain sediments comprise 63 % of the section on Titan Nunatak, where thick individual beds of homogeneous sandstones containing *in situ* upright fossil trees occur, suggesting that these floods were, on occasions catastrophic. On Citadel Bastion, flood sandstones were thinner and interbedded with overbank fines suggesting that floods were more frequent and possibly more short-lived or of lower-energy.

Although the floodplain deposits were less common within the CNM they still accounted for a high proportion of the total, suggesting that although the CNM was deposited under the more stable conditions of a meandering river system (Section 2.3.2.1), flooding was still frequent and a significant process of sedimentation.

Primary volcanic sediments are found in both upper and lower parts of the section, in both the CBM and the CNM (Figure 2.14), providing evidence for continuous, contemporaneous volcanic activity on the volcanic arc throughout the deposition of the Triton Point Formation irrespective of depositional environment.

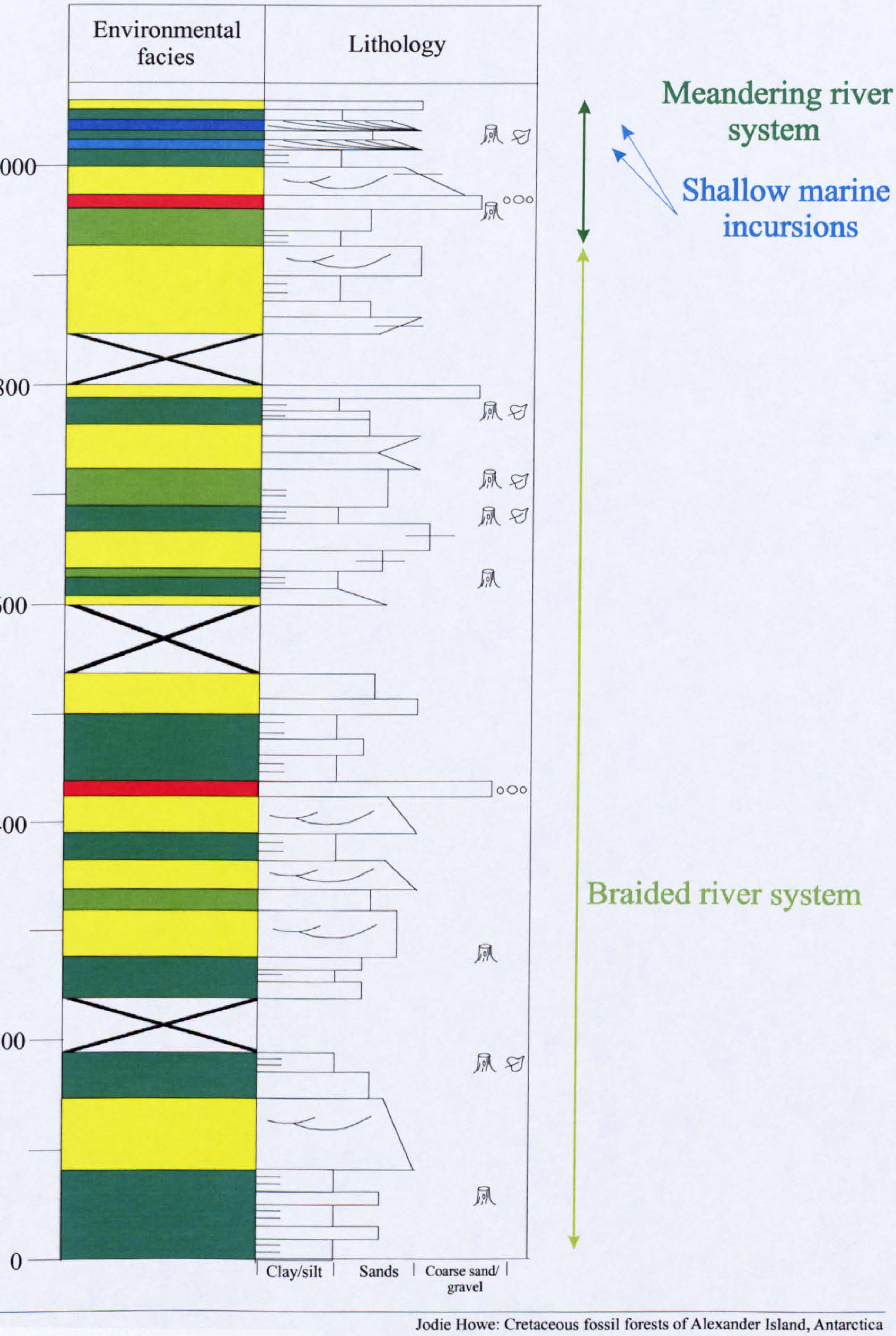
The change in channel morphology from sheet-like to shoestring between the sediments of the CBM to those of the CNM, indicates a change in palaeoenvironment from a braided to meandering river system. This change in palaeoenvironment suggests that there was a decrease in the gradient of deposition from a high gradient or steeper slope with faster flowing channels in the braided river system to a lower gradient, or more gentle sloping relief with slower flows in the meandering river system.

A decrease in the proportion of channel sandstones from the CBM to the CNM (a decrease from 48 % to 42 %) suggests that a relative sea-level rise occurred between the two members (Nichols & Cantrill 2002). The marine sediments described in Section 2.3.11 represent tidal sands ridges and their presence further supports a relative sea-level rise within the upper reaches of the Triton Point Formation and indicate a change to a more coastal floodplain environment.

The Triton Point Formation occurs as a thick wedge within the Neptune Glacier Formation (Chapter 1, Figure 1.6) and the sequence of sediments from the Neptune Glacier Formation and the Triton Point Formation have long been regarded as representing a regression-transgression cycle. This cycle is seen within changes of the lithofacies and biofacies (Chapter 1, Figure 1.7) and have been interpreted as a result of 'tectonoeustatic' cycles in a rapidly subsiding basin (Moncrieff & Kelly 1993). The unusual display of thick floodplain fines interbedded with channel sediments within a braided river setting also suggests major tectonic or base level controls on sedimentation (Reading 1996).

A lack of evidence for any coeval sea-level fall in other parts of the Antarctic Peninsula makes a eustatic interpretation equivocal (Moncrieff & Kelly 1993) and regional uplift in the volcanic arc, related to a mid-Cretaceous mantle plume has been suggested as a cause of the shallowing (Vaughn 1995; Nichols & Cantrill 2002). A gradual reduction in depositional gradient (a change from braided to meandering river systems) and a return to shallow marine sediments is interpreted as a consequence of erosion of the arc and subsidence within the basin (Nichols & Cantrill 2002).

Figure 2.14. A summary log for the total section of the Triton Point Formation that outcrops on the southeastern nunataks of Alexander Island, identifying the change in environment through the section. For meaning of symbols and colours see key for Fig 2.2, with the exception of the plant symbol which represents the location of a plant sampling site.



Chapter 3 Palaeosols

3.1 Introduction

This chapter looks in detail at the well-developed palaeosols identified on the southeastern nunataks of Alexander Island. They were briefly introduced in the previous chapter, occurring within the sections on Citadel Bastion, Titan Nunataks and Coal Nunatak, as laterally continuous horizons containing large upright fossil trees and fossil plants in their original growth positions.

The palaeosols of the Cretaceous forests on Alexander Island are exceptionally well preserved. They show distinctive soil structures such as peds, and soil horizons are apparent, and even though the soils have suffered some burial metamorphism, the original soil structures have not been destroyed. Despite this, the palaeosols have not been previously well described nor their important palaeoenvironmental record deciphered. The palaeosols not only provide evidence for the ancient vegetation and ecosystems within the Cretaceous forest, but also contain important signals of the palaeoclimate that are independent of evidence from other associated sediments and fossils. In addition the palaeosols also provide information on the diagenesis of the Triton Point Formation.

In this chapter the palaeosols are described in detail, looking at their occurrence in the field as well as micro-morphological features, and then classified according to modern soil classification schemes. The palaeoenvironmental significance of the palaeosols is then discussed with interpretations for the general prevailing climate of the Cretaceous forests. Finally this chapter looks at the metamorphic overprint of the palaeosols and the diagenesis of the Triton Point Formation.

3.2 Sedimentary occurrence

The palaeosols occur throughout the section on the southeastern nunataks, interbedded with overbank fines, crevasse splay sandstones and channel-fill sediments, representing the pedogenic alteration of exposed floodplain sediments (Chapter 2, Section 2.3.7). The palaeosols (lithofacies P; Chapter 2, Section 2.3.7) either occur as carbonaceous mudstones, representing the organic-rich upper horizon of a soil, or as weathered sandstones showing soil characteristics (Chapter 2, Section 2.3.7). The palaeosols occur above almost all other lithofacies, including floodplain sediments such as Su and Shl lithofacies, and channel-fill sediments such as Scg and Sxb lithofacies (Chapter 2; Appendix 2, Sedimentary logs). They are frequently overlain by overbank fines, commonly Z, ZS and Sf lithofacies which contain *in situ* fossil plants, or by coarser flood deposits such as Su and Shl, which contain plant debris and *in situ* fossil trees (Chapter 2; Appendix 2, Sedimentary logs).

Ninety-nine palaeosol horizons were identified throughout the strata on Citadel Bastion, Titan Nunataks and Coal Nunatak on Alexander Island. Fifty-one palaeosol horizons were identified on Citadel Bastion Nunataks, three of which had *in situ* palaeosol material that could be sampled for petrographic work (locations: KG.4911, KG.4912, KG.4915; Figure 2.1). On Titan Nunataks twenty-five palaeosol horizons were recorded, six of which were preserved well enough to sample (locations: KG.4935, KG.4937, KG.4938, KG.4941, KG.4942, KG.4943; Figure 2.1); the rest were identified mainly by rootlet horizons and *in situ* trees. Twenty-three palaeosol horizons were logged on the southern end of Coal Nunatak; three had *in situ* palaeosol material that was sampled (locations: two from the log KG.4919 & KG.4922; Figure 2.1). Table 3.1 gives detailed field descriptions of the palaeosols sampled, while information on all the palaeosols identified within this study can be found in Table A3.1 in Appendix 3. The occurrence of palaeosol horizons are also identified upon the sedimentary logs in Appendix 2 (e.g. Ps12).

Table 3.1 Field descriptions of palaeosols sampled from the southeastern nunataks of Alexander Island. The localities are shown on Figure 2.1 (Chapter 2), locality descriptions can be found in Table A2.1 (Appendix 2), Ps Number (Palaeosol Number) corresponds to numbers given on sedimentary logs (Appendix 2). For lithofacies descriptions refer to Chapter 2.

Locality	Ps No.	Field Description
Citadel Bastion KG 4911	Ps 13	**Upper horizon**: Fine siltstone of varying thickness (max 0.5 m), thinly bedded with an abundance of plant and rootlet debris. Underlain by Sxl and overlain by Shl lithofacies. Palaeosol extends for ~ 100 m of outcrop along which it undulates and peters out, following Cretaceous topography.
KG 4912	Ps 15	**Upper horizon**: Friable mudstone (Msf lithofacies) with plant and rootlet debris, undulates for ~ 20 m before it peters out. Range in thickness from 0.08-0.6 m. Overlain by fine sandstone with organic rich bands and fossilised liverwort mats. **Lower horizon**: Fine sandstone (Sf lithofacies) with plant and wood debris (1 m). Five samples taken.
KG 4915	Ps 31	**Upper horizon**: Friable mudstone (P lithofacies) very weathered and present mainly as scree. No samples taken **Lower horizon**: Palaeosol crops out as fine to medium-grained sandstone beds (Shl lithofacies). Concretions, mottling and ped structures visible over a thickness of 4 m. Palaeosol has poor lateral extent and is lost after ~ 15 m. Eight samples taken.
Titan Nunataks KG 4941	Ps 65	**Upper horizon**: Friable light-grey mudstone (P lithofacies) with black organic material, 0.15 m thick, beneath an *in situ* fossilised tree. P lithofacies undulates and changes thickness for ~ 30 m. Overlain by coarse sandstone (Sxl lithofacies) containing *in situ* fossilised trees. **Lower horizon**: Coarse sandstone bed (Shl lithofacies), 3 m's thick with large-scale (0.25 m wide) columnar ped structures.
KG 4935	Ps 70	**Upper horizon**: Friable mudstone containing an abundance of plant and rootlet debris, 0.3 m thick and exposed for ~ 20 m. Overlain by fine sandstones (Sf lithofacies).
KG 4943	Ps 74	**Upper horizon**: Fine black mudstone (P lithofacies), 0.1 m thick with organic matter. Overlain by coarse sandstone units (Shl) > 10 m's thick, which contain *in situ* fossilised trees rooted within the palaeosol. Laterally extends for ~ 150 m.
KG 4937	Ps 75	**Upper horizon**: Friable light-grey mudstone 0.02 – 0.06 m thick, followed for ~300 m. Overlain by sandstone units (Shl lithofacies) with *in situ* fossilised trees rooted within the palaeosol. **Lower horizon**: Siltstone (Z lithofacies), that contains plant and rootlet debris, 1 m thick.
KG 4938	Ps 76	**Upper horizon**: Friable light-grey mudstone (P lithofacies), 0.3 m thick with plant and rootlet debris. Overlain by thick coarse sandstones (Sxb lithofacies) with fossil wood debris. **Lower horizon**: Siltstone band (0.2 m) with rootlets. Below this, sandstone beds (Sxb lithofacies) with rootlets from above. Exposure of upper horizon only 15 m but palaeosol features seen for ~ 250 m laterally.
KG 4942	Ps 76 (lateral variation)	**Lower horizon**: Light-grey siltstone, 0.3 m thick, containing plant and rootlet debris, traceable for ~70 m. Underlain by coarse grey sandstone (Sxb lithofacies) and overlain by a fine white sandstone (Sf).
Coal Nunatak KG 4919	Ps 79	**Lower horizon**: Fine, light-grey sandstone (Sf), 0.65 m thick with mottling and prominent peds. Overlain by fine siltstones (Z) and underlain by medium sandstone (Su lithofacies).
KG 4919	Ps 83	**Lower horizon**: Fine, off-white sandstone/siltstone (ZS lithofacies), 0.5 m thick with mottling, rootlets from above and rooted *in situ* fossilised trees. Overlain by a volcanic tuff layer (6 m thick) containing *in situ* fossilised trees.
KG 4922	Ps 86	**Lower horizon**: Dark-grey, crumbly mudstone, 0.1 m thick with black plant and rootlet debris. Underlain by a bar unit (Sxs lithofacies) and overlain by fine sandstones interbedded with siltstones (Msf lithofacies), 4 m's thick, with *in situ* fossilised trees.

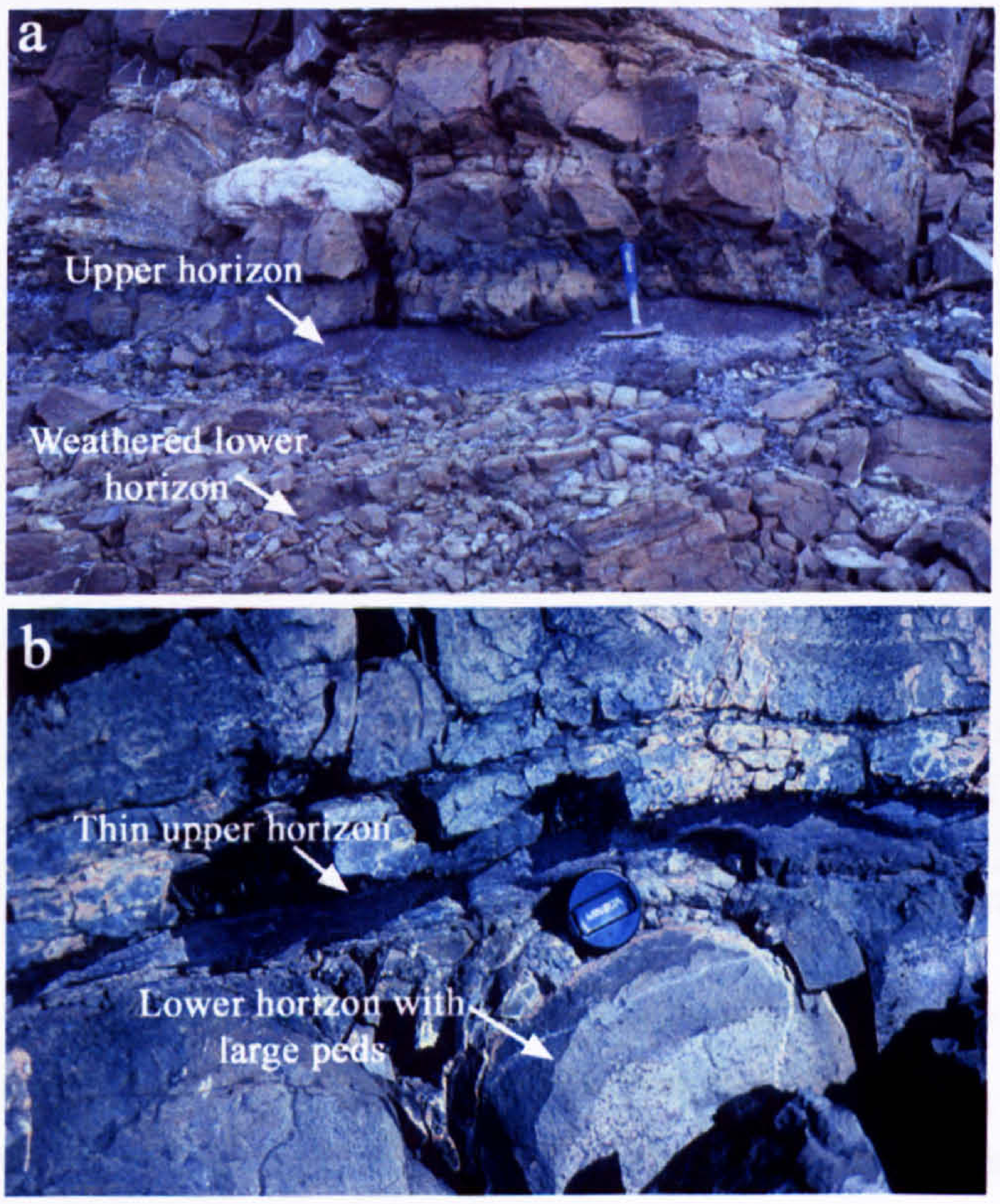
3.3 Field and petrographic descriptions

Palaeosol horizons were identified using the following criteria:

- The presence of *in-situ* tree trunks and other plants with rootlets in the palaeosols
- Recognisable palaeosol features such as ped structures (Section 3.4.2)
- Distinctive organic-rich layers.

The palaeosols have a consistent structure throughout all exposures, although some profiles appear less mature than others. Where well developed, the palaeosols consist of two distinct horizons (Figure 3.1) described below.

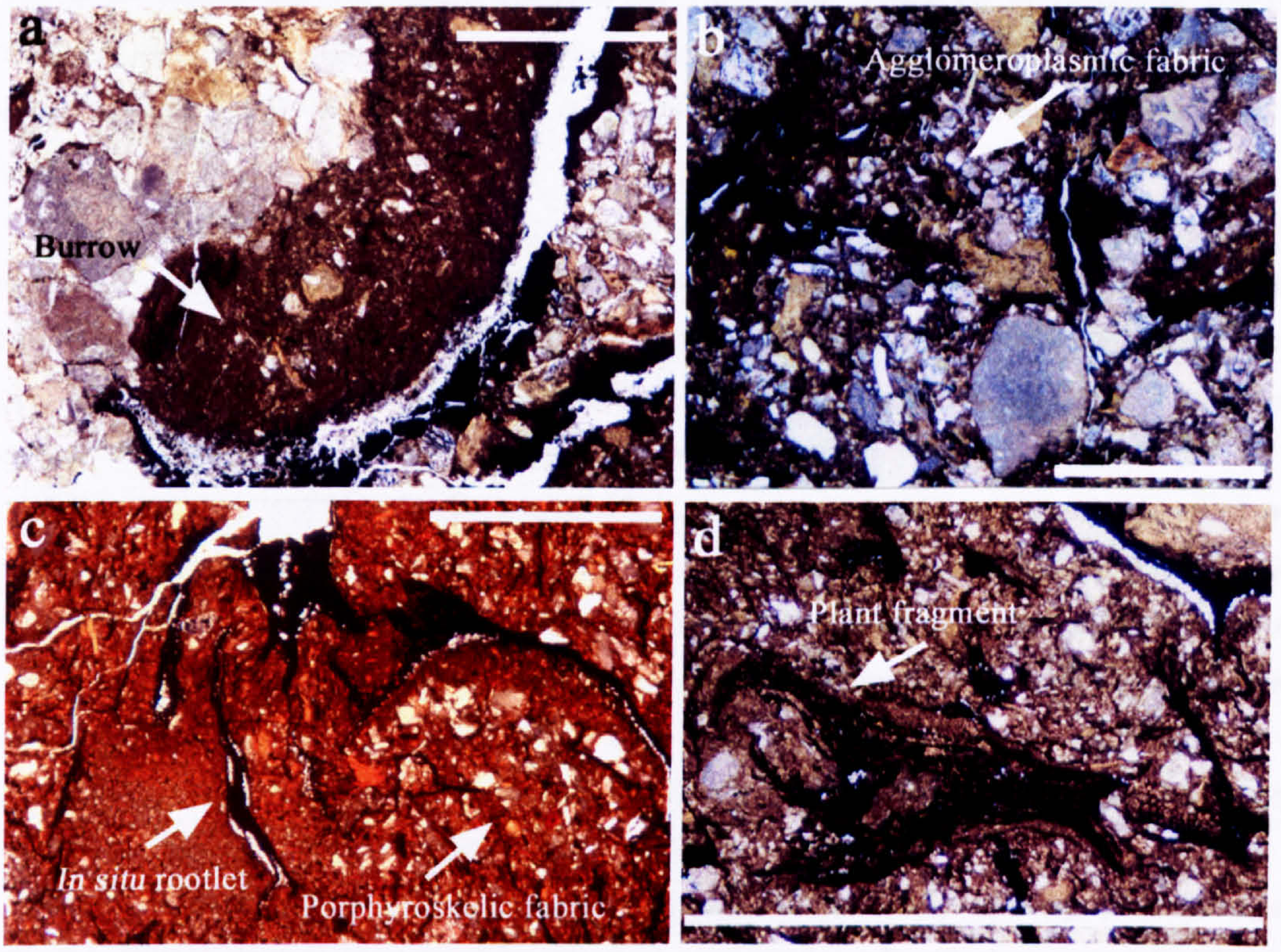
Figure 3.1 Two distinct horizons are visible within the palaeosols on the southeastern nunataks of Alexander Island. a) Palaeosol with a thick organic-rich upper horizon (arrow) and a weathered lower horizon (arrow), KG 4912, Bed 52, Log 1. Hammer is 35 cm high. b) Palaeosol horizon with a thin organic-rich upper horizon (arrow) and a lower horizon with large-scale blocky ped structures (arrow), KG 4941, Bed 434, Log 7. Lens cap is 5.5 cm in diameter.



3.3.1 Upper horizon

The upper horizon is black or dark brown in colour, and varies in thickness from 0.05–0.6 m with lateral undulations (Figure 3.1). These horizons are mainly massive but with a crumbly texture. Occasionally fine laminations of aligned organic material are present but in general all sedimentary structures are lost. The upper horizon is frequently mottled, (mottled areas average 3-4 mm long and 2-6 mm wide) by structures which could be burrows or rootlets, filled with white, fine-grained sandstone or brown clay (Figure 3.2 a).

Figure 3.2 Features within the upper horizons of the palaeosols. Photographs of palaeosol at KG 4935, Bed 479, Log 7. a) A burrow in-filled with brown clay. b) An agglomeroplasmic fabric within the upper horizon. c) Delicate branching *in situ* rootlets in a porphyroskelic fabric. d) A plant fragment with some cell detail. Scale bar in all photographs is 1 mm.



The matrix is dominantly organic or clay rich, with either an agglomeroplasmic (local matrix areas surrounding skeletal grains, terminology of Brewer 1976; Figure 3.2 b) or porphyroskelic (larger grains set within a fine matrix, Brewer 1976; Figure 3.2 c) fabric. In places the matrix contains the clay mineral smectite, which replaces some mineral grains. Detrital grains of quartz, altered feldspars, laumontite, chlorite, volcanic glass shards and rock fragments comprise 5–45 % of this horizon. The chlorite crystals are iron-rich and are often split and contorted. Organic matter (5-40 %) either occurs as brown amorphous material or as identifiable plant structures (Figure 3.2 d), or as branched rootlets (Figure 3.2 c). In most of the upper horizon large pieces of plant debris are coated by laumontite. Laumontite also occurs as small particles within the matrix.

3.3.2 Lower horizon

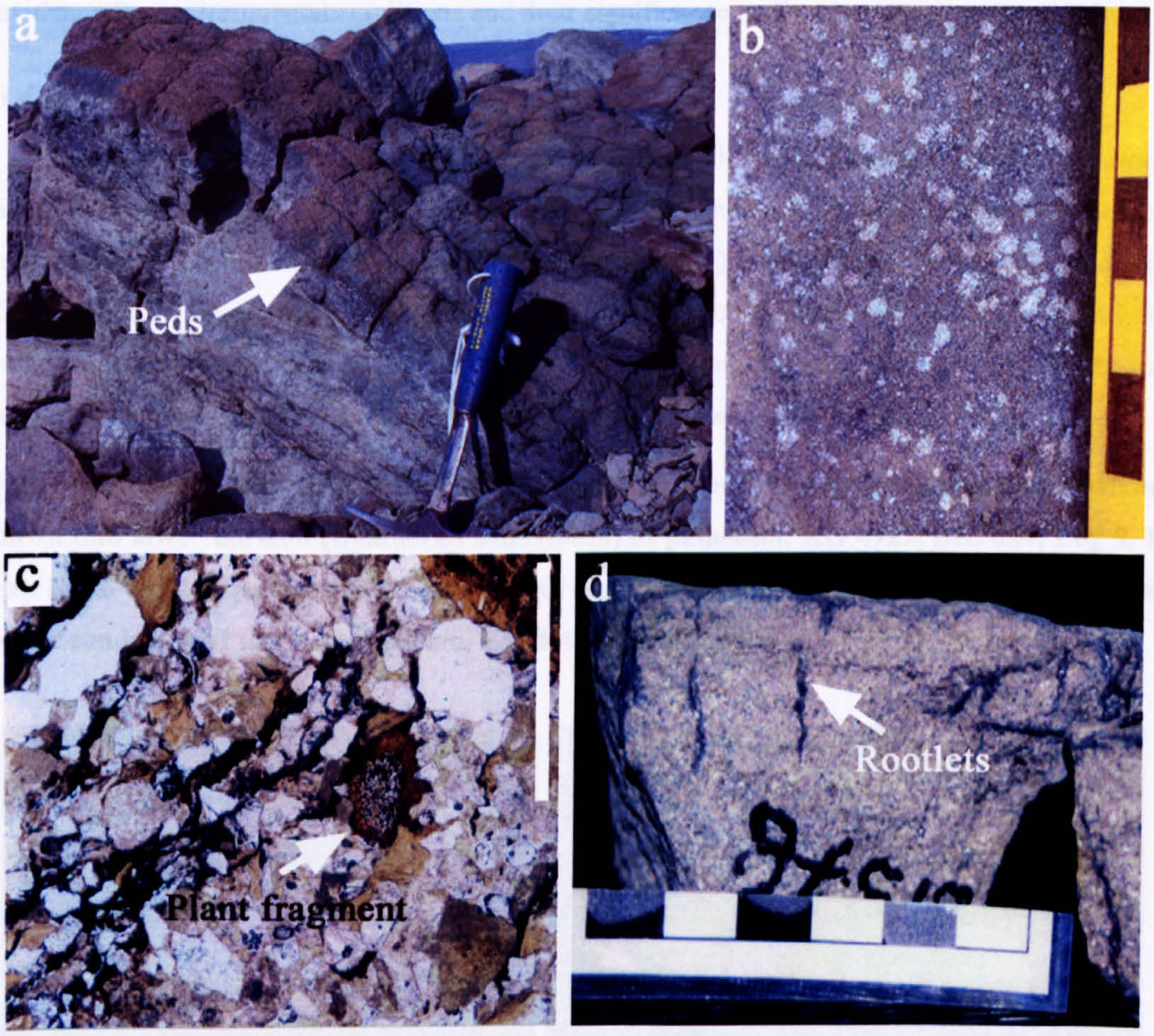
The lower horizon typically consists of light coloured, fine to coarse-grained sandstone (Figure 3.1). This horizon is massive, up to 2 m thick and occasionally banded (20 mm wide bands) due to variations in grain size. These sandstones are similar to the normal fluvial sandstones common throughout the sequence. The upper parts of the lower horizon are commonly darker than the sediment below and are cracked and jointed, forming well-defined ped structures (Figure 3.3 a). The joints around the peds extend vertically for 18-30 mm. Using the classification scheme of Retallack (2001), the peds can be described as either of prismatic type (medium size with 20-50 mm ped diameter) or angular blocky types (fine with 5-10 mm ped diameter or coarse > 50 mm diameter).

Mottling (irregular patterns of two or more colours with sharp boundaries) is also common in the lower horizon, occurring as grey or white patches and elongate interconnected areas (Figure 3.3 b). According to the classification of the Soil Survey Staff (1975), the mottles can be described as prominent (outstanding feature of the horizon), many, (occupying more than 20 % of the exposed surface) and medium (5-15 mm) to coarse (15-20 mm) in size.

The lower horizon is generally dominated by mineral grains and has a granular (skeletal grains touching with little matrix, Brewer 1976; Figure 3.3 c) to intertextic fabric (skeletal grains dominant with inter-granular braces of matrix, Brewer 1976). Quartz is the dominant mineral, commonly comprising 40-50 % of the unit. The feldspars (30-40 %) are often weakly to moderately altered to smectite with original crystal shape lost. Other minor components of the lower horizon with variable abundance include: organic matter, volcanic rock fragments, chlorite, a laumontite or calcite matrix, and the metamorphic minerals laumontite and prehnite.

The organic matter is often scattered throughout the rock, forming fine (< 1 mm) discontinuous laminae and occasionally forming concentrations. Fossil plant material and rootlets are also scattered throughout the finer grained matrix, with cell anatomy visible in some plant fragments (Figure 3.3 c). Rootlets commonly occur as black carbonaceous material extending for < 20 mm, either down from the upper surface or running parallel to bedding (Figure 3.3 d).

Figure 3.3 Features within the lower horizons of the palaeosols. a) Prismatic, columnar ped structures (arrow), KG 4915, Bed 52, Log 1. Hammer is 35 cm high. b) Mottling within the sandstone of the lower horizon, KG 4919, Bed 582, Log 9. Increments on scale are 2 cm. c) Granular fabric of lower horizon sandstone, also contains a plant fragment (arrow) with cell detail, KG 4937, Bed 525, Log 8. Scale bar is 1 mm. d) Lower horizon grey sandstone with rootlets (arrow) from upper surface, KG 4919, Bed 593, Log 9. Increments on scale are 1 cm.



Volcanic rock fragments are sub-angular to sub-rounded in shape. The chlorite crystals are iron-rich and occur in a hydrated state. The laumontite or calcite matrix is a minor component of the lower horizon and infills gaps between grains or occurs as plugs and coatings.

Within the matrix, clay minerals (smectite, illite and chlorite) occur with a skelsepic microfabric (highly birefringent clay crystals growing parallel to mineral grains, Brewer 1976), occasionally forming embedded grain or ped cutans (concentration of a soil constitute or *in situ* modification forming a 'skin' around a grain or ped surface, Brewer 1976; Figure 3.5 b).

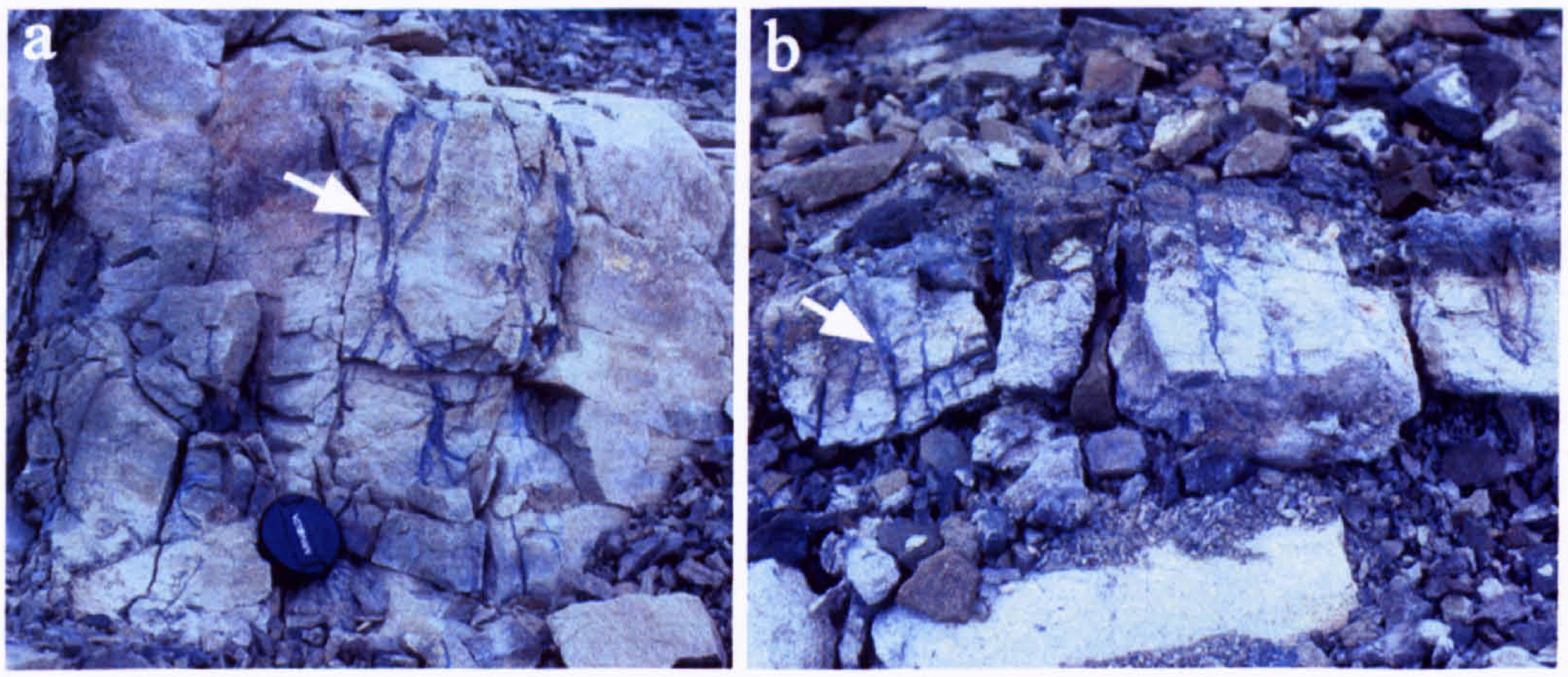
3.4 Significant environmental features

The palaeosols described above contain important features comparable to those of modern soils, such as rootlet horizons, ped structures and mottling. These features provide important evidence for environmental conditions and their significance is discussed in more detail below.

3.4.1 Rootlet horizons

Nearly all palaeosols examined on Alexander Island are associated with large *in situ* tree stumps, finer rootlets or rootlet traces. The tree roots branch and extend down into the palaeosols to a depth of < 1 m (commonly 0.2-0.3 m) (Figure 3.4 a), and radiate from single tree trunks, frequently on a horizontal plane for up to 2 m. Finer rootlets (up to 1 cm in diameter) were found concentrated in rootlet masses (15 cm thick) directly beneath the upper horizon, commonly visible as dark, organic rich material within the lighter coloured lower horizon (Figure 3.4 b).

Figure 3.4 Roots and rootlets beneath palaeosol horizons. a) Large roots (arrow) extending down into lower horizon (weathered sandstones) of palaeosol, KG 4922, Bed 624, Log 9. Lens cap is 5.5 cm. b) Dark organic rich rootlets (up to 6 cm long; arrow) clearly visible within a white sandstone of the lower horizon, KG 4906, Bed 8, Log 1.



Pedotubules (tubular features made by roots or organisms, Brewer 1976) also occur within the lower horizon. They are < 5 mm wide and penetrate the sediment for 10 mm. They can be described as isotubules (internal fabric is clay) and metatubules (internal composition different from the surrounding material, Retallack 2001), as they were found within fine white sandstone and infilled by dark clay.

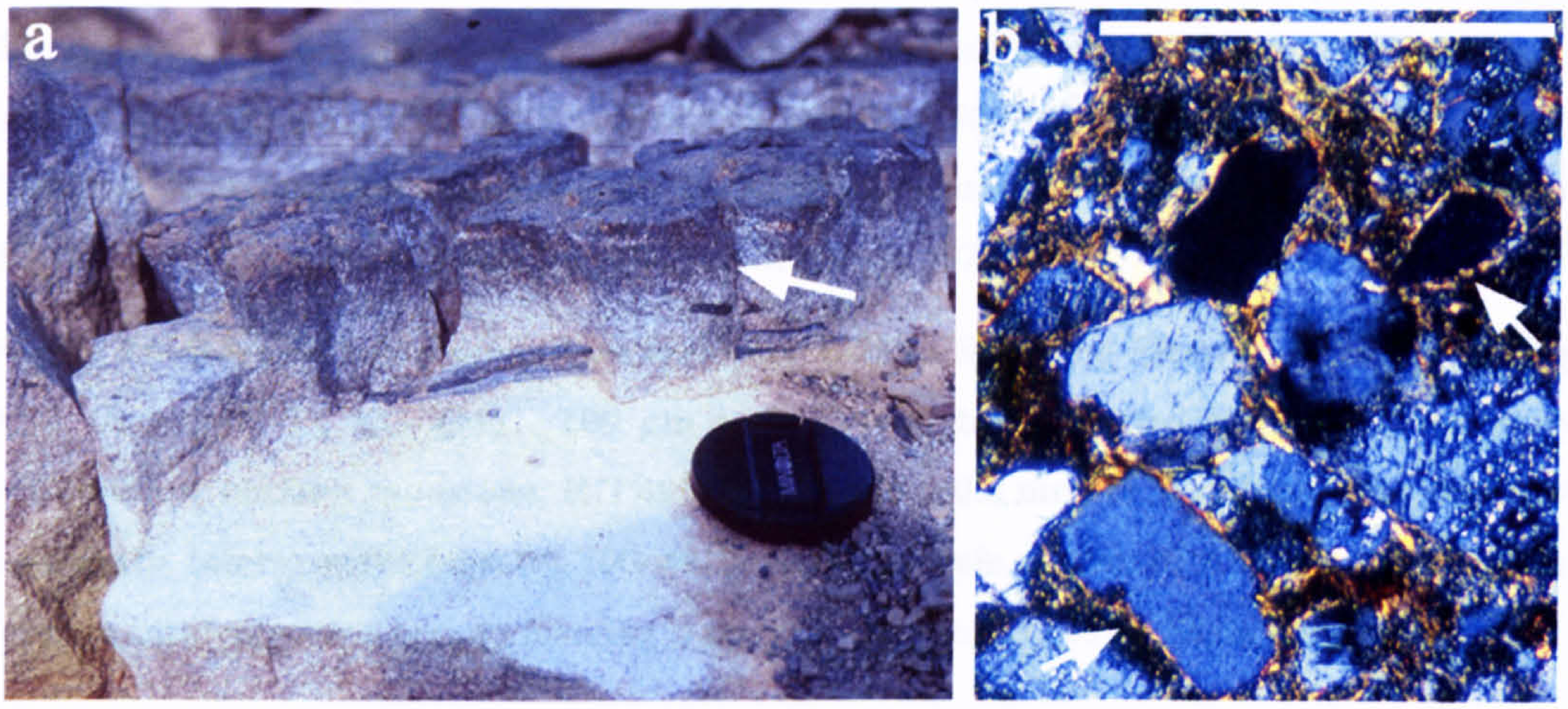
The presence of such a diverse range of roots confirms that these palaeosols were fertile and supported substantial vegetation. Plant roots need oxygen for the uptake of water and nutrients and so do not penetrate below the water table (apart from those such as mangrove types with special adaptations, not seen here). Fossil roots penetrating to a depth of 1 m suggest that the Cretaceous water table was at least 1 m below the surface. Water logging due to flooding clearly did not last for such significant periods of time that plant growth was inhibited.

3.4.2 Ped structures

Peds are blocky structures formed in soils as a result of wetting and drying processes under seasonal climate regimes (Retallack 2001). Within the palaeosol horizons on Alexander Island two types of ped structures were seen: a) prismatic columnar peds, taller than they are wide, with flat tops and of medium size with diameters of 20-50 mm (Figure 3.5 a), and b) angular blocky peds that are more irregular in shape but have interlocking faces, occurring as both fine in size with a diameter of 5-10 mm and very coarse with a diameter > 50 mm (Figure 3.1 b). The variable sizes of these blocky peds are the result of cracks that formed around rootlets, and thus signify a particularly rootlet-rich soil horizon.

The presence of ped structures indicates that the Cretaceous climate in which these soils developed consisted of periods of relatively wet conditions followed by prolonged dryness, similar to mid latitude temperate climates. The peds have clay cutans (clay coatings), which were formed either as material washed down into cracks or from alteration of the ped surface that they coat (Figure 3.5 b). Clay cutans are characteristic of soils formed above the water table and are common in well-drained soils (Brewer 1976), indicating that these palaeosols were not waterlogged but received water input mostly as precipitation.

Figure 3.5 a) Prismatic columnar ped structures (arrow) with a darker upper layer. Lower horizon, KG 4915, Bed 52, Log 1. Lens cap is 5.5 cm in diameter. b) Clay cutans; clay particles (high-birefringent, orange flecks) forming a coating around detrital grains (arrow) within the sandstone of the ped structure. Lower horizon, KG 4915, Bed 52, Log 1. Scale bar in photograph is 0.5 mm long.



3.4.3 Mottling

Mottling is present within the upper and lower horizons of the palaeosols (Figure 3.3 b). The mottling does not have the classic red and grey colours of gley soils, typically formed in waterlogged soils (Retallack 2001). These drab-haloed root traces (Retallack 2001) are areas of reduction due to anaerobic bacterial decay of organic matter in the rootlets. The extensive occurrence of these mottles, found up to 1 m beneath the upper horizon, indicates that there was a significant amount of vegetation and biological activity deep within the soil profile, indicating that the soil was rich and fertile.

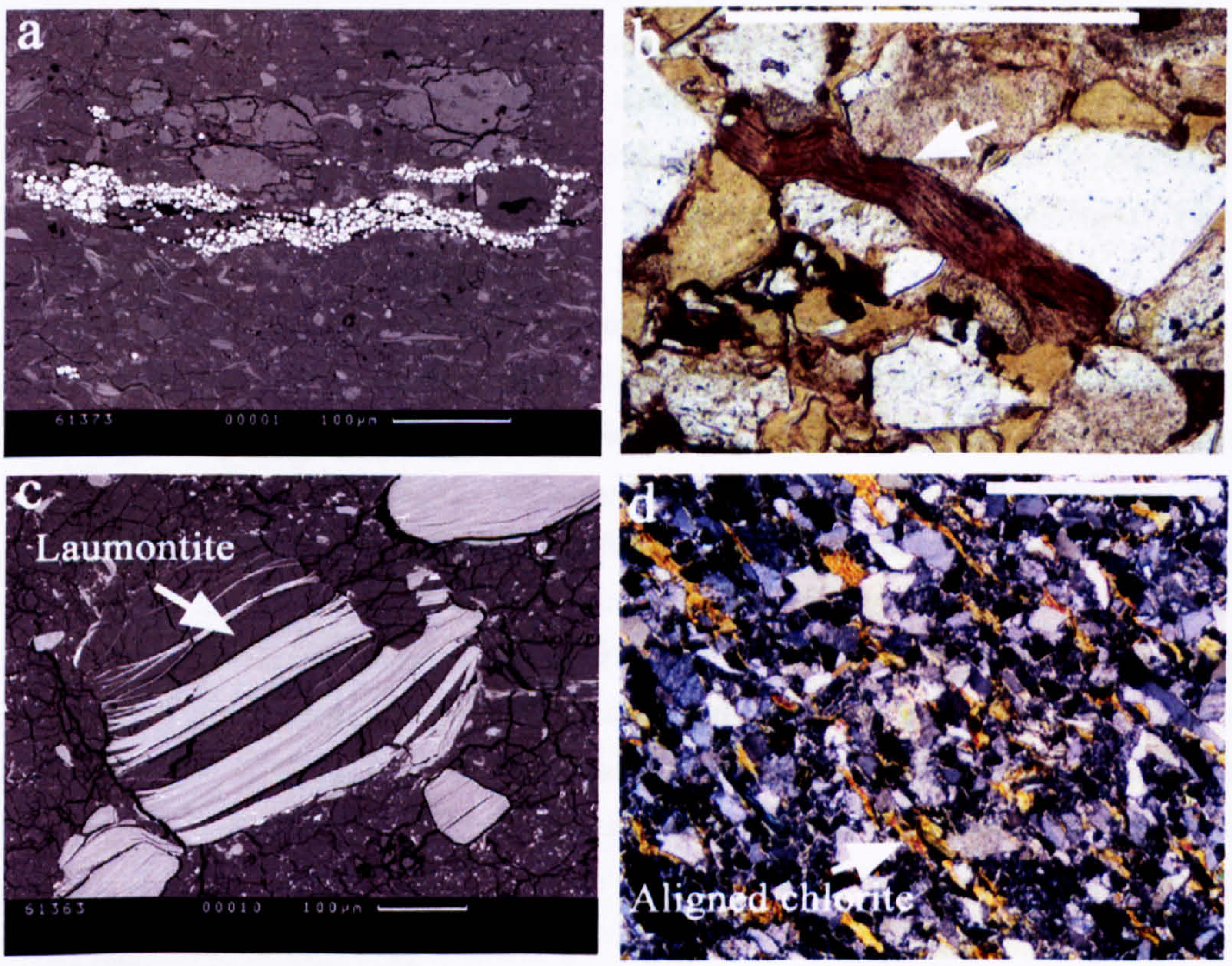
3.4.4 Iron oxides

Iron oxides, although not common, are present within the palaeosols (Figure 3.6 a) and their occurrence is significant because they are formed during periods of saturation of soils. When soils are waterlogged the iron compounds are reduced to soluble forms and migrate within the soil matrix. Iron oxides then precipitate along grains and in open spaces within the matrix (Kemp 1985). Their rarity suggests that the palaeosols were occasionally but not consistently saturated.

3.4.5 Clay minerals

The clay minerals illite, chlorite and montmorillonite (a smectite mineral) were identified within the palaeosols by X-ray diffraction (See Appendix 3, Figure A3.1 for methods and results). Montmorillonite is a swelling clay formed from the degradation of silicates such as feldspars, volcanic minerals, chlorite and illite, and is commonly found in alkaline soils today (Retallack 2001). It occurs today in well-drained soils where leaching is not a dominant process, suggesting that there was no significant transport of soluble minerals in these palaeosols. Smectite is also a major component of modern soils that receive less than 500 mm mean annual rainfall (Retallack 2001). Illite and chlorite are more stable clay minerals, formed mainly during diagenesis from the dehydration of smectite minerals (Dunoyer de Segonzac 1970).

Figure 3.6 a) Iron-oxide segregations identified using a Scanning Electron Microscope (Figure A3.2, Appendix 3), KG 4911. 100 μm scale shown. b) Contorted chlorite crystal (arrow) within lower horizon sandstone, KG 4912. Scale bar is 0.5 mm. c) A split chlorite crystal with laumontite intergrowths (arrow), KG 4912. 100 μm scale shown. d) Aligned chlorite crystals (orange birefringence; arrow) forming a skelsepic fabric, KG 4915. Scale bar is 1 mm.



3.4.6 Hydrated chlorite

Iron-rich chlorite was identified within the palaeosols but its optical properties make it difficult to distinguish from weathered biotite, and it is likely that both are present. The chlorite frequently shows signs of alteration, such as exfoliation and contortion (Figure 3.6 b), reflecting the *in situ* weathering processes that had occurred within the palaeosol profile. Exfoliation is caused by the process of hydration whereby the crystal structure takes in water, splits and expands, creating cavities that are later infilled and expanded further by other minerals (Fitzpatrick 1993). In these palaeosols, laumontite intergrowths are commonly present within split chlorites (Figure 3.6 c). Chlorite is found as aligned grains, a result of the realignment of clay particles during wet phases (Figure 3.6 d); this skelsepic fabric is seen in modern temperate soils that are subject to expansion and contraction during seasonal wet and dry periods (Kemp 1985).

3.5 Classification of palaeosols

The Cretaceous palaeosols on Alexander Island contain many features characteristic of modern soils and can be classified using modern soil classification schemes. According to the US soil taxonomy scheme (Soil Survey Staff 1975), the palaeosols studied here can be classified as mollisols. Mollisols, by definition, have a thick, dark-coloured and humus-rich upper horizon (mollic epipedon) over 18 cm thick (10 cm if formed on bedrock), formed by the underground decomposition of organic residues of roots and plant material brought down by organisms. The lower horizon (cambic horizon) is usually fine-grained sand that has undergone significant alteration and weathering.

Physical alteration due to the movement of the soil particles by frost, roots or animals destroys the original rock structure, including stratification in alluvial deposits, and causes aggregation of the soil particles into peds. Chemical alteration also occurs due to the hydrolysis of primary minerals to form clays, along with biological decomposition of organic matter. In mollisols, alteration predominantly occurs *in situ*, with little significant addition of extra minerals or clays from above by the process of illuviation (leaching) (Soil Survey Staff 1975).

The palaeosols on Alexander Island have similar structures. The upper and lower horizons of the palaeosols correspond to the mollic epipedon and cambic horizon respectively. The mollic epipedon consists of organic-rich material (mostly > 18 cm). The epipedon material is dark brown or black with soil textures and a high detrital mineral component. A well developed cambic horizon (≥ 25 cm depth) and a fine-grained matrix are present. Peds and mottling are also preserved in the upper part of the cambic horizon.

There is little evidence in the Alexander Island palaeosols for movement of clays through the soils. No argillic (soil horizon containing a high concentration of illuvial clays) or bleached horizons (heavily leached horizon lighter than underlying horizons) are present between the mollic epipedon and the cambic horizon and there was no alignment or draping features of clays within the matrix that suggests significant leaching of clays from layers above. The occurrence of hydrated chlorite indicates chemical weathering by hydrolysis and the clay fabric within the matrix is evidence of *in situ* weathering of primary minerals. The lack of evidence for significant leaching processes suggests that the Cretaceous soils were not saturated with water for long periods of time, also supported by the lack of red/grey mottling within the cambic horizon, which would indicate a waterlogged soil.

Mollisols are extensive today in sub-humid to semi-arid, predominantly mid-latitude, areas such as the plains of North America, Europe, Asia and South America. They occur on a range of landscapes from flat alluvial plains to mountain slopes (Wilding *et al.* 1983). The accumulation and turnover of the organic matter within them is rapid and they are known as particularly fertile soils today (Foth 1990). In some modern mollisols the radiocarbon age of the organic carbon has been dated as just a few 100 years (Soil Survey Staff 1975). Most develop today under grassland vegetation but some mollisols occur under well-drained forest vegetation (formerly classified as Brown Forest soils, Brady 1999), such as beneath deciduous forests of central and southern Europe and under mixed forests of the Southern Hemisphere characterised by trees such as *Araucaria*, *Podocarpus* and *Agathis* (Pritchett & Fisher 1987).

3.6 Palaeoenvironmental significance of the palaeosols

Several features of the palaeosols described above are indicative of seasonal, semi-arid (or at least seasonally dry) climates. However, the sedimentary sequence of the Triton Point Formation is dominated by fluvial sandstones and floodplain sediments, leading to interpretation of this high latitude environment as one of waterlogged conditions with frequent flooding under a rather wet climate regime (Jefferson 1982a; Moncrieff 1989, Cantrill & Nichols 1996; Falcon-Lang *et al.* 2001; Nichols & Cantrill 2002). These flood sediments are likely to have been deposited rapidly in short periods of time; Moncrieff (1989) suggests a matter of days or weeks while Jefferson (1981) suggests up to several months.

However, the palaeosols probably represent much longer periods of time, possibly from 100s to 1000s of years for soil development and forest growth, if not longer. Growth rings in the tree stumps indicate that the trees lived for more than 100-200 years (Falcon Lang *et al.* 2001) providing a minimum age for many of the palaeosols, but the presence of unaltered feldspars and volcanic glass suggest that weathering had not occurred over more than perhaps 5000 years (Fitzpatrick 1980).

The palaeosols thus provide a more realistic picture of the general prevailing climate at that time. Palaeosol features such as the development of peds and clay cutans, plus the lack of bleached horizons, imply little water flow through the profile; the deeply penetrating roots suggest low water tables; and the absence of gley features excludes waterlogging. In summary, the palaeosols suggest that drainage was good and the climate seasonally dry, and that any flood events were intermittent.

Falcon-Lang *et al.* (2001) described palaeosol horizons from Triton Point (the northern limit of the TPF) on Alexander Island. These more northerly palaeosols were interpreted as podzols, comprising an upper leaf horizon (O-horizon), a middle brown carbonaceous mudstone layer (A-horizon) and a lower bleached sandstone (E/C-horizon). Podzols are dominated by leaching processes under acidic and oxidising conditions, typically under conifer forests, in moderately to well-drained soils of humid climates (Retallack 2001). This podzol and wetter environment contrasts with the much drier soils described in this paper, and may represent a more northerly part of the delta that was more susceptible to waterlogging and poor drainage.

3.7 Metamorphic overprint

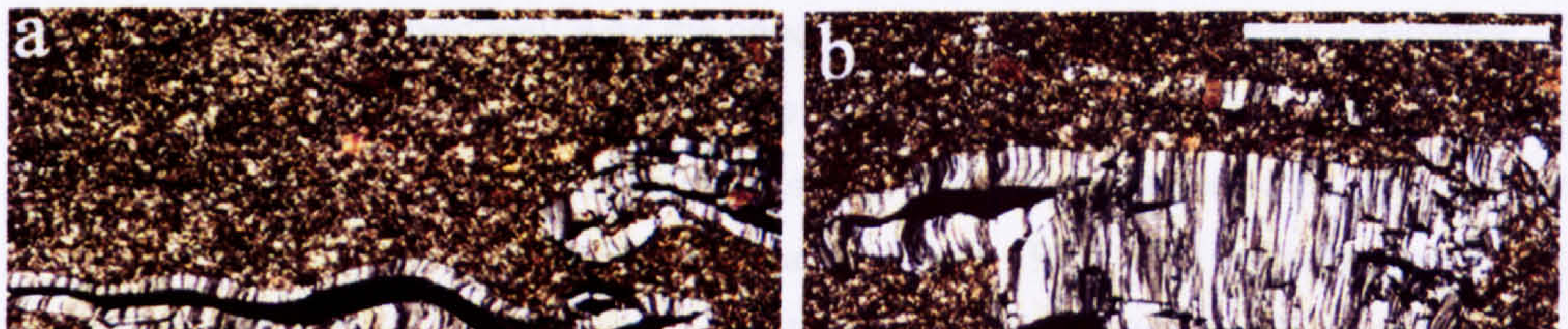
The palaeosols on Alexander Island contain an abundance of the zeolite facies mineral laumontite, plus prehnite and pumpellyite (identified through Microprobe, Figure A3.2, Appendix 3). The laumontite occurs as very fine-grained crystals in the matrix, as round crystals (< 200 µm) and as laumontite cutans (mineral coatings) a few millimetres thick around plant remains (Figure 3.7 a, b). Prehnite occurs as small (< 50 µm) globular masses overgrowing laumontite cutans and feldspar crystals, or as tabular groups of crystals forming rosette shapes (1500 µm) overgrowing a laumontite matrix, resulting in a spotted appearance (Figure 3.7 c). Pumpellyite is a rarer mineral within the palaeosols, found between fragments of organic matter within laumontite cutans, as small tabular crystals within albite crystals, or as overgrowths of the laumontite matrix (Figure 3.7 d).

Zeolitic minerals and prehnite have previously been described in sandstones of the Fossil Bluff Group (Horne 1968; Jefferson 1982b; Browne 1996), but pumpellyite has not been described from the Triton Point Formation. Jefferson (1982b) also described laumontite growths around fossil leaves, destroying plant cuticles.

Zeolite minerals are diagenetic minerals formed from the breakdown of volcanic glass and minerals by fluids circulating through the rocks and thus are commonly found in sedimentary rocks that have a high volcaniclastic component. Zeolites form cements and replace mineral grains, such as plagioclase and the clay matrix (Hay 1966). However zeolitic rocks do preserve the texture of the original sediments (Miyashiro 1994). In these palaeosols, the zeolites provide a metamorphic overprint of the original palaeosol textures but have not destroyed them.

Laumontite tends to occur at depths between 1-14 km and temperatures between 150 and 250° C (Deer *et al.* 1992). Pumpellyite and prehnite usually overlap the laumontite zone with minimum depths of burial of 3-14 km and temperatures between 150 and 300 ° C (Hay 1966).

Figure 3.7 Metamorphic features within the palaeosols on the southeastern nunataks of Alexander Island. a-b) Laumontite, overgrowing the matrix as tiny crystals and forming cutans around organic fragments, KG 4912, Bed 52, Log 1. c) Prehnite occurring as tabular groups of crystals forming rosette shapes (arrow), KG 4938, Bed 540, Log 8. d) Pumpellyite crystals overgrowing the laumontite matrix (arrow), KG 4911, Bed 45, Log 1. Scale bar in photographs a-c is 1mm, in d scale bar is 0.5 mm.



3.7.1 Temperature and depth of burial

Vitrinite, derived from woody tissue, is the main constitute of coalified organic matter found in most sedimentary rocks. Its reflectance values are used as a measure of coal rank, burial depth and temperature (Bostick 1979). The reflectance values of vitrinite (see Appendix 3, Figure A3.3 for method and results) in the Alexander Island palaeosols (random reflectance Ro of 1.6 %) indicate a palaeotemperature of between 150-170 ° C and a burial depth of ~ 3.3–3.7 km (using a geothermal gradient of 45 ° C / km).

Although some of the clay minerals in the palaeosols appear to have been primary components of the original soils (due to the nature of their occurrence on the XRD curves; see Appendix 3 Figure A3.1) most of the illites and chlorites have formed during burial diagenesis at maximum depths of 5-7 km and temperatures of 200 ° C. The presence of smectite minerals suggests burial depths closer to 2 km and temperatures of 120 ° C as smectite is unstable in natural systems below this depth and above this temperature (Velde 1985).

These estimates of palaeotemperatures and depths from both vitrinite and clay minerals within the palaeosols correspond well with the conditions required for zeolite mineralisation.

Sediments of the Fossil Bluff Group containing the palaeosols were deposited during the Albian on the eastern parts of a synclinal fore-arc basin during a period of increased subsidence and basin inversion (Doubleday 1994; Doubleday & Storey 1998). The sediments were then overlain by approximately 3.8 km of sediment of unknown character during which time they would have reached maximum burial temperatures (~100 Ma, Storey *et al.* 1996). In the early Tertiary (40 Ma) rapid uplift occurred and subsequently 3.8 km of overburden was removed.

Previous investigations of the maximum temperatures reached during burial of the Fossil Bluff Group suggested a range of 170-235 ° C based on vitrinite reflectance measurements (Doubleday 1994), using a burial depth of 3.8–5.2 km and a geothermal gradient of 45 ° C. These temperatures are similar to the estimates of 150–170 ° C from the palaeosols. The proposed depths and temperatures also agree with the assemblage of clay minerals present.

Chapter 4 Fossil plant and fossil tree distribution on forest horizons

4.1 Introduction

This chapter looks at fossil plant and fossil tree spatial distribution data collected in the field in order to gain an understanding of the composition and structure of the Alexander Island forest communities. Fossil plant distributions on bedding planes are used to study the occurrence and location of different plant species to answer questions on the distribution of fossils and thus the composition of the forests and how they changed through time and the influences on such changes.

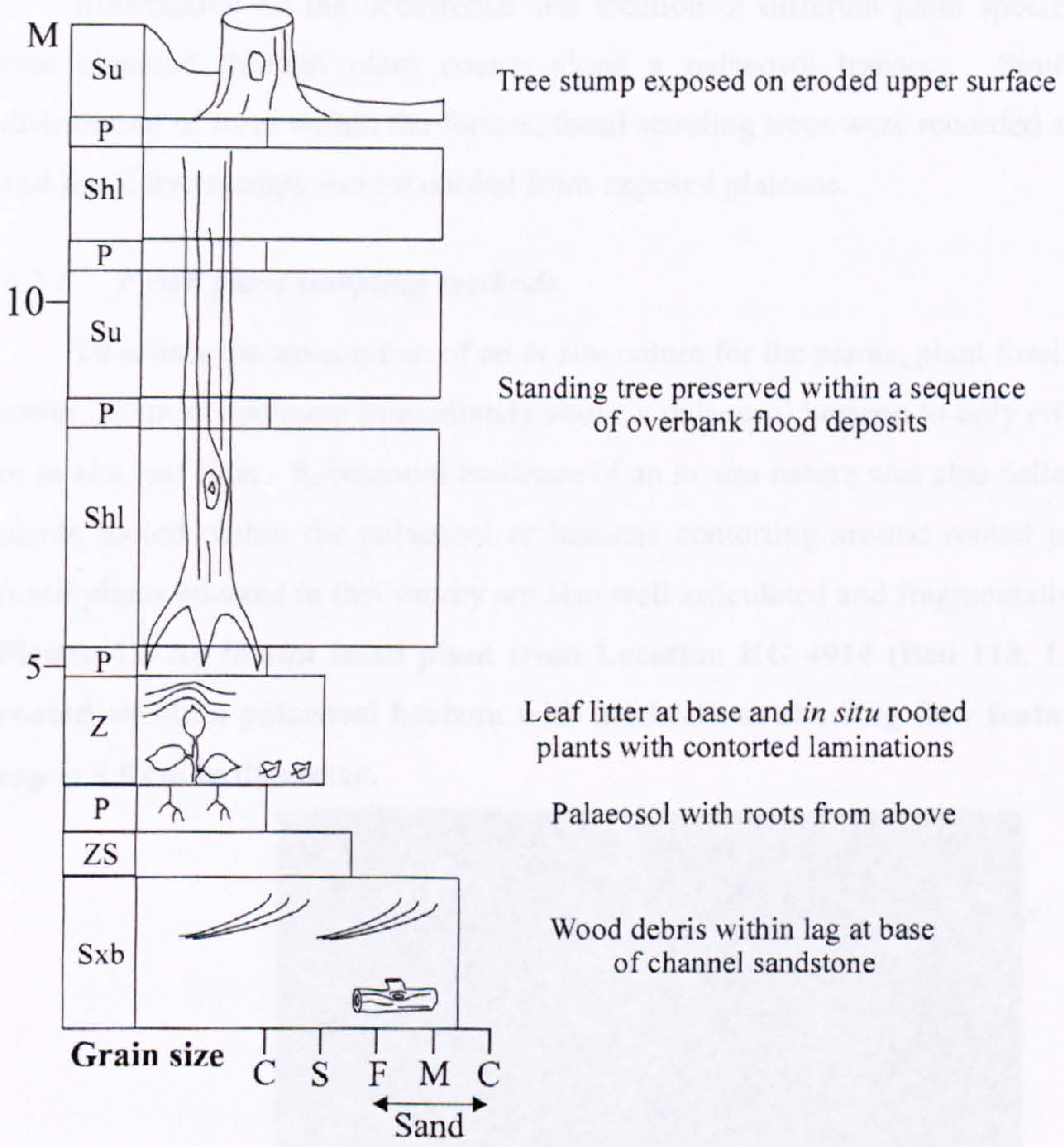
Mapped areas with tree stumps provide data for estimates of forest density and productivity, allowing comparisons with modern forest communities, as well as investigations into the pattern of distribution of the trees within the forest and influences on such patterns. Beds containing *in situ* plant fossils were identified on all three nunataks and those with good lateral exposure were sampled. Similarly, exposures of *in situ* standing trees and tree stumps were also recorded. All together thirteen forest floor horizons were recorded.

4.1.1 The occurrence of fossil plants

Fossil plant material is found in abundance throughout the sediments on the southeastern nunataks of Alexander Island. The plant fossils occur either as fragments representing drifted plant material or as whole or well preserved plant fossils representing *in situ* plants preserved in their life position. All plants counted in the field and used in the studies of spatial distribution and later in statistical calculations (Chapter 6) are considered to be either rooted *in situ* plants or *in situ* leaf litter. Leaf litter has been used to represent the living vegetation by numerous previous studies and is a well-established method for studying the vegetation that grew within the forest canopy (Gastaldo 1986; Burnham 1994,1997).

The plant beds were typically found in sequences of overbank sandstones and siltstones interbedded with palaeosol horizons (Figure 4.1). Whole fossil plants were found lying in upright positions cross-cutting laminations within the siltstones, while individual leaves were predominantly found lying flat on lamination planes, horizontal to bedding.

Figure 4.1 Summary sedimentary log of a typical sequence within which plant beds and *in situ* fossilised trees occur



4.1.2 The occurrence of fossil trees

Fossilised wood is present throughout the sedimentary units on the southeastern nunataks. It occurs either as drifted fragments of wood in both floodplain sediments and channel sandstones, as horizontal logs predominantly found in thick crevasse splay / sheet flood deposits and as *in situ* standing trees within cliff sections and stumps on exposed plateaus. The *in situ* fossilised trees are commonly found in thick sequences of crevasse splay / sheet flood deposits interbedded with siltstones and palaeosol horizons (Figure 4.1). There is an abundance of preserved horizontal logs and branches concentrated in particular units, and on several occasions uprooted tree trunks are lying horizontally (Figure 4.10C). At one location (KG 4937) a tree stump is present with a broken-off tree trunk approximately 3 m long lying horizontally next to it (Figure 4.10A).

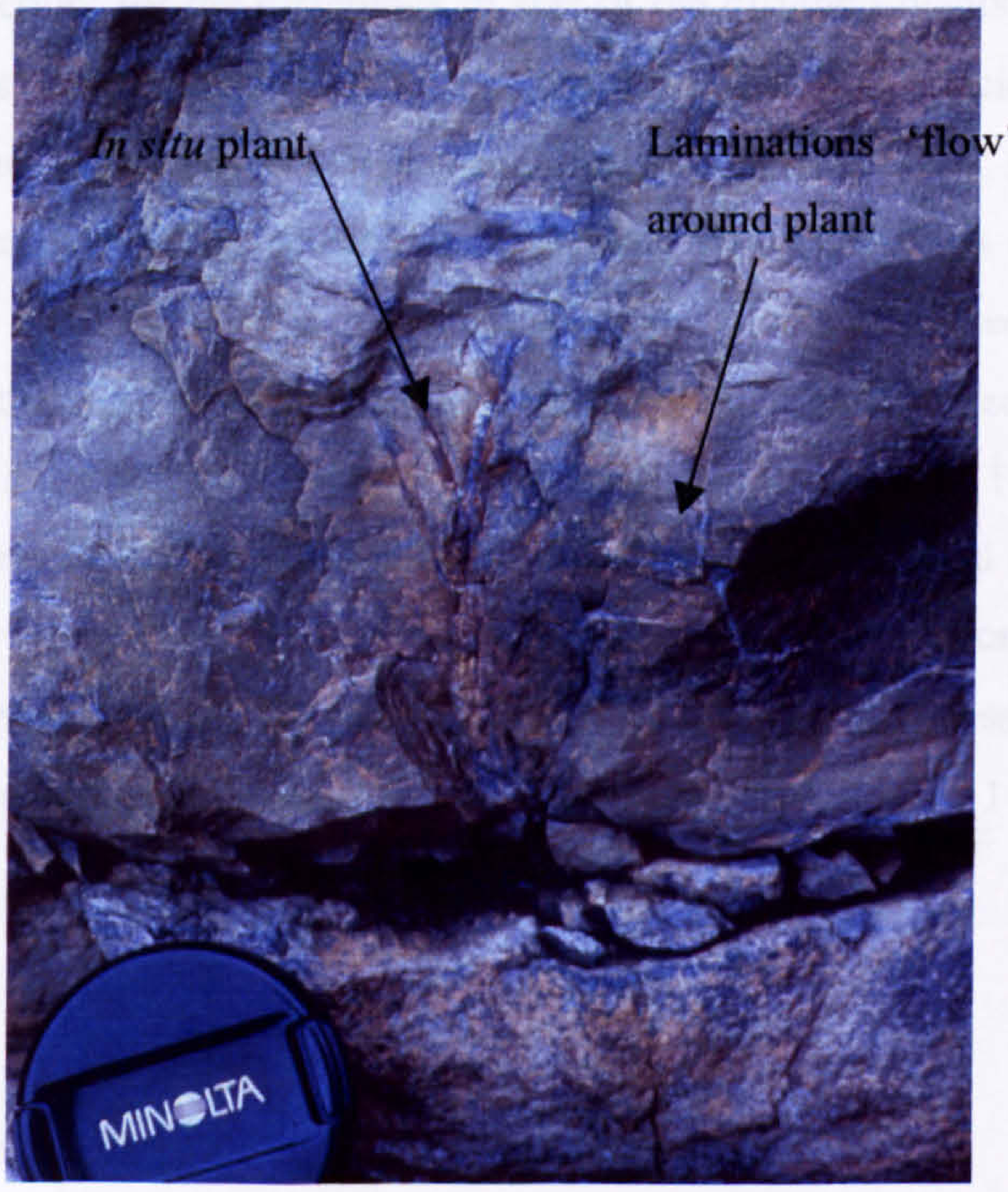
4.2 Field Techniques

Information on the occurrence and location of different plant species along a forest horizon was obtained through plant counts along a palaeosol transect. Similarly to understand the distribution of trees within the forests, fossil standing trees were recorded along a palaeosol horizon and fossil tree stumps were recorded from exposed plateaus.

4.2.1 Fossil plant sampling methods

To satisfy the assumption of an *in situ* nature for the plants, plant fossils were counted from the lower 20 cm of sediment immediately above a palaeosol horizon to only collect *in situ* rooted plants or *in situ* leaf litter. Substantial evidence of an *in situ* nature was also collected in the field, such as plants rooted within the palaeosol or laminae contorting around rooted plants (Figure 4.2). The fossil plants counted in this survey are also well articulated and fragmentation is minimal.

Figure 4.2 An *in situ* fossil plant from Location KG 4914 (Bed 118, Log 2), Citadel Bastion, rooted within a palaeosol horizon with laminations showing flow features around it. The lens cap is 5.5 cm in diameter.



Fossil plants were counted from plant beds that were exposed laterally for some distance and were accessible for sampling. These criteria were met on two types of outcrop: cliff sections where plant beds were exposed in one plane but usually extend laterally for several hundreds of metres, and exposed flat bedding planes where plant beds cropped out and were ideal for sampling. Spatial distribution data from cliff sections were collected from Citadel Bastion and Titan Nunataks and data from exposed plateau's were collected from Coal Nunatak. From both types of outcrop the plant beds were sampled as follows:

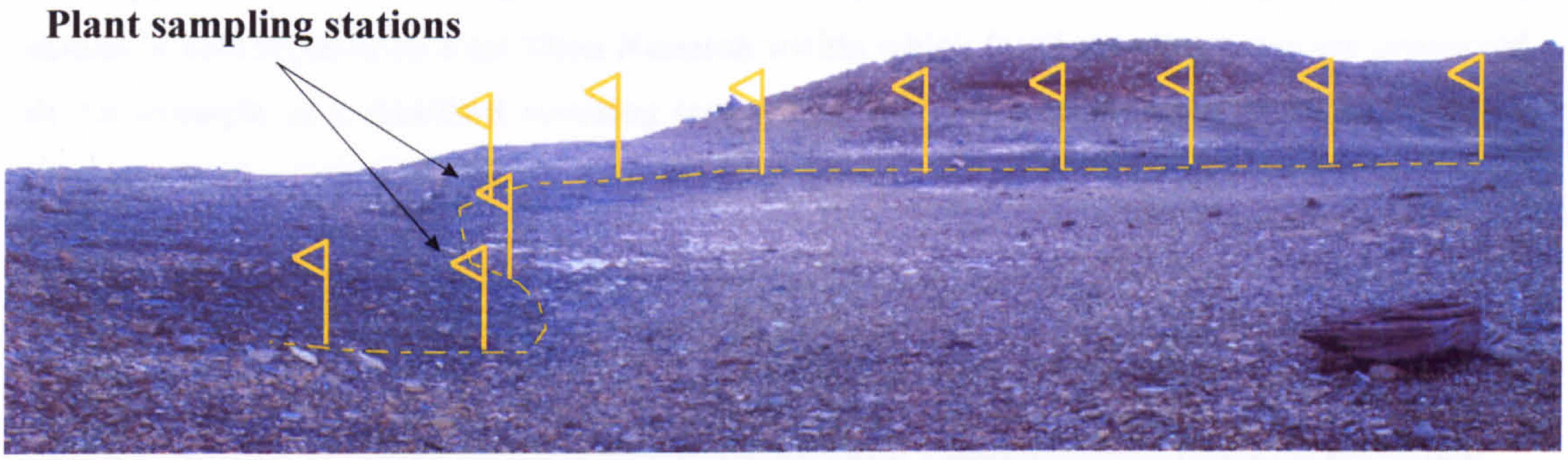
a) Lateral extent of plant bed was measured and sampling stations were placed at regular intervals along its exposure (Figure 4.3).

b) Where possible 100 fossil plants were counted at each station (a number chosen for practical purposes of time spent on each sampling station in the field). However in some areas the plant fossils were preserved in hard, cherty siltstone that made extraction of *in situ* fossils very difficult. On such occasions less plant fossils were counted at each station, usually 25. In order to make comparisons between stations with different sample numbers this data was converted into percentage data (See Section 4.3.2).

c) At each sampling station the first 100 plant fossils extracted from the basal 20 cm of the plant bed were identified and recorded (on exposed plateaus an area of 20 cm around the site was sampled).

d) In order to account for the difference in size of the different plants sampled, up to five fossil conifer leaves were recorded as one single count for that species and up to three fossil *Ginkgoites* and cycadophyte leaves were recorded as one count for that species. For the smaller species of ferns and shrubs one fossil leaf was recorded as one count for that species. These figures were based on a combination of the plants estimated size, nature, and height. For example the conifer trees are approximately 20 times the size of the ferns (tree height estimated at 15-20 m (See Chapter 4), fern height approximately 1-2 m (modern analogue)), and thus 20 times the amount of conifer leaves would be expected in the leaf litter. However the conifers were predominately evergreen (Chapter 7) and thus only approximately 25% of the foliage of the conifer is represented in the leaf litter. Thus 5 fossil conifer leaves represent 1 count for that species compared to 1 fossil fern leaf representing 1 count for that species.

Figure 4.3 An exposed surface on top of Coal Nunatak (KG 4921, Bed 637, Log 9). The yellow line outlines the position of the plant bed that was sampled. Flags are the stations that were sampled for plant fossils. The plant bed sampled is 120 m long.

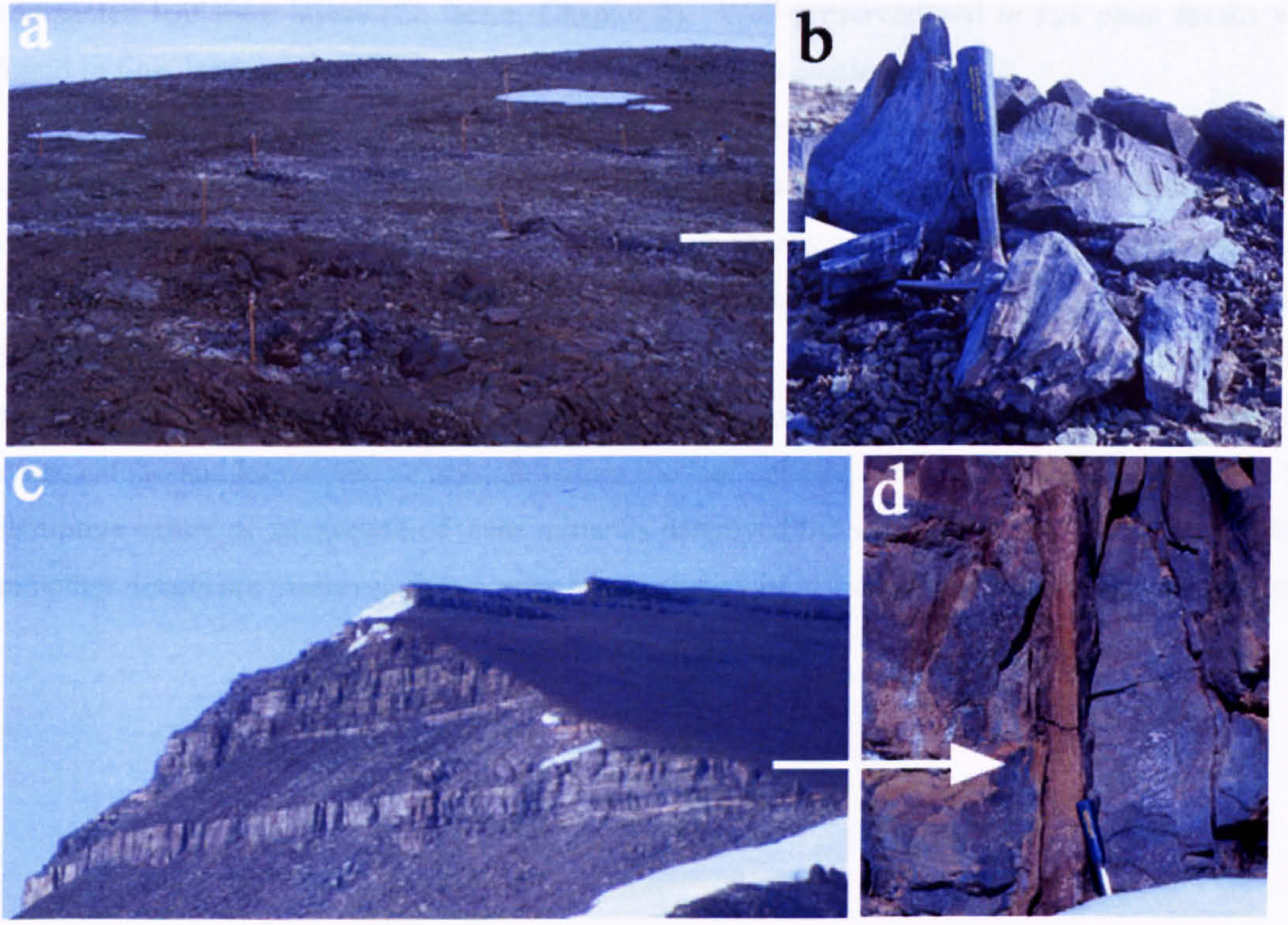


4.2.2 *Fossil tree sampling methods*

Fossil standing trees were found within cliff sections on both Titan Nunataks and Citadel Bastion and tree stumps were recorded from exposed plateau areas on the upper surfaces of Coal Nunatak (Figure 4.4). The beds containing *in situ* standing trees were identified from seven locations, where they occurred in laterally extensive units. The sedimentary sequence within which they occurred was logged and lateral changes within the facies were noted. The distance between standing trees was recorded, along with the dimensions (width at base, height and width at top) of the fossilised trees (Table A4.1, App. 4). The tree density of these forest horizons was calculated for an area 1 m wide by the length of the cliff section sampled (Section 4.4.2, Table 4.6).

Fossil stumps were recorded from two exposed plateaus on the upper surfaces of Coal Nunatak. The stumps outcropped in an area ~ 1000 m long in total that was defined by marker points at regular intervals along the limits of exposure of the plateaus. The subset areas (see Section 4.4.3) were defined by tracing the plant bed exposure to its full extent and marking the area in a similar way to the plateaus. The areas of exposure were mapped by locating tree stumps accurately through compass bearings from predefined transect points. The dimensions of the tree stumps (Table A4.2, App.4) along with changes in the facies were recorded and wood samples were taken where possible. The density of these forests was calculated first by creating maps of the stumps within the area (Section 4.4.3, Figures 4.13 & 4.14) then calculating the total area of the exposed plateaus and the subset areas using the software Rhino. The densities calculated are given in Section 4.4.4, Table 4.6 and Section 4.4.3, Figure 4.13 & 4.14.

Figure 4.4 Tree sampling sites. a) An exposed plateau area upon the upper surface of Coal Nunatak, KG 4926 (Bed 637, Log 9), with fossil tree stumps mapped. Sticks visible in the picture mark the locations of fossil tree stumps. b) An example of one of the fossil tree stumps outcropping within the mapped area shown in a). Hammer is 35 cm high. c) Laterally extensive cliff sections on East Titan Nunatak within which fossil standing trees are preserved. d) An example of a fossilised standing tree within the cliff sections on East Titan Nunatak. Hammer is 35 cm high. KG 4939, Bed 433, Log 7.



4.3 The spatial distribution of fossil plants

In situ plants were recorded from 17 different plant beds. Seven of these were laterally continuous and thus fossils were counted from numerous sampling stations along them (e.g. the location in Figure 4.3) following the method described in Section 4.2.1. The data collected from these seven plant beds is used for spatial distribution information and the beds are given forest horizon numbers (Table 4.1, many corresponding to tree data horizons; Table 4.3). The other ten plant beds have counts from a single or two sampling stations and information on these is given in Table A4.3 and Table A4.4, Appendix 4.

Descriptions of the seven plant beds are given in Table 4.1 including information on the facies, the type of outcrop, and where the sampling stations appear on the sedimentary logs within the appendix (App.2). The plant beds occur on all three nunataks and represent six forest horizons. They are predominantly overbank fine facies sediments overlying palaeosols (Table 4.1).

4.3.1 Preservation of fossil plants

Most of the fossil plant material preserved is in the form of leaf, stem and rootlet impressions, with original organic matter only seen as traces of coaly material on fossilised plant debris found in compacted leaf litter layers (Zc facies, Chapter 2). Well-preserved and *in situ* plant fossils were found in fine, laminated siltstones with a thin, mineral-film coating.

Jefferson (1981, 1982b) looked in detail at the preservation of the fossil plant leaves from the southeastern nunataks of Alexander Island. He concluded that during zeolite metamorphism, volcanic minerals within the sediments, such as glass shards, clay minerals and plagioclase, broke down to form new mineral phases in a mobile fluid; this fluid used the leaves as easy pathways through the sediments. Growth of these minerals thus concentrated in and around the leaves, depositing titanium oxide within the organic matter, chlorite as a thin film coating the leaf, and silica, calcite and laumontite as crystals within the leaf cuticles (Jefferson 1982b; Chapter 3). The disruptive nature of the growth of these minerals destroyed the structure of the leaf cuticles. Veins and other details are preserved however as impressions within the chlorite film (Jefferson 1982b).

Table 4.1 Table summarising the main features of the plant sampling sites. For lithofacies key see Chapter 2. For locality descriptions see Table A2.1, Appendix 2.

Location	Nunatak	Number of sample stations	Forest Horizon	Metres between stations	Description of plant bed location	Plant bed lithofacies	Plant bed colour	Plant bed structure	Overlying facies	Underlying facies	Sedimentary log on which plant bed occurs (App. 2)
KG 4914	S.Citadel Bastion	13	F3	30	Within a 3 m high cliff section. Lateral extent 300 m	Z	Grey/ green	Laminated and cherty	Shl- contains *in situ* trees	Shl- contains *in situ* trees	65 m on Logs 2 & 3
KG 4941	Titan Nunataks	4	F6	~ 50 (2 together)	Within a 20 m + cliff section. Latera extent ~ 170 m	Sf	Grey	Horizontal laminations	Sf	P	Equivalant of 88 m on Log 7
KG 4945	Titan Nunataks	5	F9	~ 60	Within 20 m cliff section.	Sf	Grey	Horizontal laminations	M	P	Equivalant of 8-9 m on Log 8
KG 4946	Titan Nunataks	4	F9 & F10	45, 90, 20	Within 20 m cliff section.	Z	Grey	Horizontal laminations	M	P	Equivalant of 8-9 m on Log 8
KG 4947	Titan Nunataks	3	F10	150 (2 together)	Within 20 m cliff section.	Sf	Grey	Horizontal laminations	M	P	Equivalant of 14 m on Log 7
KG 4921	Coal Nunatak	12	F12	15	Exposed upper surface of nunatak, 150 m	Z	Grey/ green	Laminated and cherty	Sxl	P	178 m on Log 9
KG 4931	Coal Nunatak	15	F13	15	Exposed upper surface of nunatak, 210 m	Z	Grey	Structureless	Sf	ZS	20 m on Log 11

Table 4.2 Summary table of plant counts from the seven plant sampling locations: KG 4914, Citadel Bastion, KG 4921 & KG 4931, Coal Nunatak, KG 4941 & KG 4947, East Titan Nunatak and KG 4945 & KG 4946,West Titan Nunatak. Taxa names as those used in Chapter 5. For lithofacies see Chapter 2. Numbers in table represent the number of plant fossils of that taxa counted at that sampling station. For locality descriptions see Table A2.1, Appendix 2.

Location	4914, (CZ), 30m spacing													4921 (Z), 15 m spacing												4931 (Z), 15 m spacing															4941 (Sf) 50 m				4947 (sf) 150m			4945 (Sf) 60m					4946 (Z), ~40m			
Station	1	2	3	4	5	6	7	8	9	10	11	12	13	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1	2	3	4	1	2	3	1	2	3	4	5	1	2	3	4
FERNS																																																								
Phyllopteroides antarctica																1																													3	2	6				2	4	12			
Sphenopteris sanjuliensis																																																4			3					
Matonia jeffersonii																																																								
Sphenopteris warragulensis	3			1		1	2					5	3			3	3		2	4	6	5	4	2		12	15	15	17	15	10	13	10	15	12	15	10	10	1	14	4	8		2		7	14	8	6	4	3		4			5
Aculea acicularis	1				13	3	4						2	1	1	2	10	6	3	10	5		7	8	2	3	3	2		4	2	3	5	6	3	5	5	4		4	3	10	30	18	4	5	11	5	8	6	5	6	19	7		8
Microphyllopteris unisorus				4																1							1				1				2		1				7	9	8		6									3		
Tetragleichenites acuta				3	2			1																																																
Cladophlebis drinnanii											1																					2			1						3	2	4						8				3	12	6	
Cladophlebis oblonga	3				1	3			1	5				1		1		1	3		4		2								4						1		20		7	5	10	3	7		4		3		2			9		
Cladophlebis gallentiensis				1		2	1				5					3															3														3											
Cladophlebis macloughlinii				3			1									1																																								
Cladophlebis dissectus	3			5		4	4	1	1		7			1		1															1										10	3		12	5						2					
? Marsileaceae	5						1		4				1																												3															
Adiantitephyllum serrata																1																																								
Hausmannia papilio																																									2			1												
CONIFERS																																																								
Podozamites binatus																												1			2				1	3	1	4			12	15	2	24	2		5	3	5	4	3	3	7	13		4
Athrotaxites ungeri							5											1																																			1			
Araucaria chambersii																																									3	10	3									3				4
Araucaria alexandrensis												3	2		2	9	7	5	11	5	3	11	6	10	4			1	1	3	1	1	2		3	2	1	2									1	4				2	3	3		1
Araucarites wollemiaformis		2																7	3	4			2	2																			1												1	
Cone Stem																						2																					1				1									
Bellingshausium willeyii																1																										1					3							4		4
Elatocladus confertus																															1													3	3									2		
Elatocladus linearis	1										1	2	1		1																		1				3	3	1	2	5	6	20	13	13		15	4	22	5	3	3	18	15	10	12
Brachyphyllum														1																	1	2									8	6	5	7	12		4		5				9	8	4	8
Pagiophyllum sp.1																	2		1	1		1		1																	1	2														
LIVERWORTS																											1														17						17									
Hepaticites sp1																			1																																					
Marchantites taenioides					1	4		3																																																
Marchantites rosulatus																																																								
ANGIOSPERMS								4															1																																	
Hydrocotylophyllum alexandri								1				3																																	5											
Gnafalea jeffersonii													3									1																																		
Araliaephyllum quinquelobatus								2				2																																												
Timothyia trinervis					1																																																			
OTHERS																																																								
Cycadophyte																																										4	5	4	3					7		4	7	3		4
Ginkgoites	1															2																									7	5	3		12	5	9		12				8			
Ptilophyllum																																																								
Nilssonia																																									14	6		3					7		3			9		4
Taeniopteris daintreei	13	23	8	8	7	8	7	13	18	20	11	10	13		1		3	5			6																					7		7	9	3	11		12			3				3
Equisetales																			1		1	5	3	2	2	10	5	6	7	3		4	7	4	3		3	2	3	5	9	1	7	3	5	3	7	2	12	4	4	2	11	7	4	7
TOTAL	30	25	8	25	25	25	25	25	24	25	25	25	25	4	5	25	25	25	25	25	25	25	25	25	8	25	25	25	25	25	26	25	25	25	25	25	25	25	25	25	98	100	99	100	92	25	91	30	100	30	30	30	100	95	25	64

4.3.2 Fossil plant distribution

The fossil plants recorded from the plant beds indicate that the forests consisted of conifers, ferns, types of shrubs and small ground plants such as angiosperms and liverworts. All the taxa recorded within the plant beds are listed in Table 4.2 and discussed in more detail in Chapter 5. Table 4.2 also summaries the plant counts from all sampling stations from the seven plant beds with spatial information.

The plant counts (Table 4.2) were transformed into percentage occurrence of different plant species at each sample station so that data were comparable from station to station. In order to gain an insight into the composition and structure of the fossil plant communities, and to see pictorially how the plants were distributed, plant distribution plots were made (Figures 4.5, 4.6 & 4.7). The horizontal axis on the distribution plots represents the palaeosol transects with plant sampling stations marked. The vertical axis represents the percentage occurrence of different plant species at each sampling station. Each plant type (e.g. angiosperm) has it's own symbol on the graph (identified on the key) and the blue line that runs through the graph separates the overstory plants from the understory ones. The idealised plant types along the transect were then drawn based on the general structure of the forest suggested by the distribution plots, to create a schematic reconstruction of what the forests may have looked liked (Figure 4.5 B, 4.6 D, & 4.7 C).

The counts recorded for the *in situ* fossil plants represent the leaves occurring within the *in situ* leaf litter of the Cretaceous forests. Leaf litter has been shown to represent the living vegetation by numerous previous studies and is a well established method for studying the composition and relative abundance of species (i.e. how abundant one species is compared to another) of the forest canopy (Gastaldo 1986; Burnham 1994;1997). Thus the counts recorded here from the *in situ* fossil plants are representative of the composition and relative abundance of the individual plant species that grew within the Cretaceous forests. Thus using the fossil plant counts to represent the relative percentage occurrence of individual plant species is justified and allows interpretation on the structure and composition of the forests without making specific assumptions on the actual numbers of individual species that occurred. However this approach does have some limitations; not all the plants within the Cretaceous forests may have been preserved and of those that were, not all may have been recorded, this is an unavoidable error involved in working with fossil data and the interpretations on the number of species within the Cretaceous forests are thus minimum estimates.

Citadel Bastion: Very little conifer foliage occurs along the palaeosol transect for Citadel Bastion (Figure 4.5 A) with just a few rare occurrences of araucarian foliage (e.g. 180 m on Figure 4.5 A). The foliage *Taeniopteris* dominates, comprising on average 50 % of the total plant fossils recorded from each sampling station and at two stations is the only plant fossil recorded. Fern foliage is also abundant along the whole transect with four types recorded and is the second most abundant foliage found. Clusters of angiosperm and liverwort foliage are found at two of the sample stations (120 m & 210 m on Figure 4.5 A) where they comprise 10 and 45 % of the plant fossils respectively and *Ginkgo* tree (*Ginkgoites*) foliage is found at just one station (0 m on Figure 4.5 A).

Titan Nunatak: Conifer foliage comprises 30-45 % of the total plant fossils recorded from each sampling station along the palaeosol transects for Titan Nunataks (Figure 4.6 A-C), with podocarp foliage dominating and just a few occurrences of araucarian foliage. Fern foliage is again abundant occurring at all sampling stations on all three transects and comprising ~ 30 % of the total plant fossils from each station. Four fern types occur but *Sphenopteris* and *Cladophlebis* foliage dominates (e.g. 131 m on Figure 4.6 B). Cycadophyte and horsetail (Equisetales) foliage is also fairly abundant occurring at all but two sampling stations. Together they comprise between 5-35 % of the total plant fossils recorded from each station. Rare fossils of *Taeniopteris* and *Ginkgo* tree foliage also occur at a few sampling stations (e.g. 77 m on Figure 4.6 A).

Coal Nunatak: Foliage of both araucarian and podocarp conifers are common on the Coal Nunatak palaeosol transects. Araucarian foliage dominates however at KG 4921 (Figure 4.7 A) where it makes up on average ~ 45 % of the total plant fossils from each station. Fern fossils are very abundant on both transects with *Sphenopteris* dominating at KG 4921 and ?Marsileaceae dominating at KG 4931. Other ferns also occur including *Cladophlebis* which forms the majority of plant fossils counted at one sampling station (195 m on Figure 4.7 B), and Gleicheniaceae and *Hausmannia*, which occur together in small clusters (75 & 135 m on Figure 4.7 B). *Taeniopteris* foliage is either found in small patches such as those at KG 4921 or comprise up to 35 % of the fossils at each station, occurring persistently along the transect, as at KG 4931. Small clusters of angiosperm and horsetail foliage, comprising 5-15% of the fossils counted at each station, make up the remainder of the fossil plant distribution on Coal Nunatak.

Figure 4.5 Citadel Bastion forest horizon 3. A) A distribution plot of fossil plant types along a fossil forest transect at Location KG 4914, number of fossils counted at each station (N) = 25. B) A reconstruction of the forest floor at Location KG 4914. C) Key to all symbols used in Figures 4.5 - 4.7.

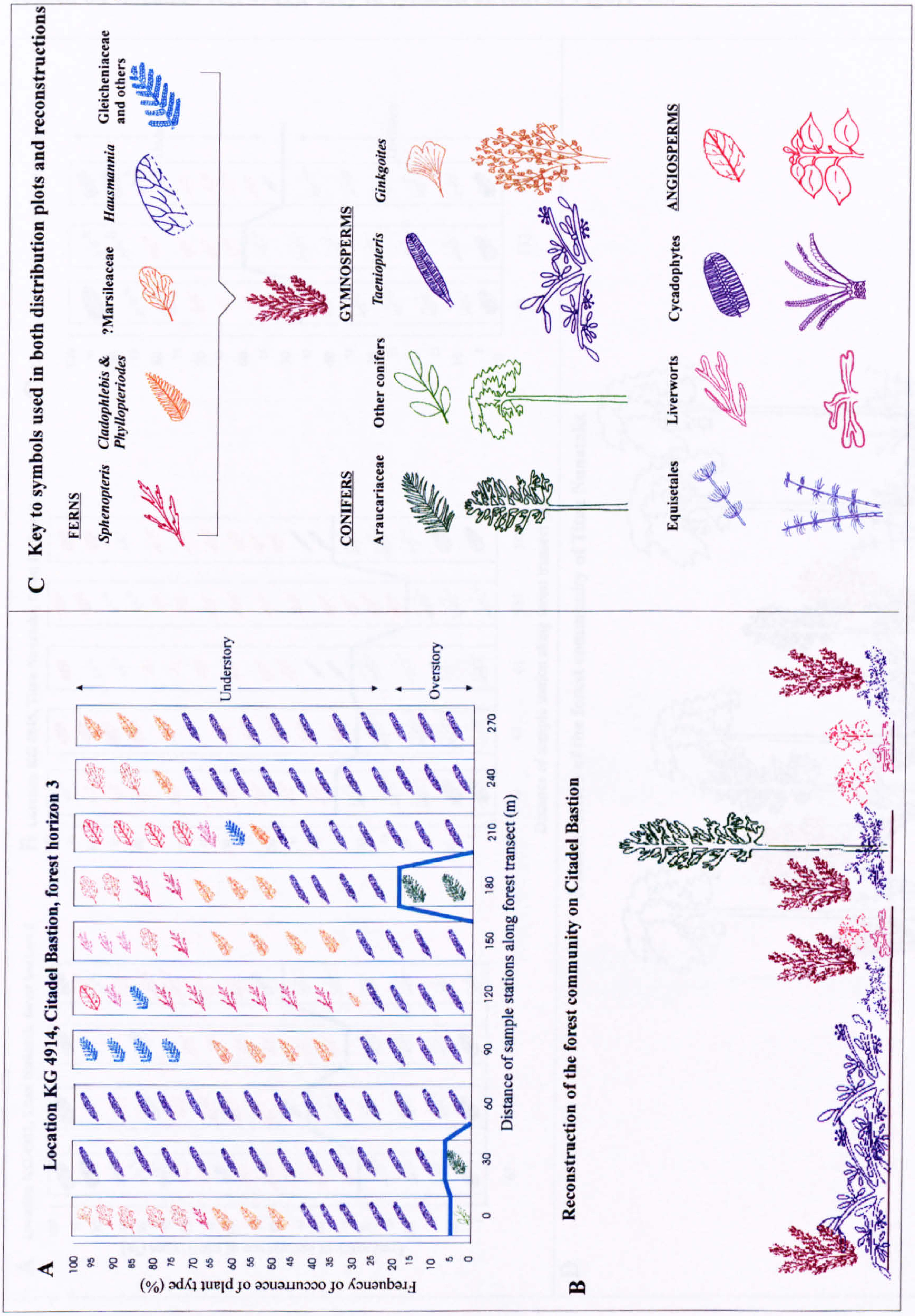


Figure 4.6 Titan Nunataks forest horizons 6, 9 and 10. A-C, distribution plots of the fossil plant types along fossil forest transects at Locations: A) KG 4941, N = 100; B) KG 4945, N= 30; C) KG 4946, N=25-100. D) A representative forest reconstruction for Titan Nunataks (based on Location KG 4941). Key to symbols as that in Figure 4.5.

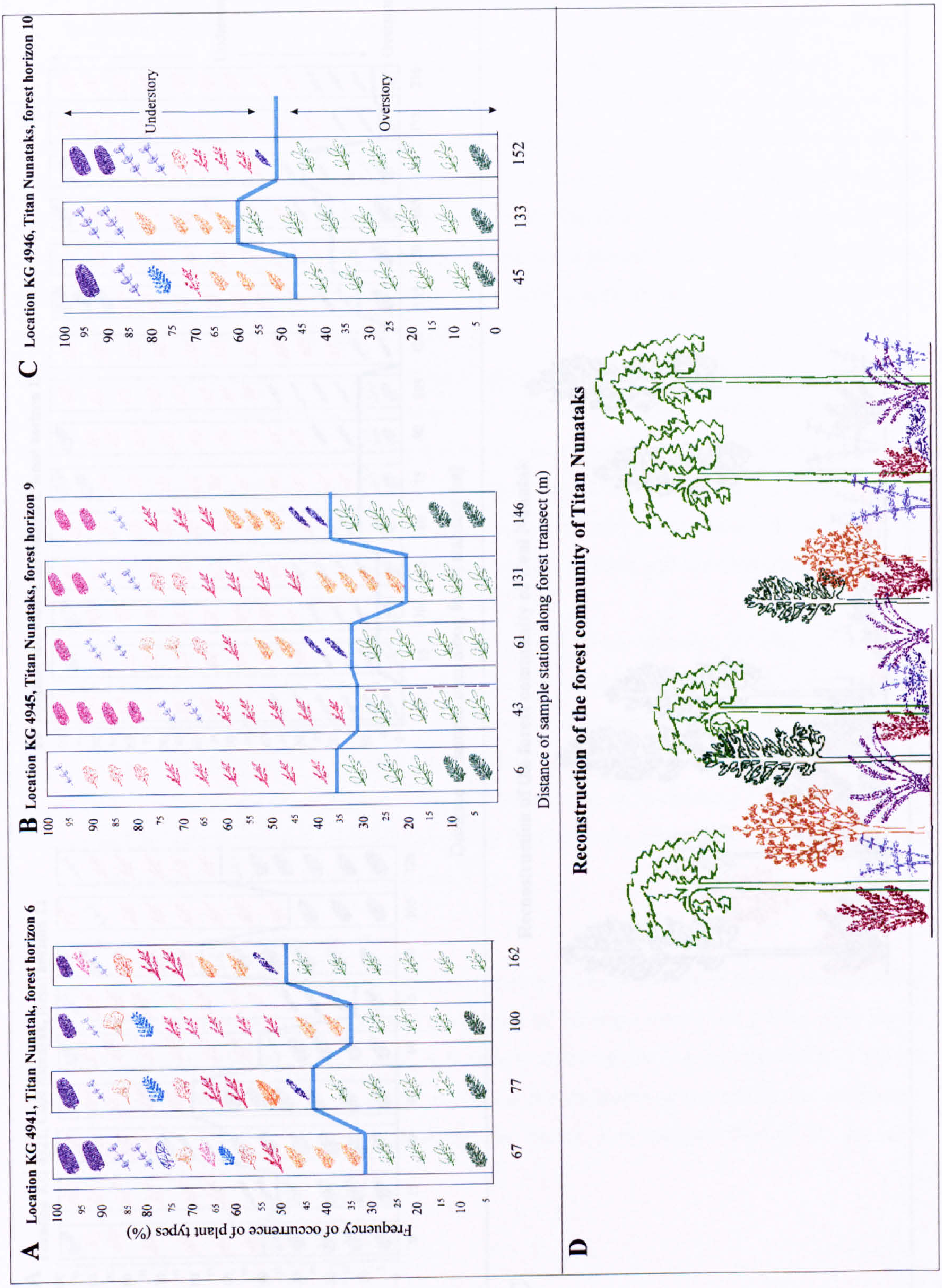
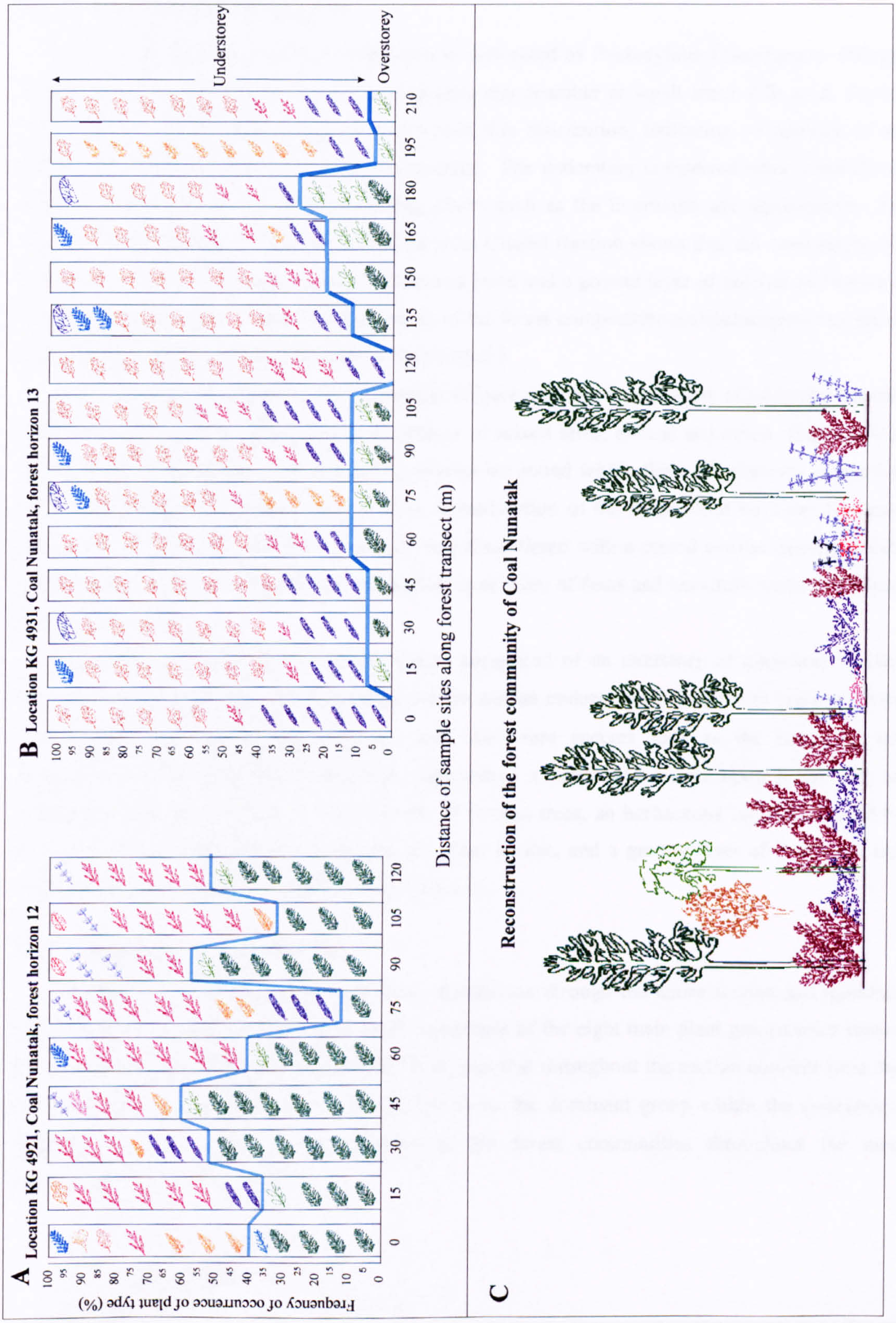


Figure 4.7 Coal Nunatak forest horizons 12 and 13. A-B, distribution plots of the fossil plant types along fossil forest transects at Locations: A) KG 4921, N=25; B) KG 4931, N=25. C) A representative forest reconstruction for Coal Nunatak (based on Location KG 4921). Key to symbols as that in Figure 4.5.



4.3.3 Forest community structure

On Citadel Bastion (Figure 4.5) the forest is dominated by Pentoxylales (*Taeniopteris* foliage), which is an extinct plant but similar to a modern day bramble or small shrub (Howe & Cantrill 2001; Chapter 5). Conifer foliage is rare within this distribution, indicating an absence of any canopy layer and a fairly young forest community. The understory comprised other small shrubs and a mixture of ferns and early colonising plants such as the liverworts and angiosperms. The reconstruction (Figure 4.5 B) of the forest floor on Citadel Bastion shows that the community was two-tiered, with a dense upper layer of shrubs and ferns and a ground layer of patches of liverworts and small angiosperms. A detailed description of the forest composition and palaeoenvironment on Citadel Bastion is discussed in Chapter 6, Section 6.5.3.

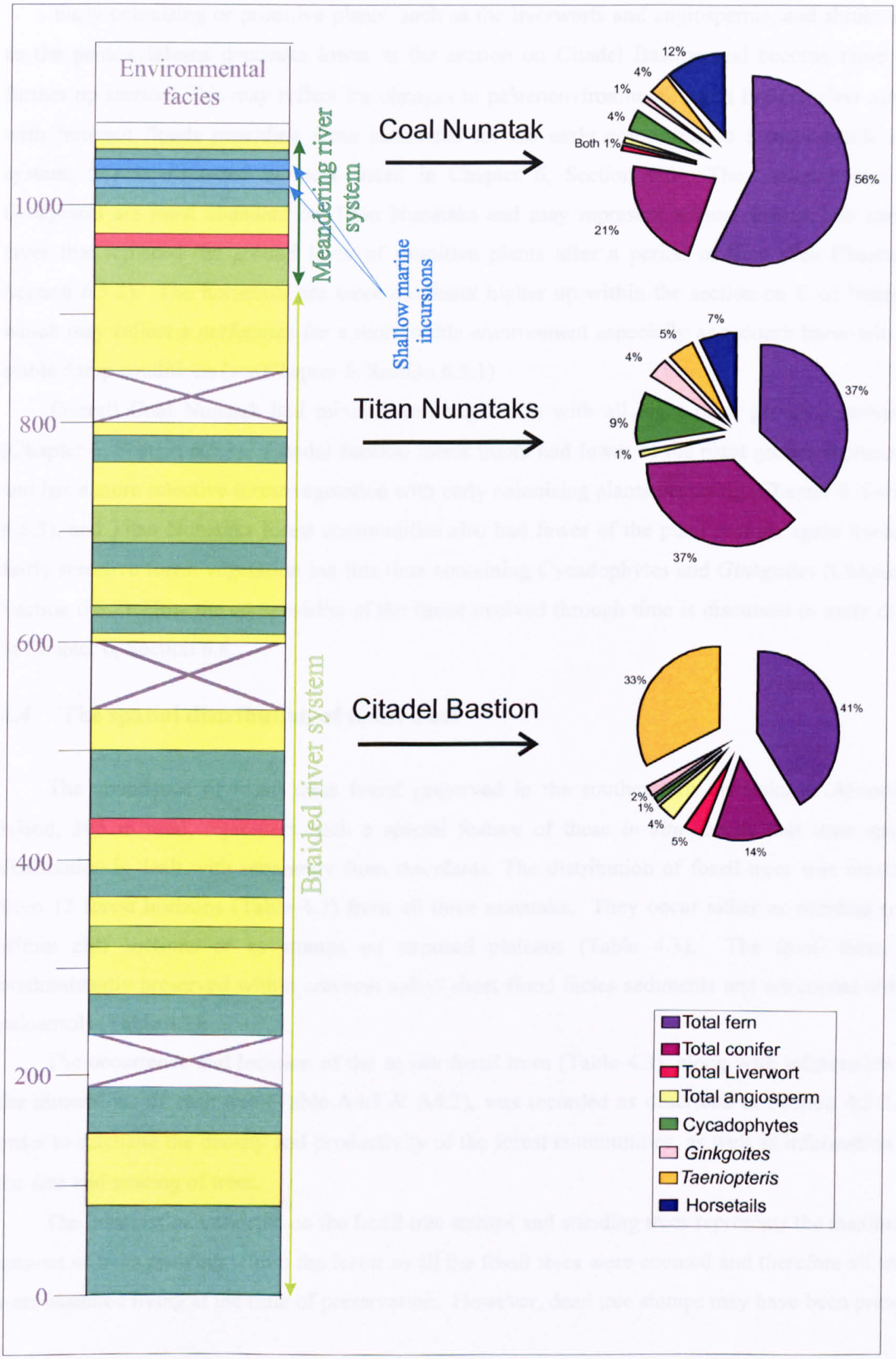
The forest communities on Titan Nunataks (Figure 4.6) had an overstory of podocarp conifers with a few araucarian conifers, and an understory of mixed ferns, cycads and others plants such as horsetails and *Ginkgo* trees. No colonising species are found within these distributions suggesting the forests were mature climax forests. The reconstruction of the forest floor on Titan Nunataks (Figure 4.6 D) indicates that the community was three-tiered with a mixed conifer canopy, a sub-canopy of *Ginkgo* trees and cycadophytes and an understory of ferns and horsetails (refer to Chapter 6, Section 6.5.2).

On Coal Nunatak (Figure 4.7) the forests comprised of an overstory of abundant conifers dominated by a single type, the araucarian conifer and an undergrowth of different types of ferns, small shrubs such as the pentoxylalean, and other rare species such as the horsetails and angiosperms. This four-tiered community represented a stable and mature open forest with an overstory of araucarian conifers, a sub-canopy of *Ginkgo* trees, an herbaceous layer dominated by ferns as well as pentoxylaleans, horsetails and other shrubs, and a ground layer of liverworts and small angiosperms (refer to Chapter 6, Section 6.5.1).

4.3.4 Evolving forest communities

In order to identify changes in the fossil distribution through the entire section and therefore forest composition through time, the overall occurrence of the eight main plant groups were shown for each of the three nunataks (Figure 4.8). It is clear that throughout the section conifers form the dominant plant group within the overstory, and ferns the dominant group within the understory. Together they dominated the composition of the forest communities throughout the time represented.

Figure 4.8 Changes in composition of the forest communities through time. The environmental facies column is based on that in Figure 2.14, Chapter 2.



Early colonising or primitive plants, such as the liverworts and angiosperms, and shrubs such as the pentoxylaleans dominate lower in the section on Citadel Bastion and become more rare further up section. This may reflect the changes in palaeoenvironment from a braided river system with frequent floods providing fresh sediments for the early colonisers, to a more stable river system; this is discussed in more detail in Chapter 6, Section 6.6. The Cycadophytes and *Ginkgoites* are most abundant on Titan Nunataks and may represent a more mature sub canopy layer that replaced the ground layer of primitive plants after a period of time (See Chapter 6, Section 6.5.2). The horsetails are more dominant higher up within the section on Coal Nunatak, which may reflect a preference for a more stable environment especially as modern horsetails like stable damp conditions (see Chapter 6, Section 6.5.1)

Overall Coal Nunatak had mixed forest vegetation with all eight plant groups represented (Chapter 6, Section 6.5.1). Citadel Bastion forest floors had fewer of the plant groups represented and has a more selective forest vegetation with early colonising plants occurring (Chapter 6, Section 6.5.3), and Titan Nunataks forest communities also had fewer of the plant groups, again having a fairly selective forest vegetation but this time containing Cycadophytes and *Ginkgoites* (Chapter 6, Section 6.5.2). How the composition of the forest evolved through time is discussed in more detail in Chapter 6, Section 6.6.

4.4 The spatial distribution of fossil trees

The abundance of fossil trees found preserved in the southeastern nunataks of Alexander Island, 305 in total, represents such a special feature of these *in situ* forests that their spatial distribution is dealt with separately from the plants. The distribution of fossil trees was recorded from 12 forest horizons (Table 4.3) from all three nunataks. They occur either as standing trees within cliff sections or as stumps on exposed plateaus (Table 4.3). The fossil trees are predominantly preserved within crevasse splay/ sheet flood facies sediments and are rooted within palaeosols (Table 4.3).

The occurrence and location of the *in situ* fossil trees (Table 4.3), along with information on the dimensions of each tree (Table A4.1 & A4.2), was recorded as described in Section 4.2.2, in order to calculate the density and productivity of the forest communities, as well as information on the size and spacing of trees.

The information collected on the fossil tree stumps and standing trees represents the maximum amount of trees growing within the forest as all the fossil trees were counted and therefore all trees were assumed living at the time of preservation. However, dead tree stumps may have been present in the Cretaceous forests when they were inundated by flood sediments. The maximum length of time dead trees have remained standing before rotting away has been recorded in modern forests as approximately 50 years (Jefferson 1981). Thus at the time that the Cretaceous forests were inundated by flood sediments, the forest would include trees of all ages but also any trees that had died within the past 50 years. In modern forests it is estimated that at any one time 10 % of the trees within the forest are dead (Nilsson *et al.* 2003), although this percentage may be greater for the Cretaceous forests because they include trees that had died over a 50 year period it does give some estimation of the error involved in calculating forest density and productivity from the fossil trees counted in the field. This estimation of the error is considered when comparing fossil information with the densities and productivities of modern forests that are based on what is living within the forests at any one time and is discussed further in Sections 4.4.3.1, 4.4.4.3 and 4.4.4.4. The comparison of information between different fossil forests are unaffected by the assumption that all the fossil trees counted were living.

Table 4.3 Table summarising the main features of the tree sampling locations. For lithofacies see Chapter 2. For locality descriptions see Table A2.1, Appendix 2.

Location	Nunatak	Number of forest horizons	Description of sample area	Area of study	Number of trees recorded	Facies trees preserved within	Overlying facies	Underlying facies	Sedimentary log sample site occurs on
KG 4914	Citadel Bastion	3 (F1 - F3)	3 m cliff section forming a ridge in the middle of Citadel Bastion	300 m lateral extent	6	Shl & MSf	Z & Shl	Z and MSf	63-67 m on Log 2 & 3
KG 4939	Titan Nunatak	2 (F4 & F6)	Within the sedimentary log of North Titan (West ridgeline)	No lateral extent	3	Shl	Shl	P, ZS & Z	6 m and 53 m on Log 6
KG 4941	Titan Nunatak	2 (F5 & F6)	5 m cliff section forming ridge on eastern side of East Titan	160 m lateral extent	11	Shl	P & Sf	P	84 and 87 m on Log 7
KG 4944	Titan Nunatak	3 (F5-F7)	20 m cliff section forming prominent ridge at base of southern tip of East Titan	~ 400 m lateral extent	35	Shl	P, Shl & Sf	P & Sf	84 m, 87 m and 93 m on Log 7
KG 4945	Titan Nunatak	3 (F8-F10)	6 m cliff section forming a NW - SE ridge at the base of the eastern side of West Titan	~ 270 m lateral extent	23	Shl	P	P	7 -12 m on Log 8
KG 4946	Titan Nunatak	3 (F8-F10)	As above - NE - SW running ridge line	~ 150m lateral extent	10	Shl	P	P	7 -12 m on Log 8
KG 4937	Titan Nunatak	1(F11)	6 m cliff section forming a ridge on the south side of West Titan	~ 250 m lateral extent	14	Shl	Shl	Z	44-50 m on Log 8
KG 4927	Coal Nunatak	1(F12)	Exposed upper surface on top of Coal Nunatak (middle of Coal Nunatak)	150 m by ~ 80 m	6	Sxl	n/a	Z (P)	178 m on Log 9
KG 4928	Coal Nunatak	1(F12)	Continued surface from above	150 m by ~ 90 m	66	Sxl	n/a	Z (P)	178 m on Log 9
KG 4929	Coal Nunatak	1(F12)	Continued surface from above	150 m by ~ 40 m	31	Sxl	n/a	Z (P)	178 m on Log 9
KG 4921	Coal Nunatak	1(F12)	Continued surface from above	150 m by ~ 40 m	23	Sxl	n/a	Z (P)	178 m on Log 9
KG 4923	Coal Nunatak	1(F12)	Continued surface from above	150 m by ~ 115 m	69	Sxl	n/a	Z (P)	178 m on Log 9
KG 4926	Coal Nunatak	1(F12)	Continued surface from above (south end of Coal Nunatak)	150 m by ~ 35 m	7	Sxl	n/a	Z (P)	178 m on Log 9

4.4.1 *Preservation of the fossil trees*

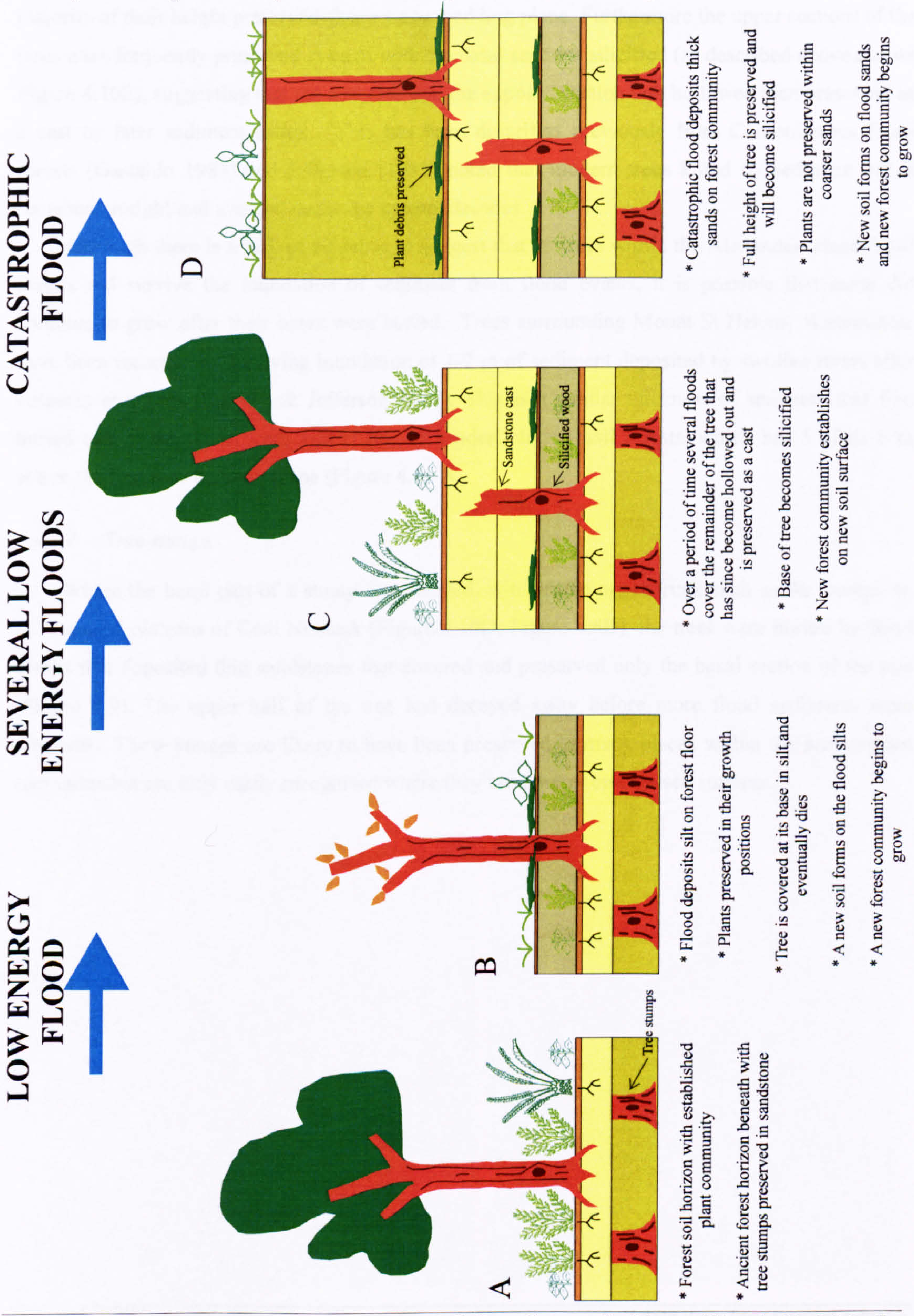
Wood fragments are preserved as impressions while *in situ* trees are either preserved as casts in-filled by sandstone or the wood is silicified (Figure 4.10B;C-E respectively), preserving cell detail and allowing identification of the tree (Chapter 5). Jefferson (1981) looked in detail at the preservation of the wood from the southeastern nunataks of Alexander Island. He described the preservation as a result of mineral-rich fluids moving freely through coarse, porous sandstones, such as the Shl and Sxl facies (Chapter 2) in which the trees are found preserved (Table 4.3). The fluids were rich in free silica, formed from the breakdown of volcanic material within the sandstones soon after burial (Jefferson 1981).

4.4.1.1 *Standing trees*

In order for large standing trees to become silicified they must have been buried by several sediment pulses in quick succession or rapidly covered by a thick single influx of sediment (Figure 4.9; Figure 4.10F), such as the standing trees found in cliff sections (e.g. KG 4945), which are covered by crevasse splay sandstones several metres thick. In places the standing trees were silicified at the base and preserved as a cast in the upper parts of the trunk (Figure 4.10E). This suggests that the tree was covered by sandstone at its base, preserving the basal portions but killing the tree. The upper sections were then exposed as the trunk began to decay and become hollow. The tree was then buried by later flooding episodes that preserved the upper sections as a sandstone in-filled cast (Figure 4.10E). A cartoon of the events leading to the preservation of the fossil trees is shown in Figure 4.9.

Whether the standing trees within the cliff sections of Titan Nunataks lived through the influxes of sediment is debatable. Jefferson (1982a) describes forest horizons from Titan Nunataks and Triton Point (further north than this study) and concluded that the trees did survive inundation by sediment and water. He argued that most fossil tree trunks extend above the new bedding plane and that asymmetry of growth rings within the preserved wood over several years suggests that the trees continued to grow after they were tilted by the sediment influx. He also described the bulbous base of the fossil trees as similar to those found in modern trees that have been buried to depths of 1 m such as the Redwoods in Western Canada (Stone & Vasey 1968).

Figure 4.9 A cartoon to show the preservation of fossil plants and trees. A) Forest community grows on soil with ancient fossilised tree stumps preserved by thin sandstone beneath. B) Silt deposition after a low energy flood preserves base of tree and plants in their growth position. C) After time tree dies and becomes hollow, subsequent floods preserve trunk as cast. D) Catastrophic flood preserves full height of new tree in single sand influx.



A

* Forest soil horizon with established plant community

* Ancient forest horizon beneath with tree stumps preserved in sandstone

B

* Flood deposits silt on forest floor

* Plants preserved in their growth positions

* Tree is covered at its base in silt,and eventually dies

* A new soil forms on the flood silts

* A new forest community begins to grow

C

* Over a period of time several floods cover the remainder of the tree that has since become hollowed out and is preserved as a cast

* Base of tree becomes silicified

* New forest community establishes on new soil surface

D

* Catastrophic flood deposits thick sands on forest community

* Full height of tree is preserved and will become silicified

* Plants are not preserved within coarser sands

* New soil forms on flood sands and new forest community begins to grow

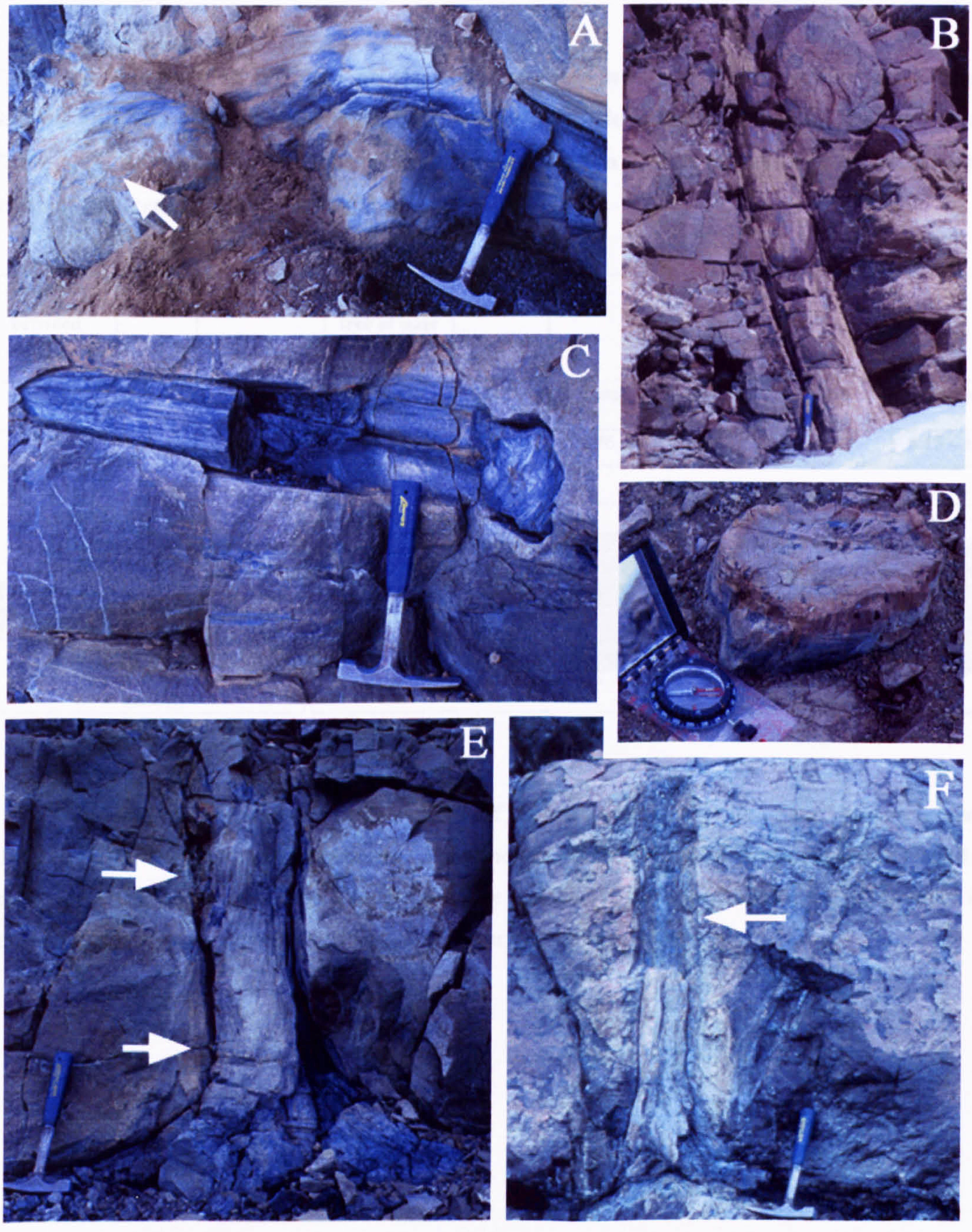
However in the data shown in Figure 4.11 only 11 trees out of 88 were found to have the majority of their height preserved above a new bedding plane. Furthermore the upper sections of the trees were frequently preserved as casts with the basal sections silicified (as described above and on Figure 4.10E), suggesting that the tree died and the exposed section was hollowed then preserved as a cast by later sediment influx. This has been described previously from Carboniferous fossil forests (Gastaldo 1985) and Jefferson (1981) noted that modern trees killed by sediment influx remained upright and avoided decay for several decades.

Although there is a lack of evidence to suggest that all trees within the Alexander Island fossil forests did survive the inundation of sediment from flood events, it is possible that some did continue to grow after their bases were buried. Trees surrounding Mount St Helens, Washington, have been recorded as surviving inundation of 1-2 m of sediment deposited by swollen rivers after volcanic eruptions (Karowe & Jefferson 1987). This is a similar thickness of sediment that first buried one of the tallest trees within the Alexander Island fossil forests, which has 5 of its 6 m above the first new bedding plane (Figure 4.11 A).

4.4.1.2 Tree stumps

Where the basal part of a stump is preserved, without the upper trunk such as the stumps on the exposed plateaus of Coal Nunatak (Figure 4.10D; Figure 4.4B), the trees were buried by flood events that deposited thin sandstones that covered and preserved only the basal section of the tree (Figure 4.9). The upper half of the tree had decayed away before more flood sediments were deposited. These stumps are likely to have been preserved in many places within the sedimentary sequences but are only easily recognised where they are present on exposed surfaces.

Figure 4.10 Fossilised trees within the southeastern nunataks of Alexander Island. A) A tree lying horizontal broken off from it's upright base (arrow; KG 4937, Bed 526, Log 8). B) The tallest fossilised *in situ* tree found on Alexander Island, preserved to a height of 7 m as a sandstone infilled cast (KG 4901, North Coal Nunatak). C) A silicified tree log lying horizontally (KG 4937, Bed 526, Log 8). D) A silicified tree stump outcroppping on an exposed plateau surface (KG 4921, Bed 637, Log 9). E) An *in situ* fossilised tree silicified at its base (bottom arrow) and preserved as a sandstone infilled cast higher up (top arrow; KG 4923, Bed 637, Log 9). F) An *in situ* silicified tree, preserved in one single unit of sandstone (arrow;KG 4945, bed 498, Log 8). Hammer in all photos is 35 cm high, compass is 10 cm long.

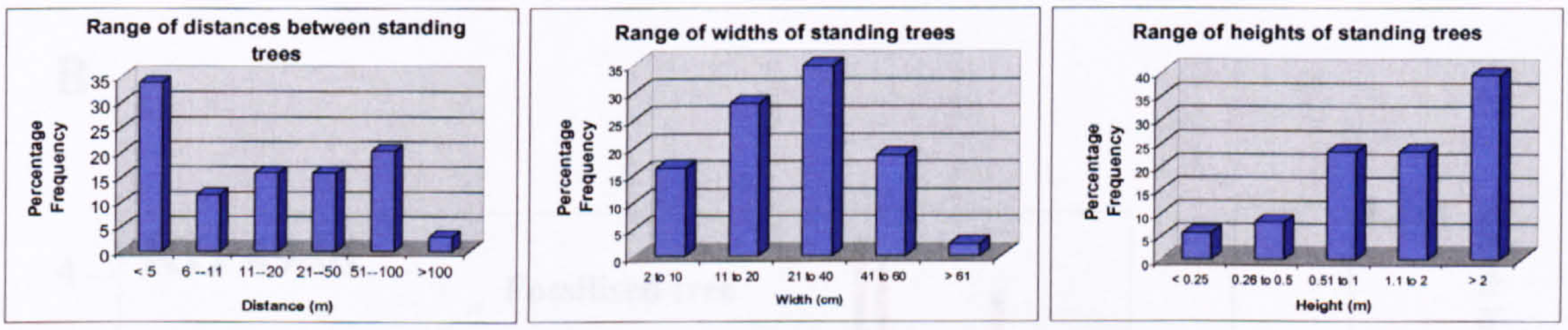


4.4.2 The distribution of trees within cliff sections

Fossil standing trees were recorded from 11 forest horizons (Horizons 1-11, Table 4.3) on Citadel Bastion and Titan Nunataks and the distribution of the fossil trees can be seen in plots of four cliff sections containing the most abundant trees (Figure 4.11). A summary of the data collected on the standing trees found within the cliff section is given in Table 4.4 (based on data from Table A4.1).

Table 4.4 Summary of the data on the standing trees within the cliff sections on Citadel Bastion and Titan Nunataks (N=89). Data within the table is calculated using the data from Table A4.1, Appendix 4. Histograms show the distribution in data of distances between trees, width of the trees and the tree height respectively.

Distance between trees			**Width of tree at base**			**Height of tree**		
Average	s.d	Range	Average	s.d	Range	Average	s.d	Range
29.9 m	**36.1**	**0.3 – 168 m**	**29 cm**	**18**	**5 – 76 cm**	**1.8 m**	**1.27**	**0.15 – 6 m**



The majority of the standing trees within cliff sections were spaced less than 5 m apart, were 11-40 cm wide and preserved to more than 2 m in height (Table 4.4). On average these forests had a density of 1 tree per 37 m^2, with a range of 1 tree per 22-49 m^2 (Table 4.6). If the 10 % error is considered (Section 4.4) the density would be closer to 1 tree per 41 m^2.

Figure 4.11 Distribution plots of standing trees within cliff sections at locations: A) KG 4945, West Titan Nunatak. B) KG 4946, West Titan Nunatak. Leaf symbol indicates the location of plant sampling stations (see Tables 4.1 & 4.4). F1, F2 etc correspond to forest horizon numbers in Tables 4.1 and 4.3.

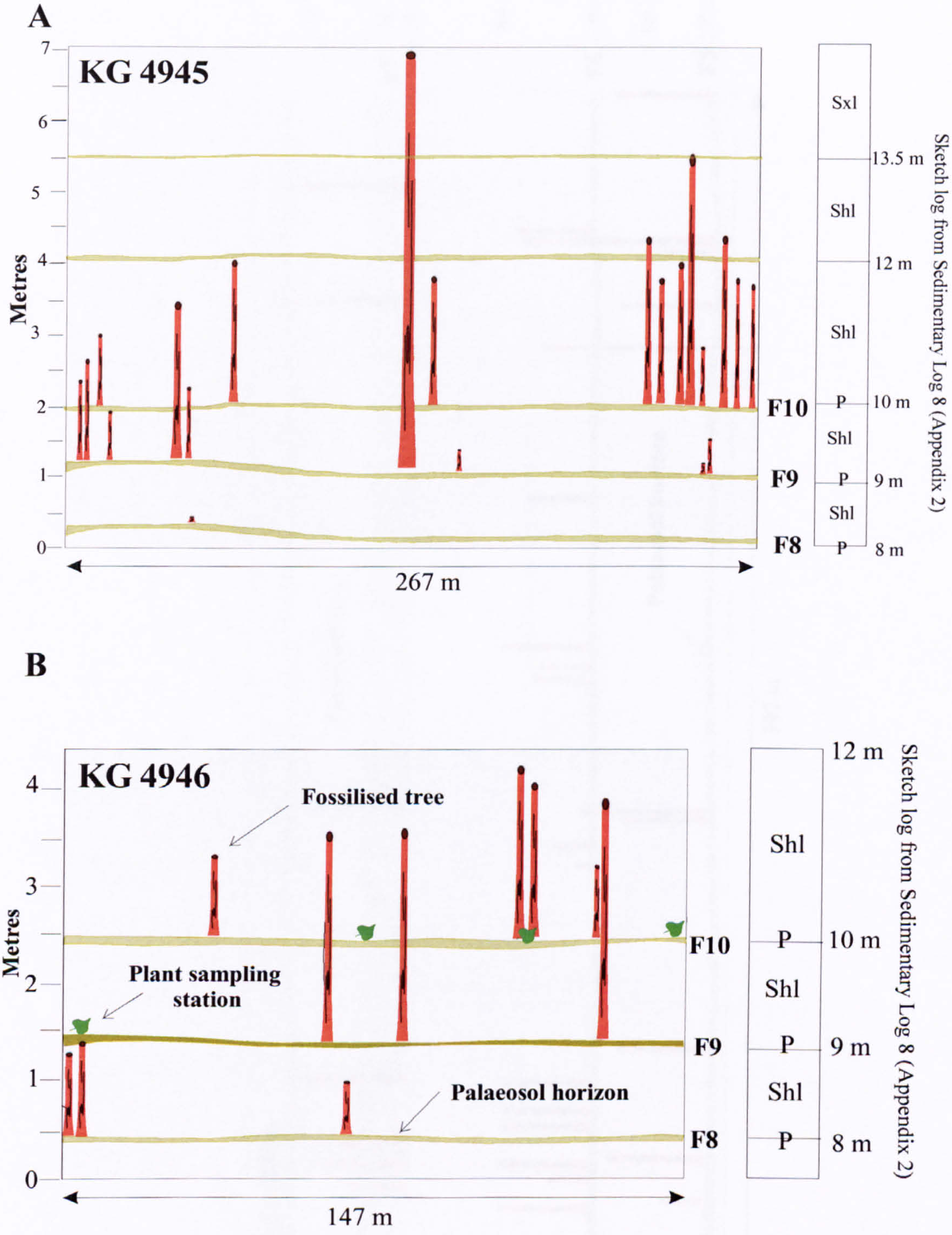
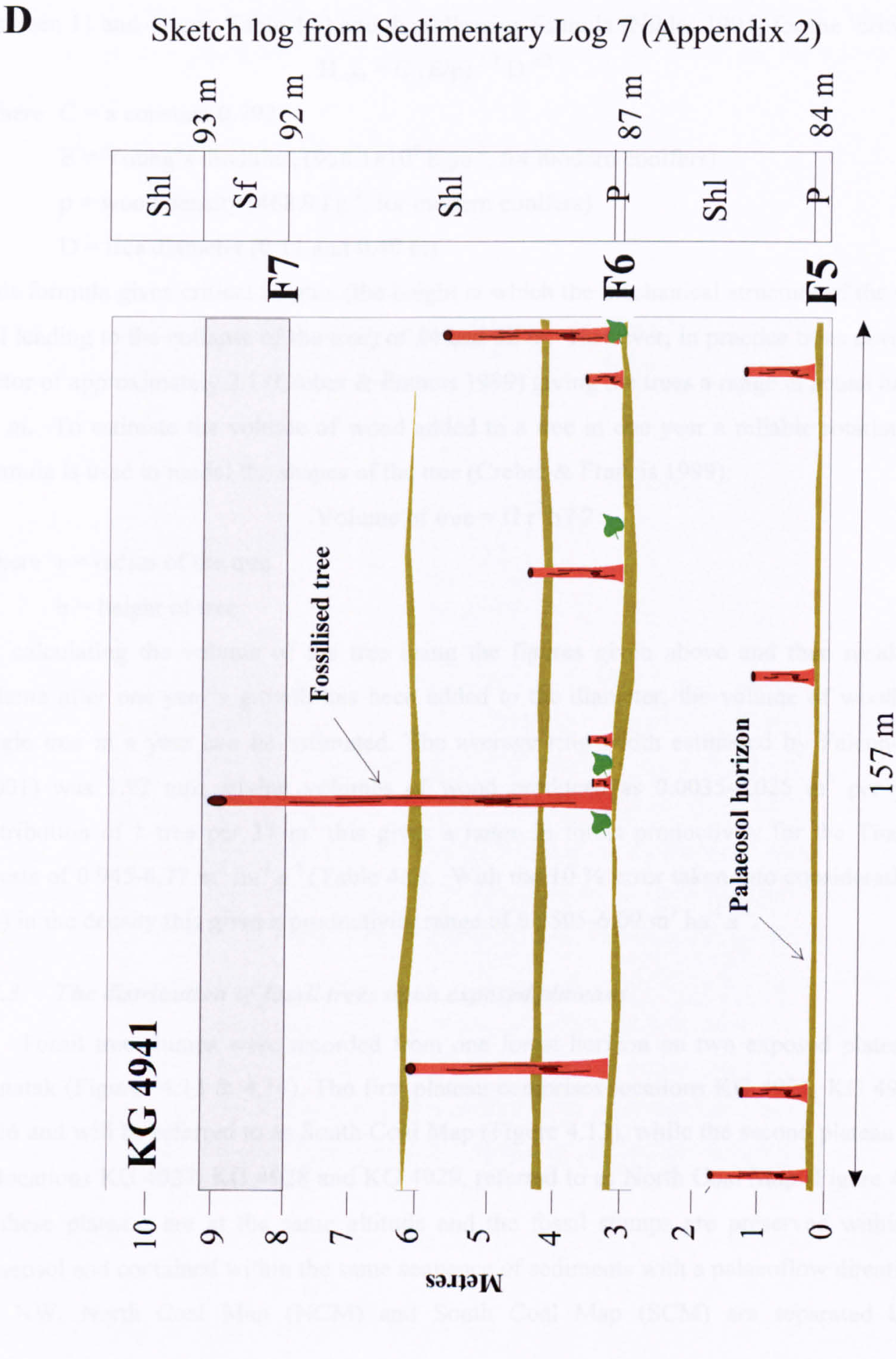


Figure 4.11 continued. C) A distribution plot of standing trees within a cliff section at Location KG 4944, East Titan Nunatak (see Table 4.4). F5, F6 etc correspond to forest horizon numbers in Tables 4.1 and 4.3.

Figure 4.11 continued. D) A distribution plot of standing trees within a cliff section at Location KG 4941, East Titan Nunatak (see Table 4.4). F5, F6 etc correspond to forest horizon numbers in Tables 4.1 and 4.3.



The productivity of the forests on Titan Nunataks (based on the standing trees within cliff section) can be calculated using an adapted modern method used by Creber & Francis (1999). First the original tree height is calculated using a range of tree diameters (the majority of the trees were between 11 and 40 cm; Table 4.4) and the following formula (Niklas 1994) for the 'critical height':

$$H_{crit} = C\,(E/\rho)^{1/3}\,D^{2/3}$$

Where C = a constant 0.792

E = Young's modulus, (958.1×10^6 kgm^{-2}, for modern conifers)

ρ = wood density (468.9 kg^{-2}, for modern conifers)

D = tree diameter (0.11 and 0.40 m)

This formula gives critical heights (the height at which the mechanical structure of the wood would fail leading to the collapse of the tree) of 34 and 52 m. However, in practice trees develop a safety factor of approximately 2.1 (Creber & Francis 1999) giving the trees a range in actual heights of 16-25 m. To estimate the volume of wood added to a tree in one year a reliable rotation paraboloid formula is used to model the shapes of the tree (Creber & Francis 1999):

$$\text{Volume of tree} = \Pi\, r^2 h / 2$$

Where r = radius of the tree

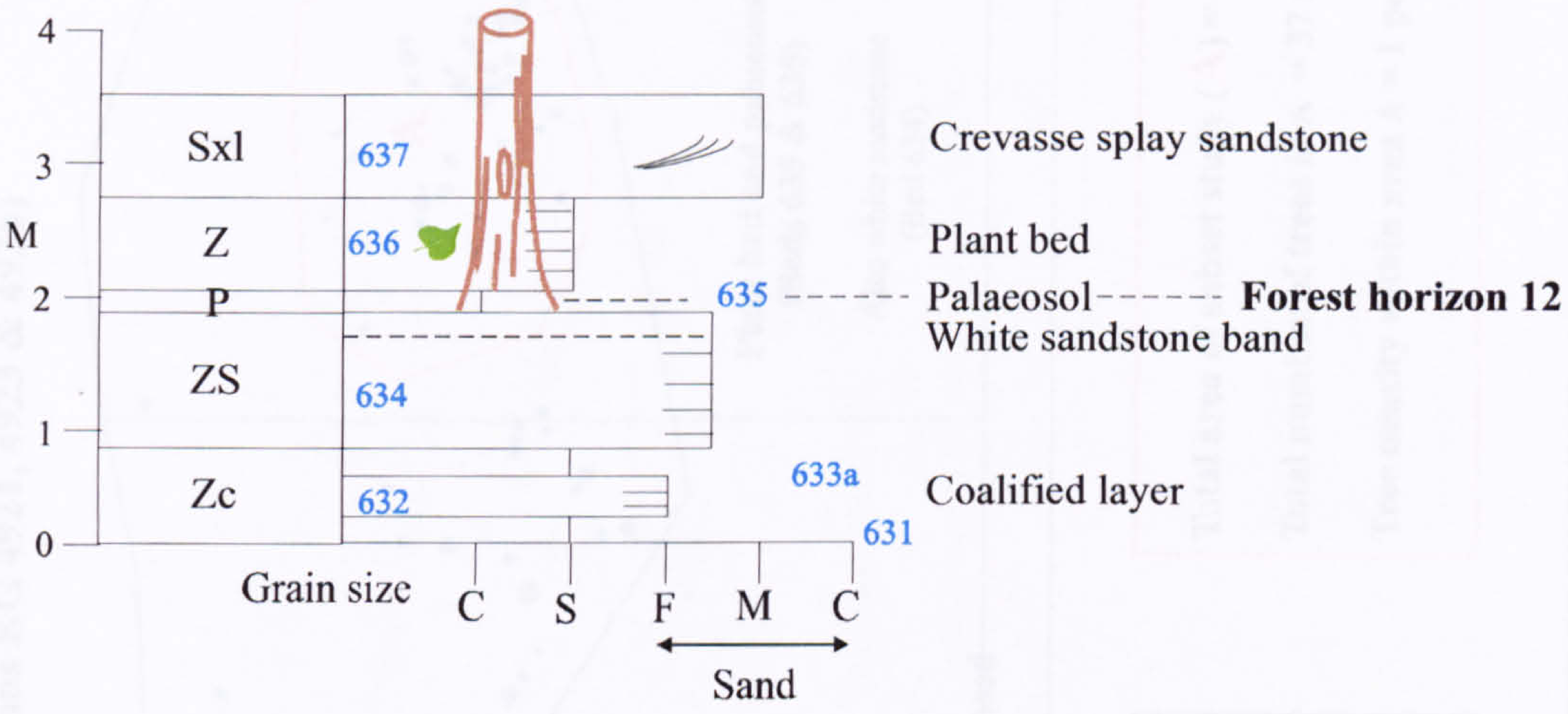
h = height of tree

By calculating the volume of the tree using the figures given above and then recalculating the volume after one year's growth has been added to the diameter, the volume of wood added to a single tree in a year can be estimated. The average ring width estimated by Falcon-Lang *et al.* (2001) was 1.92 mm, giving volumes of wood produced as 0.0035-0.025 m^3 per year. At a distribution of 1 tree per 37 m^2 this gives a range in forest productivity for the Titan Nunataks forests of 0.945-6.77 $m^3\,ha^{-1}\,a^{-1}$ (Table 4.6). With the 10 % error taken into consideration (Section 4.4) in the density this gives a productivity range of 0.8505-6.09 $m^3\,ha^{-1}\,a^{-1}$.

4.4.3 The distribution of fossil trees upon exposed plateaus

Fossil tree stumps were recorded from one forest horizon on two exposed plateaus of Coal Nunatak (Figures 4.13 & 4.14). The first plateau comprises locations KG 4921, KG 4923 and KG 4926 and will be referred to as South Coal Map (Figure 4.13), while the second plateau is made up of locations KG 4927, KG 4928 and KG 4929, referred to as North Coal Map (Figure 4.14). Both of these plateaus are at the same altitude and the fossil stumps are preserved within the same palaeosol and contained within the same sequence of sediments with a palaeoflow direction towards the NW. North Coal Map (NCM) and South Coal Map (SCM) are separated laterally by approximately 650 m. Figure 4.12 outlines the sedimentary sequence within which the tree stumps are found and maps of the tree stumps are shown in Figures 4.13 and 4.14.

Figure 4.12 Summary sedimentary log of the sequence of sediments within which the fossil tree stumps are preserved. Bed numbers correspond to those on Sedimentary Log 9, Appendix 2.


Sequence from Sedimentary Log 9 from KG 4919 (Appendix 2)

Upon the exposed plateaus of the North and South Coal Map areas various facies outcrop (Figure 4.12). The siltstone plant bed (Bed 636) is most commonly exposed and along with the sandstone unit (Bed 637) and the palaeosol (Bed 635) contain the tree stumps. In one area on South Coal Map, where the full thickness of the plant bed outcropped (Figure 4.13), it was possible to sample the plant bed over a distance of 120 m (plant sampling location KG 4921, forest horizon 12; Table 4.1) providing information on the plants that grew within the same forest horizon as the tree stumps. South Coal Map is a total area of 30,075 m^2 and North Coal Map is a total area of 50,283 m^2. One hundred and ninety five tree stumps were thus recorded from a total area of 80,358 m^2.

Due to the patchy exposure on the plateaus, subset areas were marked on each (see Section 4.2.2) where only the plant bed (Bed 636, Figure 4.12) outcropped and did not vary, in order to obtain a sample area that would give a tree density more representative of the density within the forests, because it removed factors of poor exposure, and facies change that may affect tree preservation. The subset areas are also only concerned with the facies directly above the palaeosol, which is more likely to preserve all the trees that were present in the forest before sediment influx, as it would include trees that were only preserved to a short height that would not be represented within the facies above the plant bed. Subset area A on South Coal Map (Figure 4.13) is a total of 4.111 m^2, and subset area B on North Coal Map (Figure 4.14) is a total of 10, 726 m^2.

Figure 4.13 Map of the tree stumps cropping out on the exposed upper surface of Coal Nunatak, South Coal Map, Locations KG 4921, 4923 and 4926. Tree stumps are represented by blue circles, diameter proportional to diameter of tree (see key). See Table 4.3 and Appendix Table A4.2 (App.4).

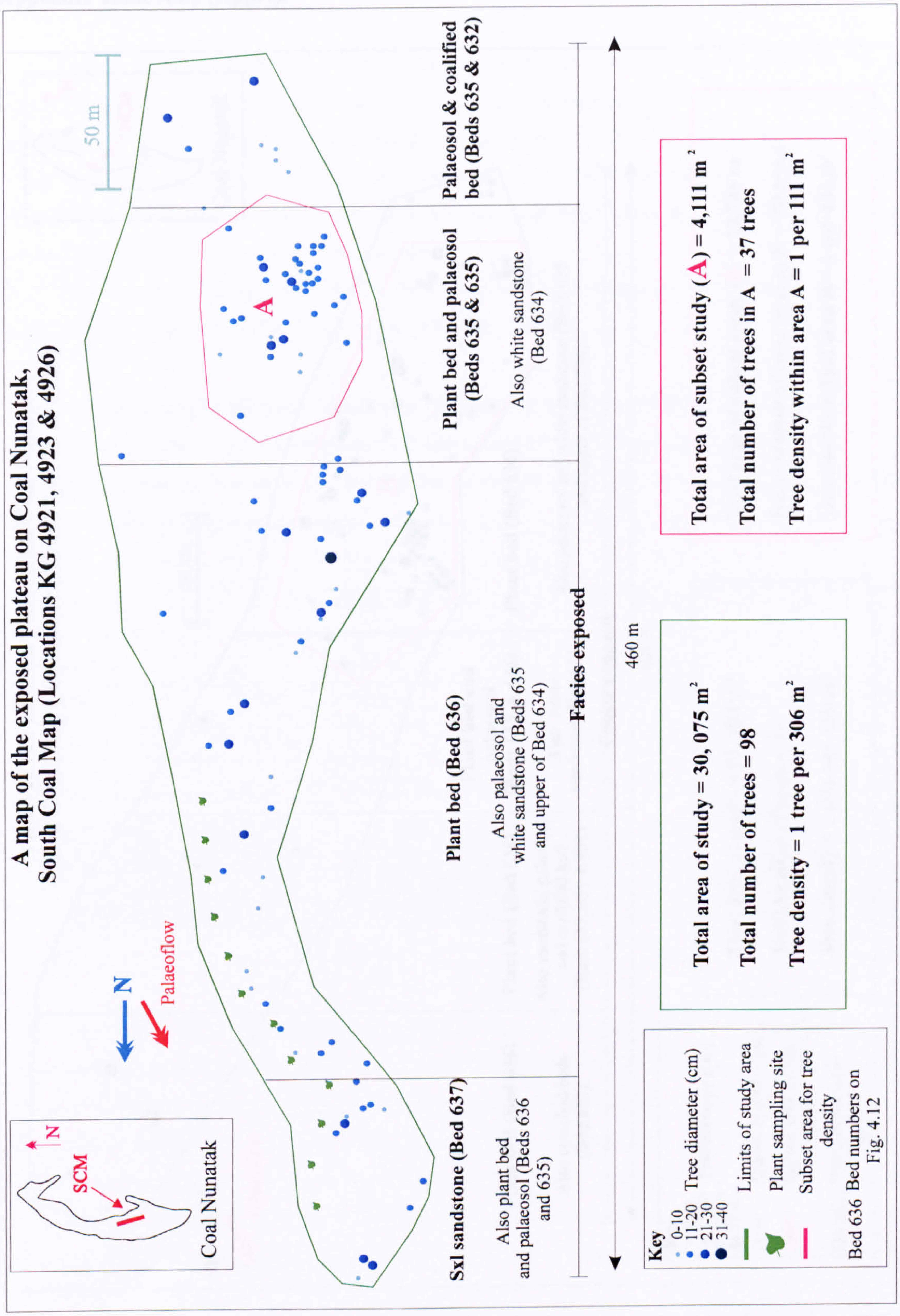
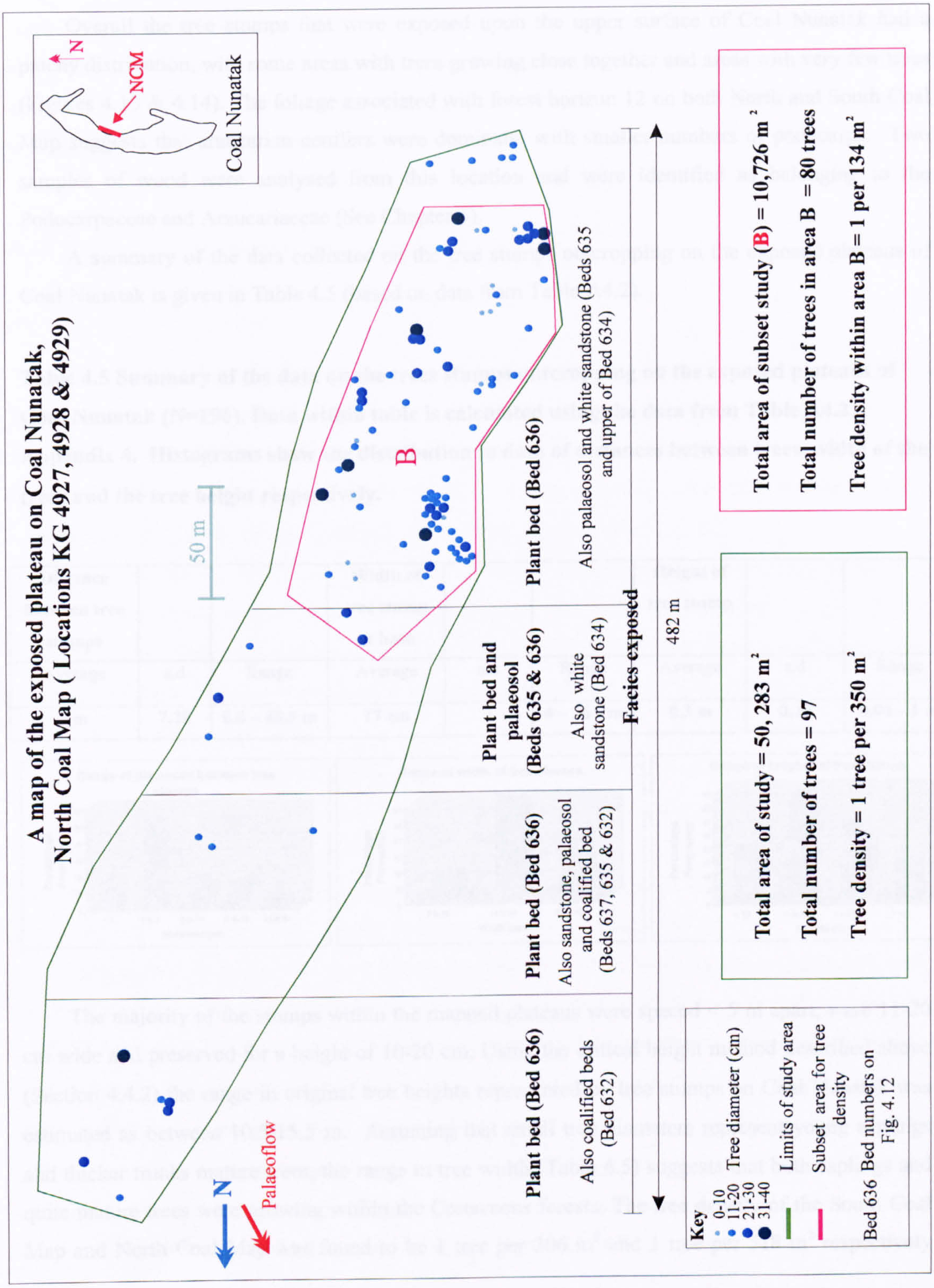


Figure 4.14 Map of the tree stumps cropping out on the exposed upper surface of Coal Nunatak, North Coal Map, Locations KG 4927, 4928 and 4929. Tree stumps are represented by blue circles, diameter proportional to diameter of tree (see key). See Table 4.3 and Appendix Table A4.2 (App.4).



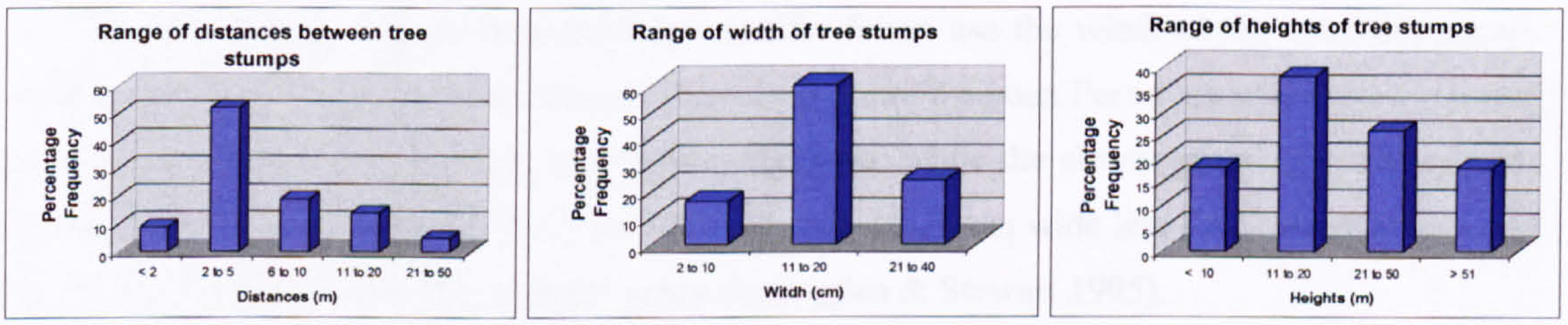
4.4.3.1 Forest density

Overall the tree stumps that were exposed upon the upper surface of Coal Nunatak had a patchy distribution, with some areas with trees growing close together and areas with very few trees (Figures 4.13 & 4.14). The foliage associated with forest horizon 12 on both North and South Coal Map suggests that araucarian conifers were dominant, with smaller numbers of podocarps. Two samples of wood were analysed from this location and were identified as belonging to the Podocarpaceae and Araucariaceae (See Chapter 5).

A summary of the data collected on the tree stumps outcropping on the exposed plateaus of Coal Nunatak is given in Table 4.5 (based on data from Table A4.2).

Table 4.5 Summary of the data on the trees stumps outcropping on the exposed plateaus of Coal Nunatak (N=196). Data within table is calculated using the data from Table A4.2, Appendix 4. Histograms show the distribution in data of distances between trees, width of the trees and the tree height respectively.

Distance between tree stumps			**Width of tree stump at base**			**Height of tree stump**		
Average	s.d	Range	Average	s.d	Range	Average	s.d	Range
7 m	**7.28**	**0.6 – 48.5 m**	**17 cm**	**7**	**4 – 36 cm**	**0.3 m**	**0.29**	**0.04 – 1 m**



The majority of the stumps within the mapped plateaus were spaced < 5 m apart, were 11-20 cm wide and preserved for a height of 10-20 cm. Using the critical height method described above (Section 4.4.2) the range in original tree heights represented by tree stumps on Coal Nunatak was estimated as between 10.5-15.5 m. Assuming that small tree diameters represent young saplings and thicker trunks mature trees, the range in tree width (Table 4.5) suggests that both saplings and quite mature trees were growing within the Cretaceous forests. The tree density of the South Coal Map and North Coal Map was found to be 1 tree per 306 m^2 and 1 tree per 518 m^2 respectively

(Table 4.6). Subset area A had a density of 1 tree per 111 m^2 while subset area B had a density of 1 tree per 132 m^2 (Table 4.6). With the 10 % error considered (Section 4.4) the densities of the sub set areas A and B are 1 tree per 122 m^2 and 1 tree per 145 m^2 respectively. The productivity of these forests on Coal Nunatak was calculated for trees ranging from 11- 20 cm wide from subset areas A and B (Figure 4.13 & 4.14) as 0.31-0.83 m^3 ha^{-1} a^{-1} (Table 4.6) and with the 10 % error the productivity range is 0.279–0.747 m^3 ha^{-1} a^{-1}.

4.4.4 Discussion of conifer density and distribution

4.4.4.1 Maturity of forest

The majority of the fossil stumps are 11-20 cm wide on Coal Nunatak and represent trees that are estimated to have grown to heights of 15 m. Creber & Francis (1999) estimated tree height to be 17 m, based on Jefferson's data from Coal Nunatak. On Titan Nunataks the standing trees were larger at 21-40 cm wide representing trees up to 25 m high, which is comparable to data of Falcon-Lang & Cantrill (2000) who estimate canopy height as approximately 30 m.

These figures are similar to Araucariaceae and Podocarpaceae trees growing today in the Southern Hemisphere: podocarp and araucarian conifers with widths up to 2 m and heights reaching up to 45 m (but more typically growing 25 to 30 m high) are described from temperate forests in South Africa, New Zealand, New Caledonia and Chile (Midgley *et al* 1995; Ogden & Stewart 1995; Jaffre 1995; Armesto *et al.* 1995).

Modern studies on podocarp/araucarian conifer forest use the width of the trees to estimate their maturity. For example, New Zealand araucarias from Waipoua Forest are considered young if less than 10 cm wide at their base and mature otherwise, while the slower growing podocarps less than 10 cm wide are considered less than 100 years old, 10-20 cm wide less than 300 years old, and above 30 cm in width are more than 400 years old (Ogden & Stewart 1995).

Using this as a guide, the trees within the forest on Coal Nunatak could be considered as mature but mixed with saplings, young trees and older, more mature trees, given the range in tree width of 4-36 cm. The Coal Nunatak forest was dominated by araucarian trees that are described today as long-lived pioneer species that like to colonise after disturbance events (Ogden & Stewart 1995), opening up areas for sapling growth while still allowing areas of mature forest to develop. Today these types of forest usually have patches dominated by young trees that have re-colonised areas after gaps have been made by windfall, flooding or landslides (Armestro *et al.* 1995; Ogden & Stewart 1995), as well as the shade tolerant young trees and saplings growing along side the more mature trees (Ogden & Stewart 1995; Jaffre 1995). While the Coal Nunatak forest does contain young trees growing amongst the more mature trees, no specific areas with only young trees were found. It is possible that the patches of exposed area on Coal Nunatak with no trees within them represent the areas that would have been covered in young trees but which may have been uprooted and washed away by the floodwaters that covered the forest floor.

The trees within the Titan Nunataks forests were more mature, with some trees possibly reaching ages up to 400 years but with very few young trees or saplings. The Titan Nunataks forests are dominated by the slower growing, long-lived podocarp conifers that today rely on advance regeneration rather than occupancy of gaps by seedlings after disturbance events (Midgley *et al.* 1995). This allows mature forest communities to develop, with the podocarps occupying a 'senescence niche'. Previous estimates based on long growth ring sequences preserved within the woods suggest that some of the Alexander Island forest trees may have attained ages > 180 years old (Chapman 1994).

4.4.4.2 Distribution

These Cretaceous forests have a patchy distribution with fossil stumps closer together in some parts than other areas. If this is a true representation of the original forest it suggests that they had the potential to grow at high densities and space was not a limiting factor. This poses the question of why the trees grew in clusters rather than a more uniform high-density distribution.

The patchy outcrop of the sediments containing the fossil trees may influence the distribution of the trees within the entire study area on the exposed plateau of Coal Nunatak. However during sampling of the subset areas A and B there was no facies change. Therefore, although facies exposure was likely to have some influence on stump distribution it is unlikely to explain the entire pattern of tree stump occurrence.

Environmental influences such as soil type and fertility, drainage, sun availability and competition from plants are all likely to have influenced the distribution of trees within the forests. Although palaeosol type remained the same over the study area, original soil thickness and fertility were difficult to establish and these may have varied with topography. Similarly, subtle changes in drainage across the area and changes in light availability may have varied over the Cretaceous topography. However poor drainage was not apparent within the palaeosols or sediments and no large topographical changes were seen within the rock sequences. Competition from plants may have been a factor in preventing conifer saplings from becoming established, as was the case on Citadel Bastion (plant sampling location KG 4914, Section 4.3.2, Figure 4.5), where the pentoxylalean plant dominated the forest floors. However no single plant species such as the pentoxylalean plant, was found to dominate the forests in which the fossil stumps occurred (KG 4921, Section 4.3.2, Figure 4.7).

One other consideration is that areas of young 'vulnerable' trees, re-colonising gaps previously made within the forest canopy (Section 4.3.1), were uprooted and removed by the flood event that buried the other trees within the forests, thus forming areas without tree stumps preserved. Such patchy distribution is seen in modern temperate forests of New Zealand, where storm damage creates gaps within the canopy that are re-colonised by young conifer saplings. These young trees would be highly susceptible to removal by flood events. Previous studies on the Alexander Island forests structure and density also suggest that the forests did not attain the densities possible under the prevailing light conditions, suggesting that frequent disturbance by flooding may ultimately have affected the density of the trees (Spicer 1989; Pole 1999).

4.4.4.3 Forest density

The tree density of Coal Nunatak forests is estimated as between 67.5–81 trees ha^{-1} (10 % error considered) with a maximum estimate of 75-90 trees ha^{-1} (assuming all trees were living at the time of inundation; Table 4.6). These estimates are low compared to those calculated from the same location on Coal Nunatak by Jefferson (1982a) (Table 4.6). However, Jefferson's (1982a) data was taken from a limited area of 950 m^2 with no record of continuous facies exposure and so are likely to be less representative than the densities calculated here from a larger study area of the ideal facies and with no facies change.

Titan Nunatak forest was estimated as having a density of 245 trees ha^{-1} (10 % error considered) and a maximum estimate of 270 trees ha^{-1}, which is high compared to the estimate by Falcon Lang *et al.* (2001) from other braidplain sediments of 91 trees ha^{-1}. However the sampling area for both of these studies is limited; on Titan Nunatak the area represents a transect line through the forest rather than a 2-D area and the density calculated by Falcon-Lang *et al.* (2001) was a mean of densities calculated for undefined 'clumps' of tree stumps. The error of assuming all trees were living at the time of inundation by sediment may also be more than the estimated 10 % and thus a more realistic figure maybe less than this. For example if 50 % of the forest trees were standing dead trees at the time of inundation the density would be closer to 135 trees ha^{-1}.

However due to disturbance on the river floodplains from frequent or catastrophic flood events, the forests probably didn't reach their 'density potential' with the prevailing light conditions (Spicer 1989; Pole 1999), and so the estimates above may also represent only a lower limit.

Table 4.6 A summary table of the densities and productivities calculated for the Alexander Island forest from this study and from previous studies.

	THIS STUDY			FALCON-LANG *ET AL.* (2001) Braidplain average	JEFFERSON (1982a) and CREBER & FRANCIS (1999)
	SCM	NCM	Titan Nunataks (average)		
TREE DENSITY	1 per 306 m^2	1 per 518 m^2	1 per 37 m^2	1 per 110 m^2	1 per 17 m^2
Trees per hectare (ha^{-1})	33	19	270	91	588
Area of study (m^2)	30,075	50,283	242	1540	950
DENSITY IN SUBSET AREA	1 per 111 m^2	1 per 134 m^2	n/a	n/a	1 per 18 m^2
Trees per hectare (ha^{-1})	90	75	n/a	n/a	555
Area of study (m^2)	4,111	10,726	n/a	n/a	550
PRODUCTIVITY ($m^3ha^{-1}a^{-1}$)	0.31 - 0.85		0.95 - 6.77	5.62 - 7.33	17.65
Density used	1 per 111 m^2		1 per 37 m^2	Not known	1 per 17 m^2
Ring width used (mm)	1.92			1.92	5 (largest recorded)

Modern podocarp/araucaria forests have densities very similar to those estimated in this study, after taking into consideration that the majority of today's forests are dominated by angiosperms, which had only just evolved in the Cretaceous and were a minor component, and considering the error of assumption that all the standing trees preserved were living at the time of inundation. For example, the araucaria forests of warm temperate New Zealand, probably the closest living relative to the Alexander Island forests, have typical densities of 50-200 trees ha^{-1} (Ogden & Stewart 1995), a range which includes the 67-81 trees ha^{-1} (10 % error considered) calculated for the araucarian forest on Coal Nunatak. Similarly the density calculated for the podocarp forests of Titan Nunatak of 245 trees ha^{-1} (10% error considered) is within the range given for mature podocarp forests of New Zealand with densities of 200-500 trees ha^{-1} (Ogden & Stewart 1995).

Falcon-Lang *et al.* (2001) describe the maximum forest density within the braided river sediments of Titan Nunatak as only one sixth of that within the meandering coastal sediments of Coal Nunatak. They argued that the forest density was low (91 trees ha^{-1}) on the braided river floodplain because the forests were subject to regular catastrophic floods, whereas the forest density on the meandering river floodplain was high (568 trees ha^{-1}, Jefferson, 1982a) because of a more stable environment. The forest densities calculated here, along with the sedimentary data, do not support this, instead it seems that the forest densities may be related more to species composition rather than stability of environment.

4.4.4.4 Forest productivity

The total productivity of these Cretaceous forests is estimated as between 0.279-6.09 ha^{-1}a^{-1} (considering the 10 % error of assumption; Section 4.4) with a maximum estimate of 0.31-6.77 m^3 ha^{-1}a^{-1} (assuming all the trees were living in the forests; Table 4.6), with the upper value comparable to previous estimates of 5.62-7.33 m^3 ha^{-1}a^{-1} (Falcon-Lang *et al.* 2001; Table 4.6). Falcon-Lang *et al.* (2001) describe the productivity of these forests as comparable to those of the compositionally similar araucarian/podocarp rainforest of New Zealand, which have productivities between 4.5-7.5 m^3 ha^{-1}a^{-1} (Wardle 1991). The productivity of these forests was also calculated by Creber & Francis (1999) using Jefferson's (1982a) data as 17.65 m^3 ha^{-1}a^{-1} (Table 4.6). This estimate uses the maximum ring width recorded from the conifer wood and therefore provides an estimate of the maximum productivity of the forests. The lower estimates of productivity calculated in this study from Coal Nunatak may reflect the patchy distribution of the forest that was seen in the fossil record, caused by frequent flooding events.

However there are some limitations in calculating the productivities of fossil forests. Within the calculation, densities with and without the 10 % error of assumption are considered but this error may be underestimated (Section 4.4). For example if 50 % of the trees were dead standing trees at the time of inundation of the forest by flood sediments, the productivity range calculated in this study would be reduced to 0.155-3.045 m^3 $ha^{-1}a^{-1}$. The estimates calculated by Falcon-Lang *et al.* (2001) (who did not consider dead standing trees) would be reduced to 2.81-3.665 m^3 $ha^{-1}a^{-1}$, making these estimates less comparable to those of the modern New Zealand forests.

Estimates of forest productivity have also been questioned by Chapman (1994) who has shown that due to buttressing in the lower sections of tree trunks, stumps often have very wide growth rings. Given that the productivity estimates are based on ring data from fossil wood that is often sampled from fossil tree stumps they may over estimate the forest productivity. Rare samples of wood collected from further up the trunk within this study indicate ring widths of 1.44 mm compared to the total average of 1.92 calculated by Falcon-Lang *et al.* (2001). Thus the ratio between the tree ring widths higher up the trunk to those from the base is 1:1.5. The productivity calculated in this study may, therefore, be an overestimate by approximately a third. The productivity range calculated in this study taking into consideration this ratio would be 0.2-4.6 m^3 $ha^{-1}a^{-1}$.

Thus although the productivities calculated in this study compare well to those of modern forests, caution is needed in interpreting too much from productivity calculations of fossil trees.

Chapter 5 Palaeobotany

5.1 Introduction

Within the fossil plant material collected and recorded from the southeastern nunataks of Alexander Island, 34 form genera and 42 different species have been identified in this study. Systematic descriptions and taxonomic work on all the plants and trees that occurred within the Cretaceous forests of Alexander Island is beyond the remit of this thesis and many of the taxa have been described (Jefferson 1981; Cantrill 1995, 1997b; Cantrill & Nichols 1996; Falcon-Lang & Cantrill 2000, 2001; Howe & Cantrill 2001b) or are part of ongoing work by D. Cantrill (Swedish National History Museum, Stockholm) and N. Nagalingum (Univ. Melbourne, Australia). Fieldwork did, however, require the identification of plant types and all species identified during fieldwork for this research are given in this chapter. Material of an interesting extinct plant type, Pentoxylales, was also found during fieldwork for this thesis and research on this plant has since lead to publication, a summary of which is given below. In addition to identifying plants and conifer foliage in the field, fossil wood types were also identified in the lab to provide information on the type of conifers that occurred within the Cretaceous forests and link the fossil wood to the conifer foliage.

In this chapter, the plant taxa identified in this study are listed with extended information on the primitive angiosperms that occur within the Cretaceous forests. The plant group Pentoxylales is then discussed with information on its habit and habitat from palaeoecological reconstructions. The taxonomy of the fossil wood is then discussed; with fossil wood types identified through anatomical characteristics and palaeoenvironmental information determined through growth ring analysis.

5.2 Plant taxa within the Cretaceous forests

All plants identified in this study were done so in the field by the use of pictures and descriptions compiled from both published and unpublished samples from the collection held at the British Antarctic Survey, Cambridge. All the plants identified within this study are given in Table 5.1. Examples of some of the different plant types identified are also shown in Figures 5.1 – 5.4 (Conifers, Figure 5.1; Ferns, Figure 5.2; Liverworts and angiosperms, Figure 5.3; Other plant types, Figure 5.4).

Table 5.1 A table of all the taxa identified in this study within the sediments of the southeastern nunataks of Alexander Island. For details of systematic taxonomy see: liverworts (Cantrill 1997a), ferns (Jefferson 1981; Cantrill 1995, 1996, 1997a), conifers (Falcon-Lang & Cantrill 2000, 2001b), angiosperms (Cantrill & Nichols 1996) and Pentoxylales (Howe & Cantrill 2001). The systematic taxonomy of ferns is based on the unpublished revision by N. Nagalingum (Univ. Melbourne, Australia). ****Podozamites binatus* **(Figure 5.1d); morphologically this foliage appears similar to that seen in extant species of Araucariaceae and Podocarpaceae, but in the absence of reproductive material or cuticle features it is impossible to classify this foliage further (Falcon-Lang & Cantrill 2001b). ****Elatocladus confertus, Elatocladus linearis*** **(Figure 5.1 a); this foliage has many features that are consistent with placement in the Podocarpaceae, but the lack of micromorphological features precludes confident assignment to this family (Falcon-Lang & Cantrill 2001b). ****Pagiophyllum*** **sp.; this foliage is placed in the form genus** ***Pagiophyllum,*** **a form seen in many plant groups but which here has many features supporting a placement within the Coniferales.** ***Pagiophyllum*****-type foliage characterises some members of the Araucariaceae, Podocarpaceae and Taxodiaceae (Falcon-Lang & Cantrill 2001b).**

Coniferopsida

- Coniferales (conifers)
  - Araucariaceae
    - *Araucaria chambersii* (leaves)
    - *Araucaria alexandrensis* (leaves)
    - *Araucarites wollemiaformis* (cone scale)
    - *Araucariopitys* (1 Sp., wood)
  - Podocarpaceae
    - *Podocarpoxylon* (1 Sp., wood)
    - *Bellingshausium willeyii* (leaves)
  - Taxodiaceae
    - *Athrotaxites ungeri* (cones)
  - Incertae sedis
    - *Brachyphyllum* sp. (stem)
    - *Elatocladus confertus** (leaves)
    - *Elatocladus linearis** (leaves)
    - *Pagiophyllum* sp.* (leaves)
    - *Podozamites binatus** (leaves)

Other minor gymnosperms

- Cycadales (cycadophytes, leaves)
- Ginkgoales (ginkgos)
  - *Ginkgoites* (leaves)
- Pentoxylales
  - *Taeniopteris daintreei* (leaves)
  - *Carnoconites cranwelli* (fruit)
  - *Pentoxylon* sp. (stem)
- Bennettitales
  - *Ptilophyllum* (leaves)
  - *Nilssonia* (leaves)

Filicopsida (ferns)

- Dipteridaceae
  - *Hausmannia papilio* (leaves)
- Matoniaceae
  - *Matonia jeffersonii* (leaves)
- Osmundaceae
  - *Cladophlebis drinnanii* (leaves)
  - *Cladophlebis oblonga* (leaves)
  - *Cladophlebis gallentiensis* (leaves)
  - *Cladophlebis macloughlinii* (leaves)
  - *Cladophlebis dissectus* (leaves)
  - *Phyllopteroides antarctica* (leaves)
- Gleicheniaceae
  - *Tetragleichenites acuta* (leaves)
- ? Lophosoriaceae
  - *Microphyllopteris unisorus* (leaves)
- ? Marsileaceae (1 Sp., leaves)
- Incertae sedis
  - *Aculea acicularis* (leaves)
  - *Adiantitephyllum serrata* (leaves)
  - *Sphenopteris sanjuliensis* (leaves)
  - *Sphenopteris warragulensis* (leaves)

Angiospermopsida (flowering plants)

- *Araliaephyllum quinquelobatus* (leaves)
- *Gnafalea jeffersonii* (leaves)
- *Hydrocotylophyllum alexandri* (leaves)
- *Timothyia trinervis* (leaves)

Hepatopsida (liverworts)

- Marchantiales
  - *Marchantites taenioides* (leaves)
  - *Marchantites rosulatus* (leaves)
  - *Hepaticites.* (1 Sp., leaves)

Sphenopsida (horse-tails)

- Equisetales (1 Sp., leaves)

5.2.1 Angiosperms

It is well understood that angiosperm plants underwent a major diversification during the Early Cretaceous between 130 and 90 Ma. There are many current theories for the roots of the early angiosperm plants including the idea that the Bennettitales, Gnetales and Pentoxylales form a seed plant group that is most closely related to the angiosperms (Crane *et al.* 1995). Fossil angiosperm material from the Early Cretaceous thus plays a crucial role in bridging the gap between angiosperms and their gymnosperm relatives.

Angiosperms have widespread occurrence in the northern Antarctic Peninsula in Upper Cretaceous – Lower Tertiary sediments, including specimens from Snow Hill Island (Cantrill 2000), James Ross Island (Francis 1991; Askin & Baldoni 1998), Seymour Island (Askin & Baldoni 1998) and Adelaide Island (Jefferson 1980), but the seven angiosperms species identified within the sediments of the Triton Point Formation on Alexander Island are the oldest known specimens (Jefferson 1981; Cantrill & Nichols 1996).

Fossil angiosperm material was found at 11 of a total of 47 locations visited in this study and was recorded from 7 sampling sites out of the 17 sampled all together. They were found preserved in siltstones as *in situ* material above palaeosol horizons (Figure 5.3 c, d) or as drifted material within sandstones in overbank flood deposits. An insight into the palaeoecology of the angiosperm plants occurring on Alexander Island during the Early Cretaceous is obtained through the associations of the angiosperm material with that of other plants, based on plant distributions along forest floor transects (Chapter 4) and statistical analysis of quantitative plant data (Chapter 6).

It is found that the angiosperms commonly occurred with ground layer species of liverworts and were associated with herbaceous species such as the Pentoxylales, horsetails and ferns, but had little relationship with more mature species such as the conifers (Section 4.3.2, Figure 4.5; Section 6.2, Table 6.1). Whole specimens of angiosperm foliage were most common at location KG 4914 on Citadel Bastion where Pentoxylales formed the dominant component of the vegetation and laminated siltstones suggest a back-swamp palaeoenvironment with young vegetation colonising fresh sediments brought in by low-energy floods. Angiosperms are also more common lower down in the section on the southeastern nunataks where low-energy flooding is considered to have been more frequent (Section 4.3.4). The occurrence of angiosperm material here suggests the early flowering plants were small ground plants that colonised fresh sediments after disturbance events, supporting current views that early angiosperms were small herbaceous plants (Crane *et al.* 1995).

Figure 5.1 Conifers. a) ***Elatocladus linearis,*** **KG 4941, Bed 435, Log 7. b)** ***Araucaria alexandrensis,*** **KG 4922, Bed 636, Log 9. c)** ***Araucaria chambersii,*** **KG 4922, Bed 636, Log 9. d)** ***Podozamites binatus,*** **KG 494941, Bed 435, Log 7. e)** ***Araucarites wollenmiaformis,*** **KG 4921, Bed 636, Log 9. Scale bars in all photographs are 2 cm long.**

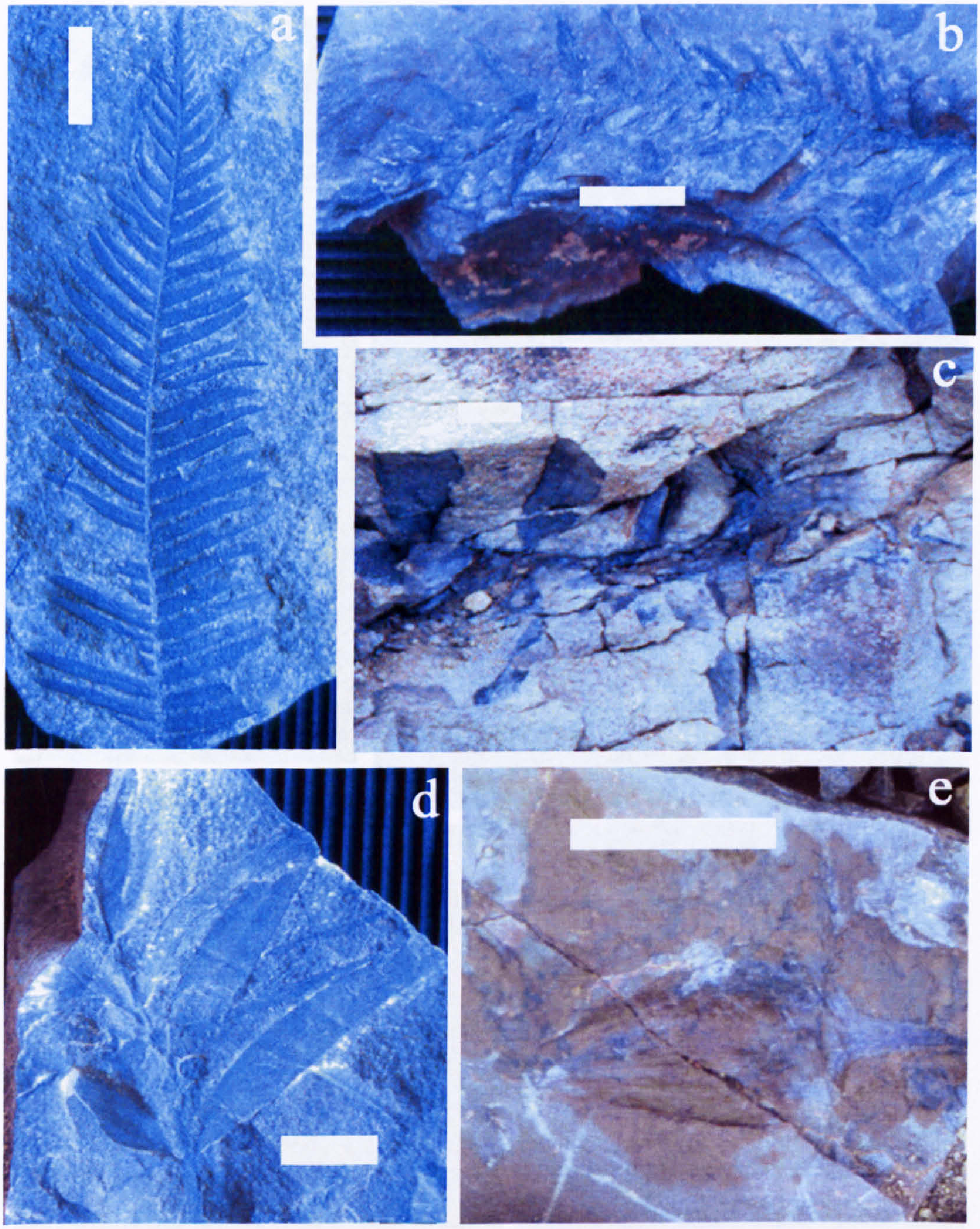


Figure 5.2 Ferns. a) Different species of *Cladophlebis* and *Tetragleichenites acuta* (arrow), KG 4906, Bed 3, Log 1. b) *Phyllopteroides antarctica,* KG 4941, Bed 435, Log 7. c) *Cladophlebis drinnani,* KG 4944, Bed 435, Log 7. d) *Aculea aciculari,* KG 4921, Bed 636, Log 9. e) ?Marsileaceae, KG 4903, Bed 656, Log 11. Scale bars in all photographs are 2 cm long.

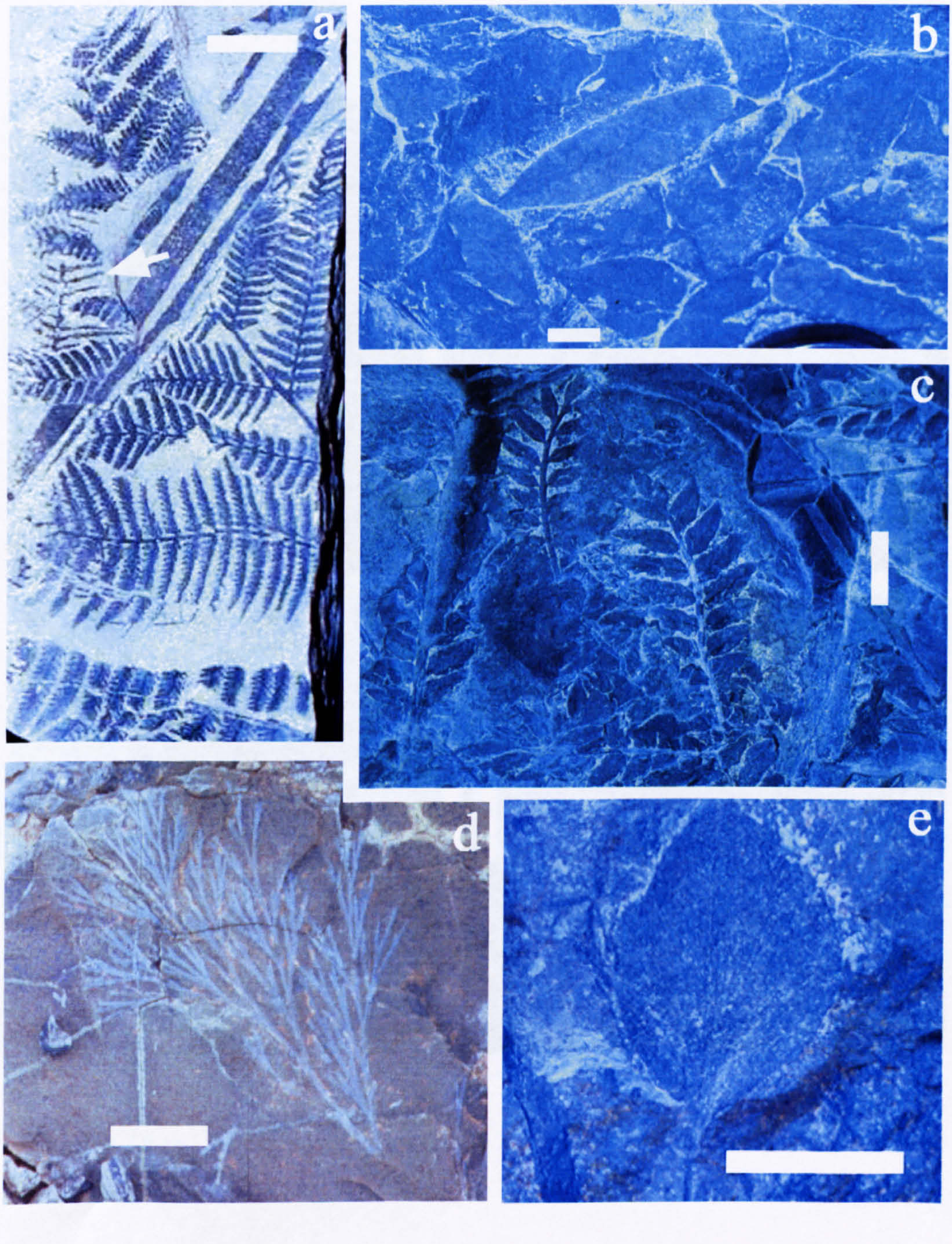


Figure 5.3 Liverwort and angiosperms. a) *Marchantites rosulatus,* KG 4931, Bed 656, Log 11. b) *Marchantites taenioides,* KG 4906, Bed 34, Log 1. c) *Gnafalea jeffersonii,* KG 4906, Bed 34, Log 1. d) *Araliaephyllum quinquelobatus,* KG 4914, Bed 118, Log 2. Scale bars in all photographs are 2 cm long.

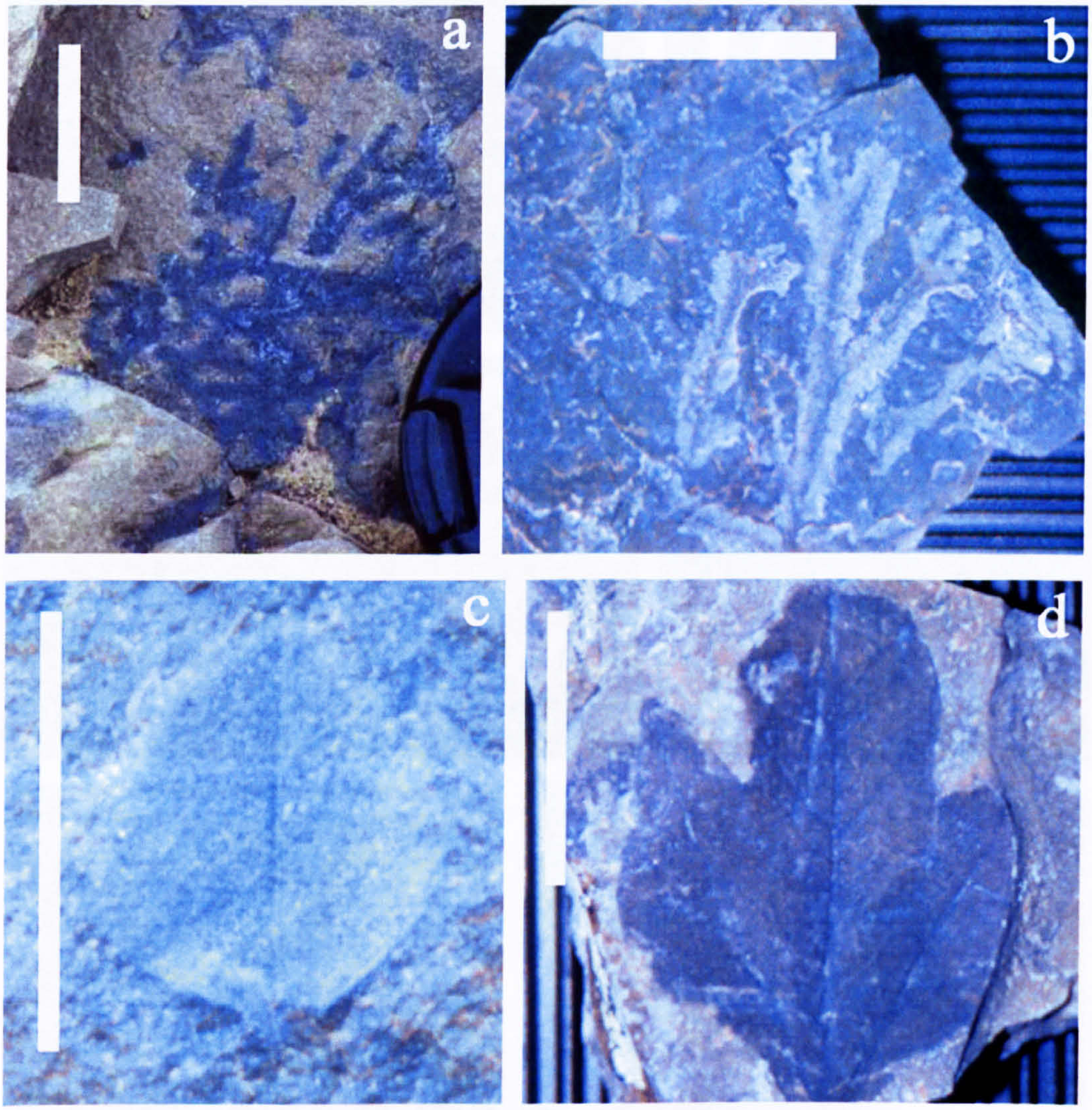
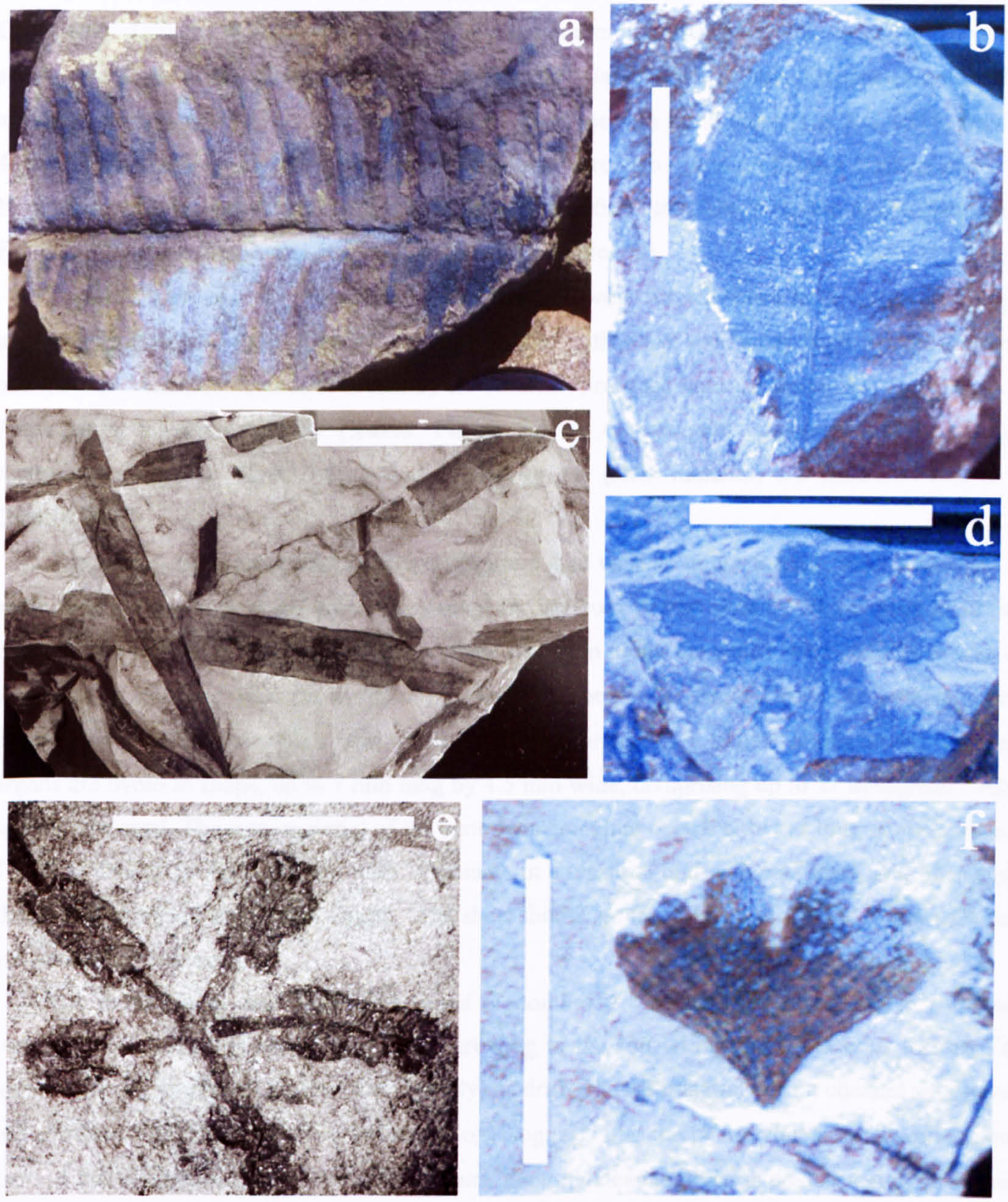


Figure 5.4 Other plant types. a) *Ptilophyllum,* KG 4935, Bed 402, Log 7. b) *Nilssonia,* KG 4941, Bed 435, Log 7. c) *Taeniopteris daintreei,* KG 4914, Bed 118, Log 2 . d) Cycadophyte, KG 4903, Bed 656, Log 11. e) *Carnoconites cranwelli,* KG 4905, Bed 60, Log 11 . f) *Ginkgoites,* KG 4936, Bed 462, Log 7. Scale bars in all photographs are 2 cm long.



5.3 Pentoxylales

Pentoxylales is an extinct plant order that formed a distinctive element in Southern Hemisphere vegetation, occurring widespread across Gondwana from the Jurassic to Early Cretaceous (Drinnan & Chambers 1985). The most common part of this plant to occur within the sediments of the southeastern nunataks of Alexander Island is the foliage *Taeniopteris,* found at almost all sampling locations and as a dominant component in some areas (e.g. KG 4914, Section 4.3.2). The 'fruits' or reproductive parts of the plant were also found on Citadel Bastion and Coal Nunatak, and this reproductive pentoxylalean material from the Albian Triton Point Formation, Fossil Bluff Group, is the youngest record of this group globally.

The fossil leaves and 'fruits' found during the fieldwork for this thesis have contributed to the understanding of the whole plant type, when studied with other specimens from the southeastern nunataks of Alexander Island, collected by D. Cantrill. From the material found, new specimens of *Taeniopteris daintreei* McCoy (leaves; Figure 5.4 c), *Carnoconites cranwelli* Harris (ovulate reproductive organs; Figure 5.4 e), and *Pentoxylon* sp. (stem material) are described (Howe & Cantrill 2001).

The leaves are oblanceolate in shape (Figure 5.4 c) with an entire margin, both a rounded or acute apex and a petiole at the base. They range in size from 10 mm wide by 50 mm long to 30 mm wide by 135 mm long. The leaves have a single mid-vein along the centre with parallel secondary veins arising from the mid-vein at approximately 90 °. The pentoxylalean 'fruits', or ovulate organs occur upon short shoots which bear up to 23 ovulate organs in a helical arrangement. Ovulate organs are ovoid in shape, up to 7 mm long by 4.5 mm wide, comprising up to 37 hexagonal ovules spirally arranged. The stem material of the pentoxylalean plant occurs either as long or short shoots. The long shoots are up to 10 mm wide, terminate in a terminal bud with leaf scars, and have short shoots branching off along their length. The short shoots are up to 15 mm long and 7 mm wide and are covered by leaf scars.

The fossil leaves and 'fruits' are found predominantly in leaf litter layers above palaeosol surfaces, representing pentoxylalean plants growing in the soil within the Cretaceous forests. The leaves also commonly occur (the 'fruits' rarely) as drifted fossil material within channel sandstones and overbank flood deposits. The sedimentology suggests that the pentoxylalean plants grew upon areas of the floodplain distal to the river channel. Pentoxylalean material is predominately preserved in fine-grained siltstones that formed from suspension fallout in pools of sediment-loaded water, suggesting that the forest floor at these sites was periodically covered by standing water, producing boggy conditions. Sites where plants were buried in coarser grained sandstones indicate an area more proximal to the river channel. The absence of sedimentary structures such as cross bedding, in any of the overlying strata does suggest, however, that the floodwaters overall were low energy flows, and certainly not the high energy floodwaters found adjacent to the river channel. The pentoxylalean plant established in areas of the floodplain that were subjected to periods of standing water and frequently flooded, inundating the forest floor in sediment.

The palaeoecology of this plant group was established from the association and relationship of the material to sedimentary facies, in conjunction with frequency distributions of the pentoxylalean material, and associations with other flora types laterally along individual leaf litter layers (Howe & Cantrill 2001). The evidence points to the pentoxylalean plant being of low stature and lacking a trunk, yet forming large monodominant communities. It may be that the plant grew with a similar habit to the modern bramble, colonising patches on the forest floor and overtaking the undergrowth where competition for light and space was low. It grew on the river floodplain, distal to the river channel, but preferred fairly boggy conditions in clearings or on the outskirts of the forest. Where light was reduced from a greater canopy of conifers, it colonised the forest floor in patches, and together with fern thickets, presumably preferred areas of the canopy with less dense stands of trees. It shared the ground with other water-lovers such as Equisetales and liverworts.

A publication documenting Pentoxylales is enclosed at the back of this thesis.

5.4 Fossil wood taxonomy

The abundance of fossil trees preserved *in situ* within the sediments of the southeastern nunataks is an important feature of these Cretaceous fossil forests. Plant distributions along fossil forest transects (Chapter 4, Section 4.3.2) show that conifer foliage is abundant, indicating that conifer trees were a dominant component within the forest communities. However, tree type cannot be identified in the field from fossil wood, unlike the fossil plants and conifer foliage. Identification of the fossil wood through thin section work therefore allows the identification of the type of conifer that forms stands of trees within the forest communities.

The wood was preserved by the process of silicification, which requires silica-rich fluids to be available and mobile within the preserving sediment prior to decay of the wood. Silica-acid is released during the devitrification of volcanic glass and the diagenesis of clay minerals within volcaniclastic sediments (Sigleo 1979). The silica coats the cell walls of the wood forming an exact replication of cell wall structures. However, the wood collected from the southeastern nunataks of Alexander Island is generally poorly and unevenly preserved with many of the cells crushed. This may be due to heterogeneous distribution, or low proportions, of volcanic glass within the sediments as well as low porosity within fine sediments impeding silica-fluid mobility.

More than eighty samples of wood were taken from *in situ* standing trees and tree stumps as well as from wood found in scree alongside *in situ* fossil tree outcrops. However, due to the uneven preservation only seven of the fossil wood samples are preserved well enough to be identified through analysis of thin sections.

Standard thin sections were prepared for all seven samples in radial longitudinal (RLS), tangential longitudinal (TLS) and transverse sections (TS). The wood was studied and assigned to the form taxa established through quantitative analysis by Falcon-Lang & Cantrill (2000), and classified to the generic level using Kraüsel's (1949) scheme, considering the most recent review of conifer taxonomy by Bamford & Philippe (2001).

The anatomical characteristics that were identified are shown in Table 5.2, along with all the numerical data recorded for the seven samples. Figure 5.5 is a simple sketch of the internal structures of wood with technical terms used in the text annotated.

Figure 5.5 A schematic sketch of the internal features of wood shown in the radial (RLS), tangential (TLS) and transverse (TS) sections. Technical terms used in the text are annotated. Sketch based on that from Greguss (1955).

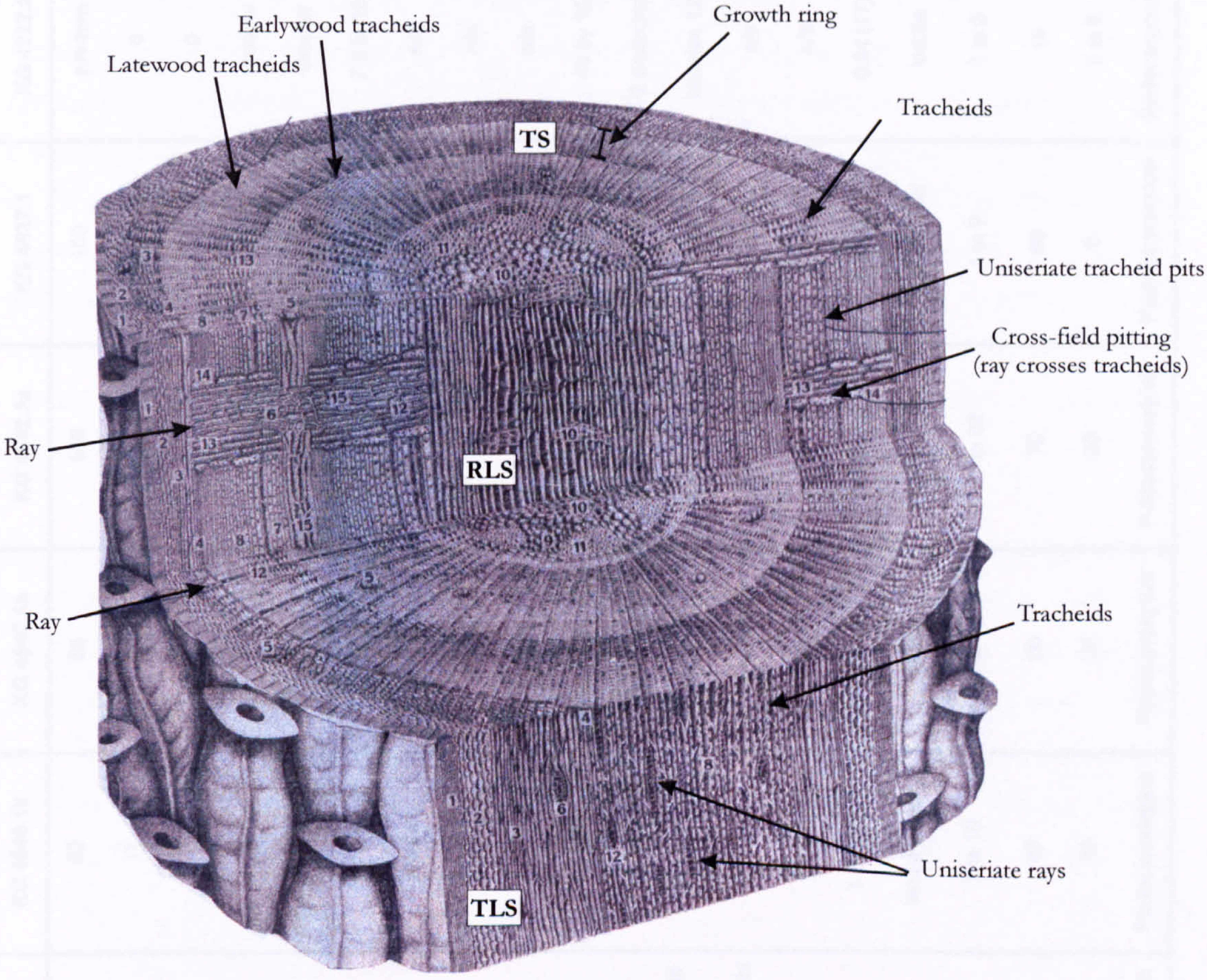


Table 5.2 A summary table of numerical data of the anatomical characteristics within the fossil wood collected from the southeastern nunataks of Alexander Island. Information on the locations samples were collected from (e.g. Sample KG 4929.2 was collected from Location KG 4929) can be found in Table A2.1, Appendix 2.

Anatomical characteristics	KG 4940.3a	KG 4940.19	KG 4940.4a	KG 4942.2a	KG 4937.1	KG 4922.25	KG 4929.2
RLS - % uniseriate pitting	85	82	85	100	100	predom	86
% alternate pitting	13	11	15	0	0	0	14
% opposite pitting	2	7	0	0	0	0	0
% touching pits	89	77	94	59	90	predom	100
Shape of pit	circular	circular-hexagonal	circular	cirular	circular - oblong	circular	circular - hexagonal
diametre of pit (µm)	18 (12-25)	25 to 30	25	20	20	7.5 to 10	3 to 5
shape of aperture of pit	circular to oval	circular	circular	circular	circular - oval	n/a	circular
size of aperture of pit (µm)	5	5 to 10	4 to 8	5	3.75	n/a	2
Length of rays (mm)	1 to 2	3 to 5.5	1 to 5	2	2.5	n/a	n/a
Cells in rays (µm)	25 by 17.5	42.5 by 25	32 by 70 by 22.5	47 by 15	22.5 by 17.5	45 by 15	15 by 15
Cross field pitting	1-2 podcarpoid	1-3 podocarpoid	1-2 podocarpoid	1-2 podocarpoid	1-2 podocarpoid	1-2 podocarpoid	1-4 araucaroid
Cross field pits - shape and size (µm)	circular-oval, 10 to 15	circular, 10	circular, 10	circular, 10 to 15	circular, 10	circular, 12.5	circular, 3 to 5
TLS - Type of rays	uniseriate, rarely bi	uniseriate	uniseriate	uniseriate	uniseriate, rarely bi	n/a	uniseriate and bi
Ray cell height	2 to 26	4 to 18	3 to 12	1 to 14	1 to 19	n/a	1 to 6
TS - Growth ring width (mm)(number)	2.74 (24)	1.54 (32)	2.54 (22)	3.96 (9)	1.32 (21)	0.94 (17)	1.9 (7)
Boundaries of growth rings	well defined	well defined	subtle	well defined	well defined	subtle	subtle
Ratio of late wood to early wood	1 to 11	1 to 10	1 to 13	1 to 32	1 to 9	1 to 6	1 to 2
Radial diameter (max) earlywood (µm)	80	80	60	70	60	10	15
Radial diameter (min) latewood (µm)	10	10	20	20	5	2 to 5	2 to 3
Species	**Podocarpoxylon**	**Podocarpoxylon**	**Podocaroxylon**	**Podocarpoxylon**	**Podocarpoxylon**	**Podocarpoxylon**	**Araucaciopitys**

5.4.1 Description of the fossil wood

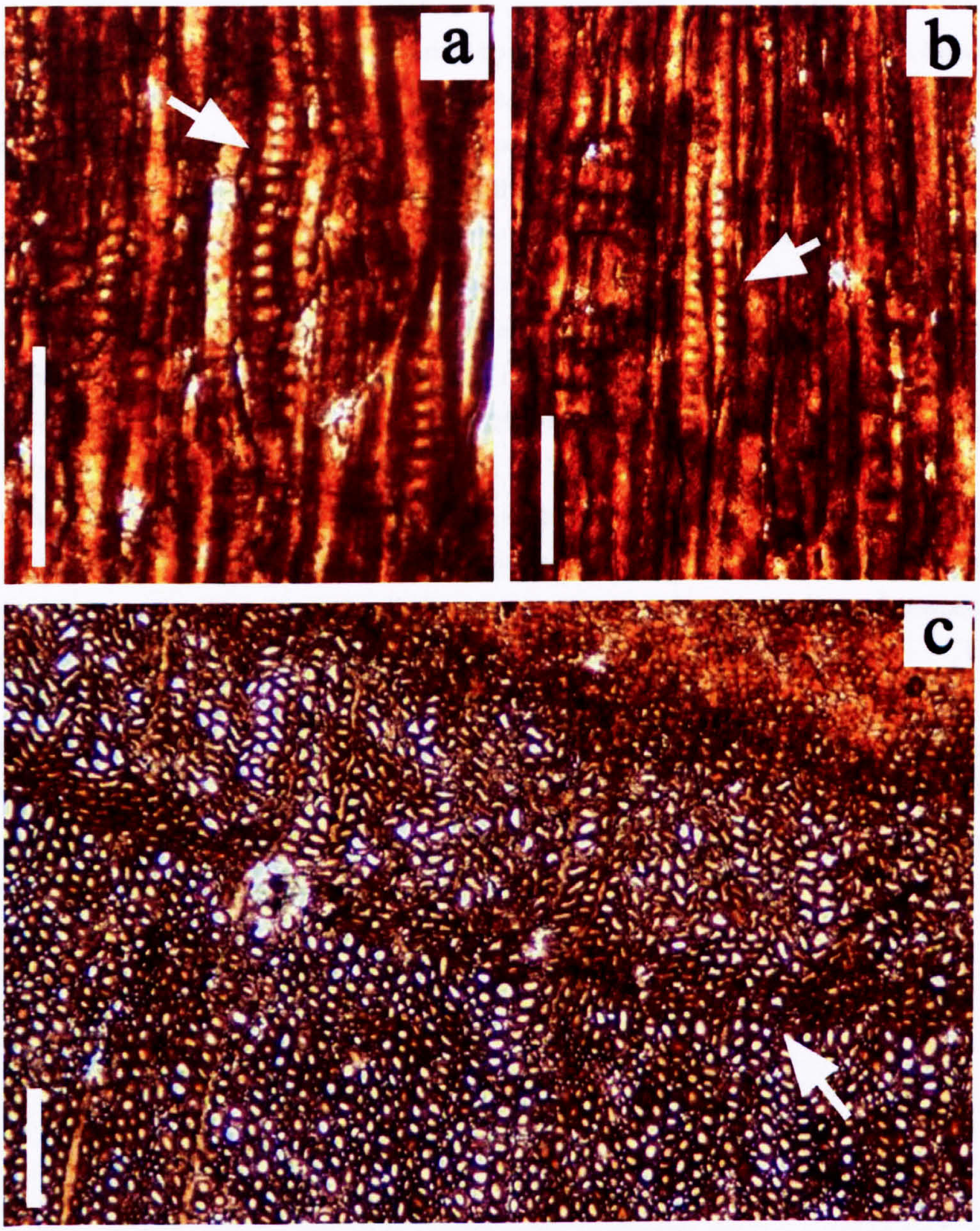
Araucariopitys Jeffery 1907 (Figure 5.6)

Material: One specimen has been assigned to this taxon. KG 4929.2 (*In situ* trunk from North Coal Nunatak).

Description: In RLS, tracheids have uniseriate (86 %) or biseriate (14 %) bordered pitting (Figure 5.6 a). Pits are circular to hexagonal (5-10 μm diameter) with circular apertures (2-4 μm diameter) and are always touching (100 %). Where pits are biseriate they are alternately arranged. Tangential tracheids walls are blank. Rays are abundant and are composed of parenchymous cells, 15 μm wide by 15 μm high, with thin horizontal cell walls. Ray tracheids are absent. Cross-field pitting is characterised by 1-4 araucaroid pits (3-5 μm diameter) with inclined apertures. In TLS, rays are uniseriate (rarely biseriate) and 1-11 cells high (Figure 5.6 b). In TS, growth rings have a mean width of 1.9 mm (N=7) and subtle ring boundaries with a ratio of late- to earlywood of 1:2 (Figure 5.6 c). Mean maximum earlywood cell diameter is 15 μm and mean minimum latewood cell diameter is 2-3 μm.

Identity: This taxon has araucaroid cross-field pitting but does not demonstrate the characteristic radial tracheid pitting in 2 to 3 rows (Greguss, 1955), instead the radial tracheid pitting is predominately uniseriate. Following Kraüsel's (1949) key this taxon is classified as *Araucariopitys* as it has circular pits on the radial walls of tracheids, exhibits mixed radial tracheid pitting (both uniseriate and biseriate) and the pits are predominately uniseriate rather than typically araucariod. *Araucariopitys* is believed to belong to the family Araucariaceae because some modern species are also dominated by uniseriate radial tracheid pitting (Falcon-Lang & Cantrill 2000).

Figure 5.6 ***Araucariopitys*****, Sample KG 4929.2 (Bed 637, Log 9) a) Uniseriate circular touching bordered tracheid pitting (arrow), RLS. Scale bar is 100 µm in length. b) A long uniseriate rays (arrow), TLS. Scale bar is 100 µm in length. c) Growth rings of irregular width possessing subtle ring boundaries (arrow), TS. Scale bar is 1 mm in length.**



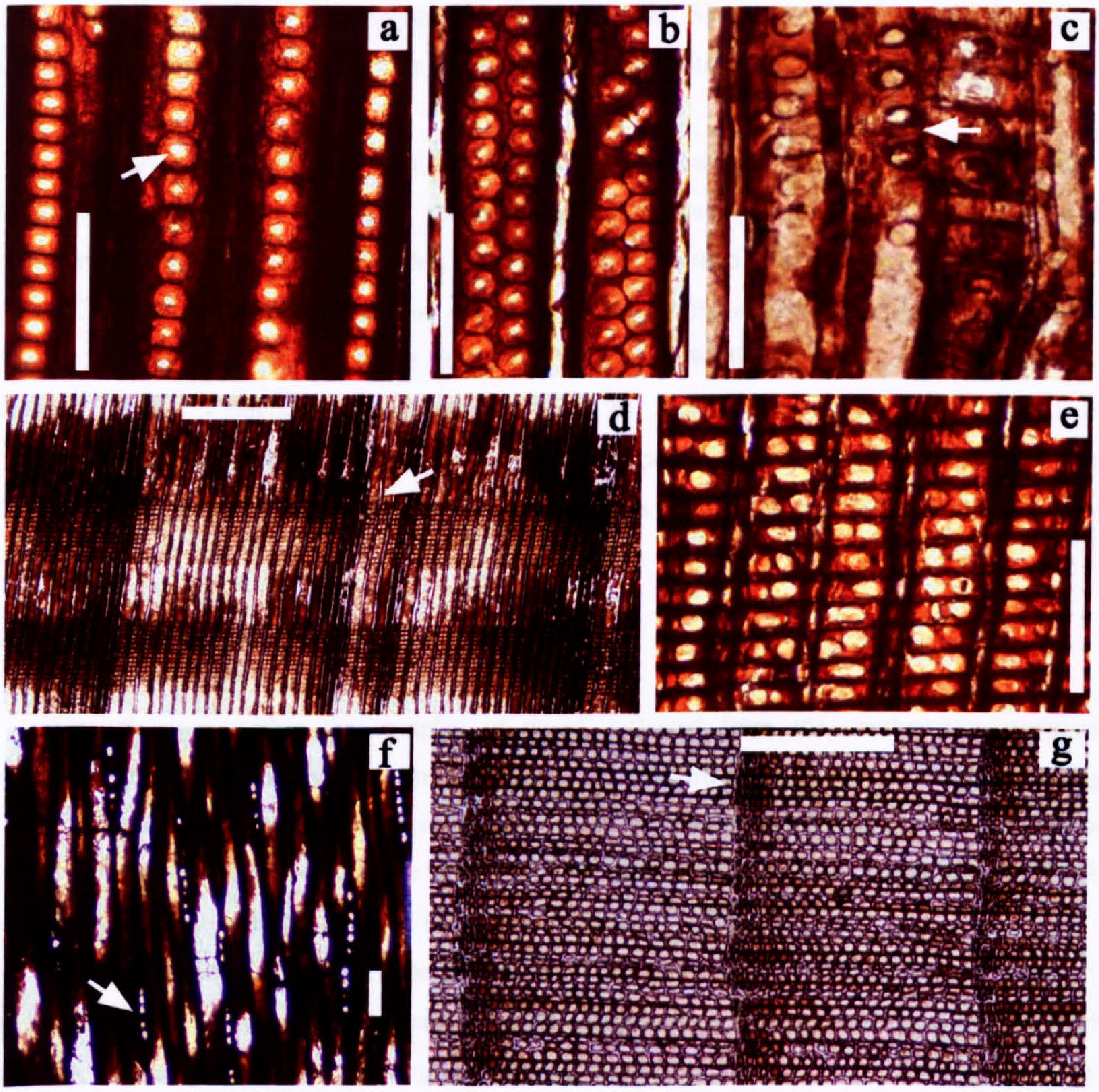
Podocarpoxylon Gothan 1905 sp.1 (Figure 5.7)

Material: This taxon is described from six specimens. KG 4940.3a, KG 4940.19 and KG 4940.4a (allochthonous wood from Hyperion Nunatak); KG 4942.2a (*in situ* stump from West Titan); KG 4937.1 (drifted horizontal wood from West Titan); KG 4922.25 (root from *in situ* tree on South Coal Nunatak).

Description: In RLS, tracheids exhibit uniseriate bordered pitting (82 -100%, mean 90%; Figure 5.7 a), with rare biseriate tracheids (10%; Figure 5.7 b). Pits are circular, occasionally hexagonal (mean 20 µm diameter) with circular aperture (mean 5 µm diameter) and are dominantly touching (59-99%, mean 81 %) or less commonly spaced either one (mean 10%;) or more (mean 8%) pit diameter apart (Figure 5.7 c). Where multiseriate pits are present they exhibit either an alternate (61-100%, mean 82%; Figure 5.7 b) or opposite arrangement (14-39 %, mean 26 %). Tangential tracheid walls are blank. Cross-field pitting is varied but dominated by 1-2 podocarpoid pits (10-15 µm diameter; Figure 5.7 e). Rays are abundant (1-5 mm long), occasionally resin-filled, and are composed of parenchymous cells, 70 µm long by 20 µm high and 18 µm wide, with thin horizontal cell walls (Figure 5.7 d). Ray tracheids are absent. In TLS, rays are uniseriate (Figure 5.7 f), very rarely biseriate and 1-26 cells high. In TS, growth rings have a mean width of 2.2 mm (N=26) and possess well-defined boundaries (rarely subtle), with a ratio of late- to earlywood of 1:10 (Figure 5.7 g). Mean maximum earlywood cell diameter is 60 µm and mean minimum latewood cell diameter is 10 µm.

Identity: This taxon is assigned to *Podocarpoxylon* after Kraüsel (1949) and Falcon-Lang & Cantrill (2000) on the basis of its uniseriate radial tracheid pitting and podocarpoid cross-field pits. Falcon-Lang & Cantrill (2000) describe the modern genera *Podocarpus*, *Dacrydium* and *Microstrobus* as most similar to the Alexander Island fossil woods.

Figure 5.7 *Podocarpoxylon*. a) Uniseriate circular touching bordered tracheid pitting with circular apertures (arrow), KG 4942.2a (Bed 533, Log 8), RLS. Scale bar is 100 μm in length. b) Biseriate bordered tracheid pitting with an alternate arrangement, KG 4940.19 (N.Titan), RLS. Scale bar is 100 μm in length. c) Uniseriate tracheid pitting spaced either one (arrow) or more than one pit diameter apart, KG 4937.1 (Bed 526, Log 8), RLS. Scale bar is 100 μm in length. d) Rays (arrow) and tracheid pitting, KG 4940.19 (N.Titan), RLS. Scale bar is 500 μm in length. e) 1-2 podocarpoid cross-field pitting, KG 4940.19 (N.Titan), RLS. Scale bar is 100 μm in length. f) Short uniseriate rays (arrow), KG 4942.2a (Bed 533, Log 8), TLS. Scale bar is 100 μm in length. g) Growth rings of regular width possessing well defined ring boundaries (arrow), KG 4940.19 (N.Titan), TS. Scale bar is 1 mm in length.



Two form taxa are described here as present in the Alexander Island fossil forests, *Araucariopitys* belonging to the Araucariaceae and *Podocarpoxylon* belonging to the Podocarpaceae. In previous studies the form genus *Araucarioxylon,* considered to belong to Araucariaceae and *Taxodioxylon,* which belongs to the Taxodiaceae, were also described (Falcon-Lang & Cantrill, 2000). The diversity in the type of conifers occurring as fossil wood is reflected in the other fossil material (including foliage, stems and reproductive parts), which includes, *Araucaria, Araucarites, Podocarpites, Athrotaxites, Podozamites, Elatocladus, Pagiophyllum* and *Brachyphyllum.* At individual sampling sites the fossil wood identified corresponds to that of the conifer foliage recorded. For example at location KG 4921 the dominant component of the forest communities was found to be araucarian foliage (Section 4.3.2) and the fossil wood from the same site was identified as belonging to Araucariaceae. Similarly fossil wood belonging to Podocarpaceae was identified within the cliff sections of Titan Nunatak where *Elatocladus* foliage was common (Section 4.3.2).

Araucarian and podocarp conifers are typical of Southern Hemisphere forests throughout Gondwana during the Mesozoic. At high palaeolatitudes podocarp and araucarian conifer-dominated forests have been recorded from the South Shetland Islands, Antarctica (palaeolatitude 63°S; Chapman & Smellie 1992), the Antarctic Peninsula (Palaeolatitude 59-62 ° S; Francis 1986, 1991), SE Australia (palaeolatitude 60-65°S; Douglas & Williams 1982; Dettmann *et al.* 1992; Cantrill 1992), Patagonia (palaeolatitude 55-65°S; Vakhrameev 1991) and New Zealand (palaeolatitude 70°S; Mildenhall 1976). Further north podocarp, araucarian and taxodian conifers have also been recorded from NE and Western Australia (McLoughlin & Hill 1996; McLoughlin *et al.* 2000).

5.5 Growth rings in the conifer wood

Growth rings within the samples of wood collected from the southeastern nunataks of Alexander Island are fairly well defined and represent a record of the growing conditions during the life of the tree. Characteristics of growth rings that are useful in determining the palaeoenvironment of the Cretaceous forests include the ring width, the interannual variability in the ring width (mean sensitivity) and the ratio of latewood to early wood (Francis 1986).

The mean ring width of a tree is a measure of the annual productivity and therefore the environment during the growing season. The ratio of latewood to earlywood measures the width of the ring formed early in the growing season compared to that formed later on and therefore can reflect the nature of seasonality. The mean sensitivity (MS) is a numerical expression of the year to year variability in growth ring width and is given by the formula:

$$MS = \frac{1}{n-1}\sum_{t=1}^{t=n-1}\left|\frac{2(x_{t+1}-x_t)}{x_{t+1}+x_t}\right|$$

where x is ring width, n is the number of rings in the sequence analysed and t is the year number of each ring. Woods with mean sensitivities less than 0.3 are termed 'complacent' and are interpreted to have grown under conditions that were stable from year to year. Woods with mean sensitivities more than 0.3 are termed 'sensitive' with variable conditions from year to year.

These three characteristics were recorded for the seven specimens of wood analysed and are compared to those obtained in previous studies (Jefferson 1982a; Falcon-Lang & Cantrill 2000) based on larger data sets in Table 5.3.

Table 5.3 A summary of the characteristics described from the growth rings within the fossil wood found on the southeastern nunataks of Alexander Island (Note larger sample size of Falcon-Lang & Cantrill make this the most representative study).

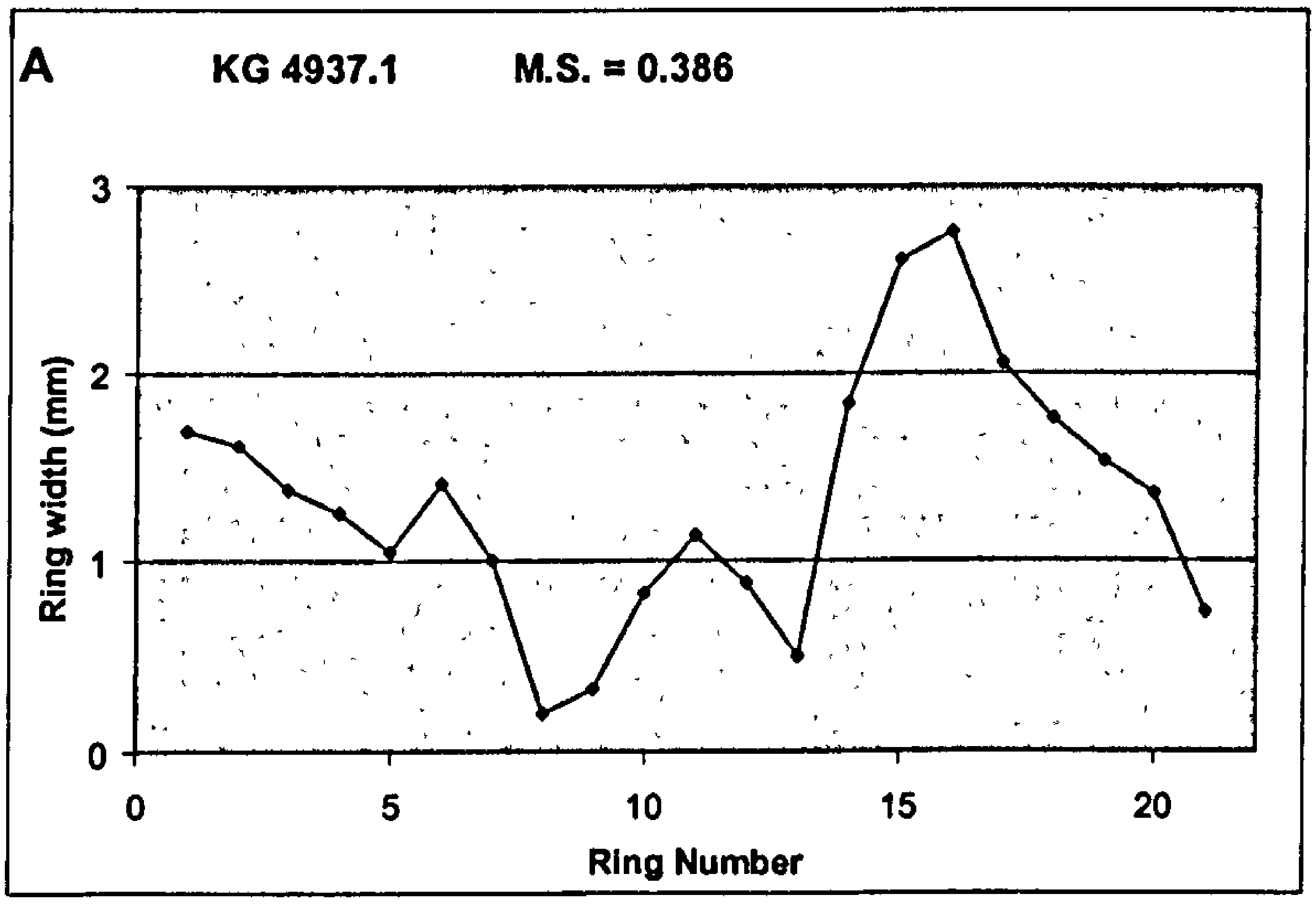
	This study	**Falcon-Lang & Cantrill (2000)**	**Jefferson (1982a)**
Wood samples in study	7	49	21
Ring width (mm)			
Range of ring width	0.35 – 6.5		
Range of mean ring width	0.94 – 3.96	0.45 – 12.96	0.401 – 3.581
Average mean ring width	2.1	1.92	1.4
Mean sensitivity			
Range	0.179 – 0.783	0.094 – 0.573	0.029 – 0.739
Mean	0.36	0.35	0.42
Ratio of latewood to earlywood	1:10		

Growth rings wider than 5 mm are considered to indicate favourable growing conditions, with enough light, water, warmth and stability to allow continuous growth (Spicer & Parrish 1990). The growth rings within the fossil wood analysed here have a mean width of 2.1 mm, similar to previous means (Jefferson 1982a; Falcon-Lang & Cantrill 2000), suggesting that the conifers grew in less than favourable conditions. Although the samples of wood may represent both large trunks and small branches the consistency of the small ring widths (< 5 mm) in all three studies (Table 5.3) suggests that they are a direct result of climatic influence rather than due to positional effects on the tree.

The ratio of latewood to earlywood was considerably low within the seven wood samples studied here suggesting rapid cessation of growth owing to abrupt changes in growing conditions (Table 5.3). Given the high palaeolatitude of these Cretaceous forests the narrow latewood probably reflects the changes in light as the months of winter darkness set in, a feature noted previously in Cretaceous woods from high northern latitudes (Francis 1986; Spicer & Parish 1990b).

The mean sensitivity of the woods (Table 5.3) indicates the conifers were fairly 'sensitive' with some year-to-year variability in the growing conditions, as can be seen in the range of growth ring widths (Figure 5.8). Individual annual sensitivity values range from 0 to 1.3 representing years with no variation from those with great variability (Figure 5.9). The annual sensitivities, represented in the graphs on Figure 5.9, indicate that the limiting factors affecting the growth of the trees did not occur periodically but irregularly, such as the frequent but irregular flooding occurring on the Alexander Island floodplains where the forests grew.

Figure 5.8 Graphs to show the variation in growth ring widths from year to year within two samples of wood from the southeastern nunataks of Alexander Island, Antarctica. A) KG 4937.1 (Bed 526, Log 8); B) KG 4940.19 (N.Titan).



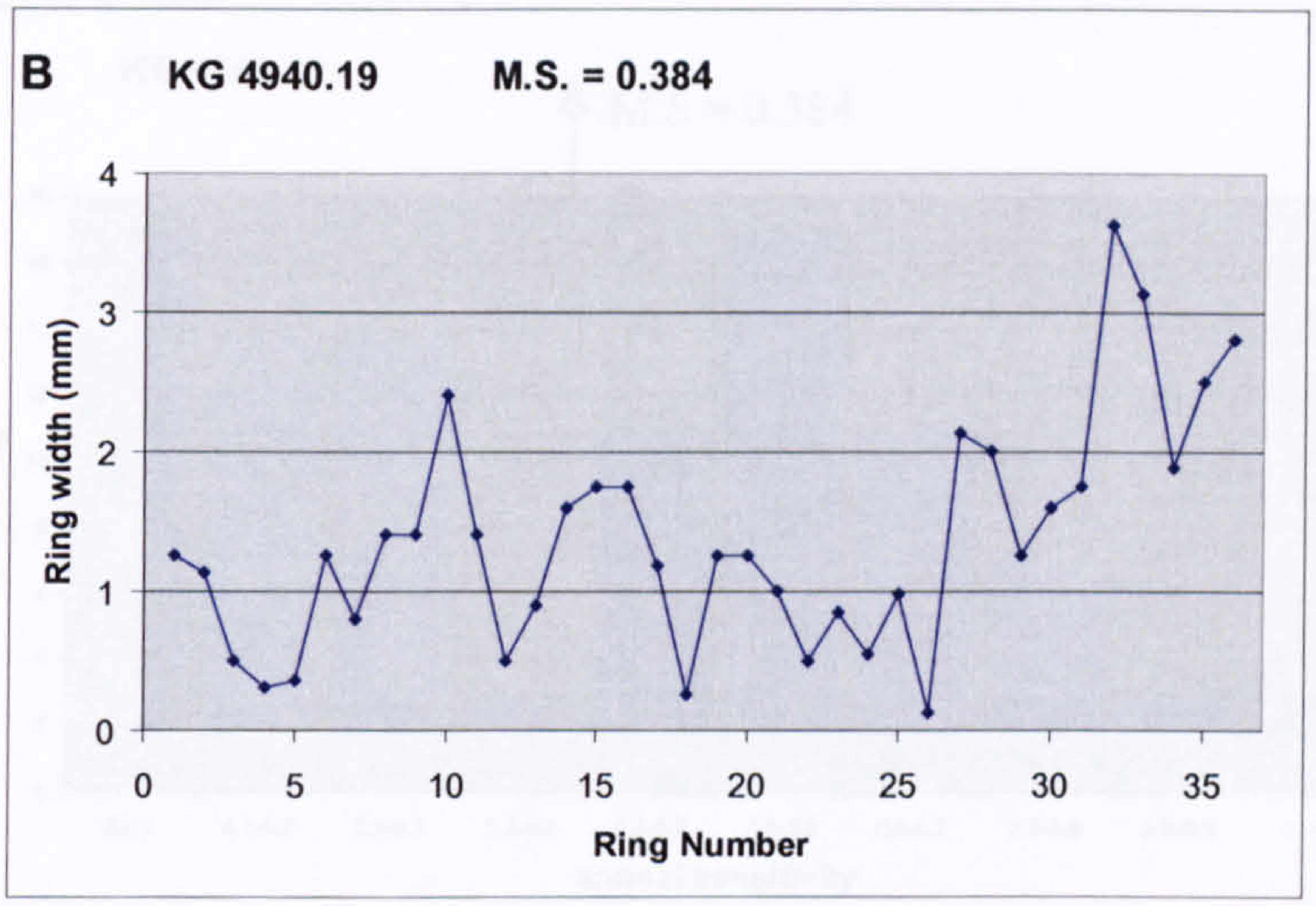
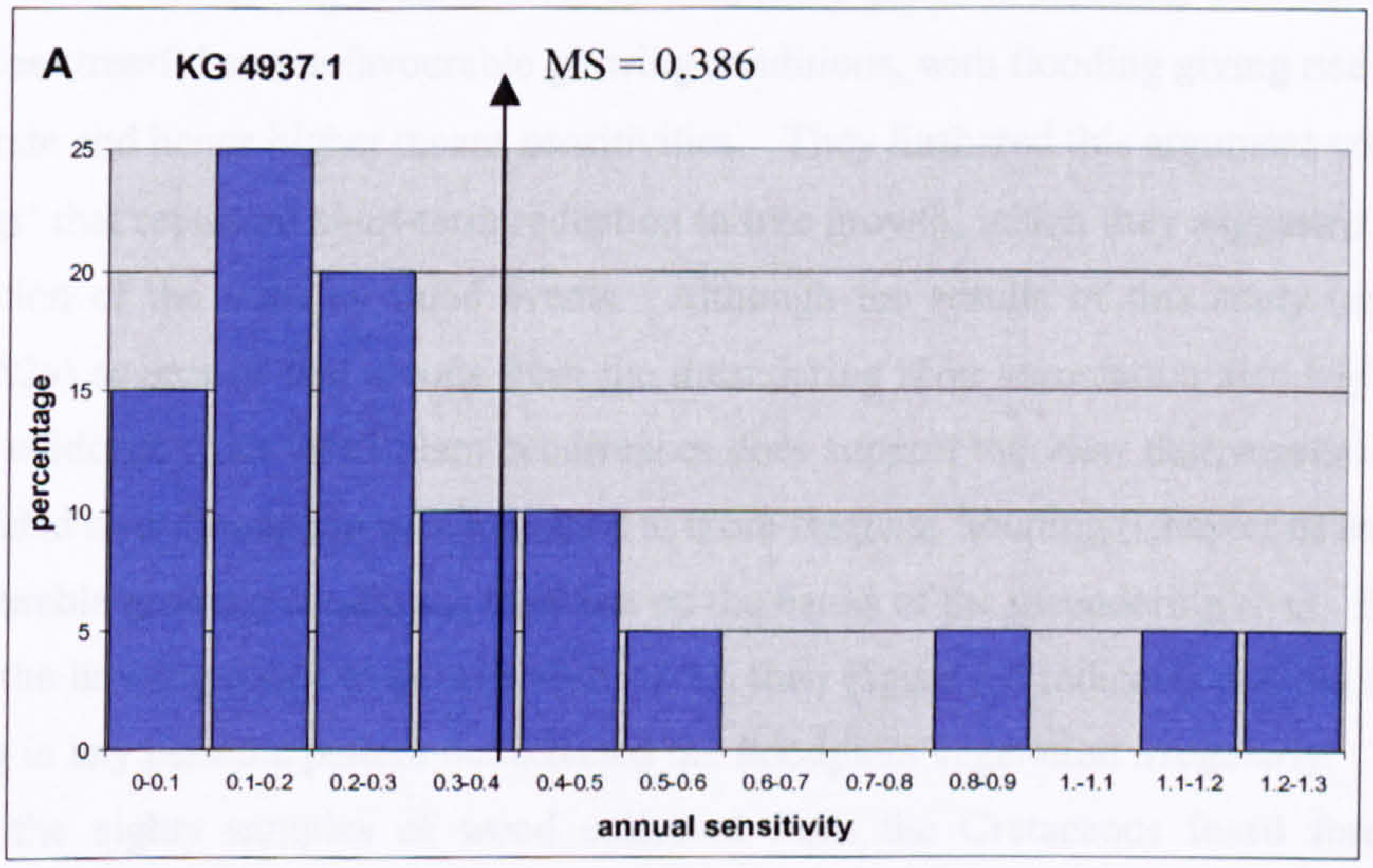
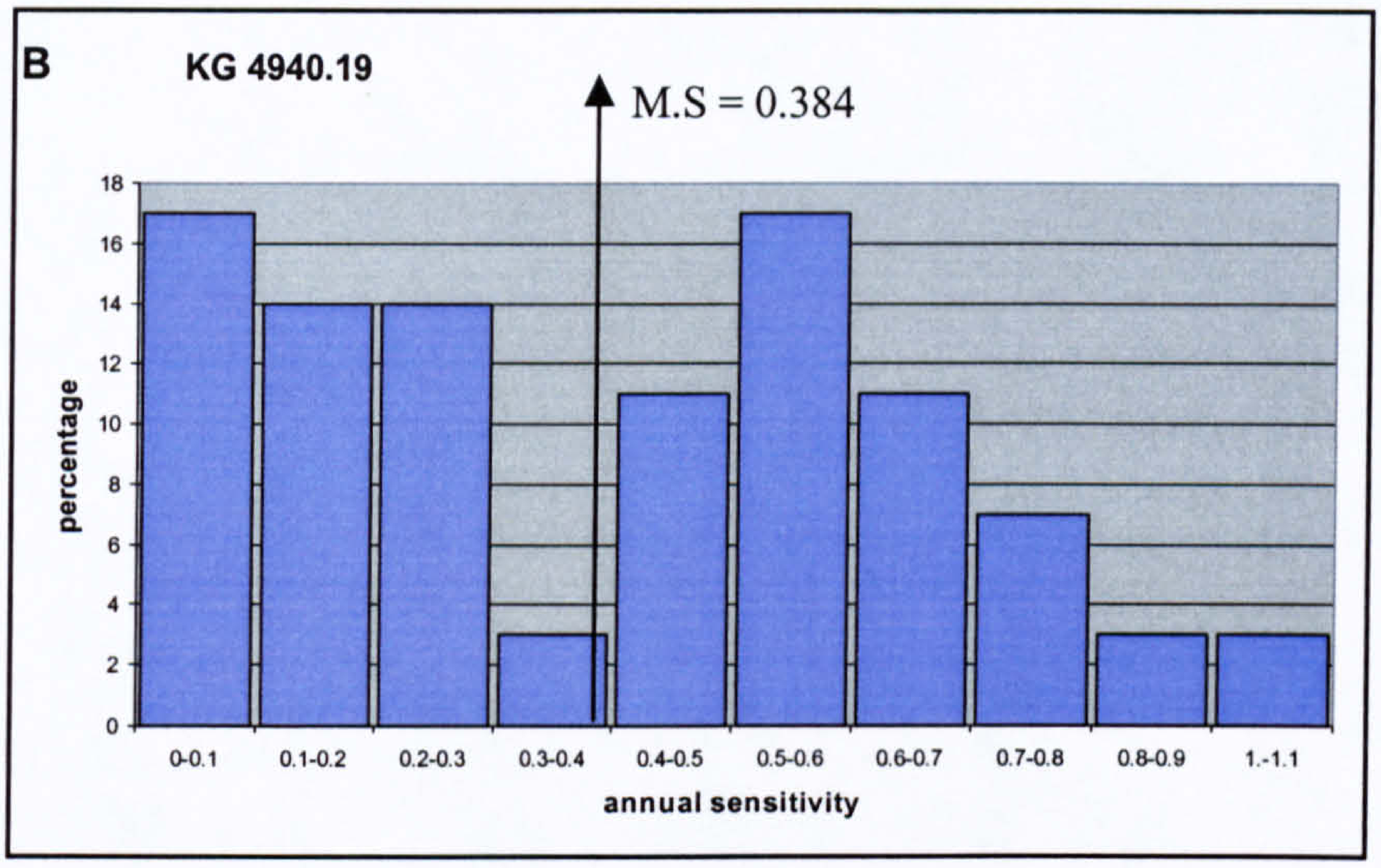


Figure 5.9 Graphs to show the spread of annual sensitivity within two samples of wood from the southeastern nunataks of Alexander Island. A) KG 4937.1; B) KG 4940.19. Note that all classes of annual sensitivity are represented.





Falcon-Lang & Cantrill (2000) described Cretaceous fossil woods from braided river associations as being more sensitive with narrower growth rings compared to those from meandering associations, implying that growing conditions on the meandering river floodplain were more favourable than those of the braided river floodplain. They suggested that the unstable environment of the Cretaceous braided river system, more prone to flooding than the meandering river, produces stressful and unfavourable growing conditions, with flooding giving rise to irregular tree growth rate and hence higher means sensitivities. They furthered this argument with evidence of 'false rings' that represent short-term reduction in tree growth, which they suggested are formed from inundation of the trees by flood events. Although the results of this study (and those of Jefferson 1982a) suggested that woods from the meandering river association also had high mean sensitivities, evidence from fossil plant occurrences does support the view that vegetation growing upon the braided river floodplain was subjected to more frequent flooding (Chapter 6) and therefore more unfavourable growing conditions than that on the banks of the meandering river. If the floods were indeed the limiting factor to growth of the trees, then Figure 5.8 indicates that the floods were not occurring in any periodic pattern but affected the floodplain vegetation irregularly.

Out of the eighty samples of wood collected from the Cretaceous fossil forests of the southeastern nunataks of Alexander Island, only seven were preserved well enough for growth ring analysis. Due to this small sample size further discussion on the palaeoenvironmental implications of the fossil wood is not justified.

Chapter 6 Quantitative statistical analysis of plant data

6.1 Introduction

In Chapter 4 the occurrence of different plant types was studied using fossil plant and fossil tree spatial distribution data in order to gain an understanding of the composition and structure of the Alexander Island forest communities. The fossil plants recorded from the plant beds indicate that the forests consisted of an overstory of different types of conifers, a sub canopy of smaller trees such as *Ginkgo* and cycadophytes, an undergrowth of ferns and other types of shrubs and a ground layer of plants such as angiosperms and liverworts.

To investigate further the structure and composition of the Cretaceous forests, in particular environmental influences on the plants, quantitative statistical techniques were employed. The aims of this chapter are: a) to establish, using ordination and analysis of variance (ANOVA) techniques, if any specific plant communities occurred within the Cretaceous forest, b) if the lithology that the fossil plants occur within (and therefore palaeoenvironment) had an influence on the fossil plant assemblages that occur there, and c) whether individual plant species were related to the sediments in which they grew. Ordination and ANOVA analyses were performed using the software Twinspan, Canoco 4.02 (Braak & Šmilauer 1998) and Splus® 6.

Throughout this chapter the term 'fossil plant assemblage' will be used to refer to the group of fossil plant specimens, with the term 'lithology' referring to the type of rock these fossils occur within. The term 'plant community' refers to the group of plant types that occurred together within the Cretaceous forests. These plant communities are based on numerous fossil plant assemblages. The lithology the fossil plant assemblages occur within is interpreted as a palaeoenvironment that the plant communities would have grown in within the Cretaceous forests. Thus throughout this chapter the lithologies are linked to palaeoenvironments.

6.2 Plant communities

Initially all the fossil plant count data collected in the field from the seven palaeosol transects, discussed previously in Chapter 4 (Section 4.3) were converted to simple presence/absence data to assess if there are any relationships within the species data that are not influenced by the percentage abundance calculated from the original fossil plant counts. The percentage abundance information is later converted to presence/absence classes (e.g. rare, occasional, abundant) and is used in more complex statistical analyses. The initial analysis of the presence/absence data is thus used as a control or sensitivity test for the analyses performed on the abundance data.

Correspondence analysis (CA) was performed on the presence/absence data to see if there were any relationships between the different plant species. CA is an ordination technique that arranges sampling sites along axes on the basis of species composition. The result of the CA process is a 2D diagram in which species are represented as points, with points that are close together representing plant species that commonly occur together. The CA technique constructs theoretical variables that best explain the distribution of the species data (using a two-way weighted averaging algorithm; Jongman *et al.* 1995). The theoretical variable constructed by the CA that has the greatest influence on the species data is termed the first ordination axis; the second axis represents the second greatest influence.

The results of the CA performed on the fossil plant presence/absence data from the southeastern nunataks is shown in Figure 6.1, with the first two CA axes represented. Although plant communities cannot be statistically identified, it is clear that there are groups of certain plant species that commonly occur together. For example the ferns Family? Marsileaceae (F13; See Table 6.1), *Cladophlebis macloughlinii* (F11), *Tetragleichenites acuta* (F7), the angiosperm *Hydrocotylophyllum alexandri* (A1) and *Taeniopteris* (TAE) all occur in a cluster around the first CA axis, suggesting that they commonly occur together and are all influenced by the theoretical variable represented by axis 1.

Figure 6.1 A CA ordination of the presence/absence fossil species data. Key for plant species are shown in Table 6.1. The colour of the species in the plot identifies which plant assemblage as identified by Twinspan that species occurs within. Those in blue were later identified as plant assemblage 1, those in green were identified as plant assemblage 2, those in red as plant assemblage 3 and those in purple as plant assemblage 4 For example the fern F12 in red, was identified by Twinspan as within plant assemblage 3 (Figure 6.4).

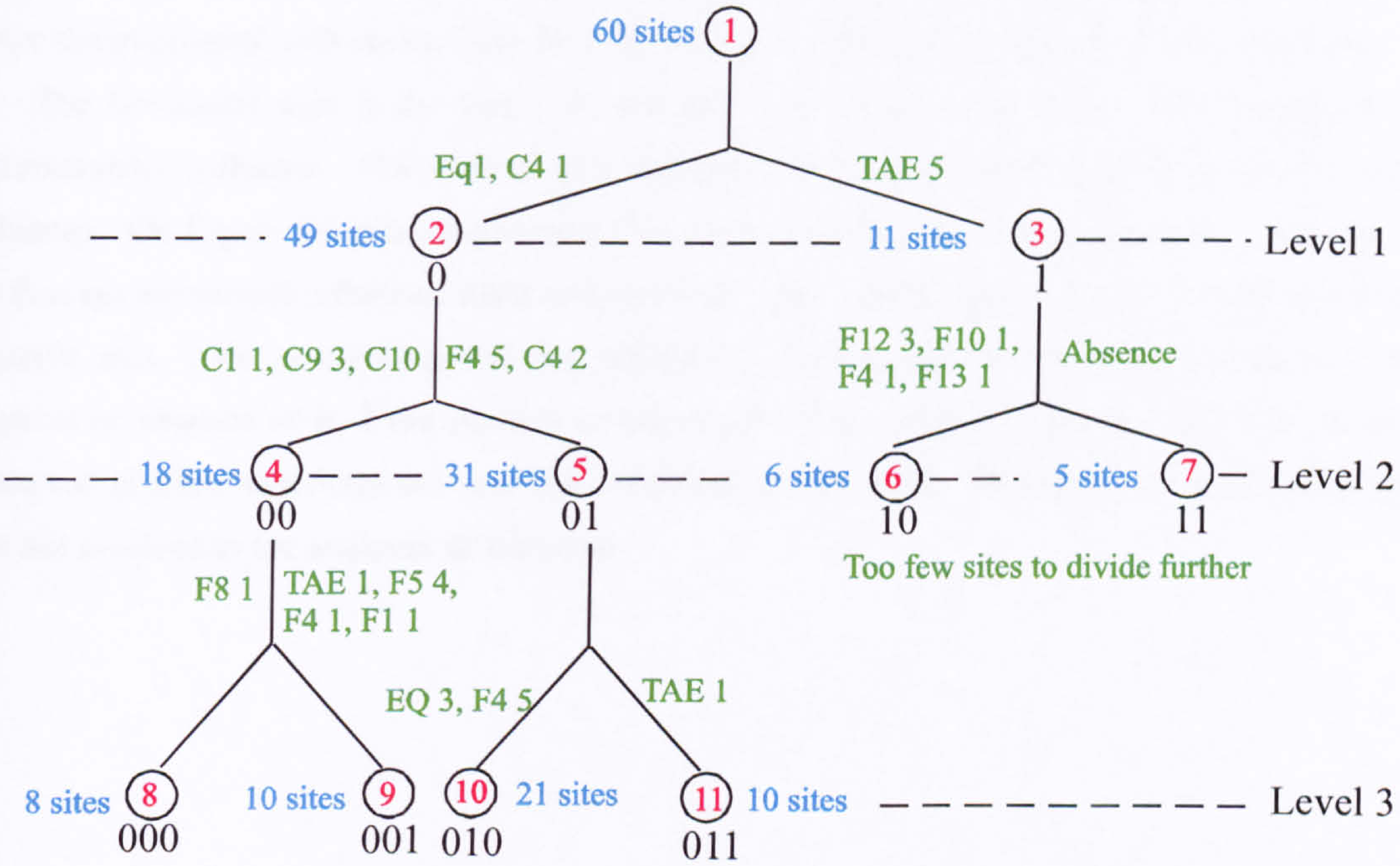
To investigate this further, a more complex technique, Twinspan, was used to statistically analyse if there were any plant communities within the Cretaceous forests. For the Twinspan analyses the fossil plant count data were amalgamated into one 'sample site by species' table with the counts converted to percentage occurrence. A similar table was also made for the environmental data with the lithology type recorded at each site. The data set comprised 60 sample sites, 39 species and 4 lithologies. Plant communities were then determined through the process of Twinspan classification and correspondence analysis.

Twinspan classification is a type of cluster analysis that aims to classify sites and species to establish community types. One of the basic ideas of Twinspan is that each group of sampling sites can be characterised by a particular group of species. The percentage abundance of each species at the sampling sites is recorded in Twinspan through the occurrence of pseudospecies (see below), which convert the abundance data into presence/absence classes. These classes determine whether a species is present, rare, occasional, frequent or abundant. The more abundant a species is at a particular site the more pseudospecies are defined. For example from the pseudospecies outlined below for the species *Taeniopteris daintreei*; if *Taeniopteris* accounted for 25 % of the fossil plants at a sampling site, that sampling site would be characterised by *Taeniopteris* pseudospecies 5. The percentage limits outlined below represent the standard classes used within Twinspan (Hill 1979) if there are species within the data set with rare occurrences. These standards are set in order to reduce the influence of these rare species within the analysis.

Taeniopteris pseudospecies 1 – 0-2 % abundance
Taeniopteris pseudospecies 2 – 2-5 %
Taeniopteris pseudospecies 3 – 5-10 %
Taeniopteris pseudospecies 4 – 10-20 %
Taeniopteris pseudospecies 5 - >20 %

Twinspan classifies the sites according to the pseudospecies that occur at them. This is done by ordinating samples using CA. Twinspan then classifies the species in light of the sampling site classification. The dendrogram in Figure 6.2 is an illustration of the divisions of sampling sites according to the differential species that were recorded at them. The first division in the dendrogram outlines that *Taeniopteris* (TAE) was abundant at 11 sampling sites and Equisetales and *Araucaria alexandrensis* (EQ, C4) was present at 49 sampling sites (Figure 6.2).

Figure 6.2 Dendrogram of the Twinspan classification of sample sites. The labels in green are the pseudospecies that define that divide (using the plant species code outlined in Table 6.1), the labels in red are the numbers of the site groups, the labels in blue are the number of sites in that defined group and the labels in black are the code for that group that is used in Table A6-1, Appendix 6. The second level is taken as the most realistic cut off level as further division creates groups of sampling sites with fewer than 5 sites within them.



The results of Twinspan are displayed in a species-by-site table, which allows four plant communities and four sampling site groups to be easily identified (Table A6.1). From the table, CA ordination plots are made of the sampling site groups and plant communities (using Canoco software), by plotting data points (for example the species data), in a two dimensional space. Data points that are close together correspond to species that most commonly occur together at various sampling sites.

6.2.1 Ordination for plant communities and sampling site groups

The ordination plot of the sampling sites is shown in Figure 6.3. Four sampling site groups are outlined with each group being characterised by a certain combination of plant species. Figure 6.4 is an ordination plot of the plant species, with four plant communities identified representing the fossil plants that most commonly occur together. The axes on both plots are the axes derived by CA, representing the most significant environmental influences on the data. Four axes were found to be significant (through the 'broken stick test' which is variance test; Jongman *et al.* 1995), the first two accounting for 30 % of the distribution of the data, the other two only accounting for a further 14 %. The remaining 56 % of the spread of data is explained through an infinite number of minor environmental influences. Only the first two axes are plotted on Figure 6.3 and Figure 6.4.

The horizontal axis is the first CA axis and is the axis representing the most significant environmental influence. The vertical axis represents the second most important environmental influence. On Figure 6.4 plant community 3 is clustered along the first axis and so is affected by the first environmental influence, plant communities 1 and 2 are plotted along the second axis (1 the negative axis, 2 the positive) and so are affected by the second environmental influence (1 the negative or absence of it, 2 the positive or presence). The lithologies that the fossil plants were preserved in were superimposed over the ordination plots, but the lithological environmental data was not involved in the analyses at this stage.

Figure 6.3 CA ordination diagram of sampling site groups showing the sampling sites that are characterised by a specific combination of plant species. The sampling site labels describe the sampling location and the site number at that location (e.g. 1-2, sampling site 2 at sampling location 1). Sampling location 1 is on Citadel Bastion, 2,3,4,5,6,7,8, are on Titan Nunataks and 9,10 are on Coal Nunatak. The lithofacies are superimposed upon the diagram and explained in the key. See Table 6.2 and Chapter 2 for a full description of the lithofacies and the palaeoenvironments they represent.

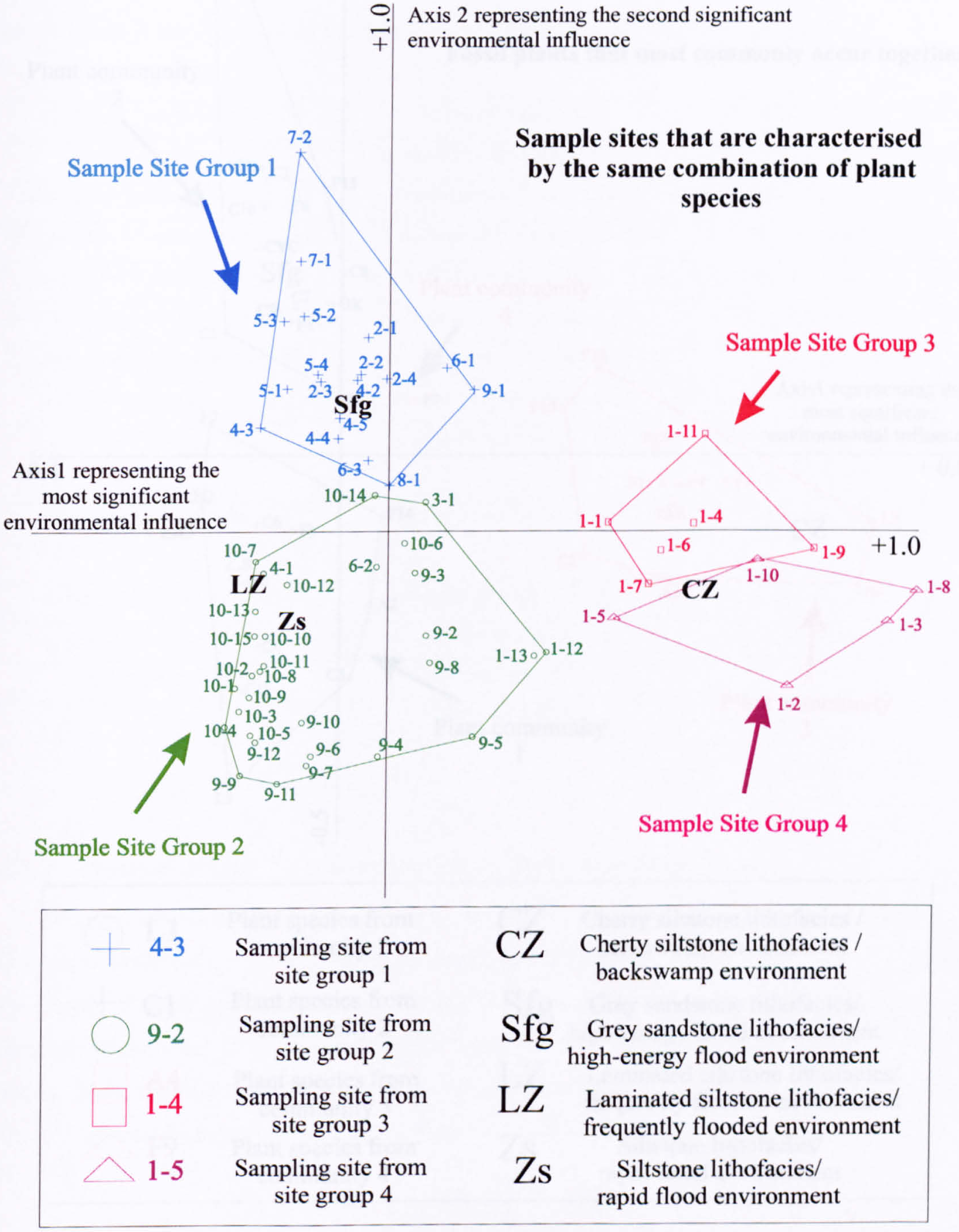
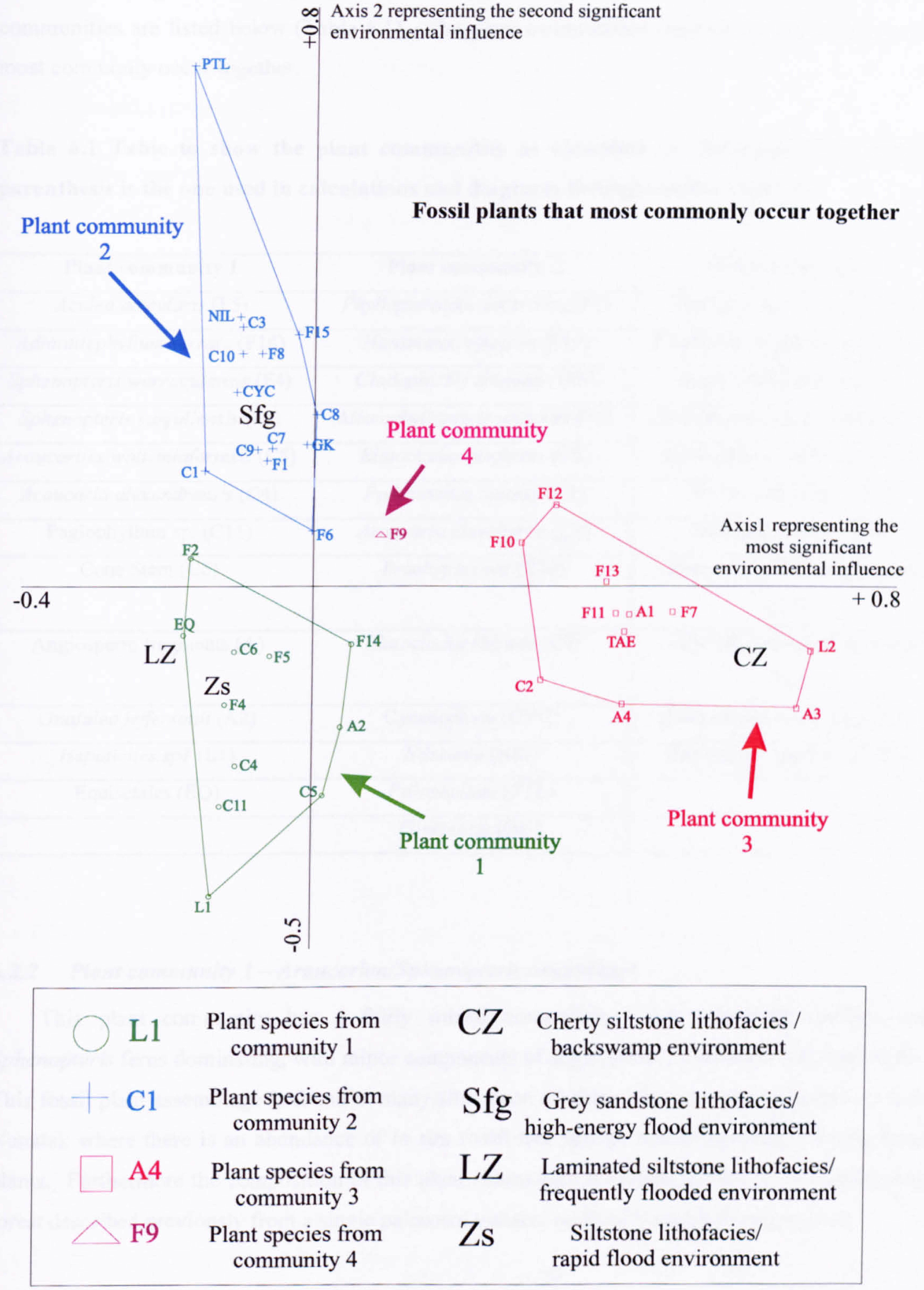


Figure 6.4 CA ordination diagram of plant communities (species groups) showing the fossil plant species that most commonly occur together. Key for plant labels are shown in Table 6.1. The lithofacies are superimposed upon the diagram and explained in the key. See Table 6.2 and Chapter 2 for a full description of the lithofacies and the palaeoenvironments they represent.



Four plant communities were identified using Twinspan. One community has just one fern within it, *Cladophlebis oblonga* (plant community 4), which occurs everywhere; the other three communities are listed below (Table 6.1). The plant communities describe the plant species that most commonly occur together.

Table 6.1 Table to show the plant communities as identified by Twinspan. (The code in parenthesis is the one used in calculations and diagrams throughout this chapter)

Plant community 1	Plant community 2	Plant community 3
Aculea acicularis (F5)	*Phyllopteroides antarctica* (F1)	*Tetragleichenites acuta* (F7).
Adiantitephyllum serrata (F14)	*Hausmannia papillo* (F15)	*Cladophlebis gallentiensis* (F10)
Sphenopteris warragulensis (F4)	*Cladophlebis drinnanii* (F8)	Family? Marsileaceae (F13)
Sphenopteris sanjuliensis (F2)	*Microphyllopteris unisorus* (F6)	*Cladophlebis macloughlinii* (F11)
Araucarites wollemiaformsis (C5)	*Elatocladus confertus* (C8)	*Cladophlebis dissectus* (F12)
Araucaria alexandrensis (C4)	*Podozamites binatus* (C1)	*Athrotaxites ungeri* (C2)
Pagiophyllum sp. (C11)	*Araucaria chambersii* (C3)	*Timothyia trinervis* (A4)
Cone Stem (C6)	*Brachyphyllum* (C10)	*Hydrocotylophyllum alexandri* (A1)
Angiosperm fragments (A)	*Elatocladus linearis* (C9)	*Araliaephyllum quinquelobatus* (A3)
Gnafalea jeffersonii (A2)	Cycadophyte (CYC)	*Marchantites taenioides* (L2)
Hepaticites.sp1 (L1)	*Nilssonia* (NIL)	*Taeniopteris daintreei* (TAE)
Equisetales (EQ)	*Ptilophyllum* (PTL)	
	Ginkgoites (GK)	

6.2.2 Plant community 1 – Araucarian/Sphenopteris assemblage

This plant community has a fairly mixed composition with *Araucaria* conifers and *Sphenopteris* ferns dominating, with minor components of angiosperms, liverworts and Equisetales. This fossil plant assemblage is found at many sites upon all three nunataks but dominates on Coal Nunatak where there is an abundance of *in situ* fossil tree stumps occurring along with the fossil plants. Furthermore the composition of this plant community is similar to that of the climax fossil forest described previously from a single palaeosol transect on Coal Nunatak (Section 4.3.2).

This plant community suggests open woodland with a diverse understorey of ferns, liverworts and angiosperms opening out into a conifer community with a canopy of *Araucaria* and *Podozamites*. The composition of this community suggests the plants grew on an area of the floodplain distal to the river channel with more stable conditions for the conifers to establish but still subjected to frequent flooding.

6.2.3 Plant community 2 – Mixed conifer/fern and cycad assemblage

This plant community has a very mixed and varied composition with elements of conifers, ferns, cycadophytes, *Ginkgoites* and Bennettitales. It does not have any pioneer or disturbance vegetation such as angiosperms, liverworts or Equisetales, suggesting that this community represents well-established vegetation. This fossil plant assemblage was only found at sites on Titan Nunataks and Coal Nunatak. It is dominant on Titan Nunataks, but occurs only at one site on Coal Nunatak. At all sites there was an abundance of *in situ* fossilised tree stumps occurring with the fossil plant foliage. This plant community is very similar to the mature three-tiered forest community described previously from Titan Nunataks (Section 4.3.2).

This community is composed of an understorey of low shrubs including angiosperms and ferns with a scattered sub-canopy of Ginkgo trees and cycadophytes, and an overstorey of *Podozamites* and *Elatocladus* conifers. The composition of this community suggests that the plants grew on areas of the floodplain that were stable for long enough to allow a mixed community to establish.

6.2.4 Plant community 3 – Taeniopteris/ferns/shrub assemblage

This community is dominated by *Taeniopteris daintreei* with small understorey shrubs and ferns and a variety of angiosperms and liverworts. There is a complete lack of conifer foliage, with the Taxodiaceae conifer cones (*Athrotaxites ungeri*) being the only conifer material within this fossil plant assemblage. This plant assemblage was only found on Citadel Bastion where *in situ* fossil tree stumps occur rarely. This community is similar to the plant types described previously from a single forest transect on Citadel Bastion where conifer foliage was also rare (Section 4.3.2).

Many of the plant types within this community were probably pioneer plants, such as the liverworts that are today commonly found in frequently disturbed environments or growing on fresh sediments. The absence of conifer foliage suggests that either the understorey species were so varied and abundant that they prevented conifer saplings from growing or that the flooding events were so frequent that the vegetation was never stable enough for trees to become established. The composition of this community suggests that the vegetation became established in an area of the floodplain that was regularly disturbed by flood events.

6.2.5 Discussion on errors and assumptions

The Twinspan classification scheme is a robust and well-known method for statistically identifying communities from abundance data. There have been many previous studies that use Twinspan analysis to identify community types. For example Twinspan and correspondence analysis were used on a similar data set on the modern broad-leaved deciduous forests in Hordaland, Western Norway (Aarrestad 2000). In this study two distinct vegetation types were identified by Twinspan, separated along a moisture gradient identified by CA (Aarrestad 2000). Twinspan was also used on the forests of Prince Edward Island, Canada, where five vegetation types were identified from counts of species occurrence (Sobey & Glen 2002). Each vegetation type was characterised by particular tree species and soil drainage properties (Sobey & Glen 2002). A similar study was also undertaken on a large data set on the spruce and fir forests of the Eastern Alps, where two species groups were identified by Twinspan, separated by the substrate type (Exner *et al.* 2002).

The Twinspan classification scheme is thus a reliable method of statistically identifying plant communities from species abundance data. The abundance data used here in the Twinspan analysis and in further analyses (Section 6.3) are converted to presence/absence classes of present, rare, occasional, frequent and abundant. The fossil plant counts recorded from the *in situ* fossil plants are representative of the composition and relative abundance of the individual plant species that grew within the Cretaceous forests and therefore the use of the fossil plant counts to represent the relative percentage occurrence of individual plant species is justified as discussed previously in Chapter 4.

The initial CA analysis performed on the presence/absence data identified the same plant groupings as that identified within the Twinspan analysis, indicating that the abundance data used did not influence the plant communities identified. Thus any errors or assumptions made during the collection in the field, the conversion of the original plant count data to percentage occurrence data, and in choosing the percentage classes used for the pseudospecies will not effect the plant communities identified. Twinspan requires the use of abundance data and it was performed to statistically identify the plant communities that were visually identified within the CA analysis using presence/absence data.

6.3 Lithological influence on fossil plant assemblages

The lithology in which the fossil plants are preserved was recorded to investigate whether there was a correlation between sedimentary lithofacies and the fossil plant assemblages. Each lithology was interpreted as a particular palaeoenvironment (shown in Table 6.2); thus a correlation between lithology and the fossil plant assemblages would indicate a link between the palaeoenvironment and the plant communities within the Cretaceous forests.

Table 6.2 Description of the lithologies in which the plant fossils are preserved and the palaeoenvironment interpreted from the lithology. For full descriptions of lithofacies see Chapter 2. The locations refer to palaeosol sampling transects at which each lithofacies occur. For location descriptions see Table A2.1, Appendix 2.

Lithofacies	Locations	Description	Palaeoenvironment
Grey sandstone (Sfg)	KG 4941, KG 4945, KG 4947 (Titan Nunataks)	Fine sandstone lithofacies with cross bedding and horizontal laminae; occur within sequences of sandstones and siltstones.	High-energy flood environment: Sandstone deposited by decelerating floodwaters (crevasse splay). Plants preserved in Sfg grew upon floodplain areas subjected to less frequent high-energy flood events.
Siltstone (Zs)	KG 4946 (Titan Nunataks), KG 4921 (Coal Nunatak)	Siltstone lithofacies with no sedimentary structures	Rapid flood environment: Siltstone formed from rapid deposition by floodwaters. Plants preserved within Zs grew on areas of floodplain characterised by rapid short-lived floods
Laminated siltstone (LZ)	KG 4938, KG 4942 (Titan Nunataks), KG 4931 (Coal Nunatak)	Siltstone lithofacies with fine horizontal, black laminations of carbonaceous material and thicker laminations of lighter silts.	Frequently flooded environment: Formed by suspension fallout of silt in standing water after flood event. Plants preserved within LZ grew on floodplain areas subject to frequent floods and periods of standing water.

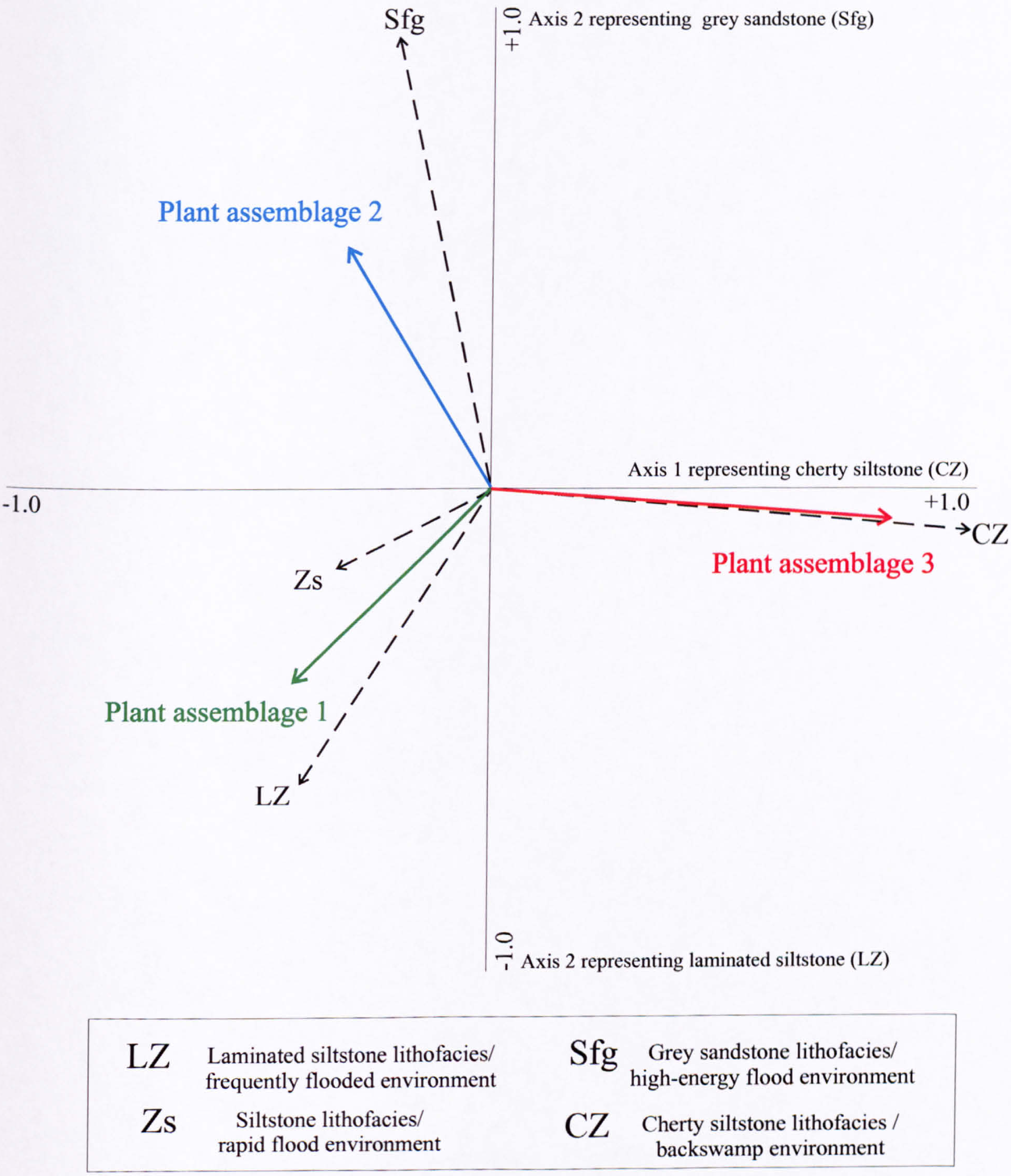
Cherty siltstone (CZ)	KG 4914 (Citadel Bastion)	Siltstone lithofacies but very fine grained giving it a cherty appearance. Weathers to a distinctive green. Fine laminations (<1 mm) distort around *in situ* plant fossils	**Back-swamp environment**: Formed by suspension fallout of silt in standing water after flood event or water table rise. Plants preserved in CZ grew in areas subject to frequent low energy floods.

The relationship between lithology (palaeoenvironment) and plant communities was determined through redundancy analysis (RDA), which is a constrained linear ordination method, similar to principal component analysis that has the ability to rank the importance of individual environmental influences. In this case RDA correlates the co-occurrence of fossil plant types in particular lithologies. It establishes which plant community, as defined by Twinspan, is best related to which lithology (palaeoenvironment) using least-squares regression.

RDA indicated that all lithologies were significantly related to the distribution of fossil plant assemblages. The lithology cherty siltstone has the strongest relationship to the distribution of fossil plant assemblages, followed by grey sandstone, laminated siltstone, and siltstone respectively (Figure 6.5).

The results of the RDA (Figure 6.5) indicate that plant community 3 has a high positive correlation with the palaeoenvironment suggested by cherty siltstone. This indicates that disturbance vegetation grew on areas of the river floodplain distal to the river channel but subjected to frequent low energy floods (Table 6.2). Plant community 2 has a high positive correlation with the palaeoenvironment suggested by grey sandstone. This implies that the well-established community of plants within plant community 2 grew upon areas of the river floodplain subjected to less frequent, high-energy flood events (Table 6.2). Plant community 1 has a high positive correlation to the palaeoenvironment suggested by laminated siltstone and siltstone. This indicates that the open woodland community grew on parts of the river floodplain that were distal to the river channel and were subjected to frequent rapid and short-lived floods and periods of standing water (Table 6.2).

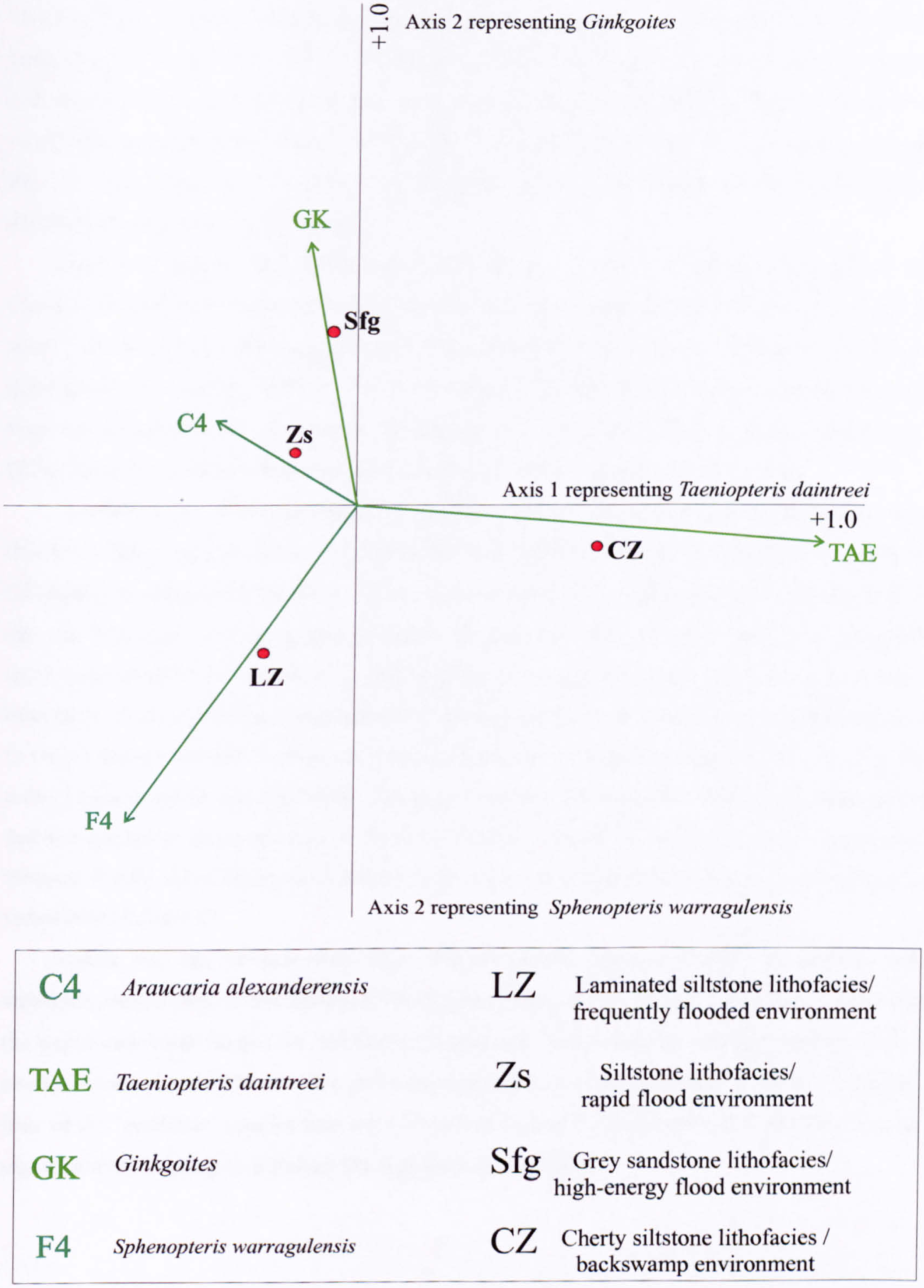
Figure 6.5 RDA showing the statistical relationship between the plant communities as defined by Twinspan and the lithofacies (see Table 6.2 and Chapter 2). Plant communities and lithofacies are represented by arrows. Arrows pointing in the same direction indicate a high positive correlation, arrows pointing in opposite directions indicate a high negative relationship. The first axis on the plot relates to cherty siltstone and accounts for 24% of the distribution in data. The second axis relates to grey siltstone (positive side) and laminated siltstone (negative side) and accounts for a further 11% of the distribution in data.



6.4 Lithological influence on individual fossil plant species

To determine if there were relationships between individual fossil plant species and specific lithologies (palaeoenvironments), multiple discriminant analysis was used to test whether the lithologies could be 'predicted' by individual fossil plant species. Multiple discriminant analysis (Canonical correspondence analysis (CCA in Canoco)) is an ordination technique that selects a linear combination of variables, in this case the distribution of individual fossil plant species, that best explains the dispersion of the lithologies that occur. The CCA process establishes the species with the strongest relationship to lithology (or the species that best 'predicts' a certain lithology and hence palaeoenvironment) and lists them in order of most importance. Figure 6.6 indicates that *Taeniopteris daintreei* showed the strongest relationship to lithology followed by *Sphenopteris warragulensis, Araucaria alexandrensis* and *Ginkgoites,* respectively.

Figure 6.6 CCA plot showing the fossil plant species that 'predict' the lithofacies (See Table 6.2 and Chapter 2 for full lithofacies descriptions). The four fossil plant species are represented as arrows. The first two axes were found to explain 53 % of the distribution in the lithofacies data and only these two are plotted on the CCA ordination diagram. The first axis represents *Taeniopteris daintreei* which is the fossil plant species with the strongest relationship to the lithofacies. The positive side of axis 2 is represented by *Ginkgoites,* the negative side by *Sphenopteris warragulensis.*



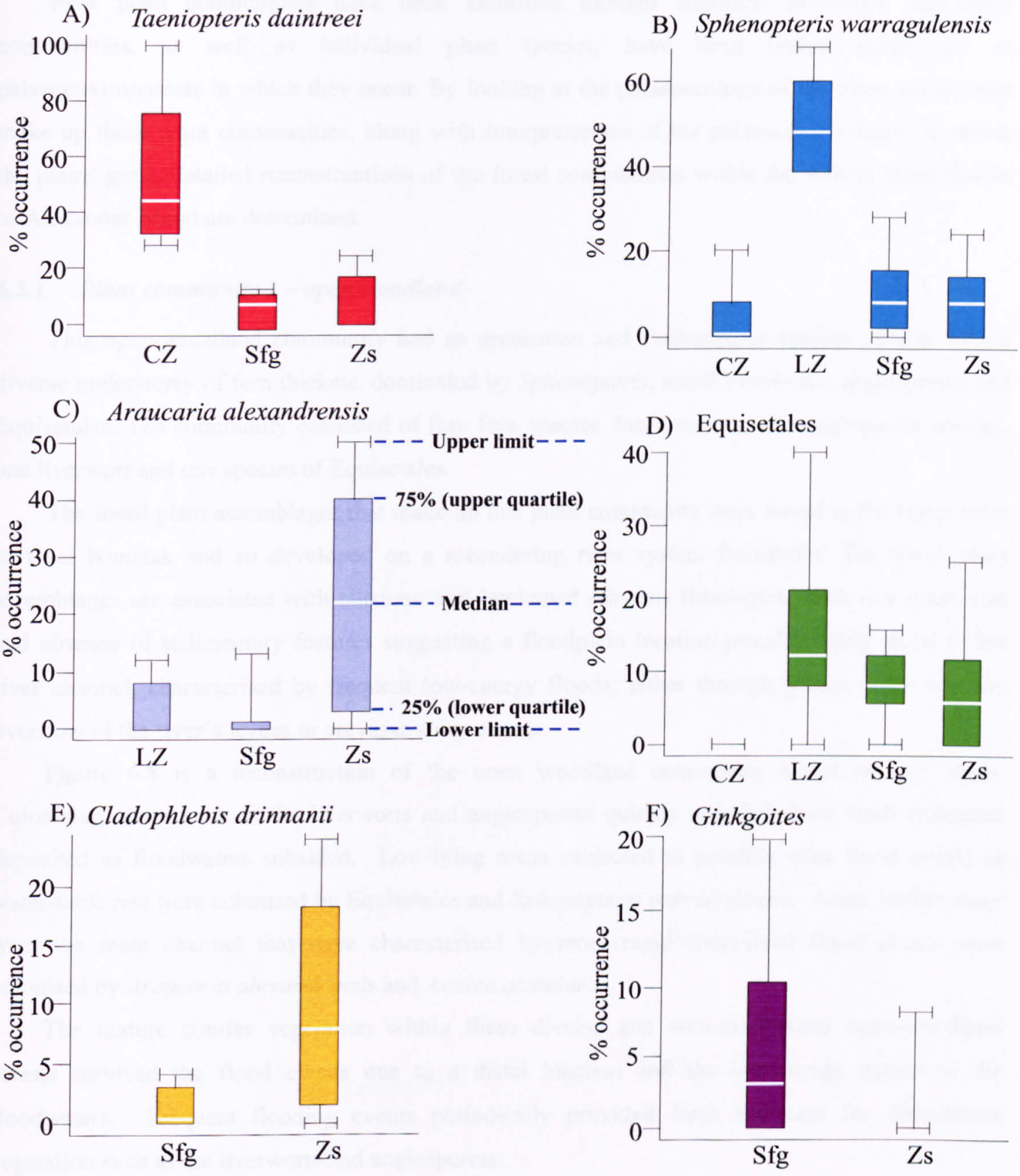
The CCA analysis gives an initial indication that certain individual fossil plant species are related to certain lithologies and hence palaeoenvironments. To investigate this further, analysis of variance (ANOVA) techniques were employed using Splus®. ANOVA is a simple regression technique that looks at the differences between the numerical mean of samples taken from different populations. In this case ANOVA calculates if there is a difference between the mean percentage occurrence of a particular fossil plant species found in each of the different lithologies. If there was no difference between the means, the lithology makes no difference to the percentage occurrence of the fossil plant species. A difference between the means would suggest a relationship between the fossil plant species and the lithology.

However because the plant species data does not show a normal, binomial or Poison distribution and because there is not a constant variance, simple ANOVA techniques could not be used. Instead a bootstrapped generalized linear model (GLM) was used, which works on the same principles as the simple ANOVA. The bootstrapping simply randomizes the data set, removing the need for the assumption of constant variance and for the data to fit to a certain distribution. The GLM method is a more robust test than the simple ANOVA (Jongman *et al.* 1995).

Seventeen out of the possible 39 fossil plant species occurred in enough abundance to apply this test. Eight of them showed a significant relationship to lithology. *Araucaria alexandrensis*, *Cladophlebis drinnanii*, *Ginkgoites, Elatocladus linearis* and *Aculea acicularis* are all related to the siltstone lithology, indicating they preferred to grow on areas of the floodplain characterised by rapid short-lived floods (Table 6.2). *Sphenopteris warragulensis* and Equisetales are related to the laminated siltstone lithology suggesting that these plants preferred to grow on floodplain areas distal to river channel, subject to frequent floods and periods of standing water (Table 6.2). Equisetales today prefer damp or wet conditions. *Taeniopteris daintreei* is related to cherty siltstone, indicating that it preferred to grow on areas of the river floodplain distal to the river channel characterised by frequent floods and standing water but not large volumes of sand deposition or any significant water turbulence (Table 6.2).

Simple box and whisker plots show the occurrence of the 6 fossil plant species with the strongest relationship, in the different lithologies (Figure 6.7). The box and whisker plots identify the upper and lower limits (the 'whiskers'), upper and lower quartiles (top and bottom of the box) and the median (central line) of the percentage occurrence of the plant species in that lithology. All four of the 'predictor' species that were identified by the CCA (Figure 6.6) were found to have a significant relationship to lithology through the GLM method.

Figure 6.7 Box and Whisker plots showing the percentage occurrence (median, quartiles and upper and lower limits; see C) of the fossil plant species in the different lithofacies for all sample sites. For example , on A, at all sample sites with cherty siltstone lithofacies, the occurrence of *Taeniopteris daintreei* ranged from an upper limit of 100% of all fossil plants counted to a lower limit of 26% and a median of 44%.



LZ	Laminated siltstone lithofacies/ frequently flooded environment	Sfg	Grey sandstone lithofacies/ high-energy flood environment
Zs	Siltstone lithofacies/ rapid flood environment	CZ	Cherty siltstone lithofacies / backswamp environment

6.5 Discussion

Four plant communities have been identified through statistical processes, and these communities, as well as individual plant species, have been linked statistically to palaeoenvironments in which they occur. By looking at the palaeoecology of the plant species that make up these plant communities, along with interpretations of the palaeoenvironments in which the plants grew, detailed reconstructions of the forest communities within the Albian fossil forests of Alexander Island are determined.

6.5.1 Plant community 1 – open woodland

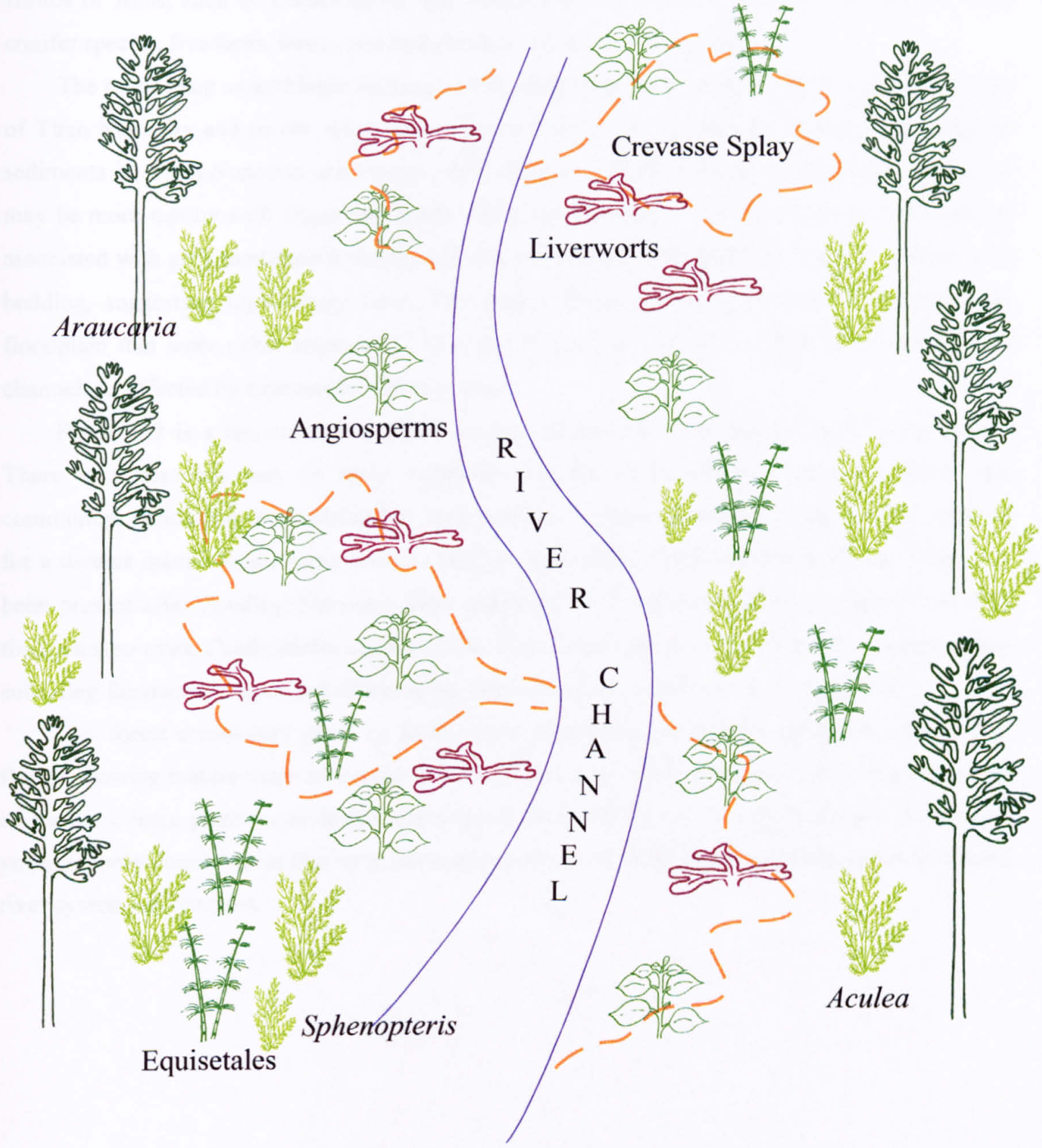
This open-woodland community had an araucarian and *Podozamites* conifer canopy with a diverse understorey of fern thickets, dominated by *Sphenopteris*, small liverworts, angiosperms and Equisetales. The community consisted of four fern species, four conifers, two angiosperm species, one liverwort and one species of Equisetales.

The fossil plant assemblages that make up this plant community were found in the upper units of Coal Nunatak and so developed on a meandering river system floodplain. The fossil plant assemblages are associated with siltstone and laminated siltstone lithologies, with fine grain size and absence of sedimentary features suggesting a floodplain location possibly fairly distal to the river channel, characterised by frequent low-energy floods; either through gentle water rise and overflow of the river's levees or crevasse splay events.

Figure 6.8 is a reconstruction of the open woodland community based on this study. Colonising plants such as the liverworts and angiosperms quickly established on fresh sediments deposited as floodwaters subsided. Low-lying areas subjected to ponding after flood events or water-table rise were colonised by Equisetales and *Sphenopteris warragulensis*. Areas further away from the main channel that were characterised by more rapid short-lived flood events were colonised by *Araucaria alexandrensis* and *Aculea acicularis*.

The mature conifer vegetation within these diverse and well-established open-woodland forests survived the flood events due to a distal location and the low-energy nature of the floodwaters. Frequent flooding events periodically provided fresh sediment for disturbance vegetation such as the liverworts and angiosperms.

Figure 6.8 A schematic reconstruction of the palaeoenvironment in which the open woodland forest of plant community 1 grew.



6.5.2 Plant community 2 - patchy climax forest

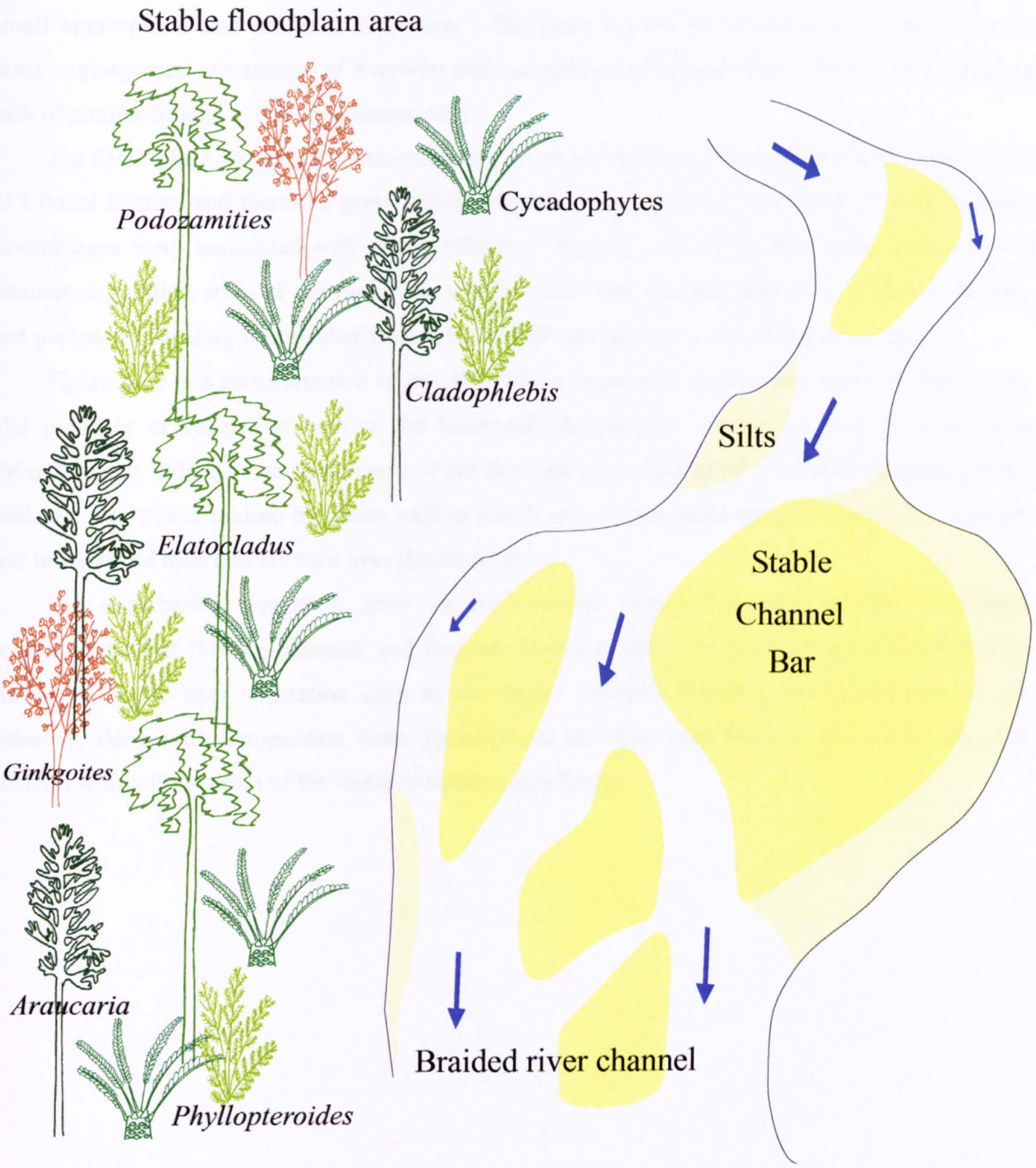
This patchy climax forest had a diverse mixed conifer canopy of *Araucaria*, *Elatocladus* and *Podozamites*, a sub-canopy of cycadophytes with scattered Ginkgo trees and an understorey of low shrubs of ferns, such as *Cladophlebis* and *Phyllopteroides*. The community consisted of seven conifer species, five ferns, three cycadophytes and one species of Ginkgo.

The fossil plant assemblages making up this plant community were found throughout the units of Titan Nunataks and so the plants grew upon a braided river system floodplain. Given that the sediments on Titan Nunataks are younger than those on Citadel Bastion, the braided river system may be more mature with larger and fewer individual channels. The fossil plant assemblages are associated with grey sandstone lithology with the grain size and sedimentary features such as cross bedding, suggesting high-energy flow. This patchy forest grew on parts of the braided river floodplain that were either adjacent to the river channel or were more stable parts distal to the channel but affected by catastrophic flood events.

Figure 6.9 is a reconstruction of the patchy climax forest community based on this study. There is a complete lack of early colonising species or disturbance vegetation within this community, which may be explained by long periods of time between flood events, allowing time for a diverse mature forest community to become established. Early colonising plants would have been present after flooding deposited fresh sediments but conifers and ferns replaced these over time. Ginkgo trees, *Cladophlebis drinnanii* and *Elatocladus linearis* grew in low-lying areas where subsiding floodwaters deposited silts or areas of the forest more distal to the river channel.

This forest community grew on areas of the floodplain affected by infrequent catastrophic floods allowing mature vegetation such as the conifers to develop. They may have formed patches of mature climax plant communities growing on more stable areas of the floodplain in-between younger forest communities that were more susceptible to flooding in the generally unstable braided river system environment.

Figure 6.9 A schematic reconstruction of the palaeoenvironment in which the patchy climax forest of plant community 2 grew.



6.5.3 Plant community 3 – disturbance vegetation

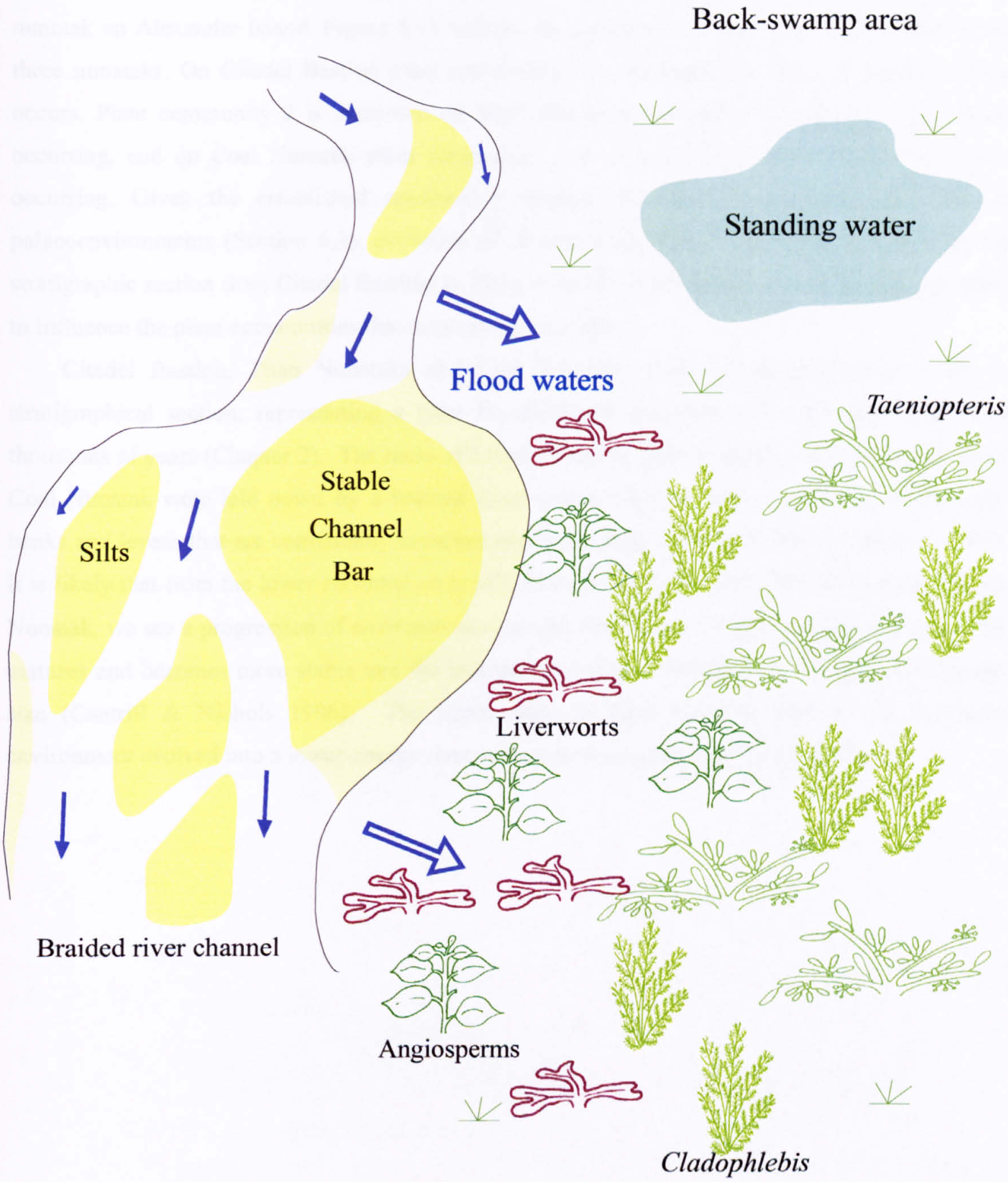
This disturbance vegetation is dominated by the 'bramble-like' species, *Taeniopteris daintreei* with an understorey of ferns, such as *Cladophlebis macloughlinii* and *Cladophlebis gallentiensis*, small angiosperms and scattered liverworts. The plant community comprises five fern species, three angiosperms, one species of liverwort and one species of *Taeniopteris*. There was a complete lack of conifer foliage within this community.

The fossil plant assemblages that make up this plant community were found in the upper units of Citadel Bastion and therefore grew within a braided river system environment. The fossil plant assemblages were associated with cherty siltstone lithology, with very fine grain size and fine laminae suggesting areas of the floodplain distal to the river channel, subject to frequent flooding and periods of standing water either from subsiding floodwaters or a rise in the water table.

Figure 6.10 is a reconstruction of the disturbance vegetation community based on this study. The presence of vegetation such as the liverwort *Marchantites taenioides*, and the water fern ?Marsileaceae, indicates that these areas of the floodplain were frequently flooded, depositing fresh sediment that was colonised by plants such as the liverworts and angiosperms. *Taeniopteris* plants and ferns would then quickly take over the forest floor.

The disturbance vegetation grew on back-swamp areas of a very unstable floodplain dominated by fast flowing channels and frequent flooding. Early colonising plants helped to bind the sediment for later vegetation such as the ferns. Frequent flooding and disturbance of the sediment along with competition from *Taeniopteris daintreei* may have made conifer survival difficult within these areas of the unstable braided floodplain.

Figure 6.10 A schematic reconstruction of the palaeoenvironment in which the disturbance vegetation of plant community 3 grew.

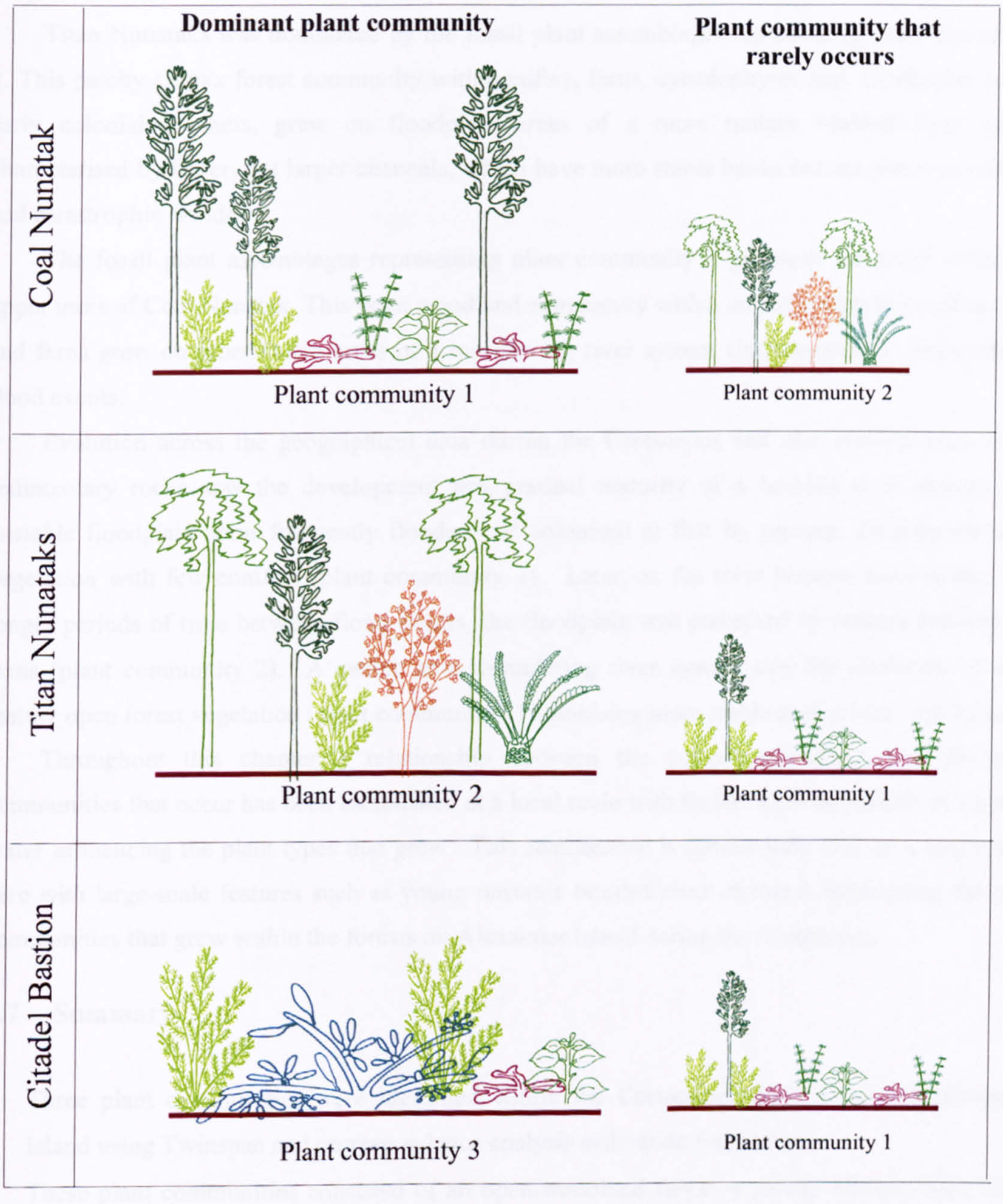


6.6 Evolution of forest communities

Each of the three plant communities identified within this study was dominant on a particular nunatak on Alexander Island. Figure 6.11 outlines the occurrence of each plant community on the three nunataks. On Citadel Bastion plant community 3 is dominant but plant assemblage 1 also occurs. Plant community 2 is dominant on Titan Nunataks with plant assemblage 1 also rarely occurring, and on Coal Nunatak plant community 1 is dominant with plant community 2 also occurring. Given the established relationship between the plant communities and different palaeoenvironments (Section 6.3), evolution of environments through time and thus through the stratigraphic section from Citadel Bastion, to Titan Nunataks and finally to Coal Nunatak, are likely to influence the plant communities that occur at any one time.

Citadel Bastion, Titan Nunataks and Coal Nunatak consist of approximately 1 km of stratigraphical section, representing a river floodplain environment evolving over hundreds of thousands of years (Chapter 2). The rocks of Citadel Bastion, Titan Nunataks and the basal units of Coal Nunatak were laid down by a braided river system with multiple, unstable river channels, banks and levees that are consistently breached and broad channel belts (Cantrill & Nichols 1996). It is likely that from the lower recorded units of Citadel Bastion, through to the basal units of Coal Nunatak, we see a progression of environments through time as the braided river channel gradually matures and becomes more stable and the braided river system decreases in gradient and channel size (Cantrill & Nichols 1996). The upper units of Coal Nunatak suggest the braidplain environment evolved into a lower-energy river system with meandering river channels.

Figure 6.11 A schematic diagram showing the occurrence of each plant community on the three southeastern nunataks of Alexander Island.



The fossil plant assemblages representing plant community 3 occurred primarily upon Citadel Bastion. This disturbance vegetation community was characterised by pioneer species and early colonisers growing on floodplain areas of the immature braided river system that were unstable and frequently flooded.

Titan Nunataks was dominated by the fossil plant assemblages representing plant community 2. This patchy climax forest community with conifers, ferns, cycadophytes and *Ginkgoites* but no early colonising plants, grew on floodplain areas of a more mature braided river system characterised by fewer, but larger channels, which have more stable banks but are prone to collapse and catastrophic floods.

The fossil plant assemblages representing plant community 1 primarily occurred within the upper units of Coal Nunatak. This open woodland community with a varied composition of conifers and ferns grew on more stable areas of a meandering river system characterised by lower-energy flood events.

Evolution across the geographical area during the Cretaceous and also through time in the sedimentary rocks saw the development and gradual maturity of a braided river system with unstable floodplain areas frequently flooded and colonised at first by pioneer, disturbance forest vegetation with few conifers (plant community 3). Later, as the river became more stable with longer periods of time between flood events, the floodplain was colonised by mature conifers and ferns (plant community 2). A switch to a meandering river system saw the evolution of more mature open forest vegetation (plant community 1) colonising more stable parts of the floodplain.

Throughout this chapter a relationship between the palaeoenvironment and the plant communities that occur has been established at a local scale with factors such as periods of standing water influencing the plant types that grew. This relationship is further indicated on a larger scale here with large-scale features such as young unstable braided river channels influencing the plant communities that grew within the forests on Alexander Island during the Cretaceous.

6.7 Summary

- Three plant communities were identified within the Cretaceous fossil forests of Alexander Island using Twinspan and correspondence analysis ordination techniques.
- These plant communities consisted of an open-woodland forest, a patchy climax forest and a disturbance vegetation community.

- The lithology in which the fossil plants are preserved was correlated to the fossil plant assemblages that make up the plant communities using redundancy analysis ordination techniques. Each lithology was interpreted as a particular palaeoenvironment.
- This correlation suggested that there was a relationship between the palaeoenvironment and the plant communities within the Cretaceous forests.
- The open woodland forest was linked to a frequently flooded environment, the patchy climax forest was related to a high-energy flood environment and the disturbance vegetation was correlated to a back-swamp environment.
- Individual fossil plant species were also correlated to different lithologies and hence different palaeoenvironments.
- Reconstructions of the different forests communities that occur upon different parts of the floodplain within the Cretaceous fossil forests of Alexander Island were determined by looking at the palaeoecology of the plant species that make up these plant communities, along with interpretations of the palaeoenvironments in which the plants grew.
- The forest communities identified in this study evolve through time along with the development and gradual maturity of a braided river system into a meandering river system.
- Unstable floodplain areas of the braided river channel were colonised at first by pioneer, disturbance forest vegetation with few conifers and later, as the river matured with longer periods between floods, by mature conifers and ferns. A switch to a meandering river system saw the evolution of more mature open forest vegetation colonising more stable parts of the floodplain.

Chapter 7 Discussion

7.1 Vegetation

7.1.1 Reconstruction of the Alexander Island forests

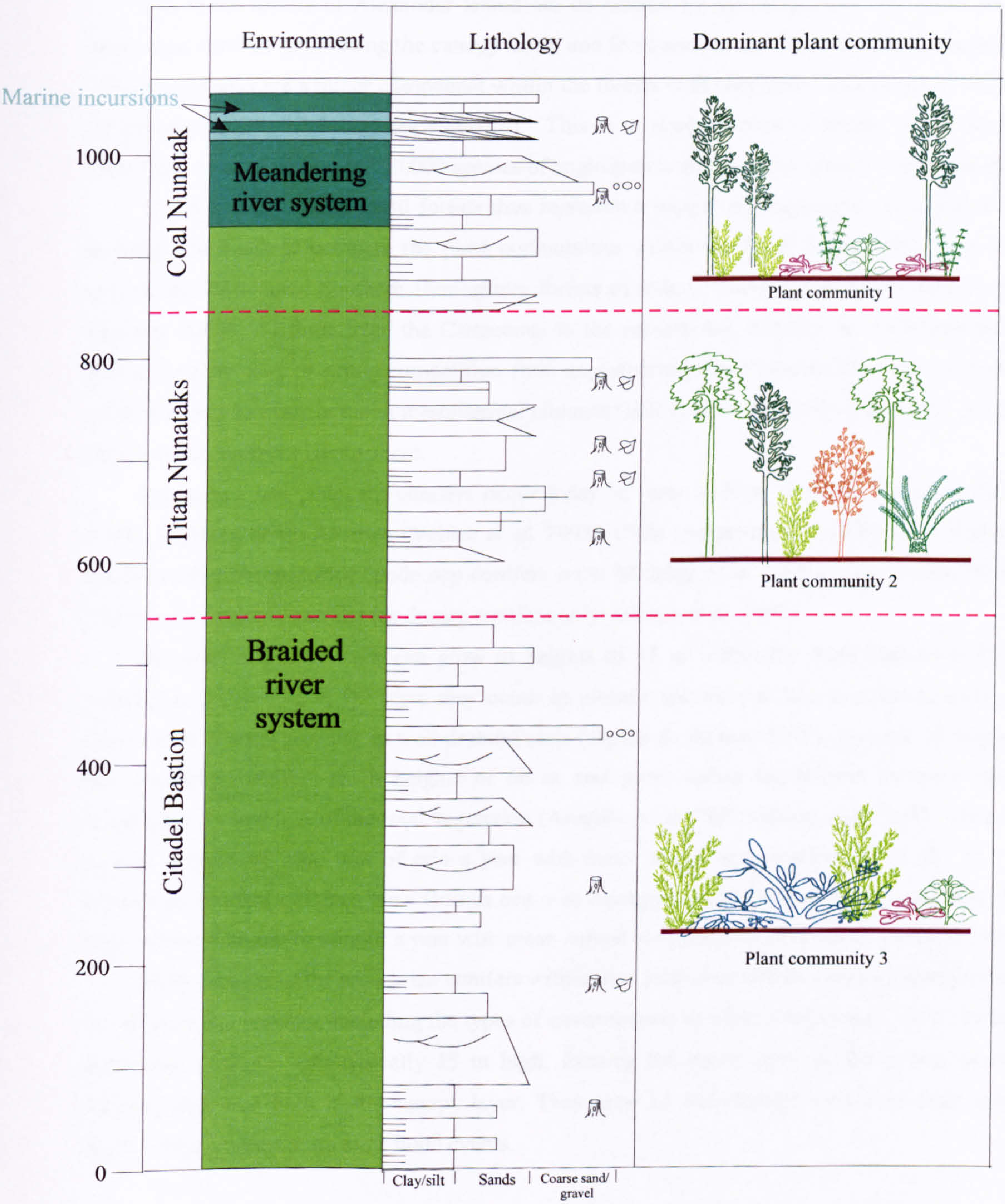
The fossil forests of Alexander Island were diverse in floral composition with 42 different form genera and 69 species (Falcon-Lang *et al.* 2001). They occurred as well structured communities growing on different areas of the floodplain. Open woodland forests, dominated by araucarian conifers and *Sphenopteris* ferns with liverworts and angiosperms, occurred on areas of the floodplain that were frequently flooded by low-energy flood events (see Chapter 6). These floods covered the understory plants in fine sands and silts but did not affect the more mature conifer trees. The flood sediments would have provided fresh surfaces on which early colonising plants could grow, with light and space available on the ground due to the open nature of the woodland. These forests grew as long-lived pioneer forests with densities of 90 trees ha $^{-1}$, containing araucarian trees ranging in size from saplings to young trees to mature trees reaching 50 cm in diameter. Young trees occurred in patches, colonising areas that had previously been disturbed by crevasse splays (see Chapter 4).

Disturbance vegetation communities, dominated by *Taeniopteris*, liverworts and ferns, occupied river channel banks and back-swamp areas of the river floodplain (see Chapter 6). These areas were not constantly waterlogged but subjected to periods of water saturation after flood events, allowing water-loving species to flourish such as Equisetales, liverworts and water ferns. These were joined by the pentoxylalean plants (*Taeniopteris*) and other ferns, which dominated the forest floor and were competition for conifers. Conifer saplings may also have been prevented from becoming established by frequent inundation by water on the floodplain.

Patch forest communities with a mixed conifer canopy dominated by podocarp trees, a sub canopy of Ginkgo trees and cycadophytes and an understory of ferns and shrubs, grew on areas of the floodplain distal to the river channels (see Chapter 6). These climax forest communities were too far away from the river channel to be affected by low-energy floods. Fresh sediment surfaces were therefore not provided for early colonising plants. The lack of frequent flooding created a more stable environment that allowed mature forest vegetation to become established. These areas of the floodplain were, however, affected by rare catastrophic flood events that covered the forest floor in coarse sands, entombing the forest trees. These forests were dominated by slow growing podocarps with densities of 250 trees ha^{-1}. In the absence of frequent disturbance events due to flooding, which would normally have been needed to regenerate the forests by occupancy of gaps by seedlings, these forests may have relied on advanced regeneration to form mature climax communities. This method of regenerating is seen today in podocarp forests of southern Africa where young saplings are shade tolerant and can regenerate close to the long-lived adult trees in areas not subjected to frequent disturbance events (Midgley *et al.* 1995).

The Cretaceous forests of Alexander Island occurred as well structured communities growing on different areas of the floodplain. The pattern of occurrence of the different plant communities may have been influenced by floodplain stability and flooding frequency. This is suggested by the evolution of the plant communities through the deposition of the Triton Point Formation (see Chapter 6). Disturbance vegetation occurred in the Citadel Bastion area, dominated by unstable floodplains of a braided river system, while mature open woodland forest predominantly occurred in the Coal Nunatak area, characterised by floodplain sediments of a mature meandering river system (see Chapter 2, 6 and Figure 7.1).

Figure 7.1 A schematic diagram showing the occurrence of each plant community on the three southeastern nunataks of Alexander Island, Antarctica.



7.1.2 Comparable modern floras

The fossil forests of Alexander Island are dominated by gymnosperms, with podocarp and araucarian conifers dominating the canopy layer, and ferns and shrubs forming a dense understorey. The angiosperms are a minor component within the forests with only seven species out of a total of 69 (accounting for 12 % species diversity). This is in stark contrast to forests of the Southern Hemisphere today with over 200,000 species of angiosperms and just 556 species of gymnosperms.

The Alexander Island fossil forests thus represent a unique pre-angiosperm Cretaceous flora, making it difficult to compare the plant communities within the fossil forests with those of the angiosperm-dominated Southern Hemisphere forests of today. There are, however, specific plant families that do continue from the Cretaceous to the present day, notably the Araucariaceae and Podocarpaceae. Due to strong competition from angiosperms, these families have been reduced to predominantly existing in moist mesothermal climates (Hill & Brodribb 1999; Kershaw & Wagstaff 2001) of the Southern Hemisphere.

Araucarian and podocarp conifers occur today in parts of New Zealand (Ogden & Stewart 1995), southern South America (Veblen *et al.* 1995), Chile (Armesto *et al.* 1995), New Caledonia (Jaffre 1995), South Africa (podocarp conifers only; Midgley *et al.* 1995), New Guinea (Enright 1995) and southern Australia (podocarp conifers only; Gibson *et al.* 1995).

Araucarian conifer trees can grow to heights of 45 m within the New Zealand temperate rainforests (Figure 7.2 e, f). Here they occur as pioneer species that like to colonise areas after disturbance events, growing in well-drained soils (Ogden & Stewart 1995). In areas of Argentina the araucarian conifers reach heights of 50 m and grow within sub-tropical montane forests, accounting for just 5 % of the total vegetation (Armesto *et al.* 1995;Veblen *et al.* 1995). Here they receive a mean of 1500 mm of rain a year with mean annual temperatures of 10-18 ° C. The araucarian conifers of Papua New Guinea occur as emergent species within the canopy layer; here they receive 850 mm of rainfall a year with mean annual temperatures of 11-26 ° C (Enright 1995).

Many features of the araucarian conifers within the Cretaceous forests are also characteristic of the modern day conifers, including the types of environments in which they occur. The Cretaceous araucarian conifers were typically 15 m high, forming the upper layer of the forests, possibly forming emergent trees in the canopy layer. They grew in well-drained soils as pioneer species regenerating in open areas after flood events.

Figure 7.2 Modern conifers from Australia and New Zealand. a) & b) *Podocarpus spinuiosa*, Bakarat Botanical Gardens, Victoria, Australia. c) *Podocarpus taxifolia*, d) *Podocarpus hallii*, Hinewai Reserve, Banks Peninsula, New Zealand. e) & f) *Araucaria bidwillii*, Christchurch Botanical Gardens, New Zealand.

Podocarp conifer trees today are long-lived species, commonly growing to ages of 250 years or more with heights typically 20-30 m (Figure 7.2 a-d). In South African forests the podocarp conifers occur in nutrient poor habitats, as do those of New Zealand that grow extensively on infertile floodplain areas, covering 500,000 hectares on North Island and 400,000 hectares on South Island (Midgley *et al.* 1995; Ogden & Stewart 1995). Podocarp conifers exist today under many different climate regimes from the subtropical forests of southern South America (Veblen *et al.* 1995), to the cool temperate regions of south east Australia (Gibson *et al.* 1995). Within the forests of north Patagonia podocarp conifer trees make up just 12.8 % of the forest vegetation.

The podocarp conifers within the Cretaceous forests of Alexander Island show similar features to those of the modern species described above. They grew to heights of up to 25 m and based on their width can be considered as mature, long-lived trees that grew on more stable areas of the floodplain, relying on advanced regeneration.

Araucarian and podocarp conifer forests today occur in a wide range of climates and environments from the wet, temperate areas of New Zealand to the warm, subtropical areas of southern South America. The Cretaceous forests are believed to have grown under a warm-temperate, semi-arid climate with seasonal precipitation and wet phases (see Section 7.2.3), suggesting that the tolerances of Cretaceous araucarian and podocarp conifers are similar to those of modern species.

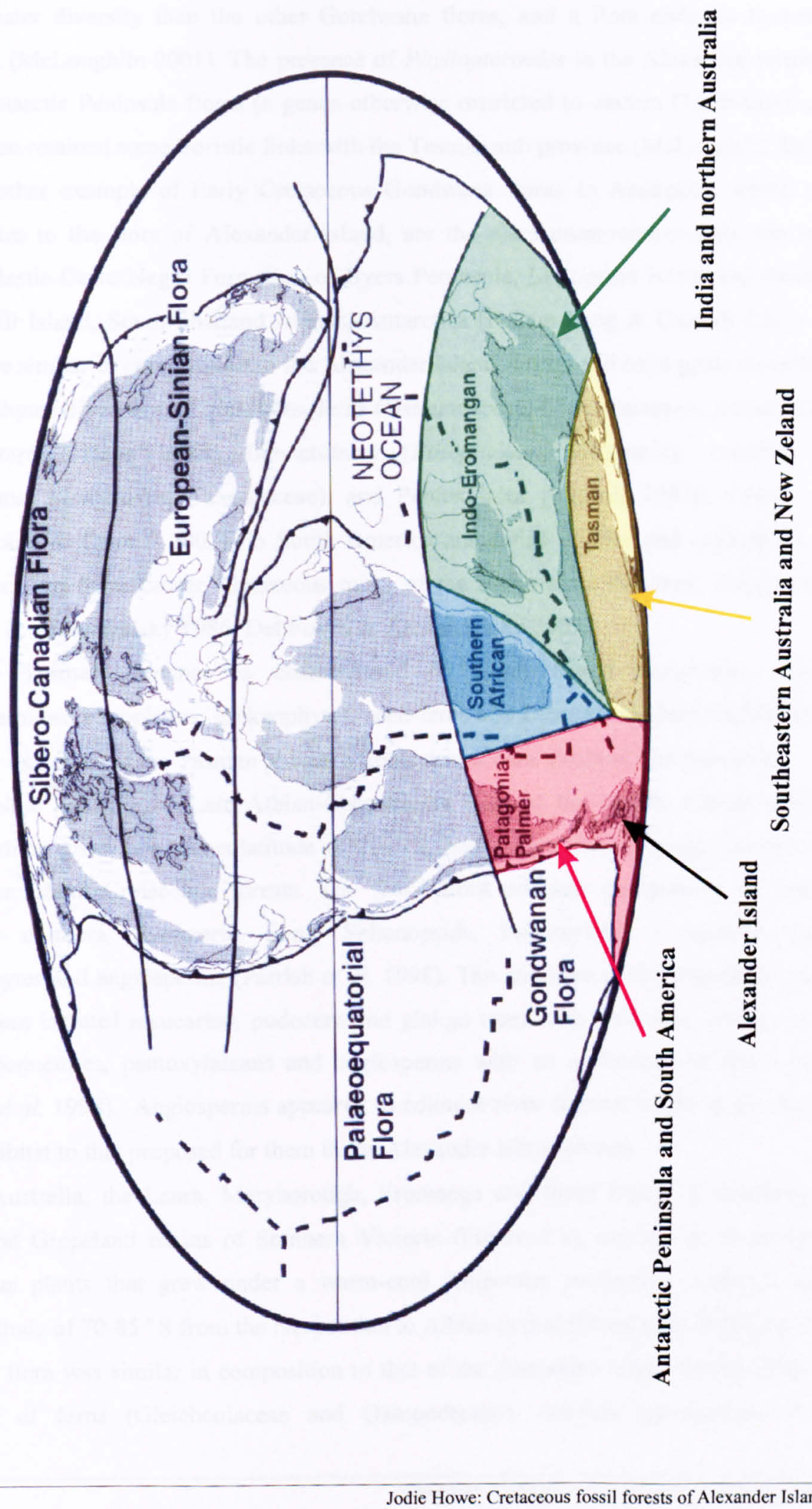
7.1.3 The biogeography of Cretaceous flora

The Early Cretaceous flora occurring within the fossil forests of Alexander Island represents forests growing at a crucial time of angiosperm evolution. Prior to the Early Cretaceous, gymnosperms such as the conifers and bennettitaleans dominated the forests of the Jurassic and by the Late Cretaceous the angiosperms had diversified and were a significant component of the flora.

The Alexander Island flora thus forms part of a distinctive Early Cretaceous Gondwana flora that was widespread across the Southern Hemisphere continents of Gondwana during the Cretaceous, prior to angiosperm-dominated floras. During the Albian period, the Antarctic Peninsula and the other blocks that make up West Antarctica were attached to South America (Lawver & Gahagan 1998), New Zealand (Storey 1996) and East Antarctica (Grunow *et al.* 1991; Figure 7.3). East Antarctica in turn was also linked to Australia at this time (Veever *et al.*1991), forming a land-bridge between the major continents in the Southern Hemisphere and a possible migration route for angiosperms into Antarctica from both South America and from South East Asia via Australia (Hill & Scriven 1995). The southern continents of Australia, New Zealand, South America and Antarctica all have components of the distinct Early Cretaceous Gondwana flora.

However, although the flora of the southern continents show great similarity in composition across Gondwana and several specific genera are distributed widely across the supercontinent, it has been shown that eastern and western Gondwana floras can be broadly distinguished by the distribution, variation and range of unique taxa (McLoughlin 2001). Four sub-provinces have been identified (Figure 7.3) with the Alexander Island forest flora occurring within the Patagonia-Palmer region along with other Antarctic Peninsula floras and floras of southern South America. The other provinces include South Africa, Indo-Eromanga (India and northern Australia) and Tasman (southeastern Australia and New Zealand; Figure 7.3). Differentiation of these floras was largely based on latitudinal or climatic differences and tectonic segregation of formerly connected landmasses (McLoughlin 2001).

Figure 7.3 Mid Cretaceous (94 Ma) continental reconstruction with Cretaceous floristic provinces (after McLoughlin 2001). The four Gondwanan floral provinces are shaded. The Alexander Island flora discussed within this study is within the Patagonia-Palmer province along with floras of the Antarctic Peninsula and southern South America.



The Patagonia-Palmer province is characterised by bennettites with large leaves, assemblages with greater diversity than the other Gondwana floras, and a flora endemic to southern South America (McLoughlin 2001). The presence of *Phyllopteroides* in the Alexander Island forests and other Antarctic Peninsula floras (a genus otherwise restricted to eastern Gondwana), suggests that this region retained some floristic links with the Tasman sub province (McLoughlin 2001).

Another example of Early Cretaceous Gondwana floras in Antarctica, which shows many similarities to the flora of Alexander Island, are the plant communities from the early Aptian, volcaniclastic Cerro Negro Formation of Byers Peninsula, Livingston Island and Presidents Head, Snow Hill Island, South Shetland Islands, Antarctica (Falcon-Lang & Cantrill 2002). The forests here were similar in composition to the Alexander Island forests and have great diversity consisting of Bryophytes, liverworts, Equisetales, ferns (Osmundaceae, Gleicheniaceae, *Aculea*, *Cladophlebis*, *Sphenopteris*), large leafed Bennettitales (*Ptilophyllum*, *Nilssonia*), conifers (podocarps, araucarians, *Elatocladus*, Taxodiaceae), and Pentoxylales (Cantrill 1997b; Cesari *et al.* 1999; Falcon-Lang & Cantrill 2002). In South America araucarian conifer and angiosperm foliage has been described from Lower Cretaceous rocks of the Santa Cruz Province, Patagonia, Argentina (Romero & Archangelsky 1986; Del Fueyo & Archangelsky 2002).

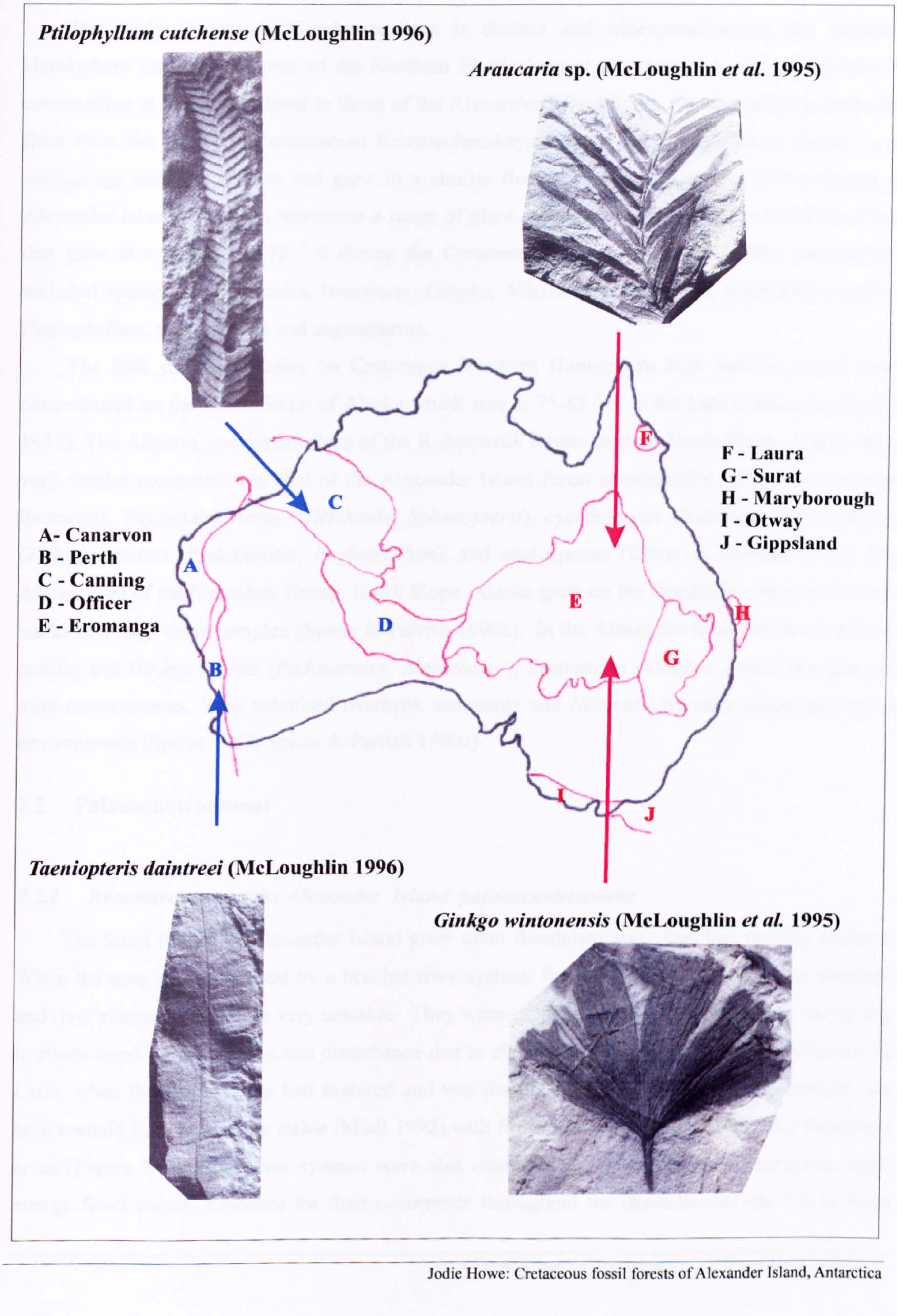
The Tasman province is characterised by small leafed bennettites, pentoxylaleans, Phyllopteroides, Bryophytes, ginkgophytes, seed-ferns and Lycophytes (McLoughlin 2001). There are many examples of the Tasman province floras across New Zealand and Australia.

In New Zealand the Late Albian-Cenomanian flora of the Middle Clarence Valley, South Island, which grew at a palaeolatitude of 70 ° S, had a very similar composition to that of the Alexander Island Cretaceous forests. The fossil flora contains components of araucarian and podocarp conifers, liverworts, ferns, Sphenopsids, Pentoxylales, Cycadales, Bennettitales, ginkgophytes and angiosperms (Parrish *et al.* 1998). The structure of the vegetation was described as emergent isolated araucarian, podocarp and ginkgo trees with a shrubby canopy of seed-ferns, cycads, bennettites, pentoxylaleans and angiosperms with an understory of ferns and horsetails (Parrish *et al.* 1998). Angiosperms appeared to colonise river channel banks within these forests, a similar habitat to that proposed for them in the Alexander Island forests.

In Australia, the Laura, Maryborough, Eromanga and Surat basins of Queensland and the Otway and Gippsland basins of Southern Victoria (Figure 7.4), contain an abundance of Early Cretaceous plants that grew under a warm-cool temperate, moderately seasonal climate at a palaeolatitude of 70-85 ° S from the Neocomian to Albian period (Douglas & Williams 1982; Figure 7.4). The flora was similar in composition to that of the Alexander Island forests (Figure 7.4) and consisted of ferns (Gleicheniaceae and Osmundaceae), conifers (araucarians, *Podozamites,* *Elatocladus, Pagiophyllum* and *Brachyphyllum*), liverworts, Sphenopsids, Pteridosperms, Pentoxylales, *Phyllopteroides*, Cycadophytes, Bennettitales, Ginkgoites, Equisetales and one angiosperm species (*Hydrocotylophyllum*) (Douglas & Williams 1982; Cantrill 1991; Dettmann *et al.* 1992; Cantrill 1992; McLoughlin *et al.* 1995; Cantrill & Webb 1987; McLoughlin *et al.* 2000). Similar floral compositions are found in the Canning, Carnarvon, Officer and Perth basins of Western Australia at this time (Barriasian-Albian; Figure 7.4) including Lycopods, *Hausmannia, Cladophlebis, Phyllopteroides, Sphenopteris,* Gleicheniaceae, Pentoxylales, Bennettitales, *Nilssonia, Elatocladus, Aculea, Ptilophyllum*, Araucariaceae, and fungi (Dettmann *et al.* 1992; McLoughlin 1996; McLoughlin & Hill 1996).

The South African province is characterised by large leafed bennettites and large leafed Pentoxylales, and the Indo-Eromanga floras contain more araucarian conifers than podocarps, dipteridacean and gleicheniacean ferns and large leafed bennettites (McLoughlin 2001).

Figure 7.4 Australian sedimentary basins mentioned in the text, labelled A-J (after Dettmann *et al.* 1992) along with examples of plant fossils collected from three of the basins. The plant fossils pictured here from Australian Cretaceous floras are all genera that occur within the Alexander Island flora.



7.1.4 Flora of the Northern Hemisphere

The Early Cretaceous Gondwana flora is distinct and widespread across the Southern Hemisphere continents. Floras of the Northern Hemisphere at this time had some similarities in composition at the generic level to those of the Alexander Island floras. For example the Grebenka flora from the Albian – Cenomanian Krivorechenskaya Formation of northeastern Russia is of similar age and composition and grew in a similar fluvial environment to that of the forests of Alexander Island. The flora represents a range of plant communities from pioneer to mature forest that grew at a latitude of 72 ° N during the Cretaceous (Spicer *et al.* 2002). The communities included species of Equisetales, liverworts, *Gingko*, *Nilssonia*, *Gleichenites*, araucarian conifers, *Pagiophyllum*, taxodiaceous and angiosperms.

The bulk of other studies on Cretaceous Northern Hemisphere high latitude forests have concentrated on the North Slope of Alaska which was at 75-85 ° N in the Late Cretaceous (Spicer 1989). The Albian-Cenomanian flora of the Kukpowruk River, western North Slope, Alaska has a very similar composition to that of the Alexander Island forest communities. The flora included liverworts, Equisetales, ferns (*Gleichenia*, *Sphenopteris*), cycadophytes (*Nilssonia, Taeniopteris*), *Ginkgo*, conifers (*Podozamites*, *Pagiophyllum*), and angiosperms (Spicer & Herman 2001). The Albian flora of the Nanushuk Group, North Slope, Alaska grew on the floodplain and river channel banks of a large delta complex (Spicer & Parrish 1990a). In the Albian the flora was dominated by conifer and *Ginkgo* forests (*Podozamites, Elatocladus*), Equisetales occupied fluvial margins and mire environments, ferns colonised overbank sediments and *Nilssonia* typically colonised coastal environments (Spicer 1989; Spicer & Parrish 1990a).

7.2 Palaeoenvironment

7.2.1 Reconstruction of the Alexander Island palaeoenvironment

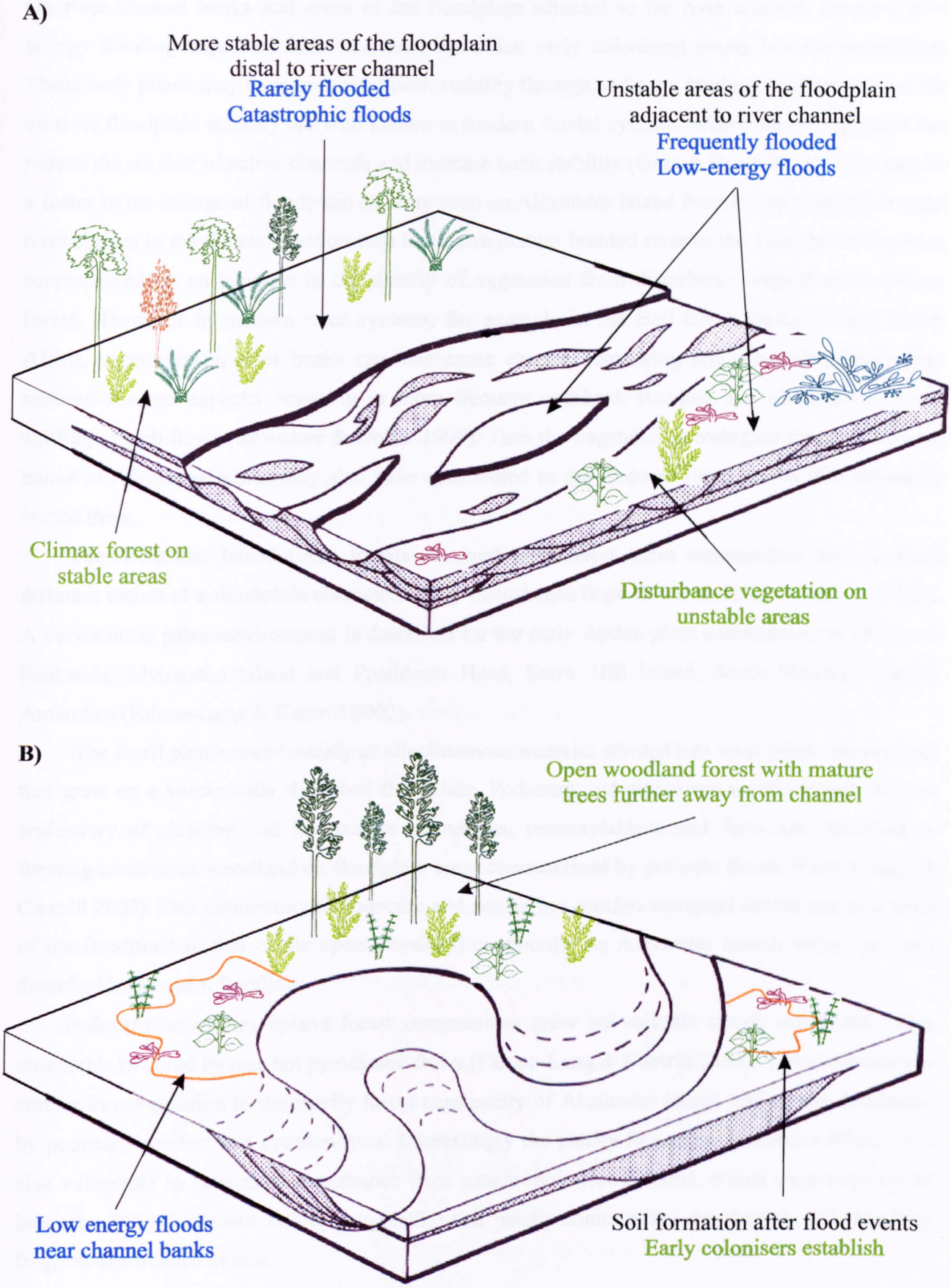
The fossil forests of Alexander Island grew upon floodplain areas that had varying stability. When the area was dominated by a braided river system, floodplain areas close to river channels and river channel banks were very unstable. They were subjected to frequent low energy floods due to rivers breaking their banks and disturbance due to channel avulsion (Figure 7.5; see Chapter 2). Later, when the river system had matured and was dominated by meandering river channels, the banks would have been more stable (Miall 1992) with fewer low-energy floods affecting floodplain areas (Figure 7.5). Both river systems were also characterised by infrequent catastrophic, high-energy flood events. Evidence for their occurrence throughout the deposition of the Triton Point

Formation suggests that these large flood events were not caused by local controls but regional phenomena such as volcanic activity (see Section 7.2.2). The deposition of sediment from these large flood events was rapid, possibly lasting between just a few days or weeks to up to several months (Jefferson 1981; Moncrief 1989).

In stable areas of the Alexander Island floodplains, forest vegetation grew for long periods of time, possibly for as long as 400 years based on fossil tree diameter, forming mature forest communities aiding floodplain stability (see Chapter 4; Figure 7.5). Although these areas were beyond the influence of low-energy floods caused by breaking riverbanks, they were subjected to catastrophic floods that brought large quantities of sand on to the floodplain and buried the trees.

Between flood events, areas of the river floodplain were bare and undisturbed for long periods of time, exposing surfaces to weathering processes and soil formation (see Chapter 3). Pioneer plants, such as liverworts, became established in the new soils, binding the sediment, adding organic matter and forming rich, fertile soils that supported large trees (Figure 7.5). The soils were well-drained and supported diverse forest communities. They represent the majority of time during the deposition of the Triton Point Formation, with each palaeosol representing possibly as much as 5,000 years (Fitzpatrick 1993).

Figure 7.5 The fluvial palaeoenvironments of Alexander Island. A) A braided river system. B) A meandering river system. Floodplain areas adjacent to the river channels were flooded frequently by low-energy flood events, areas further away were affected by catastrophic floods. (Adapted from Cantrill & Nichols 1996).



Vegetation probably had a significant effect on deposition within the Triton Point Formation. On river channel banks and areas of the floodplain adjacent to the river channel, frequent low-energy flooding deposited fresh sediment on which early colonising plants became established. These early plants may have improved bank stability through sediment binding. Vegetation controls on river floodplain stability are well known in modern fluvial systems, where dense vegetation can reduce the number of active channels and increase bank stability (Gran & Paola 2001). This may be a factor in the change of floodplain stability seen on Alexander Island from a very unstable braided river system in the Citadel Bastion area to a more mature braided river in the Titan Nunataks area, accompanied by an increase in the density of vegetation from disturbance vegetation to climax forest. However in modern river systems, for example in the Bell River, Eastern Cape, South Africa, vegetation on river banks can also cause channel narrowing and deepening which may reduced channel capacity resulting in more frequent overbank flooding and ultimately channel shifting at high flows (Rowntree & Dollar 1999). Thus the vegetation growing on the river channel banks of Alexander Island may also have contributed to the frequent flood events that ultimately buried them.

The Alexander Island fossil forests occurred as different plant communities that occupied different niches of a floodplain characterised by disturbance from floods and rare volcanic ash falls. A very similar palaeoenvironment is described for the early Aptian plant communities of the Byers Peninsula, Livingston Island and Presidents Head, Snow Hill Island, South Shetland Islands, Antarctica (Falcon-Lang & Cantrill 2002).

The fossil plants occur mainly as allochthonous material divided into three plant communities that grew on a volcanically disturbed floodplain. Podocarp and araucarian conifer stands with an understory of shrubby and herbaceous bennettites, pentoxylaleans and ferns are described as forming continuous woodland on floodplain areas characterised by periodic floods (Falcon-Lang & Cantrill 2002). This community of podocarp and araucarian conifers occupied similar unstable areas of the floodplain to that of the open woodland community on Alexander Island, which was also disturbed by frequent flooding.

Podocarp-bennettites upland forest communities grew on volcanic slopes where they were vulnerable to burial by rare hot pyroclastic flows (Falcon-Lang & Cantrill 2002). This community is similar in composition to the patchy forest community of Alexander Island, which was dominated by podocarp conifers and cycadophytes. Interestingly the patchy forests on Alexander Island were also vulnerable to infrequent disturbance from catastrophic flood events, which were possibly an indirect result of volcanic activity, suggesting that patchy communities are strongly influenced by frequent disturbance events.

The third community was a shrubby bennettites-dominated short-lived community consisting of shrubby bennettites, pentoxylaleans, herbaceous liverworts and ferns with isolated conifer stands (Falcon-Lang & Cantrill 2002). This community colonised disturbed sites of the floodplain after frequent volcanic activity, just as the disturbance vegetation of Alexander Island, with a similar composition, occupied disturbed floodplain areas after frequent flooding.

The structure and composition of the plant communities on the Byers Peninsula changed from conifer-dominated communities to more shrubby communities in response to changing volcanic style, with increasing eruption frequency through time progressively favouring disturbance-adapted shrubby plants (Falcon-Lang & Cantrill 2002). This response of floral composition and structure to a change in regional scale palaeoenvironment was also reflected within the communities of Alexander Island that matured from early colonising plants on unstable braided floodplain areas to open woodland on a meandering river system floodplain.

A similar palaeoenvironment to the Alexander Island forests is also described for the Grebenka flora from the Albian – Cenomanian Krivorechenskaya Formation of northeastern Russia (Spicer *et al.* 2002). The plant communities grew on a braided river floodplain within a fore-arc basin, where frequent flooding and channel avulsion preserved the flora in thick sequences of volcaniclastic channel, crevasse-splay and flood deposits (Spicer *et al.* 2002). In between flood events floral communities colonised flood deposits but palaeosol development was poor (Spicer *et al.* 2002) in contrast to the well-developed soils of Alexander Island. Volcanic activity probably occurred throughout sedimentation with eruptive periods promoting floods (Spicer *et al.* 2002) similar to the catastrophic floods recorded on the floodplains of Alexander Island. Equisetales and liverworts were the first to colonise exposed flood deposits as they were within the Alexander Island flora. *Hausmannia* is described as a water fern by Spicer *et al.* (2002) occurring as mono-dominant communities, in contrast to its occurrence in the undergrowth of the mature climax forests of Alexander Island. As the flora developed angiosperm-cycadophyte-fern shrub communities occurred including *Ginkgo, Nilssonia* and *Gleichenites*, with angiosperms becoming more diverse as the vegetation matured. As the community continued to develop conifers became dominant with araucarian trees and *Pagiophyllum* preferring drier areas of the floodplain (Spicer *et al.* 2002), similar to the araucarian conifers of the open woodland forests on Alexander Island that preferred more stable areas of the floodplain.

7.2.2 Volcanic and tectonic influences on the palaeoenvironment

The Alexander Island fossil forests occur within the fluvial sandstones of the Triton Point Formation that represent a period of emergence during the Albian on the southeastern parts of

Alexander Island. Further north and to the west of the southeastern nunataks, sediments reflect an inter-tidal shoreface/shallow marine setting grading into a deeper water shelf environment (Horne 1969, Adie 1964), indicating that topography sloped down towards sea level in the north.

The Triton Point Formation was rapidly deposited by high sedimentation rates within a tectonically active fore-arc basin (Chapter 1; Macdonald 1993; Doubleday 1994). The basin was bounded to the east by the magmatic arc and to the west by an intermittently emergent trench slope break on the accretionary complex (Browne 1996). There is little evidence for any significant topography surrounding the southeastern nunataks apart from the active volcanic mountains on the magmatic arc approximately 200 km away to the east. Palaeocurrent directions towards the NW within the Triton Point Formation suggest that the source of sediment to the basin was from the magmatic arc, also indicated by the abundance of reworked volcanic material within the Triton Point Formation sandstones (see Chapter 2).

Volcanic activity occurred throughout the deposition of the Triton Point Formation, as evidenced by ash beds and these pulses of volcanic material suggest that sedimentation on Alexander Island was strongly influenced by arc volcanism. Sedimentation within fore-arc settings is well known to be strongly influenced by tectonics particularly arc volcanism (Macdonald 1993).

The continuous volcanic and tectonic activity during the deposition of the Triton Point Formation would have been a significant influence in shaping the overall environment in which the forests grew. For example high-energy catastrophic floods affected both river systems and were probably regional phenomena caused by tectonic or volcanic activity in the fore-arc basin. This was the case in the present day fore-arc basin in Guatemala where large volcanic eruptions in 1902 had a catastrophic effect on river systems, raising their beds by up to 15 m and leading to rapid vertical aggradation (Kuenzi *et al.* 1979). If such volcanic activity can cause large changes in the river systems in a modern fore-arc setting, it is possible that similar activity may have caused the catastrophic floods that affected the floodplains of Alexander Island.

However there are examples in the fossil record where catastrophic floods have been attributed to climatic as well as tectonic influences. For example, thick flood sandstones in the Miocene Siwalik Group, deposited in the Himalayan fore-land basin, were deposited under a monsoonal driven climate that may have periodically influenced sediment supply and water to the river systems causing high-energy flood events (Khan *et al.* 1997). The thick sandstone bodies recording catastrophic flood events on Alexander Island, however, occur randomly throughout the stratigraphy, suggesting an episodic influence such as volcanic activity rather than a periodic one such as a monsoonal climate.

7.2.3 *Climate of the Alexander Island forests*

The Alexander Island palaeosols of this study suggest that the climate during the Albian was generally semi-arid, as there is no evidence for periods of prolonged waterlogging but features are present such as clay cutans that suggest well-drained soils (see Chapter 3). Ped structures and aligned clay minerals indicate annual wet and dry periods, which suggests at least seasonal precipitation. The clay minerals present within the fossil soils are similar to those formed today in soils of moderate climate with precipitation levels of 500-1000 mm per year.

Strong annual seasonality is also suggested by tree ring data (this study; Jefferson 1982, Falcon-Lang *et al.* 2001) which indicate rapid growth and high climatic seasonality (see Chapter 5), features typical of trees growing in warm-temperate regions today. However the seasonal features within the tree rings were probably caused by changes in light levels throughout the year rather than variations in temperature or precipitation. No evidence for frost was found in the palaeosols and fossil wood of this study. Modern araucarian and podocarp conifers are frost hardy to temperatures of -11 ° C and -23 ° C respectively, suggesting that the minimum temperature of the Alexander Island forests could have been above these estimates (Falcon-Lang *et al.* 2001).

Evidence for infrequent catastrophic flood events within the sediments of Alexander Island suggest that episodically, river levels were exceptionally high, during intermittent wet phases that punctuated the generally semi-arid climate. These wet phases may have been driven by volcanic activity (as discussed in Section 7.2.2).

The Alexander Island Cretaceous forests are similar in composition and structure to the temperate rainforests of New Zealand (Falcon-Lang *et al.* 2001; Figure 7.6). These New Zealand rainforests are dominated by podocarp-araucarian conifer vegetation, growing under humid (1500 mm per annum) and warm (mean monthly summer temperature of 16-22 ° C, mean monthly winter temperature of 3-8 ° C) temperate climate (Wardle 1991). Cantrill (1995) argued that the presence of particular flora (*Hausmannia* Dunker) suggests that the climate had high but seasonal rainfall and experienced mean annual temperatures in the range 13 ° to 27 ° C.

Figure 7.6 Endemic podocarp/araucaria forest of the Hinewai Reserve, Banks Peninsula, South Island, New Zealand. These forests are the most comparable modern forests to the Cretaceous forests of Alexander Island.

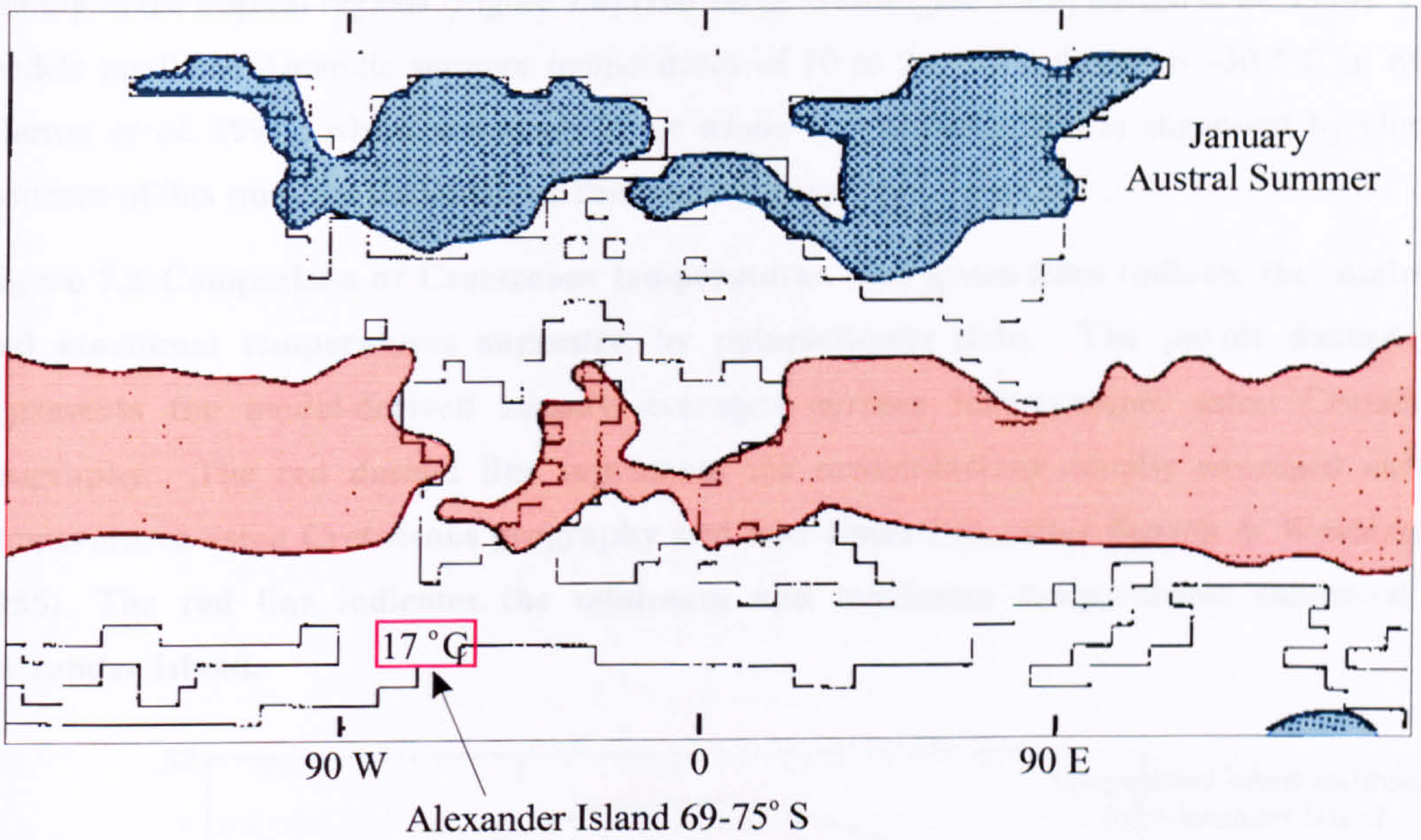
Evidence from this study, described above, suggests that the fossil forest of Alexander Island grew within a warm, temperate, semi-arid climate with annual rainfall and intermittent wet phases. A warm temperate climate in Antarctica during the Albian was also deduced by Rees & Smellie (1989) who predicted mean annual temperatures of 13-20 ° C, based on leaf margin analysis of the angiosperms within the Williams Point flora of Livingston Island. A slightly cooler estimate of 10 ° C (mean annual temperature) was predicted for the Early Cretaceous of New Zealand based on a similar study (Parrish *et al.* 1998). Model simulations of global climate by Valdes *et al.* (1996) using the mid Cretaceous palaeogeography of Smith *et al.* (1994) suggest that south eastern Alexander Island was characterised by a mild climate, with winter temperatures of 0 ° C to -4 ° C and summer temperatures of 20 to 24 ° C. These estimates correspond well to the warm seasonally dry climate suggested by the palaeosols and flora of this study.

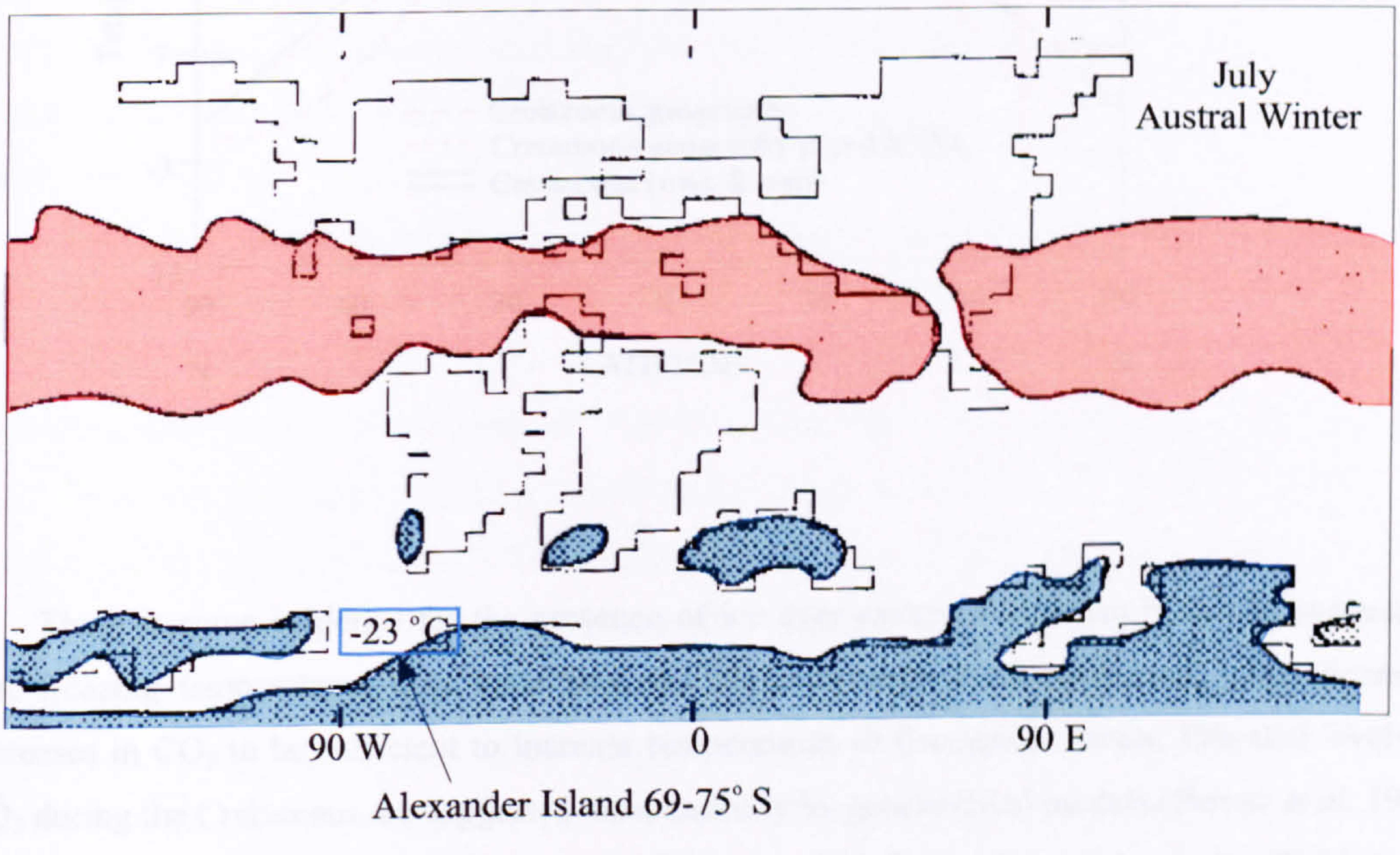
The freezing temperatures for Antarctica predicted within this model however are not supported by this study as no evidence for frost or freezing was found within the fossil material on

Alexander Island. Jefferson (1983) also predicted winter temperatures above 0 ° C for much of the year based on the extensive lamina area of large leaves with entire margins within the flora.

Global climate has been studied for the Cretaceous period by computer climate models, which use Cretaceous palaeogeography along with modern atmospheric circulation patterns to predict global temperatures (Figure 7.7). However early computer models found that palaeogeography alone can only account for a 3 ° C increase in global mean temperatures with Antarctic interiors warmed by just a few degrees. Palaeoclimatic data clearly suggests a global Cretaceous climate 6 to 14 ° C higher than present (Barron & Washington 1982), with evidence from this study suggesting temperatures over Antarctica were much more than a few degrees higher than present day. With the addition of warm polar oceans (keeping oceans above 10 ° C) coastal regions of high latitude landmass were warmed but continental interiors were still found to be well below freezing during winter (Barron & Washington 1982; Figure 7.7).

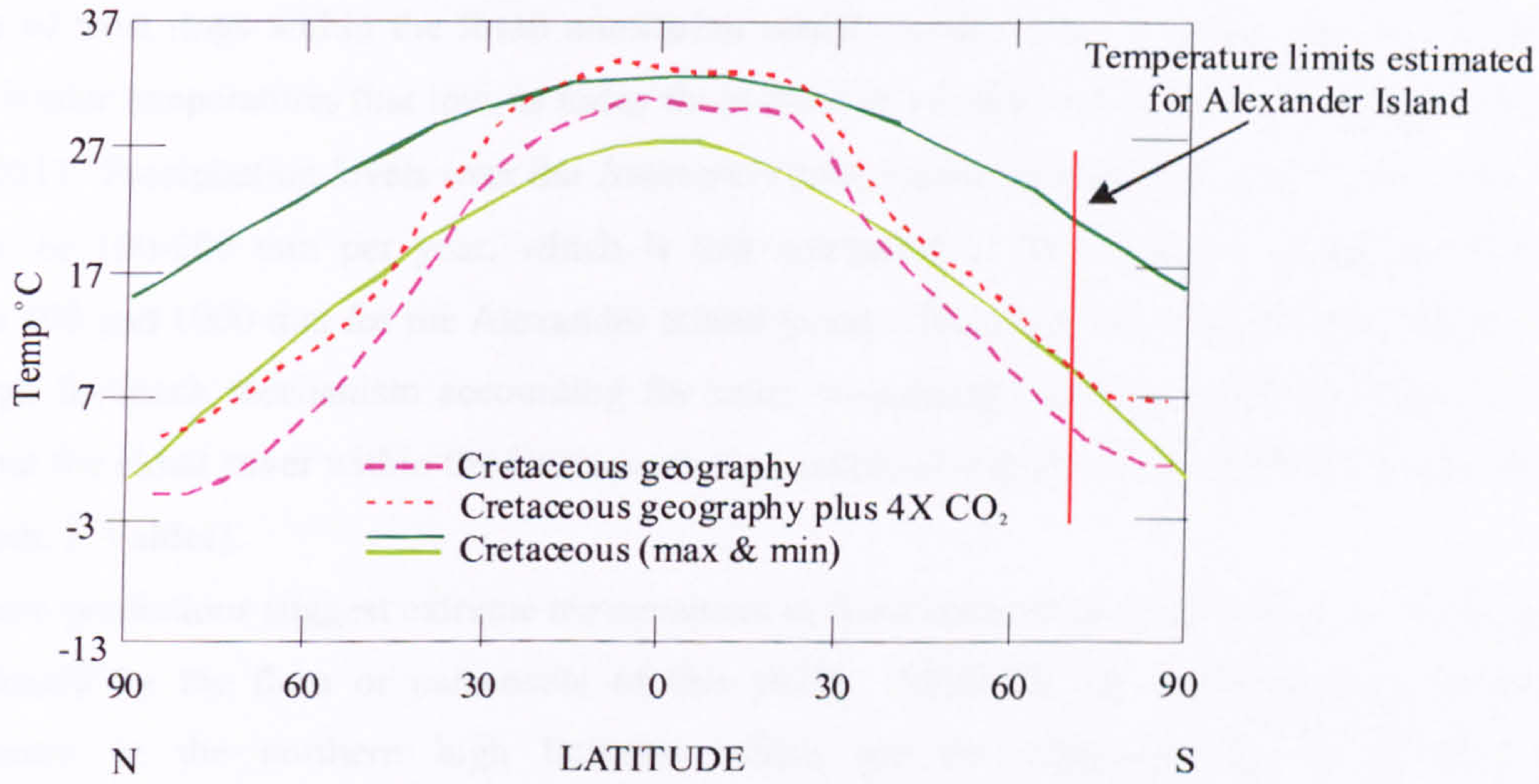
Figure 7.7 The results of global climate modelling for the mid Cretaceous. The figures show the predicted mean temperatures at ground level for January and July, using mid Cretaceous palaeogeography and warm seas (set at 10 ° C). The red shaded areas are those above 27 ° C the blue shaded areas are those below freezing. The temperatures in the boxes are the temperatures predicted by this model for the Antarctic Peninsula. Adapted from Francis & Frakes (1993), modelling from Barron & Washington (1982).





Later models incorporated a seasonal cycle and increased atmospheric CO_2 levels to two to ten fold present day values to create the necessary warmth but more than four times CO_2 caused over heating in the tropical regions (Figure 7.8) (Barron & Washington 1985; Barron *et al.* 1994). These models predicted Antarctic summer temperatures of 10 to 20 ° C and –10 to –30 ° C in winter (Barron *et al.* 1994), which are much lower winter temperatures than is suggested by climatic evidence of this study for the Antarctic Peninsula (Figure 7.8).

Figure 7.8 Comparison of Cretaceous temperatures. The green lines indicate the minimum and maximum temperatures suggested by palaeoclimate data. The purple dashed line represents the model-derived zonally averaged surface temperatures using Cretaceous geography. The red dashed line represents the model-derived zonally averaged surface temperatures using Cretaceous geography and four times CO_2 (after Barron & Washington, 1985). The red line indicates the minimum and maximum temperatures estimated for Alexander Island.



There is some evidence for the presence of ice over eastern Antarctica however, suggesting that freezing temperatures may have occurred in continental interiors, allowing less dramatic increases in CO_2 to be sufficient to increase temperatures to Cretaceous levels. Elevated levels of CO_2 during the Cretaceous are suggested independently by geochemical models (Berner *et al.* 1983) and from increased mantle degassing caused by the mid Cretaceous super plume (Caldeira &

Rampino 1991). Physical 'feedback' mechanisms (Barron *et al.* 1981) and vegetation cover (Otto-Bellesner & Upchurch 1997) have also been proposed as contributing to high-latitude warmth during the Cretaceous.

High-latitude vegetation has been shown to be a strong feedback mechanism for Late Cretaceous warmth (Upchurch *et al.* 1998; Deconto *et al.* 2000) indicating that the Alexander Island forests may have helped to sustain a temperate climate. Deconto *et al.* (2000) used a coupled climate-vegetation model with four times the CO_2 levels of the present day to reproduce the overall warmth and warm winter continental interiors of Antarctica during the Campanian. This model suggests that Antarctic and northern high-latitude forests acted as strong feedback mechanisms, reducing surface albedo, increasing net radiation and latent heat flux.

The Hadley Centre Model (The Hadley Centre for Climate Prediction and Research, Meteorological Office) is the most up-to-date coupled ocean and atmosphere climate model that is used to predict future climate change. When the model is used to simulate Cretaceous climate using a Cretaceous palaeogeography and four times the present CO_2 levels it predicts surface average temperatures of -26 ° C in winter and 28 ° C in summer in Antarctica (pers. com. P.Valdes). The absence of frost rings within the fossil araucarian conifer wood found on Alexander Island argue against winter temperatures that low, as today these conifers are frost hardy to –11 ° C (Falcon-Lang *et al.* 2001). Precipitation levels over the Antarctic Peninsula are predicted as fairly constant at 2-4 mm/day, or 100-200 mm per year, which is low compared to the estimated annual rainfall of between 500 and 1000 mm for the Alexander Island forests. The cloud cover within this model acts as a large feedback mechanism accounting for more temperature variations than increased CO_2 levels, but the cloud cover within the Cretaceous is an unknown variable that is difficult to constrain (pers. com. P.Valdes).

These predictions suggest extreme temperatures in Antarctica within the Cretaceous, which are not indicated by the flora or palaeosols of this study. Similarly the model predicts extreme temperatures in the northern high latitudes which are not supported by the Cretaceous palaeobotanical data. In northeastern Russia during the Albian-Cenomanian, mean annual temperatures are predicted by statistical analysis of the flora as 13 ± 1.8 ° C with a cold month mean of 5.5 ± 3.3 ° C (Spicer *et al.* 2002). These estimates and those of the North Slope, Alaska (Spicer & Parrish 1990b) indicate that much of northeastern Asia and possibly Alaska were above freezing during the dark winter months of the Cretaceous (Spicer *et al.* 2002). The palaeoclimatic evidence clearly does not fit the predictions of the Hadley Centre Model, which may suggest that the model is not valid for warm periods with low meridional heat gradients (pers. com. P.Valdes). This is of great importance because the same climate models are the basis of future climate change predictions. Further work on high-latitude palaeoclimatic indicators is clearly needed to help constrain present climate models.

7.2.4 Problems facing vegetation growing at high-latitudes

The Cretaceous fossil forests of Alexander Island grew at a palaeolatitude of 69-75 ° S and would have been subjected to polar light regimes of up to two months of total darkness (List 1963; Neiburger 1982). The trees probably survived this period of darkness by becoming dormant. Laboratory experiments that grew tree species in cool winter darkness for up to 10 weeks indicated that very little tissue damage occurred. Fourteen of the 16 trees survived the winter darkness (Read & Francis 1992).

The cells of the fossil wood growth rings in this study also suggest dormancy of the trees during the winter darkness. The ratio of late to early wood was low (Chapter 5) suggesting rapid cessation of growth, possibly due to the changes in light conditions at the end of summer. Evidence for dormancy of trees at high latitudes has been described from many fossil wood studies including within fossil woods from the Cenomanian-early Campanian trees of Williams Point, Livingston Island, Antarctica (Chapman & Smellie 1992).

The greatest problem for plants subjected to winter darkness at high polar latitudes would have been high rates of respiration during winter when photosynthesis was minimal. During the Cretaceous this may not have been as big a problem as it would be today because of the greenhouse climate. Elevated carbon dioxide levels have been found to reduce respiration rates through direct inhibition of enzyme activity (Osborne & Beerling 2002; Beerling & Osborne 2002).

The fossil forests of Alexander Island may also have been more suited to the polar dark winters as they were dominated by evergreen species with long leaf longevity (Falcon-Lang & Cantrill 2001a). An evergreen habit may be advantageous at polar latitudes as it would allow photosynthesis to begin as soon as light levels were high enough as well as reducing energy loss through the making a new leaf canopy each season (Falcon-Lang & Cantrill 2001a). Recent laboratory experiments by Royer *et al.* (2003) grew both deciduous and evergreen trees within a simulated polar climate with and without elevated carbon dioxide levels. These experiments showed that the carbon lost annually through shedding a deciduous canopy was greater than that lost by evergreen trees through winter respiration, irrespective of carbon dioxide concentration. These experiments thus indicate that an evergreen habit may be advantageous at polar latitudes. Furthermore if temperatures were low during the dark winters at these latitudes respiration may also have been minimised through suppressed metabolic activity.

Falcon-Lang & Cantrill (2001a) used five independent techniques to determine the leaf-longevity of the fossil plants within the forests of Alexander Island. The dominant araucarian and podocarp conifers were evergreen with leaf retention times of 5-13 years, taxodioid conifers were both evergreen and deciduous and Gingko trees and the pentoxylalean plant were interpreted as possessing a deciduous habit (Falcon-Lang & Cantrill 2001a). The predominance of evergreen conifers was also found in other Southern Hemisphere Cretaceous high-latitude forest communities in New Zealand (Parrish *et al.* 1998) and Australia (Douglas & Williams 1982; Dettman *et al.* 1992) indicating that an evergreen habit may be an adaptation of high latitude forests.

Cretaceous forests may also have adopted certain adaptations such as photoperiodic ecotypes, (for example certain species growing optimally in short growing seasons at high latitudes), higher rates of cambial activity during the short growing season and an appropriate crown structure to optimally intercept the solar radiation from low angles of elevation (Chaloner & Creber 1989). If the conifers within the Cretaceous forests of Alexander Island possessed a crown height much greater than its basal radius, the resultant cone-shape of the tree would have been optimal for intercepting solar radiation from low angles of elevation at high-latitudes (Creber & Chaloner 1985). Another problem caused by the low angle of incidence of the sun's rays at high latitudes is that of shading from other trees and plants (Jefferson 1982). The rather wide spacing of the trees within the Alexander Island forests, estimated in this study and by Jefferson (1980) would have helped to minimise mutual shading at these low angles of solar elevation (Jefferson 1982). However although the trees were spaced wide enough to survive, the number of hours of effective sunlight per day would be reduced and some shading of ground dwelling plants and small trees would still occur (Jefferson 1982).

7.3 Painting of the palaeoenvironment of the fossil forests of Alexander Island, Antarctica

The picture in Figure 7.9 is a reconstruction of the Cretaceous fossil forests of Alexander Island painted by Robert Nichols. The painting is a scientific reconstruction based on the evidence discussed within this thesis. The forest depicted in the painting was reconstructed using evidence for spacing between trees, tree density and calculations of tree height discussed in Chapter 4. The composition and community structure of the vegetation within the painting was based on inter-species relationships and relationships between plant species and particular sedimentary environments discussed in Chapter 6. The sedimentary environment in which the forests are growing within the painting is based on all sedimentological information discussed in Chapter 2. The appearance of much of the vegetation within the Alexander Island forests is based on fossil material from this study as well as information from the work of David Cantrill, Howard Falcon-Lang and Gary Nichols. General information on Cretaceous vegetation, climate and environments is based on work of Jane Francis.

To the right in the background of the painting podocarp conifers form a canopy layer with an undergrowth of ferns and cycadophytes, representing the mature climax forest communities that preferred more stable areas of the floodplain away from the main river channel. These open out in the foreground of the painting into an open woodland forest with araucarian conifers widely spaced forming an overstorey with an understory of ferns and shrubs, growing on areas closer to the river channel where they would have been subjected to frequent flooding. *Taeniopteris* can be seen forming dense patches in clearings and in the centre of the painting, colonising the forest floor between stands of cycadophytes and conifers where more light was available. Dead conifer trunks can be seen adjacent to the river channel after catastrophic flood events have buried them in coarse sand, possibly as a result of a recent eruption from the volcanoes of the magmatic arc, clearly seen in the far distance. Fresh sediments on the river channel banks are colonised by small angiosperms, liverworts and Equisetales.

Figure 7.9 A reconstruction of the Albian fossil forests of Alexander Island, Antarctica, by Robert Nichols (Paleocreations).

Chapter 8 Conclusions

- Diverse forest communities grew upon the floodplain areas of Alexander Island during the Albian at a palaeolatitude of 69-75 ° S.
- The fossil forests are preserved within the fluvial sediments of the Triton Point Formation of the Fossil Bluff Group, which represents the infill of a fore-arc basin.
- Ash beds indicate that volcanic activity was consistent throughout the deposition of the Triton Point Formation and was likely to have influenced sedimentation and regional palaeoenvironment.
- The fluvial environment matured from a braided river system with frequent floods and unstable channel banks to a more mature meandering river system with fewer floods and more stable floodplain areas.
- Catastrophic floods occurred upon the floodplains of both river systems and throughout the deposition of the Triton Point Formation. These high-energy floods were probably a result of volcanic activity upon the magmatic arc, 200 km to the east.
- Low energy floods preserved plants that grew on the river channel banks in fine muds and silts; rarer high-energy catastrophic floods preserved trees in their growth positions in coarse sands.
- Soils formed on emergent surfaces in-between flood events with early colonising plants helping to bind the sediment, adding organic matter, forming rich fertile soils that supported forest communities.
- The palaeosols were well developed and contained features present in many modern soils such as peds, mottling and clay cutans. These features indicate the palaeosols were well-drained mollisols.
- The palaeosols had a metamorphic overprint that indicates the Triton Point Formation was buried to depths of 3.3-3.7 km and was metamorphosed to the zeolite facies.
- The flora within the fossil forests of Alexander Island forms part of a distinctive Early Cretaceous Gondwana flora that was widespread across the continents of the Southern Hemisphere during the Early Cretaceous. Australia, New Zealand, South America and Antarctica all have components of this distinct flora.
- The flora within the fossil forests of Alexander Island occurred as well structured communities that occupied different parts of the river floodplain.
- Open-woodland forests dominated by araucarian conifers, ferns and small shrubs, occupied stable areas of the floodplain where low-energy floods covered smaller plants in fine sands and

silts. These forests were long-lived pioneer forests with densities of 90 trees ha $^{-1}$, with young saplings occupying disturbed areas after floods.

- Disturbance vegetation dominated by *Taeniopteris*, liverworts, angiosperms and ferns, occupied river channel banks were they were frequently covered in sediment when the river broke its banks. These areas of the floodplain were subjected to periods of water saturation after flood events, allowing water-loving species to flourish.
- Patch forest communities dominated by podocarp conifers, ginkgo trees, cycadophytes and ferns, grew on stable areas of the floodplain distal to the river channel. These climax forests grew too far away from the river to be affected by frequent low-energy floods allowing mature slow growing podocarps to become established with densities of 250 trees ha $^{-1}$. These forests were affected by catastrophic floods that covered the forest floor in coarse sands, entombing the forest trees.
- Angiosperms were an important component of these forests as they had only just evolved in the Early Cretaceous. In the Alexander Island forest communities the early angiosperm plants grew in disturbed areas on fresh sediments along with early colonising plants such as the liverworts.
- Today araucarian and podocarp conifers grow in a wide range of climates and environments from the wet, temperate areas of New Zealand to the warm subtropical areas of southern South America. It is likely that the podocarps and araucarias of Alexander Island had similar tolerances to those of the modern species.
- Evidence from the palaeosols, sediments and fossil wood of Alexander Island suggest that the climate was warm, temperate, and semi-arid with seasonal precipitation and intermittent wet phases.
- In structure and composition, the Alexander Island forests are very similar to the present day warm temperate rainforests of New Zealand characterised by mean summer temperatures of 16-22 ° C and mean winter temperatures of 3-8 ° C.

Chapter 9 References

Aarrestad, P. A. 2000. Plant communities in broad-leaved deciduous forests in Hordaland county, Western Norway. *Nordic Journal of Botany*, **20** **(4)**, 449-466.

Adie, R. J. 1964. Geological History. *In*: Priestley, R. E., Adie, R. J. & Robin, G. de Q. (eds.) *Antarctic Research*, 118-162. Butterworth and Co., London.

Allen, J. R. L. 1963. The classification of cross-stratified units, with notes on their origin. *Sedimentology*, **2**, 93-114.

Allison, P. A. 1990. Taphonomy; Diagenesis; Carbonate nodules and plattenkalks. *In*: Briggs, D. E. G. Crowther, P. R. (eds.) *Palaeobiology; a synthesis*, 250-253. Blackwell Scientific Publications, Oxford.

Armesto, J. J., Villagran, C., Aravena, J. C., Perez, C., Smith-Ramirez, C., Cortes, M. & Lars Hedin. 1995. Conifer forests of the Chilean coastal range. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 156 – 170. Melbourne University Press.

Askin, R. A. & Baldoni, A. M. 1998. The Santonian through Paleogene record of Proteaceae in the Southern South America - Antarctic Peninsula region. *Australian Systematic Botany*, **11(3-4)**, 373-390.

Bamford, M. K. & Philippe, M. 2001. Jurassic-Early Cretaceous Gondwanan homoxylous woods: a nomenclatural revision of the genera with taxonomic notes. *Review of Palaeobotany and Palynology*, **113**, 287-297.

Bardintzeff, J. 2000. Eruptive styles and pyroclastic deposits. *In*: Leyrit, H. & Montenat (eds.) *Volcaniclastic rocks, from magmas to sediments*, 33-51. Gordon and Breach Science Publishers.

Barker, P. F., Dalziel, I. W. D. & Storey, B. C. 1991. Tectonic development of the Scotia arc region. *In*: Tingey, R. J. (ed.) *Geology of Antarctica*, 215-248. Oxford Monographs on Geology and Geophysics.

Barron, E. J. & Washington, W. M. 1982. Cretaceous climate: a comparison of atmospheric simulations with the geologic record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **40**, 103-133.

Barron, E. J. & Washington, W. M. 1985. Warm Cretaceous climates: High atmospheric CO2 as a plausible mechanism. *In*: Sundquist, E. T. & Broecker, W. S. (eds.) *The Carbon Cycle and atmospheric CO2: Natural variations Archean to present*, 546-553. American Geophysical Union, Washington.

Barron, E. J., Thompson, S. L. & Schneider, S. H. 1981. An ice-free Cretaceous? Results from climate model simulations. *Science*, **212**, 501-508.

Barron, E. J., Fawcett, P. J., Pollard, D. & Thompson, S. 1994. Model simulations of Cretaceous climates: the role of geography and carbon dioxide. *In*: Allen, J. R. L *et al.* (eds.), *Palaeoclimates and their modelling: with specific reference to the Mesozoic era*, 99-108. Chapman & Hall.

Beerling, D. J. & Osborne, C. P. 2002. Physiological Ecology of Mesozoic polar forests in a high CO2 environment. *Annals of Botany*, **89**, 329-339.

Berner, R. A., Lasaga, C. C. & Garrels, R. M. 1983. The carbonate-silicate geochemical cycle and its effects on atmospheric carbon dioxide over the past 100 million years. *American Journal of Science*, **283**, 641-683.

Bostick, N. H. 1979. Microscopic measurement of the level of catagenesis of solid organic matter in sedimentary rocks to aid exploration for petroleum and to determine former burial temperatures – A review. *In*: Scholle, P. A. & Schluger, P. R. (eds.) *Aspects of Diagenesis. The Society of Economic Paleontologists and Mineralogists, Special Publication*, **26**, 17-43.

Braak, C. J. F. ter. & Šmilauer, P. 1998. *Canoco Reference manual and User's guide to Canoco for Windows*. Centre for Biometry, Wageningen.

Brady, N. C. 1999. *The nature and properties of soils*, Twelfth Edition, 47-89. Prentice Hall, USA.

Brewer, R. 1976. *Fabric and mineral analysis of soils*, Second Edition. Krieger, New York.

British Standard BS6127, PART 5. 1981. *Petrographic analysis of bitumous coals and anthracite.* Part 5, Method of determining microscopically the reflectance of vitrinite.

Browne, J. R. 1996. *Sandstone provenance and diagenesis of arc-related basins: James Ross Island and Alexander Island, Antarctica.* PhD thesis. University of Exeter.

Burn, R. W. 1981. Early Tertiary calc-alkaline volcanism on Alexander Island. *British Antarctic Survey Bulletin*, **53**,175-193.

Burnham, R. J. 1994. Patterns in tropical leaf litter and implications for angiosperm palaeobotany. *Review of Palaeobotany and Palynology*, **81**, 99-113.

Burnham, R. J. 1997. Stand characteristics and leaf litter composition of a dry forest hectare in Santa Rosa National Park, Costa Rica. *Biotropica*, **29(4)**, 384-395.

Butterworth, P. J., Crame, J. A., Howlett, P. J. & Macdonald, D. I. M. 1988. Lithostratigraphy of Upper Jurassic-Lower Cretaceous strata of eastern Alexander Island, Antarctica. *Cretaceous Research*, **9**, 249-264.

Caldeira, K. & Rampino, M. R. 1991. The mid-Cretaceous super plume, carbon dioxide, and global warming. *Geophysical Research Letters*, **18(6)**, 987-990.

Cant, D. J. & Walker, R. G. 1978. Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. *Sedimentology*, **25(5)**, 625-646.

Cantrill, D. J. 1991. Broad leafed coniferous foliage from the Lower Cretaceous Otway Group, southeastern Australia. *Alcheringa*, **15**, 177-190.

Cantrill, D. J. 1992. Araucarian foliage from the Lower Cretaceous of Southern Victoria, Australia. *International Journal of Planetary Science*, **153(4)**, 622-645.

Cantrill, D. J. 1995. The occurrence of the fern *Hausmannia* Dunker (Dipteridaceae) in the Cretaceous of Alexander Island, Antarctica. *Alcheringa*, **19**, 243-254.

Cantrill, D. J. 1996. Fern thickets from the Cretaceous of Alexander Island, Antarctica containing *Alamatus bifarius* Douglas and *Aculea acicularis* sp.nov. *Cretaceous Research*, **17**, 169-182.

Cantrill, D. J. 1997a. Hepatophytes from the Cretaceous of Alexander Island, Antarctica: systematics and ecology. *International Journal of Plant Sciences*, **158**, 476-488.

Cantrill, D. J. 1997b. Floristics of a Lower Cretaceous freshwater lake deposit from Presidents Head, Snow Island, South Shetland Islands. *In*: Ricci, C. A. (ed.) *The Antarctic region: Geological Evolution and Processes*, 1017-1022. Terra Antarctica Publications, Sienna.

Cantrill, D. J. 2000. A Cretaceous (Aptian) flora from President Head, Snow Island, Antarctica. *Palaeontographica Abteilungen B Paläophylogie*, **253**, 153-191.

Cantrill, D. J. & Webb, J. A. 1987. A reappraisal of Phyllopteroides Medwell (Osmundaceae) and its stratigraphic significance in the Lower Cretaceous of eastern Australia. *Alcheringa*, **11**, 59-85.

Cantrill, D. J. & Nichols, G. J. 1996. Taxonomy and palaeoecology of Early Cretaceous (Late Albian) angiosperm leaves from Alexander Island, Antarctica. *Review of Palaeobotany and Palynology*, **92**, 1-28.

Cesari, S., Parica, C., Remesal, M. & Salani, F. 1999. Lower Cretaceous flora from Byers Peninsula, South Shetland Islands, Antarctica. *Ameghiniana*, **36(1)**, 3-22.

Chaloner, W. G. & Creber, G. T. 1989. The phenomenon of forest growth in Antarctica: a review. *In*: Crame, J. A. (ed.) *Origins and Evolution of the Antarctic Biota*, Geological Society Special Publication, **47**, 85-88.

Chapman, J. L. 1994. Distinguishing internal development characteristics from external palaeoenvironmental effects in fossil wood. *Review of Palaeobotany and Palynology*, **81**, 19-32.

Chapman, J. L. & Smellie, J. L. 1992. Cretaceous fossil wood and palynomorphs from Williams Point, Livingston Island, Antarctic Peninsula. *Review of Palaeobotany and Palynology*, 74(3-4), 163-192.

Coleman, J. M. 1969. Brahmaputra River: Channel processes and sedimentation. *Sedimentary Geology*, 3 (2-3), 131-239.

Collinson, J. D. 1996. Alluvial sediments. *In:* Reading, H. G (ed.) *Sedimentary environments and facies*, 37- 82. Blackwell Scientific Publications, Oxford.

Crame, J. A. & Howlett, P. J. 1988. Late Jurassic and early Cretaceous biostratigraphy of the Fossil Bluff Formation, Alexander Island. *British Antarctic Survey Bulletin*, **78**, 1-35.

Crane, P. R., Frils, E. M. & Pedersen, K. R. 1995. The origin and early diversification of angiosperms. *Nature*, **374**, 27-33.

Creber, G. T. & Chaloner, W. G. 1985. Tree growth in the Mesozoic and early Tertiary and the reconstruction of palaeoclimates. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **52**, 35-60.

Creber, G. T. & Francis, J. E. 1999. Fossil tree-analysis: palaeodendrology. *In*: Jones, T. P. & Rowe, N. P. (eds.) *Fossil plants and spores: modern techniques.* Geological Society London, 245-250.

Crowe, B. M. & Fisher, R. V. 1973. Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California. *Geological Society American Bulletin*, **84**, 663-682.

Deconto, R. M., Brady, E. C., Bergengren, J. & Hay, W. W. 2000. Late Cretaceous climate, vegetation and ocean interactions. *In*: Huber, B. T., Macleod, K. G. & Wing, S. L. (eds.) *Warm climates in Earth History*, 275-296. University of Cambridge Press.

Deer, W. A., Howie, R. A. & Zussman, J. 1992. *An introduction to the rock-forming minerals*, Second Edition. London, Longmans.

Del Fueyo, G. M. & Archangelsky, A. 2002. *Araucaria grandifolia* Feruglio from the Lower Cretaceous of Patagonia, Argentina. *Cretaceous Research*, **23(2)**, 265-277.

Dettmann, M. E., Molnar, R. E. & Douglas, J. G. 1992. Australian Cretaceous terrestrial faunas and flora: biostratigraphic and biogeographic implications. *Cretaceous Research*, **13**, 207-262.

Dimichele, W. A., Phillips, T. L. & McBrinn, G. E. 1991. Quantitative analysis and Paleoecology of the Secor Coal and roof-shale floras (middle Pennsylvanian, Oklahoma). *Palaios*, **6**, 390-409.

Doubleday, P. A. 1994. *Structural and tectonic evolution of parts of the Mesozoic fore-arc of Alexander Island, Antarctica.* PhD Thesis. The University of Leeds.

Doubleday, P. A. & Storey, B. C. 1998. Deformation history of a Mesozoic fore-arc basin sequence in Alexander Island, Antarctic Peninsula. *Journal of South American Earth Sciences,* **11(1)**, 1-21.

Douglas, J. G. & Williams, G. E. 1982. Southern polar forests: the Early Cretaceous floras of Victoria and their palaeoclimatic significance. *Palaeogeography, Palaeoclimatology and Palaeoecology,* **39**, 171-185.

Drinnan, A. N. & Chambers, T. C. 1985. A reassessment of *Taeniopteris daintreei* from the Victorian Early Cretaceous: a member of the Pentoxylales and a significant Gondwanaland plant. *Australian Journal of Botany,* **33**, 89-100.

Dunoyer de Segonzac, G. 1970. The transformation of clay minerals during diagenesis and low-grade metamorphism: A review. *Sedimentology,* **15**, 281-346.

Elliot, D. H. 1988. Tectonic setting and evolution of the James Ross Basin, northern Antarctic Peninsula. *Geological Society of America,* **169**, 541-555.

Enright, N. J. 1995. Conifers of tropical Australasia. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers,* 197 – 223. Melbourne University Press.

Exner, A., Willner, W. & Grabherr, G. 2002. Picea abies and Albies alba forests of the Austrian Alps: Numerical classification and ordination. *Folla Geobotanica,* **37 (4)**, 383-402.

Falcon-Lang, H. J. & Cantrill, D. J. 2000. Cretaceous (Late Albian) Coniferales of Alexander Island, Antarctica. 1: Wood taxonomy : a quantitative approach. *Review of Palaeobotany and Palynology,* **111**, 1-17.

Falcon-Lang, H. J. & Cantrill, D. J. 2001a Leaf phenology of some mid-Cretaceous polar forests, Alexander Island, Antarctica. *Geological Magazine,* **138**, 39-52.

Falcon-Lang, H. J. & Cantrill, D. J. 2001b. Cretaceous (Late Albian) Coniferales of Alexander Island, Antarctica. 2: Leaves, reproductive structures and roots. *Review of Palaeobotany and Palynology,* **115**, 119-145.

Falcon-Lang, H. J. & Cantrill, D. J. 2002. Terrestrial palaeoecology of the Cretaceous (early Aptian) Cerro Negro Formation, South Shetlands Islands, Antarctica: A record of polar vegetation in a volcanic arc environment. *Palaios,* **17(5)**, 491-506.

Falcon-Lang, H. J., Cantrill, D. J. & Nichols, G. J. 2001. Biodiversity and terrestrial ecology of a mid-Cretaceous, high-latitude floodplain, Alexander Island, Antarctica. *Journal of the Geological Society, London,* **158**, 709-724.

Fisher, R. V. & Schmincke, H. U. 1984. Pyroclastic fragments and deposits. *In*: Fisher, R.V. & Schmincke, H. U. (eds.) *Pyroclastic rocks*, 89-123. Springer-Verlag.

Fitzpatrick, E. A. 1980. *Soils: formation, classification and distribution.* Longman Group, New York.

Fitzpatrick, E. A. 1993. *Soil microscopy and micromorphology.* John Wiley & Sons, New York.

Fleming, W. L. S. 1938. *In*: Fleming, W. L. S., Stephenson, A. & Roberts, A. (eds.) Notes on the Scientific work of the British Graham Land Expedition, 1934-1937. *Geographical Journal*, **91 (6)**, 508-512.

Foth, H. D. 1990. *Fundamentals of soil science*, Eighth Edition, 285-318. John Wiley & Sons, New York.

Francis, J. E. 1986. Growth rings in Cretaceous and tertiary woods from Antarctica and their palaeoclimatic implications. *Palaeontology*, **29(4)**, 665-684.

Francis, J. E. 1991. Palaeoclimatic significance of Cretaceous-early Tertiary fossil forests of the Antarctic Peninsula. *In*: Thomson, M. R. A., Crame, J. A. & Thomson, J. W. (eds.) *Geological evolution of Antarctica*, 623-627. Cambridge University Press.

Francis, J. E. & Frakes, L. A. 1993. Cretaceous climates. *Sedimentary Review*, **1**, 17-30.

Friend, P. F., Slater, M. J. & Williams, R. C. 1979. Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain. *Journal of the Geological Society of London*, **136**, 39-46.

Gastaldo, R. A. 1985. Taphonomic processes responsible for the preservation of an autochthonous lycopod deltaic swamp in the Early Pennsylvanian of Alabama. *American Journal of Botany*, **72(6)**, 893-894.

Gastaldo, R. A. 1986. Taphonomy of natural levees and alluvial swamps, Mobile Delta, Alabama: a preliminary assessment. *American Journal of Botany*, **73(5)**, 699-700.

Gibson, N., Barker, P. C. J., Cullen, P. J. & Shapcott, A. 1995. Conifers of Southern Australia. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 223 – 252. Melbourne University Press.

Gothan, W. 1905. Zur anatomie lebender und fossiler Gymnospermum Hölzer. Abh. Preuss. Geol. Landesant. **44**, 1-108.

Gran, K. & Paola, C. 2001. Riparian vegetation controls on braided stream dynamics. *Water Resources Research*, **37(12)**, 3275-3283.

Greguss, P. 1955. *Identification of living gymnosperms on the basis of Xylotomy.* Akademia Kiado, Budapest.

Grunow, A. M., Kent, D. V. & Dalziel, I. W. D. 1991. New paleomagnetic data from Thurston Island; implications for the tectonics of West Antarctica and Weddell Sea opening. *Journal of Geophysical Research, B, Solid Earth and Planets*, **96**, 17935-17954.

Hay, R. L. 1966. Zeolites and zeolitic reactions in sedimentary rocks. *Geological Society of America, Special Papers*, **85**, 1-122.

Hill, M. O. 1979. *TWINSPAN – A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of individuals and attributes.* Cornell University Ithaca, New York.

Hill, R. S. & Scriven, L. J. 1995. The angiosperm-dominated woody vegetation of Antarctica: a review. *Review of Palaeobotany and Palynology*, **86**, 175-198.

Hill, R. S. & Brodribb, T. J. 1999. Southern conifers in time and space (Turner Review No. 2). *Australian Journal of Botany*, **47**(5), 639-696.

Horne, R. R. 1968. Authigenic prehnite, laumontite and chlorite in the Lower Cretaceous sediments of southeastern Alexander Island. *British Antarctic Survey Bulletin*, **18**, 1-10.

Horne, R. R. 1969. Sedimentology and palaeogeography of the Lower Cretaceous depositional trough of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, **22**, 61-76.

Horne, R. R. & Taylor, B. J. 1969. Calcareous concretions in the Lower Cretaceous sediments of southeastern Alexander Island. *British Antarctic Survey Bulletin*, **21**, 19-32.

Howe, J. & Cantrill, D. J. 2001. Palaeoecology and taxonomy of Pentoxylales from the Albian of Antarctica. *Cretaceous Research*, **22**, 779-793.

Jaffre, T. 1995. Distribution and ecology of the conifers of New Caledonia. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 171 – 196. Melbourne University Press.

Jefferson, T. H. 1980. Angiosperm fossils in supposed Jurassic volcanogenic shales, Antarctica. *Nature*, **285**, 157-158.

Jefferson, T. H., 1981. Palaeobotanical contributions to the geology of Alexander Island, Antarctica. PhD thesis, University of Cambridge.

Jefferson, T. H. 1982a. Fossil forests from the Lower Cretaceous of Alexander Island, Antarctica. *Palaeontology*, **25** (4), 681-708.

Jefferson, T. H. 1982b. The preservation of fossil leaves in Cretaceous volcaniclastic rocks from Alexander Island, Antarctica. *The Geological Magazine*, **119** (3), 291-300.

Jefferson, T. H. 1983. Palaeoclimatic significance of some Mesozoic Antarctic fossil floras. *In*: Oliver, R. L., James, P. R. & Jago, J. B. (eds.), *Antarctic Earth Science*. Cambridge University Press, Cambridge, 593-598.

Jeffrey, E. C. 1907. *Araucariopitys*, a new genus of araucarians. *Botanical Gazette*, **44**, 435-444.

Johnson, H. G. 1977. Shallow marine sand bar sequences: an example from the late Precambrian of North Norway. *Sedimentology*, **24**, 245-270.

Johnson, H. D. & Baldwin, C. T. 1996. Shallow clastic seas. *In:* Reading, H. G (ed.) *Sedimentary environments and facies*, 232- 277. Blackwell Scientific Publications, Oxford.

Jongman, R. H. G., Ter Braak, C. J. F. & Van Tongeren, O. F. R. 1995. *Data analysis in Community and landscape ecology*. Cambridge University Press

Jorgensen, P. & Fielding, C. R. 1996. Facies architecture of alluvial floodbasin deposits: three-dimensional data from the Upper Triassic Callide Coal Measure of east-central Queensland, Australia. *Sedimentology*, **43**, 479-495.

Karowe, A. L. & Jefferson, T. H. 1987. Burial of trees by eruptions of Mount St Helens, Washington: implications for the interpretation of fossil forests. *Geological Magazine*, **124(3)**, 191-204.

Kelly, S. R. A. 1993. Biofacies and biostratigraphic constraints on regression in the uppermost Fossil Bluff Group (Aptian-Albian), Alexander Island, Antarctica. *In*: Findley, Unrug, Banks & Veevers (eds.), *Gondwana Eight*, 425-437. Balkema, Rotterdam.

Kelly, S. R. A. & Moncrieff, A. C. M. 1992. Marine molluscan constraints on the age of Cretaceous fossil forests of Alexander Island, Antarctica. *Geological Magazine*, **129(6)**, 771-778.

Kemp, R. A. 1985. Soil micromorphology and the Quaternary. *Quaternary Research Association Technical Guide*, **2**, Cambridge.

Kennedy, E. M., Spicer, R. A. & Rees, P. M. 2002. Quantitative palaeoclimate estimates from Late Cretaceous and Paleocene leaf floras in the northwest of the South Island, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **184**, 321-345.

Kershaw, P. & Wagstaff, B. 2001. The southern conifer family Araucariaceae: History, status and value for paleoenvironmental reconstruction. *Annual Review of Ecology and Systematics*, **32**, 397-414.

Khan, I. A., Bridge, J. S., Kappelman, J. & Wilson, R. 1997. Evolution of Miocene fluvial environments, eastern Potwar plateau, northern Pakistan. *Sedimentology*, **44**, 221-251.

Kraüsel, R. 1949. Identification key for genera and species of identifiable fossil conifer woods. *Palaeontographica*, **89B(94)**, 150-189. Translated extracts by C.R. Hill.

Kuenzi, W. D., Horst, O. H. & McGehee. 1979. Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala. *Bulletin of the Geological Society of America*, **90**, 827-838.

Lawver, L. A. & Gahagan, L. M., 1998. Opening of the Drake Passage and its impact on Cenozoic ocean circulation. *In*: Crowley, T. J. & Burke, K. C. (eds.), *Tectonic boundary conditions for climate reconstructions'*. Oxford Monographs on Geology and Geophysics, **39**, 212-223.

Lawver, L. A., Sclater, J. G. & Meinke, L. 1985. Mesozoic and Cenozoic reconstructions of the South Atlantic. *Tectonophysics*, **114 (1-4)**, 233-254.

List, R. J. 1963. Smithsonian Meteorological Tables. *Smithsonian Miscellaneous Collection*, **114**, 442-520. Publication 4014 of the Smithsonian Institute, Washington.

Macdonald, D. I. M. 1993. Controls on sedimentation at convergent plant margins. *In*: Frostick, L. & Steel, R. (eds.), *Tectonic controls and signatures in sedimentary successions*. Special Publications of the International Association of Sedimentologist, **20**, 225-257.

Macdonald, D. I. M., Leat, P. T., Doubleday, P. A. & Kelly, S. R. 1999. On the origin of fore-arc basins: new evidence of formation by rifting from the Jurassic of Alexander Island, Antarctica. *Terra Nova*, **11**, 186-193.

McLoughlin, S. 1996. Early Cretaceous macrofloras of Western Australia. *Records of the Western Australian Museum*, **18**, 19-65.

McLoughlin, S. 2001. The break-up history of Gondwana and its impact on pre-Cenozoic floristic provincialism. *Australian Journal of Botany*, **49**, 271-300.

McLoughlin, S. & Hill, R. S. 1996. The succession of Western Australian Phanerozoic terrestrial floras. *In*: Hooper *et al.* (eds.) *Gondwana Heritage: Past, present and future of the Western Australian Biota,* 61-80. Surrey Beatty & Sons, Chipping Norton.

McLoughlin, S., Drinnan, A. N. & Rozefelds, A. C. 1995. A Cenomanian flora from the Winton Formation, Eromanga Basin, Queensland, Australia. *Memoirs of the Queensland Museum*, **38(1)**, 273-313.

McLoughlin, S., Tosolini, A. P. & Drinnan, A. N. 2000. Revision of an Early Cretaceous macroflora from the Maryborough Formation, Maryborough Basin, Queensland, Australia. *Memoirs of the Queensland Museum*, **45(2)**, 483-503.

Miall, A. D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1-62.

Miall, A. D. 1978. Lithofacies types and vertical profile models in braided river deposits: A summary. *In*: Miall, A. D. (ed.) *Fluvial Sedimentology*. Canadian Society of Petroleum Geologists, **5**, 597-603.

Miall, A. D. 1992. Alluvial Deposits. *In*: Walker, R. G. & James, N. P. (eds.) *Facies models: response to sea level change*. Geological Association of Canada, 119-142.

Midgley, J. J., Bond, W. J. & Geldenhuys, C. J. 1995. The ecology of Southern African conifers. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 164 – 80. Melbourne University Press.

Mildenhall, D. C. 1976. Early Cretaceous *Podocarp megastrobilus* (note). *New Zealand Journal of Geology and Geophysics*, **19**, 389-391.

Miyashiro, A. 1994. *Metamorphic Petrology*, 264-274. London, UCL Press.

Moncrieff, A. C. M. 1989. *Field report of sedimentological studies in southeastern Alexander Island, Antarctica 1988/1989.* British Antarctic Survey Field Report, AD6/2R/1988/G4.

Moncrieff, A. C. M. & Kelly, S. R. A. 1993. Lithostratigraphy of the uppermost Fossil Bluff Group (early Cretaceous) of Alexander Island, Antarctica: history of an Albian regression. *Cretaceous Research*, **14**, 1-15.

Moore, D. M. & Reynolds, R. C. 1997. *X-ray diffraction and the identification of clay minerals.* Second Edition. Oxford University Press, Oxford.

Neiburger, M. 1982. *In*: Neiburger, M., Edinger, J. G. & Bonner, W. D. *Understanding our atmospheric environment* Second Edition. W. H. Freeman, San Francisco.

Nichols, G. J. & Cantrill, D. J. 2002. Tectonic and climatic controls on a Mesozoic forearc basin succession, Alexander Island, Antarctica. *Geological Magazine*, **139 (3)**, 313-330.

Niklas, K. J. 1994. Predicting the height of fossil plant remains: an allometric approach to an old problem. *American Journal of Botany*, **81**, 1235-1243.

Nilsson, S.G., Niklasson, M., Hedin, J., Aronsson, G., Gutowski, J.M., Linder, P., Ljungberg, H., Mikusinski, G. & Ranius, T. 2003. Densities of large living and dead trees in old-growth temperate and boreal forests. *Forest Ecology and Management*, **178 (3)**, 353-360.

Ogden, J. & Stewart, G. H. 1995. Community dynamics of New Zealand conifers. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 81 – 119. Melbourne University Press.

Osborne, C. P. & Beerling, D. J. 2002. Sensitivity of tree growth to a high CO2 environment: consequences for interpreting the characteristics of fossil woods from ancient 'greenhouse' worlds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **182(1-2)**, 15-29.

Otto-Bliesner, B. L. & Upchurch, G. R. 1997. Vegetation-induced warming of high-latitude regions during the Late Cretaceous period. *Nature*, **385**, 804-807.

Parrish, J. T., Daniel, I. L., Kennedy, E. M. & Spicer, R. A. 1998. Palaeoclimatic significance of mid-Cretaceous floras from the Middle Clarence Valley, New Zealand. *Palaios*, **13**, 149-159.

Pole, M. 1999. Structure of a near-polar latitude forest from the New Zealand Jurassic. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **147**, 121-139.

Pritchett, W. L. & Fisher, R. F. 1987. *Properties and management of forest soils*, 35-55. John Wiley & Sons, New York.

Pryor, J. S. & Gastaldo, R. A. 2000 Paleoecological analysis of two early Pennsylvanian mineral-substrate Wetlands. *Palaios*, **15 (1)**, 3-13.

Read, J. & Francis, J. 1992. Responses of some Southern Hemisphere tree species to a prolonged dark period and their implications for high-latitude Cretaceous and Tertiary floras. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **99**, 271-290.

Reading, H. G. 1996. *Sedimentary environments and facies.* Blackwell Scientific Publications, Oxford.

Reading, H. G. & Collinson, J. D. 1996. Clastic Coasts. *In:* Reading, H. G (ed.) *Sedimentary environments and facies*, 154- 228. Blackwell Scientific Publications, Oxford.

Rees, P. M. & Smellie, J. L. 1989. Cretaceous angiosperms from allegedly Triassic flora of Williams Point, Livingston Island, South Shetland Islands. *Antarctic Science*, **1**, 239-248.

Reid, I. & Frostick, L. E. 1994. Fluvial sediment transport and deposition. *In*: Pye, K. (ed.) *Sediment transport and depositional processes,* 89-155. Blackwell Scientific Publications, Edinburgh, United Kingdom.

Retallack, G. J. 2001. *Soils of the past; An introduction to paleopedology*, Second Edition. Blackwell Science.

Romero, E. J. & Archangelsky, S. 1986. Early Cretaceous angiosperm leaves from southern South America. *Science*, **234**,1580-1582.

Rowntree, K. M. & Dollar, E. S. J. 1999. Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. *Earth Surface Processes and Landforms*, **24(2)**, 127-134.

Royer, D. L., Osborne, C. P. & Beerling, D. J. 2003. Carbon loss by deciduous trees in a CO2-rich ancient polar environment. *Nature*, **424(6944)**, 60-62.

Schumm, S. A. 1977. *The Fluvial System*, 388. John Wiley and Sons, Chichester, England.

Shi, G. R. 1993. Multivariate data analysis in palaeoecology and palaeobiology – a review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **105**, 199-234.

Sigleo, A. C. 1979. Geochemistry of silicified wood and associated sediments, Petrified Forest National Park, Arizona. *Chemical Geology*, **26**, 151-163.

Smellie, J. L. 1981. A complete arc-trench system recognised in Gondwana sequences of the Antarctic Peninsula region. *Geological Magazine*, **118(2)**, 139-159.

Smith, D. G. 1983. Anastomosed fluvial deposits; examples from Western Canada. *In*: Collinson, J. D. & Lewin, J. (eds.) *Modern and Ancient Fluvial Systems*. Special Publication of the International Assembly of Sedimentology, **6**, 155-168.

Smith, A. G., Smith, D. G. & Funnel, B. M. 1994. *Atlas of Mesozoic and Cenozoic coastlines*. Cambridge University Press, Cambridge.

Sobey, D. G. & Glen, W. M. 2002. The forests of Prince Edward Island: A classification and ordination using multivariate methods. *Canadian Field-Naturalist*, **116 (4)**, 585-602.

Soil Survey Staff, 1975. Soil Taxonomy, a basic system of soil classification for making and interpreting soil surveys. *Handbook, US Department of Agriculture* **436**.

Spicer, R. A. 1989. Reconstructing high-latitude Cretaceous vegetation and climate: Arctic and Antarctic Compared. *In*: Taylor, T. N. & Taylor, E. L. (eds.) *Antarctic Paleobiology: Its role in the reconstruction of Gondwana*. Springer- Verlag.

Spicer, R. A. & Parrish, J. T. 1990a. Late Cretaceous –early Tertiary palaeoclimates of northern high latitudes: a quantitative review. *Journal of the Geological Society, London*, **147**, 329-341.

Spicer, R. A. & Parrish, J. T. 1990b. Latest Cretaceous woods of the Central North Slope, Alaska. *Palaeontology*, **33(1)**, 225-242.

Spicer, R. A. & Herman, A. B. 2001. The Albian-Cenomanian flora of the Kukpowruk River, western North Slope, Alaska: stratigraphy, palaeofloristics and plant communities. *Cretaceous Research*, **22(1)**, 1-40.

Spicer, R. A., McA.Rees, P. & Chapman, J. L. 1993. Cretaceous phytogeography and climate signals. *Philosophical Transfers of the Royal Society, London*, **341**, 277-286.

Spicer, R. A., Ahlberg, A., Herman, A. B., Kelley, S. P., Raikevich, M. I & Rees, P. M. 2002. Palaeoenvironment and ecology of the middle Cretaceous Grebenka flora of northeastern Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **184**, 65-105.

Stone, E. C. & Vasey, R. B. 1968. Preservation of Coast Redwood on alluvial flats. *Science*, N.Y., **159**, 157-161.

Storey, B. C. 1996. Microplates and mantle plumes in Antarctica. *Terra Antarctica*, **3**, 91-102.

Storey, B. C. & Garrett, S. W. 1985. Crustal growth of the Antarctic Peninsula by accretion, magmatism and extension. *Geological Magazine*, **122(1)**, 5-14.

Storey, B. C., Carter, A., Doubleday, P. A., Hurford, A. J., Macdonald, D. I. M. & Nell P. A. R. 1996. Thermotectonic evolution of a Mesozoic-Cenozoic fore-arc region, Alexander Island, Antarctica: evidence from fission track analysis. *Journal of the Geological Society, London*, **153**, 65-82.

Suarez, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to southern Andes. *Geology*, 4(4), 211-214.

Sweeny, J. J. & Burnham, A. K. 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *The American Association of Petroleum Geologists Bulletin*, **74(10)**, 1559-1570.

Taylor, B. J., Thomson, M. R. A. & Willey, L. E. 1979. The geology of the Ablation Point-Keystone Cliffs area, Alexander Island. *British Antarctic Survey Scientific Reports*, **82**, 65.

Upchurch, G. R., Otto-Bliesner, G. R. & Scotese, C. 1998. Vegetation-atmosphere interactions and their role in global warming during the latest Cretaceous. *Philosophical Transfers of the Royal Society, London*, **353(1365)**, 97-111.

Vakhrameev, V. A. 1991. *Jurassic and Cretaceous Floras and climates of the Earth.* Cambridge University Press. Cambridge.

Valdes, P. J., Sellwood, B. W. & Price, G. D. 1996. Evaluating concepts of Cretaceous equability. *Palaeoclimates*, **2**, 139-158.

Vaughn, A. P. M. 1995. Circum-Pacific mid-Cretaceous deformation and uplift: A superplume related event? *Geology*, **23(6)**, 491-494.

Vaughn, A. P. M., Pankhurst, R. J. & Fanning, C. M. 2002. A mid-Cretaceous age for the Palmer Land event: implications for terrain accretion timing and Gondwana palaeolatitudes. *Journal of the Geological Society, London*, **159**, 113-116.

Veblen, T.T., Burns, B.R., Kitzberger, T., Lara, A. & Villalba, R. 1995. The ecology of the conifers of Southern South America. *In*: Enright, N. J. & Hill, R. S. (eds.), *Ecology of the southern conifers*, 120 – 155. Melbourne University Press.

Veevers, J. J., Powell, C. McA. & Roots, S. R. 1991. Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. *Australian Journal of Earth Sciences*, **38**, 373-389.

Velde, B. 1985. Clay minerals: A physico-chemical explanation of their occurrence. *In*: Velde, B. (ed.), *Developments in Sedimentology*, **40**. Elsevier Science Publishers, New York.

Walker, R. G. & Cant, D. J. 1984. Sandy Fluvial Systems. *In*: Walker, R.G. (ed.) *Facies Models, Second Edition*, 71-89. Geoscience Canada Reprint Series **1**.

Wardle, P. 1991. *Vegetation of New Zealand.* Cambridge University Press.

Wilding, L. P., Smeck, N. E. & Hall, G. F. 1983. Pedogenesis and soil taxonomy. *Developments in soil science*, **2**, 11B. Elsevier

Wolfe, J. A. 1993. A method of obtaining climatic parameters from leaf assemblages. U. S. *Geological Survey Bulletin*, **2040**, 1-73.

Appendix

Appendix **Pages**

Key to all sedimentary logs within Appendix 2. For descriptions of lithofacies and facies associations see Chapter 2. For locations see Figure 2.1, Chapter 2. For locality descriptions see Table A2.1, Appendix 2. For details on palaeosols numbered see Chapter 3 and Table A3.1, Appendix 3. For details on forest horizons numbered see Chapter 4. Unless otherwise stated a Jacobs Staff was used for all sedimentary logging within the field.

Lithology

⁚	Sandstone
▤	Mudstone
▒	Siltstone
▦	Interbedded sandstone and siltstone
V V V V V V V V	Volcanic tuff
/\	Missing strata

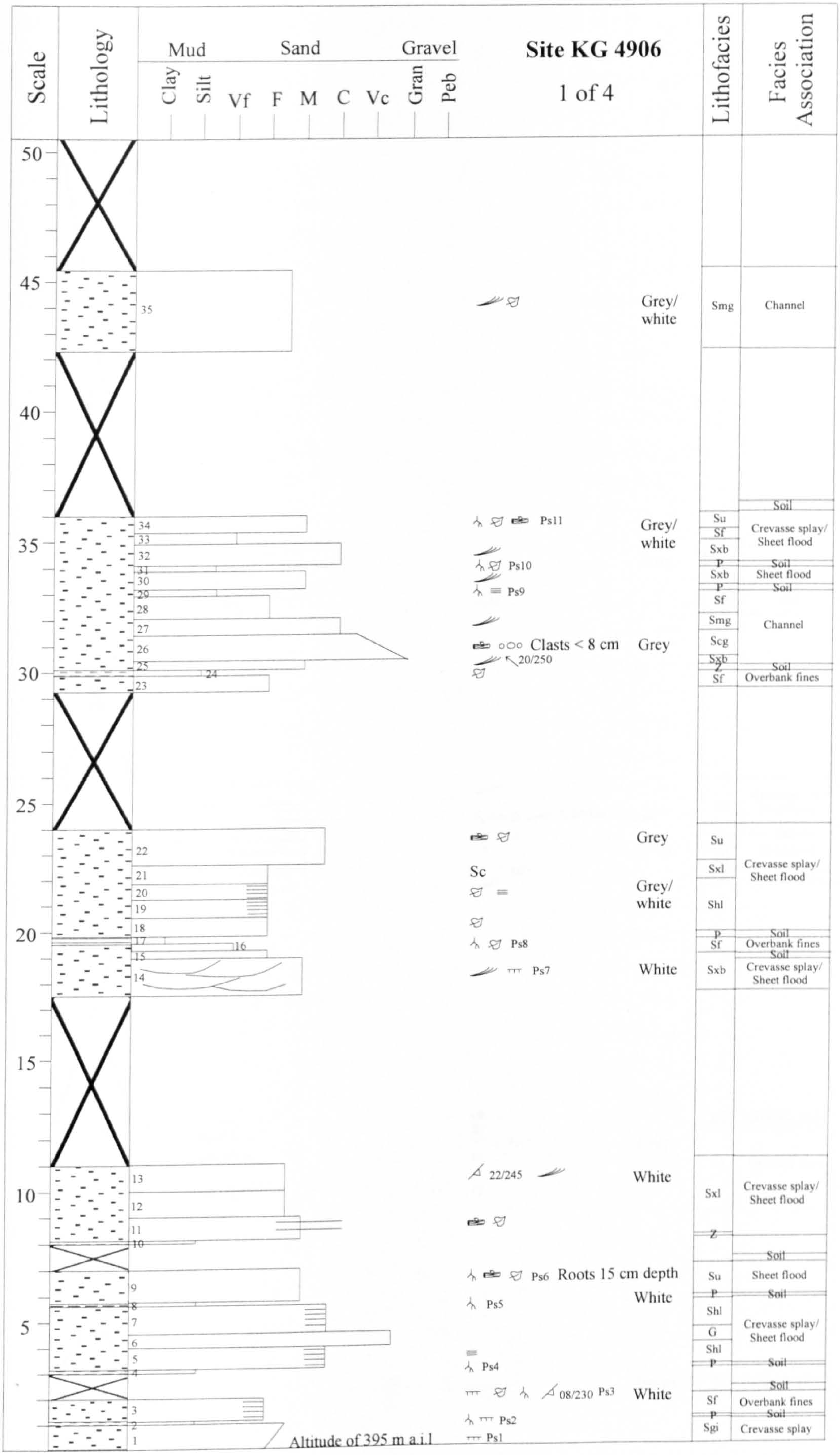
Bedding features

18	Bed number
▭ ─	Coarser bands within bed
∽	Undulating boundary
○○○	Concretions
≈	Extensive trough cross-bedding
≡	Thinly bedded

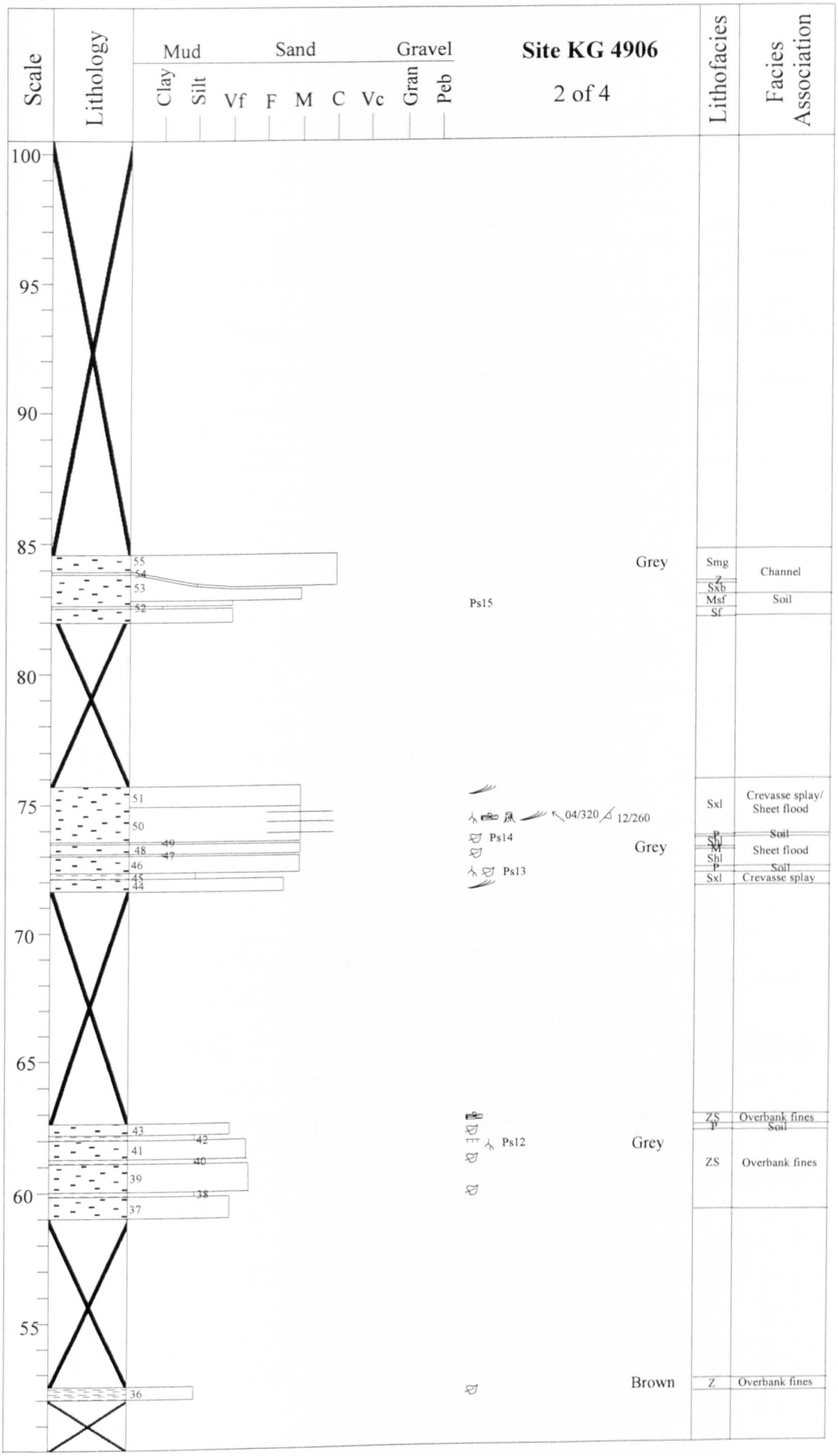
Other features

⊿ 22/245	Bedding Dip/strike	○◯○	Clasts
↖ 20/250	Palaeoflow dip/dip direction	∽	Ripples
Sc	Scour features	═	Horizontal laminations
F12	Forest floor horizon number 12	⫽	Cross bedding
Ps11	Palaeosol number 11	▭	Wood debris
ψ	Rootlets	┬┬┬	Ped features
♣	*In situ* fossilised tree	❦	Fossil plant material

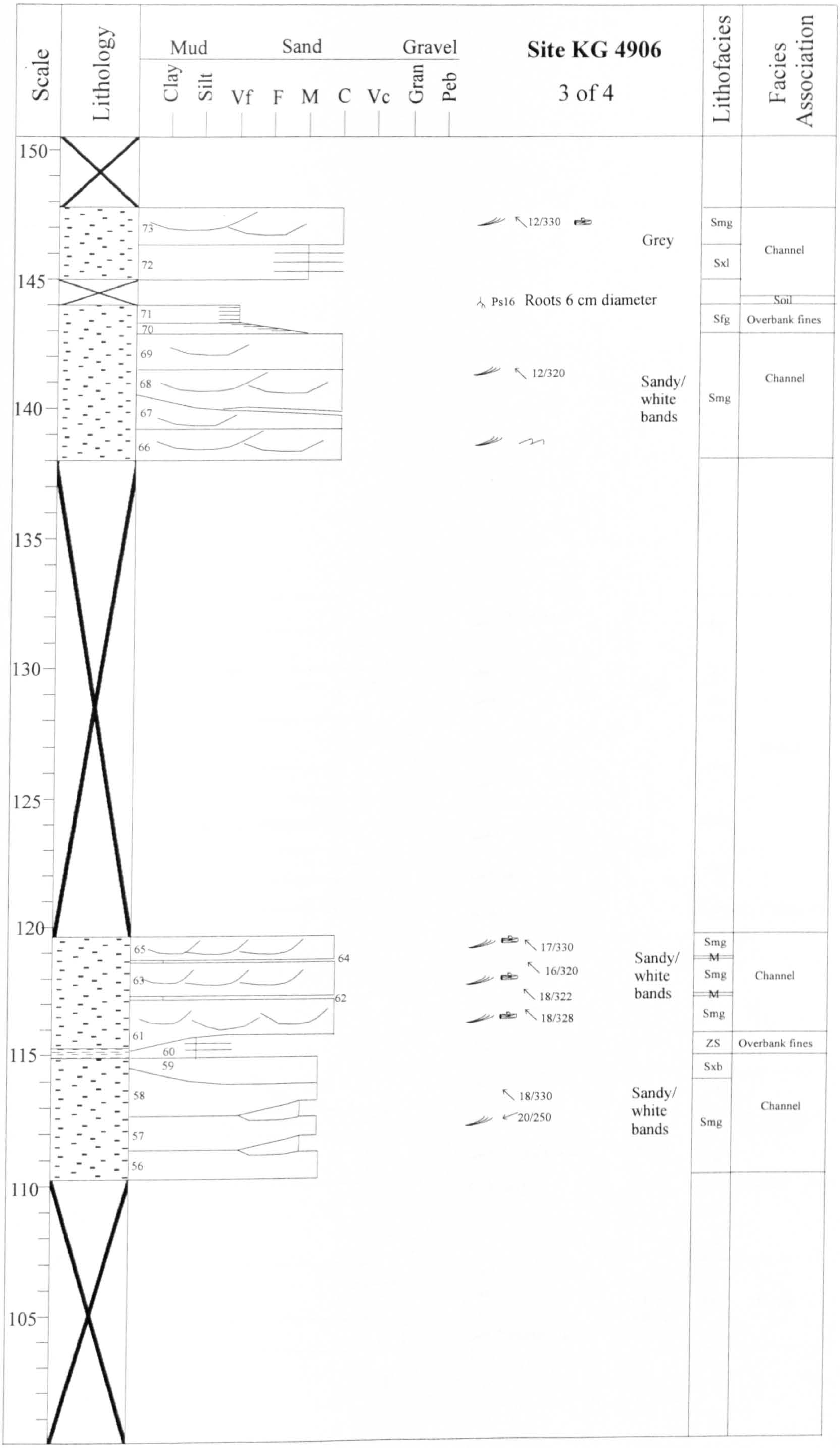
Appendix 2. Log 1, Citadel Bastion sedimentary log



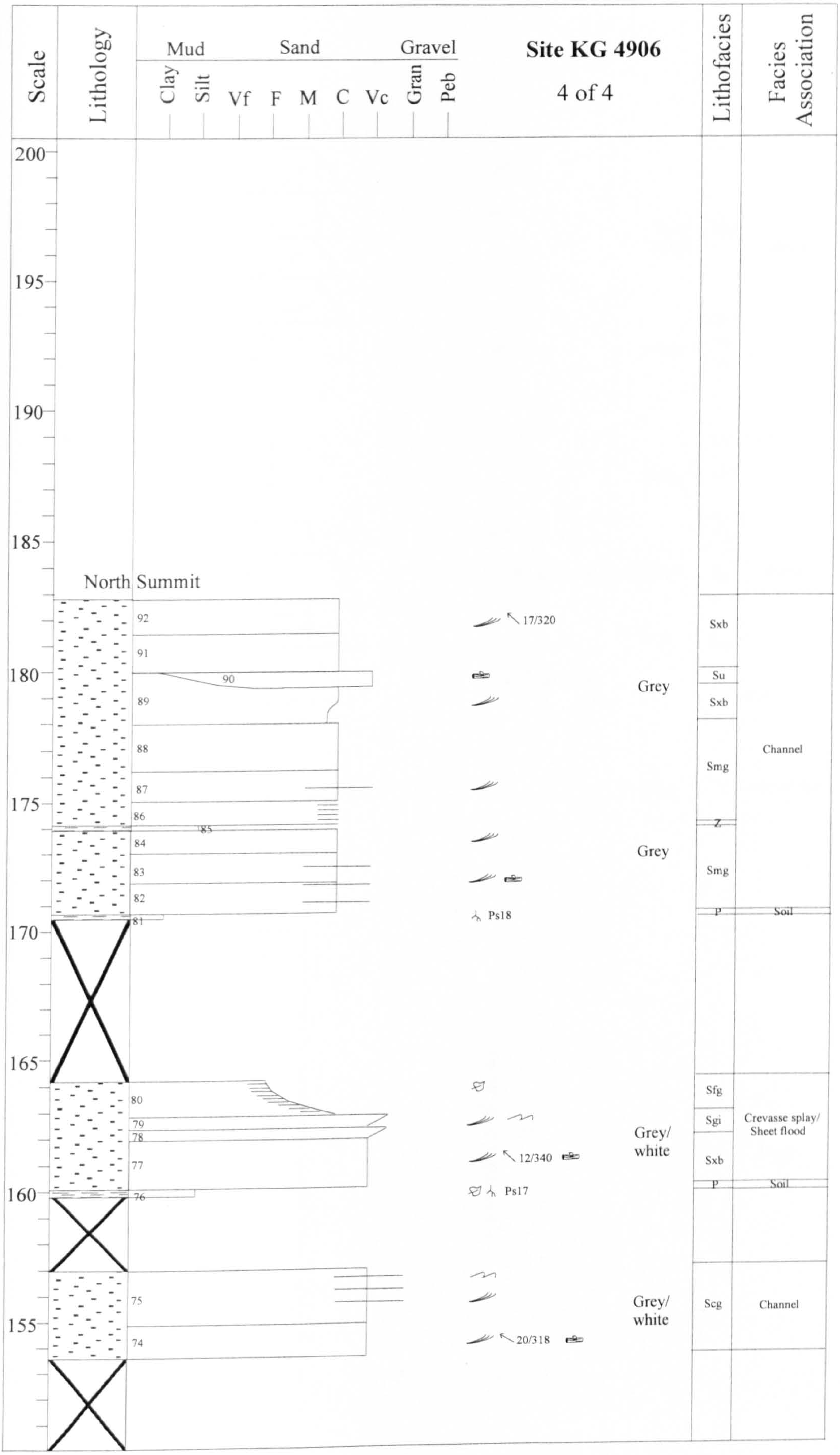
Appendix 2. Log 1, Citadel Bastion sedimentary log



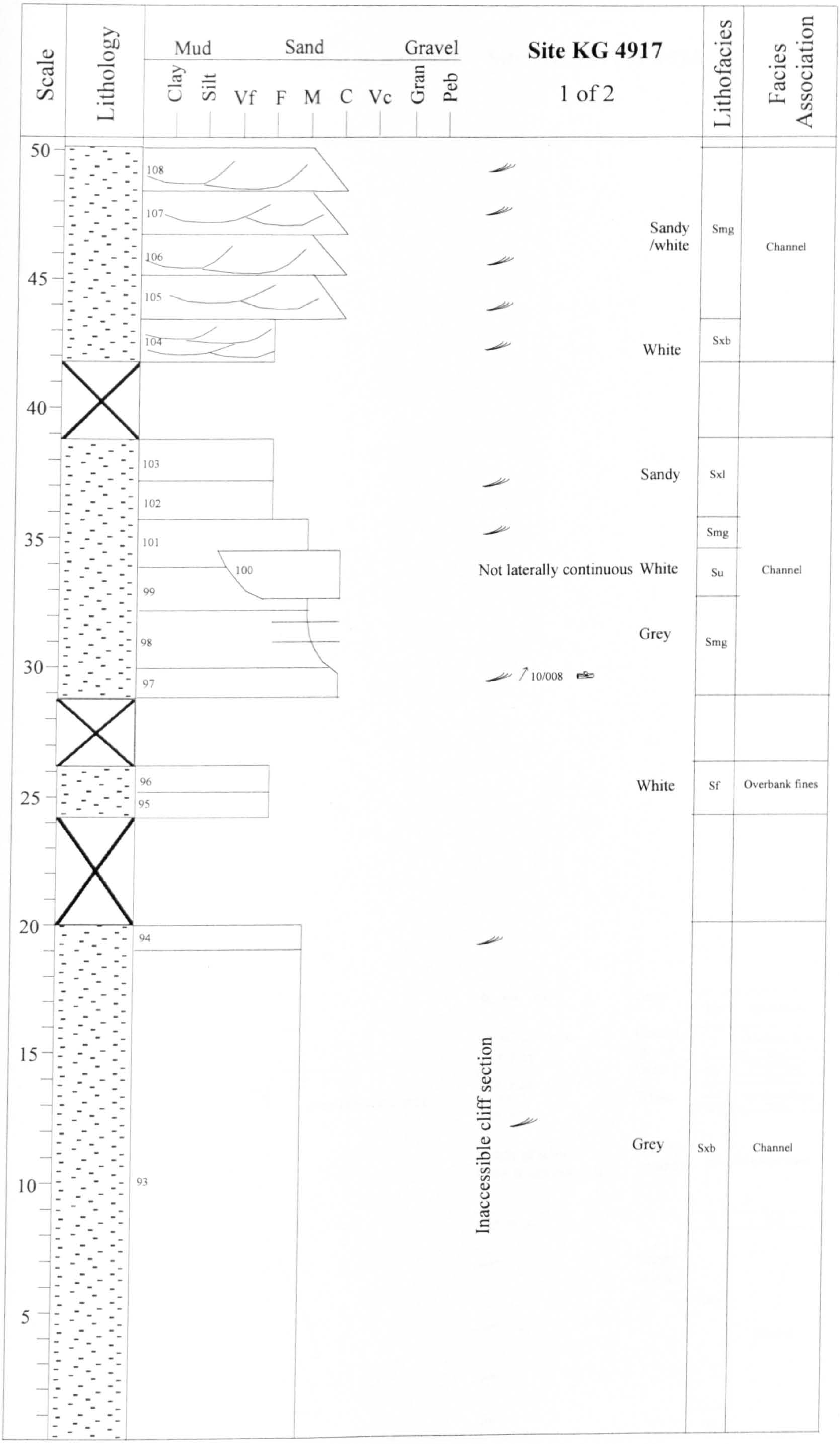
Appendix 2. Log 1, Citadel Bastion sedimentary log



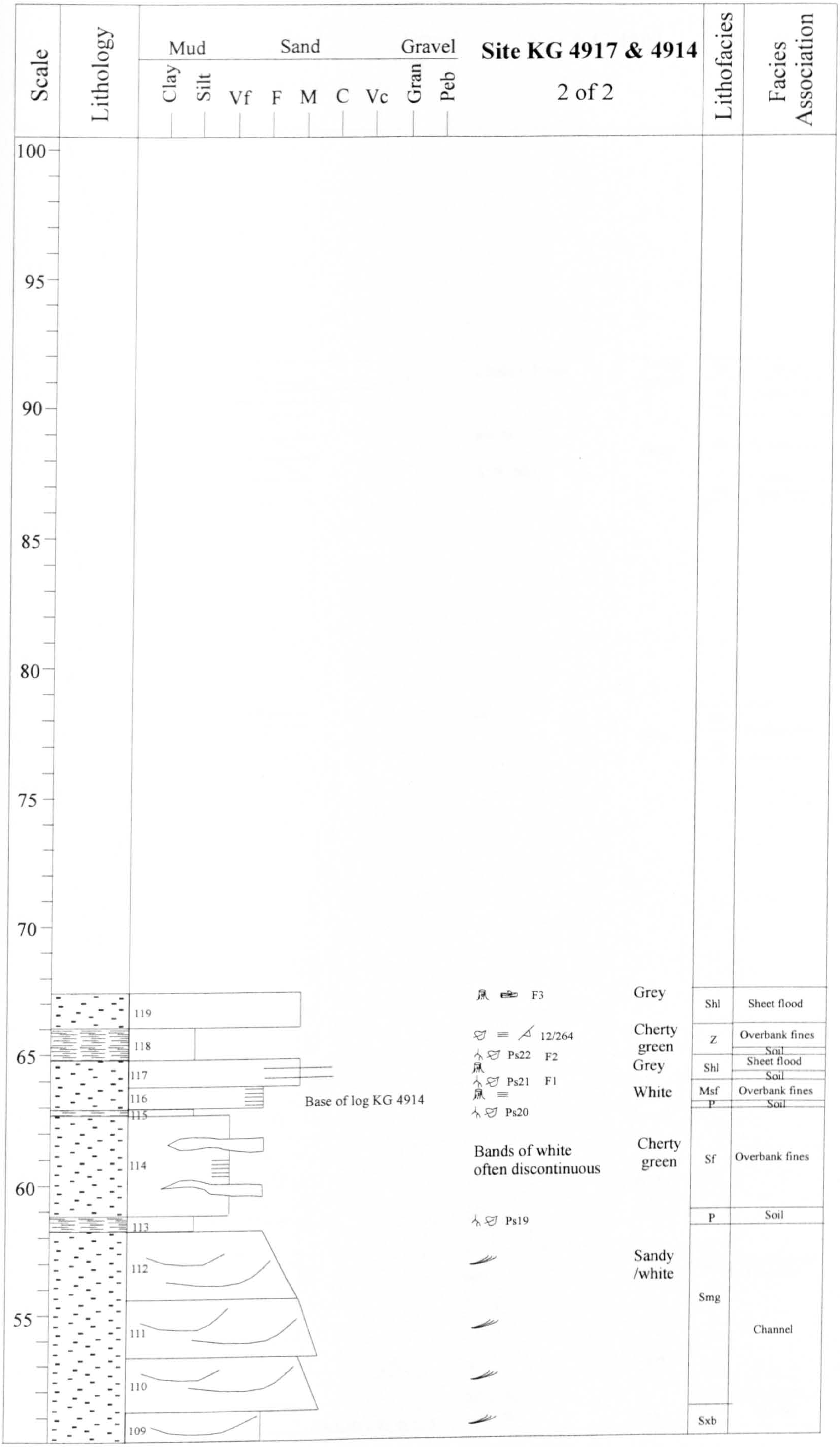
Appendix 2. Log 1, Citadel Bastion sedimentary log



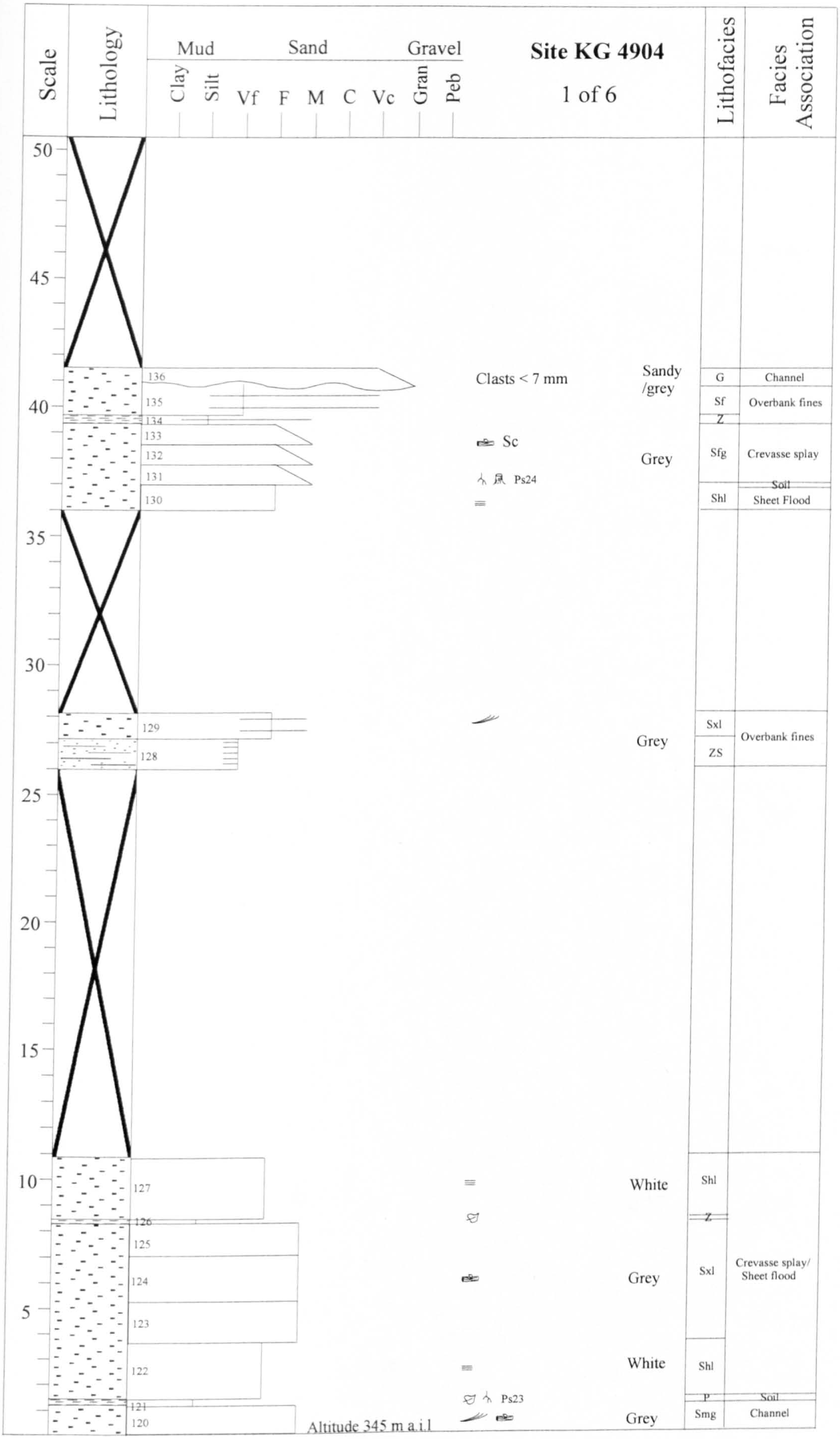
Appendix 2. Log 2 & 3, Citadel Bastion sedimentary log



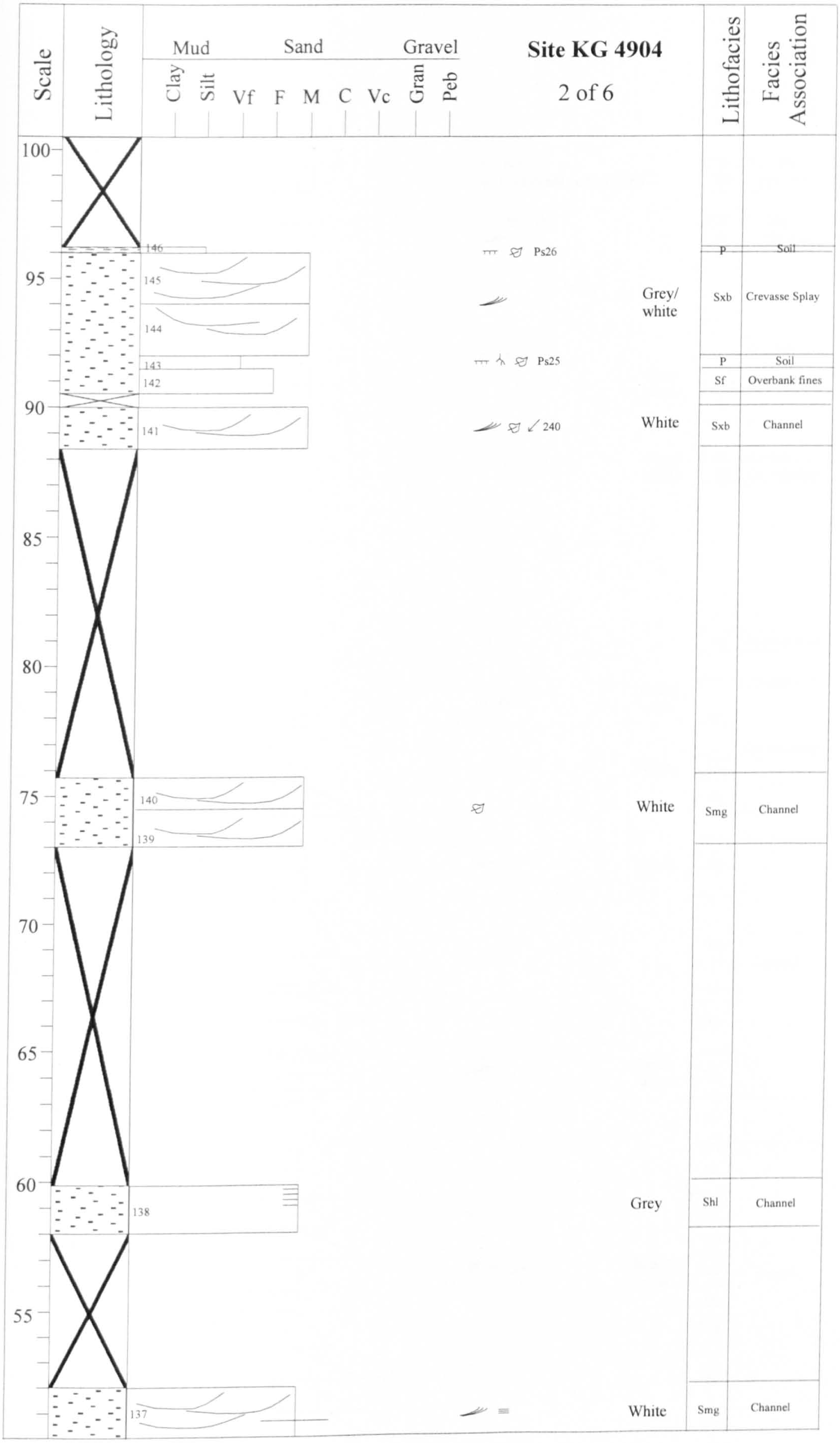
Appendix 2. Log 2 & 3, Citadel Bastion sedimentary log



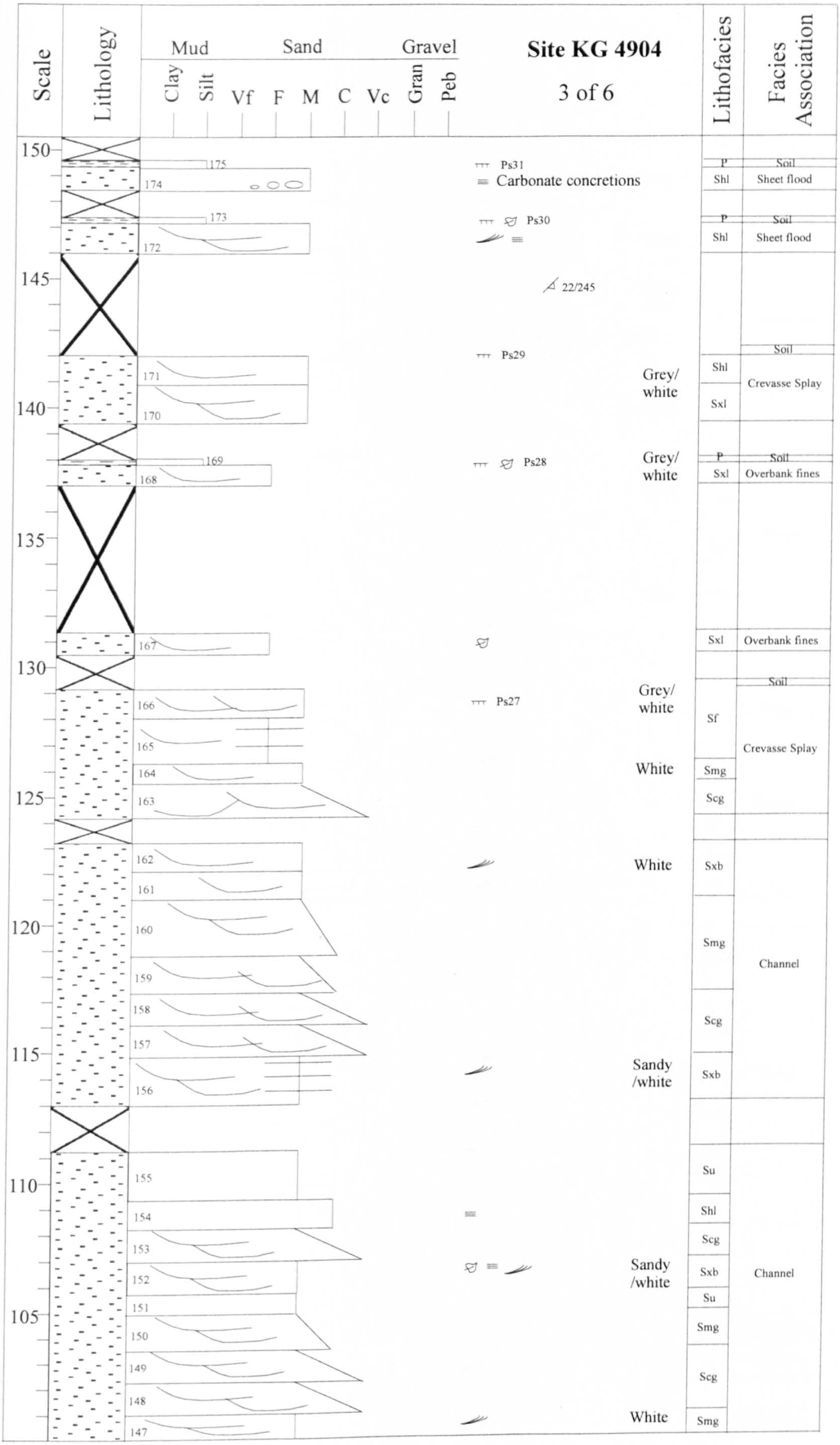
Appendix 2. Log 4, Citadel Bastion sedimentary log



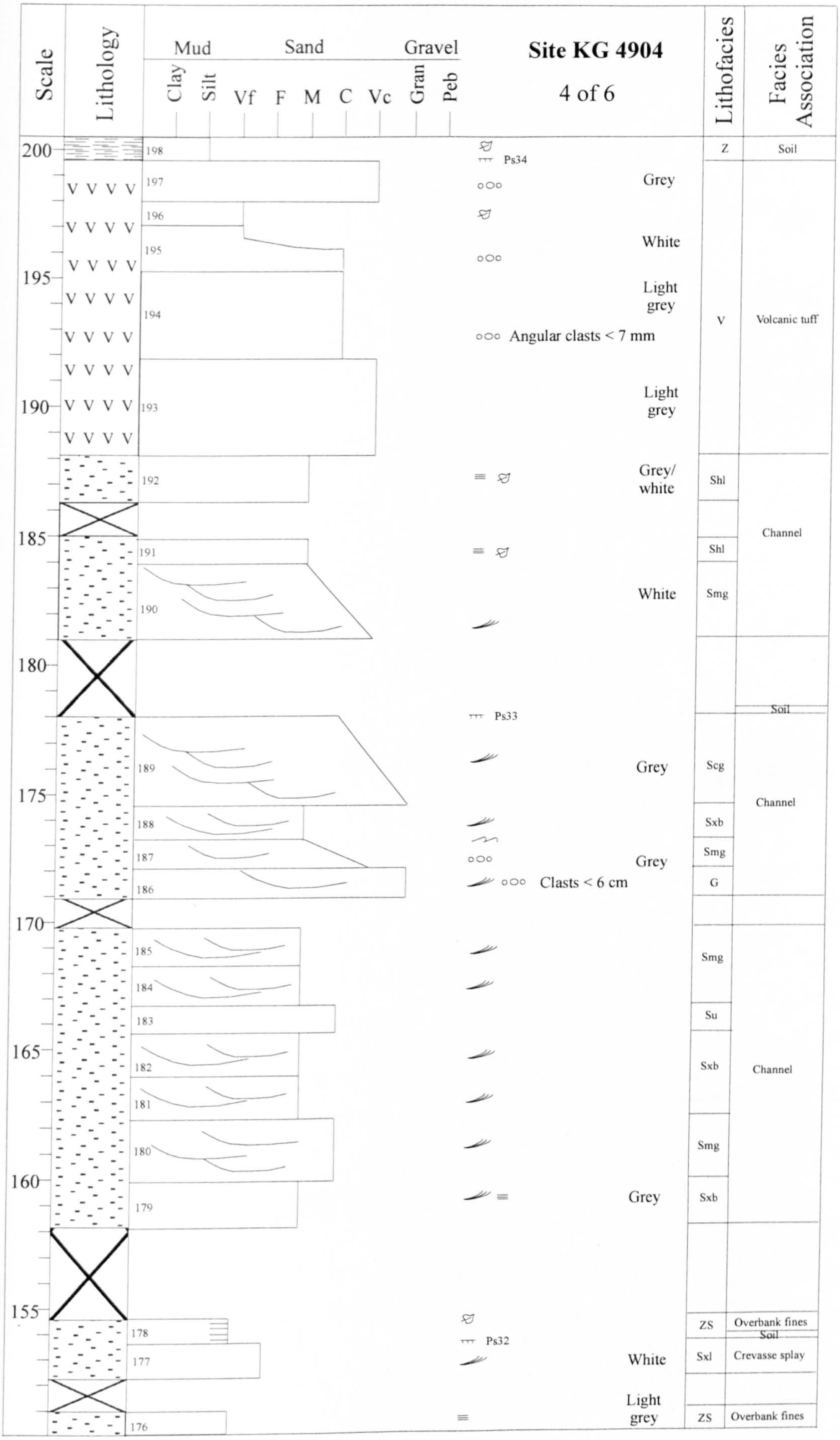
Appendix 2. Log 4, Citadel Bastion sedimentary log



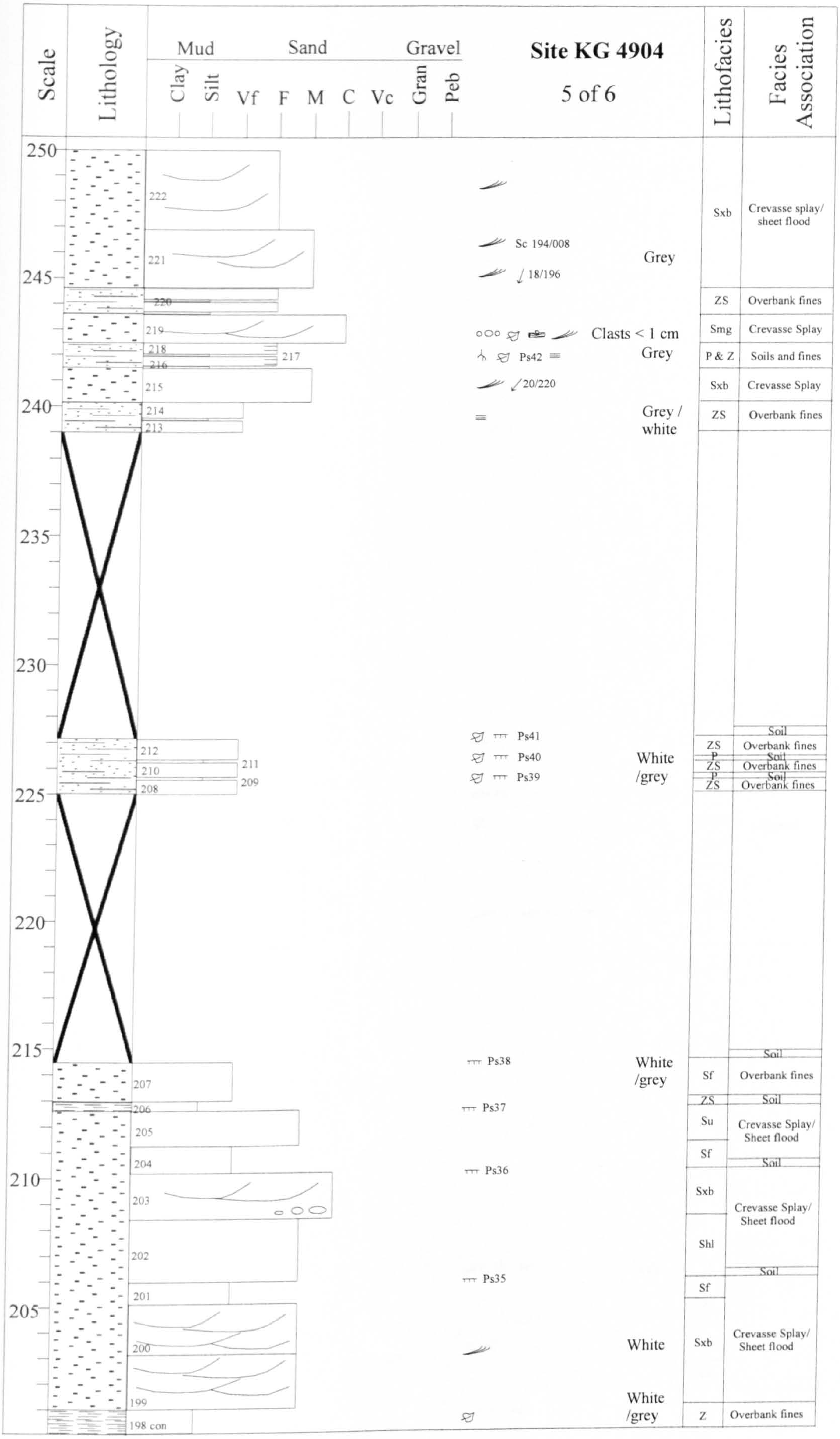
Appendix 2. Log 4, Citadel Bastion sedimentary log



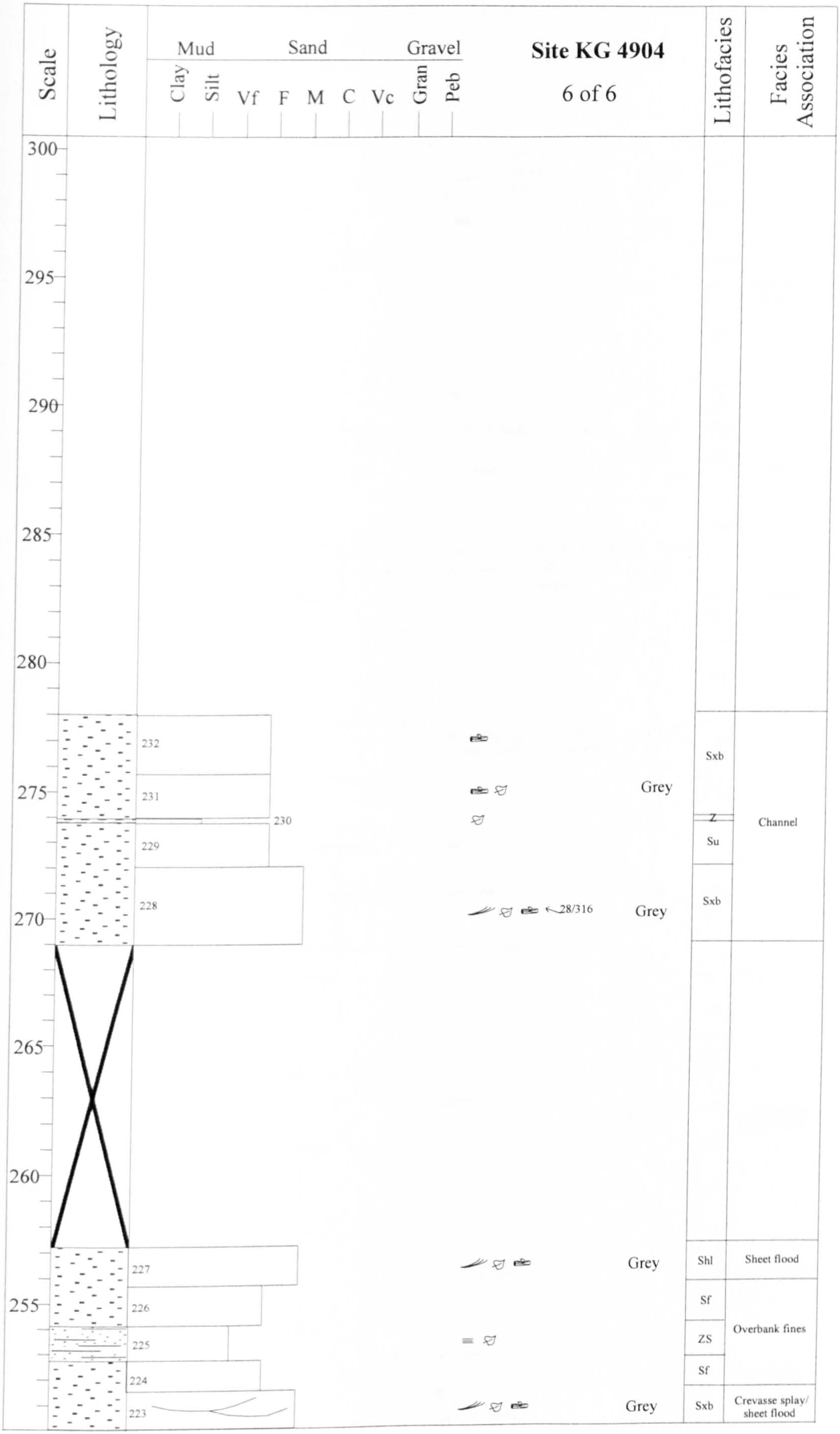
Appendix 2. Log 4, Citadel Bastion sedimentary log



Appendix 2. Log 4, Citadel Bastion sedimentary log

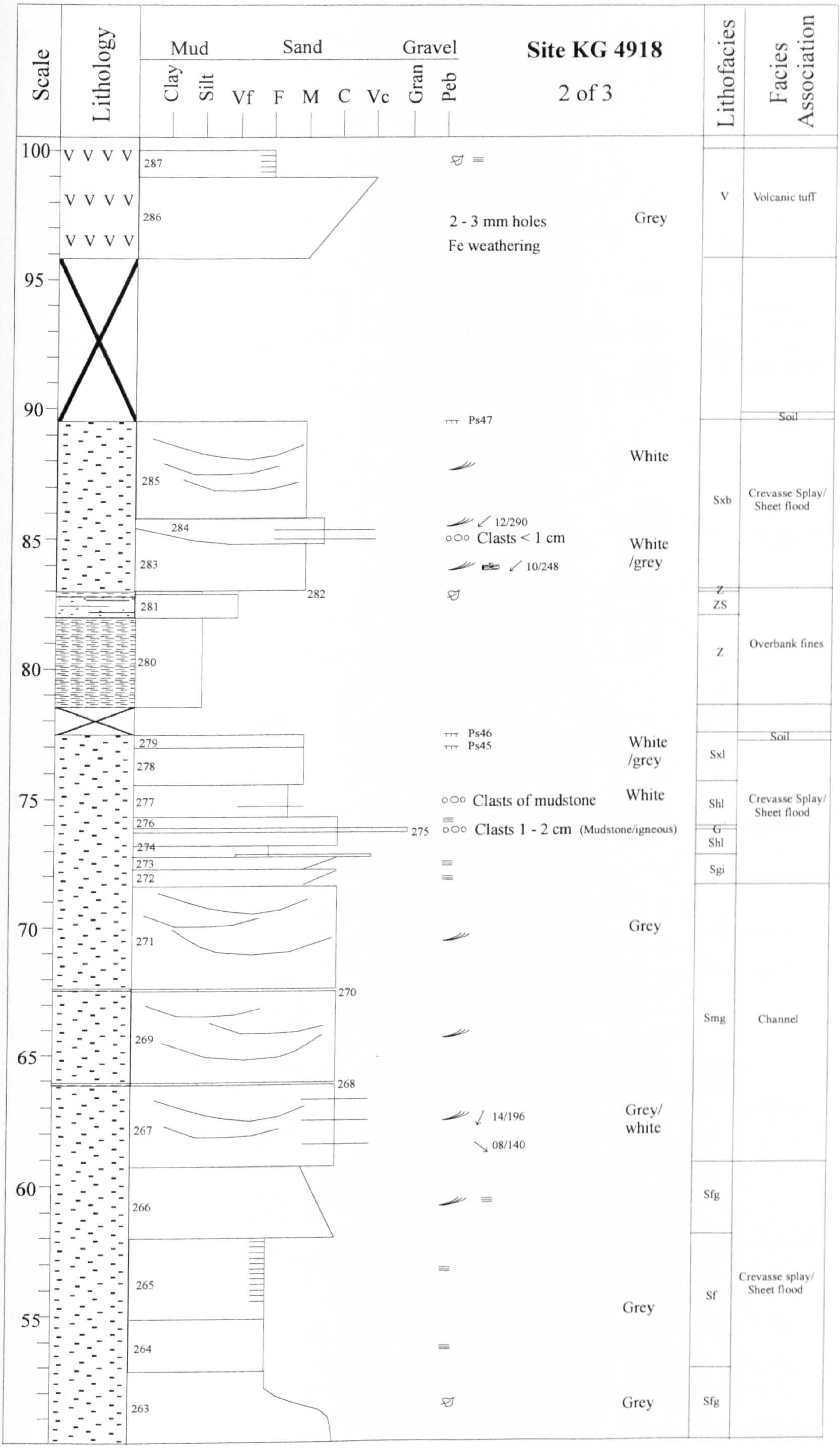


Appendix 2. Log 4, Citadel Bastion sedimentary log

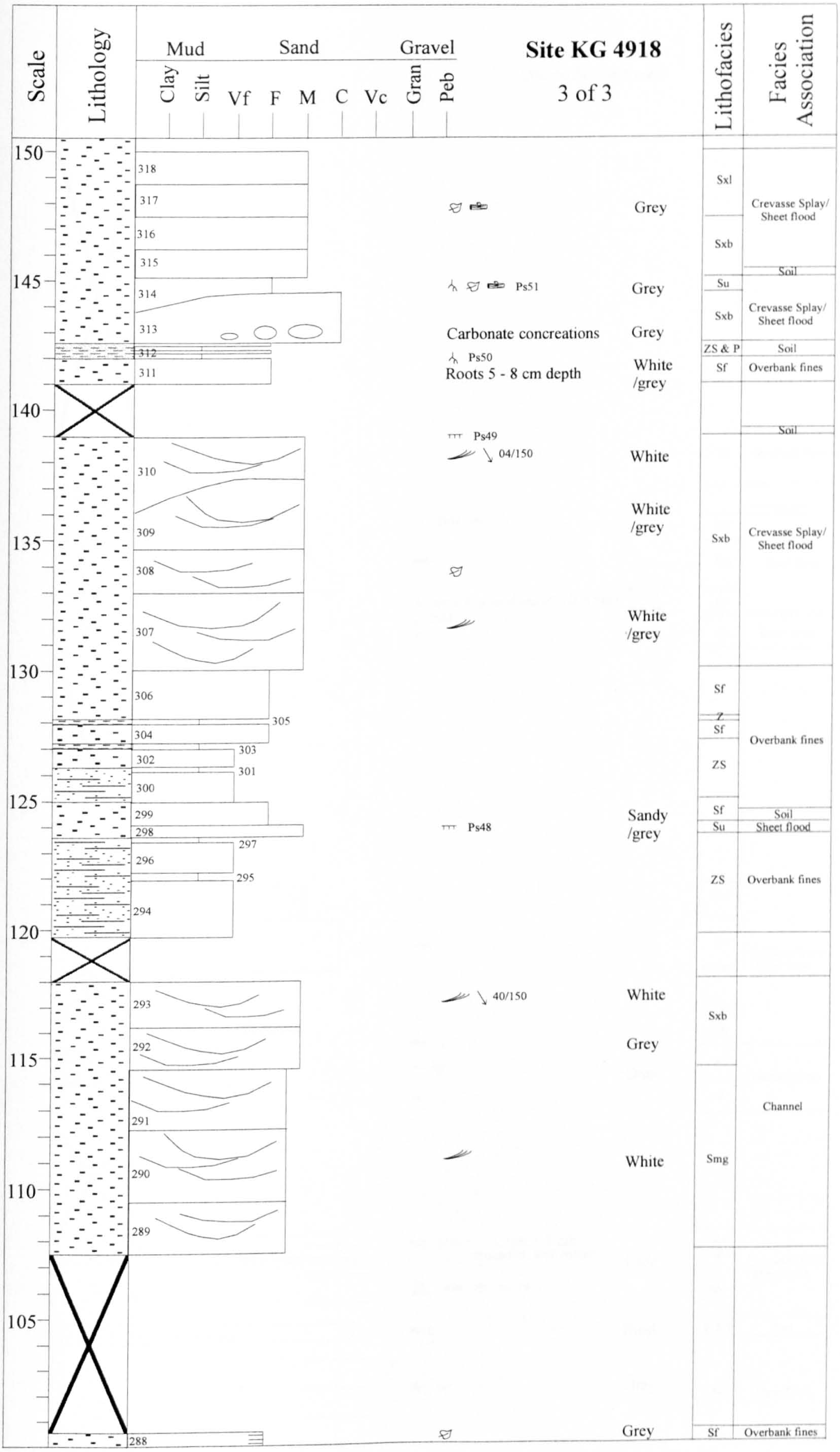


Appendix 2. Log 5, Citadel Bastion sedimentary log

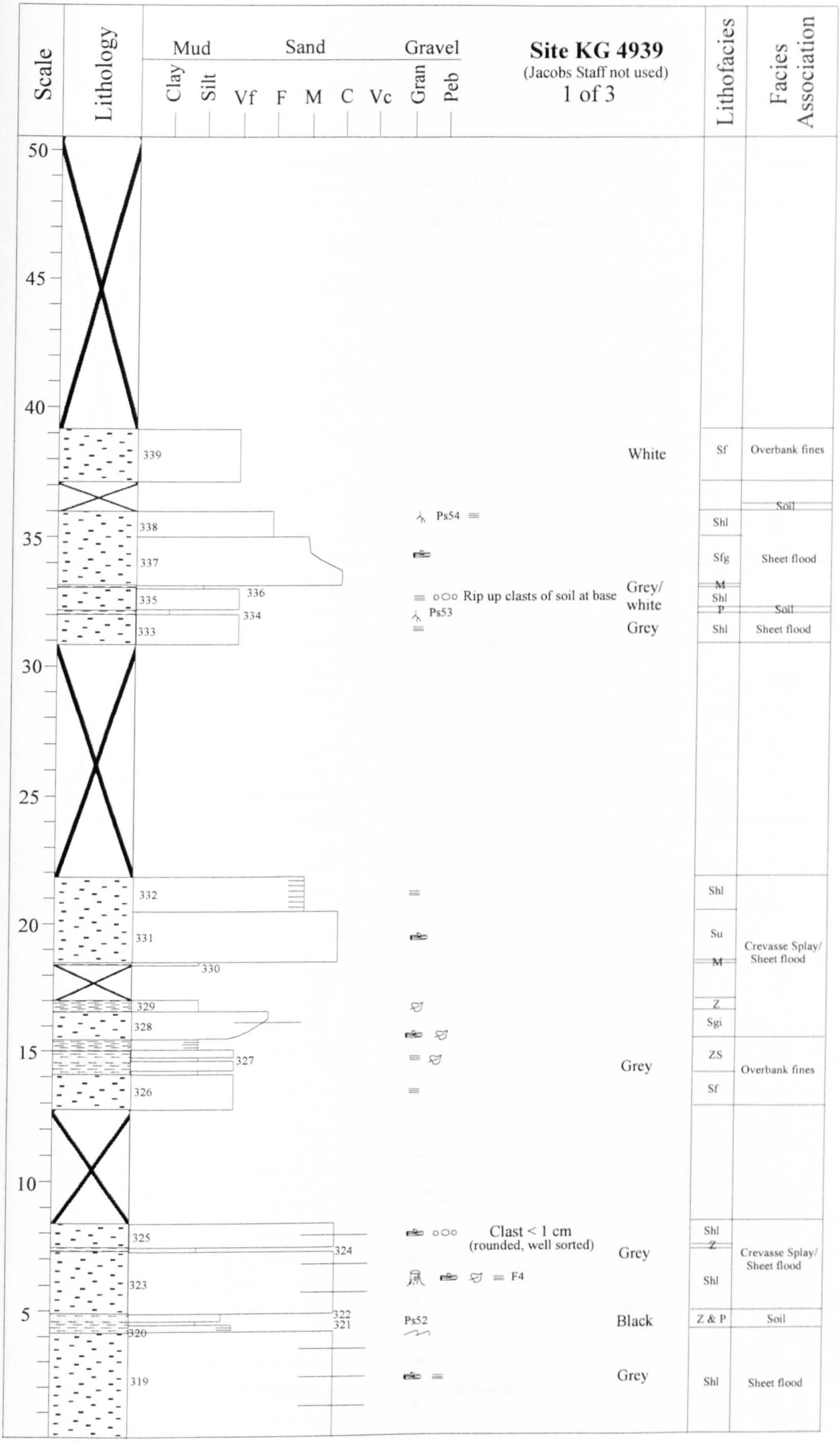
Appendix 2. Log 5, Citadel Bastion sedimentary log



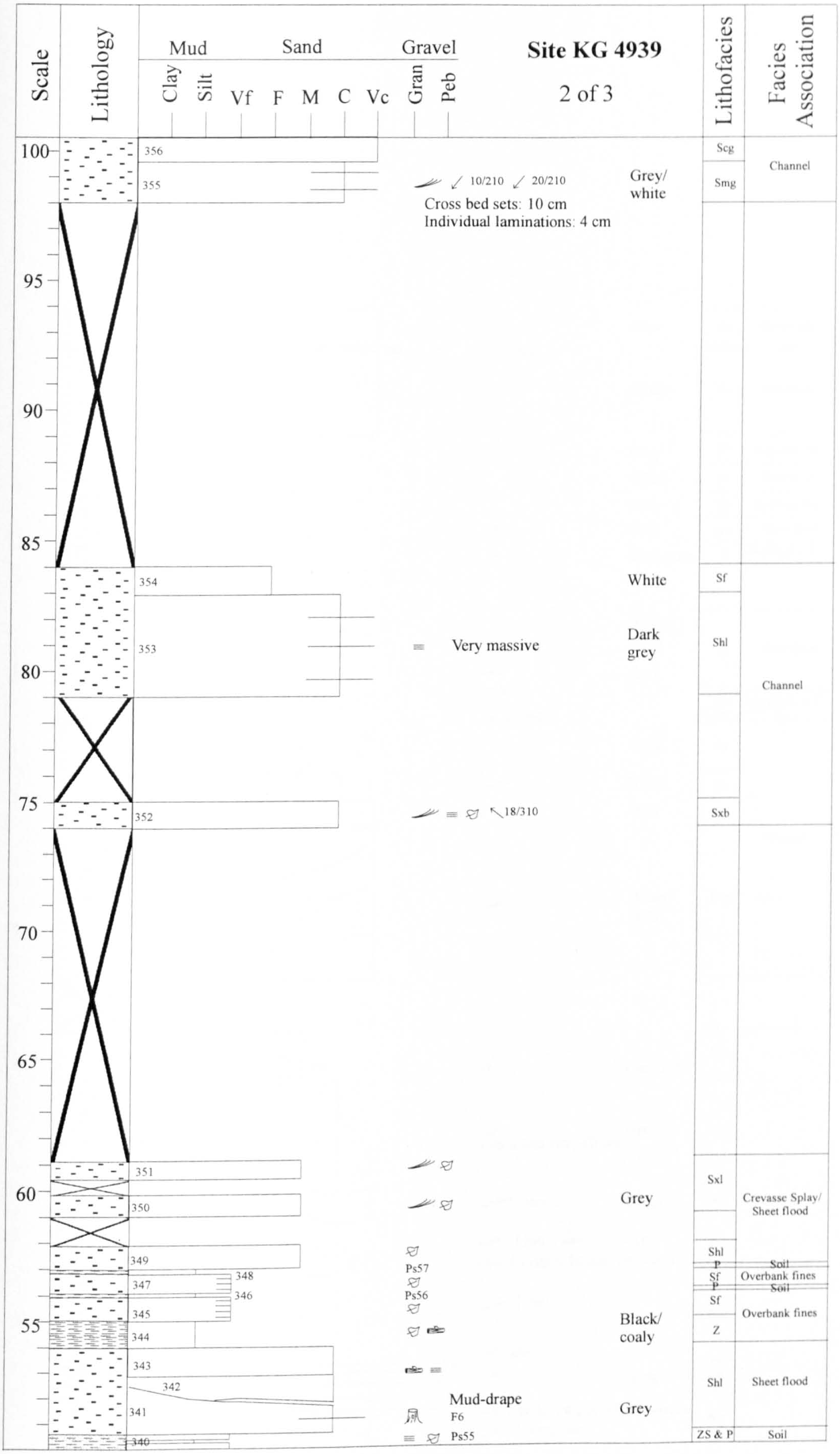
Appendix 2. Log 5, Citadel Bastion sedimentary log



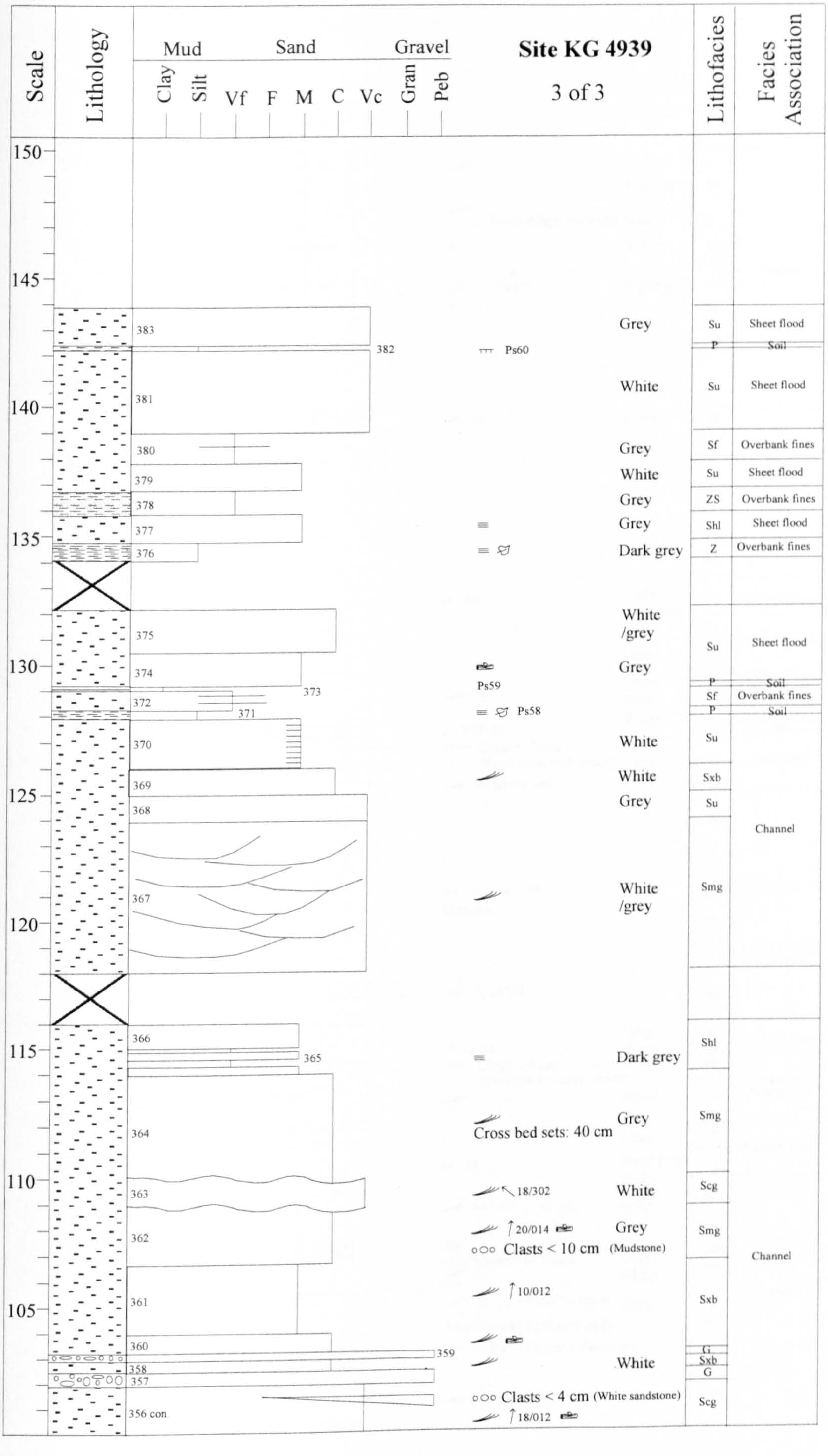
Appendix 2. Log 6, North Titan Nunatak sedimentary log



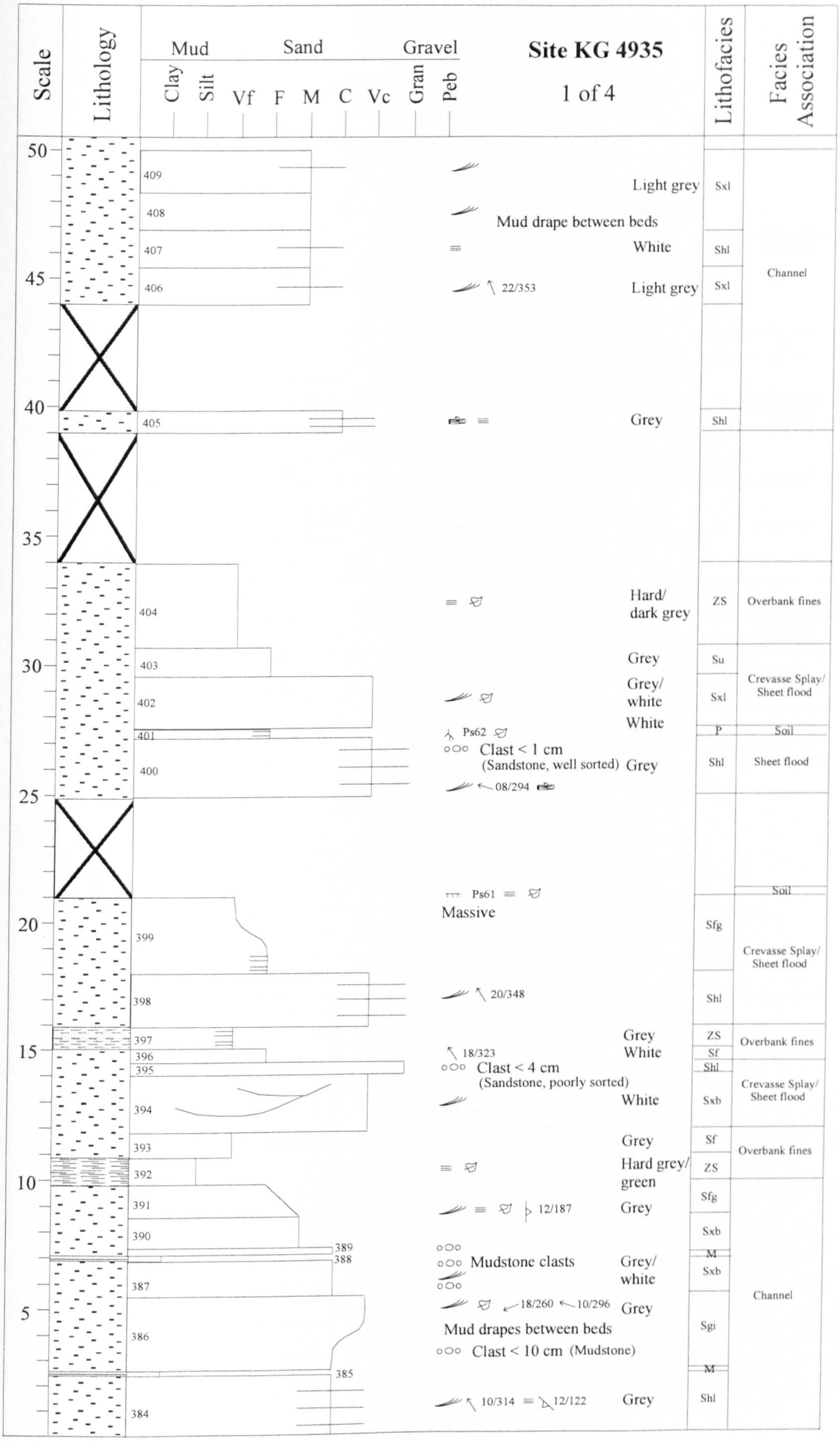
Appendix 2. Log 6, North Titan Nunatak sedimentary log



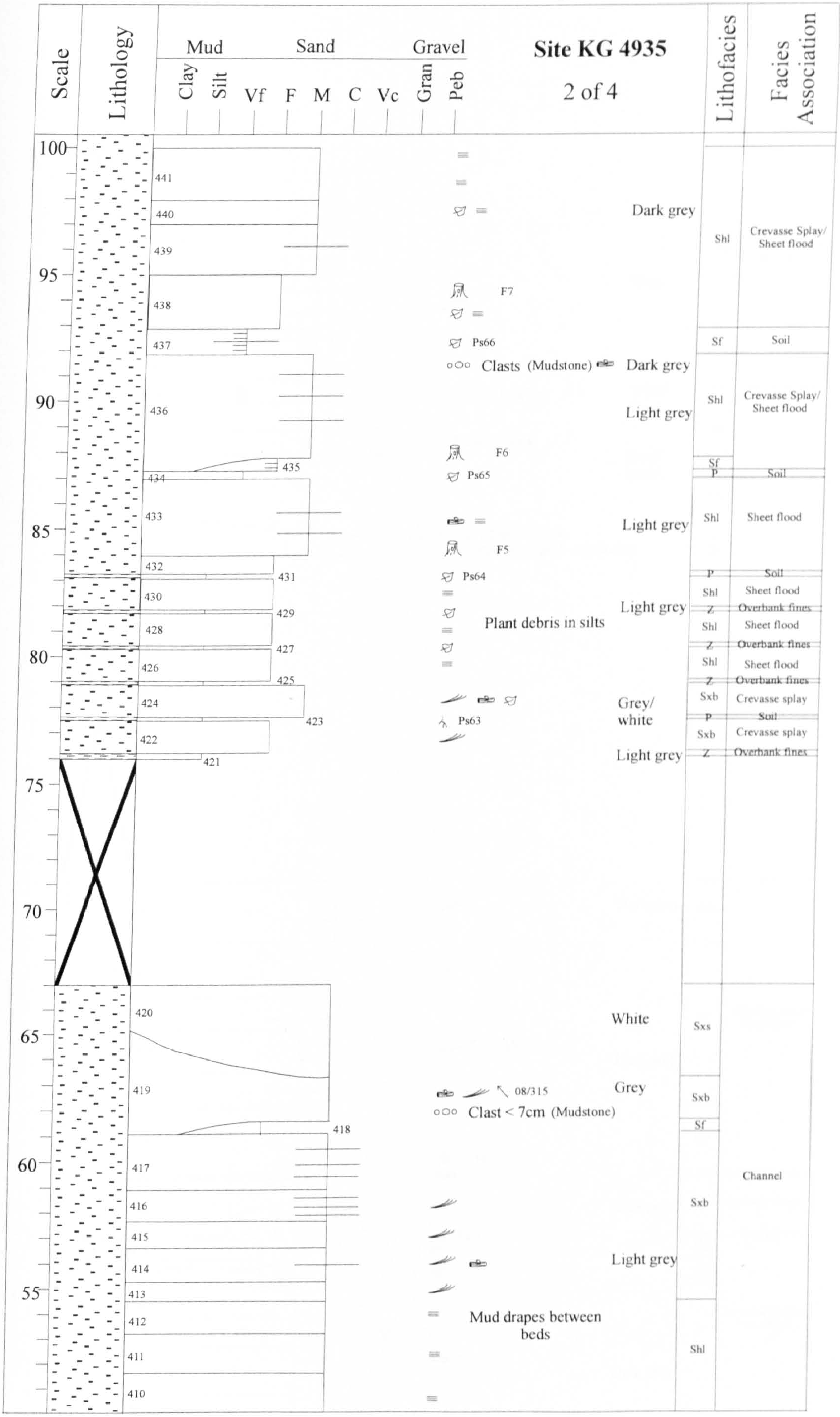
Appendix 2. Log 6, North Titan Nunatak sedimentary log



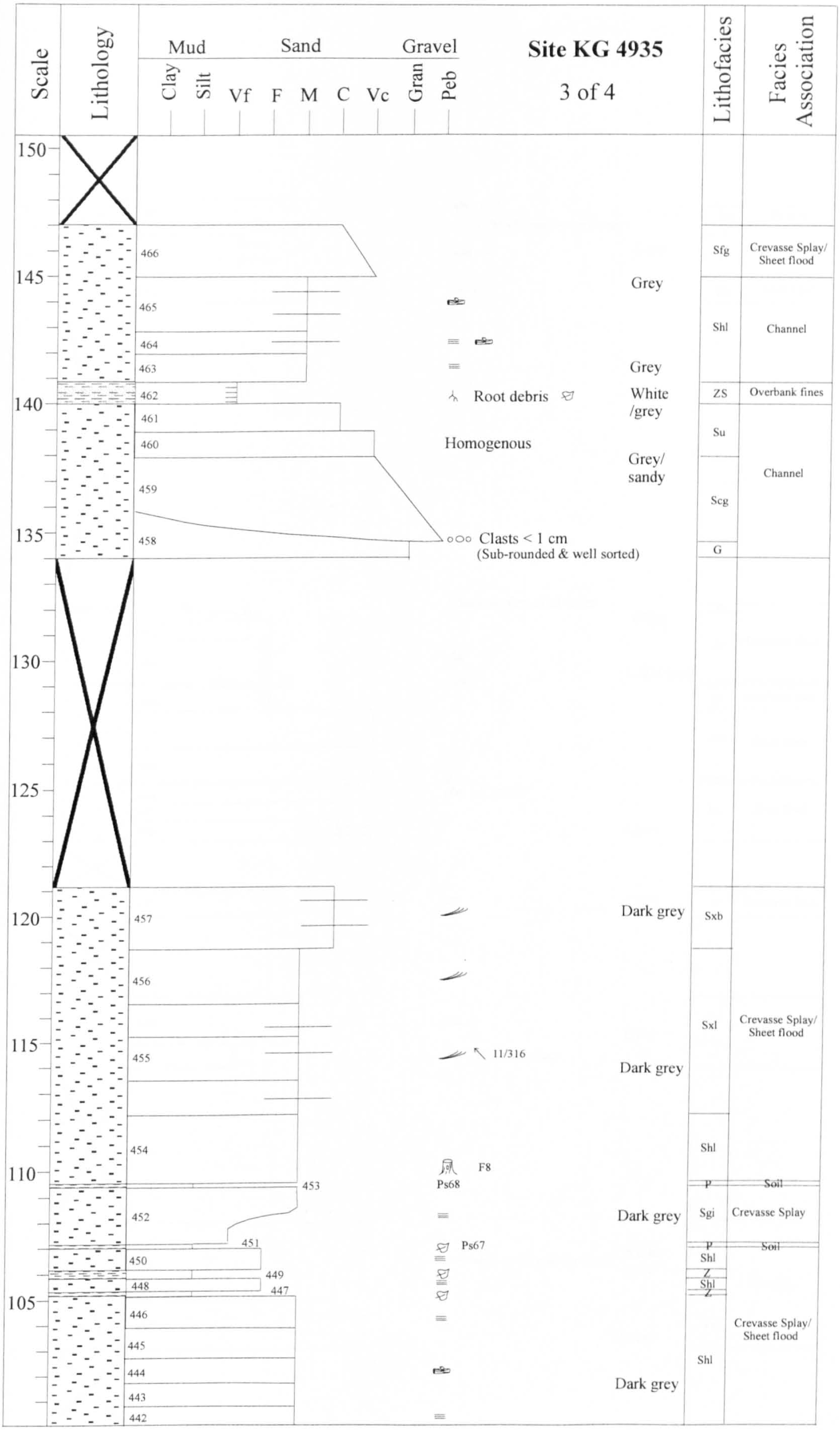
Appendix 2. Log 7, East Titan Nunatak sedimentary log



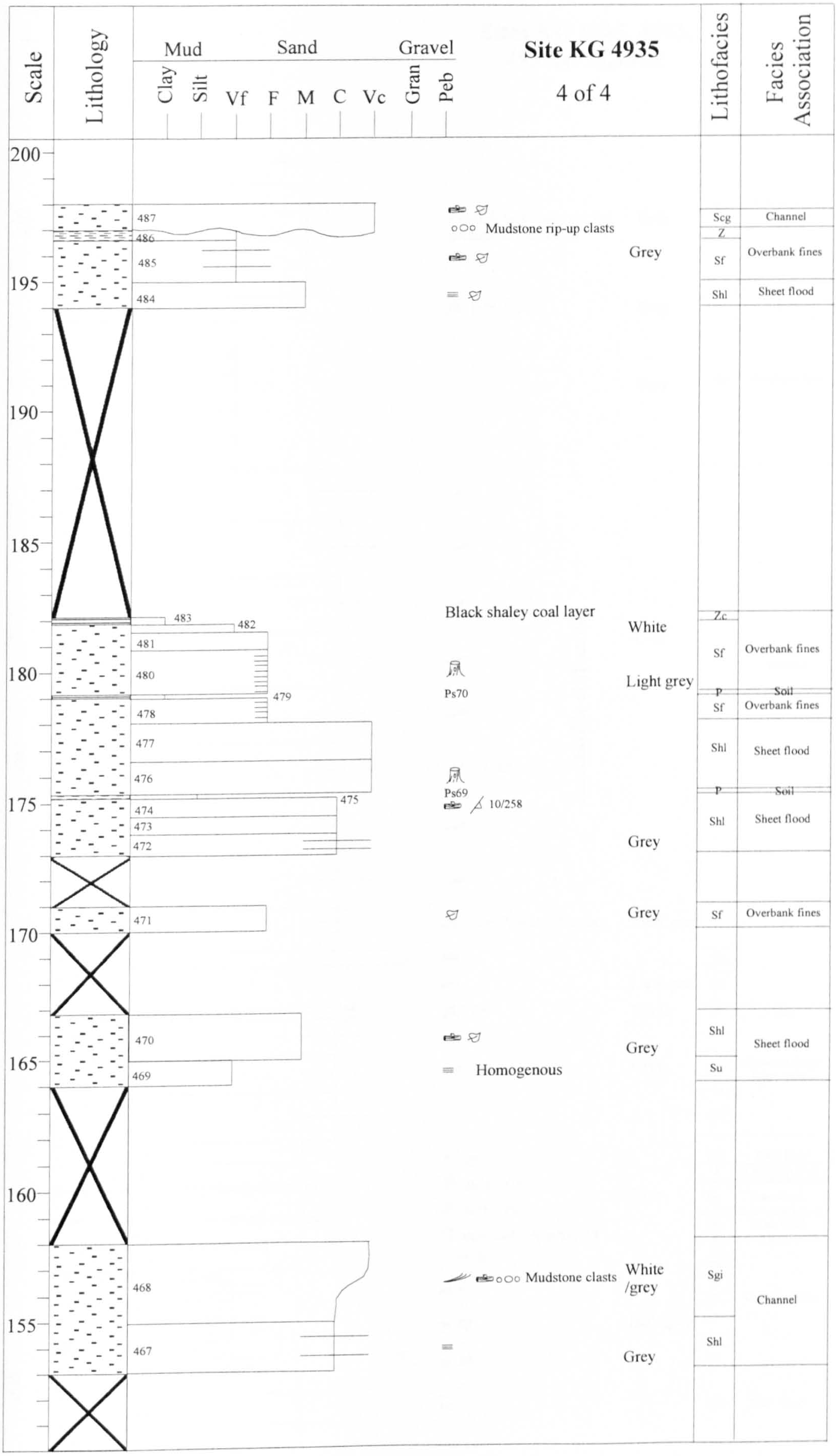
Appendix 2. Log 7, East Titan Nunatak sedimentary log



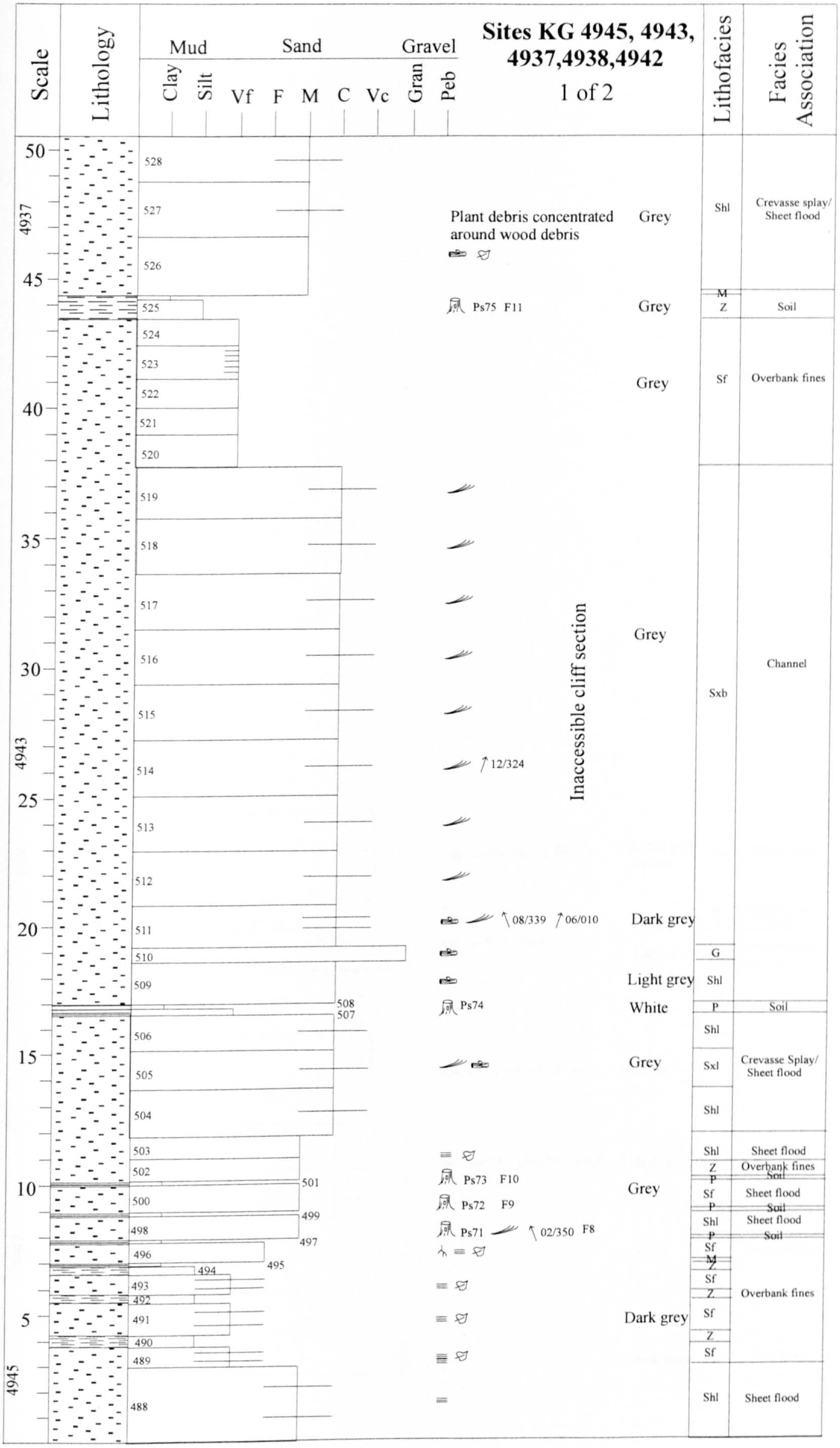
Appendix 2. Log 7, East Titan Nunatak sedimentary log



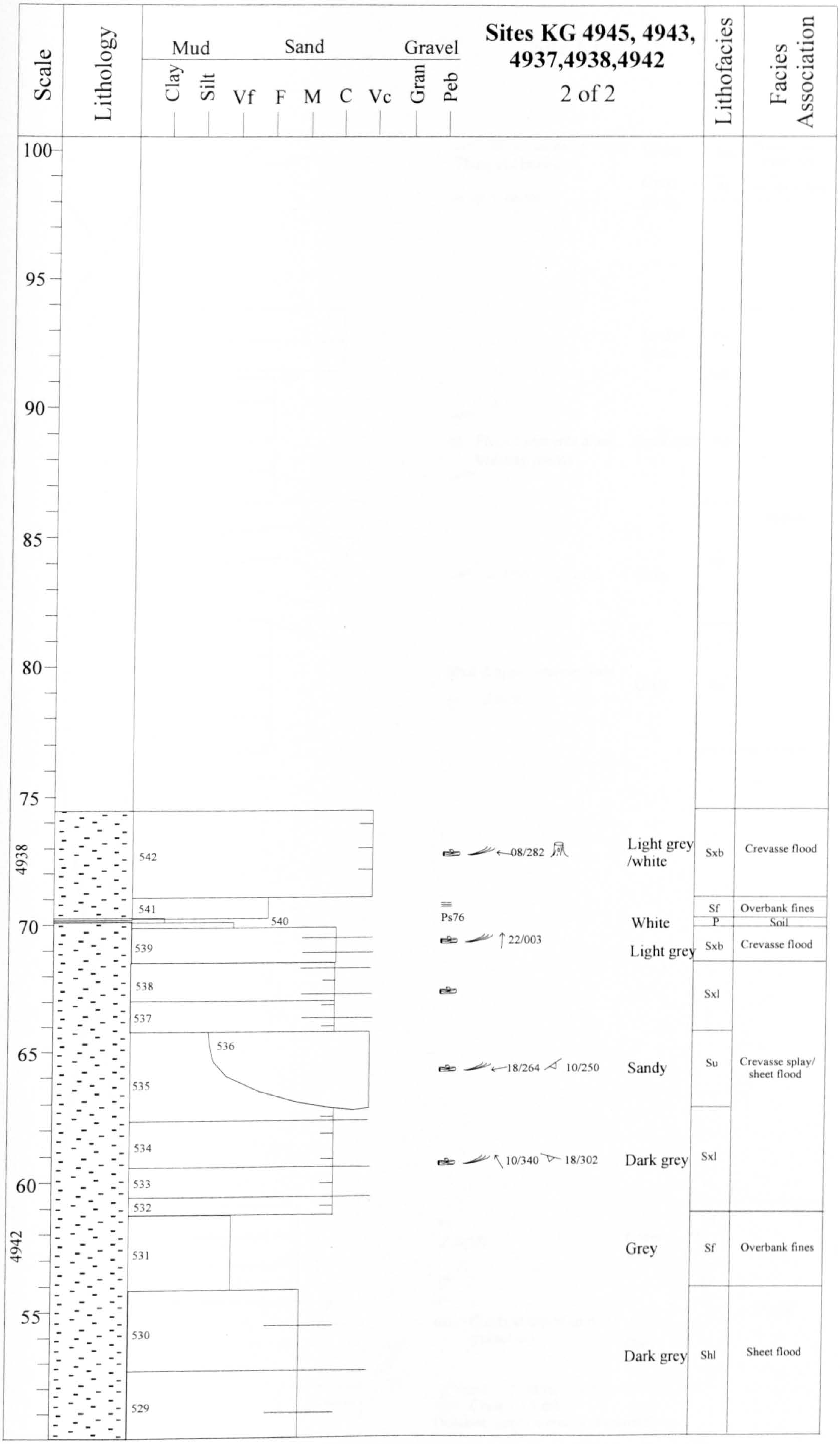
Appendix 2. Log 7, East Titan Nunatak sedimentary log



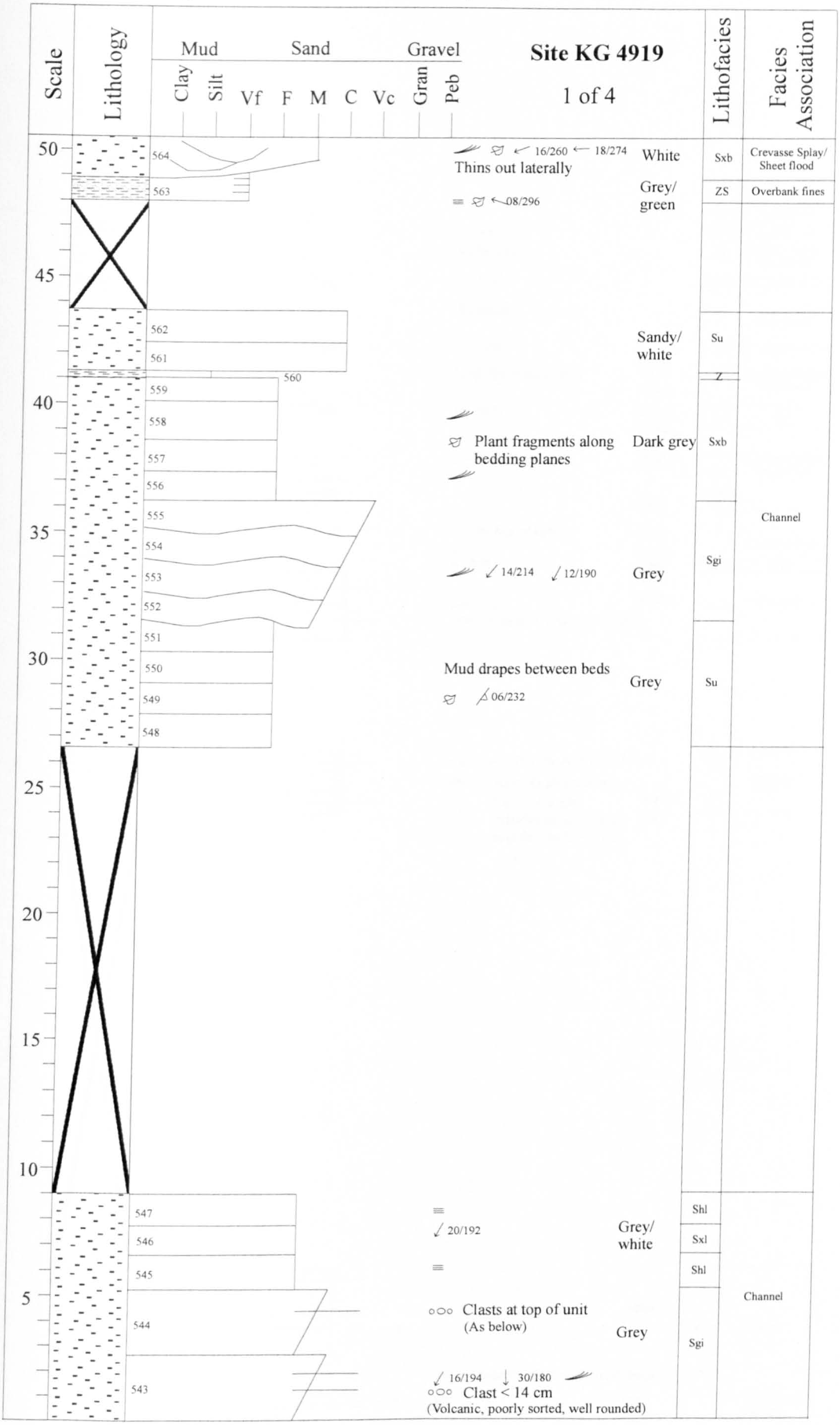
Appendix 2. Log 8, West Titan Nunatak composite sedimentary log



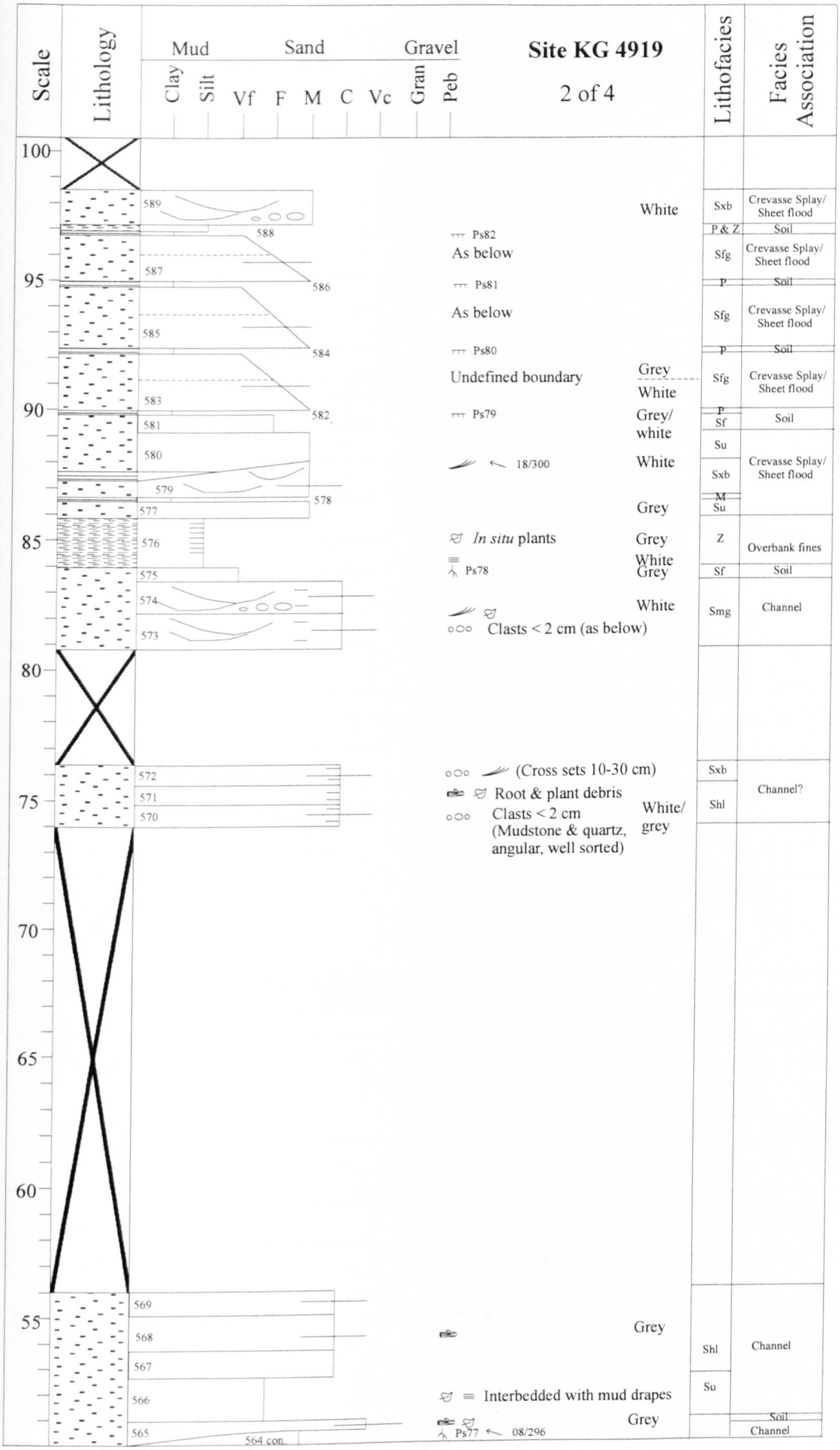
Appendix 2. Log 8, West Titan Nunatak composite sedimentary log



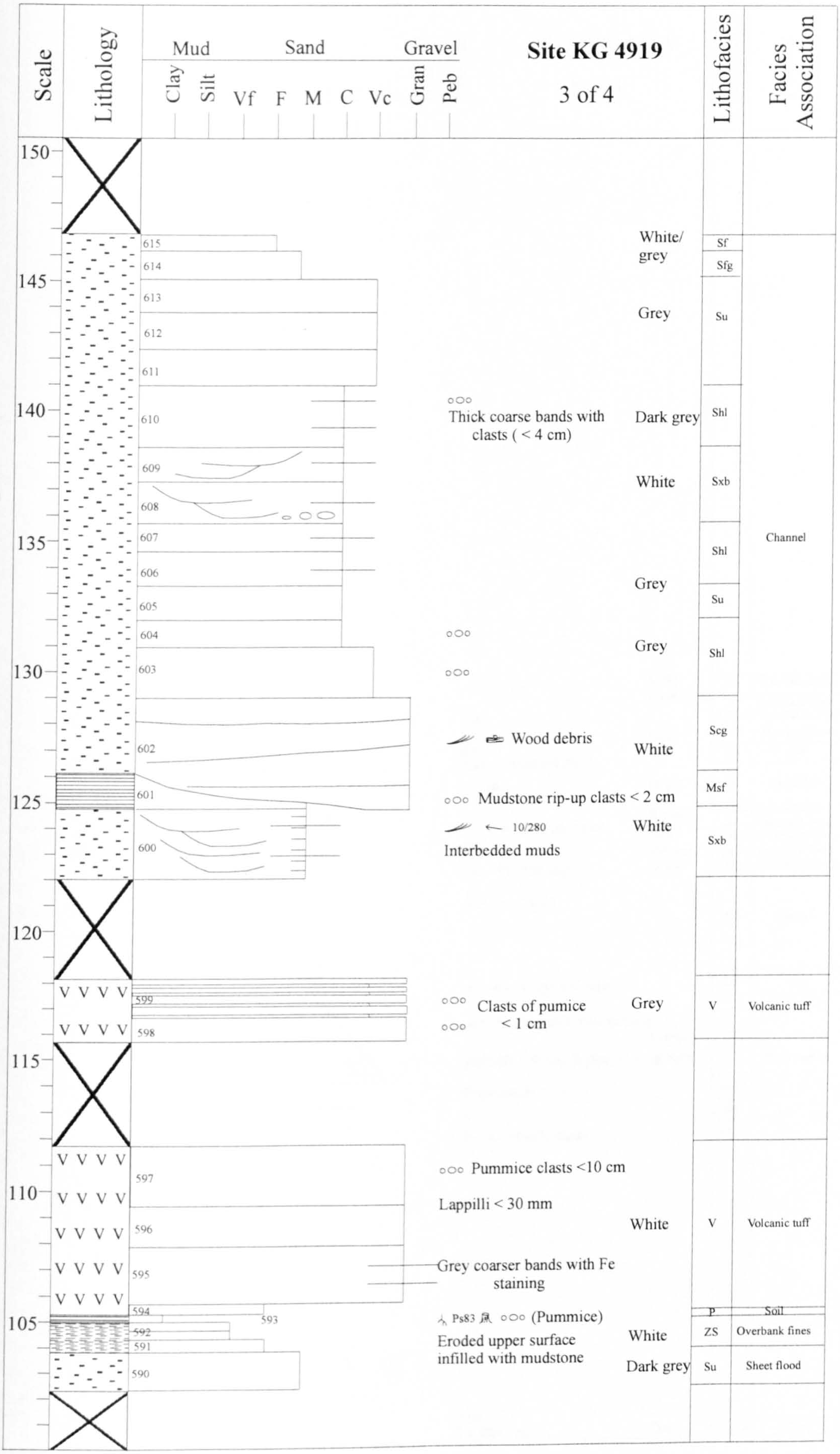
Appendix 2. Log 9, Coal Nunatak sedimentary log



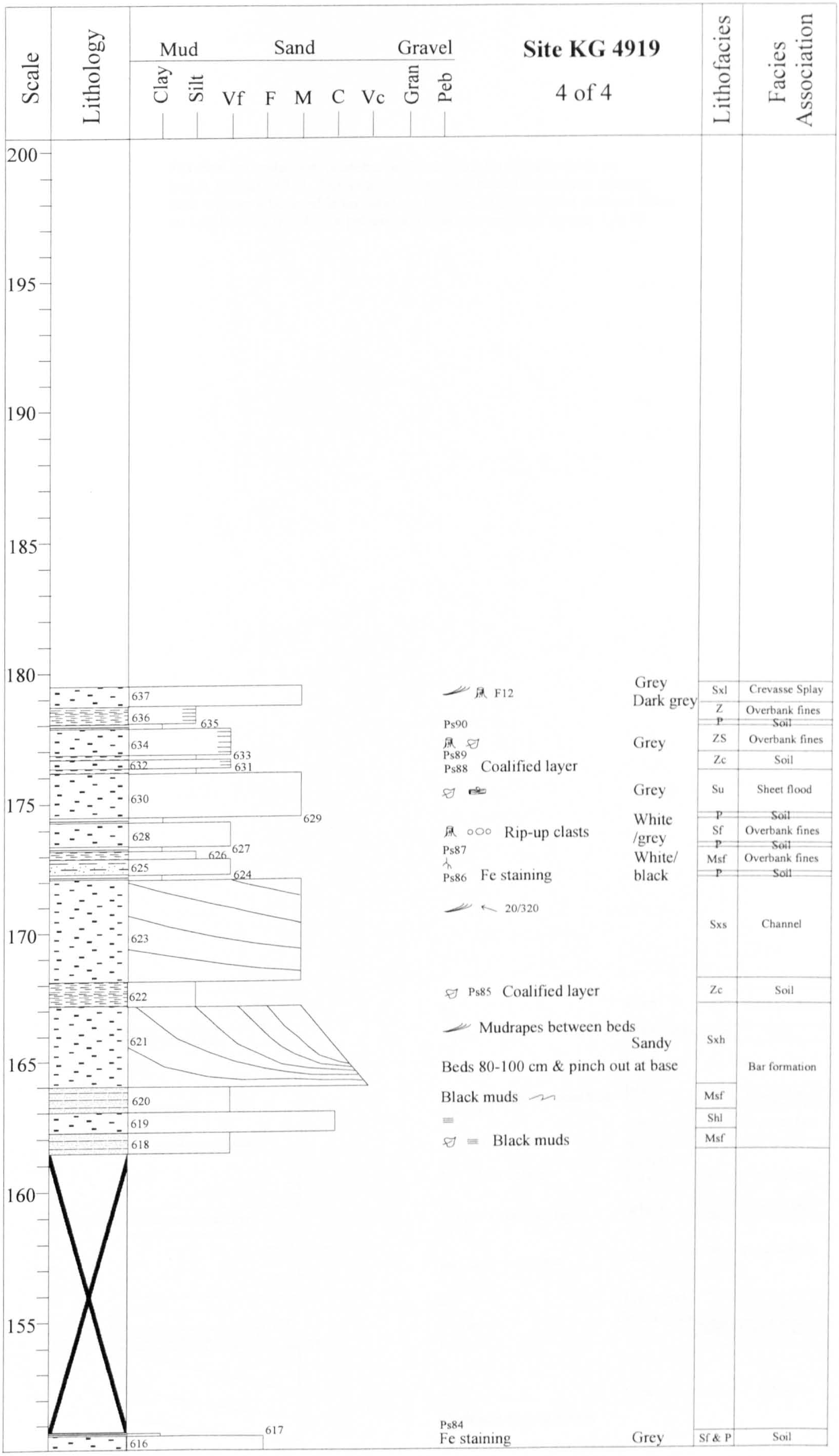
Appendix 2. Log 9, Coal Nunatak sedimentary log



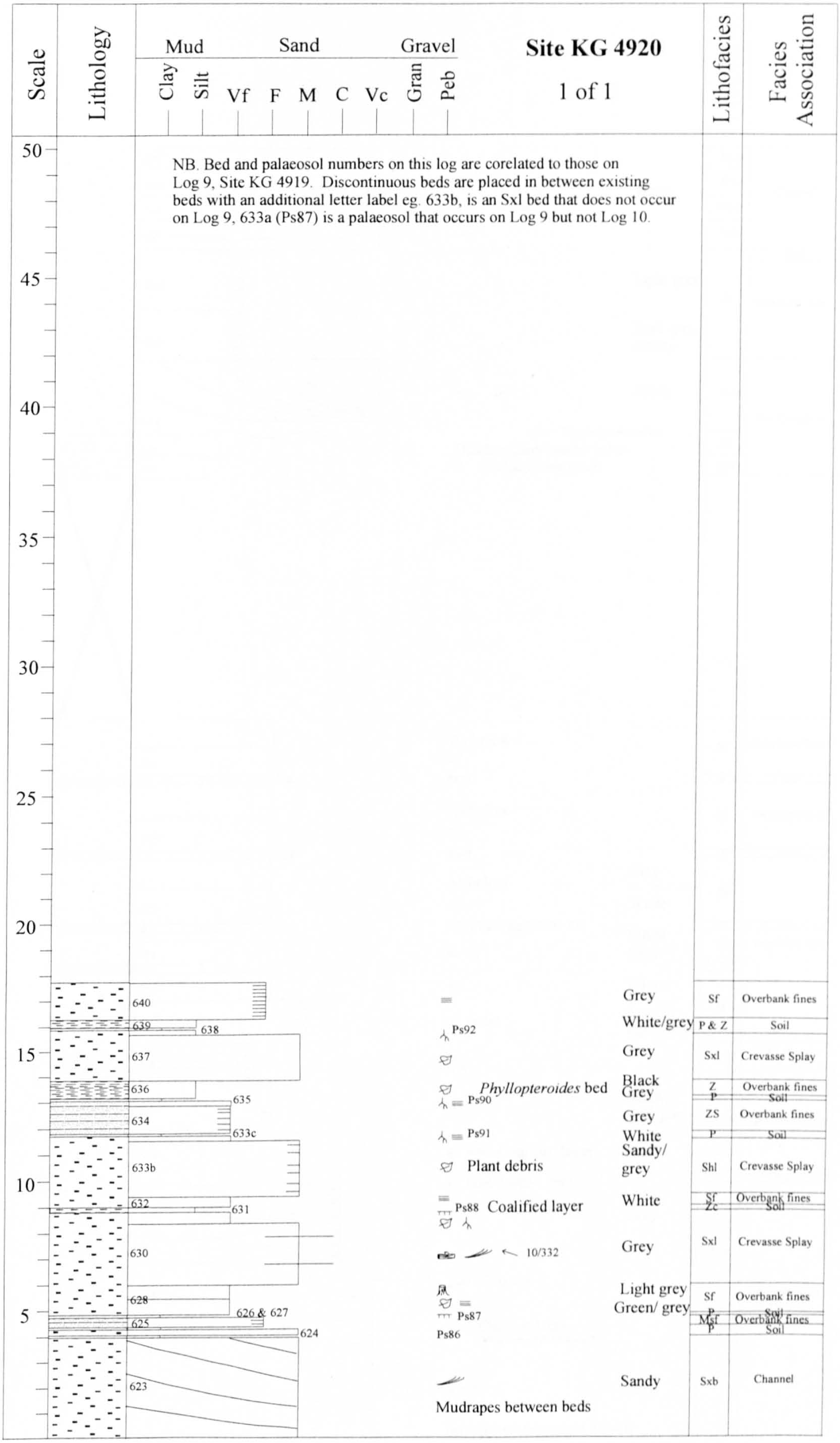
Appendix 2. Log 9, Coal Nunatak sedimentary log



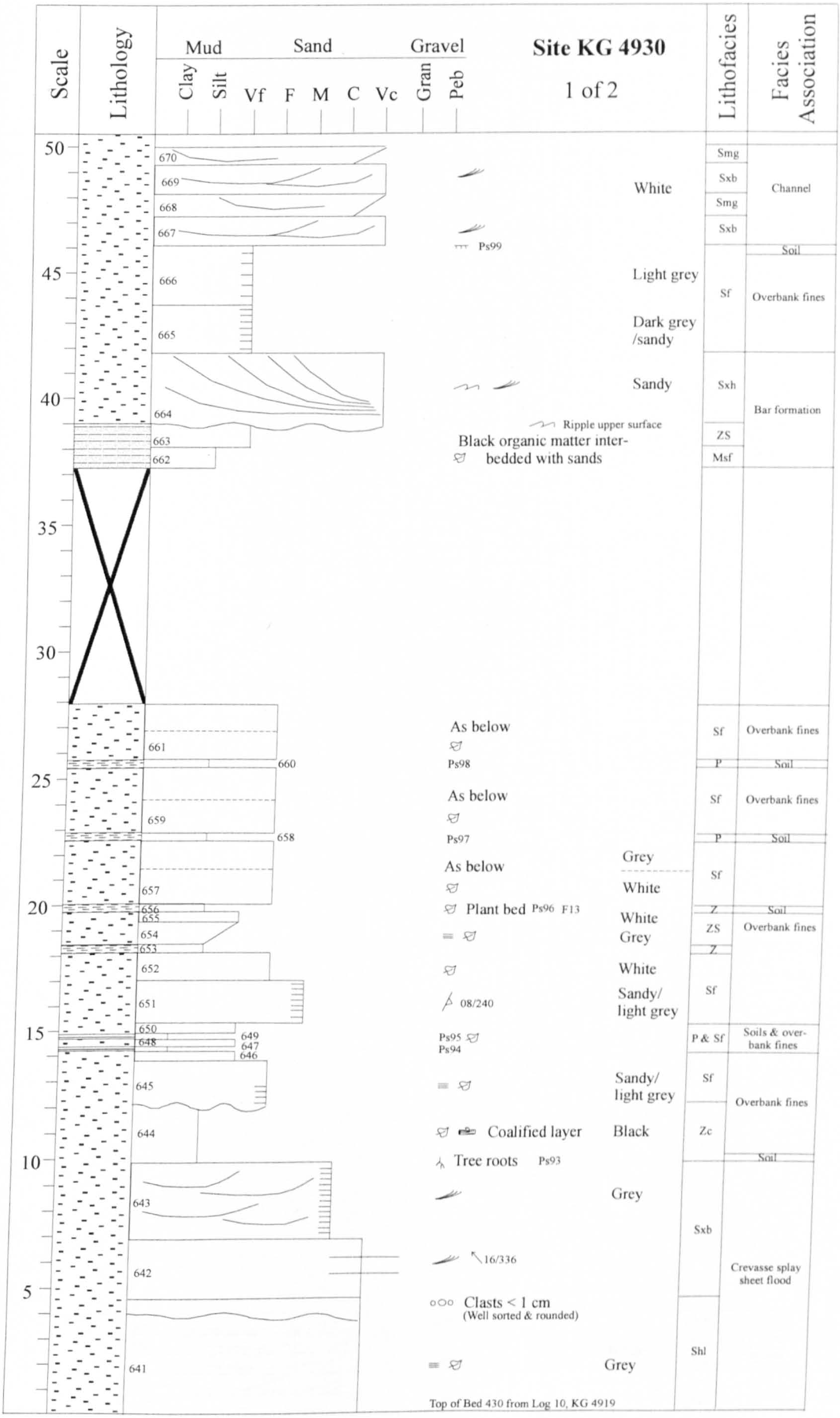
Appendix 2. Log 9, Coal Nunatak sedimentary log



Appendix 2. Log 10, Coal Nunatak sedimentary log


NB. Bed and palaeosol numbers on this log are corelated to those on Log 9, Site KG 4919. Discontinuous beds are placed in between existing beds with an additional letter label eg. 633b, is an Sxl bed that does not occur on Log 9, 633a (Ps87) is a palaeosol that occurs on Log 9 but not Log 10.

Appendix 2. Log 11, Coal Nunatak sedimentary log



Appendix 2. Log 11, Coal Nunatak sedimentary log

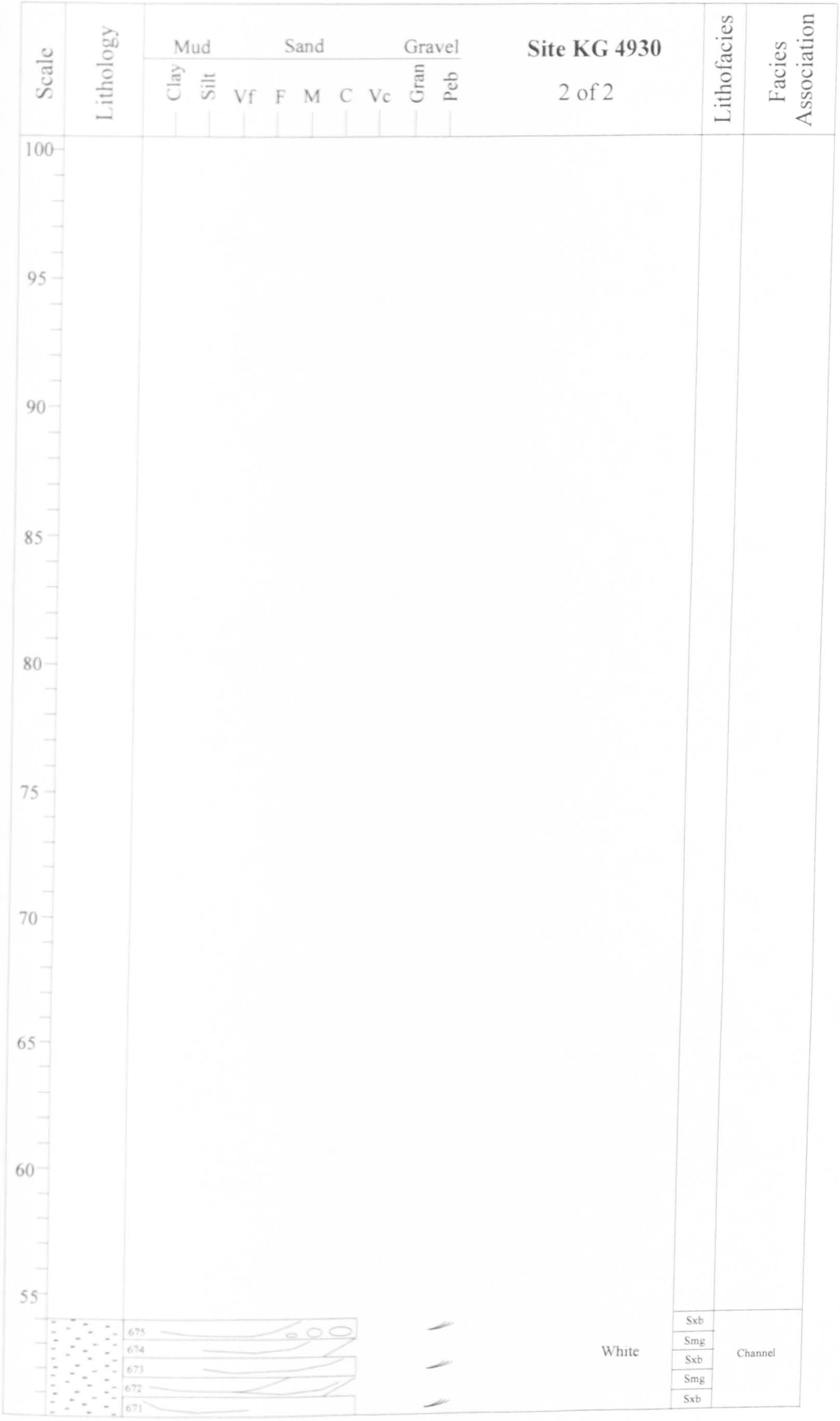


Table A 2.1. Descriptions of all localities mentioned in the text and annotated on Figure 2.1. Table includes information on longitude and latitude, a description of where the location occurs upon the nunatak and comments about work undertaken at each locality.

LOCATION NUMBER	LATITUDE (S)	LONGITUDE (W)	SAMPLES	DESCRIPTION OF LOCATION	NOTES
North Coal Nunatak					
KG 4901	n/a	n/a	none	Runs from northern tip of Coal to the base of KG 4902	log section
KG 4902	n/a	n/a	none	100m outcrop of bar unit that runs from E to W. It forms a promient ridge on route to the northern summit	Log section continuing on from KG 4901
KG 4903	n/a	n/a	12	Plateau surface just down from the northern summit	Two palaeosol horizons visable, only one sampled but not extensively
Citadel Bastion					
KG 4904	7201 034	6832 819	10	Slope of outcrop facing 340N. Runs from first col along length of Citadel to S summit	Log section, Jacob staff (JS) used
KG 4905	7200 391	6832 296	12	Palaeosol horizon between N and mid summit of Citadel, in a crag of rocks along planear surface	Two plant sample sites ~50m apart
KG 4906	n/a	n/a	4	Furthest N point that is accessible on N Cit. ~30m down from edge, running up to N summit	Log section. Specimens taken from various sites along the log
KG 4907	n/a	n/a	1	Outcrop of sandstone - 6m above start of 4906	Unproductive plant sample site
KG 4908	n/a	n/a	1	20m above 4906	Unproductive plant sample site
KG 4909	n/a	n/a	10	45m above 4906	Plant sample site - one band very productive
KG 4910	n/a	n/a	3	65m above 4906	Plant sample site
KG 4911	n/a	n/a	2	73m above 4906	Plant sample site
KG 4912	n/a	n/a	5	82m above 4906	Palaeosol sample site
KG 4913	n/a	n/a	10	85m above 4906	Good sampling area. Bed discontinuous - little lateral info
KG 4914	n/a	n/a	24	Top of northern most S summit. Crag at top	Good lateral data from palaeosol that can be traced for ~300m. Tree trunks in vertical section. Plants sampled
KG 4915	7201 287	6833 023	14	Between 57m and 63m of the log section for KG 4904	Palaeosol horizons sampled
KG 4916	7201 298	6832 982	6	Between 100m and 103m on log 4904	Palaeosol and plant bed. No soil in situ for samples
KG4917	7200 456	6832 053	none	On top of ridge S of mid col	Log section up to mid summit (4914) JS used
KG 4918	7201 382	6834 871	14	Most southernly ridge of Citadel from an altitude of 405m to 505m	Log section. JS used
South Coal Nunatak					
KG 4919	7204 573	6832 712	none	Base of access gully - half way along Coal	Log section. JS used
KG 4920	7204 994	6832 314	none	Below very southern end of S summit plateau (SSP)	Bar unit outcrop
KG 4921	7204 624	6832 485	31	Very N end of SSP	Area 150m long - tree mapping and plant bed sampling
KG 4922	7204 642	6832 398	28	Vertical section on W side of SSP ~60m S from top of Log 4919	Plant sampling and in situ trees
KG 4923	Starts7204 793 Ends7204 904	Starts 6832 408 Ends 6832 305	7	Continues on from end of 4921	Next 300m section of tree mapping
KG 4924	7204 634	6832 331	none	Within the area of 4921 on western ridge line	Tree cross cut by fault
KG 4925	7204 845	6832 381	1	50m north of S summit Cairn	Coal layer - sample taken
KG 4926	Starts7204 904 Ends7204 994	Starts 6832 305 Ends 6832 314	15	From the S summit cairn to the end of the SSP	Next area of Tree mapping 230m long
KG 4927	Starts7203 704 Ends7203 946	Starts 6831 427 Ends 6831 921	3	First Plateau under the northern summit	Tree mapping area running for 300m
KG 4928	Starts 7203 946 Ends 7204 06	Starts 6831 921 Ends 6832 069	6	Begins where 4927 ends and runs south for 300m	Tree mapping area
KG 4929	Starts 7204 06 Ends 7204 222	Starts 6832 069 Ends 6832 181	7	Begins where 4928 ends and runs south for 292m	Tree mapping area
KG 4930	Starts 7203 653 Ends 7203 738	Starts 6831 717 Ends 6831 622	10	Below N summit on W side ~150m south of the bar unit	Log section from bar unit to top, JS used
KG 4931	7203 653	6831 717	57	Base of the N summit first terrace on the north side	Plant sampling locality
Titan Nunataks					
KG 4932	n/a	n/a	2	Most southernly slump on East Titan	Slump
KG 4933	n/a	n/a	3	Most northerly slump on East Titan	Slump
KG 4934	n/a	n/a	17	Most southernly slump in the middle of East Titan	Slump with palaeosol
KG 4935	Starts 7206 444 Ends 7207 195	Starts 6840 615 Ends 6841 264	32	Most northern point of E Titan up to summit	Logging section. JS used
KG 4936	7206 862	6840 761	10	On eastern side of E Titan lowest outcrop of the section beneath the summit	Location of coal and some plant sampling

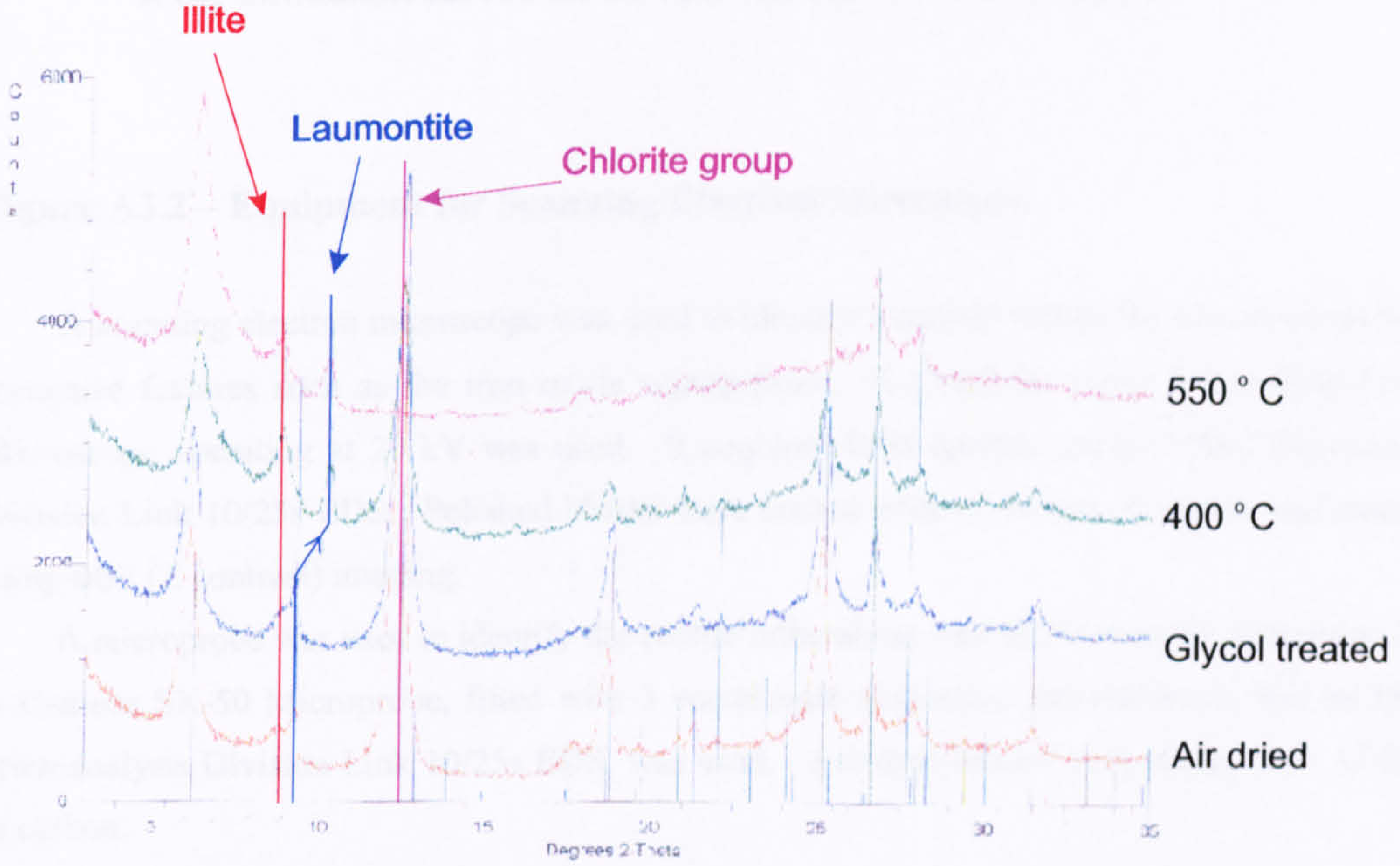
Table A 2.1. Continued.

LOCATION NUMBER	LATITUDE (S)	LONGITUDE (W)	SAMPLES	DESCRIPTION OF LOCATION	NOTES
Titan Nunataks					
KG 4937	Starts 7206.879 Ends 7206.695	Starts 6843.986 Ends 6844.475	9	W Titan . Ridge line running SW-NE Begins where s'stes exposed on northern ridge of W.Titan	Data on horizontal tree casts
KG 4938	7206.454	6844.423	32	First prominent ridge visable after the large plateau of W. Titan	Plant sampling
KG 4939	Starts 7205.129 Ends 7205.246	Starts 6842.573 Ends 6842.564	none	Western ridge of N Titan	Logging section. JS used
KG 4940	Starts 7204.112 Ends 7203.664	Starts 6844.256 (E) Ends 6843.282 (N)	18	Long eastern Hyperion	Sketch logging
KG 4941	7206.645	6840.812	31	Ridge section on eastern side of E Titan Ridge is o|o 76-96m on log 4935	Tree data and plant sampling over 300m long section
KG 4942	7206.059	6844.097	15	North end of W Titan on and below summit	Log section from first cliff section down from summit up to it
KG 4943	7206.331	6844.779	3	Ridge line along W side of W Titan	Tree data collected over 300m
KG 4944	7207.325	6841.299	7	Most southern tip of E Titan - lower cliff sections mainly on western face	Tree data collection plus some plant data
KG 4945	7206.533	6843.807	9	W Titan eastern side. Lowest cliff section to outcrop. Ridge line runs E-W	Tree data + plant samples
KG 4946	7206.417	6844.234	9	As above but ridge that runs 330-150.	Tree data + plant samples
KG 4947	n/a	n/a	5	E Titan part of the nunatak that extends out to the west and corresponds to the ridge line of 4945 on W Titan	Tree data + plant samples

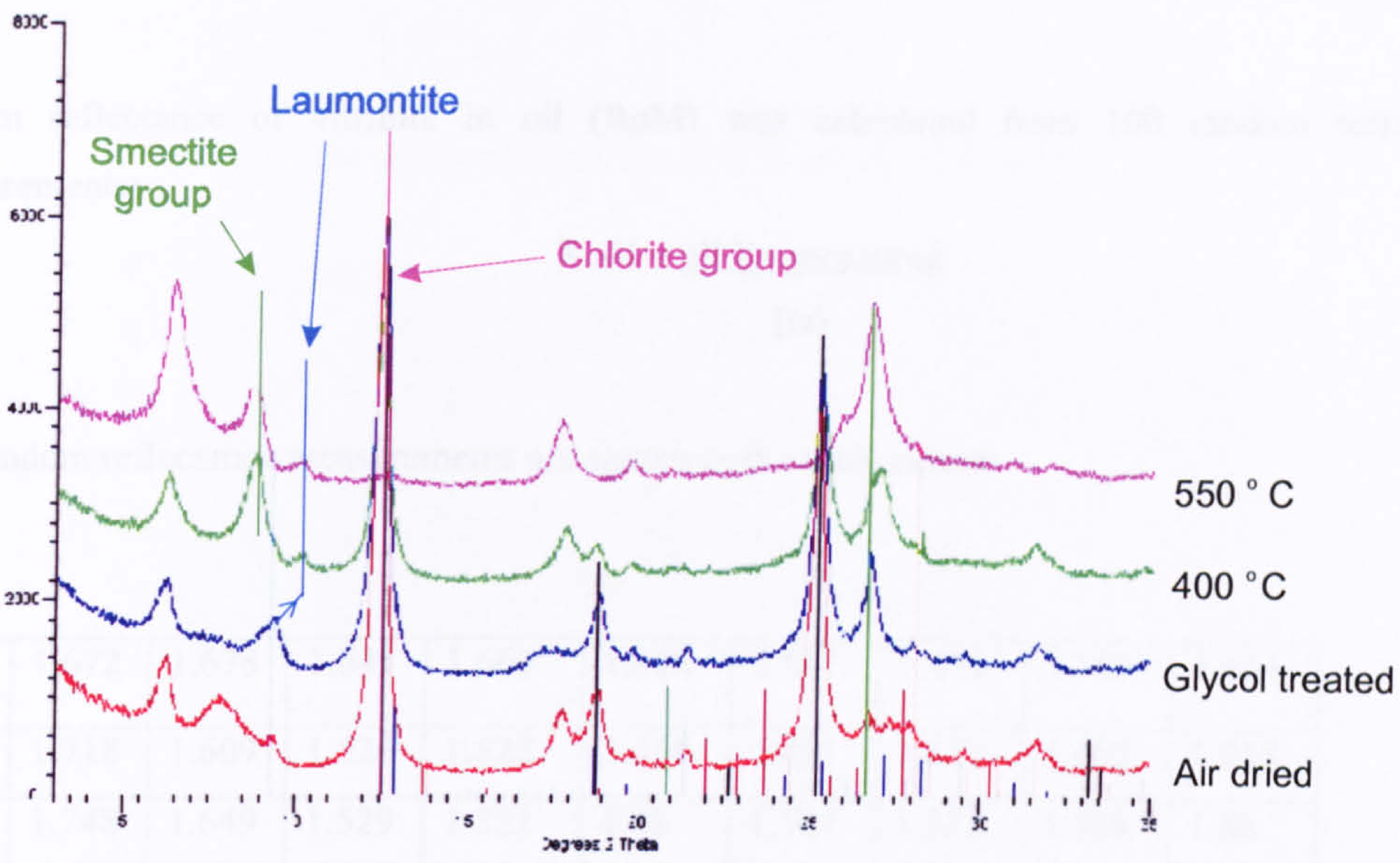
Figure A3.1 – Methodology and equipment for X-Ray diffraction.

The clay minerals were analysed through the process of x-ray diffraction using a Phillips PW 1050 X-ray diffractometer equipped with a graphite monochromator using CuKα radiation, according to Standards LP 5A of the University of Leeds. The clay fraction of the palaeosol samples was separated by centrifugation and then left to settle for 16 hours. The clay fraction was then smeared upon slides and left to air dry. For each palaeosol sample three slides were prepared: an air-dried slide, an ethylene glycol treated slide (used to identify swelling clays), and a slide for heat treatment (300 & 500 ° C).

The resulting diffraction diagrams allowed identification of the different minerals based on their characteristic reflections (see Moore & Reynolds 1997 for explanation of XRD).



X-ray diffraction curves for Sample KG 4915.3, Citadel Bastion



X-ray diffraction curves for Sample KG 4937.7, Titan Nunataks

Figure A3.2 – Equipment for Scanning Electron Microscope

A scanning electron microscope was used to identify minerals within the palaeosols as well as recognise features such as the iron oxide segregations. A CamScan series 4 Scanning Electron Microscope operating at 20 kV was used. It acquired EDS spectra using Oxford Microanalysis Division Link 10/25s EDS. Polished blocks were coated with 15-20 nm of carbon and examined using BSE (Z contrast) imaging.

A microprobe was used to identify the zeolite minerals as well as the prehnite and pumpellyite. A Cameca SX-50 Microprobe, fitted with 3 wavelength dispersive spectrometers, and an Oxford Microanalysis Division Link 10/25s EDS, was used. Polished blocks were coated with 15-20 nm of carbon.

Figure A3.3 – Methodology and equipment for vitrinite reflectance

Vitrinite reflectance experiments were undertaken at the University of Sheffield. Preparation and measurement was according to British Standard BS 6127 part 5 (1981). Standards used were both glass and had a reflectance of 1.24 % and 1.67 % in oil. A reflectance microscope with a x 50 (0.85) oil lens was used. Non-drying immersion oil was smeared over the sample. The mean random reflectance of vitrinite in oil (RoM) was calculated from 100 random reflectance measurements:

$$\mathrm{RoM} = \frac{\text{all Ro measured}}{100}$$

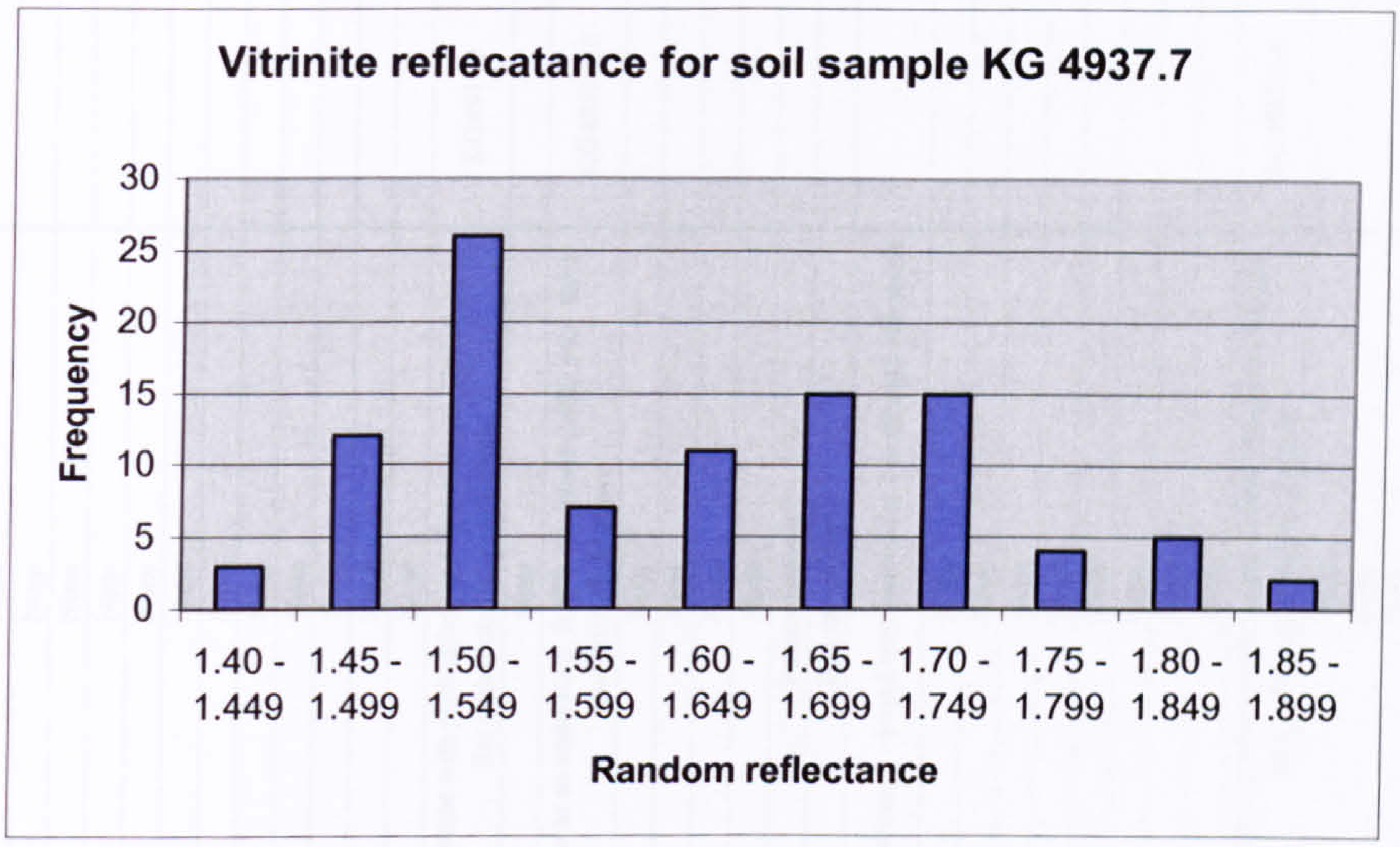
The random reflectance measurements are shown in the table below:

1.673	1.672	1.678	1.641	1.666	1.418	1.567	1.491	1.566	1.664
1.622	1.718	1.609	1.526	1.522	1.436	1.451	1.671	1.652	1.718
1.622	1.748	1.649	1.529	1.522	1.48	1.501	1.522	1.524	1.88
1.84	1.722	1.666	1.514	1.707	1.47	1.49	1.666	1.725	1.753
1.732	1.708	1.675	1.531	1.453	1.527	1.487	1.585	1.697	1.564
1.732	1.732	1.864	1.609	1.522	1.544	1.627	1.514	1.834	1.728
1.844	1.762	1.584	1.519	1.459	1.51	1.507	1.516	1.696	1.699
1.739	1.691	1.791	1.526	1.515	1.483	1.501	1.524	1.695	1.713
1.837	1.691	1.579	1.532	1.493	1.425	1.544	1.524	1.625	1.722
1.833	1.604	1.567	1.537	1.505	1.497	1.454	1.622	1.755	1.678

The average mean random reflectance = **1.61525**

R_o max = 1.066 x 1.61525

= **1.72**



A RoM of 1.6 % suggests a palaeotemperature of between 150-170 ° C and burial depth of 3.3-3.7 km based on a geothermal gradient of 45 ° C / Km. The geothermal gradient of 45 ° C / Km was estimated through a combination of vitrinite reflectance, chlorite crystalinity and authigenic mineralogy (S. Miller & D. MacDonald unpublished report, Doubleday 1994). The temperature and depth estimates were obtained from the graph in Doubleday (1994), based on curves from (Sweeney & Burnham 1990) and heating times of 10-50 Ma (Doubleday 1994).

Table A3.1. A summary table for all palaeosols identified on the southeastern nunataks of Alexander Island. Ps no (Palaeosol number) are those identified on the sedimentary logs in Appendix 2. Locations are identified on Figure 2.1, Chapter 2. For locality descriptions see Table A2.1, Appendix 2. Log (m) identifies the height in metres at which the palaeosol occurs, within the sedimentary log numbered (Appendix 2).

Nunatak	Ps No.	Location	Log (m)	Features present	Description	Samples
Citadel Bastion	Ps1	KG.4906	0 (Log 1)	Rootlets	None	
Citadel Bastion	Ps2	KG.4906	1 (Log 1)	Rootlets and peds	None	
Citadel Bastion	Ps3	KG.4906	2 (Log 1)	Rootlets	None	
Citadel Bastion	Ps4	KG.4906	3 (Log 1)	Rootlets	None	
Citadel Bastion	Ps5	KG.4906	6 (Log 1)	Mottling	None	
Citadel Bastion	Ps6	KG.4907	6.5 (Log 1)	Rootlets	None	
Citadel Bastion	Ps7	KG.4906	17.5 (Log 1)	Mottling and peds	None	
Citadel Bastion	Ps8	KG.4906	18.5 (Log 1)	Rootlets	None	
Citadel Bastion	Ps9	KG.4906	33 (Log 1)	Mottling and rootlets	None	
Citadel Bastion	Ps10	KG.4906	33.5 (Log 1)	Rootlets	None	
Citadel Bastion	Ps11	KG.4906	35.5 (Log 1)	Mottling and rootlets	None	
Citadel Bastion	Ps12	KG.4906	62 (Log 1)	Rootlets, mottling and peds	None	
Citadel Bastion	Ps13	KG.4911	72 (Log 1)	Rootlets and A-horizon	Fine siltstone with plant debris and root material. Underlain by Sxl with roots on upper surface.	KG.4911.2
Citadel Bastion	Ps14	KG.4906	73.5 (Log 1)	Fossil tree	None	
Citadel Bastion	Ps15	KG.4912	82.5 (Log 1)	Profile with an A-horizon	Outcrops as an undulating, friable mudstone (MSf) with thick sandstone (Sxb) above	KG.4912.1-5
Citadel Bastion	Ps16	KG.4906	144 (Log 1)	Rootlets	None	
Citadel Bastion	Ps17	KG.4906	160 (Log 1)	Mottling and rootlets	None	
Citadel Bastion	Ps18	KG.4906	170.5 (Log 1)	Rootlets	None	
Citadel Bastion	Ps19	KG.4917	58.5 (Log 2 & 3)	Rootlets and A-horizon	None	
Citadel Bastion	Ps20	KG.4914	63 (Log 2 & 3)	Fossil tree & rootlets	Forests horizon 1	
Citadel Bastion	Ps21	KG.4914	64 (Log 2 & 3)	Fossil tree & rootlets	Forests horizon 2	
Citadel Bastion	Ps22	KG.4914	65 (Log 2 & 3)	Fossil tree & rootlets	Forests horizon 3 - Fossil trees extend for 2 m through Shl above.	
Citadel Bastion	Ps23	KG.4904	1.2 (Log 4)	Mottling and rootlets	None	
Citadel Bastion	Ps24	KG.4904	37.5 (Log 4)	Fossil tree	None	
Citadel Bastion	Ps25	KG.4904	91.5 (Log 4)	Rootlets, mottling and peds	None	
Citadel Bastion	Ps26	KG.4904	96 (Log 4)	Peds	None	
Citadel Bastion	Ps27	KG.4904	129 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps28	KG.4904	138 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps29	KG.4904	142 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps30	KG.4904	147 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps31	KG.4915	149.5 Log 4)	Profile	Profile showed peds, mottling and rootlets. Palaeosol features seen within a 4m section of slope.	KG.4915.1-8
Citadel Bastion	Ps32	KG.4904	153.5 (Log 4)	Peds	None	
Citadel Bastion	Ps33	KG.4904	178 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps34	KG.4904	199.5 (Log 4)	Peds	None	
Citadel Bastion	Ps35	KG.4904	206 (Log 4)	Peds	None	
Citadel Bastion	Ps36	KG.4904	210 (Log 4)	Mottling and peds	None	
Citadel Bastion	Ps37	KG.4904	213 (Log 4)	Peds	None	
Citadel Bastion	Ps38	KG.4904	214.5 (Log 4)	Peds	None	

Table A3.1 continued

Nunatak	Ps No.	Location	Log (m)	Features present	Description	Samples
Citadel Bastion	Ps39	KG.4904	225.5 (Log 4)	Peds	None	
Citadel Bastion	Ps40	KG.4904	226.2 (Log 4)	Peds	None	
Citadel Bastion	Ps41	KG.4904	227.2 (Log 4)	Peds	None	
Citadel Bastion	Ps42	KG.4904	242 (Log 4)	Mottling and rootlets	None	
Citadel Bastion	Ps43	KG.4918	6 (Log 5)	Peds	None	
Citadel Bastion	Ps44	KG.4918	37.5 (Log 5)	Peds	None	
Citadel Bastion	Ps45	KG.4918	77 (Log 5)	Peds	None	
Citadel Bastion	Ps46	KG.4918	77.5 (Log 5)	Peds	None	
Citadel Bastion	Ps47	KG.4918	89.5 (Log 5)	Peds	None	
Citadel Bastion	Ps48	KG.4918	124 (Log 5)	Peds	None	
Citadel Bastion	Ps49	KG.4918	139 (Log 5)	Peds	None	
Citadel Bastion	Ps50	KG.4918	142 (Log5)	Rootlets and A-horizon	None	
Citadel Bastion	Ps51	KG.4918	145 (Log 5)	Rootlets	None	
North Titan	Ps52	KG.4939	4.5 (Log 6)	A-horizon and fossil tree	Forest horizon 4	
North Titan	Ps53	KG.4939	32 (Log 6)	Rootlets	None	
North Titan	Ps54	KG.4939	36 (Log 6)	Rootlets	None	
North Titan	Ps55	KG.4939	50.5 (Log 6)	Fossil tree and A-horizon	Forets horizon 6	
North Titan	Ps56	KG.4939	56 (Log 6)	A-horizon	None	
North Titan	Ps57	KG.4939	57 (Log 6)	A-horizon	None	
North Titan	Ps58	KG.4939	128 (Log 6)	Mottling and A-horizon	None	
North Titan	Ps59	KG.4939	129 (Log 6)	Mottling and A-horizon	None	
North Titan	Ps60	KG.4939	142.5 (Log 6)	Peds	None	
East Titan	Ps61	KG.4935	21 (log 7)	Peds	None	
East Titan	Ps62	KG.4935	27 (Log 7)	A-horizon and rootlets	None	
East Titan	Ps63	KG.4935	77.5 (Log 7)	Rootlets	None	
East Titan	Ps64	KG.4935	83.5 (Log 7)	Fossil tree and A-horizon	Forets horizon 5	
East Titan	Ps65	KG 4941	87 (Log 7)	Fossil tree and A-horizon	Forets horizon 6 A-Horizon - friable grey mudstone B-Horizon - sandstone with large peds	KG.4941.1
East Titan	Ps66	KG.4935	92 (Log 7)	Fossil tree and A-horizon	Forest horizon 7	
East Titan	Ps67	KG.4935	107 (Log 7)	A-horizon	None	
East Titan	Ps68	KG.4935	109.5 (Log 7)	A-horizon and fossil tree	Forets horizon 8	
East Titan	Ps69	KG.4935	175 (Log 7)	A-horizon and fossil tree	None	
East Titan	Ps70	KG.4935	179 (Log 7)	Rootlets	A-Horizon - friable grey mudstone	KG.4935.27
East Titan	Ps71	KG.4945	8 (Log 8)	Fossil tree	Forets horizon 8	
East Titan	Ps72	KG.4945	9 (Log 8)	Fossil tree	Forets horizon 9	
East Titan	Ps73	KG.4945	10 (Log 8)	Fossil tree	Forets horizon 10	
West Titan	Ps74	KG.4943	17 (Log 8)	A-Horizon and fossil trees	A-Horizon - black siltstone at the base of 20 m of Coarse sandstone. Fossil trees rooted in palaeosol.	KG.4943.3

Table A3.1 continued

Nunatak	Ps No.	Location	Log (m)	Features present	Description	Samples
West Titan	Ps 75	KG.4937	44 (Log 8)	A-Horizon and fossil tree	Forets horizon 11 A-Horizon - friable grey mudstone or massive siltstone outcropping at the base of thick coarse sandstone units	KG.4937.6, 7
West Titan	Ps76	KG.4938/ KG. 4943	70 (Log 8)	A-Horizon, fossil trees and rootlets	A-Horizon - friable grey mudstone with rootlet material and fossil plant debris. Under- and overlain by coarse sandstone (overlain by fine white sandstone at KG.4943)	KG.4938.1/ KG 4942.2-4
South Coal	Ps77	KG.4919	50 (Log 9)	Rootlets	None	
South Coal	Ps78	KG.4919	83.5 (Log 9)	Rootlets	None	
South Coal	Ps79	KG.4919	90 (Log 9)	Mottling and peds	Fine light grey sandstone within a sequence of fine sandstones and siltstones	KG.4919.13
South Coal	Ps80	KG.4919	92 (Log 9)	Peds and A-horizon	None	
South Coal	Ps81	KG.4919	95 (Log 9)	Peds and A-horizon	None	
South Coal	Ps82	KG.4919	97 (Log 9)	Peds and A-horizon	None	
South Coal	Ps83	KG.4919	105 (Log 9)	Rootlets and fossil tree	Fine off-white sandstone beneath a volcanic tuff	KG.4919.12
South Coal	Ps84	KG.4919	150.5 (Log 9)	A-horizon	None	
South Coal	Ps85	KG.4919	167 (Log 9)	A - horizon	None	
South Coal	Ps86	KG.4919	172 (Log 9)	Fossil tree and A-horizon	A-Horizon - black, friable mudstone within a sequence of interbedded sandstones and siltstones	KG.4922.1
South Coal	Ps87	KG.4919	173.5 (Log 9)	A-horizon and fossil tree	None	
South Coal	Ps88	KG.4919	176 (Log 9)	A-horizon	None	
South Coal	Ps89	KG.4919	176.5 (Log 9)	A-horizon and fossil treel	None	
South Coal	Ps90	KG.4919	178 (Log 9)	A-horizon and fossil treel	Forest horizon 12	
South Coal	Ps91	KG.4920	11.5 (Log 10)	A-horizon and rootlets	None	
South Coal	Ps92	KG.4920	16 (Log 10)	A-horizon and rootlets	None	
North Coal	Ps93	KG.4930	10 (Log 11)	Roots	None	
North Coal	Ps94	KG.4930	14 (Log 11)	A-horizon	None	
North Coal	Ps95	KG.4930	15 (Log 11)	A-horizon	None	
North Coal	Ps96	KG.4930	20 (Log 11)	A-horizon	Forest horizon 13	
North Coal	Ps97	KG.4930	22.5 (Log 11)	A-horizon	None	
North Coal	Ps98	KG.4930	25.5 (Log 11)	A-horizon	None	
North Coal	Ps99	KG.4930	46 (Log 11)	A-horizon	None	

Table A4.1. A summary table of all the data collected relating to the standing fossil trees within the seven cliff sections sampled. For locality descriptions see Table A2.1, Appendix 2.

Location	Forest Horizon	Tree Number	Distance between trees (M)	Range	Average	Width of trees at base (M)	Range	Average	Width of trees at top (M)	Range	Average	Height of trees (M)	Range	Average
KG 4914	F3	1	n/a			0.25			0.2			1.25		
		2	6.7			0.18			n/a			0.4		
		3	65			0.24			0.2			0.6		
		4	65			0.17			0.15			0.35		
		5	2			0.28			n/a			0.2		
		6	8.3	2 to 65	29.4	0.13	0.13 to 0.28	0.21	n/a	0.15 to 0.2	0.18	0.3	0.3 to 1.25	0.52
KG 4939	F4	1	n/a			0.2			n/a			2.5		
		2	3	n/a	3	0.1	0.1 to 0.2	0.15	n/a	n/a	n/a	1	1-2.5	1.75
	F6	1	n/a			0.07	n/a	0.07	n/a	n/a	n/a	0.9	n/a	0.9
KG 4941	F5	1	n/a			0.16			n/a			1.51		
		2	13.2			0.6			n/a			1		
		3	73.5			0.55			n/a			0.95		
		4	51.4	13.2 to 51.4	46.03	0.27	0.6 to 0.27	0.40	0.1	n/a	0.1	1	0.4 to 1.51	1.12
	F6	1	n/a			0.4			n/a			3		
		2	44			0.43			n/a			6		
		3	1			0.22			n/a			0.2		
		4	4.5			0.1			n/a			0.3		
		5	15.5			0.2			n/a			1.2		
		6	32			0.07			n/a			0.4		
		7	5.8	1 to 44	17.13	0.6	0.1 to 0.2	0.29	0.6	n/a	0.6	2.5	0.1 to 6	1.94
KG 4944	F5	1	n/a			0.42			n/a			6		
		2	13			0.34			n/a			1.2		
		3	11.8			0.35			0.4			2.6		
		4	33.8			0.6			n/a			2.3		
		5	75			0.5			n/a			2.3		
		6	1.4			0.76			0.33			3.4		
		7	153			0.25			0.3			4.3		
		8	10.2			0.5			0.27			2.3		
		9	16			0.27			n/a			1.2		
		10	1			0.5			n/a			5		
		11	45.5	1 to 153	36.07	0.4	0.34 to 0.76	0.44454545	0.3	0.27 to 0.4	0.32	2.5	1 to 6	3.01
	F6	1	n/a			0.3			0.2			2.5		
		2	11.7			0.6			n/a			1.1		
		3	3			0.3			0.2			2.5		
		4	8.8			0.3			0.2			2.5		
		5	1.5			0.5			0.3			2.4		
		6	5.5			n/a			n/a			2.5		
		7	72			0.4			n/a			0.4		
		8	4.4			0.5			n/a			1		
		9	45			0.4			n/a			1.7		
		10	1.2			0.27			n/a			1.5		
		11	3			0.1			n/a			2.5		
		12	45.6			0.25			0.15			1.7		
		13	89	1.2 to 89	24.23	0.32	0.1 to 0.6	0.35	n/a	0.15 to 0.3	0.21	2	0.4 to 2.5	1.87

Table A4.1 continued.

Location	Forest Horizon	Tree Number	Distance between trees (M)	Range	Average	Width of trees at base (M)	Range	Average	Width of trees at top (M)	Range	Average	Height of trees (M)	Range	Average
	F7	1	n/a			0.5			n/a			2		
		2	13			0.16			n/a			1.7		
		3	5.7			0.2			n/a			2.3		
		4	3			0.4			0.35			1.7		
		5	17.6			0.15			n/a			2.7		
		6	91			0.1			n/a			1		
		7	31			0.45			0.25			2.5		
		8	168			0.3			n/a			3.4		
		9	33.8	3 to 168	45.39	0.14	0.1 to 0.45	0.27	n/a	0.25 to 0.35	0.3	3.5	1.1 to 5	2.31
KG 4945	F8	1	n/a	n/a	n/a	0.73	n/a	n/a	n/a	n/a	n/a	0.1	n/a	0.1
	F9	1	n/a			0.26			0.14			1.3		
		2	1.3			0.28			n/a			1.6		
		3	5.8			0.25			n/a			1		
		4	28			0.1			n/a			2.5		
		5	0.8			0.2			n/a			1.3		
		6	75			1			0.53			6		
		7	15.4			0.23			n/a			0.36		
		8	92.6			0.03			n/a			0.15		
		9	0.6			0.03	0.1 to 1	0.26	n/a	0.14 to 0.53	0.34	0.52	0.15 to 6	1.64
	F10	1	n/a			n/a			n/a			1		
		2	47			0.11			n/a			2		
		3	75			0.2			n/a			1.7		
		4	80.8			0.17			n/a			2.3		
		5	2.9			0.1			n/a			1.8		
		6	5			0.3			0.13			2		
		7	0.3			n/a			n/a			3.49		
		8	3			0.1			n/a			0.8		
		9	5.8			0.2			n/a			2.4		
		10	4.4			0.33			n/a			1.8		
		11	4.5	0.3 to 80.8	22.87	0.15	0.1 to 0.33	0.18	n/a	n/a	n/a	1.7	0.8 to 3.5	1.9
KG 4946	F8	1	n/a			0.32			0.2			0.93		
		2	0.7			0.05			n/a			1		
		3	63	0.7 to 63	31.85	0.14	0.05 to 0.32	0.17	n/a	n/a	n/a	0.6	0.6 to 0.93	0.84
	F9	1	n/a			0.51			n/a			2.13		
		2	16			0.2			n/a			2.2		
		3	45.6	16 to 45.6	30.8	0.12	0.2 to 0.51	0.28	n/a	n/a	n/a	2.56	2.2 to 2.56	2.30
	F10	1	n/a			0.12			n/a			0.9		
		2	70.5			0.34			0.25			2.4		
		3	1.5			0.28			0.1			2.4		
		4	13.2	1.5 to 70.2	28.4	0.35	0.12 to 0.35	0.27	0.15	0.15 to 0.25	0.17	0.87	0.9 to 2.4	1.64
KG 4937	F11	1	n/a			0.08			n/a			n/a		
		2	n/a			0.18			n/a			0.35		
		3	n/a			0.2			n/a			0.7		
		4	n/a			0.3			n/a			1.35		
		5	n/a	n/a	n/a	0.25	0.08 to 0.25	0.20	0.19	n/a	n/a	0.51	0.35 to 1.35	0.73

Table A4.2. A summary table of all the data collected on the tree stumps cropping out on the six exposed areas of Coal Nunatak. For locality descriptions see Table A2.1, Appendix 2.

Location	Tree number	Distance to nearest tree	Max width of trunk (cm)	Long axis orientation (degrees)	Height of exposed tree stump (cm)	Location	Tree number	Distance to nearest tree	Max width of trunk (cm)	Long axis orientation (degrees)	Height of exposed tree stump (cm)
KG 4921	1	11	16	120	4	KG 4923 cont.	43	4	14	189	n/a
	2	11	12	310	13		44	2.5	19	270	n/a
	3	7	8.5	40	70		45	2.5	17	n/a	n/a
	4	5.5	20	n/a	23		46	3.5	13	n/a	n/a
	5	0.8	10	160	18		47	8.6	16	270	n/a
	6	5	13	n/a	35		48	8.6	34	n/a	n/a
	7	10	9	n/a	69		49	11	20	260	n/a
	8	6.6	12	n/a	5		50	9	16	n/a	n/a
	9	7	8	n/a	8		51	9	28	n/a	n/a
	10	7	7	n/a	30		52	41	14	226	n/a
	11	16	15	96	20		53	46	16	350	n/a
	12	12	8	n/a	23		54	5	10	n/a	n/a
	13	12	5	n/a	10		55	5	10	296	n/a
	14	7.8	17	24	104		56	12	13	n/a	25
	15	7.8	14	n/a	18		57	4	16	n/a	n/a
	16	1	26	194	10		58	6	19	312	n/a
	17	2.5	15	440	12		59	6	28	310	n/a
	18	2.5	19	n/a	12		60	4	8	335	n/a
	19	5	7	70	9		61	3.5	28	349	n/a
	20	4	29	n/a	12		62	4	18	n/a	n/a
	21	4	26	346	26		63	8.5	10	n/a	n/a
	22	9.5	16	n/a	13		64	0.6	12	n/a	n/a
	23	5	20	n/a	11		65	0.6	17	n/a	n/a
KG4923	24	15	22	n/a	7		66	6	11	312	n/a
	25	12	15	n/a	14		67	23	15	n/a	n/a
	26	12	7	292	23		68	11.5	10	327	n/a
	27	7.6	29	332	n/a		69	11.5	16	337	n/a
	28	7.6	16	n/a	n/a		70	3	14	341	n/a
	29	5.5	24	n/a	n/a		71	3	22	n/a	n/a
	30	5.5	13	n/a	n/a		72	5	18	360	n/a
	31	4.5	7	n/a	99		73	4	13	n/a	n/a
	32	4.5	17	n/a	100		74	3	27	360	n/a
	33	0.8	11	8	n/a		75	3	18	n/a	n/a
	34	0.8	30	352	54		76	1.2	13	n/a	n/a
	35	4.5	20	2	98		77	1.2	17	n/a	n/a
	36	5.5	10	286	33		78	2	14	n/a	n/a
	37	9.5	10	154	34		79	8	20	n/a	n/a
	38	5.5	23	352	n/a		80	4	16	n/a	n/a
	39	5.5	20	348	n/a		81	2.4	11	n/a	n/a
	40	0.6	13	n/a	n/a		82	4.5	17	n/a	n/a
	41	0.6	26	n/a	n/a		83	2	11	325	n/a
	42	4	14	n/a	n/a		84	3	12	n/a	n/a

Table A4.2 continued.

Location	Tree number	Distance to nearest tree	Max width of trunk (cm)	Long axis orientation (degrees)	Height of exposed tree stump (cm)	Location	Tree number	Distance to nearest tree	Max width of trunk (cm)	Long axis orientation (degrees)	Height of exposed tree stump (cm)
KG 4923 cont.	85	3	19	308	n/a	KG 4928 cont.	28	2	19	167	n/a
	86	2	15	202	n/a		29	3	21	n/a	n/a
	87	5	20	n/a	n/a		30	5	18	n/a	n/a
	88	1.8	17	n/a	n/a		31	5	11	n/a	n/a
	89	1.8	19	313	n/a		32	4.5	32	132	n/a
	90	2.4	15	322	n/a		33	1.8	15	n/a	n/a
	91	2.4	10.5	325	n/a		34	1.8	14	n/a	n/a
92	92	24	16	n/a	n/a		35	3	10	n/a	n/a
KG4926	93	34	26	348	n/a		36	3	23	188	n/a
	94	12	21	n/a	12		37	2	21	n/a	n/a
	95	5	9	360	n/a		38	2	19	n/a	n/a
	96	7	14	275	n/a		39	1.6	23	117	n/a
	97	5	19	318	n/a		40	2	18	204	n/a
	98	5	10	n/a	n/a		41	1.8	15	n/a	n/a
	99	3.5	n/a	n/a	n/a		42	4	18	n/a	n/a
KG 4927	1	21	14	n/a	n/a		43	4	12	288	n/a
	2	21	30	180	20		44	3.5	13	238	n/a
	3	21.5	35	280	14		45	3.5	19	n/a	n/a
	4	3.5	16	282	10		46	9.5	12	252	n/a
	5	2.5	23	322	n/a		47	6	9.5	4	n/a
	6	2.5	29	297	n/a		48	14	40	145	n/a
KG 4928	7	48.5	20	164	n/a		49	2.5	15	158	n/a
	8	8.5	18	n/a	n/a		50	2.5	36	158	n/a
	9	8.5	12	n/a	n/a		51	11.5	20	147	n/a
	10	18	15	n/a	n/a		52	2.5	9	n/a	n/a
	11	18	21	n/a	n/a		53	2.5	11	107	n/a
	12	29	18	n/a	n/a		54	3.5	12	n/a	n/a
	13	14.5	23	172	n/a		55	3.5	30	136	n/a
	14	10.5	17	n/a	n/a		56	4	21	n/a	n/a
	15	8.6	10	n/a	n/a		57	6.5	18	n/a	n/a
	16	8.6	4.5	227	n/a		58	15	20	n/a	n/a
	17	4.5	21	164	n/a		59	15	12	214	n/a
	18	4.5	15	157	n/a		60	18	20	n/a	n/a
	19	9	11	n/a	20		61	3.5	16	238	n/a
	20	15	26	229	n/a		62	3.5	10	269	n/a
	21	11.5	15	262	n/a		63	1.5	14	224	n/a
	22	6	11	292	n/a		64	2.5	13	244	n/a
	23	7	15	n/a	n/a		65	2.5	16	258	n/a
	24	2	20	204	n/a		66	8.7	27	338	n/a
	25	1.5	17	n/a	n/a		67	8	20	360	n/a
	26	1.5	14	186	n/a		68	14	23	344	n/a
	27	2	20	165	n/a		69	2.5	23	278	n/a

Table A4.2 continued.

Location	Tree number	Distance to nearest tree	Max width of trunk (cm)	Long axis orientation (degrees)	Height of exposed tree stump (cm)
KG 4928 cont.	70	2.5	27	327	n/a
	71	2.5	36	n/a	n/a
	72	12	20	308	n/a
KG 4929	73	3.5	11	130	n/a
	74	3.5	21	n/a	n/a
	75	4	25	n/a	n/a
	76	10.5	31	358	n/a
	77	3.3	3.5	84	n/a
	78	3.3	4	n/a	n/a
	79	15.5	14	n/a	n/a
	80	3	2.3	132	n/a
	81	4	11	212	n/a
	82	4.5	6	232	n/a
	83	20	20	319	n/a
	84	3	10	n/a	n/a
	85	3	20	214	n/a
	86	5	9	n/a	n/a
	87	2.5	29	152	n/a
	88	2	24	153	n/a
	89	2	26	n/a	n/a
	90	6.5	33	338	n/a
	91	3.5	31	346	n/a
	92	3	23	n/a	n/a
	93	12.5	16	277	n/a
	94	16.5	19	179	n/a
	95	3	12	n/a	n/a
	96	3	20	310	85
	97	5.5	16	n/a	n/a

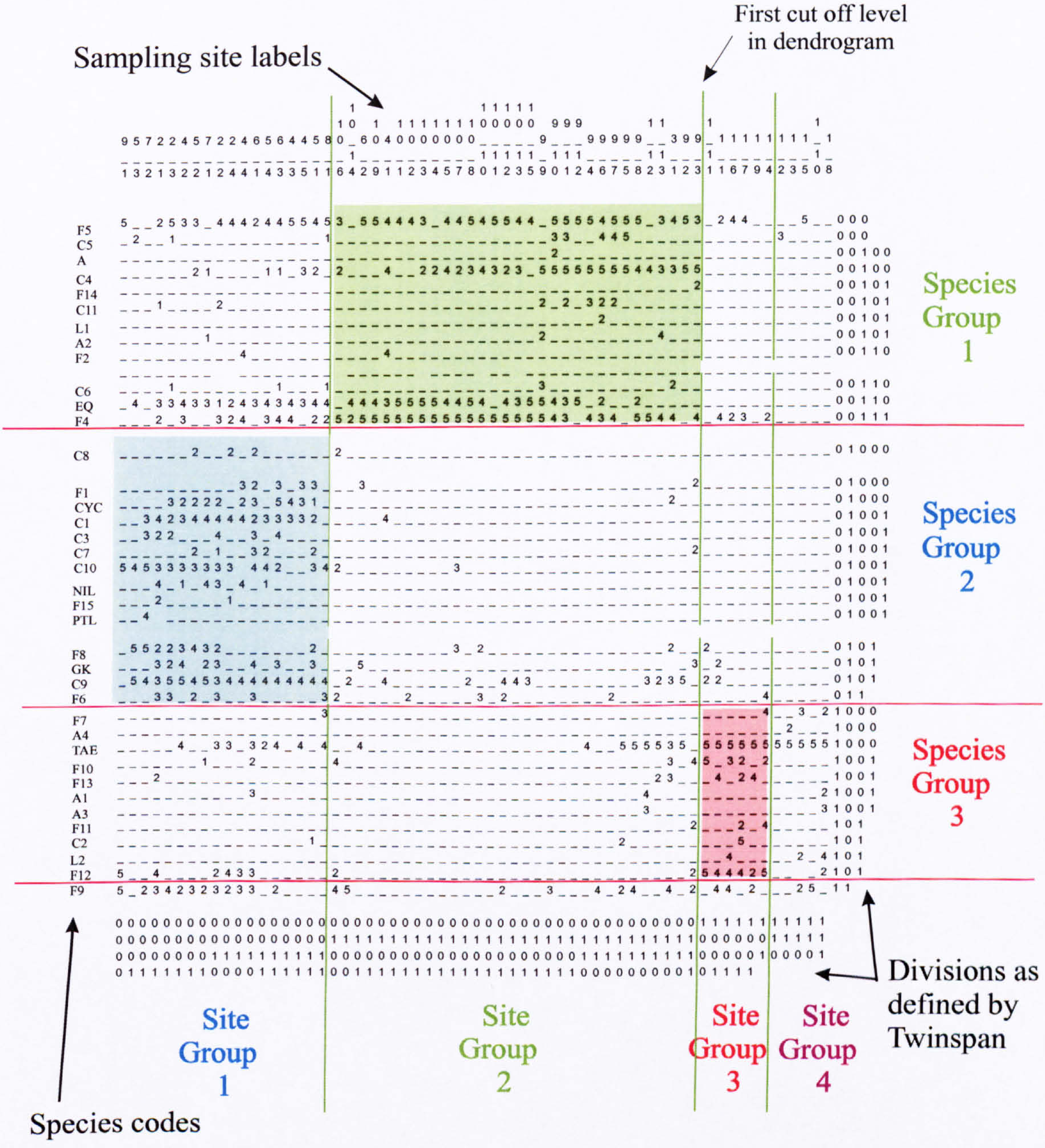
Table A4.3 Table summarising the main features of the single plant sampling locations For lithofacies key see Chapter 2. For locality descriptions see Table A2.1, Appendix 2.

Location	Nunatak	Number of sample sites	Metres between sites	Description of plant bed location	Plant bed facies	Plant bed colour	Plant bed structure	Overlying facies	Underlying facies	Sedimentary log plant bed occurs on
KG 4905	N.Citadel Bastion	2	50	Within a 2.4 m cliff section. Lateral extent 50 m	Z	Dark grey	Laminated and thinnley bedded	Shl	Sf- forming rootlet bed	Equivalant of 52 m on Log 2
KG 4906	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	ZS	Dark grey	Horizontal laminations	Sf	Sgi - with peds on upper surface	1m on Log 2
KG 4907	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	MSf	Black	Thinnly bedded	Su	Shl- forming rootlet bed	5-6 m on Log 2
KG 4908	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	MSf	Black	Thinnly bedded	Shl	Sf- forming rootlet bed	19.5 m on Log 2
KG 4910	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	Z	Grey	Structureless	ZS	ZS - with peds on upper surface	62 m on Log 2
KG 4911	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	ZS	Light Grey	Thinnly bedded	Shl	Sxl - rootlets and plant debris	72.5 m on Log 2
KG 4913	N.Citadel Bastion	1	n/a	Within the sedimentary log section KG 4906	Z	Light Grey	Thinnly bedded	Smg	Sxb	84 m on Log 2
KG 4938	Titan Nunataks	2	150	Within a 2.5 m cliff section. Laterally covered by scree	Z	Dark grey	Stuctureless	ZS	Sf- forming rootlet bed	Equivalant of 70 m on Log 9
KG 4942	Titan Nunataks	1	n/a	Within a 7 m cliff section.Little lateral extent	ZS	Grey	Thinnly bedded	Sf	Sf- with some rootlets	Equivalant of 57 m on Log 9
KG 4944	Titan Nunataks	1	n/a	Within 20 m cliff section.	Sf	Dark grey	Horizontal laminations	M	P	Equivalant of 88 m on Log 8

Table A4.4 Summary table of plant counts from the ten single plant sample locations. For locality descriptions see Table A2.1, Appendix 2.

Location	4905		4906	4907	4908	4910	4911	4913	4942	4944	4938	
Station	1	2									1	2
FERNS												
Phyllopteroides antarctica	1	7								3		
Sphenopteris sanjuliensis												
Matonia jeffersonii												
Sphenopteris warragulensis		8	3		1	7	2	5	4	18		
Aculea acicularis		2	7		2		2		23	12		
Microphyllopteris unisorus	3		7					14	11			
Tetragleichenites acuta	3	10							7			
Cladophlebis drinnanii					1					4	6	12
Cladophlebis oblonga				2				3		12	4	2
Cladophlebis gallentiensis										9	1	
Cladophlebis macloughlinii												
Cladophlebis dissectus												
? Marsileaceae										7		
Adiantitephyllum serrata						2	3					
Hausmannia papilio												
CONIFERS												
Podozamites binatus					1					4	21	5
Athrotaxites ungeri		1										
Araucaria chambersii												3
Araucaria alexandrensis	2									5	1	
Araucarites wollemiaformis									2			
Cone Stem									2	2		
Bellingshausium willeyii									5			
Elatocladus confertus												
Elatocladus linearis	14				1	4			20	8	21	8
Brachyphyllum	1	7		7	2	7	3		13		8	18
Pagiophyllum sp.1		1			3							
LIVERWORTS												
Hepaticites.sp1							2	3				
Marchantites taenioides						3	2					
Marchantites rosulatus												
ANGIOSPERMS												
Hydrocotylophyllum alexandri								1				
Gnafalea jeffersonii						3		2			1	
Araliaephyllum quinquelobatus								1				
Timothyia trinervis		1						1				
OTHERS	1											
Cycadophyte									1	3	3	
Ginkgoites						4	3	4			3	
Ptilophyllum												7
Nilssonia											23	
Taeniopteris daintreei		3							12	8		
Equisetales									12		8	
TOTAL	**25**	**40**	**17**	**9**	**11**	**30**	**17**	**34**	**112**	**95**	**100**	**55**

Table A6.1 A species -by-site table showing the results of Twinspan. The species codes are those defined in Table 6.1, Chapter 6. The sampling site labels are explained in Figure 6.2, Chapter 6. The numbers within the table are the occurrence of each plant species at each sampling site. For example at sampling site 9_1 (first sampling site in table), 5 fossils of the species F5 (*Aculea acicularis*) occurred. Four sampling site groups and four plant species groups were identified (labelled). The shaded areas correspond to the sampling site group and plant speices group of the same colour. For example species group 1 (in green) characterises the sampling sites in site group 2 (in green) and is represented by the shaded green area. The red and green lines show the cut off levels as defined by the branches of the dendrogram in Figure 6.1, Chapter 6. For example the first branch in Figure 6.1 separates 49 sampling sites (to the left of sampling site 9_3) from the other 11 sampling sites (to the right of sampling site 9_3), which is the divide between 0 and 1 (at bottom of diagram)



```
                         1          11111
                        10 1 111111100000 999     11   1        1
      9572245722465644580_6040000000_____9___99999__399_11111111_1
      ___________________1__________11111_111_____11___1_________1_
      132132212441433511642911234578012359012467582312311679423508

F5    5__2533_44424455453_554443_44545544_55554555_3453_244____5__ 000
C5    _2__1____________1__________________33__445____________3____ 000
A     ____________________________________2_______________________ 00100
C4    ______21____11_32_2___4__224234323_55555555443355___________ 00100
F14   _________________________________________________2__________ 00101
C11   ___1____2__________________________2_2_322__________________ 00101
L1    ________________________________________2___________________ 00101
A2    _______1___________________________2_________4______________ 00101
F2    __________4___________4_____________________________________ 00110
      ________  ________ ______ ____ __ __________________________
C6    ____1________1___1_________________3__________2_____________ 00110
EQ    _4_334331243434344_444355554454_4355435_2__2________________ 00110
F4    ___2_3__324_344_2252555555555555555543_434_5544_4_423_2_____ 00111
C8    ______2__2_2______2__________________________________________ 01000
F1    __________32_3_33___3___________________________2___________ 01000
CYC   ____32222_23_5431_____________________________2_____________ 01000
C1    __342344444233332_____4_____________________________________ 01001
C3    __322___4__3_4______________________________________________ 01001
C7    ______2_1__32___2_______________________________2___________ 01001
C10   5453333333 442__342_________3____________________ __________ 01001
NIL   ___4_1_43_4_1_______________________________________________ 01001
F15   ___2_____1__________________________________________________ 01001
PTL   __4 ________________________________________________________ 01001
F8    _55223432_______2___________3_2_______________2__2__________ 0101
GK    ___324 23__4_3__3___5_________________________ _3_2_________ 0101
C9    _54355453444444444_2__4______2__443_________3235_22_________ 0101
F6    ___33_2_3__3_____32_____2_____3_2________2____________4_____ 011
F7    _________________3__________________________________4__3_2 1000
A4    ________________________________________________________2___ 1000
TAE   _____4__33_324_4_4__4__________________4__555535_5555555555 1000
F10   _______1___2______4___________________________3_45_32_2_____ 1001
F13   ___2_______________________________________23___4_24______ 1001
A1    ___________3______________________________4______________2 1001
A3    __________________________________________3______________3 1001
F11   ________________________________________________2___2_4_____ 101
C2    ________________1_________________________2_______5_______ 101
L2    ___________________________________________________4_____2_4 101
F12   5__4____2433______2_____________________________2544425__ _2 101
F9    5_2342323233_2____45____________2___3___4_24__4_2_44_2___25_ 11

      000000000000000000000000000000000000000000000000011111111111
      000000000000000000111111111111111111111111111111100000011111
      000000001111111111000000000000000000000111111111100000100001
      0111111100001111110011111111111111111110000000001011111
```

Cretaceous Research (2001) 22, 779–793
doi:10.1006/cres.2001.0286, available online at http://www.idealibrary.com on IDEAL®

Palaeoecology and taxonomy of Pentoxylales from the Albian of Antarctica

***†Jodie Howe and †David J. Cantrill**

**The University of Leeds, Department of Earth Sciences, Leeds LS2 9JT, UK; e-mail: J.Howe@earth.leeds.ac.uk*
†British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 OET, UK; e-mail: DJCA@pcmail.nerc-bas.ac.uk

Received manuscript accepted 5 October 2001

Reproductive pentoxylalean material from the Albian Triton Point Formation, Fossil Bluff Group of Alexander Island, Antarctica is the youngest record of this group globally. Leaves are referred to *Taeniopteris daintreei* McCoy, ovulate reproductive organs to *Carnoconites cranwelli* Harris, and stem material to *Pentoxylon* sp. Occurring in leaf litter layers on palaeosol surfaces the sedimentology suggests that pentoxylalean plants grew upon areas of the floodplain distal to the river channel, where they covered the forest floor in a similar habit to modern brambles. The forest floor was shared with Equisetales and liverworts, an abundance of ferns [*Cladophlebis* Brongniart, *Gleichenites* Goeppert, *Phyllopteroides* Medwell, *Sphenopteris* (Brongniart) Sternberg], as well as angiosperms. Bennettitales, *Ginkgoites* Seward and *Nilssonia* Brongniart were rare within these communities, as were coniferous trees.

Key Words: Pentoxylales; *Pentoxylon*; *Taeniopteris*; *Carnoconites*; Antarctica; Albian.

1. Introduction

Pentoxylales were first instituted by Sahni (1948) for petrified fossil leaves (*Nipaniophyllum* Sahni, formerly *Taeniopteris spatulata* McClelland), stems (*Pentoxylon* Srivastava) and ovulate reproductive organs (*Carnoconites* Srivastava), found in the Upper Jurassic–Lower Cretaceous Rajmahal Formation of India (Vijaya, 1999). The pollen organ (*Sahnia* Vishnu-Mittre) was later described by Vishnu-Mittre (1953) from the same locality. Although no organic connection has ever been found linking the different organs, they have been established as belonging to the same plant based on anatomy and the frequent association of the parts at the same locality (Sahni, 1948; Vishnu Mittre, 1957; Harris, 1962; Bose *et al.*, 1985; Drinnan & Chambers, 1985).

Now known to be widespread across Gondwana from the Jurassic to Early Cretaceous (Drinnan & Chambers, 1985), Pentoxylales formed a distinctive element in the Southern Hemisphere vegetation. *Taeniopteris* Brongniart leaves and ovulate reproductive organs are found in Jurassic rocks of Waikato Head and Malvern Hills, New Zealand (Arber, 1917; Harris, 1962; Blaschke & Grant-Mackie, 1976). Pentoxylalean pollen and ovulate organs occur co-fossilized with *Taeniopteris* leaves in the Lower–Middle Jurassic Talbragar Fish Beds of New South Wales, Australia (White, 1981), while Lower Cretaceous rocks in Victoria, Australia, have yielded leaves along with ovulate and pollen organs (Drinnan & Chambers, 1985). Sterile *Taeniopteris* leaves have also been described from Lower Cretaceous rocks in South Africa (Anderson & Anderson, 1985). Recently pentoxylalean material has been described from Antarctica, where both *Taeniopteris* foliage and *Carnoconites* co-occur in Aptian rocks of the Byers Peninsula (Césari *et al.*, 1998).

Although there are relatively few records of reproductive material, *Taeniopteris* foliage is widely distributed in the Jurassic and Cretaceous of India, South Africa, Australia and New Zealand, and even of Vietnam, Sri Lanka and Korea; however, some of the determinations are unconvincing (Harris, 1962). Harris (1962, p. 26) attributed this wide use of the term *Taeniopteris* for Southern Hemisphere foliage with similar gross morphology to the Pentoxylales, as a 'fashion', with much of the material possibly related to the cycadophytes and Bennettitales rather than the Pentoxylales. Although this remains to be substantiated, some of the earlier records of *Taeniopteris* in Australia, such as *T. crassinervis* (Feistmantel)

0195–6671/01/060779+15 $35.00/0

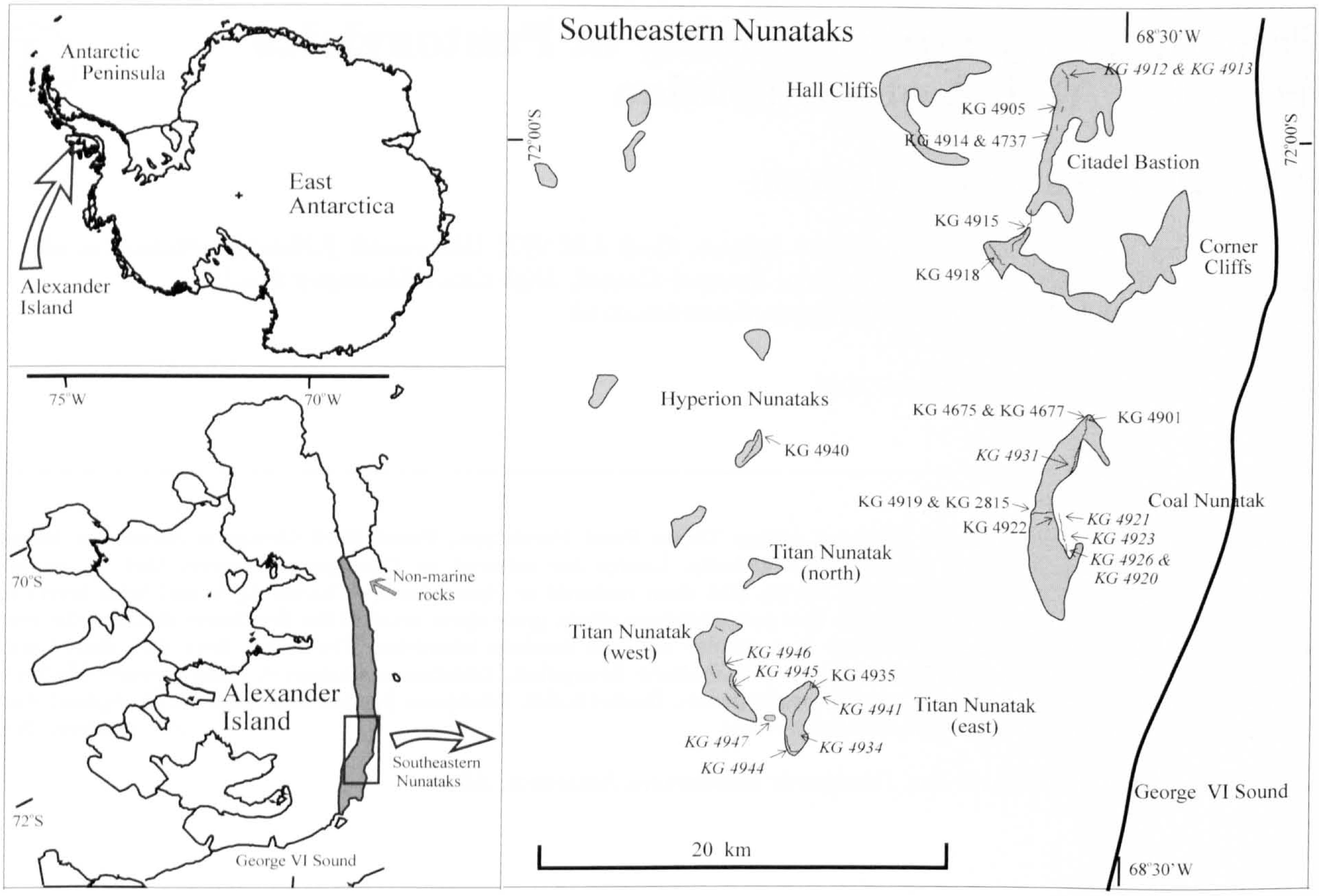


Figure 1. Location map for Alexander Island, Antarctica, showing the position of all localities mentioned in the text. Site numbers in normal type (e.g., KG 4901) are locations where samples of pentoxylalean plant material were taken. Site numbers in italics (e.g., *KG 4912*) are locations where *Taeniopteris* foliage was recorded.

Walkom, have been demonstrated to belong to pteridophytes (Webb, 1983). Thus caution is needed when attributing *Taeniopteris* foliage to the Pentoxylales.

New specimens of *Taeniopteris daintreei, Carnoconites cranwelli* and *Pentoxylon* are described here from Albian rocks of Alexander Island, Antarctica. The association of leaves, female reproductive organs and stem material establishes their pentoxylalean affiliation, and their occurrence in the Albian marks the youngest record of this group based on reproductive material. The material was recovered from *in situ* leaf litter layers at the top of palaeosols, and in sequences of fine-grained sandstones and siltstones exposed on four nunataks at the southeastern end of Alexander Island (Figure 1). These nonmarine rocks form the Triton Point Formation (Nichols & Cantrill, in press) within the Fossil Bluff Group. The palaeoecology of the pentoxylalean plants is established from the association and relationship of the material to sedimentary facies, in conjunction with frequency distributions of the pentoxylalean material, and associations with other types of flora laterally along individual leaf litter layers.

2. Material and methods

All reproductive Pentoxylales specimens, along with foliage, were collected from the southeastern nunataks of Alexander Island, Antarctica (Figure 1). The specimens are housed at the British Antarctic Survey and are assigned British Antarctic Survey numbers (prefix KG for Alexander Island). Largely preserved as impressions, the material occurs in dark grey siltstones and fine-grained sandstones on the tops of palaeosol horizons. No cuticle material was preserved but details of venation can be seen in some specimens, and cell structure can be seen in the ovulate organs preserved in siltstones. Detailed sedimentary logging and mapping was undertaken to establish sedimentary facies to aid in the determination of relationships between pentoxylalean occurrence and sedimentary environment. In the laboratory, material was photographed under a low-angle incident light with an

Olympus SZH10 stereo dissecting microscope and camera attachment. Kodak Technical Pan (2415) black and white film was used.

3. Systematic palaeontology

Order: Pentoxylales

Genus *Taeniopteris* A. Brongniart, 1828

Taeniopteris daintreei F. McCoy, 1874
Figure 2

Synonymy of Antarctic Taeniopteris

1981 cfA *Taeniopteris daintreei* McCoy; Jefferson pp. 95–99, pl. 4.10, pl. 4.11, figs 1–4.
1981 TAENIOPT-TENUIS Jefferson, pp. 99, 100, pl. 4.11, fig. 8.
1982 cf. *Taeniopteris daintreei* McCoy; Jefferson, pl. 1g.
1983 cf. *Taeniopteris daintreei* McCoy; Jefferson, fig. 5 (4–5).

Lectotype. Taeniopteris daintreei selected by Drinnan & Chambers (1985): NMVP12270, National Museum of Victoria. Strzelecki Group, Lower *Phyllopteroides serrata* Zone (?Barremian – Aptian), Cape Paterson, Victoria.

Description. Fragments of leaves ranging in size from less than 10 mm wide by 50 mm long up to 30 mm wide by 135 mm long. Leaves simple, linear, oblanceolate and petiolate. Petiole 1 mm thick, continuing into the leaf at a constant thickness to form the mid-vein. Secondary veins parallel, arising from the mid-vein at angles of 70–90°, exceptionally 60–110°, dichotomizing near to the mid-vein. Secondary vein density is on average 28 per 10 mm, measured midway between the mid-vein and leaf margin. Leaf margin entire or gently undulate, lobed margins occurring rarely. The margin tapers to a narrowly luneate base over a length of 32 mm, and terminates distally either in a pungent, narrowly acute or blunt, retuse apex.

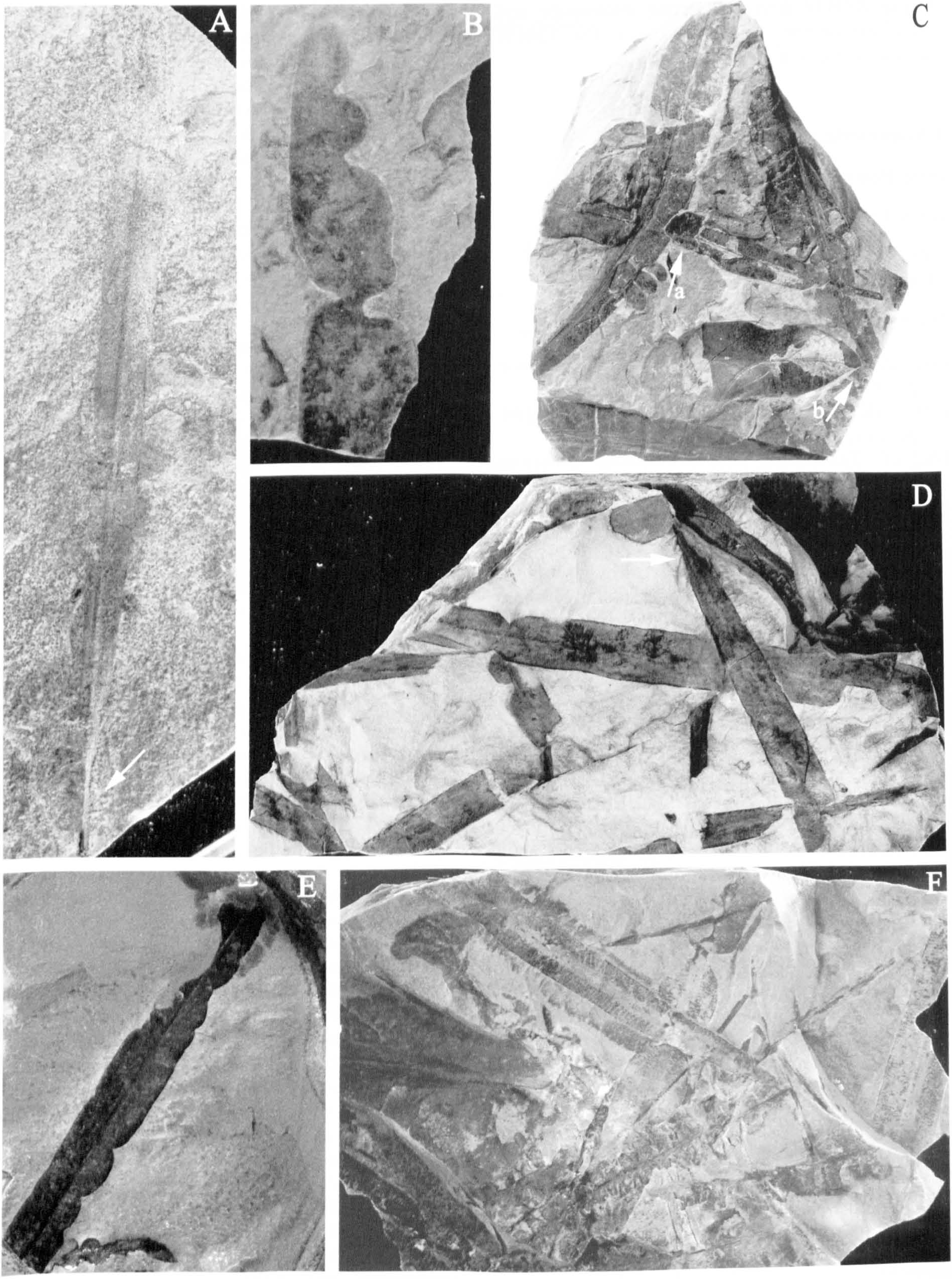
Specimens examined. Thirty-eight specimens as follows: KG 2815.54, .141–143, .147, .148, .149, .154, .156, .158, .167, .172, .173, .181, KG 4675.8, KG 4677.3, KG 4737.5, .6, .13, .26, .31, .38, .75, .76, .106, .113, .120, .131, .133, .148, .152, KG 4901.1, KG 4905.2, .5, KG 4919.31, KG 4922.2, KG 4935.16a, KG 4940.16 from Citadel Bastion, Coal Nunatak, Titan Nunatak and Hyperion Nunataks, Alexander Island, Antarctica.

Variation of Alexander Island specimens. The leaf fragments occur preserved in either very fine-grained, grey sandstones or fine siltstones (Figure 2). No available specimens were complete. The leaf base is symmetrical (Figure 2A) and terminates in a short petiole (KG 4737.113), which is 1 mm wide at the base. The petiole continues on through the leaf as the mid-vein, which is on average 1.2 mm thick within the narrow leaves, but varies from 1 to 1.75 mm thick. Within wider leaves the mid-vein is on average 1.6 mm, with a range from 0.5 to 2.5 mm. This thickness remains constant until it reaches the apex of the leaf where it either narrows and then terminates, or narrows until it peters out at the apex.

Secondary veins arise from the mid-vein at an angle of between 60 and 110°. No correlation was found between the angle of the secondary veins and any other feature of the leaf such as width or length. The density of secondary veins varies from 22 to 44 per 10 mm. There is little variation in vein density within individual leaves; if any, it is merely by two or three veins more or less per 10 mm. No correlation was found between vein density and leaf width, as described in the Victorian *Taeniopteris* specimens (Drinnan & Chambers, 1985). Secondary veins dichotomize once close to the mid-rib and extend to the leaf margin.

The leaf margin is predominantly entire with a smooth straight outline. In some cases small notches occur along the leaf margin (specimens KG 4937.133 and KG 4919.31), probably as a result of damage to the leaf during development. Two specimens, 7.7 mm and 7.3 mm wide (KG 4737.6 and KG 4935.16a), have margins that appear to be lobed (Figure 2B, E). The lobes are curved indentations that are both regular in size, shape and distribution, and it is possible that these specimens represent a distinct species. However, as the material is limited (two specimens) they are retained in *T. daintreei.*

Leaf apices are preserved in 15 specimens; eight are pungent or narrowly acute and seven are blunt to retuse (e.g., KG 2815.54). The angle of the apex within acute specimens ranges from 70 to 83°, and blunt specimens from 25 to 50°. There appears to be a correlation between the angle of the apex and the size of the leaf. Seven of the acute leaves are within the size range of <10 mm wide by 50 mm long (Figure 2B, D). Four of the blunt leaves are the wider specimens at 30 mm wide by 135 mm long (Figure 2C). However two specimens that have blunt apices are also the smallest leaves found (3 mm wide and a maximum of 80 mm long), and one specimen of the wider leaves has an acute apex (Figure 2C). This relationship may outline four different species of


A
B
C
a
b
D
E
F

Taeniopteris, leaves from different parts of the plant or a different expression of characters during phases of leaf expansion or plant development (discussed below).

Comparisons. Many different species of *Taeniopteris* have been described from the Southern Hemisphere including India (Sahni, 1948; Vishnu-Mittre, 1957), New Zealand (Blaschke & Grant-Mackie, 1976), Australia (Drinnan & Chambers, 1985), South Africa (Anderson & Anderson, 1985), South America (Baldoni & de Vera, 1980) and Antarctica (Hernández & Azcárate, 1971; Césari *et al.*, 1998, 1999; Cantrill, 2000). McCoy first described *Taeniopteris daintreei* in 1874 from Lower Cretaceous strata in Victoria (Australia), and Jurassic specimens were later described from New Zealand by Arber (1917). Drinnan & Chambers (1985) assigned specimens from Victoria to *T. daintreei*, preferring not to use *Nipaniophyllum* Sahni, as this diagnosis was based on vascular anatomy that was unavailable in the Victorian specimens. It has long been considered that *Nipaniophyllum raoi* Sahni from the Rajmahal Hills, India (previously known as *T. spatulata*) is conspecific with *T. daintreei* (Chapman, 1909; Medwell, 1954). This is supported by the overlapping range in the leaf size and shape of *N. raoi*, as described by Vishnu-Mittre (1957), with the Victorian specimens described by Drinnan & Chambers (1985) and the Alexander Island specimens described here.

Taeniopteris daintreei leaves described from Victoria (Drinnan & Chambers, 1985) are almost identical to the Alexander Island specimens. Drinnan & Chambers (1985) described two variations of leaf size and shape. One leaf form is larger and wider (30 mm wide by 300 mm long), with undulating margins, obtuse apices and dichotomizing secondary veins. The other is a narrower leaf, 10 mm wide by 100 mm long that tends to have straight margins, acute apices and secondary veins that are less dense than the wider leaves. This vein density-size correlation was not seen in the Alexander Island specimens. However, there are two different size classes present. This variation may be related to the growth habit of the plant with its long shoot, short shoot system. For example, in extant *Ginkgo biloba* short shoots produce the typical leaf form, but where the shoot system is damaged or when short shoots elongate and become long shoots the leaves produced on the elongate long shoot are often larger and more dissected (D. Cantrill, pers. obs.). This may explain why there is often a large variation in leaf morphology within deposits containing *Taeniopteris*.

The association of *T. daintreei* with the ovulate organs *Carnoconites cranwelli* has been noted by Harris (1962) and Blaschke & Grant-Mackie (1976) in specimens from Port Waikato, New Zealand. Blaschke & Grant-Mackie (1976) considered the *Taeniopteris* foliage from Port Waikato beds to be identical to *T. daintreei*, and although organic connection to reproductive organs was not found, they are co-preserved with the ovulate organs. The assignment of the Alexander Island specimens to the species *T. daintreei* is further supported by their occurrence with *C. cranwelli*. *Taeniopteris daintreei* has also been described from the Lower Cretaceous rocks of Western Australia (McLoughlin, 1996). He described foliage with obtuse apices up to 20 mm wide with secondary veins arising from the mid-axes at >60°. No reproductive organs were found with these specimens.

Taeniopteris spatulata has been described from the Lower–Middle Jurassic Talbragar Fish Beds in New South Wales (White, 1981), and from the Middle Jurassic Walloon Coal Measures in Queensland (McLoughlin & Drinnan, 1995). This species of *Taeniopteris* is very similar to the Alexander Island specimens in size and vein structure. Although the specimens from the Walloon Coal Measures are described as being spathulate in shape (McLoughlin & Drinnan, 1995), the leaves are very narrow with tapering, acute bases and appear to have the same elongate obovate shape as some of the *T. daintreei* specimens described here. *Taeniopteris lobatus* described by Cantrill from the Lower Cretaceous rocks of Snow Island (Cantrill, 2000), Antarctica, are very different in shape from the majority of specimens from Alexander Island. Cantrill (2000) described the specimens as lanceolate to spathulate, 4.6–9 mm wide with a lobed leaf margin and acute apex. This is comparable to two specimens (KG 4737.6, KG 4935.16a) found on Alexander Island and it may be appropriate to assign these to the *T. lobatus* species. However, out of the two specimens described from Antarctica, only one of them (KG 4937.6) has the apex present, and that is only 30 mm long; it is, therefore, still uncertain as to which species these two specimens belong.

Figure 2. *Taeniopteris daintreei.* A, KG 4737.108, tapering of the leaf base (arrow); × 1.5. B, KG 4737.6, a narrowly acute apex; × 2.5. C, KG 2815.149, wider variety leaves with blunt (arrow a) and acute (arrow b) apices; × 0.75. D, KG 4737.76, collection of leaf fragments, one with a pungent apex (arrow); × 1.1. E, KG 4935.16a, lobed leaf margin; × 1.25. F, KG 4737.106, collection of leaf fragments with distinct high angle, straight, secondary veins; × 1.75.

Taeniopteris has been rarely recorded from South America where it is known from the southern part of the continent (Baldoni & de Vera, 1980). Three species have been recorded: *T. argentinica* Feruglio, *T. dissecta* Baldoni & de Vera, and *T. patagonica* Feruglio. *Taeniopteris dissecta* is lobed and appears more similar to genera such as *Nilssonia* or *Nilssoniopteris* (Cantrill, 2000) rather than the material described here. Both *T. argentinica* and *T. patagonica* are small, strap-shaped leaves similar to our material. However, they are poorly circumscribed and it is difficult to compare them further.

Fragments of leaves assigned at the generic level to *Taeniopteris* have been described from Upper Cretaceous rocks of Queensland (McLoughlin *et al.*, 1995), Lower Cretaceous rocks of Southern Africa (Anderson & Anderson, 1985), and more recently from the Lower Cretaceous of the Byers Peninsula (Cesari *et al.*, 1998). The limited material and generally poor preservation makes comparison with our material difficult.

Genus *Carnoconites* Srivastava, 1944

Carnoconites cranwelli Harris, 1960
Figure 3D–G

1962 *Carnoconites cranwelli* Harris, p. 20; pl. 1, figs 1–7; pl. 2, figs 1–3; pl. 3, figs 1–6; text-figs 2A, B, 3A–E.
1985 *C. cranwelli* Harris; Drinnan & Chambers, pp. 93–95, figs 5–8.

Holotype. V35779, British Museum (Natural History), Huriwai Formation, Middle–Late Tithonian (Late Jurassic); Port Waikato, New Zealand.

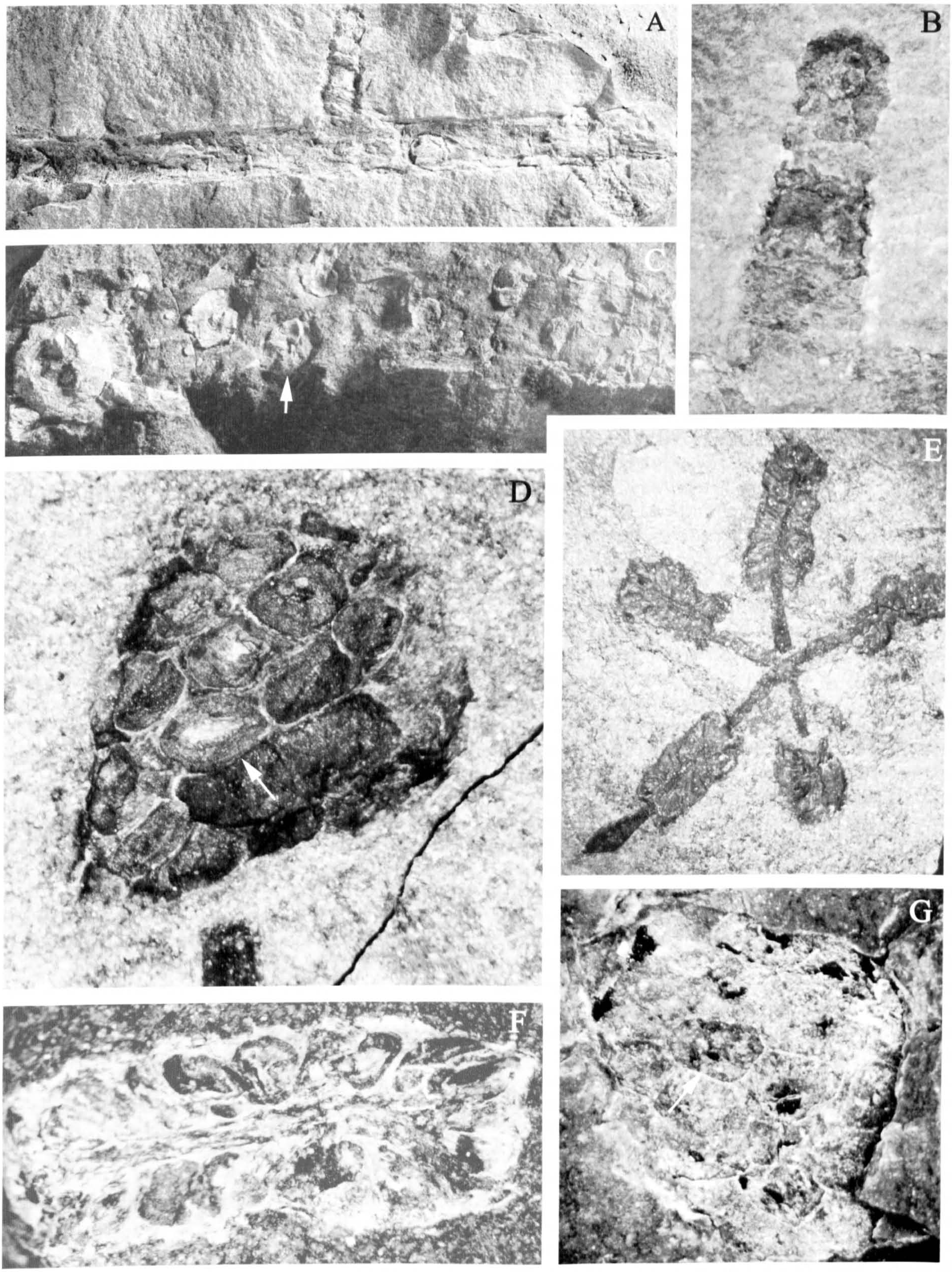
Description. Short shoot up to 7 mm long by 5.5 mm in diameter, bearing up to 23 pedunculate organs in a crowded helical arrangement. Pedicel up to 13 mm long by 1.6 mm wide, terminating in an ovulate structure that is elongate and ovoid in longitudinal outline, up to 7 mm long by 4.5 mm wide. The ovulate organs have at least 37 spirally inserted, apparently sessile, erect ovules attached to a central axis that is 0.5 mm wide. Ovules are 1.5 mm long by 1 mm wide and oval in longitudinal section. Viewed from the outer surface the ovules are rhomboidal or hexagonal in shape, with the micropyle located in the centre of the distal face.

Specimens examined. Nine slabs as follows: KG 4737.145, .146, .147, 4905.1, .16, 4914.13, 4915.9, 4918.6, from Citadel Bastion, and one specimen, KG.4901.4, from Coal Nunatak, Alexander Island, Antarctica.

Variation of Alexander Island specimens. Ovulate organs and attachments are preserved as impressions in fine-grained silt. Eight specimens show the ovulate organs and pedicels attached to a short shoot. The short shoot occurs as a transverse section in all instances except one (KG 4914.13b), which occurs as an oblique longitudinal section of the short shoot. In four of the specimens (KG 4905.1a, KG 4905.1d, KG 4905.16) the short shoot is 2.4 mm long by 1.6 mm wide with a maximum of five pedicels with attached ovulate organs visible (Figure 3E). In the other four specimens (KG 4737.147, KG 4918.6, KG 4915.9, KG 4914.13b) the shoot is 5.5 mm long by 4.8 mm wide with up to 23 pedicels attached, but not all pedicels terminate in ovulate structures, suggesting that the ovulate structures were shed. The pedicels and ovulate organs are inserted spirally on the short shoot axis.

Ovulate organs vary in shape from a round, elongate-ovoid to a shorter, round-oblong shape, although the majority are the former (Figure 3D, F). Both shapes have been found attached to the same short shoot (Figure 3E) and it appears that the variation in shapes is largely a result of the compaction processes. Ovulate organs vary in size from 14 mm long by 8.5 mm wide to 2.6 mm long by 2.2 mm wide. The majority (60%) of the organs are preserved with the outer faces visible (Figure 3G), the rest (40%) as longitudinal sections through the organ (Figure 3F). A few specimens (KG 4905.1e, KG 4905.16) are preserved showing both the outer surface and a section through the organ. Where a longitudinal section of the ovulate organ was observed, the pedicel continues through the organ as a centrally positioned axis, with a constant thickness, terminating beneath the uppermost ovule. Ovules observed in longitudinal sections are generally ovoid to obovoid in shape (Figure 3F).

Figure 3. A–C, *Pentoxylon*. A, KG 4901.1, a long shoot with two short shoots attached; × 1.25. B, KG 4901.1, short shoot with rhomboidal leaf scars; × 4. C, KG 4905.2, unusual long shoot with broken off woody short shoots (arrow); × 2.5. D–G, *Carnoconites cranwelli*. D, KG 4905.1d, a rounded, oblong ovulate organ with the outer surface preserved; some ovules show internal structure (arrow); × 12. E, KG 4905.1a, a section through the top of a short shoot with five pedicels and ovulate organs attached; × 2.5. F, KG 4905.1e, longitudinal section of an elongate ovulate organ with the cone axis and ovules visible; × 10. G, KG 4901.4, outer surface of a circular ovulate organ; ovules with micropyle visible (arrow); × 7.


A
B
C
D
E
F
G

No clear method of attachment of the ovules to the cone axis could be seen, but they are inserted in a distinct spiral arrangement. On average 14 ovules surround the cone axis in longitudinal section but this could be as few as five when an oblique or transverse cross section is preserved (KG 4905.16). The maximum number of ovules was determined from one specimen (KG 4905.1a) where the cone axis of the ovulate structure has scars along its length outlining the attachment of further ovules. This specimen indicates that ovulate organs had at least 37 ovules. Ovules range in size from 3.3 mm long by 3.6 mm wide to just 0.3 mm long by 0.3 mm wide. In two specimens (KG 4905.16, KG 4905.1e) some structure and cell detail of the ovules could be discerned. The ovules appear to have an outer layer that is composed of thick-walled stony cells. The material preserved showing the outer surface of the organ demonstrates that the ovules are normally hexagonal in transverse section but vary to rhomboid or circular. In some ovules the micropyle could be identified in the middle of the outer face as a raised, nipple-like region, with a circular opening in the centre (Figure 3G). These represent immature ovules, as in most specimens the micropylar region is not visible.

Comparisons. There are five previously described species of *Carnoconites*: *C. compactus* Srivastava, *C. laxum* Srivastava, *C. rajmahalensis* (Feistmantel) Bose, *C. llambiasii* Cesari, and *C. cranwelli* Harris. Sahni (1948) described the ovulate organs of *C. compactus* and *C. laxum* from the Rajmahal Hills, India, as being pedunculate and occurring as pairs on bifurcating stalks. However, Vishnu-Mittre (1953) reinterpreted the Indian specimens as arising singularly from a simple shoot, with ovules in a whorled or spiral arrangement. The Alexander Island specimens show a similar arrangement with each organ occurring on a single pedicel, but in the size and shape of the organs they differ greatly. Nearly all the specimens of *C. compactus* are 10–11 mm wide with ovules that are elliptical with acute apices. *Carnoconites laxum* has ovules that are more rounded and oval in shape but the organ itself is 25 mm long.

Bose *et al.* (1985) proposed the species *Carnoconites rajmahalensis* for one imprint that was described by Feistmantel (1877) from the Rajmahal Hills and referred to by Wieland (1911) as *Williamsonia*(?) *rajmahalensis*. This species is thought to be equivalent to *C. laxum* as it is a similar size and thus too long to be compared to the specimens described here.

Harris (1962) described *C. cranwelli* from Port Waikato, New Zealand as oval and compact cones with ovules in alternating whorls. These cones are closely correlated with the specimens described by Drinnan & Chambers (1985) from Victoria, Australia. Both described the ovulate organs as being rhomboidal in shape, 7 mm long by 5 mm wide and occurring on pedicels 20 mm long by 1.5 mm thick. Both the Victoria and New Zealand specimens illustrate up to 12 organs arising from a common base, with each organ having up to 40 ovules (Drinnan & Chambers, 1985). The Alexander Island specimens are almost identical to *C. cranwelli* in size, shape and arrangement of the ovules. The only variation seen in the specimens described here is that the short shoots bear up to 23 organs. Harris (1962) recognised that the pedicels were not arranged in a true whorl but with some placed above the others. Indeed, he assigned each of the 12 pedicels to a different position on the shoot, suggesting a helical insertion. In the specimens described here there is clear evidence that this is the case. Specimen KG. 4905.1a (Figure 3E), for example, shows a short shoot with five pedicels arising from different points along the length of the shoot. This arrangement suggests that the ovulate organs arose from a short shoot along its length in a spiral pattern; coupled with the lack of any branching pedicels, this indicates that the organs did not occur as a dense conical head, as suggested in the reconstruction proposed by Bose *et al.* (1985) for *C. compactus*, but arose from the short shoot, individually and along its full length. The fewer pedicels arising from the Victoria and New Zealand specimens may represent a section higher up the short shoot than the Alexander Island specimens.

The Alexander Island specimens are very similar in size and shape to those previously described from Antarctica by Césari *et al.* (1998). These *C. llambiasii* specimens from the Byers Peninsula are 6 mm long by 5 mm wide, oval, and in some cases compact in shape with up to 35 ovules per organ. Indeed the *C. cranwelli* specimens from Alexander Island only differ from *C. llambiasii* in the arrangement of the organs on the short shoot. Césari *et al.* (1998) described a main pedicel axis with an apical cone, the other organs spirally inserted on short secondary axes. Césari *et al.* (1998) described such attachment from a single specimen (Holotype BAFCPB 16118). It is unclear whether any of the 'secondary axes' are attached to the main axes, or whether it is a group of detached organs with pedicels that have been preserved next to each other in such a way as to suggest they might branch from a long main axis. If the pedicels are not attached to a main axis then *C. llambiasii* from the Byers Peninsula may also be synonymous with *C. cranwelli*.

Genus *Pentoxylon* Srivastava, 1944

Pentoxylon sp.
Figure 3A–C

Description. Long shoot varying in width from 4 to 10 mm, becoming more slender up the shoot, at least 93.7 mm long. Leaf scars subtending short shoots. Short shoots 1.5–4.5 mm long, occurring approximately 16 mm apart. Terminal bud scale scar is 5.8 mm wide by 5.6 mm broad, circular in shape, with rhomboidal leaf scars placed in a dense spiral arrangement, all approximately 1.6 mm long with some smaller scars occurring towards the outer parts of the terminal bud scale. At the distal end, shoot terminates in a rounded terminal bud with leaf scars.

Short shoots branching off the long shoot at an angle of 60–90° in an open helical arrangement. Short shoots are 12–15 mm long by 4–7 mm wide, 6–14 mm apart, and covered with an armour of close-fitting rhomboidal leaf scars similar to those found on the terminal bud (Figure 3B). Leaf scars are spirally arranged, at a shallow angle, around the short shoot and range from 0.7 to 1.5 mm long. Terminal bud at the end of the shoot is 5.25 mm long by 4.25 mm wide.

Specimens examined. Four specimens as follows: KG 4905.2 from Citadel Bastion and KG 4675.4, 4901.1, .4, from Coal Nunatak, Alexander Island, Antarctica.

Variation of Alexander Island specimens. Five long shoots were examined, three with many short shoots attached (Figure 3A). All specimens are preserved in very fine-grained, dark grey sandstone. All three long shoots with attached short shoots show evidence for a leaf scar beneath a short shoot. No long or short shoots are found with organic connection to any reproductive organs but the long shoot on specimen KG 4901.4 is found in very close association with many (14) *C. cranwelli* ovulate organs. Furthermore, a pedicel without an organ attached can be seen directly above the short shoot in this specimen as if it is arising from it. This would suggest that both leaves and reproductive organs were borne on the same shoot. Although no connection is seen in this specimen, previously described material (Bose *et al.*, 1985) has suggested such an association of the organs to a short shoot with leaf scars.

Specimen KG 4905.2 (Figure 3C) is unusual in its appearance; it has a number of circular structures 2.5–5 mm wide that contain small fragments of fossilized wood, with sporadic protrusions that extend away from the long shoot margin. These probably represent small, short, woody shoots that have been broken. Between these woody shoots are small circular hollows, 0.5 mm diameter, that are spirally arranged. Specimen KG 4905.2 may represent an elongating short shoot system with leaf scars and new short shoots. Its close association with *Taeniopteris* foliage suggests that its inclusion in the Pentoxylales shoot material described here is valid.

Comparison. Stem material has only been described previously from the Rajmahal Hills, India (Srivastava, 1944; Sahni, 1948). Vishnu-Mittre (1957) redescribed Sahni's material along with new findings of his own, and more recently Bose *et al.* (1985) described four different types of stems from the Pentoxylales plant. Sahni (1948) described a short shoot (*Pentoxylon sahnii* Srivastava), 5–7.5 mm thick, with close-fitting rhomboidal leaf cushions. The anatomical structure of the petrified stem shows five steles and a well-preserved pith and cortex. Vishnu-Mittre (1957) extended the size range of *Pentoxylon sahnii* to 3–20 mm wide and at least 150 mm long, based on new specimens found in the Rajmahal Hills. He also described short shoot specimens possessing more (8–9) or less (3–4) than the usual number of steles. He assigned his material to *P. sahnii* based on the anatomical structure of his specimens. *Nipaniophyllum* (i.e. *Taeniopteris*) leaves were found enveloped around shoots in sections and suggested to be the pentoxylalean foliage (Srivastava, 1944). This correlation confirms the pentoxylalean affinities of the stem material from India. The Alexander Island short shoots described here are of similar age and are very similar in size, shape and leaf scar pattern to those of *P. sahnii.* However, the Alexander Island specimens differ from *P. sahnii* in preservation as they lack anatomical details used to diagnose this species. *Pentoxylon sahnii* specimens are described in association with the foliage *Nipaniophyllum raoi* and the reproductive organs *Carnoconites compactus*, which represent different species from those found in association with the Alexander Island specimens. The stem material described here is recognized as clearly being very similar to *P. sahnii* and, therefore, it is likely to be pentoxylalean. Sahni (1948) suggested that the short shoots were deciduous, based on the specimens only ever being found in a detached state from the long shoot. In contrast the Alexander Island specimens are all found attached to a long shoot apart from the detached examples bearing reproductive organs. Other evidence of a deciduous nature is equivocal.

Bose *et al.* (1985) described long shoots, short woody shoots (thought to be those that bore the female reproductive organs *Carnoconites*), slender

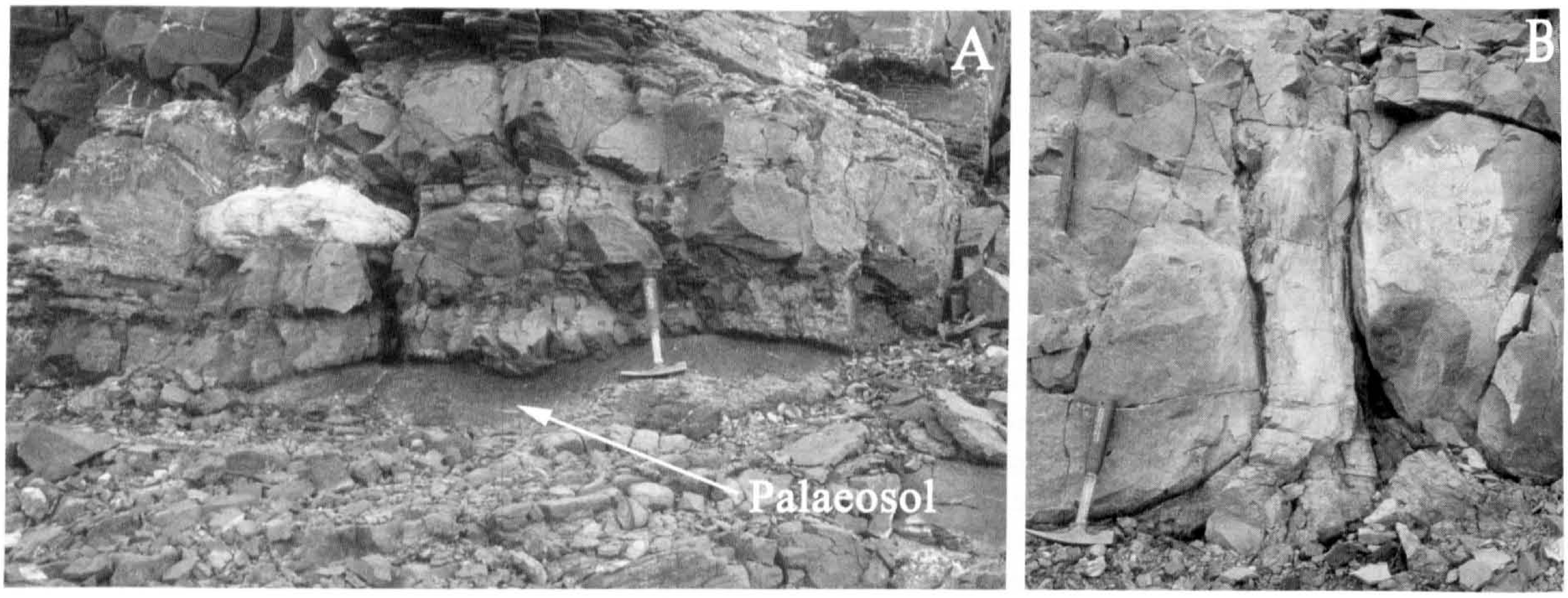


Figure 4. A, KG 4912, an undulating palaeosol horizon overlain by a siltstone containing an organic rich band with a thick over-bank sandstone above. B, KG 4923, a tree fossilized *in situ*. The hammer in both photographs is 35 cm high.

parenchymatous short shoots (*Pentoxylon sahnii*), and thick parenchymatous short shoots (thought to bear the male reproductive organ *Sahnia*). The long woody shoots are petrified and, therefore, are mainly described on their anatomical features. They are predominantly 10–20 mm wide but have been shown to occur up to 40 mm wide, with broad leaf scars, 3 mm wide, widely spaced and subtending short shoot scars 5 mm wide. Numerous bases of woody branches are seen along the long shoot but their nature is uncertain; they may be a combination of smaller woody long shoots, or thick short shoots bearing male or female reproductive organs. The long shoots from the Alexander Island specimens fall within the size range of the Indian specimens described by Bose *et al.* (1985), and show a very similar pattern of short shoots above leaf scars. However, once again, as the anatomical structure of the Alexander Island specimens is not preserved their correlation with the Indian long shoots is uncertain.

4. Sedimentology

The sedimentary units that make up the rocks of the southeastern nunataks of Alexander Island are composed of sandstones, siltstones and palaeosols, formed in a fluvial palaeoenvironment dominated at first by a braided and then a meandering river system with a broad river belt and extensive floodplain (Cantrill & Nichols, 1996). Both the floodplain and mid-channel bars of the wide river channel supported diverse vegetation that withstood the harsh polar climate of Antarctica during the Early Cretaceous, with up to two months of total darkness (List, 1963). The fluvial sedimentary rocks that contain the pentoxylalean material form part of the Triton Point Formation of the Fossil Bluff Group. This unit is under- and overlain by marine sequences containing a fauna which indicates a Late Albian age (Kelly & Moncrieff, 1992). The Triton Point Formation is approximately 800–900 m thick and incorporates the Citadel Bastion Member, representing deposition in a predominantly braided fluvial environment, and the Coal Nunatak Member, recording deposition in a meandering river system (Nichols & Cantrill, in press). The Citadel Bastion Member is exposed on the Hyperion Nunataks, Citadel Bastion, Titan Nunatak and the basal 60 m of Coal Nunatak, southeastern Alexander Island (Figure 1). The Coal Nunatak Member is exposed on the upper parts of Coal Nunatak. The strata dip at approximately 4–10° to the southeast and therefore the rocks young from the Hyperion Nunataks to Citadel Bastion to Titan Nunatak and finally to Coal Nunatak. Both the Citadel Bastion and Coal Nunatak members comprise sequences of channel and over-bank sandstones that contain *in situ* fossilized trees and siltstones and palaeosol horizons that contain fossilized plant material.

The over-bank coarse sandstones form sequences up to 10 m thick that are typically featureless, have sharp but non-erosive bases, and contain *in situ* fossil trees (Figure 4B). These sheet flood deposits indicate that the river system was unstable and prone to flooding. Channel sandstones occur in beds that range from 1–4 m thick but form multi-storey units that reach 15 m thick. They characteristically have scoured, erosional bases with rip-up clasts. In the Citadel Bastion Member these channel sandstones form ribbon sand deposits characteristic of a braided river system, and in the Coal Nunatak Member they have a lenticular morphology indicating meandering river systems (Reading, 1986). The pentoxylalean leaves and ovulate organs are found predominantly in sequences of over-bank fine sandstones and thick units of finely laminated siltstones, interbedded with palaeosol horizons (Figure 4A; Table 1; KG 4901, KG 4905, KG 4914). The sedimentary log from Site KG 4914 represents a typical sequence (Figure 5). The pentoxylalean material is found within the bottom 10 cm of siltstones that overlie a palaeosol horizon. These siltstones are dark grey and have abundant horizontal laminations. Occasionally these laminations are seen to distort around fossil plants suggesting that the plants were buried *in situ* by the silts. Palaeosols are always preserved underneath the siltstones either as fossilized organic-rich layers or by rootlets and ped structures. The sandstones that characteristically overlie the siltstones are grey, fine-grained, often finely laminated with dark organic matter, and contain an abundance of plant debris. They occur in units 0.2–0.75 m thick and contain sparse fossilized tree trunks.

Two specimens of pentoxylalean material were found in very different sequences of sediments. At Site KG 4915 on Citadel Bastion, a peduncle and attached pedicels were found preserved within light grey, fine-grained sandstone. The sandstone is thinly bedded, and contains an abundance of plant debris. It is underlain by a palaeosol horizon but the lack of any rootlets and the fragmented plant material suggests that this sandstone was a flood deposit, and that the plant debris within it was brought in with the floodwaters. Similarly, at Site KG 4918 a peduncle with many pedicels attached was found within a 10-m-thick, medium-grained, channel sandstone that contains an abundance of wood debris, but only a few rare specimens of fossil plants. Thus, at these sites Pentoxylales are not *in situ* but brought in from the regional flora. *Taeniopteris* was recorded but not collected from 12 other sites on the southeastern nunataks (Figure 1). At all of these sites the *Taeniopteris* leaves were preserved in fine siltstones, underlain by a palaeosol horizon and overlain by a sandstone flood deposit of varying nature.

Palaeoenvironment

The sedimentological evidence suggests that the pentoxylalean plant grew upon areas of the floodplain distal to the river channel (Table 1). Pentoxylalean material is predominately preserved in fine-grained siltstones that formed from suspension fallout in pools of sediment-loaded water, suggesting that the forest floor at these sites was periodically covered by standing water, producing boggy conditions. Sites where plants were buried in coarser grained sandstones indicate an area more proximal to the river channel. The absence of sedimentary structures, such as cross bedding, in any of the overlying strata does suggest, however, that the floodwaters overall were low energy flows, and certainly not the high energy floodwaters found adjacent to the river channel. The pentoxylalean plant became established in areas of the floodplain that were frequently flooded, inundating the forest floor in sediment.

5. Palaeoecology

In order to interpret fossil leaf assemblages it is necessary to understand the process of their accumulation and probable taphonomic biases. This can be achieved by reference to studies of extant systems (e.g. Burnham, 1993, 1994; Ferguson, 1985; Greenwood, 1991, 1992). These indicate that leaf litter accumulations on palaeosol surfaces represent accumulations of the local vegetation and that the distance of leaf fall from any individual tree is generally restricted to the radius of canopy height (Burnham, 1994). Although this holds true in closed canopy forests, the distance of transport from the parent tree becomes more significant in open situations (Ferguson, 1985). In general, more accurate estimates are obtained from leaf litter in temperate climates than tropical ones (Burnham, 1993, 1994). Qualitatively, overstorey trees would be expected to contribute larger quantities of leaf litter spread over wider areas than understorey trees or ground dwelling plants.

At Site KG 4914 a palaeosol horizon and overlying siltstone could be followed laterally for several hundreds of metres allowing the lateral distribution of plant remains to be observed. *Taeniopteris daintreei* is abundant along the whole outcrop (60–100% specimens per slab) (Cantrill & Nichols, 1996) suggesting that the pentoxylalean plant was the main overstorey element in the vegetation. Ferns such as *Cladophlebis* and *Sphenopteris* occur as small isolated concentrations spread over a few metres and associated with raised mounds on the palaeosol surface bearing stems (Cantrill & Nichols, 1996, pl. 6, figs 1, 3). These represent individual understorey plants up to 70 cm tall. Between the mounds, local concentrations of marchantioid liverworts (*Marchantites arcuatus* Cantrill, 1997; *M. taenioides* Cantrill, 1997), Dipteridaceae (*Hausmannia papilio* Feruglio), and aquatic ferns (cf. *Regnellidium* Lindman) are more restricted in their distribution, suggesting that these were small plants growing between the

Table 1. Summary of the sedimentology, palaeobotany and interpreted palaeoenvironment for the localities at which the pentoxylalean reproductive material was collected. The substrate refers to the sediments in which the pentoxylalean material is preserved; the overlying substrate refers to the sediments that occur above the preserving substrate; the flora listed indicates the species of fossil plants that are found in association with the pentoxylalean material at the sites.

Locality	Substrate	Overlying substrate	Flora found in association	Palaeoenvironment
KG 4901	Fine-grained siltstone 0.2 m thick with horizontal laminations. Dark grey, with an undulating contact.	Fine-grained sandstone with ripple laminations. Plant debris abundant but very fragmented.	*Elatocladus linearis* *Phyllopteroides* *Sphenopteris* *Cladophlebis* *Ptilophyllum*	Boggy environment distal to the river channel. Over-bank sediments colonized by forest floor vegetation and inundated by fine sediments brought in by floodwaters.
KG 4905	Siltstone 0.05–0.1 m thick with some laminations. Dark grey with an undulating contact.	Fine- to medium-grained brown sandstone with flow features around trees *in situ.*	*Elatocladus confertus* *Gleichenites* *Araucaria chambersii* *Araucarites wollemiaformis* *Phyllopteroides*	Boggy environment distal to the river channel. Over-bank sediments colonized by forest floor vegetation and inundated by sediments brought in by floodwaters.
KG 4914 KG 4737	Grey-green siltstone 1.25 m thick. Very fine-grained with abundant horizontal laminations.	Medium-grained sandstone with flow features around trees *in situ* and some ripple laminations.	*Sphenopteris* *Cladophlebis* ?*Regnellidium* *Araucarites wollemiaformis* *Elatocladus confertus* *Podocarpites* *Araliaephyllum quinquelobatus* *Marchantites taenioides* *Ginkgoites*	Back-swamp environment, distal to river channel. Over-bank sediments colonized by forest floor vegetation and inundated by sediments deposited from standing water after flood events.
KG 4915	Fine-grained, light grey sandstone 0.5 m thick. Thinly bedded with an abundance of plant debris.	Scree	*Aculea acicularis* *Gleichenites*	Floodplain environment proximal to river channel. Over-bank sediments and levees colonized by forest floor vegetation and frequently inundated by floodwaters bringing in plant debris and sediments from nearby areas.
KG 4918	Channel sandstone 10 m thick with abundant wood debris.	None	?*Regnellidium*	River channel in-filled by sediments containing flora from all over region.

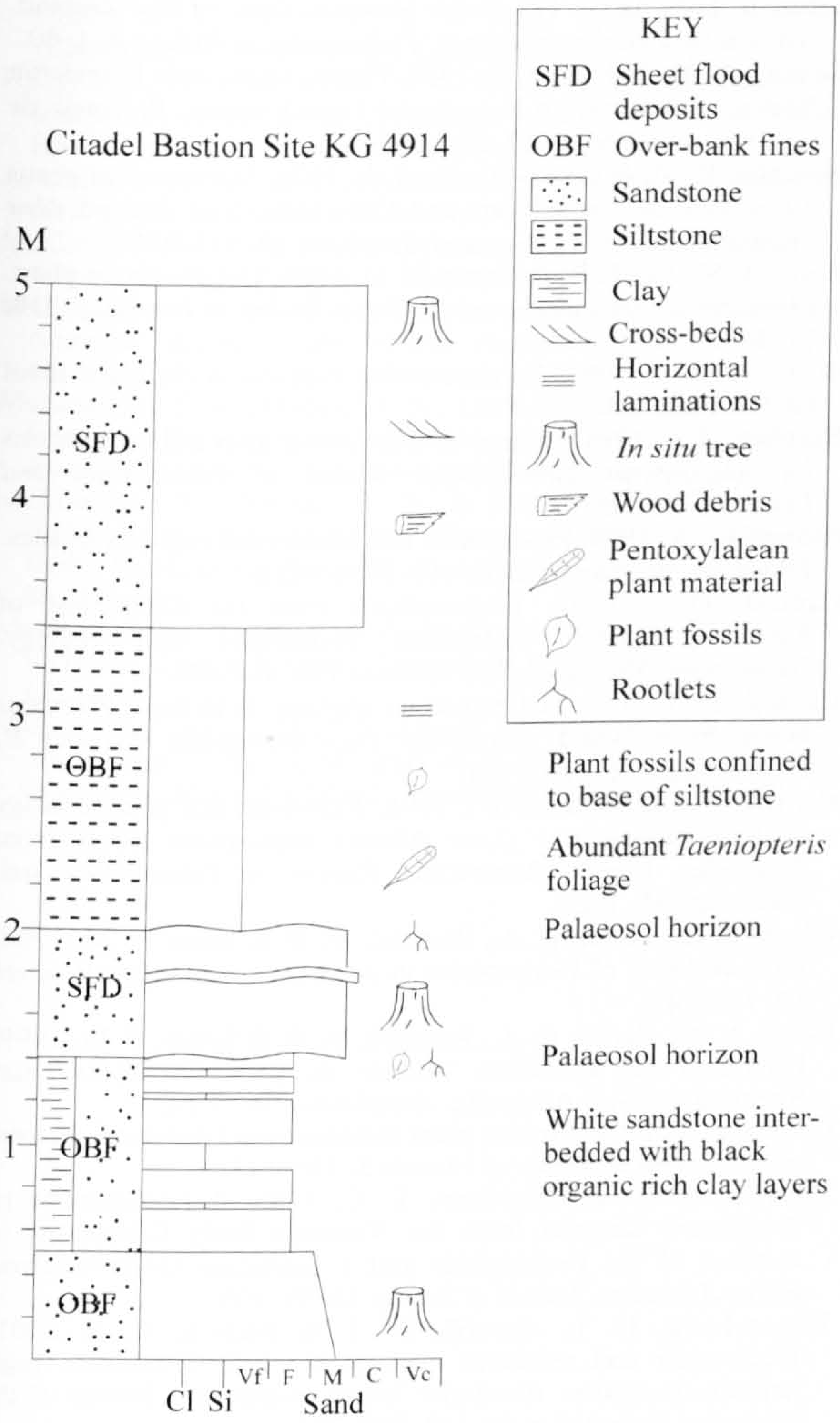


Figure 5. A sedimentary log at Site KG 4914 on Citadel Bastion, showing a typical sequence of sediments within which pentoxylalean material is found.

mounds. Discontinuous clusters and isolated leaves of angiosperm foliage are also present.

At other sites (KG 4921, KG 4941, KG 4931) where palaeosol horizons could be followed laterally, *T. daintreei* is not dominant but occurs in localized clusters (up to 15 m) between conifer- (*Araucaria* and *Elatocladus*) and fern- (*Cladophlebis*, *Phyllopteroides*, *Sphenopteris*) dominated assemblages. Here they make up 5–40% of the foliage per sample site, and are also commonly associated with Equisetales and liverworts, and sparse *Ginkgoites* and angiosperms. The association of *Taeniopteris* with plants such as Equisetales and liverworts appears to provide evidence for the preference of fairly boggy conditions. The clustering of *Taeniopteris* foliage at these sites suggests that the pentoxylalean plant colonised the forest floor in areas between fern thickets. The presence of a wider variety of understorey floras compared to Site KG 4914 indicates that the pentoxylalean plant was not as dominant here and competed for light and space with the other plants on the forest floor. The low abundance of conifer foliage associated with the *Taeniopteris* leaves, however, suggests once again that the pentoxylalean preferred areas of the forest that had just a scattering of conifers forming a sparse canopy layer.

This leaf association is also seen in localities KG 4901, KG 4905 and KG 4915 with allochthonous assemblages, reflecting the occurrence of *Taeniopteris* with fern foliage of *Cladophlebis*, *Gleichenites*, *Phyllopteroides* and *Sphenopteris* (Table 1). Very little conifer foliage was found, but some *Elatocladus* and araucarian leaves, and a few araucarian cones, were preserved along with *Taeniopteris*. Bennettitales, Equisetales, liverworts, *Ginkgoites* and *Nilssonia*, made up other minor components of the vegetation.

Although the habitat and community associations of pentoxylaleans can now be inferred a good understanding of its overall habit is still lacking. At KG 4901 (Coal Nunatak) immature ovules, as indicated by the open and prominent nipple-like projection of the micropyle, occur with small, narrow, *Taeniopteris* leaves. A similar association is seen at Smythes Creek in southeastern Australia. This locality also contains numerous small *Taeniopteris* leaves along with *Carnoconites cranwelli*. The *C. cranwelli* specimens are often small and immature, as evidenced by the open micropyles (e.g., Drinnan & Chambers, 1985, figs 6–8). Extant *Ginkgo* provides a model for understanding these assemblages. Following bud burst in the spring the short shoot systems first produce pollen cones or ovulate cones, followed by leaves. The reproductive structures are seen on the plant with small leaves that are yet to fully expand. So the preservation of both immature ovulate structures along with small, presumably unexpanded, leaves suggests a similar developmental pattern. The fact that no leaves from larger size classes occur at these localities suggests that the plant was probably deciduous. If the plant was evergreen, leaves of different size classes should be seen.

The *Gingko* model of development can also be extended to the short shoot-long shoot system. In *Ginkgo* some short shoots rapidly elongate in the spring to produce new long shoots. These long shoots have sparse leaf cover and in the axils of the leaves new short shoots develop. Short shoots are subtended by a leaf scar and long shoots have regions of closely spaced scars indicating the short shoot stage of development. It is, therefore, most likely that the Pentoxylales expressed a similar developmental syndrome.

This may help explain the variations seen in leaf morphology. Elongating short shoots produce atypical leaves in modern *Ginkgo* (especially when the plant has been physically damaged). Sparse atypical leaves occur among the leaf assemblages containing leaves in the largest (thus mature) size classes, and it may well be that these atypical leaves are those that developed on the elongating short shoots.

The *Ginkgo* model holds up well in interpreting the structures seen in the fossil material, along with the associations of immature leaves and ovules. However, none of the *in situ* leaf litter layers and palaeosols containing pentoxylalean material has trees preserved on them. Despite the extensive exposures of fossil forest levels on Alexander Island (Jefferson, 1982; Falcon-Lang *et al.*, 2001) *Taeniopteris* foliage and other pentoxylalean material are not associated with *in situ* tree-trunk horizons. Two options are possible: either the pentoxylalean plants were widely spaced large trees and so not likely to be sampled, or they had another habit. The trunk anatomy of Jurassic pentoxylaleans, with large multisteled stems, is structurally similar to that seen in modern lianes and it could well be that the Cretaceous forms had a similar habit.

The evidence points to the Alexander Island pentoxylalean plant being of low stature, lacking a trunk yet forming large monodominant communities. It may well be that the plant grew with a similar habit to the modern bramble, colonizing patches on the forest floor and overtaking the undergrowth where competition for light and space was low. It grew on the river floodplain, distal to the river channel, but preferred fairly boggy conditions in clearings or on the outskirts of the forest. Where light was reduced from a greater canopy of conifers, it colonised the forest floor in patches and, together with fern thickets, presumably preferred areas of the canopy with less dense stands of trees. It shared the ground with other water lovers such as water ferns, Equisetales and liverworts.

Acknowledgements

We thank the British Antarctic Survey for the funding of the fieldwork for this project through a NERC CASE studentship. BAS photographers Pete Bucktrout and Chris Gilbert are also thanked for their help with the photography of the specimens.

References

Anderson, J. M. & Anderson, H. M. 1985. *Palaeoflora of southern Africa: prodromus of South African megafloras, Devonian to Lower Cretaceous*, 423 pp. (A. A. Balkema, Rotterdam).

Arber, E. A. N. 1917. The earlier Mesozoic floras of New Zealand. *New Zealand Geological Survey, Palaeontological Bulletin* **6**, 1–80.

Baldoni, A. M. & de Vera, H. 1980. Plantas fósiles de la Formación Apeley (Cretácico) en la zona del Lago Fontana, Provincia de Chubut. *Ameghiniana* **17**, 289–299.

Blaschke, P. M. & Grant-Mackie, J. A. 1976. Mesozoic leaf genus *Taeniopteris* at Port Waikato and Clent Hills, New Zealand. *New Zealand Journal of Geology and Geophysics* **19**, 933–941.

Bose, M. N., Pal, P. K. & Harris, T. M. 1985. The *Pentoxylon* plant. *Philosophical Transactions of the Royal Society of London B* **310**, 77–108.

Burnham, R. J. 1993. Reconstructing richness in the plant fossil record. *Palaios* **8**, 376–384.

Burnham, R. J. 1994. Patterns in tropical leaf litter and implications for angiosperm paleobotany. *Review of Palaeobotany and Palynology* **81**, 93–113.

Brongniart, A. 1828. Prodrome d'une histoire des végétaux fossiles. *Dictionaire des Sciences Naturelles* **57**, 16–212.

Cantrill, D. J. 1997. Hepatophytes from the Cretaceous of Alexander Island, Antarctica: systematics and ecology. *International Journal of Plant Sciences* **158**, 476–488.

Cantrill, D. J. 2000. A Cretaceous (Aptian) flora from President Head, Snow Island, Antarctica. *Palaeontographica Abteilung B, Paläophylogie* **253**, 153–191.

Cantrill, D. J. & Nichols, G. J. 1996. Taxonomy and palaeoecology of Early Cretaceous (Late Albian) angiosperm leaves from Alexander Island, Antarctica. *Review of Palaeobotany and Palynology* **92**, 1–28.

Césari, S. N., Parica, C. A., Remesal, M. B. & Salani, F. M. 1998. First evidence of Pentoxylales in Antarctica. *Cretaceous Research* **19**, 733–743.

Césari, S. N., Parica, C. A., Remesal, M. B. & Salani, F. M. 1999. Paleoflora del Cretácico Inferior de península Byers, islas Sheltand del Sur, Antártida. *Ameghinana* **36**, 3–22.

Chapman, F. 1909. Jurassic plant remains from Gippsland. *Records of the Geological Survey of Victoria* **3**, 103–111.

Drinnan, A. N. & Chambers, T. C. 1985. A reassessment of *Taeniopteris daintreei* from the Victorian Early Cretaceous: a member of the Pentoxylales and a significant Gondwanaland plant. *Australian Journal of Botany* **33**, 89–100.

Falcon-Lang, H. J., Cantrill, D. J. & Nichols, G. J. 2001. Biodiversity and terrestrial ecology of a mid-Cretaceous, high latitude floodplain, Alexander Island, Antarctica. *Journal of the Geological Society, London* **158**, 709–724.

Feistmantel, O. 1877. Jurassic (Liassic) flora of the Rajmahal Group, in the Rajmahal Hills. *Memoirs of the Geological Survey of India, Palaeontologica Indica Series* **2** (1), 53–162.

Ferguson, D. K. 1985. The origin of the leaf-assemblages – new light on an old problem. *Review of Palaeobotany and Palynology* **46**, 117–188.

Greenwood, D. R. 1991. The taphonomy of plant macrofossils. In *The process of fossilization* (ed. Donovan, S. K.), pp. 141–169 (Belhaven Press, London).

Greenwood, D. R. 1992. Taphonomic constraints on foliar physiognomic interpretations of Late Cretaceous and Tertiary paleoclimates. *Review of Palaeobotany and Palynology* **71**, 149–190.

Harris, T. M. 1962. The occurrence of the fructification *Carnoconites* in New Zealand. *Transactions of the Royal Society of New Zealand, Geology* **1**, 17–27.

Hernández, P. & Azcárate, V. 1971. Estudio paleobotánico preliminar sobre restos de una tafoflora de la Península Byers (Cerro Negro), Isla Livingston, Islas Shetland del Sur, Antárctica. *Instituto Antarctico Chileno, Serie Científica* **2**, 15–50.

Jefferson, T. H. 1981. *Palaeobotanical contributions to the geology of Alexander Island, Antarctica.* Unpublished PhD thesis, University of Cambridge, 263 pp.

Jefferson, T. H. 1982. Fossil forests from the Lower Cretaceous of Alexander Island, Antarctica. *Palaeontology* **25**, 681–708.

Jefferson, T. H. 1983. Palaeoclimatic significance of some Mesozoic Antarctic fossil floras. In *Antarctic Earth Science* (eds

Oliver, R. L., James, P. R. & Jago, J. B.), pp. 593–598 (Cambridge University Press, Cambridge).

Kelly, S. R. A. & Moncrieff, A. C. M. 1992. Marine molluscan constraints on the age of Cretaceous fossil forests of Alexander Island, Antarctica. *Geological Magazine* **129**, 771–778.

List, R. J. 1963. Smithsonian Meteorological Tables. Sixth edition. *Smithsonian Miscellaneous Collections* **114**, 506–520.

McCoy, F. 1874. *Prodromus of the palaeontology of Victoria, Decade 1*, 43 pp. (Geological Survey of Victoria, Melbourne).

McLoughlin, S. 1996. Early Cretaceous macrofloras of Western Australia. *Records of the Western Australian Museum* **18**, 19–65.

McLoughlin, S. & Drinnan, A. N. 1995. A Middle Jurassic flora from the Walloon Coal Measures, Mutdapilly, Queensland, Australia. *Memoirs of the Queensland Museum* **38**, 257–272.

McLoughlin, S., Drinnan, A. N. & Rozefelds, A. C. 1995. A Cenomanian Flora from the Winton Formation, Eromanga Basin, Queensland, Australia. *Memoirs of the Queensland Museum* **38**, 273–313.

Medwell, L. M. 1954. A review and revision of the flora of the Victorian Lower Jurassic. *Proceedings of the Royal Society of Victoria* **65**, 63–111.

Nichols, G. J. & Cantrill, D. J. in press. Sedimentology and revised stratigraphy of the upper part of a Mesozoic fore-arc basin succession, Alexander Island, Antarctica. *Geological Magazine.*

Reading, H. G. 1986. Ancient sandy fluvial systems. In *Sedimentary environments and facies* (ed. Reading, H. G.), pp. 55–60 (Blackwell Scientific Publications, Oxford).

Sahni, B. 1948. The Pentoxyleae: a new group of Jurassic gymnosperms from the Rajmahal Hills of India. *Botanical Gazette* **110**, 47–80.

Srivastava, B. P. 1944. Silicified plant remains from the Rajmahal Hills. *Palaeobotany in India* **5**, *Proceedings of the National Academy of Science, India* **14**, 73–76.

Vijaya 1999. Palynological dating of the Neocomian–Aptian succession in the Indian Peninsula. *Cretaceous Research* **20**, 597–608.

Vishnu-Mittre 1953. A male flower of the Pentoxyleae with remarks on the structure of the female cones of the group. *Palaeobotanist* **2**, 75–89.

Vishnu-Mittre 1957. Studies of the fossil flora of Nipania (Rajmahal Series), India – Pentoxyleae. *Palaeobotanist* **6**, 31–49.

Webb, J. A. 1983. A new plant genus, possibly a marattialean fern, from the Middle Triassic of eastern Australia. *Memoirs of the Australasian Association of Palaeontologists* **1**, 363–371.

Wieland, G. R. 1911. On the *Willamsonian* tribe. *American Journal of Science, Series 4* **32**, 433–466.

White, M. E. 1981. Revision of the Talbragar Fish Bed flora (Jurassic) New South Wales. *Records of the Australian Museum* **33**, 695–721.