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A new stratigraphy for the Latady Basin, Antarctic Peninsula: Part 2, Latady Group and basin evolution

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Abstract – Recent detailed mapping, section logging and an improved understanding of the geological evolution of the Antarctic Peninsula provide a robust framework for an improved lithostratigraphic subdivision of the Latady Basin, eastern Ellsworth Land. Within the Latady Basin we recognize two main groups: Ellsworth Land Volcanic Group and Latady Group. The focus of this paper is the Latady Group, which is formally subdivided into five formations: Anderson Formation, Witte Formation, Hauberg Mountains Formation, Cape Zumberge Formation and Nordsim Formation. Middle Jurassic, shallow marine deposits of the Anderson Formation are overlain by quiet anoxic deposits assigned to the Witte Formation. The start of the Late Jurassic is marked by the deposition of higher energy deposits of the Hauberg Mountains Formation, subdivided into three members (Long Ridge, Mount Hirman and Novocin members) that reflect varying lithological and environmental characteristics. Thermal subsidence during the latest Jurassic led to deposition of the basinal Cape Zumberge Formation, while uplift of an active continental arc along the Antarctic Peninsula led to deposition of the terrestrial Nordsim Formation in the latest Jurassic to earliest Cretaceous. The evolution of the Latady Basin reflects early extension during Gondwana break-up, from the Early Jurassic to earliest Cretaceous, and is consistent with a shift in the underlying forces driving extension in the Weddell Sea area from intracontinental rifting related to a mantle plume, to active margin forces in response to subduction.

Keywords: Antarctica, Jurassic, lithostratigraphy, basin history.

1. Introduction

With its well-developed magmatic-arc, accretionary complex, fore- and back-arc regions, the Antarctic Peninsula has long been regarded as a continuation of the South American Andes, formed during subduction of palaeo-Pacific Ocean lithosphere below the fragmenting southern Gondwana supercontinent in the Mesozoic and Cenozoic (Suarez, 1976; Storey & Garrett, 1985; Hathway, 2000; Vaughan & Storey, 2000). A number of sedimentary basins in southern South America and West Antarctica developed at this time and it is vital to have a good understanding of their basin histories when considering models of lithospheric extension during Gondwana rifting. The Latady and Larsen basins (Fig. 1) on the eastern side of the Antarctic Peninsula were interpreted as back-arc basins related to a Jurassic arc (Macdonald *et al*. 1988; Laudon & Ford, 1997). However, more recent analyses of Early Jurassic facies in southern South America and the Larsen Basin suggest earliest sedimentation was driven by intracontinental extension of the Gondwana Supercontinent and formation of the Weddell Sea Basin (Pindell & Tabbutt, 1995; Urien, Zambrano & Yrigoyen, 1995; Hathway, 2000). The majority of sedimentation in these areas occurred later, from the latest Jurassic into the Cenozoic, and was related to back-arc extension after emergence of a subaerial arc in the Late Jurassic. In contrast, the sedimentary fill of the Latady Basin in the south of the Antarctic Peninsula was deposited almost entirely during the Jurassic and, as a result, the basin history contains a unique record of earliest Gondwana extension in the Weddell Sea area.

The Latady Basin crops out in eastern Ellsworth Land and SE Palmer Land, southern Antarctic Peninsula (Figs 1, 2). Early work in the region led to the definition of two main geological units (Fig. 2): Early to Middle Jurassic silicic volcanics assigned to the Mount Poster Formation (Rowley, Schmidt & Williams, 1982), and sedimentary rocks of the Latady Formation (Williams *et al.* 1972) that were interpreted to overlie the former. This study re-evaluates the Jurassic facies of the southern part of the Latady Basin (Fig. 2) and sets up a new stratigraphy that allows an interpretation of the basin history. Both the sedimentary and volcanic sequences are raised to group status as they contain a number of distinct lithofacies associations that form definable formations. The Mount Poster volcanics have been divided into two formations within the Ellsworth Land Volcanic Group: the voluminous silicic intracaldera facies of the Mount Poster Formation and the more localized basaltic

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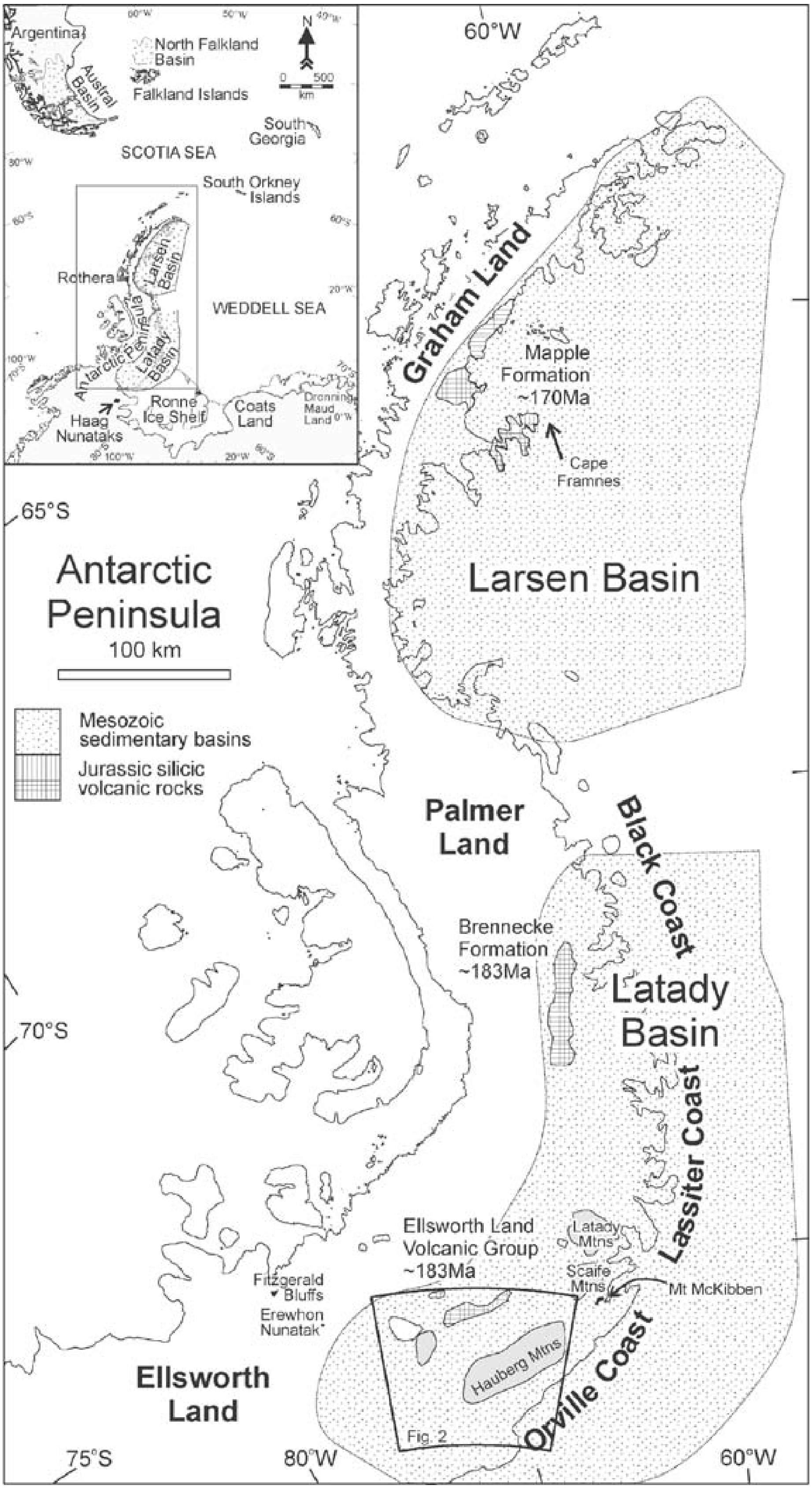

Figure 1. Map of the Antarctic Peninsula showing the distribution of the Latady and Larsen basins and their proposed extent. The margins for the Latady Basin are hypothetical, based on geophysical and geological data available. The ages of the silicic volcanic Mapple and Brenneke formations are taken from Pankhurst *et al.* (2000) and the Ellsworth Land Volcanic Group from Hunter *et al.* (2006, this issue). Inset map of the Antarctic Peninsula and southern South America showing modern day locations of the Mesozoic basins discussed in the text. Mesozoic sedimentary basins are marked with stippled fill.

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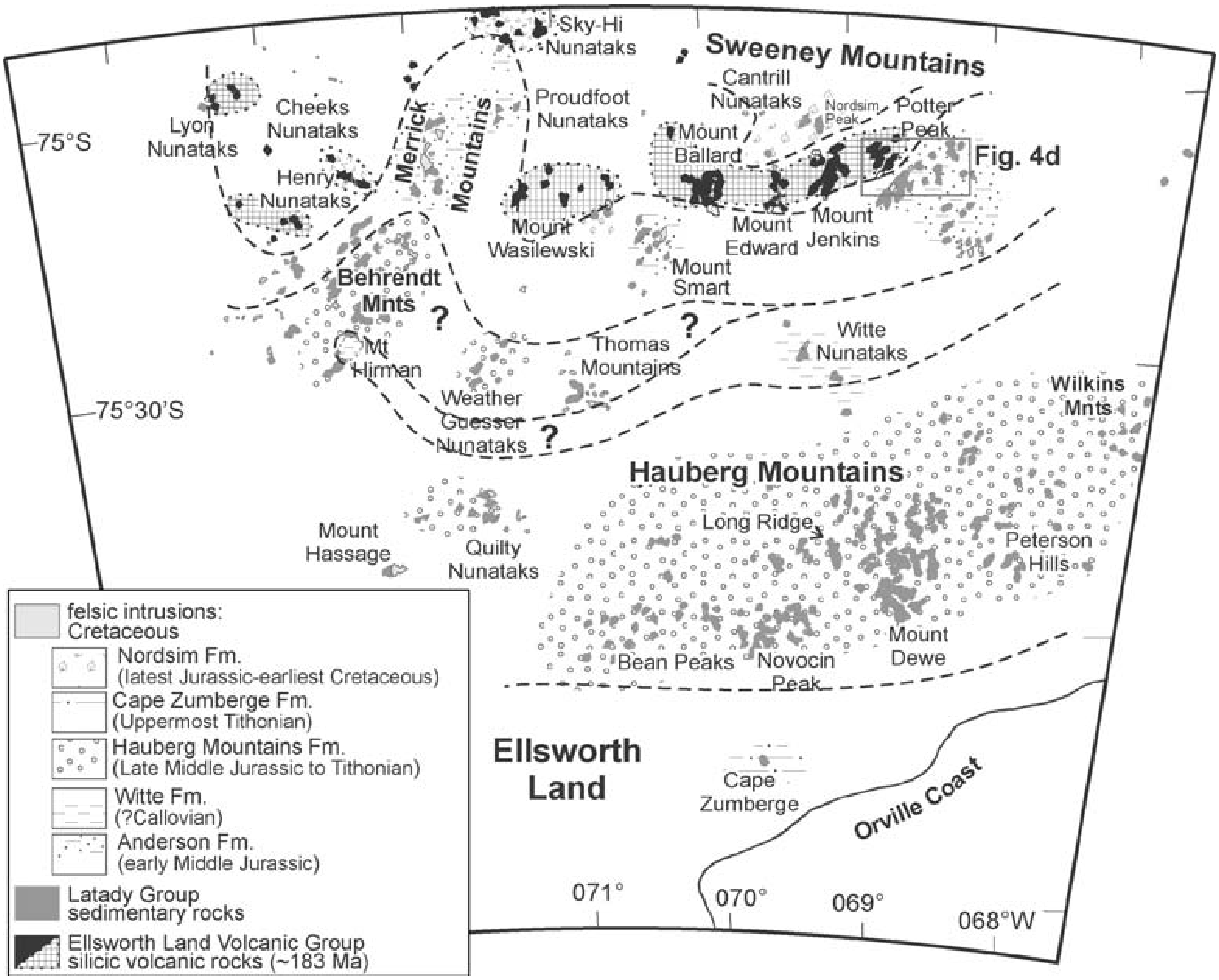

Figure 2. Geological map of eastern Ellsworth Land based on the BAS/USGS 1:500 000 geological map of southern Palmer Land and eastern Ellsworth Land (Sheet 6). Map shows the outcrop distribution and, where differentiated, the formations are indicated by patterned fill. Dashed lines represent an inferred boundary between formations.

and sedimentary extracaldera facies assigned to the Sweeney Formation (Hunter *et al.* 2006, this issue). In this paper, we formally subdivide the sedimentary group into a series of five formations. Two of these are assigned to the Middle Jurassic and three to the Upper Jurassic. The latter units are probably further divisible with more detailed work.

2. Regional setting

The Latady Basin is up to 800 km long, more than 200 km wide and filled with several kilometres of Jurassic sedimentary and volcanic rocks (Willan & Hunter, 2005). The basin encompasses the sedimentary and volcanic rocks of the Orville and Lassiter coasts, extending north as far as possible correlatives within the Mount Hill Formation (deformed metasediments) on the southern Black Coast, Palmer Land (Meneilly *et al.* 1987; Fig. 1). The basin is separated from the Larsen Basin by the NE Palmer Land arc massif (Fraser & Grimley, 1972), an area with very little sedimentary outcrop, chiefly underlain by metamorphic rocks and Cretaceous plutons related to subduction under the proto-Pacific margin. The margins of the basin are not well defined due to low levels of exposure, but hypothetical boundaries have been drawn on Figure 1 based on the limited geophysical and sedimentological evidence in the literature. The eastward extent of the Latady Basin is not known but may extend under the Ronne ice shelf and the Weddell Sea (cf. King & Bell, 1996). Late Jurassic to Early Cretaceous belemnites have been reported from the eastern Weddell Sea in the vicinity of Cape Norvegia, Dronning Maud Land (Crame, Arntz & Thomson, 2000), and although they may be derived from Latady-equivalent rocks it is unclear if they are an eastward extension of the Latady Basin, or derived from a series of smaller sedimentary basins that rimmed the Weddell Sea.

Deformation, plutonism and related metamorphism associated with the mid-Cretaceous Palmer Land Event (107 Ma: Vaughan, Pankhurst & Fanning, 2002) have affected the whole basin, but to a lesser extent in eastern Ellsworth Land (Figs 1, 2). The most extensive outcrops within the Latady Basin occur on the Orville

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Coast (approximately between 74°45′ S–76°15′ S and 068°00′ W–074°15′ W, Fig. 2). This region is the least affected by mid-Cretaceous deformation, and the intensity of metamorphism is low, ranging from zeolite to chlorite-grade (Kamenev & Orlenko, 1982; Kellogg & Rowley, 1989), making it one of the best regions in which to redefine the Latady Basin stratigraphy and study basin history during early break-up.

While the base of the basin is not seen locally, potential basement rocks crop out at Erehwon Nunatak and Fitzgerald Bluff to the west and Haag Nunataks (Proterozoic) to the south (Fig. 1). *Glossopteris* leaves from the Erehwon Nunatak suggest a Late Permian age (Gee, 1989*a*), which is consistent with a dominant Late Permian detrital zircon population (Laudon & Fanning, 2003). These Upper Permian rocks are pre-rift and are likely to be present under the Latady Basin. Detrital zircon peaks from the Fitzgerald Quartzite Beds (Laudon & Fanning, 2003) are consistent with a Lower Palaeozoic depositional age. The pattern is similar to peaks found in the lower/middle Palaeozoic quartzite Crashsite Group of the Ellsworth Mountains to the south (Laudon & Craddock, 1992), and representative of much of the Gondwana margin being deposited at that time. Much of the sedimentary material in the older part of the Latady Group (Anderson Formation) is probably recycled from this Gondwanan basement (Willan & Hunter, 2005).

3. Previous investigations

Areal exposure levels of 5–10 %, extensive folding and faulting during the Palmer Land Event, high lateral facies variation and a lack of suitable marker horizons make traditional stratigraphic analysis very difficult. The type section in the Latady Mountains represents only a fraction of the range of lithologies seen in the whole basin and much of the sedimentary detail has been masked by subsequent metamorphism. Previous attempts at a regional stratigraphy or basin history were based primarily on a few well-described fossiliferous localities and 13 small-scale logs (Laudon *et al.* 1983). There was no attempt to correlate between areas, and the sedimentary thickness of the Latady Basin was estimated to be several kilometres. Late Middle Jurassic faunas have been described from the Behrendt Mountains (Quilty, 1970, 1972, 1983; Eagle & Hikuroa, 2003). D. Hikuroa (unpub. Ph.D. thesis, Auckland Univ. 2004) has also assigned much of the northern part of the Hauberg Mountains to the Middle Jurassic. Late Jurassic faunas described from Lyon Nunataks (Stevens, 1967) can probably be reassigned to the Middle Jurassic in the light of new data from New Zealand (Westermann, Hudson & Grant-Mackie, 2002). Other sites in the Behrendt Mountains contain Late Jurassic fauna (Quilty, 1970, 1977), ammonites from the southern parts of the basin have largely been assigned to the Late Jurassic (Thomson, 1983), and Crame (1981) described Late Jurassic bivalve zones. Work on plant fossils in the northern part of the basin (Gee, 1984, 1989*b*; Cantrill & Hunter, 2005) related them to the Middle Jurassic Botany Bay Group from the Larsen Basin (Rees & Cleal, 2004; Hunter *et al.* 2005), but recent detrital zircon work in the Sweeney Mountains suggests that some of these flora are latest Jurassic or Early Cretaceous (Nordsim Formation: Hunter, Cantrill & Flowerdew, 2006).

The geological investigations described above have chiefly been done at the reconnaissance level with both palaeoenvironmental and biostratigraphic information from fossil assemblages extrapolated over wide geographic areas. This has previously made it difficult to suggest a viable stratigraphy. However, by linking changes in depositional style and sedimentary structures with the associated fauna and flora, we have been able to distinguish between different palaeoenvironments and their related lithofacies associations. This approach has then been used as a basis for the basin stratigraphy. Nevertheless, much work still needs to be done, particularly in the southern and eastern areas of the Latady Basin (Fig. 1).

4. Latady Group (newly defined)

A sequence of fossiliferous marine sandstones and mudstones was described from the Latady Mountains as the Latady Formation by Williams *et al.* (1972). These rocks are now known to crop out over a wide expanse between eastern Ellsworth Land at 76°S, and the southern Black Coast at 72°55′ S (Fig. 1). Possible correlatives include the Mount Hill Formation of the northern Black Coast, a similar but highly deformed sequence of fossiliferous volcaniclastic sandstones and argillites (Meneilly *et al.* 1987). Comparable metasedimentary rocks at Cape Framnes in Graham Land (Fig. 1) were also correlated with the Latady Formation (Riley *et al.* 1997) and significantly increased the lateral extent of these sediments to the north. Given the identification of several mappable units, this sequence of fossiliferous, marine sandstones and mudstones with minor terrestrial/shallow water facies has been raised to group status.

In the absence of marker horizons or better exposure, it has not been possible to improve on the estimate of Laudon *et al.* (1983) that the Latady Group is several kilometres thick. It is also not possible to define the new stratigraphy in terms of upper and lower contacts or formation thickness, as no boundaries have been recorded. However, the purpose of this paper is to define units that can be used to set up a regional stratigraphy in order to understand the basin history. As such, each unit is described from a ‘typical’ exposure with a corresponding sedimentary log, and this is correlated to similar exposures across the study area. Logged

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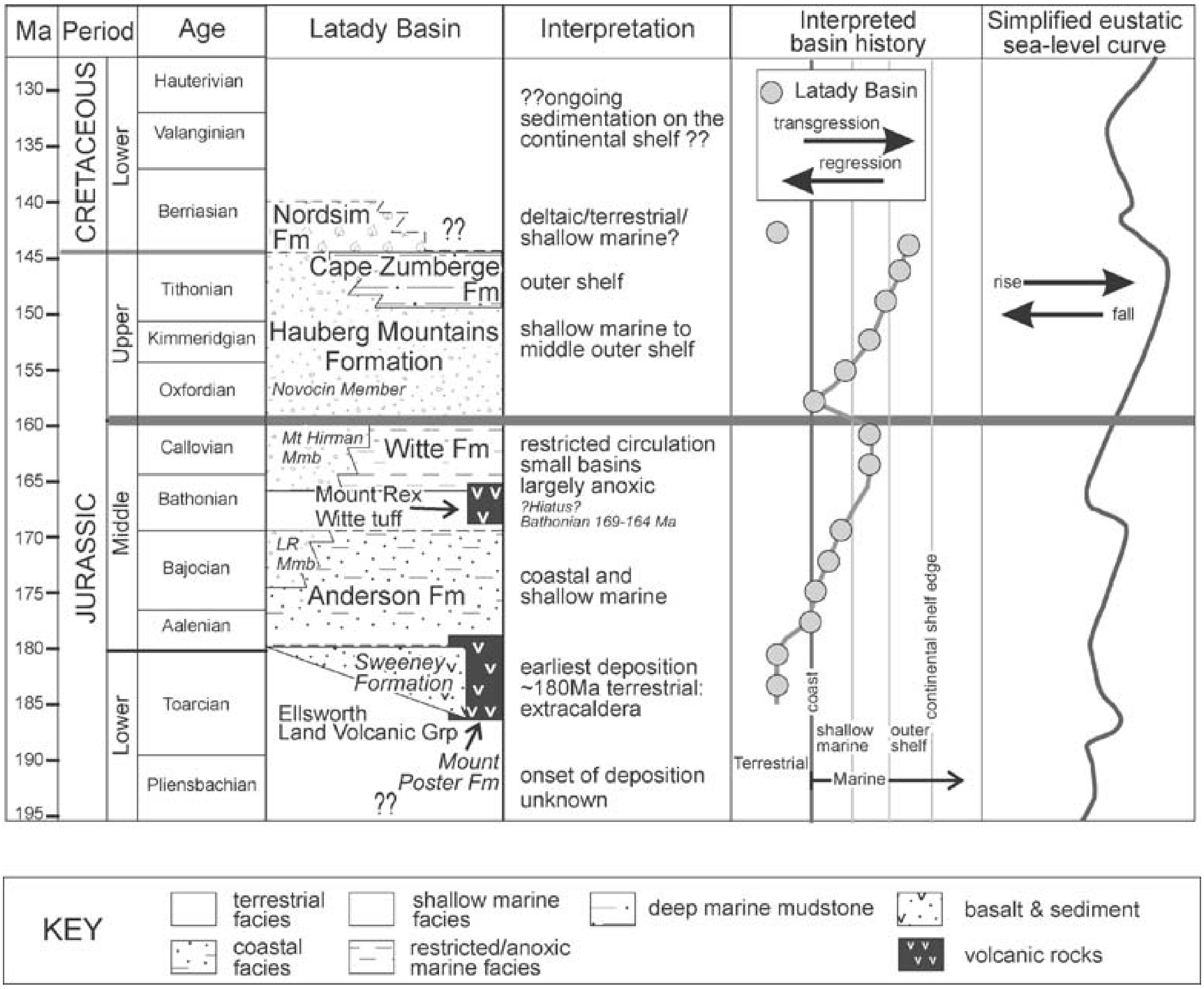

Figure 3. Chronostratigraphic chart for the Jurassic–Early Cretaceous of the Latady Basin. The basin history is approximated from changes in the interpreted depositional environment with time, based on approximate water depth or position relative to the shelf edge, and highlights the sudden regression at the Middle–Upper Jurassic boundary. Ages for the volcanism come from Hunter *et al.* (2006, this issue). Sea-level curve from Hallam (1992).

sections tend to be on the northern and sunnier side of nunataks where exposure is best. As mentioned above, the Latady Basin broadly youngs to the south, but has also been deformed during the Palmer Land Event. As a result, most of the northern ridges of nunataks preserve the northern limbs of chevron folds. Logs measured up-ridge towards the south commonly record an inverted section. It is important to check younging indicators at every locality, and some of the published sections (e.g. Laudon *et al.* 1983, section 7, reproduced here as Fig. 9c) have been logged upside down and needed to be redrawn. Relative ages are based on stratigraphic juxtaposition, fossil assemblages and/or, where available, the youngest detrital zircon group extracted from coarse-grained sandstones.

Although contact relationships are obscured by ice, outcrops of the Anderson Formation at the base of the succession not only include volcanic horizons but are geographically proximal to the Mount Poster volcanic rocks in the Sweeney Mountains. In addition, the finer-grained facies contain plant material similar to the Middle Jurassic Botany Bay Group (P. M. Rees, unpub. Ph.D. thesis, Royal Holloway and Bedford New College, Univ. London, 1990; Rees, 1993; Cantrill & Hunter, 2005). This suggests a late Early/early Middle Jurassic age for the onset of deposition. The Latady Group youngs from northwest to southeast. The top is not seen but was previously thought to be uppermost Tithonian (*c.* 145 Ma) based on ammonites from Cape Zumberge (Thomson, 1983). A young group of detrital zircons obtained from a sandstone at Cantrill Nunataks (Nordsim Formation) gives an age of 144 ± 3 Ma (Hunter, Cantrill & Flowerdew, 2006) and sandstone in the far southeasternmost part of Ellsworth Land near Mount McKibben contains detrital zircons from the earliest Cretaceous (*c.* 120 Ma: Laudon & Fanning, 2003; Fig. 1). We propose that the Latady Group be formally subdivided into five formations: Anderson, Witte, Hauberg Mountains, Cape Zumberge and Nordsim formations (Fig. 3).

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4.a. Anderson Formation

Nomenclature. Named after the nunataks to the east of the Sweeney Mountains, where the lower part of the unit is best exposed with most of its characteristic facies variation. The nunataks include Potter Peak East and its associated ridge and Anderson Nunataks, covering an area of roughly 10 km^2 (Figs 2, 4d).

Type section. A composite type section is designated for the Anderson Formation. The lower part is represented by the northern end of the Potter Peak East peak–ridge system (Fig. 4a, b), while the upper part is represented by the southern part of the ridge, 2.5 km south of the main peak (Figs 2, 4d).

Distribution, thickness and boundaries. The Anderson Formation underlies almost all of Potter Peak East and the ridge system to the south. The smaller nunataks to the east of this main peak (between 75°07′ S and 75°12′ S and west of 68°22′ W) are underlain by the lower part of the unit, and this probably also applies to the other small unvisited nunataks in the immediate area (Fig. 4d). The exposure in the type area is at least 1500 m thick along the length of the ridge. Similar facies also occur at Proudfoot Nunataks and Mount Smart (Fig. 2), and underlie the Merrick Mountains in the west.

Sedimentary facies description and fossil content. The lower and more geographically extensive part of the Anderson Formation is characterized by horizontally bedded, fine-grained, orange weathering sandstone with bed tops preserving ripples. The ripples are generally symmetrical and bifurcating (Fig. 5a), but they become straighter crested or linguoid up-section. Rippled surfaces are commonly capped with clay and may be bioturbated. The ichnofauna is dominated by simple linear or slightly sinuous crawling traces, with minor single or paired burrows, occasionally mud filled. Woody plant debris is also found on these surfaces. These sandstones are typically well sorted, with very little to no mud. They are silvery grey where fresh, reflecting a high concentration of heavy minerals. Interbedded with these sandstones are beds of black siltstone/very fine-grained sandstone associated with either bioturbated, white and black fine-grained sandstone, or rippled, orange weathering, medium-grained sandstone. Larger-scale sandstone units are not common, but where present, bedding sets are about 25 cm thick and commonly cross-bedded or horizontally bedded. In places, mud clasts occur at the base of these units, and the tops are rippled. There is relatively little mudstone in the lower part of the unit, but where it occurs in any thickness, convolute bedding or wet sediment deformation structures are common. Flaser and lenticular bedding, as well as mud flake/clast conglomerates are more typical of mudstone deposition in the system.

Volcanic facies are limited to the lower part of the Anderson Formation and found at only two localities in the Potter Peak East area (Fig. 4d). The first, smaller section, is clast dominated with a gritty fine/medium- to medium-grained, blue/grey matrix, weathering orange red. Large-scale bedding is picked out by changes in clast size throughout the unit. Clasts are elongate or ovoid, and dominated by grey to pale yellow, subangular to angular volcanic clasts (up to 1 cm), with smaller clasts of blue grey weathered material (baked mudstone?) and rare large clasts of rounded black shale or quartzite. Some of the volcanic clasts are encased in a subrounded coating, which may be a chilled margin. The matrix is of a similar composition to the clasts. The deposit grades up into pumice-rich, medium-grained sandstone, then a tuff/ash-fall horizon before passing into black, wave-rippled mudstone. Fine-grained, orange weathering, grey/green sandstone crops out over the mudstone and is bioturbated by small mud-filled burrows tentatively assigned to *Chondrites*. The second locality (Fig. 4c, d) is dominated by fine-grained, commonly cross-bedded, grey sandstone and minor green weathering siltstone (Fig. 4c). Plant debris is common, including well-preserved conifer sprigs and fern fronds, wood and rootlets (Fig. 6b; Cantrill & Hunter, 2005). Interbedded within the sediment are millimetre-thick tephra beds. These consist of orange and yellow weathered pumice clasts up to 5 mm across, in black very fine- or fine-grained sandstone. Thin units are non-erosive but thicker units show some sub-planar character and may be erosive. In these cases the pumice is concentrated in sandstone at the base of the unit, which then fines over a few centimetres to black siltstone. A distinctive brown weathering vesicular basalt crops out at the top of the section (Fig. 4c). Roots pass through this horizon but it is not clear if any originate in it.

The upper part of the Anderson Formation, including exposures in the Merrick Mountains, is dominated by buff or orange weathering, fine-grained, horizontally bedded sandstone. Interbedded, bioturbated sandstone and siltstone are perhaps proportionally greater in the Merrick Mountains, but occur throughout, as do mud flake horizons and ripples. The main difference between the lower and upper parts of the unit is the presence of marine fauna in the latter, and the very low percentages of mud in the former.

Thin conglomerate beds ($\sim$15 cm) are found throughout the unit. These are supported by a matrix of medium-grained, well-sorted sandstone, and the clasts are well rounded and dominated by vein quartz, quartzite sandstones, volcanic clasts and rare granitoids.

The unit contains both plant remains and a shallow marine fauna. Two different floras are preserved (Fig. 6). The more common consists of bennettites, ferns, *Equisetum* and woody debris (up to 30 by 10 cm). Most of this material has been deposited subaqueously,

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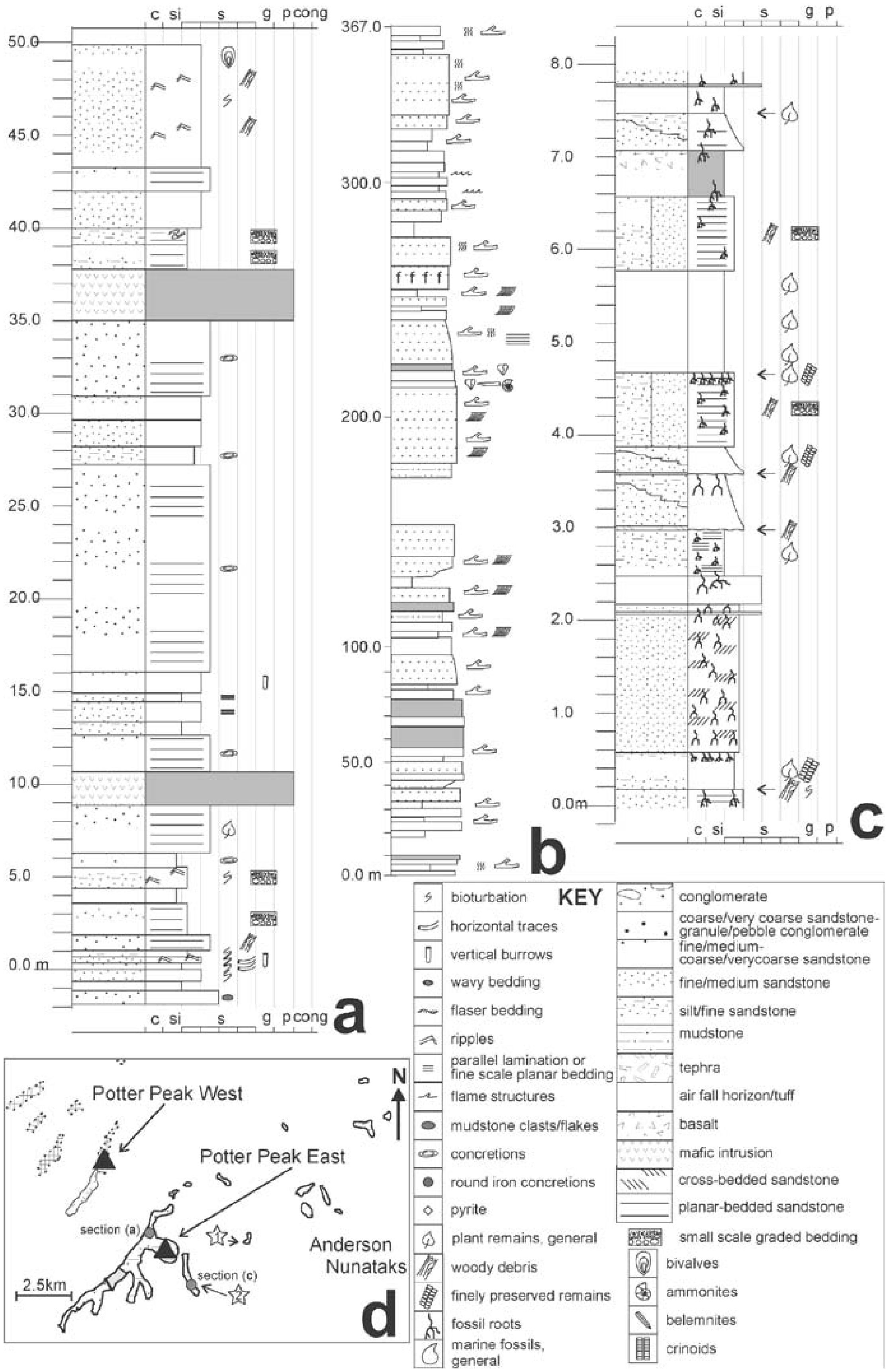

Figure 4. Measured stratigraphic sections for the Anderson Formation. For key to symbols in (b) refer to Laudon *et al.* (1983). (a) Detailed log of type section at base of Potter Peak West. (b) Six kilometres southeast of Potter Peak East measured by Laudon *et al.* (1983). (c) Detailed log of extracaldera facies ~2 km southeast of Potter Peak West. (d) Localized map for Potter Peak and Anderson nunataks; see Figure 2 for relative location. Stars indicate volcanic horizons discussed in the text.

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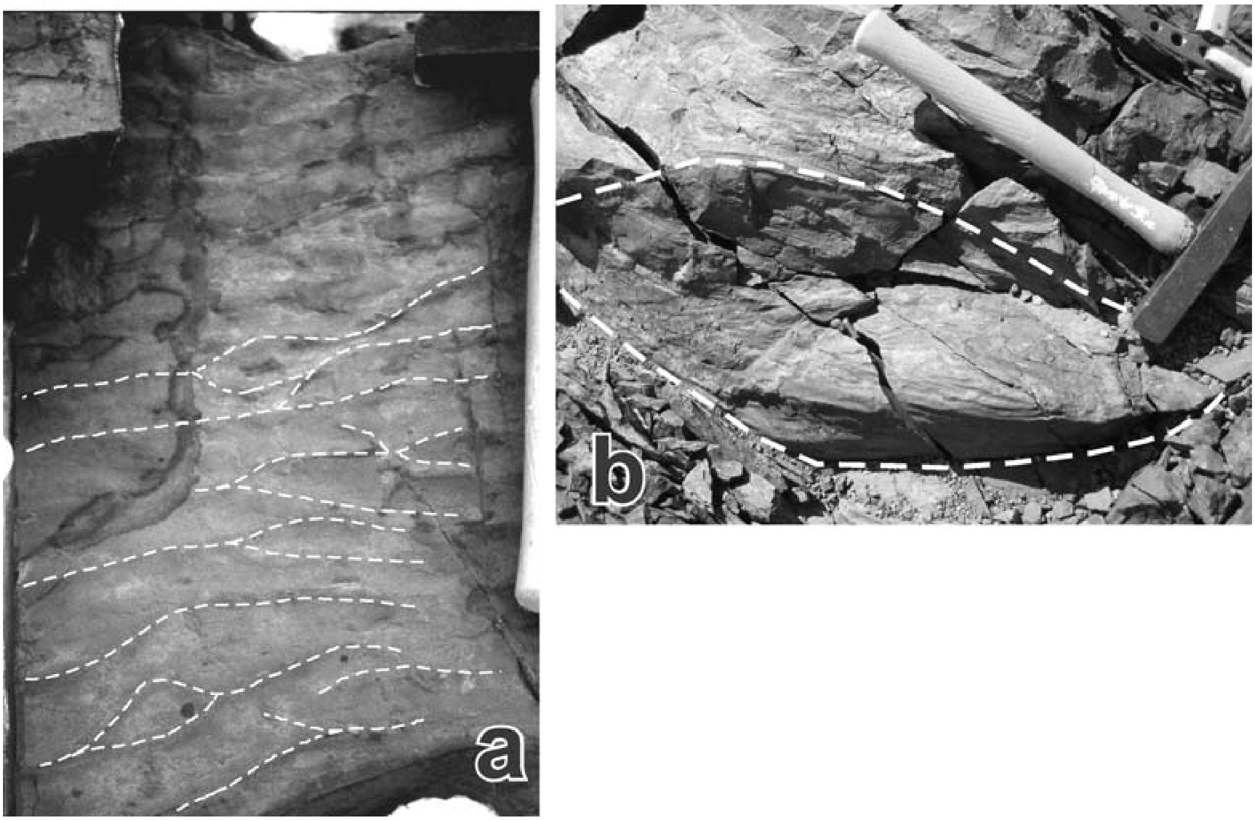

Figure 5. Anderson Formation. (a) Wave rippled sandstone. (b) Large bivalve. 35 cm hammer for scale in both.

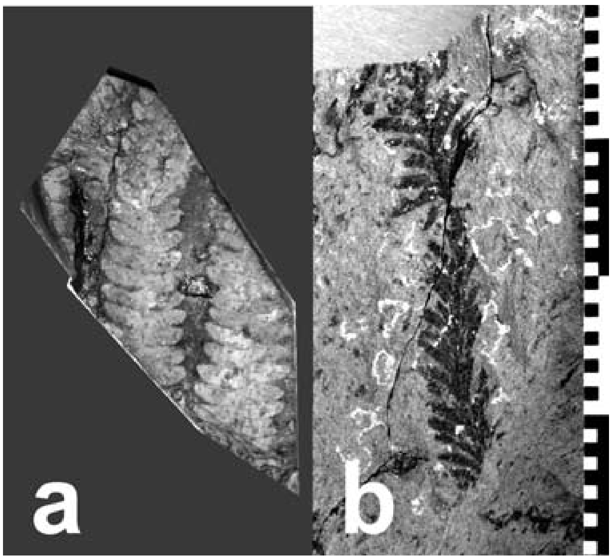

Figure 6. Plant remains from the Anderson Formation. (a) Fern pinnules from Proudfoot Nunataks, *Cladophlebis gallatinesis*. (b) *Elatocladus confertus* typical of the volcanic facies. Scale bar in millimetres.

and wood from the Merrick Mountains has been bored. However, the southwest ridge of Proudfoot Nunataks has an autochthonous flora dominated by ferns (Fig. 6a). The ferns form a thin coal horizon and roots pass down into the underlying black siltstone. The second flora consists of finely preserved ferns and conifer twigs associated with the volcanic facies at the southern end of the small ridge 2.5 km southeast of Potter Peak East Peak (Figs 4c, d, 6b). Roots are found throughout this section. The only other quantitatively significant density of conifer remains is found in the Sweeney Formation, also associated with basalt (Cantrill & Hunter, 2005; Hunter *et al.* 2006, this issue).

Marine fauna are sparse but locally common. They increase in abundance through the Anderson Formation. The lower part of the formation only has some well-preserved *Entolium* bivalves and some other poorly preserved and unidentified bivalves. In general the fauna includes poorly preserved ammonites with very fine whorls, *Rotularia*, small belemnites, various bivalve species including some very large specimens and rare trigoniid bivalves and gastropods. Fish scales and belemnites are found in the Merrick Mountains. In contrast with the younger formations (see below), the fauna in the Anderson Formation are normally whole and although certain horizons are richer in fossils they are never found in great numbers.

Depositional environment and age. The sedimentary facies of the Anderson Formation are compatible with a foreshore–shoreface transition setting, with relatively high-energy shoaling wave conditions (cf. Miocene wave-dominated sequences in southern Spain: Roep *et al.* 1979). Horizontally bedded (or perhaps originally parallel-laminated) sandstones with heavy mineral concentrates represent gently shelving sands

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of the foreshore while the symmetrical ripples and sparsely bioturbated sandstones are the shoreface. The asymmetry of the wave ripples suggests they are more likely to have come from the breaker surf zone than the swash zone, and the presence of rare conglomeratic horizons is compatible with concentration by the breaking waves (cf. the Quaternary of California: Clifton, Hunter & Philips, 1971). Conglomerate clasts are similar to the cobbles found in the clast-rich ignimbrites of the Sweeney Formation (Hunter *et al.* 2006, this issue) and other conglomerates in the Latady Basin. The clasts are dominated by resistates, but even so, do not particularly reflect any lithology from the Latady Basin and most likely represent basement. Roots, well-preserved plant specimens and volcanic deposits overlain by pebble lags and rippled sandstones indicate backshore areas protected from wave action long enough for terrestrial sedimentation to be preserved. The bioturbated black mudstone and fine-grained sandstone facies are compatible with a lower-energy system, either lower wave energy or lower shoreface conditions (Howard & Reineck, 1981). Where the higher- and lower-energy facies are interbedded on a scale of tens of metres lower in the section, it seems more likely that the energy of the setting alternated rather than that the local sea-level kept changing. However, higher in the section these finer-grained facies (bioturbated or gently rippled sandstone and siltstone) are associated with marine fossils, consistent with progradation and a change to lower shoreface or an offshore setting. The ecology is also consistent with a shallow marine setting. Pebbles are generally absent from this facies, but plant debris, particularly wood, is more prevalent, where it has been washed offshore by wave action on the foreshore and shoreface.

With a predominance of chilled volcanic subangular to angular clasts set in a bluey grey matrix, the first volcanic unit is interpreted as a block and ash deposit (following a nuée ardente generated by collapse of a lava dome: Fisher, Smith & Roobol, 1980). The presence of *Chondrites* above the volcanic facies is consistent with a low-oxygen or chemically stressed volcanic environment. The second section (Fig. 4c) contains thin tephra layers, pumice and basalt, as well as evidence for terrestrial conditions from the root horizons. The green weathering (Fig. 4c) is a feature consistent with a volcanic composition, and the bed is interpreted as a tuff. The flora preserved in this section is different to that found elsewhere in the Latady Basin, and this most likely reflects active volcanism in this part of the sequence (Cantrill & Hunter, 2005). These volcanic horizons are compatible with ongoing, proximal volcanic activity and, although much of the convoluted bedding in the finer-grained sedimentary facies can be attributed to loading, in some places the deformation probably reflects contemporaneous tectonic activity.

There has been no published work on the fauna of the Anderson Formation but the flora are similar to the Middle Jurassic flora of the Botany Bay Group in the northern part of the Antarctic Peninsula (Cantrill & Hunter, 2005). With the exception of a distal, Middle Jurassic, air fall horizon at Witte Nunataks (Hunter, Riley & Millar, 2004), the Anderson Formation is the only part of the Latady Group with interbedded volcanic facies. For these reasons we assign this formation to the early Middle Jurassic, although deposition may have begun in the late Early Jurassic.

4.b. Witte Formation

Nomenclature. Named after Witte Nunataks in the central eastern side of the study area, where the unit is best exposed (Fig. 2).

Type section. Designated from the northeasternmost of the two ridges 7.5 km SE of the main Witte Nunataks peak (Figs 2, 7a).

Distribution, thickness and boundaries. In addition to the type section, the Witte Formation crops out on a ridge at Mount Hirman in the southern Behrendt Mountains (Fig. 2). This ridge is underlain by 700 m of Witte Formation (measured by Laudon *et al*. 1983; Fig. 7b), whereas the thickness at the type locality is at least 400 m.

Sedimentary facies description and fossil content. The formation is dominated by dark blue/black siltstone and claystone interbedded with proportionally less yellow/grey medium- to fine-grained sandstone (Fig. 7). The majority of the siltstone is planar bedded, either in very fine millimetre-scale laminations or as centimetre-scale graded beds, with dense concretions forming towards the top of sedimentary units. The concretions average 4 cm in diameter (although they can be as large as 10 cm and as small as a few millimetres) and are spherical to subspherical despite the intense deformation the area has suffered. They have grown over bedding with a radial ornament preserved on the outside of the 'ball' and do not do not appear to have nucleated on anything. Quilty (1977) noted these concretions in his description of the Mount Hirman site (Quilty, 1977, site 11A) but also describes others that are irregular and contain uncrushed fossils. No irregular concretions were observed in the Witte Nunataks section. The concretions are also found in the bases of local sandstone channels, associated with plant debris and mudstone clasts.

These local channels are widespread, relatively small (average 0.5 m wide) and consist of white or yellow fine- to medium/fine-grained sandstone (Fig. 8a). They crop out in long narrow lenses with low aspect ratios (1:10), in some cases with normal grading and ripple laminated tops. Some contain plant material, concretions and mudstone clasts at the base. More

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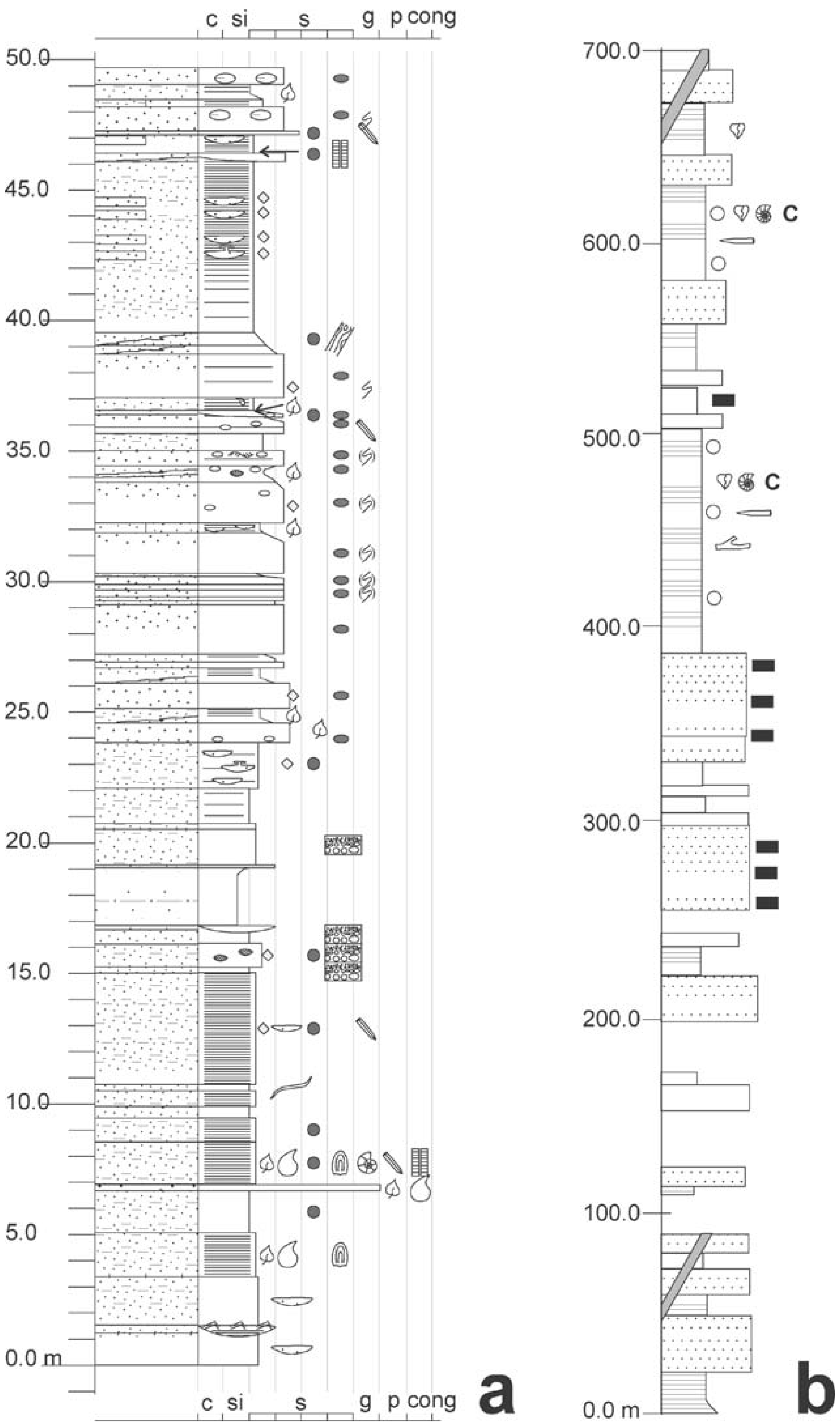

Figure 7. Measured sections for the Witte Formation. (a) Detailed log of type section from Witte Nunataks. Legend in Figure 4. (b) Callovian section 4 km northeast of summit of Mount Hirman from Laudon *et al.* (1983); refer to legend therein. Heights of Callovian indicator species marked with the letter 'C'.

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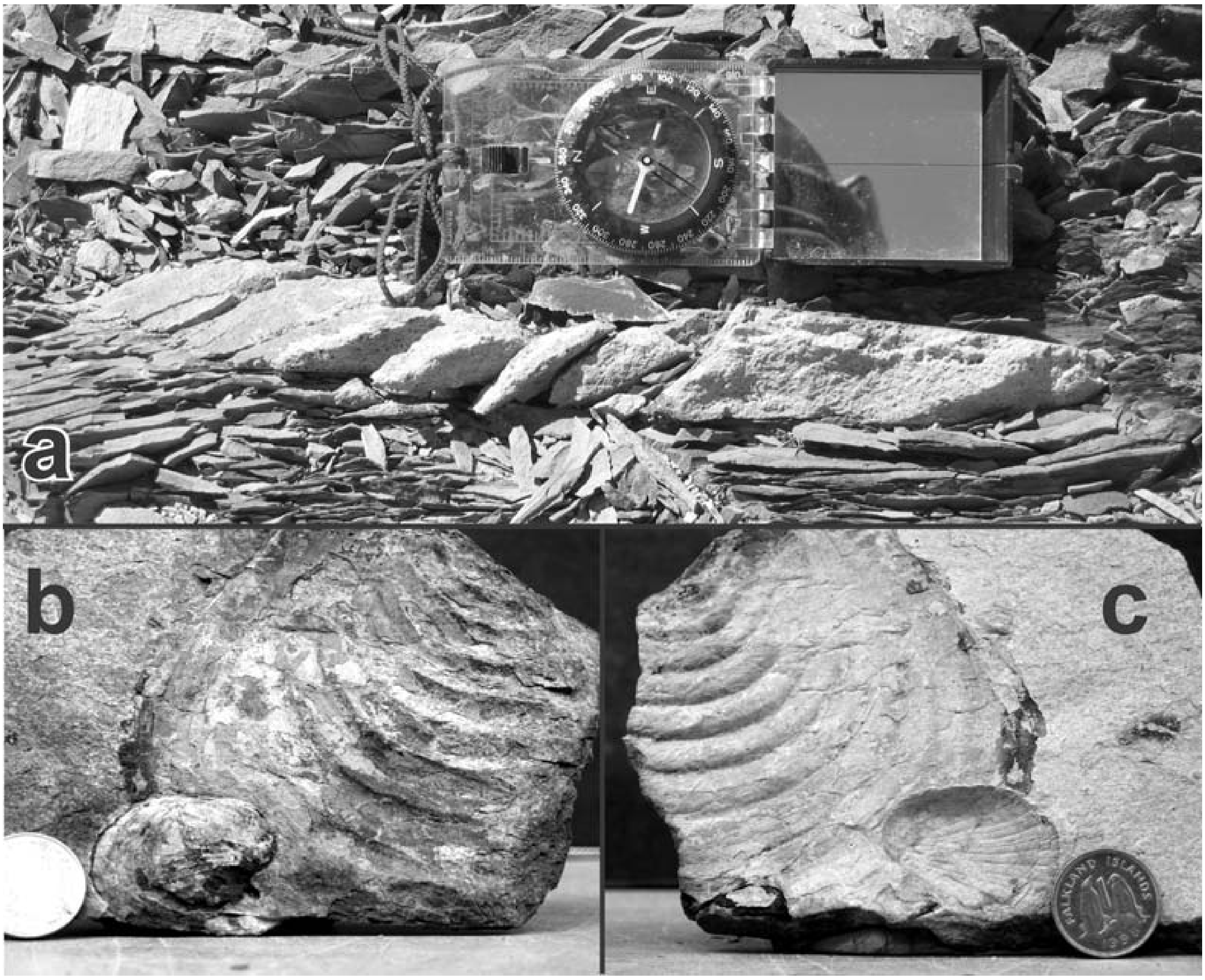

Figure 8. Witte Formation. (a) Pale-coloured sandstone lens in black mudstone. Compass clino is 17 cm long. (b, c) Oxytomid anchored on a large inoceramid valve. Coin diameter is 2 cm. (b) Internal mould. (c) External impression.

commonly the bodies are structureless with sharp tops and bases. In a few cases, centimetre-scale sandstone dykes were injected into the overlying siltstone from one of these lenses, where they pond as small sills. Other soft sediment loading structures are common between the sandier and siltier horizons. In places, the siltstone outcrops contain sets of channels that get smaller and less frequent up-section.

The yellow weathering, grey, medium-grained sandstone bodies are either horizontally bedded or structureless, or appear mottled with a better-developed cleavage. The section at Mount Hirman preserves mud flakes and some sizeable mudstone clasts in these sandstones.

Fauna at the type section are preserved in black siltstone, mostly in life position. The community is dominated by epifaunal, medium-sized, mainly coarsely ribbed *Retroceramus* and *Inoceramus* bivavles. A sparse, finely ribbed ammonite community, rare disarticulated ophiuroid remains (arms) and very occasional belemnites have been either washed in or were present in the water column. Thomson (1983) described some poorly preserved ammonites from Witte Nunataks that he provisionally assigned to *Torquasphintes* and the specimens collected here have the same characteristics. Secondary colonizers, such as oxytomids and crinoids, anchored themselves to some of the larger Inoceramid shells (Fig. 8b, c). Quilty (1977) described a very similar fauna at Mount Hirman. Evidence for short-lived, high-energy episodes comes from a death assemblage at the type section (~7 m above base, Fig. 7a). The deposit consists of reworked fauna from the surrounding mudstones, with pale-coloured mudstone granules and a greater proportion of plant debris supported in a siltstone matrix. As well as the local fauna, the mudstone also contains smaller debris: five-sided star-shaped crinoid ossicles, a few small belemnites, a possible echinoid spine impression and probable fish scales. Eagle & Hikuroa (2003) described similar crinoids from the site at Mount Hirman. Indeterminate plant material is found on bedding planes throughout the unit, but is more abundant in the Mount Hirman section.

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Depositional environment and age. The Witte Formation represents offshore facies, deposited in restricted to semi-restricted basins (cf. Upper Jurassic Kimmeridge Clay of NW Europe: Hallam & Sellwood, 1976). Background sedimentation was extremely quiet, leading to deposition of very finely planar-laminated mudstone, interbedded with fine-grained thin-bedded turbidites. This low-energy environment was punctuated by the passing of turbulent currents through the basin, creating small scours that were infilled by fine-grained sandstone either carried by the current or subsequent currents. The medium-grained sandstone bodies are probably gully or chute fills, caught on the shelf edge as a current passed overhead. Mottling and better cleavage development point to more mud in the sandstone, either as a result of bioturbation, ripples or changes in the energy of the depositional current.

The presence of the concretions in the small-scale channel structures is consistent with their early formation. The concretions probably formed only a few centimetres below the sediment–water interface from where they were readily eroded and redeposited.

Infauna are common elsewhere in the Latady Basin, but the lack of benthos apart from Retroceramids and secondary colonizers at the type section, combined with the lack of bioturbation, black colouration of the mudstone, and early development of concretions, suggests that the basin had restricted circulation (Morris, 1979). Low levels of oxygen led to anoxia at the sediment–water interface, at least periodically if not continuously. We suggest that the type section can be correlated with the Middle Jurassic facies from Mount Hirman. These sediments were more oxygenated leading to a higher biodiversity, including infauna as well as epifauna (Quilty, 1977), but circulation was still poor, with quiet low-energy deposition leading to development of concretions, a lack of bioturbation and finely laminated black mudstone.

Hunter, Riley & Millar (2004) assigned an air-fall horizon interbedded with sedimentary facies from Witte Nunataks to the late Middle Jurassic (*c.* 165 Ma) on the basis of the volcanic geochemistry. Using the ammonites, Quilty (1970) determined a Callovian age for the fauna at Mount Hirman. Based on the similarity of the lithofacies associations and species found at both sites, particularly the oxytomids, we tentatively allocate a Callovian or late Middle Jurassic age to the whole formation.

4.c. Hauberg Mountains Formation

Nomenclature. Fieldwork was principally carried out in the Hauberg and Behrendt mountains and the unit is named after the areally more extensive Hauberg Mountains.

Type section. There is no single type section for this formation. Specific areas were targeted in this study to understand the larger-scale basin evolution, but the whole area needs more detailed consideration. The formation has been divided into a number of members with their own type sections (Fig. 9). These members almost certainly grade into each other, and will probably contain several formations when studied at finer resolution. The common features between all members are preservation of most of the fauna in concentrated death assemblages, especially in the northern units, and a lack of fine plant debris. The area studied did not include the type section of Williams *et al.* (1972) in the Latady Mountains.

Distribution, thickness and boundaries. The Hauberg Mountains Formation is exposed throughout the Behrendt, Hauberg, Wilkins, Scaife and Latady mountains (including the Latady Formation type section: Williams *et al.* 1972; Figs 1, 2), the associated smaller peaks such as Quilty and Weather Guesser nunataks, Thomas Mountain, and probably extends further north up the Lassiter Coast (Fig. 1; for comparison and relative ages, see Laudon *et al.* 1983). The lack of continuous and correlatable sections makes it difficult to estimate the thickness of this formation. However, the wide geographic distribution suggests that it is the thickest unit and it is probably several kilometres thick.

Sedimentary facies description. There are two dominant facies associations in the Hauberg Mountains Formation: coarser-grained, cross-bedded and planar-bedded sandstones and finer-grained, mudstone and sandstone, often bioturbated and/or fossiliferous. The three members described below consist of varying proportions of the two main facies associations, but the formation as a whole is characterized by high lateral variability, both along- and up-strike.

Age. The formation is assigned to the Late Jurassic, although deposition across the basin was diachronous with localities ranging in age from late Middle Jurassic through to Kimmeridgian/Tithonian.

4.d. Long Ridge Member

Nomenclature. This member is named after Long Ridge, which lies north of the main Hauberg Mountain range, about 25 km NW of Mount Dewe (Fig. 2).

Type section and distribution. The type section underlies Long Ridge. The member is several hundreds of metres thick at the type locality and only the lower part has been measured (Fig. 9a). The member probably also underlies Bean Peaks in the western part of the Hauberg Mountains, Quilty Nunataks and the ridge 4 km NW of Mount Chandler, Behrendt Mountains (Fig. 2).

Sedimentary facies description and fossil content. The Long Ridge Member is dominated by sandstone (Fig. 9a). The basal part of the member consists of grey/brown (weathering cream and orange), fine- to medium-grained sandstone (Fig. 10a), either

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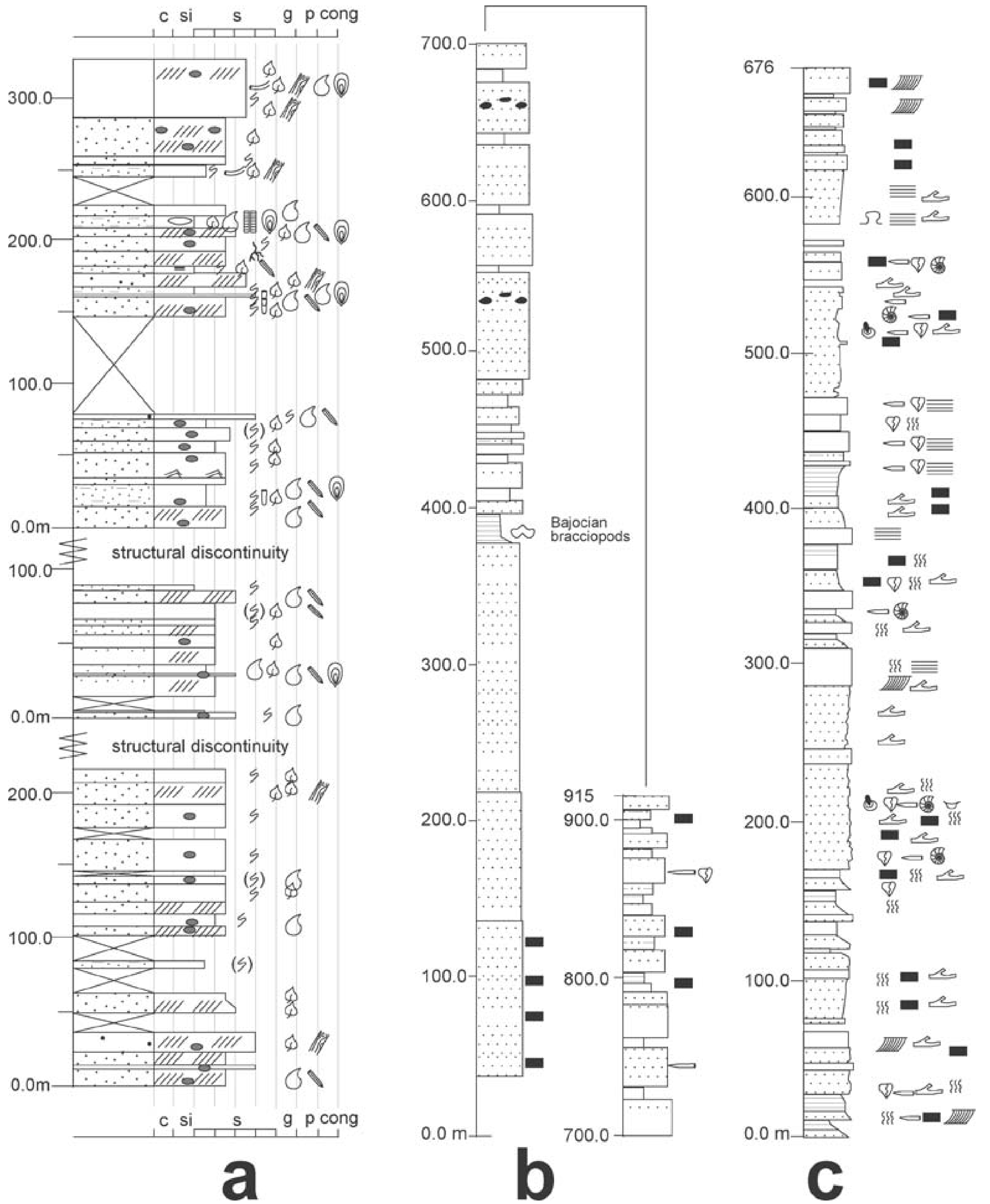

Figure 9. Measured sections for the Hauberg Mountains Formation. (a) Lower part of the long Ridge Member, Long Ridge (Fig. 2). Legend in Figure 4. (b) Mount Hirman Member, northeast summit of Mount Hirman (Laudon *et al.* 1983). (c) Novocin Member, 5 km west of Novocin Peak, summarized and inverted from section 7 of Laudon *et al.* (1983). For key to symbols in (b, c), refer to Laudon *et al*. (1983).

planar-bedded or with tabular, low-angle cross-stratification on a centimetre scale. Interbedded with this are thinner blue/black mudstone beds and cream to white coarse-grained sandstones; the latter are rich in plant remains and mudstone clasts. Up-section, the dominant lithology changes to bioturbated finer-grained sandstone and siltstone, and finally to 3–5 m coarsening-up cycles of siltstone to sandstone that are

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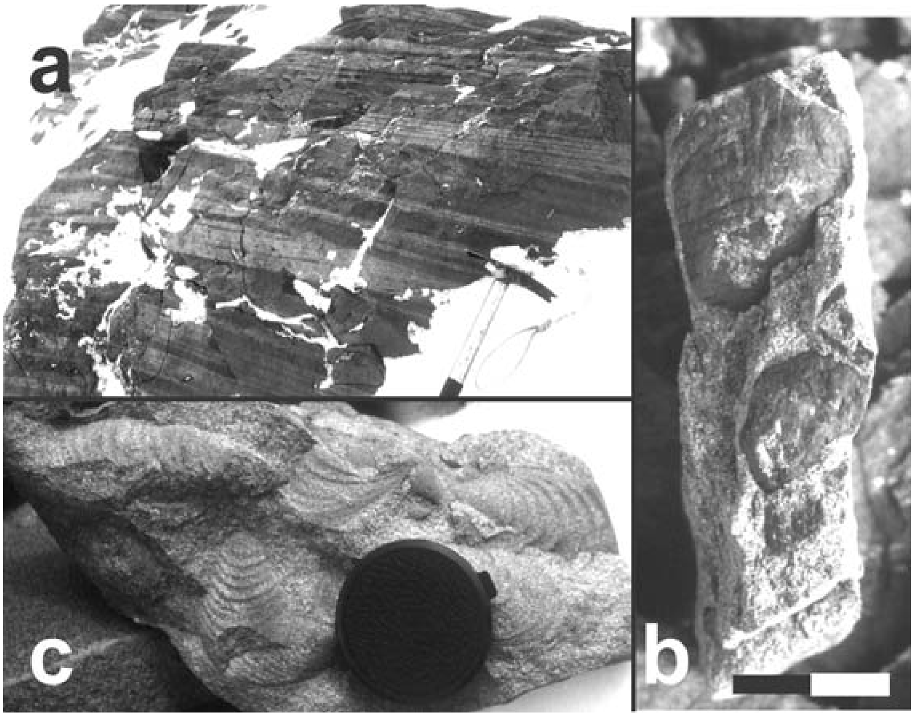

Figure 10. (a) Low-angle cross-bedded units characteristic of the lower part of the Long Ridge subunit. Ice axe head is 25 cm long. (b) Internal bivalve moulds in black mudstone from a medium-grained sandstone in the middle part of the Long Ridge subunit. Scale bar 20 mm. (c) A collection of epifaunal bivalves from a thick sequence of sandstones on the northern flank of Mount Hirman summit (base of section 9b). Lens cap diameter is 35 mm.

characteristically capped by cross-bedded, fine-grained sandstone, sometimes rich in small bivalves. Rare small-pebble conglomerates are dominated by vein quartz and quartzite clasts with subordinate granitoids, in coarse-grained sandstone.

Plant debris is fairly ubiquitous, with larger wood and *Equisetum* remains being concentrated in coarser-grained lithologies in the lower part of the member. Roots about 5 mm thick preserved in fine-grained sandstone were noted at the type section (Fig. 9a). Marine fossils (Fig. 10b) are common in the upper parts of the member, scattered throughout the finer lithologies and concentrated within thin horizons of coarser material associated with black mud clasts and plant fossils. The preserved fauna are collated in death assemblages and typically consist of high energy species such as *Rotularia*, Trigoniids and larger bivalves or thick shelled and robust species like belemnites. At Bean Peaks, finer-grained lithologies contain densely fossiliferous units dominated by retroceramid and *Malayomaorica* bivavles (D. Hikuroa, unpub. Ph.D. thesis, Auckland Univ. 2004). Ichnofauna change through the member from domichnia to crawling tracks and feeding traces on muddy rippled surfaces. Pervasive brown and white mottling of the sandier lithologies also increases up-section. Large burrows are common and include well-developed Ophiomorpha.

Depositional environment and age. The well-laminated low-angle cross-bed sets, and horizontally bedded fine- to medium-grained sandstone which dominate the lower part of the Long Ridge Member, are interpreted as lower foreshore deposits, with little evidence for subtidal channelling or dune development (Thompson, 1937; Clifton, 1969). Higher in the section, the bioturbated fine-grained sandstone and siltstone facies punctuated by thanatocoenotic horizons are interpreted as shoreface or shallow marine deposits, with associated pervasive bioturbation, finer grain sizes and the beginnings of channelling and progradational shelly bar forms. Rare plant roots (Fig. 9a) suggest water levels were very shallow and at times the environment might even have been subaerial.

There are no published ages for this subunit, but Hikuroa (unpub. Ph.D. thesis, Auckland Univ. 2004) concluded that the faunal assemblages at both Long Ridge and Bean Peaks have an affinity with the Middle Jurassic New Zealand fauna of the Murihiku Terrane.

4.e. Mount Hirman Member

Nomenclature. The member is named after Mount Hirman in the southern part of the Behrendt Mountains (Fig. 2).

Type section and distribution. The type section for this member (measured by Laudon *et al.* 1983) underlies the northern ridge and summit of the main peak in the southern part of the Mount Hirman range (Figs 2, 9b). The member may also underlie many of the other

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nunataks in central Ellsworth Land and the northern part of the Hauberg Mountains.

Sedimentary facies description and fossil content. The member consists of two main lithofacies associations interbedded on a scale of tens of metres. The first is dominated by dark, fine-grained sandstone and siltstone, commonly bioturbated and rich in scattered body fossils. Plant material concentrates in the finer units, and body fossils are scattered in the fine-grained sandstone. There is evidence of fluctuating current strengths with deposition of 60–100 cm cycles of black mudstone to planar-bedded, medium/fine-grained sandstone with poorly preserved ripples. The second lithofacies association is characterized by quite thick sequences of massive fine- to medium-grained grey sandstone (up to 300 m thick; Fig. 9b), occasionally trough cross-bedded, with bioturbated finer sediment between the troughs. These sandstones often have mudstone flakes or clasts, accompanied by a scattering of plant remains and marine fauna. Bioturbated ripple surfaces are common and include trails and tracks as well as simple burrows. Bifurcating symmetrical ripples can be found but more often, ripple forms are asymmetrical, linguoid and undulating.

Relatively common concretions in the finer-grained lithofacies association preserve a community dominated by infaunal bivalves such as *Pleuromya* and large ammonites, with minor bioturbation and plant debris. Belemnites, bivalves, crinoid ossicles and wood remains are scattered throughout. Some of the bivalves are still articulated, and Quilty (1977) commented on both an infaunal and epifaunal element to the assemblage. He concluded that the energy of the environment was low, such that the fossils were not moved much after death. In contrast, the grey, fine- to fine/medium-grained sandstone is rich in mudstone flake horizons and rarer mud pebble conglomerates, with a scattered fauna of disarticulated bivalves, belemnites and crinoid ossicles. Fossiliferous pockets represent concentration by current activity. Epifaunal bivalves are also found in clusters where communities have been able to exploit shell material or harder substrates as anchorage (Fig. 10c). Some sandstone beds contain *Rotularia* associated with mud flakes.

Depositional environment and age. The fine-grained and organic-rich elements of the dark, fossil-rich lithofacies association are consistent with a quiet, low-energy marine environment (Morris, 1979). The faunal assemblage is typical of near-shore habitats (Quilty, 1977). The repeated rapid shifts between associations reflect fluctuating energy conditions and variation in sedimentary input rates, either as a result of changes in the subaqueous topography, different water depths or a change in the terrestrial environment supplying the sedimentary material. Ripples in the sandstone facies and concentrations of belemnite or shell debris are consistent with current deposition or reworking. Although the lower-energy facies are superficially similar to the Witte Formation, the common bioturbation, high proportion of infaunal species and presence of higher energy, fossiliferous sandstones are unique. The depositional environment is similar to that found in the finer-grained parts of the Long Ridge Member and suggests that these quieter environments are offshore equivalents of the higher-energy near-shore settings.

The age of this member is based on the palaeontological work conducted by Quilty in the Mount Hirman area (e.g. Quilty, 1970, 1977, 1983). He describes a conglomerate from the type section containing Rhynconellid brachiopods, which he assigns to the Bajocian (Quilty, 1972; Fig. 9b). However, the conglomerate also contains Upper Jurassic (Kimmeridgian) bivalves (Quilty, 1977), and the interpreted high-energy environment is completely different from any of the other Middle Jurassic sections in the Latady Basin. In contrast, shallow-water, or near-shore infauna from Quilty Site 9 are assigned to the Oxfordian (Quilty, 1970) and a similar low-energy fauna is found at Weather Guesser Nunataks (Quilty, 1977). In light of this we suggest that the brachiopods from Mount Hirman have been reworked and assign an undifferentiated Upper Jurassic age to this member, although more specifically the unit is probably Oxfordian to Kimmeridgian.

4.f. Novocin Member

Nomenclature. Novocin Peak lies in the middle of the Hauberg Mountains range (Fig. 2) and is underlain by the thickest section of this member (Fig. 9c).

Type section and distribution. The type locality for this member is Novocin Peak, where Laudon *et al.* (1983) measured more than 650 m of section (Fig. 9c). The member is typical of most of the southern part of the study area and may also underlie several other localities in the Wilkins, Scaife and Latady mountains but probably fines towards the Lassiter Coast and Black Coast exposures (cf. the type section, Williams *et al.* 1972).

Sedimentary facies description and fossil content. The member is characterized by the same two lithofacies associations as the rest of the Hauberg Mountains Formation, but with proportionally more finer-grained, dark grey or black lithologies compared to the other two members. The finer-grained sediments are dominated by black siltstone and orangey fine-grained sandstone. These are commonly bioturbated and, where weathered, the fine-grained sandstone can appear mottled brown and white. Bioturbation is typically unidentifiable but, where identification is possible, falls in the *Cruziana* ichnofacies with possible *Rosselia*. Where bioturbation is absent, the finer units consist of millimetre-scale bedding between siltstone and fine-grained sandstone. Flames can be found between mudstone and sandstone beds. Ripple cross-lamination is rare and cross-bedding

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absent. Fossils scattered throughout the finer facies are dominated by nektonic species. The coarser-grained lithofacies association is volumetrically minor but typically medium-grained sandstone, regularly associated with fine-grained sandstone in centimetre-scale bedding, but includes coarse-grained to granule-grade sandstone in places. Cross-bedding is discernible from some outcrops. These coarser-grained units contain fossil and mud clast-rich horizons and can be bioturbated.

Fossils are sparse but ubiquitous in this member, predominantly scattered as single specimens throughout the dark-coloured siltstone and sandstone. Concentrated thanatocoenotic horizons still occur in coarser-grained horizons, but they are less frequent. Nektonic taxa such as belemnites and ammonites dominate the fauna, with lesser bivalves and brittle stars found almost exclusively in the coarser units. Wood and *Equisetum* debris are common in the siltstone, but unidentifiable carbon smears are common, and there are very thin coals (< 1 cm) at the southern end of Novocin Peak itself.

Depositional environment and age. The predominance of the finer-grained lithologies is consistent with lower-energy deposition on the middle to outer shelf below storm wave base. Fine millimetre-scale bedding is indicative of very gentle background sedimentation rates. Bivalves, mud clasts and cross-bedding are most common in the coarser-grained lithologies, compatible with their deposition during periods of increased energy. Higher-density currents transported the coarser-grained material into an environment dominated by nektonic taxa such as ammonites and belemnites.

Ammonites from the Novocin Member have been assigned an Early to earliest Late Tithonian age (Thomson, 1983), although Thomson remarked on the possibility that the age range of the specimens might extend back into the Kimmeridgian.

4.g. Cape Zumberge Formation

Nomenclature. Named after the exposure at Cape Zumberge, ~ 30 km south of the Hauberg Mountains on the edge of the Ronne Ice Shelf (Fig. 2).

Type section. There is no formal type section drawn up for this formation.

Distribution, thickness and boundaries. The formation underlies three rocky outcrops close to the coast (about 50 m by 30 m) but was not identified elsewhere in the study area.

Sedimentary facies description and fossil content. The Cape Zumberge Formation comprises black mudstone and very fine-grained sandstone with minor amounts of interbedded grey (weathering orange) fine-grained sandstone. Bedding is generally planar on a millimetre scale, but some surfaces are rippled and rare cross-bed sets are preserved in the fine-grained sandstone. Bioturbation is limited to small (2–5 mm across) tracks and traces on bedding surfaces. The fauna is limited to ammonites and a species of epifaunal bivalve. Dark pyrite-rich concretions found in the siltstone are commonly associated with locally deformed bedding, indicating early formation while the sediment was still wet.

Cape Zumberge is best known for the large and abundant ammonites described by Thomson (1983). The best-preserved ammonites are concentrated in a few specific horizons at the western end of the exposure, where the sedimentary rocks are predominantly fine- and very fine-grained sandstone, but occur throughout the site. Epifaunal bivalves typical of black anoxic shales and characteristic of the outer shelf are restricted to two horizons that contain no other fauna. There are a few isolated empty moulds of belemnites and no plant remains.

Depositional environment and age. The mainly surficial bioturbation, black colouration and fine grain size combined with pyrite nodules and pyritized ammonite fossils imply restricted circulation, commonly with anoxic conditions, in a very quiet, low-energy, probably outer shelf environment. The formation is assigned an latest Tithonian age based on the ammonite population (Thomson, 1983).

4.h. Nordsim Formation

Nomenclature. This unit is named after Nordsim Peak in the Cantrill Nunataks, ~ 12 km to the NNE of Mount Jenkins in the Sweeney Mountains (Fig. 2).

Type section. The type section is designated from the northern ridge of the main nunatak (Nordsim Peak) (Fig. 11a).

Distribution, thickness and boundaries. This unit underlies the Cantrill Nunataks, which consist of three small nunataks to the north of Mt Jenkins in the Sweeney Mountains (Fig. 2). The formation is a minimum of 120 m thick at the type section. Two measured sections are shown in Figure 11, including the upper 50 m of the type section. The formation underlies a geographically small area and its thickness is unknown. However, plant-bearing strata which crop out 18 km ESE of Mount Wasilewski might represent this formation further to the west (Fig. 2).

Sedimentary facies description and fossil content. The Nordsim Formation comprises fine-grained sandstone and mudstone, rich in plant remains, deposited in sequences of repeating cycles, up to 2 m thick but normally less. Cycles commonly have palaeosols rich in plant debris/carbon at their tops (Fig. 11a). Not all cycles are complete; some have thicker mudstone units and others lack the plant-rich tops. Smaller-scale (< 2–8 cm thick), graded units of fine-grained

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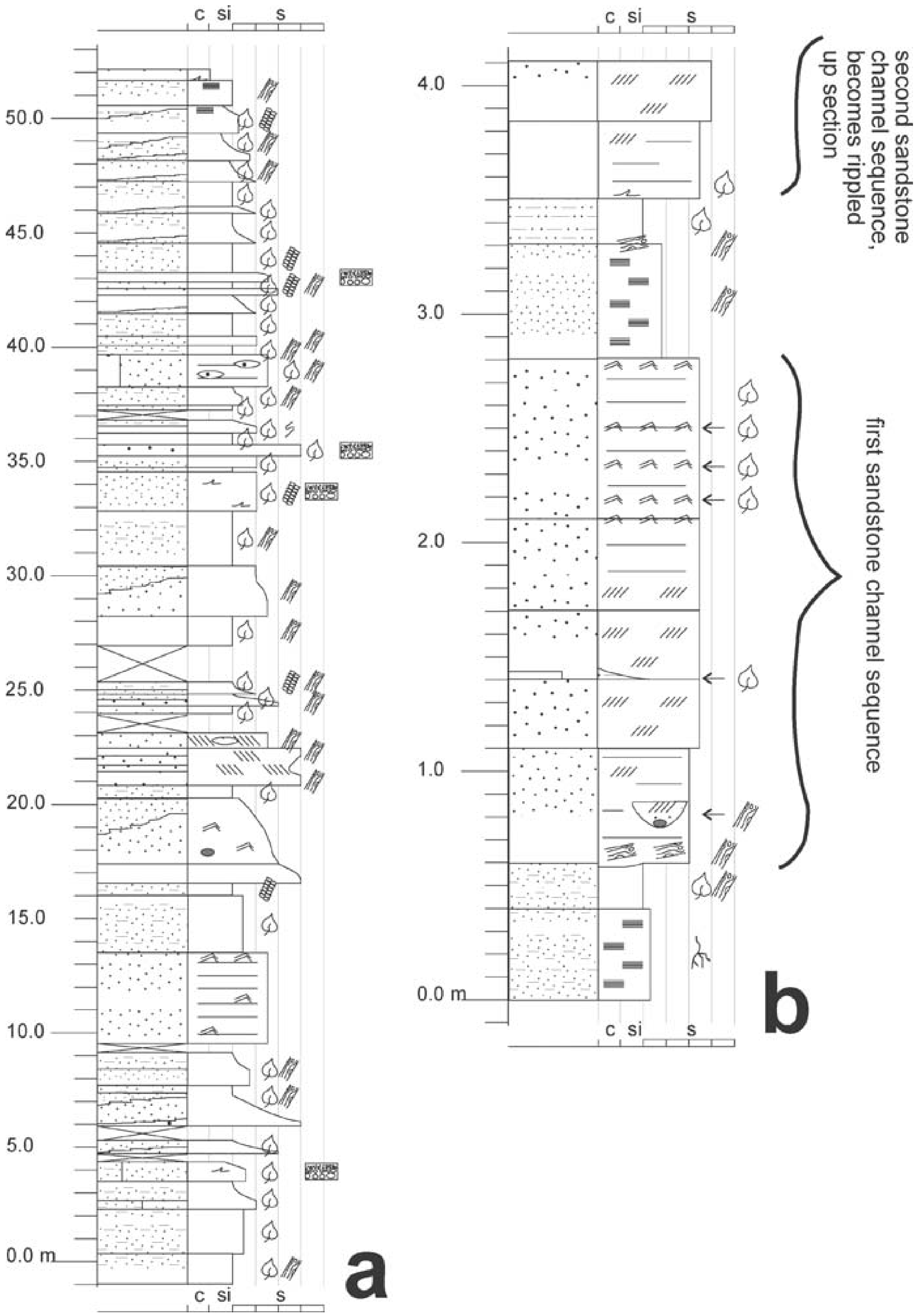

Figure 11. Nordsim Formation. For location of sections see Figure 12c. (a) Type section. (b) Section through two sandstone units, note expanded scale. For key to symbols in (a), see Figure 4. For key to (b), refer to Laudon *et al*. (1983).

sandstone to siltstone are also found. Flaser bedding and entrained mudstone flakes are common in the lower parts of the sandstone beds. Only one vertical burrow or escape structure was noted at the type section (~ 36 m; Fig. 11a), associated with loading structures suggestive of rapid sedimentation. Thicker

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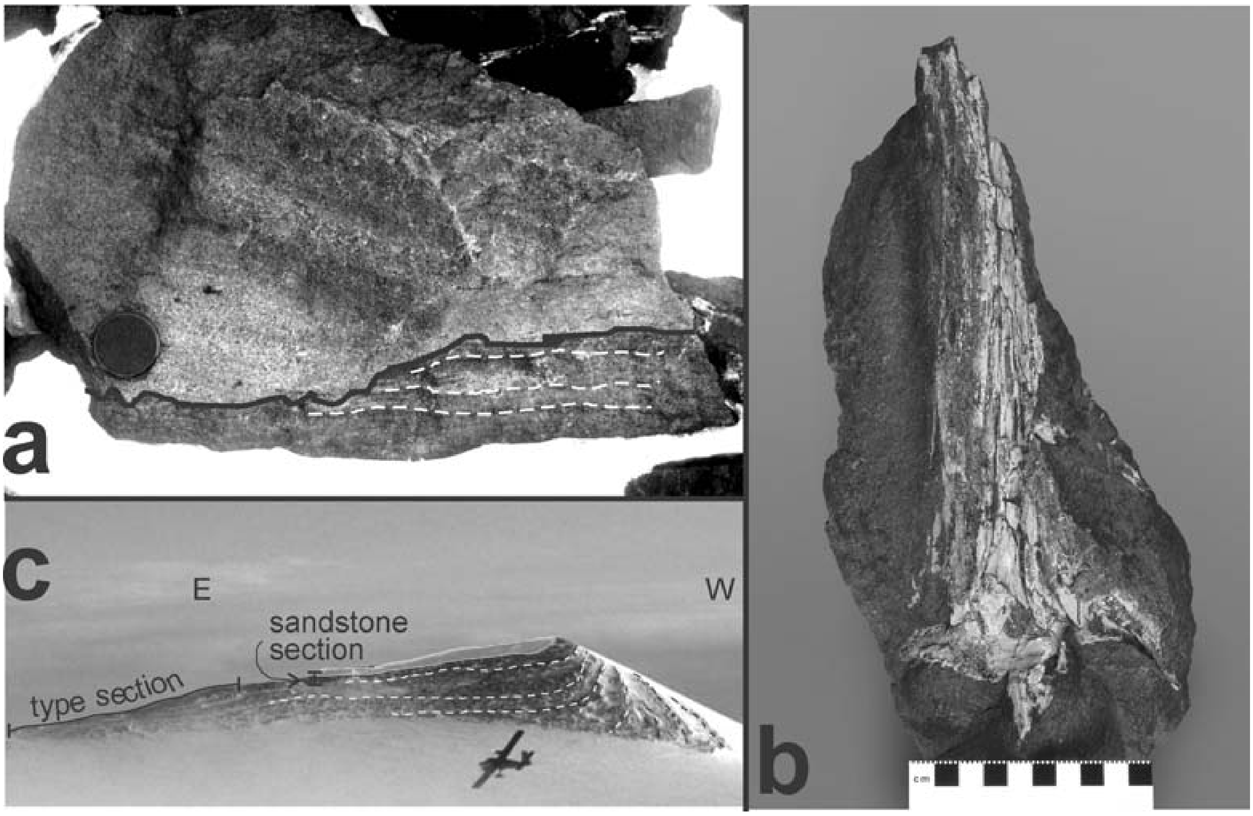

Figure 12. Nordsim Peak. (a) Contact between the basal unit of the lower sandstone in section 11b, and the underlying finely bedded siltstone; 35 mm lens cap for scale. (b) Large root caught up by a sandstone unit; 10 cm scalebar. (c) View of Nordsim Peak looking south, showing cyclicity of sandstone units.

(~ 3–5 m) cross-bedded, poorly sorted, medium- to coarse-grained sandstone units, cut down through the finer-grained sediments (Figs 11b, 12a). In places the bedding is distorted, convoluted or rippled. These coarser beds commonly contain large pieces of plant debris (~ 50 by 10 cm), often orientated subparallel to cross-bedding flow direction. Whilst many of these coarser sandstone beds are preserved as continuous sheets, some are channellized (tens of metres wide by 3–4 m thick), with fine-grained sandstone and grey plant-rich mudstone in between channels or along-strike. The flora in this setting is dominated by *Equisetum* (Fig. 13c). These channellized sandstone units occur cyclically, about every 10 to 15 m (Fig. 12c) and underlie many of the smaller outcrops to the north and south of the type section. This is almost certainly a preservation effect. Where the sequences are thicker, finer-grained cycles are still preserved between sandstone units. A discontinuous lens of conglomerate was identified at the base of a small channel structure (1–2 m by 0.5 m). Clasts 2–3 cm in diameter quickly grade into a granule-rich sandstone top before passing back into the fine-grained sandstone/mudstone cycles.

The formation is characterized by abundant plant remains (commonly comminuted) dominated by bennettites, ferns, horsetails (*Equisetum*) and woody debris (Fig. 13). Plant preservation is better in the grey/black siltstone where smaller plant remains preserve fine detail such as primary and secondary veining on leaflets and leaves (Fig. 13a, b). Small rootlet horizons are present in some mudstones and extend down into carbon-rich layers. The coarser sediments preserve woody branches and stems, commonly with silicified exteriors and virtrinized cores (Fig. 13d). Some of the coarser sandstones contain sizeable roots (Fig. 12b). These have a different preservation from the wood. Where the wood is vitrinized with a box-work texture, the roots are grey and silicified with a smooth texture. These larger roots are associated with a fair amount of plant debris but no leaf litter, suggesting slow burial and oxygenated conditions.

Depositional environment and age. The fining-up cycles, thin carbon-rich layers, restricted channels and abundance of plant material are all consistent with deposition in a deltaic setting (Elliott, 1974). Root horizons suggest very shallow water levels, perhaps even that the muddy overbank areas were water-logged rather than subaqueous. Sheeted sandstone deposits represent crevasse splays, which deposited sand more uniformly in overbank areas. Channellized sandstone with between-channel mudstone is typical of waterways through the delta. Water within the system

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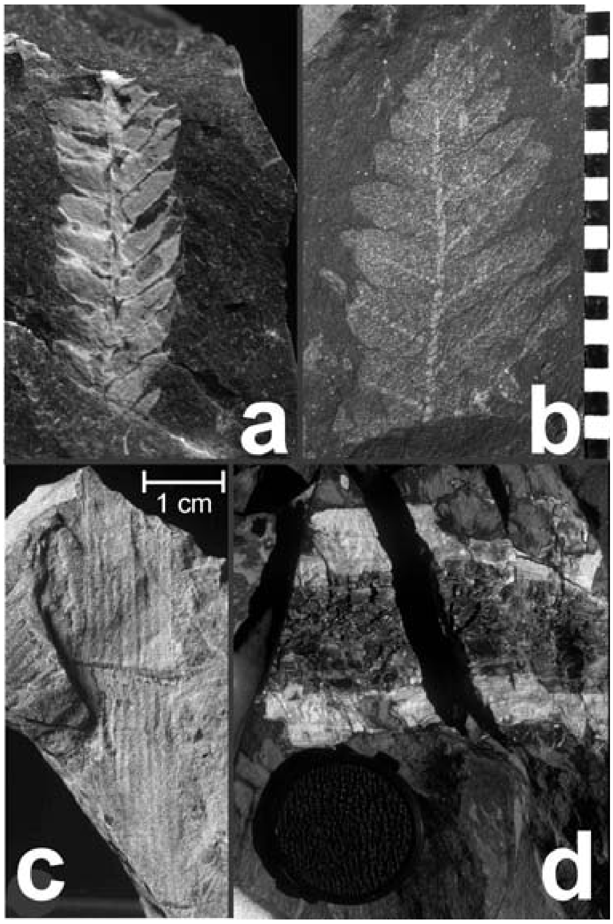

Figure 13. Plant remains from the Nordsim Formation. (a) Bennettite leaflets, *Otozamites boolensis*. (b) Fern pinnules, *Cladophlebis antarctica*. Scale bar in mm for (a) and (b). (c) Segmented stem of a horsetail, *Equisetum laterale*. (d) Woody fragment with vitrinized core; 35 mm lens cap for scale.

was flowing in defined channels tens of metres wide and at least 4 m deep, through the quieter overbank areas where plants became established. Larger debris, including big branches, was carried by these waterways and is commonly current orientated. Changes in sedimentation rate, either as a result of subsidence in the basin or seasonal changes in the climate, produced the cyclicity of the deposits.

Previous work has placed the Nordsim Formation at the base of the Latady Group (Willan & Hunter, 2005) on the basis that the palaeoflora is comparable with the Botany Bay Group flora described from the Larsen Basin to the north (Cantrill & Hunter, 2005; Rees, 1993). However, the flora lacks key taxa, such as the Early–Middle Jurassic *Goeppertella*, and recent U–Pb ion probe age data from detrital zircons in the conglomerate horizon at Cantrill Nunataks gave a maximum age of deposition in the latest Jurassic/earliest Cretaceous (Hunter, Cantrill & Flowerdew, 2006). Rather than being the oldest, the Nordsim Formation is the youngest formation in the Latady Basin.

5. Stratigraphic summary and basin evolution model

We have redefined the Latady (this paper) and Mount Poster formations (Hunter *et al.* 2006, this issue) as two groups within the Latady Basin. The Ellsworth Land Volcanic Group comprises two formations: the intracaldera Mount Poster Formation and extracaldera Sweeney Formation (Hunter *et al.* 2006, this issue). The Latady Group has been divided into five formations. With future mapping it should be possible to extend these divisions northward into the less well-preserved outcrops, and also to refine further the members of the Hauberg Mountain Formation. The stratigraphy for the Latady Basin (Fig. 3) and the sedimentary environments indicate a rifted margin, which evolved from intracontinental volcanism and terrestrial deposition (Ellsworth Land Volcanic Group: Hunter *et al.* 2006, this issue), through coastal deposition and shallow fully marine to outer shelf (Fig. 14). The stratigraphic evolution of the basin and present-day distribution of the various elements are consistent with development of the basin to the present day southeast, with land to the northwest in agreement with previous publications (e.g. Thomson, 1983; Laudon *et al.* 1983). In the absence of suitable marker horizons or better exposure, it has not been possible to improve on the estimate of Laudon *et al.* (1983) that the Latady Group is several kilometres thick.

In detail, the stratigraphy shows a Middle Jurassic transgression, followed by rapid regression and a second phase of transgression in the Late Jurassic (Figs 3, 14). Global sea-level rose through the Middle and much of the Late Jurassic, only showing a fall towards the end of the Jurassic (Hallam, 1992; Fig. 3). Thus, we propose that the pattern seen in the Latady Basin is controlled by the underlying tectonics and, more specifically, is the result of two phases of basin evolution.

Initial rifting was intracontinental and resulted in eruption of the Mount Poster Formation silicic ignimbrites and the Sweeney Formation basalts (Fig. 14a; Riley *et al.* 2001; Hunter *et al.* 2006, this issue). The contemporaneous lacustrine facies of the Sweeney Formation are the oldest preserved sedimentary rocks in the Latady Basin and mark the onset of deposition in the latest Early Jurassic (*c.* 183 Ma: Hunter *et al.* 2006, this issue). Eruption of the Karoo-Ferrar igneous provinces in South Africa and East Antarctica about 183 million years ago (Riley & Knight, 2001) was coincident with the onset of deposition in the Latady Basin. These large igneous provinces have been linked to mantle plume activity at the South Africa–East Antarctic boundary, and onset of extension leading to Gondwana break-up (Storey & Kyle, 1997). The plume activity has also been evoked as the cause of Early Jurassic silicic volcanism in the Antarctic Peninsula and southern Patagonia (Pankhurst *et al.* 2000; Riley *et al.* 2001) and for early extension in the Larsen

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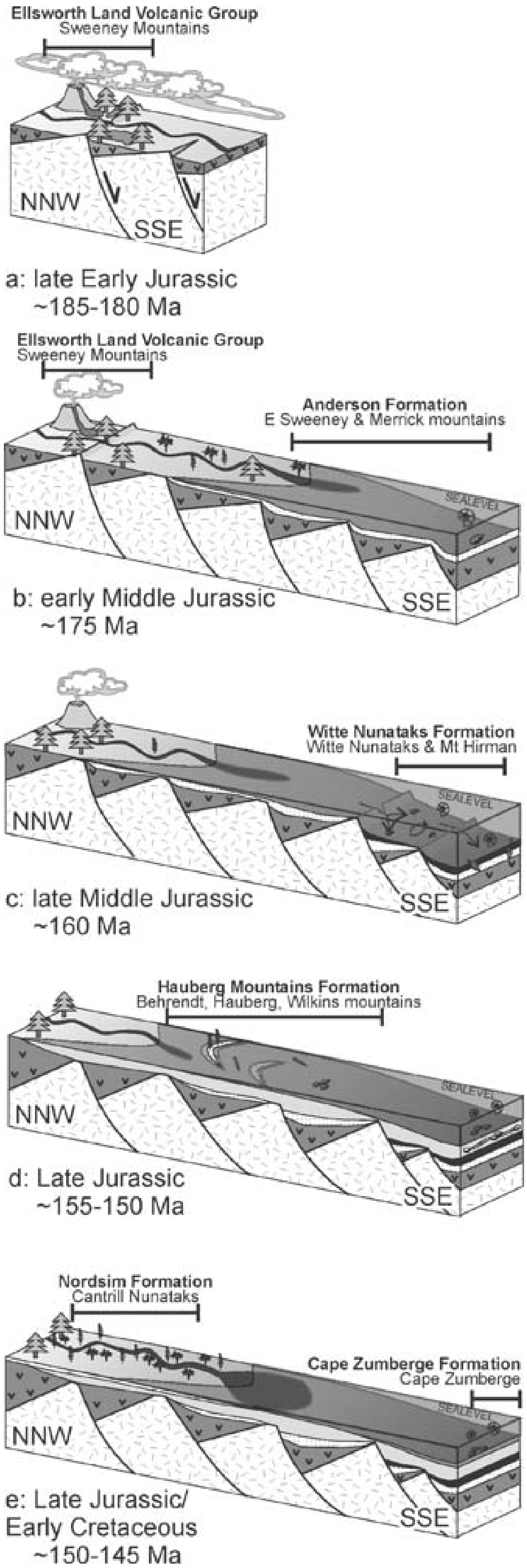

Figure 14. Sequential schematic block diagrams showing evolution of the Latady Basin through the Jurassic and into the Cretaceous. The relationship with basement is unknown and so the faulting shown is hypothetical. The main areas of exposure for each formation are indicated on each block (Fig. 2).

Bay area (Hathway, 2000). Given the nature of the exposure in the area, it is not possible to demonstrate a relationship with basement rocks, but rifting related to this plume centre seems to be the simplest model to explain early extension and silicic volcanism in the Latady Basin.

Ongoing volcanism during deposition of the Anderson Formation places sedimentation of this unit in the latest Early Jurassic or earliest Middle Jurassic (180–175 Ma). The close association of marine and terrestrial environments is consistent with a complex topography or a series of small basins (Fig. 14b). Deepening of the facies through the Anderson Formation into the quiet, restricted setting of the Middle Jurassic Witte Formation is compatible with drowning of these basins by marine transgression and/or subsidence associated with continuing extension of the incipient Weddell Sea Basin. The petrology and geochemistry of sandstones in the Anderson and Witte formations suggests derivation from local continental sources (Laudon & Ford , 1997; Willan & Hunter, 2005) and is consistent with local rifting. Restricted circulation and partial anoxia in the Witte Formation were possibly controlled by the presence of subsurface faults or horst and graben topography (Fig. 14c). Unfortunately, later deformation during the Palmer Land Event (Vaughan, Pankhurst & Fanning, 2002), mid-Cretaceous plutonism, and concomitant contact metamorphism prevents collection of structural data that could test this. However, comparison with Early to Middle Jurassic basins of southern South America (Pindell & Tabbutt, 1995; Urien, Zambrano & Yrigoyen, 1995) and the east Antarctic Peninsula (Hathway, 2000) provides corroborative support for the evolution and drowning of terrestrial rift graben along the margin of the extending Weddell Sea Basin in this way.

The high-energy, shallow marine and minor terrestrial facies of the Long Ridge and Mount Hirman members contrast starkly with the significant quiescence of the wholly marine Witte Formation (Fig. 14d). They signify an abrupt change in environment at the onset of deposition of the Hauberg Mountains Formation in the late Middle Jurassic/early Late Jurassic. This marked regression comes at a time of global transgression (Fig. 3) and suggests a change in the tectonic framework of the area leading to an increase in sediment flux sometime in the latest Middle Jurassic (*c.* 160 Ma). Not only is there a probable change in sedimentation rate, but there is also a marked change in provenance from continental sources to juvenile volcaniclastic material (Willan & Hunter, 2005; Laudon & Ford, 1997), consistent with emergence of a new source area. The sudden influx of volcaniclastic material and abrupt regression coincide with a pulse of subduction-related volcanic activity along the western margin of the Antarctic Peninsula and into southern Patagonia (157–153 Ma: Pankhurst *et al.* 2000). We propose that the change in depositional style

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relates to a tectonic shift from intracontinental rifting related to mantle plume activity, to subduction along the Pacific margin and generation of a Late Jurassic arc (cf. Hathway, 2000; Pirrie & Crame, 1995).

After the initial regression, deepening of the lithofacies through all three members of the Hauberg Mountains Formation to the relatively offshore facies of the Novocin Member is consistent with resumed marine transgression. Latest Jurassic (Tithonian)/earliest Cretaceous deposition is open marine to the south (Cape Zumberge Formation) but terrestrial/deltaic to the north (Nordsim Formation) (Fig. 14e). This is compatible with the palaeogeography of the basin, and terrestrial deposition to the north may be a consequence of Late Jurassic regression (Fig. 3) but might also reflect uplift of the basin margins by emergence of the arc (Hunter, Cantrill & Flowerdew, 2006).

6. Conclusions

Early workers proposed a simple back-arc basin model to explain deposition in the Latady Basin (e.g. Rowley *et al*. 1983), with a single phase of subsidence related to development of a continental arc to the northwest. Changes in sedimentary facies, geochemistry and petrology from northwest to southeast were interpreted in terms of palaeogeographic proximity to the proposed arc (Laudon *et al.* 1983; Laudon, 1991; Laudon & Ford, 1997). Laudon & Ford (1997) showed a change from a continental source in a passive margin setting in the northwest to arc-derived detritus in an active continental arc setting to the southeast. They explained the apparent inverse maturation of the arc by tectonic processes that brought three crustal blocks together. The new stratigraphy and basin history presented above are consistent with the published geochemical and petrological trends but suggest two phases of basin evolution with a marked transition at the end of the Middle Jurassic.

The basic pattern is still valid with a shift from older, continental detritus to younger, arc-derived detritus from north to south, but we argue that the change is not related to tectonic juxtaposition of separate blocks but to a shift in the large-scale forces driving extension. The data suggest that Jurassic extension along the margin of the Weddell Sea Basin was initially controlled by rifting related to a mantle plume and creation of a rift and graben topography. These early basins were filled with silicic volcanic rocks and terrestrial deposits. Thermal subsidence and marine transgression then drowned these basins. Renewed subduction of the Pacific plate under the Antarctic Peninsula and southern Patagonia led to emergence of a Late Jurassic arc (Pankhurst *et al.* 2000; Pirrie & Crame, 1995) and a shift to plate margin forces driving extension in the basin. This shift is identified not only by a change in provenance for the sandstones but also by a change in deposition style, signifying rapid regression in the basin. By establishing a new stratigraphy for the Latady Basin it has been possible to look at the forces driving early Gondwana extension and creation of the Weddell Sea.

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