Mid-Cretaceous stratigraphy of the James Ross Basin, Antarctica

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Abstract: The extensive Cretaceous sedimentary sequence exposed within the James Ross Basin, Antarctica, is critical for regional stratigraphic correlations in the Southern Hemisphere, and also for our understanding of the radiation and extinction of a range of taxonomic groups. However, the nature and definition of Cenomanian-Turonian strata on the NW margins of James Ross Island has previously been difficult, due both to marked lateral facies changes and to stratigraphical discontinuities within the extensive Whisky Bay Formation. Facies variation and local unconformities were the result of fault-controlled deep-marine sedimentation along the basin margin. In this study the Albian-Cenomanian boundary is defined for the first time in the upper levels of the Lewis Hill Member of the Whisky Bay Formation. However, there is a Cenomanian-late Turonian unconformity between the Lewis Hill and Brandy Bay members of the Whisky Bay Formation. Equivalent lithostratigraphical units exposed further to the SW on James Ross Island appear to be more complete with the early Cenomanian-late Turonian interval represented by the upper parts of the Tumbledown Cliffs and the lower part of the Rum Cove members of the Whisky Bay Formation. The Turonian-Coniacian boundary is provisionally placed at the junction between the Whisky Bay and Hidden Lake formations. The revised stratigraphic ages for this section show that the Late Cretaceous radiations of a number of major plant and animal groups can be traced back to at least the Turonian stage. This raises the possibility that their dissemination might be linked to the global Cretaceous thermal maximum.

The extensive Cretaceous sedimentary sequence exposed within the James Ross Basin, NE Antarctic Peninsula (Fig. 1) is assuming an ever greater significance for regional stratigraphical correlations in the Southern Hemisphere (Feldmann & Woodburne 1988; Rinaldi 1992; Crame et al. 2004). Totalling more than 5 km in thickness, this succession is now known to range in age from earliest Aptian to the latest Maastrichtian (Feldmann & Woodburne 1988; Pirrie et al. 1991a, 1997; Rinaldi 1992; Riding & Crame 2002; Crame et al. 2004). Strata representing the intervening Cenomanian–Santonian stages have traditionally been less well defined, due partly to a lack of diagnostic index fossils and partly to pronounced lateral facies changes at key localities along the NW coast of James Ross Island (Ineson et al. 1986; Olivero et al. 1986). One particularly striking anomaly has been the presence of Cenomanian strata in the Tumbledown Cliffs–Rum Cove region (Fig. 1) but their apparent absence some 25 km to the NE in the Whisky Bay–Brandy Bay region (Fig. 2). Is there a stratigraphical hiatus here of local or even regional extent?

This study examines the mid-Cretaceous (defined here as Cenomanian–Coniacian) stratigraphy of the James Ross Basin. A series of new field observations from the Brandy Bay reference section are used to recalibrate litho-, bio- and chronostratigraphies for the area, and suggest correlations with localities further SW along the coast of James Ross Island (Figs 1 & 2). It is anticipated that this revised stratigraphy will in turn facilitate the investigation of a series of major Cenomanian–Coniacian palaeoclimatic...
Fig. 1. Schematic geological map of the James Ross Island area. White areas are either the James Ross Island Volcanic Group or snow/ice cover. BB, Brandy Bay; CL, Cape Lamb; RC, Rum Cove; SMC, Santa Marta Cove; TC, Tumbledown Cliffs; WB, Whisky Bay. Area of outcrop of the Pedersen Formation on the adjacent Antarctic Peninsula shown in Hathway & Riding (2001, fig. 1). Position of the K/T (Cretaceous–Tertiary) boundary on Seymour Island is indicated.

and palaeobiological events in Antarctica (Huber 1998; Cantrill & Poole 2002).

**Background and methods**

The James Ross Basin, which may in turn be a component of the larger Larsen Basin, was one of a series of extensive back-arc basins that formed in the Patagonia–Antarctic Peninsula region during the mid-Mesozoic–early Cenozoic (Hathway 2000). The Cretaceous basin fill comprises a regressive mega-sequence of arc-derived clastic and volcanioclastic marine rocks that has been subdivided into the older Gustav Group (Aptian–Coniacian) and the younger Marambio Group (Coniacian–Danian) (Hathway 2000; Hathway & Riding 2001; Riding & Crame 2002 and references therein). The Gustav Group is confined to the NW coast of James Ross Island and certain isolated outcrops on the adjacent margins of the NE Antarctic Peninsula (Fig. 1) (Riding & Crame 2002). Reaching a maximum thickness of 2.6 km, it is characterized by coarse-grained lithologies such as pebble–boulder conglomerates, breccias and coarse- to fine-grained pebbly
sandstones, together with subordinate sandstones, siltstones and mudstones. It has been formally subdivided into five component formations (the Pedersen, Lagrelius Point, Kotick Point, Whisky Bay and Hidden Lake formations) and is generally interpreted to represent a variety of slope-apron and deep-water submarine-fan environments (Ineson 1989; Buatois & Medina 1993). The Gustav Group dips SE and passes conformably upwards into the finer grained Marambio Group (Fig. 1). The latter unit, which is up to 2.5 km thick and is exposed over the greater part of the James Ross Basin, comprises a variety of fine- to medium-grained sandstones, siltstones and silty mudstones, with minor coarser grained intervals, coquinas and other shell beds. The Marambio Group is in places intensely fossiliferous, with vertebrate, invertebrate, plant and microfossil assemblages that have been described in detail in recent years. Based on detailed field mapping and lithostratigraphy, the Marambio Group has been subdivided into three component formations (the Santa Marta, Snow Hill Island and López de Bertodano formations) (Pirrie et al. 1997). The Marambio Group was deposited in a variety of inner- to outer-shelf settings (Macellari 1988; Pirrie 1989; Pirrie et al. 1991a; Scasso et al. 1991).

The steepest structural dips in the James Ross Basin occur along the NW coastal margin, where they typically range between 45°SE and subvertical (Fig. 1). However, these dips decrease rapidly SE and within a horizontal distance of 5 km can be as low as 10°SE. The Gustav Group of NW James Ross Island is in effect exposed in a NE-trending monoclinal syncline that can be shown to be the product of syn- rather than post-depositional deformation (Whitham & Marshall 1988). In the Aptian–Coniacian this region was in close proximity to the fault-bounded basin margin where phases of arc uplift and related differential subsidence led to the accumulation of a deep-marine clastic wedge. In effect, this wedge was continually tilted to the SE and successive beds onlapped around a single, progressive unconformity (Whitham & Marshall 1988, fig. 6; Hathway 2000, fig. 9).

The reference section through both the Whisky Bay and Hidden Lake formations on the SW shore of Brandy Bay (Ineson et al. 1986;
Fig. 3. Geological map of the Brandy Bay area showing the position of the key reference section measured through the Whisky Bay and Hidden Lake formations. Location map for Figure 3 is given in Figure 1.

McArthur et al. 2000) was re-examined by two of us (J. A. Crame and D. Pirrie) in early 2002. Wherever possible, the line of the old section (D.8228) was followed and its position plotted on a topographical map by GPS (using the new station numbers DJ.1456–DJ.1460; Fig. 3). Bed thicknesses were measured using a combination of Jacob staff/abney level and tape measure techniques, and detailed collections made for macro- and micropalaeontology. Samples for the latter were analysed by one of us (J. B. Riding) in the laboratories of the British Geological Survey, Keyworth, UK. Ammonite determinations reported here are essentially
Whisky Bay Formation

Bibby Point Member. The Bibby Point Member constitutes the basal 79 m of the measured section (Figs 3 & 4). It is composed of dark green, channelized, normally graded pebble conglomerates interbedded with pebbly sandstones, sandstones and scarce mudstones. Clasts in the conglomerates are dominated by angular blocks of interbedded radiolarian mudstones and volcanic ash, interpreted as being derived from the Nordenskjöld Formation (Late Jurassic–Early Cretaceous), along with well-rounded metasedimentary clasts derived from the Trinity Peninsula Group (? uppermost Carboniferous–Triassic) and dark green, chloritic mudstones. Three dimotobelid belemnites (DJ.1457.1–DJ.1457.3) can be added to the previously known mid–late Albian molluscan fauna (Ineson et al. 1986; Riding & Crame 2002).

Lewis Hill Member. The Bibby Point Member passes conformably upwards into the 552 m-thick Lewis Hill Member (Figs 3 & 4). The lower 140 m of this unit is dominated by cobble conglomerates with minor intercalated pebbly sandstones and mudstones. The conglomerates are clast supported, with abundant silicic volcanic (Antarctic Peninsula Volcanic Group) and metasedimentary clasts (Trinity Peninsula Group), together with some Nordenskjöld Formation blocks and intraformational siltstone clasts up to 2 m across. The section then shows a gradual fining- and thinning-upwards trend with thinner bedded small pebble conglomerates interbedded with siltstones. A distinctive sequence of fossiliferous, pale grey weathering medium- to coarse-grained sandstones occurs between approximately 320 and 370 m (Fig. 4), and this proved to be a useful marker horizon for lateral correlations. The upper 250 m of the Lewis Hill Member is only intermittently exposed. Cobble–boulder conglomerates initially predominate, but at higher levels there are thick bioturbated mudstone units with subordinate fine- to medium-grained sandstones and only rare pebble conglomerates.

The most prominent macrofossil occurring within the Lewis Hill Member is a small inoce-ramid bivalve that is locally abundant between 320 and 370 m (Fig. 4). This has been referred to Actinoceramus concentricus (Parkinson), sensu lato, and has strong middle–late Albian age affinities (Ineson et al. 1986; Crampton 1996a). Other macrofossils include gaudyceratid ammonites, the bivalve Aucellina, encrusting bryozoans and indeterminate gastropod moulds. Smooth terebratulid brachiopods are associated with the uppermost 135 m of the member (496–631 m, Fig. 4).

The Lewis Hill Member is also characterized by abundant and well-preserved palynofloras. Whereas miospores are dominated by Cyathidites spp. and bisaccate pollen grains, the dinoflagellate cysts are significantly more diverse and include types such as Ascodinium spp., chorate cysts, Cribroperidinium edwardsii, Diconodinium multispinum, Odontochitina operculata and various reworked taxa interpreted to be derived from the Late Jurassic–Early Cretaceous Nordenskjöld Formation. This flora is of unequivocal Australasian affinity and is consistent with a latest Albian age for almost the entire section (Morgan 1980; Riding & Crame 2002). Nevertheless, the three highest palynological samples (DJ.1504.15, DJ.1504.17 and DJ.1504.18; Fig. 4) yielded the first records of Ascodinium serratum, sensu stricto, in Antarctica and this distinctive species is believed to be confined to the early Cenomanian (Morgan 1980). Therefore the Albian–Cenomanian boundary can be placed for the first time in Antarctica between palynological samples DJ.1504.10 and DJ.1504.15 in our reference section (Fig. 4). The same level would also mark the boundary between the Xenascus asperatus and Diconodinium multispinum interval zones of Helby et al. (1987). Previous records of Turonian taxa such as Isabelidinium glabrum from the uppermost Lewis Hill Member (Riding & Crame 2002) are now thought to belong to Brandy Bay Member samples.

Brandy Bay Member. The boundary between the Lewis Hill and Brandy Bay members is marked by a sharp lithological transition from the mudstones, muddy sandstones and green-weathering volcanioclastic sandstones of the former to the rusty red–brown pebbly sandstones and conglomerates of the latter. It is also accompanied by a pronounced change in dip, from values as high as 35°–40°SE in the uppermost Lewis Hill Member to approximately 19°SE in the basal Brandy Bay Member.

The lower 75 m of the Brandy Bay Member is poorly exposed but dominated by slabby weathering coarse- to very-coarse-grained
pebbly sandstones, interbedded with granule–small pebble conglomerates. The latter are typically clast supported, with the clasts being well rounded and overwhelmingly of vein quartz and metasedimentary rocks derived from the Trinity Peninsula Group. Interbedded mudstones become progressively more abundant higher in the section until they predominate between approximately 808 and 987.5 m (Fig. 4). The silty mudstones are dark grey, planar laminated and bioturbated. They frequently contain carbonate concretions and in places these concretions are preferentially nucleated around networks of *Thalassinoides* burrows. Synsedimentary deformation is common in these upper mudstones, with rotational slump scars, slump sheets and isolated displaced blocks.

The base of the Brandy Bay Member is marked by the abrupt incoming of inocardim bivalves that have traditionally been assigned to *Tethyoceras* *m*adagascariensis* (Heinz); these can then be traced up to about the 820 m level in the section (Fig. 4). *Tethyoceras* *m*adagascariensis* is an essentially Southern Hemisphere species with strong late Turonian or early Coniacian affinities (Ineson et al. 1986; Crampton 1996b). However, the type material, from Manasoa, SW Madagascar, has recently been revised and it is clear that *T. madagascariensis* is very closely related to three other late Turonian–early Coniacian species of *Tethyoceras* (Walaszczyk et al. 2004). Indeed, the suggestion has even been made that the Antarctic specimens may be closer to *Inoceramus? nukes* Wellman from the upper part of the Lower Coniacian in Madagascar and the undifferentiated Coniacian Teratan stage of New Zealand (Crampton 1996b). Until further taxonomic comparisons can be carried out, we prefer to leave the Antarctic material within *Tethyoceras madagascariensis, sensu lato*.

*Tethyoceras madagascariensis* is typically accompanied by a distinctive flat oyster (usually fragmented), numerous terebratulid brachiopods assigned provisionally to *Rectithyris whisky* Sandy (1991), and pleurotomariid and naticid gastropods. A large, thick-shelled astartid bivalve first occurs at 740 m and small, pieces of fossil wood are relatively common throughout. Although ammonites are rare, notable occurrences include a possible koss- 

![Fig. 4](http://sp.lyellcollection.org/Downloaded from http://sp.lyellcollection.org/ at Pennsylvania State University on September 18, 2016)  
**Fig. 4.** Summary sedimentary log through the Whisky Bay and Hidden Lake formations. Key biostratigraphic markers are indicated.
the overlying Hidden Lake Formation (see below).

**Hidden Lake Formation**

The lower 10 m of the Hidden Lake Formation in this region (Figs 3 & 4) comprises medium- to coarse-grained sandstones, largely derived from reworked pyroclastic tuffs, interbedded with wavy–planar laminated very-fine- to fine-grained sandstones and bioturbated mudstones. Overlying medium- to coarse-grained sandstones characteristically show lenticular mega-ripple bedforms thought to be tidal in origin (cf. Whitham et al. 2006). At this locality the basal Hidden Lake Formation is interpreted as representing the tosets of a substorm-wave base volcaniclastic fan delta succession passing laterally and vertically into a basin floor facies association (Whitham et al. 2006). The formation reflects a partial basin inversion event, separating the deeper water submarine-fan and slope-apron environments below from the overlying shallow-marine-shelf facies of the Santa Marta Formation. Sedimentation was intimately linked to coeval calc-alkaline pyroclastic eruptions on the adjacent volcanic arc. Between 998 and 1078 m (Fig. 4) the Hidden Lake Formation is characterized by interbedded parallel–wavy laminated bioturbated mudstones, siltstones, ripple cross-laminated and tabular cross-bedded sandstones, and normally graded sandstones. Several slump sheets, individually up to 3.5 m in thickness, are present between 1078 and 1108 m (Fig. 4), and at higher levels parallel to wavy–planar laminated medium-grained sandstones, siltstones and laminated mudstones become increasingly abundant. Broadly similar lithologies occur in the middle and upper levels of the Hidden Lake Formation, although in places exposure is rather poor. At 1330 m (Fig. 4) there is a distinctive change in lithologies to bioturbated silty sandstones yielding abundant carbonate concretions nucleated around macrofossils and Thalassinoides-type burrow networks. At approximately the 1345 m level these silty sandstones grade up into pale grey weathering siltstones and mudstones of the basal Santa Marta Formation (Figs 3 & 4).

The base of the Hidden Lake Formation is characterized by the sudden incoming of a distinctive group of inoceramid bivalves with strong Coniacian affinities. These typically show a pattern of *Anwachsringreifen* ornament, whereby narrow, regular and evenly spaced concentric rings are superimposed on low, open folds. Initial types typically have an erect valve profile and resemble European Lower Coniacian species such as *Inoceramus (Inoceramus) inaequivalvis* Schlüter and *I. (I.) koegleri* Andert (Crame 1983); they in turn grade up into more mytiloid forms provisionally assigned to *Inoceramus neocaledonicus* Jeannet. This species too has Coniacian age affinities in Europe, but may be Coniacian–Santonian in Madagascar (Sornay 1964; Herm et al. 1979; Walaszczyk 1992; Walaszczyk et al. 2004). As the *I. neocaledonicus* species group also shows some overlap with the highly variable *Inoceramus australis* Woods from the Piripauan stage (uppermost Coniacian–middle Santonian) of New Zealand (Crampton 1996b), it is clear that this whole species complex is in need of careful taxonomic revision (McArthur et al. 2000; Walaszczyk et al. 2004).

Terebratulid brachiopods, again assigned provisionally to *Rectithyris whiskyi*, oyster fragments and large asturid bivalves similar to those of the Brandy Bay Member still occur within the basal 100 m of the Hidden Lake Formation, but are noticeably less abundant. They are accompanied by bryozoans, pleuromariid and patelliform gastropods, and dimi- tobelid belemnites (*Dimitobelus cf. ongleyi* (P. Doyle pers. comm. 2002)), together with a sparse vertebrate assemblage comprising reptile bones, along with shark teeth and vertebræ. Charcoalified wood fragments are particularly characteristic of the lower Hidden Lake Formation and are largely responsible for giving the formation its distinctive rusty-orange weathering hue; some of these fragments are in excess of 30 cm in length. A distinctive bed at the 1118 m level (Fig. 4) contains abundant compressed and charcoalified wood fragments, together with small angiosperm leaves retaining veination (cf. Hayes et al. 2006).

Ammonites are generally sparse in the lower-middle-levels of the Hidden Lake Formation, but there are occasional gaudryceratids, and at 1068 m (Fig. 4) there is the first occurrence of a small–medium pachydiscid referable to *Menites* (*Neopachydiscus*) (W. J. Kennedy pers. comm. 2004). This taxon can then be traced up-section for approximately 100 m, but by 1218 m it has been replaced by a smaller, more tumid species of the same subgenus. This pachydiscid zonation may have at least local stratigraphic utility as *M. (N.) sp. 1* in the Whisky Bay region (Fig. 1) is confined to a zone between 125 and 205 m above the base of the formation (Ineson et al. 1986). A series of strongly keeled fragments from approximately the 1120 m level (Fig. 4) has been referred to *Peroniceras* (Thomson 1984), and a small, straight-shafted heteromorph from 1138 m...
placed at the base of the Hidden Lake Formation (McArthur 1988). Although the exposure is typically poor, the uppermost 150 m of the Hidden Lake Formation is more fossiliferous. Ammonites include *Gaudryceras* and *Menutites* (*Neopachydiscus*), and there are numerous large forms of *Inoceramus neocaldeonius–Inoceramus australis*. A medium–large *Baculites* ammonite is present at 1330 m and clearly ranges up into the overlying Santa Marta Formation (Olivero 1988). 87Sr/86Sr isotope ages based on large inoceramids from the uppermost Hidden Lake Formation (D.8228.94 and D.8228.303; Fig. 4) and lowermost Santa Marta Formation (D.8228.326, D.8228.331 and D.8228.333) are indistinguishable (87.0–87.1 Ma; late Coniacian) (McArthur et al. 2000). Further strontium dates indicate that the Coniacian–Santonian boundary is best placed at the 150 m level in the Santa Marta Formation (McArthur et al. 2000, p. 635). In this study the Turonian–Coniacian boundary is placed at the base of the Hidden Lake Formation, commensurate with the incoming of the distinctive Coniacian inoceramid species complex (Fig. 4).

Eleven samples of the Hidden Lake Formation produced variably productive palynofloras in which spores and pollen are more abundant than marine microplankton. The dinoflagellate cysts are of Australasian affinity and include key markers such as *?Actinotheca aphroditea, Conosphaeridium striatoconus, Spinidinium echnioideum* subsp. *rhombicum* and *Xenascus australensis*, which are all consistent with a Coniacian age, although it should be noted that these species are not restricted to the Coniacian stage (Marshall 1984; Helby et al. 1987; McMinn 1988). This is the first report of the index species *Spinidinium echnioideum* subsp. *rhombicum* from Antarctica; the range base of this form is intra Coniacian (Marshall 1984). The Hidden Lake Formation is within the largely Coniacian *Conosphaeridium striatoconus* Interval Zone of Wilson (1984) and Helby et al. (1987).

**Discussion**

**Stratigraphical synthesis**

The early Aptian age of the exposed base of the Lagrelius Point Formation corresponds with a widespread pulse of marine sedimentation at this time in the Antarctic Peninsula–Scotia Arc region (Howlett 1989; Riding et al. 1998). However, the precise lateral and vertical extent of this coarse clastic, deep-marine depositional unit is unknown, as is its exact relationship to the overlying Kotick Point Formation (Fig. 2). The latter comprises up to 1000 m of interbedded breccias, conglomerates, sandstones and mudstones that are characterized by small to extremely large allochthonous blocks of the Nordenskjöld Formation (Ineson et al. 1986). The formation is generally interpreted to represent a series of slope apron and submarine fan deposits that were sourced from the adjacent fault-bounded basin margin (Ineson 1989; Hathway 2000). The lowest macrofaunas from the Kotick Point Formation are not age-diagnostic (Ineson et al. 1986), but coeval dinoflagellate cyst floras are unequivocally of early Albian age and are attributable to the *Muderongia tetraconta-tha* Interval Zone of Helby et al. (1987) (Riding & Crame 2002). It is concluded that the Aptian–Albian boundary is not exposed in NW James Ross Island and thus there is no way of knowing whether the sequence is stratigraphically complete (Fig. 2).

On palynological evidence, a suite of taxa representing the *Canninginopsis denticulata* Interval Zone of Helby et al. (1987) suggests that the early–mid Albian transition occurs in the uppermost levels of the Kotick Point Formation (Fig. 2) (Riding et al. 1992; Riding & Crame 2002). Whereas the overlying Bibby Point Member of the Whisky Bay Formation may be mid–late Albian in age, the bulk of available macro- and micropalaeontological evidence suggests that the greater part of the Lewis Hill Member, the entire Gin Cove Member and the Lower Tumbledown Cliffs Member are all late Albian in age. Dinoflagellate cyst associations from these various units are indicative of subzone a of the *Endoceratium ludbrookiae* Interval Zone of Helby et al. (1987) (Riding & Crame 2002). Such age determinations indicate that the Gin Cove Member, from the SW region of the Gustav Group coastal outcrop (Fig. 1), must be laterally equivalent to the Bibby Point Member and the bulk of the Lewis Hill Member from the NE region (Fig. 2). Nevertheless, it is important to note that there are some significant lithological differences between the two members, with the Gin Cove Member being somewhat thinner (315 m in total thickness) and predominantly composed of finer grained rock types such as bioturbated medium- to fine-grained silty sandstones, with only subordinate graded conglomerates and pebbly sandstones (Ineson et al. 1986). In addition, two prominent bivalves from the Gin Cove Member, the medium–large *Inoceramus carsoni* McCoy and...
the distinctive oxytomid genus, *Maccoyella*, are entirely absent from the Lewis Hill Member. Although the Albian–Cenomanian boundary is necessarily placed on palynological grounds in the uppermost levels of the Lewis Hill Member, its precise position within the Tumbledown Cliffs Member is uncertain (Fig. 2). The latter unit comprises an approximately 300 m-thick succession of parallel-bedded and channelized, graded sandstones, pebbly sandstones and conglomerates that are locally affected by slumping (Ineson et al. 1986). The lower levels contain the characteristic *Actinoceramus concentricus* fauna, but in this particular instance the presence of a turritilid ammonite referable to *Mariella* may also indicate that the beds range up into the early Cenomanian (Thomson 1984). A second distinctive molluscan fauna from the upper levels of the Tumbledown Cliffs Member contains the ammonites *Newboldiceras* sp., *Sciponoceras* sp. *Desmoceras aff. latidorsatum* Michelin, *Gaudryceras* cf. *stefanini* Venzo and *Pseudoulitella* sp, together with *Inoceramus pictus* Sowerby (Thomson 1984; Ineson et al. 1986). This fauna has strong mid–late Cenomanian age affinities and indicates that this stage is much more fully represented in this region than it is to the NE. There is no direct equivalent of the upper Tumbledown Cliffs Member in the Brandy Bay–Whisky Bay region (Figs 1 & 2).

With the recalibration of the reference section presented in this study, it is clear that the base of the Brandy Bay Member is marked by the sudden incoming of both *Tethyoceramus madagascariensis* and dinoflagellate cyst taxa such as *Isabelidinium* spp. Strontium isotope dating strongly suggests that these events are late Turonian in age, and, as the Lewis Hill Member–Brandy Bay Member junction is marked by a sharp change in dip, there is good evidence for an early Cenomanian–late Turonian unconformity in the Brandy Bay region (Fig. 2). However, it is not possible to trace this hiatus to the SE and the full stratigraphical relations between the Tumbledown Cliffs and Rum Cove members are unclear. The base of the largely mudstone-dominated Rum Cove Member may be, in part at least, laterally equivalent to the top of the Tumbledown Cliffs Member but in its upper levels it contains a *T. madagascariensis* fauna (Fig. 2) (Ineson et al. 1986). A detailed palynostratigraphy for the Rum Cove Member has yet to be established (Riding & Crame 2002).

The nature of the base of the Hidden Lake Formation is a matter of some conjecture. If the Turonian–Coniacian boundary is placed at the Whisky Bay Formation–Hidden Lake Formation transition, then it is clear that there is a greater thickness of Turonian strata in the Brandy Bay region than at Rum Cove (Figs 1 & 2). Nevertheless, in both these localities the contact appears to be conformable and it is only in the Whisky Bay area that an angular unconformity at this boundary can be demonstrated (Ineson et al. 1986). The top of the Hidden Lake Formation, and thus of the Gustav Group, is well dated by strontium isotopes as late Coniacian.

**Wider implications**

As the boundary between the Lagrelius Point and Kotick Point formations is not exposed, there is no way of knowing whether the extensive Aptian–Albian succession is stratigraphically complete (Fig. 2). Thick mid–late Albian successions are present in both the NE and the SW areas of the Gustav Group outcrop (Figs 1 & 2), but in the former of these the highest levels of the Lewis Hill Member only just extend into the earliest Cenomanian. With the recalibration of samples achieved in this study, the junction between the Lewis Hill and Brandy Bay members assumes much greater stratigraphical significance, and can be regarded as an unconformity of probable early Cenomanian–late Turonian extent. However, it is clear that this discontinuity cannot be traced into the Tumbledown Cliffs–Rum Cove area where this time interval is represented by the upper part of the Tumbledown Cliffs and the lower part of the Rum Cove members (Fig. 2). There is some evidence to suggest that the base of the Hidden Lake Formation is at least locally transgressive (Ineson et al. 1986) and the Rum Cove Member would appear to be significantly thinner than its partial lateral equivalent to the NE, the Brandy Bay Member (Fig. 2). Nevertheless, it is not possible, at present, to demonstrate a regional unconformity at the base of the Hidden Lake Formation. The Hidden Lake Formation–Santa Marta Formation boundary is traceable laterally over a considerable distance and is entirely conformable (Fig. 1).

The discontinuous unconformities between the Lewis Hill and Brandy Bay members, and Whisky Bay and Hidden Lake formations, can be directly related to the proposed style of deepwater clastic sedimentation close to the basin margin. Although uplift of the Antarctic Peninsula led to the progressive tilt of the clastic wedge to the SE (Whitham & Marshall 1988), it is likely that this was at an irregular rather than constant rate. Successive beds would indeed
have onlapped onto a single progressive unconformity (Whitham & Marshall 1988, fig. 6; Hathway 2000, fig. 9), but the precise location of this feature would have shifted in both time and space. Even over a horizontal distance of as little as 25 km, there could have been a change from areas of relatively deep-water sedimentation to areas of non-deposition and erosion. The stratigraphic correlations established in this study (Fig. 2) indicate that an active fault zone located along the Prince Gustav Channel (Fig. 1) exerted strong local control over adjacent sediment accumulation from at least the early Albian through to early Coniacian times.

Global sea level fluctuated during the early Albian–early Coniacian with a marked mid-Turonian highstand followed by a mid–late Turonian regression (Haq et al. 1987; Hathway 2000; Hart et al. 2001). Deposition of the shallower water Hidden Lake Formation can be linked to a Coniacian phase of partial basin inversion coupled to reduced subsidence rates along the basin margin (Pirrie 1991). The bulk of the Marambio Group accumulated at shelf depths and only in its uppermost (Maastrichtian) levels is there evidence of base-level changes that may represent global sea-level events (Pirrie et al. 1991b; Crame et al. 2004).

The results presented here also indicate the potential importance of the Gustav Group for establishing the full biostratigraphic ranges of certain key taxonomic groups within the James Ross Basin. For example, the earliest representative of the kossmaticeratid ammonites, a group that characterizes the overlying Marambio Group, may be a specimen from the upper Brandy Bay Member referred to ?Marshallites (Figs 2 & 4). Similarly, a pronounced radiation of heteromorph ammonite taxa in the lower Santa Marta Formation (Olivero 1988) may be traced back to a series of specimens in both the Hidden Lake Formation and upper Brandy Bay Member of the Whisky Bay Formation (Fig. 4). The benthic marine faunas are still under taxonomic investigation, but it is interesting to note the concentration of a number of typically shallow-water (i.e. shelf depth) groups (i.e. oysters, astartids, bacteovellid, etc) that occurs as early as the mid-levels of the Brandy Bay Member – a time of widely recognized global sea-level fall (Fig. 4). There are indications that the radiation of certain plant taxa, including some angiosperms, may be traced back to the same level too (Keating et al. 1992; Hayes et al. 2006). Thus, the pronounced Late Cretaceous expansion of both shallow-marine and terrestrial biotas in Antarctica may possibly be traced back to at least the Turonian stage. Fuller definition of the Cenomanian–Coniacian biostratigraphy will also aid the interpretation of Late Cretaceous extinction patterns in Antarctica (Crame et al. 1996).

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