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Revised interpretations of Mesozoic palaeogeography and volcanic arc evolution in the northern Antarctic Peninsula region

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Abstract: Terrestrial sedimentary rocks at Hope Bay, northern Graham Land are well known for their diverse but poorly-preserved fossil flora, previously assigned ages ranging from Early Jurassic–Early Cretaceous. The beds form part of the Botany Bay Group, which comprises several outcrops of terrestrial sediments in northern Graham Land and the South Orkney Islands. A latest Jurassic or earliest Cretaceous age for the Hope Bay plant-bearing sequence (and by extension for the rest of the Botany Bay Group) has been adopted in most recent publications dealing with Mesozoic volcanic arc evolution and palaeogeography of the northern Antarctic Peninsula region. New evidence, based upon the study of extensive collections of previously undescribed fossil plants from Hope Bay and nearby Botany Bay, indicates that they should be assigned an Early Jurassic age. The new palaeobotanical findings, combined with recently-published radiometric data from overlying volcanic sequences, show that a Cretaceous age is no longer tenable for these floras nor, therefore, for the Botany Bay Group in Graham Land. Interpretations of Mesozoic volcanic arc evolution and palaeogeography in this region are revised accordingly.

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Introduction

Because of its great diversity and its early discovery and description (Halle 1913), the "classic" Mesozoic flora from Hope Bay, northern Graham Land, Antarctica (Fig. 1) has served as a standard for floristical and biostratigraphical studies on other Mesozoic gondwanan floras. Although Halle (1913) assigned a Middle Jurassic age to the flora, it has subsequently been variously dated as Early Jurassic (Orlando 1971) or Middle Jurassic (Rao 1953), through to latest Jurassic or earliest Cretaceous (e.g. Stipanicic & Bonetti 1970a, Archangelsky & Baldoni 1972, Baldoni 1981). A latest Jurassic or earliest Cretaceous age has been adopted in most recent publications dealing with interpretations of the geological history of the region (e.g. Thomson *et al.* 1983, Farquharson 1983a, 1984, Farquharson *et al.* 1984, Del Valle & Fourcade 1986, Macdonald *et al.* 1988).

The assemblage as originally described by Halle (1913) contains 61 species, recently revised to 43 by Gee (1989), from a study of *c.* 200 hand specimens. The study of new material, totalling some 2000 hand specimens, from Hope Bay and the nearby Botany Bay locality (Fig. 1) has enabled an extensive revision, with 38 species now recognized in the Hope Bay flora, along with two forms of unknown affinity (Rees 1990). A study of the previously undescribed flora from Botany Bay has shown it to comprise 31 species, 25 of which also occur in the Hope Bay assemblage (Rees 1990). The Hope Bay and Botany Bay floras are so closely similar that they can be considered as having the same age. The presence of the fern genus *Goeppertella* Ôishi & Yamasita (Fig. 2) indicates a latest Triassic or Early Jurassic age for these floras, an Early Jurassic age being most likely on present evidence (Rees in press). Recently published radiometric data (Millar *et al.* 1990) provide further evidence of a Jurassic, rather than Cretaceous, age for the Hope Bay and Botany Bay floras.

Age of the Botany Bay Group

An earliest Cretaceous age for the Hope Bay and Botany Bay floras (and consequently for the rest of the Botany Bay Group) has been used in most recent interpretations of Mesozoic volcanic arc evolution and palaeogeography in the northern Antarctic Peninsula region (e.g. Farquharson 1984), with the paper by Stipanicic & Bonetti (1970a) being the most frequently cited. Since the new evidence for an Early Jurassic age contradicts previous arguments, the principal ones are reviewed here (see Rees (1990) for a detailed account).

Stipanicic & Bonetti (1970a,b) reviewed the Argentine Jurassic floras and included a discussion of the affinities and age of the Hope Bay flora. They concluded that this flora shows an equal degree of affinity with what they believed to be the Early Cretaceous Rajmahal floras of India as with those from the Middle Jurassic and "Neocomian" of Europe. For this reason, the authors estimated that the Hope Bay flora was of latest Jurassic age, without discounting the possibility that it could even be earliest Cretaceous. However, it would appear that their age argument has two significant problems. Firstly, the Indian Rajmahal floras are imprecisely dated and can only be reasonably assigned an age of ?Early Jurassic–?Albian. An Albian age for the Rajmahal flora is

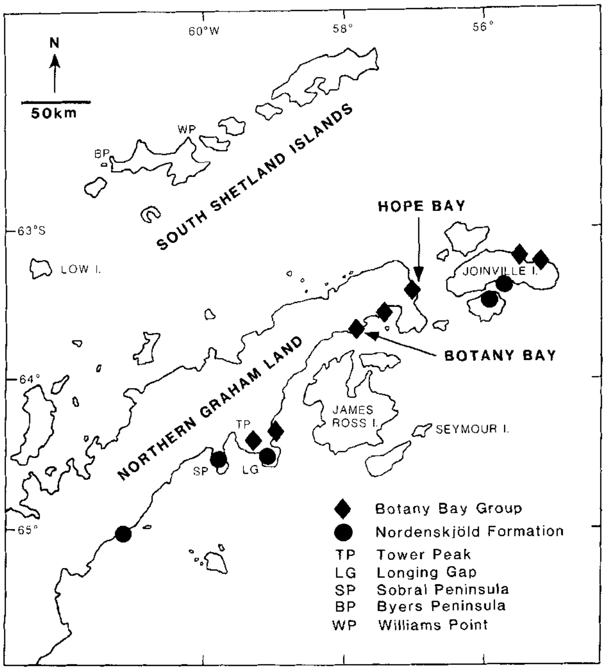

Fig. 1. Map of northern Antarctic Peninsula region, showing the distribution of localities referred to in the text.

based upon the 100–105Ma K-Ar dates for lava traps which were believed to be of the same age as the plant beds (McDougall & McElhinny 1970). Shah *et al.* (1973) considered that the only criterion for determining the age of the Rajmahal Plant Beds was the plant remains and concluded that they are of Early to Middle Jurassic age. Sengupta (1988, pp. 154–156) discussed the reasons for the contradictory radiometric (Early Cretaceous) and palaeobotanical (Jurassic) results for the age of the Rajmahal flora. He argued that, although some samples of Rajmahal basalt (e.g. those dated by McDougall & McElhinny 1970) indicate a Cretaceous age, their stratigraphical and geographical locations are poorly defined and they cannot be used to assign a lower age limit to the Rajmahal Formation. Sengupta (1988) concluded that the Rajmahal Formation may be considered as Middle Jurassic–Cretaceous. Given the uncertainty concerning the age of this and other Indian late Mesozoic plant-bearing sequences, any age assignment based upon a correlation with them is questionable. Secondly, it is difficult to accept that late Mesozoic floras from widely differing palaeolatitudes (e.g. Antarctica and northern Europe) can be correlated and used with confidence for stratigraphical purposes. When this type of correlation is carried out, it should be made clear that further refinement, based upon local correlations, will be needed. For example, an impression/coalified compression flora within the Fossil Bluff Group of Alexander Island, west of the Antarctic Peninsula (c. 71°S, 67°W), has been independently dated as ?Aptian–Albian on the basis of marine invertebrate fossils in adjacent units (Kelly & Moncrieff in press). The flora contains twelve taxa which are morphologically similar to those from the Aptian of Victoria, southern Australia, but it also has nine morphologically similar taxa in common with the Middle Jurassic flora of Yorkshire, England (Jefferson 1981). If the floras from Victoria had not been known to Jefferson, he may have concluded that the greatest affinity of the Alexander Island flora was with that from Yorkshire. A Middle Jurassic age could then have been assigned to the Cretaceous Alexander Island flora on palaeobotanical grounds. It appears that because Stipanicic & Bonetti (1970a) did not compare the Hope Bay flora with more local floras (particularly those from Argentina) they assigned a latest Jurassic–earliest Cretaceous age to what is now shown to be an Early Jurassic flora at Hope Bay (Rees in press). Bonetti, both previously (1963) and subsequently (1974), nevertheless recognized the close similarity between the floras from Hope Bay and Argentina. She then assigned ages to the latter based upon comparisons with the flora from Hope Bay. A number of subsequent studies of Argentine Mesozoic floras have included an assessment of their ages, based upon comparison with the Hope Bay flora (e.g. Baldoni 1981, Baldoni & Olivero 1983). Similar, latest Jurassic–earliest Cretaceous, ages have been assigned to these Argentine floras, although the Hope Bay flora was originally assigned this age by Stipanicic & Bonetti (1970a) on the basis of long-distance correlation.

Farquharson (1984) assigned the Hope Bay and Botany Bay plant-bearing beds to the Botany Bay Group (BBG – see Fig. 1). The BBG was defined by Farquharson (1984, p. 28) as comprising "outcrops of non-marine, mainly conglomeratic, sedimentary rocks derived from deformed metasedimentary rocks...of common but local occurrence from the South Orkney Islands south to Larsen Inlet...[which] form a significant tectono- and litho- stratigraphic unit in the northern Antarctic Peninsula". Farquharson (1982) concluded that the BBG sediments were alluvial sequences which accumulated in fault-bounded basins on an uplifted area of metasedimentary rocks, being deposited during a distinct episode between arc uplift in the Early Cretaceous and the onset of volcanism. Farquharson (1984) cited three lines of evidence for an earliest Cretaceous age for the BBG.

a) The palaeobotanical arguments put forward by Stipanicic & Bonetti (1970a) for a latest Jurassic or earliest Cretaceous age for the Hope Bay flora. As demonstrated above, however, these arguments cannot be used as reliable evidence to assign this age to the flora.

b) The presence of a marine intercalation within alluvial fan conglomerates in the South Orkney Islands (c. 61°S, 45°W) which Farquharson (1984) included in the BBG; that marine sequence contains ammonites indicative of an Early Cretaceous age (Thomson 1981). This age cannot be used reliably to date what are merely lithologically-similar sequences from BBG localities elsewhere. Lithological similarity indicates a similar provenance and sedimentological processes for the sediments and has only limited stratigraphical value.

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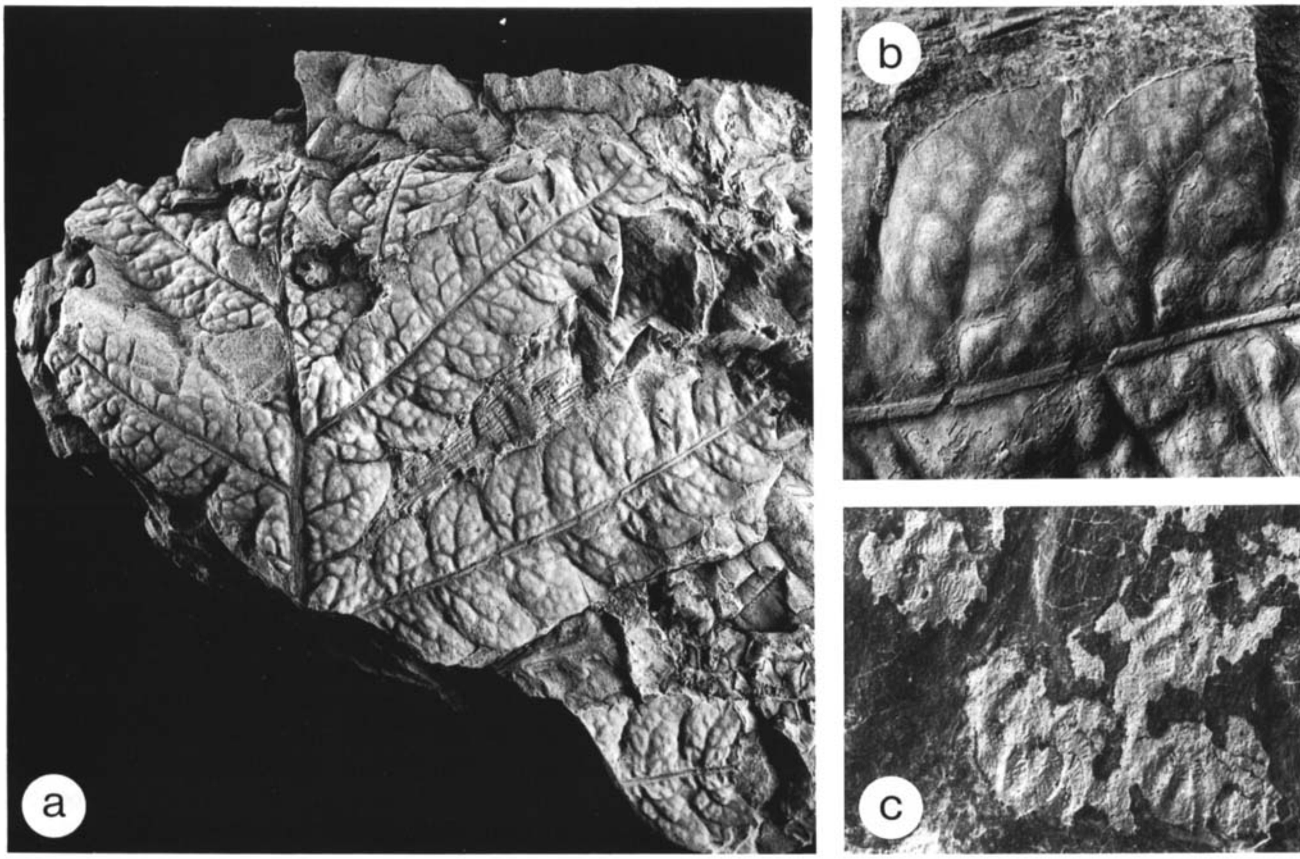

Fig. 2. Specimens of *Goeppertella* from Botany Bay. **a.** Specimen BAS V.63595, bipinnate frond-member bearing pinnae and rachial pinnules, x 2. **b.** Specimen BAS V.63595, detail of pinnule morphology and venation, with the pinnule on the left showing marginal teeth on its basiscopic margin, x 7. **c.** Specimen BAS V.63603, impressions of sori on a fertile frond-member, x 16. All specimens are housed in the collections of the Natural History Museum, London.

c) Volcanic rocks of the APVG overlie, or are commonly interbedded with, sedimentary sequences of the BBG. Two radiometric ages of 130 ± 7 Ma and 117 ± 4 Ma, obtained by Pankhurst (1982) for rocks of the Antarctic Peninsula Volcanic Group (APVG) at Hampton Bluffs and Porphyry Bluff, on the north side of Larsen Inlet (*c*. 150 km south of Hope Bay) were used by Farquharson (1984) to indicate a similar age for all of the BBG sequences. However, the relationship of these dated volcanic rocks with the sedimentary sequences of the Botany Bay Group is uncertain, since they are not in contact with them. Furthermore, Thomson & Pankhurst (1983, p. 328) remarked that "some caution is necessary in accepting these ages since Rb-Sr whole-rock systems in acid volcanic rocks are widely considered to be very easily reset without metamorphism".

Significantly, new radiometric data indicate a late Middle or Late Jurassic age at youngest for the floras from Hope Bay and Botany Bay. At Botany Bay, Sm-Nd dating of primary igneous garnets (from an andesitic sill within volcanic rocks of the Antarctic Peninsula Volcanic Group) yielded an age of 152 ± 8 Ma, believed to indicate the time of intrusion of the sill (Millar *et al.* 1990). This corresponds to an age of lower Callovian–lower Berriasian (Harland *et al.* 1982) or upper Bathonian–lower Kimmeridgian (Haq *et al.* 1987). Thus, emplacement of the sill probably occurred sometime during the late Middle or Late Jurassic, although the time interval between deposition of the volcanic rocks and intrusion of the sill is unknown. The volcanic rocks (including the dated sill) overlie the plant-bearing sedimentary sequence at Botany Bay (Fig. 3). The close similarity between the Botany Bay and Hope Bay floras indicates that the Hope Bay flora can be assigned the same age as that from Botany Bay (Rees 1990) and the presence of the dipteridaceous fern genus, *Goeppertella* (Fig. 2), in both floras indicates that they are most probably Early Jurassic (Rees in press). Most species of *Goeppertella* from the Northern Hemisphere are of Late Triassic age, with the possibility of some ranging into the lower part of the Early Jurassic and none being known from younger floras (e.g. Möller & Halle 1913, Ôishi & Yamasita (1936) and references therein, Harris 1946). The only previous records of *Goeppertella* in the Southern Hemisphere are from beds in Argentina dated as Early Jurassic (Herbst 1964, 1966, 1975,

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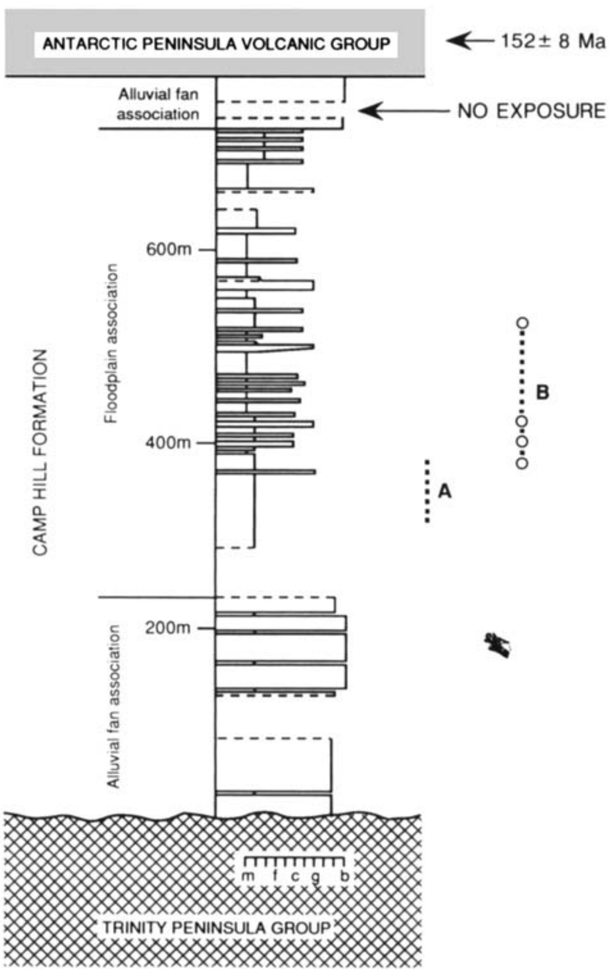

Fig. 3. Generalized section measured through the Camp Hill Formation, Botany Bay, showing the relationship between rocks of the TPG, BBG and APVG (modified from Farquharson 1984). Note the radiometric age (152 ± 8 Ma) obtained by Millar *et al.* (1990) for the overlying APVG, the exposure gap near the top of the sedimentary sequence, and the location of specimens of *Goeppertella* collected from frost-shattered debris (A) and *in situ* (B).

Arrondo & Petriella (1982) and references therein, Baldoni 1987). Thus, the previously recorded age range of the genus is from Late Triassic to uppermost Early Jurassic. It remains possible that the specimens of *Goeppertella* from Hope Bay and Botany Bay, assigned to two new species (Rees in press), *may* represent occurrences of the genus outside this range. However, an Early Jurassic age assignment for these floras is most likely on present evidence, this being consistent with the radiometric age obtained by Millar *et al.* (1990). Certainly, previous arguments for a latest Jurassic or Early Cretaceous age (based upon palaeobotanical, sedimentological and radiometric evidence) do not stand up to critical appraisal.

The new data cast considerable doubt upon the earliest Cretaceous age which was previously assigned to all of the rocks included within the Botany Bay Group (e.g. Farquharson 1984). Indeed, it now seems more probable that the BBG comprises sediments which were deposited in discrete terrestrial basins during the Early Jurassic (Hope Bay and Botany Bay), with sedimentation possibly continuing into the Early Cretaceous (South Orkney Islands). With the exception of Tower Peak (Fig. 1), the other localities which were assigned to the BBG by Farquharson (1984) can only be correlated on lithological grounds. Millar *et al.* (1990) argued for synchronous deposition of the BBG and andesitic volcanic rocks, from their study of detrital garnets within part of the BBG sequence at Tower Peak. The palaeobotanical (Early Jurassic) and the geochronological (late Middle or Late Jurassic) ages for the Botany Bay Group may therefore appear incompatible. However, the detrital garnets are from the uppermost part of the Tower Peak sequence, whereas the age-diagnostic plant fossils come from the lower and middle parts of the sequence exposed at Botany Bay (detailed collecting information is not available for the Hope Bay material). Additionally, the volcanic rocks at Botany Bay have been faulted down against the top of the main sedimentary succession. Only a thin, isolated, sequence of sedimentary rocks exposed to the east of the fault is overlain, possibly unconformably, by volcanic beds (Farquharson 1984, fig. 8). Thus, the true thickness of the sedimentary sequence above the main plant-bearing horizons at Botany Bay is unknown. There are no data for the ages of the lower and middle parts of the sequence at Tower Peak, nor for the upper parts of the sequences at Botany Bay and Hope Bay. Thus the BBG sequence at Tower Peak can only be correlated with those at Hope Bay and Botany Bay on the grounds of lithological similarity. As Farquharson (1984) remarked, sediments from different outcrops of the Botany Bay Group may not have been deposited contemporaneously, although he was clearly not implying that their deposition spanned the Early Jurassic to Early Cretaceous.

The Nordenskjöld Formation and its relationship to the BBG and APVG

Farquharson (1982, 1983b) assigned a number of outcrops of alternating Radiolaria-rich mudstones and "ash-fall" tuffs, along the south-east flank of northern Antarctic Peninsula, to the Nordenskjöld Formation (Fig. 1). Medina & Ramos (1981) had previously established the name "Formación Ameghino" for the succession at one of the localities (Longing Gap), but did not correlate this with the other outcrops assigned by Farquharson (1982, 1983b) to the Nordenskjöld Formation (see Whitham & Doyle (1989) for discussion). Beds of the Nordenskjöld Formation have yielded late Oxfordian–Berriasian marine faunas (e.g. Crame 1982, Farquharson 1983b, Medina *et al.* 1983, Whitham & Doyle 1989). Unfortunately, neither the top nor the base of the Nordenskjöld Formation is exposed, making its relationship to other formations in the region uncertain.

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Farquharson (1982, 1983b) suggested that deposition of the Nordenskjöld Formation occurred under low energy and anoxic conditions, the background fine-grained sedimentation periodically being interrupted by the settling of ash falls. The apparent virtual absence of clastic detritus was interpreted by Farquharson (1982, p. 724) as "indicating incompatibility with a nearby emergent volcanic arc". The possibility that most of the coarse detritus had been channelled into deeper water was discounted on the grounds of a "lack of adequate space for the development of an efficient by-pass system" (Farquharson 1982, p. 724). Farquharson (1983b) tentatively correlated the Nordenskjöld Formation as exposed on the east coast of the northern Antarctic Peninsula with the ?early Tithonian Mudstone member of Byers Peninsula (Livingston Island) and the Late Jurassic beds on Low Island (Fig. 1). He believed that the wide geographical distribution (on the west and east of the peninsula) of these predominantly fine-grained sequences made the existence of an appreciable Late Jurassic volcanic arc unlikely. It was proposed instead (Farquharson 1982) that the volcanic source was probably a series of small, submarine or locally subaerial, volcanoes at this time as opposed to an arc edifice with substantial subaerial relief. However, a number of lines of evidence (set out below) suggest that a continuous or near-continuous subaerial volcanic arc existed by Late Jurassic times, on the present site of the northern Antarctic Peninsula. The landmass was probably densely vegetated and possibly had low subaerial relief.

Lithology

Clastic detritus forms a greater component of Nordenskjöld Formation lithologies than was recognized by Farquharson (1982, 1983b). Medina & Ramos (1981) noted that sandstones constitute 20% of the measured section exposed at Cape Longing, while Whitham & Doyle (1989) have also described sandstone beds from some sequences of the Nordenskjöld Formation. Furthermore, sedimentary (largely volcaniclastic) strata from Low Island, South Shetland Islands (Fig. 1), have been interpreted as being predominantly turbidity current deposits (Smellie 1979). A Late Jurassic (possibly late Oxfordian) age is indicated for the Low Island beds, based upon their fossiliferous content (Thomson 1982), whereas the Nordenskjöld Formation has been dated as late Oxfordian-Berriasian (Whitham & Doyle (1989) and references therein). This indicates that the Low Island sediments may have been deposited contemporaneously with the older beds which were assigned to the Nordenskjöld Formation by Farquharson (1982, 1983b). Farquharson (1983b) interpreted the Low Island beds as representing marine volcaniclastic sediments which were deposited close to, or on the flanks of, a small volcanic centre, discounting the possibility of the existence of a continuous subaerial landmass in the region. Although Smellie (1979) noted the absence of coarse volcaniclastic material from Low Island, he also cited Fiske (1963) who had previously described coarse vent-facies agglomerates and lavas which wedge out gradually into thin-bedded tuffs and lapillistones over distances less than 2 km. It is noteworthy that the *minimum* distance between exposures of the BBG and the Nordenskjöld Formation (at Tower Peak and Longing Gap, respectively) is between 7 and 8 km.

Total organic carbon (TOC) content

Most Nordenskjöld Formation rocks (to the east of the peninsula) have a total organic carbon (TOC) content of 1–2.5%, with a mean of 1.8% (Macdonald *et al.* 1988). These authors also noted that similar rocks of the same age from the South Shetland Islands (to the west of the peninsula) never exceed 1% TOC and have a mean of only 0.5%. From this Macdonald *et al.* (1988) suggested that oxygen levels were lower on the eastern side of the peninsula, supporting a barred basin origin for the Nordenskjöld Formation and not the widespread continuous anoxic basin proposed by Farquharson (1982, 1983a,b). Furthermore, Macdonald *et al.* (1988, p. 40) stated that "the presence of relatively large proportions of airfall tuff demands subaerial volcanic edifices, if only small islands, along the line of the arc". The existence of a continuous volcanic landmass provides an equally plausible mechanism to explain both the large amounts of airfall tuff and the TOC contents in the Nordenskjöld Formation and coeval sequences from the South Shetland Islands.

Plant fossil content

Baldoni (1986) reported the occurrence of fossil plant foliage from beds of the Nordenskjöld Formation exposed on Sobral Peninsula, "Cerro Tres Amigos" and "Cerro Maneo" (possibly a typographical error; the last locality is named as "Cerro El Manco" by Medina *et al.* (1983)). Five plant taxa were listed by Baldoni (1986): *Ptilophyllum antarcticum* (Halle) Seward, *Otozamites hislopi* Seward, *Nilssonia taeniopteroides* Halle, *Sphenopteris* sp. and *Scleropteris* sp.. Other plants from these localities have been assigned to *Equisetites* sp., *Todites* sp., *Ptilophyllum* sp. and *Otozamites* sp. (Scasso & Del Valle 1989). Whitham & Doyle (1989) also noted the presence of locally-abundant leaf impressions and wood in the Nordenskjöld Formation, at the western locality on Sobral Peninsula (Fig. 1). Most of their specimens, including those assignable to some of the genera mentioned above, are relatively complete (with frond and pinna fragments often preserved). It is unlikely that specimens with pinnate frond organization, particularly ferns such as *Todites*, would be preserved in such an intact state after extensive transportation into marine sediments, which suggests the presence of a nearby vegetated landmass.

Incidentally, Baldoni (1986) and Scasso & Del Valle (1989) believed that all of the above-mentioned taxa also occur in the flora from Hope Bay and considered this (particularly the presence of *Ptilophyllum antarcticum*) to provide further confirmation of a latest Jurassic–earliest Cretaceous age for the Hope Bay flora. However, it has been shown that *Ptilophyllum* is absent from the Hope Bay flora (Gee 1989, Rees 1990). It is also absent at Botany Bay (Rees 1990). The other taxa listed by Baldoni (1986) and Scasso & Del Valle (1989) have been described previously from floras as old as Triassic or Early Jurassic (e.g. Baldoni (1981) and references therein). They cannot, therefore, be used to correlate reliably between beds of the Nordenskjöld Formation and the plant-bearing sequences at Hope Bay and Botany Bay.

Geographical distribution of Nordenskjöld Formation and equivalent exposures

All of the known Nordenskjöld Formation exposures are located on the Weddell Sea side (south and south-east) of the arc-terrane sedimentary rocks of the Botany Bay Group (Fig. 1). The Upper Jurassic marine sediments of Low Island and Livingston Island are situated to the north and north-west of these BBG beds. Marine beds (Trinity Peninsula Group) from the central area of the northern Antarctic Peninsula are of Middle Jurassic age or older, with a youngest age being obtained from radiometric dating of cross-cutting igneous intrusions. There are three possible explanations for the absence of younger marine beds from this central area:

a) They remain undiscovered or are not exposed above the ice. However, the northern Antarctic Peninsula region has been visited by many geologists for more than 40 years. The only marine sequences known from the central area of the northern Antarctic Peninsula belong to the variably-deformed metasedimentary rocks of the Trinity Peninsula Group and (possibly) the Banded Hornfelses. The Trinity Peninsula Group is poorly defined stratigraphically, with age estimates ranging from Carboniferous to Triassic (e.g. Thomson *et al.* (1983) and references therein), although a Middle Jurassic youngest age can be assigned to it on the basis of a 174 Ma radiometric age for a cross-cutting pluton (Pankhurst 1982). The Banded Hornfelses are a problematical sequence of thermally metamorphosed sedimentary rocks with a Middle Jurassic youngest age provided by a K-Ar date of 159 Ma to 174 Ma on cross-cutting plutons (Rex 1976). Although representatives of all of the other arc terrane components have been discovered, no marine rocks which can be shown to be younger than at least Middle Jurassic have been found from the central area of the northern Antarctic Peninsula.

b) They were eroded sometime after their deposition. If this were the case, one would nevertheless still expect to find at least parts of such sequences preserved, as with beds of the Trinity Peninsula Group and the Botany Bay Group. The BBG exposures (at Hope Bay, Botany Bay, etc.) undoubtedly represent only small erosional remnants of the original terrestrial sequence; locally these lie unconformably upon rocks of the Trinity Peninsula Group. The only remnants of marine sequences which are unequivocally Jurassic or younger are exposed on the margins of the peninsula and on a number of the adjacent islands.

c) Marine sediments of at least Middle Jurassic age or younger were never deposited in the central region of the northern Antarctic Peninsula. The absence of such beds does not provide conclusive evidence that they were never deposited in this area. Nevertheless, such complete absence (when they *are* preserved on the margins of the peninsula) is striking.

From the combined lines of evidence outlined above, it is concluded that a vegetated continuous or near-continuous volcanic arc was present by Late Jurassic times, on the site now occupied by the central region of northern Antarctic Peninsula. There is little evidence to support the suggestion that an extensive marine basin with only small volcanic islands occupied the area during this interval (e.g. Farquharson 1982). A densely vegetated landmass of low subaerial relief may have shed only small amounts of coarse-grained sediment into the adjacent marine basins (represented by the Nordenskjöld Formation and coeval sequences). An alternative explanation has been proposed by Whitham & Storey (1989), who cited sedimentological and structural data for the presence of a strike-slip tectonic regime during Late Jurassic–Early Cretaceous times. They suggested that the Nordenskjöld Formation may not have been deposited in its present location but was transported there by tectonic movements. However, Whitham & Doyle (1989) refined the age of the Nordenskjöld Formation and were able to subdivide it into a number of distinct lithostratigraphical units. Their work shows that older units (Kimmeridgian–Tithonian) show little or no evidence of penecontemporaneous deformation and tend to have a relatively high ratio of mudstone to ash, whereas, the younger units (Tithonian–Berriasian) commonly show evidence of penecontemporaneous deformation and tend to have a relatively low ratio of mudstone to ash. The differences between the older and younger units of the Nordenskjöld Formation can be explained in terms of vertical differentiation, as well as any lateral displacement. Volcanic arc uplift in the latest Jurassic and earliest Cretaceous may have caused an increase in synsedimentary deformation, related to seismic activity and the tectonic oversteepening of slopes, and an increase in igneous activity could have led to higher quantities of volcanic ash being deposited. Thus, renewed (post- Early Jurassic) arc uplift may have commenced in the Tithonian, with conditions having been relatively stable during the period when older sediments of the Nordenskjöld Formation were deposited. It seems equally feasible that the Nordenskjöld Formation was deposited in its present site, as it is to suggest that it was transported there subsequent to its deposition.

Conclusions

An Early Jurassic age for the Hope Bay and Botany Bay plant-bearing beds coincides with the previously recognized Early–Middle Jurassic (190–160 Ma) peak of magmatic activity on the east coast of central and southern Graham Land (Pankhurst 1982). A second, Early Cretaceous (130–100 Ma) peak (Pankhurst 1982) coincides with coarse clastic sedimentation to the east of the arc. This back-arc deposition (Farquharson 1982), now represented principally by exposures on Sobral Peninsula, James Ross Island and Seymour Island (Fig. 1), commenced in the Early Cretaceous and post-dates the deposition of Nordenskjöld Formation sediments (Farquharson 1982). The deposition of Nordenskjöld Formation sediments coincided with a relative quiescence in igneous activity in eastern Graham Land (Pankhurst 1982), although igneous activity appears to increase in the younger parts of the formation (Whitham & Doyle 1989).

Farquharson (1984) suggested that deposition of BBG sediments occurred in small fault-controlled basins on an emergent Early Cretaceous magmatic arc, prior to the onset of volcanism in the Hauterivian. However, evidence presented here suggests that the Hope Bay and Botany Bay beds of the BBG represent deposition on an emergent Early Jurassic arc. The existence of contemporaneous volcanic activity is evidenced by the sporadic occurrence of volcanic interbeds throughout the Hope Bay and Botany Bay plant-bearing sequences. These interbeds had previously been assigned an earliest Cretaceous age (e.g. Farquharson 1984). The "Neocomian" age for the conglomeratic beds on the South Orkney Islands (Thomson 1981) indicates that at least this representative of the Botany Bay Group may have been deposited during Early Cretaceous arc uplift. The exposures of the Botany Bay Group which were correlated solely on lithological grounds could have been deposited either before or after the Nordenskjöld Formation, during either Early Jurassic or Early Cretaceous arc uplift. The late Middle or Late Jurassic (152 ± 8 Ma) age, obtained by Millar *et al.* (1990) for rocks of the APVG at Botany Bay, combined with the revised age for the Hope Bay and Botany Bay plant beds (and volcanic interbeds), suggests that igneous activity may have been essentially continuous throughout the Jurassic, rather than having commenced in the Late Jurassic or Early Cretaceous (e.g. Farquharson 1984). However, it does not negate the proposal by Pankhurst (1982) that igneous activity was less pronounced at other times than it was during the Early Jurassic and Early Cretaceous.

The Hope Bay and Botany Bay leaf floras are now the oldest known from the northern Antarctic Peninsula region. The flora from Williams Point, South Shetland Islands (Fig. 1), previously assigned a Triassic age on the basis of its plant fossil content (e.g. Orlando 1968, Lacey & Lucas 1981, Banerji & Lemoigne 1987), has been redated as Cretaceous, possibly Albian–Cenomanian, on the basis of its angiosperm leaf content and radiometric evidence (Rees & Smellie 1989). The revised age for the Hope Bay and Botany Bay floras provides the first direct evidence that terrestrial sediments were deposited in at least parts of the northern Antarctic Peninsula during the Lower Jurassic. On the basis of the palaeobotanical and radiometric evidence discussed above, it is necessary to revise the model proposed by Farquharson (1983a, fig. 3) for the late Mesozoic evolution of the northern Antarctic Peninsula region. It is probable that magmatic arc uplift occurred and an integral landmass existed in this area from Early Jurassic times onwards, rather than from the Early Cretaceous as suggested previously (e.g. by Farquharson (1983a, 1984)).

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