THE NORDENSKJÖLD FORMATION OF THE NORTHERN ANTARCTIC PENINSULA: AN UPPER JURASSIC RADIOLARIAN MUDSTONE AND TUFF SEQUENCE

G. W. Farquharson

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Abstract. Distinctive outcrops of alternating Radiolaria-rich mudstones and ash-fall tuffs along the south-east flank of the Antarctic Peninsula are assigned to a new lithostratigraphic unit, the Nordenskjöld Formation. The formation is exposed at five localities, from Joinville Island south to Cape Fairweather. Deposition took place within a quiet-water, anoxic basin where background sedimentation was regularly interrupted by the settling of ash-falls. Anoxic conditions were probably the result of high plankton productivity and the consequently expanded oxygen minimum layer. The formation has yielded fish, brachiopods, inoceramid bivalves, belemnites and ammonites of Kimmeridgian–Tithonian age although there is evidence to suggest that deposition continued into the earliest Cretaceous. Recognition of identical Upper Jurassic lithologies on the South Shetland Islands and possible metamorphosed equivalents on Trinity Peninsula suggest that deposition of the mudstone/tuff facies covered much of the northern Antarctic Peninsula region. The Nordenskjöld Formation may also be correlated with certain rock units in Patagonia and South Georgia, and represents the southern part of an anoxic basin that covered the South Atlantic Ocean and surrounding areas in late Jurassic–early Cretaceous times. Uplift and extensive volcanism in the northern Antarctic Peninsula during the early Cretaceous led to the construction of an emergent volcanic arc and the cessation of fine-grained Nordenskjöld Formation deposition.

The Nordenskjöld Formation comprises a distinctive sequence of Radiolaria-rich mudstones and tuffs of late Jurassic age that are exposed in the northern Antarctic Peninsula (Farquharson, 1982*a*). Initial investigations into the geology of this region were carried out by members of Dr Nordenskjöld's Swedish Antarctic expedition of 1901–1903 (Andersson, 1906). Since the formation described here occurs at three places along the Nordenskjöld Coast (east coast of the Antarctic Peninsula lying between Longing Gap and Cape Fairweather), the name Nordenskjöld Formation has been adopted.

The Nordenskjöld Formation is exposed at five localities on the eastern side of northern Graham Land: Mount Alexander on Joinville Island, northern Dundee Island, Longing Gap, Sobral Peninsula and Cape Fairweather (Fig. 1). Neither the base nor the top of the formation is seen anywhere; intrusive contacts are the sole stratigraphic relationship observed. Longing Gap is designated the type locality because the sequence here is fossiliferous and unaffected by thermal metamorphism. The thickest development, 550 m, is seen on the Sobral Peninsula but the total thickness deposited could be much greater than this figure.

The age of the formation is known from inoceramid bivalves and ammonites collected from Longing Gap and the Sobral Peninsula. Specimens of *Retroceramus* from Longing Gap have late Jurassic affinities (Crame, 1982) and ammonites collected from the same locality include *Taramelliceras*, *Torquatisphinctes (?)* and *Lithacoceras (?)*, forms indicative of a Kimmeridgian or early Tithonian age (Thomson, 1982*a*). Possible berriasellid fragments of late Tithonian age and an

Br. Antarct. Surv. Bull. No. 60, 1983, pp.1–22

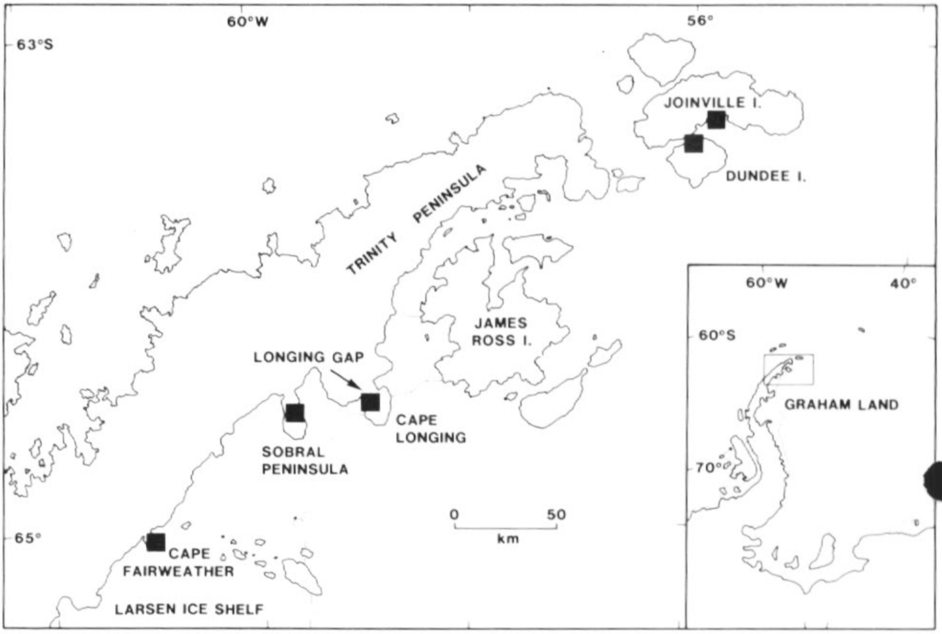


Fig. 1. Sketch map of northern Antarctic Peninsula indicating the location of Nordenskjöld Formation exposures (solid squares).

inoceramid of the *Retroceramus everesti* group (range late Tithonian–early Berriasian) suggest a late Tithonian age for the Nordenskjöld Formation on the Sobral Peninsula (M. R. A. Thomson and J. A. Crame, personal communication). Clasts of mudstone/tuff lithology found within the Cretaceous conglomerates of north-west James Ross Island contain ammonites that may be of early Neocomian age (J. A. Crame, personal communication). Although the age of outcrops, where known, is Kimmeridgian–Tithonian, it appears likely that deposition of the formation continued into the earliest Cretaceous.

Locality Descriptions

Longing Gap 64°27′30″S, 58°58′25″W

To the south of Longing Gap lies a predominantly scree-covered area of rock truncated at its southern end by several canyon-like valleys in which flat-lying thin-bedded sedimentary rocks occur. (Figs 2 and 3). R. Stoneley (unpublished data) visited the area in 1952 and in the following year J. A. Standring (1953) measured a 323 ft (98.5 m) succession through 'thinly-bedded, grey and black siltstones and shales with some calcereous sandstones and limestones'. The uniform lithology of alternating Radiolaria-rich mudstone and ash-fall tuffs is well exposed along the river-cut valleys in the south (Fig. 3) and in restricted areas in the north-west, near the Argentine hut. The ratio of mudstone to tuff is approximately 2:3. In the southern part, the beds are either horizontal or dip at a few degrees towards the east. Moving north the attitude of the beds gradually changes to become southward dipping at 10–12°. The strike of beds can be seen on the air photographs to swing from north-south to east-west (Fig. 2B).

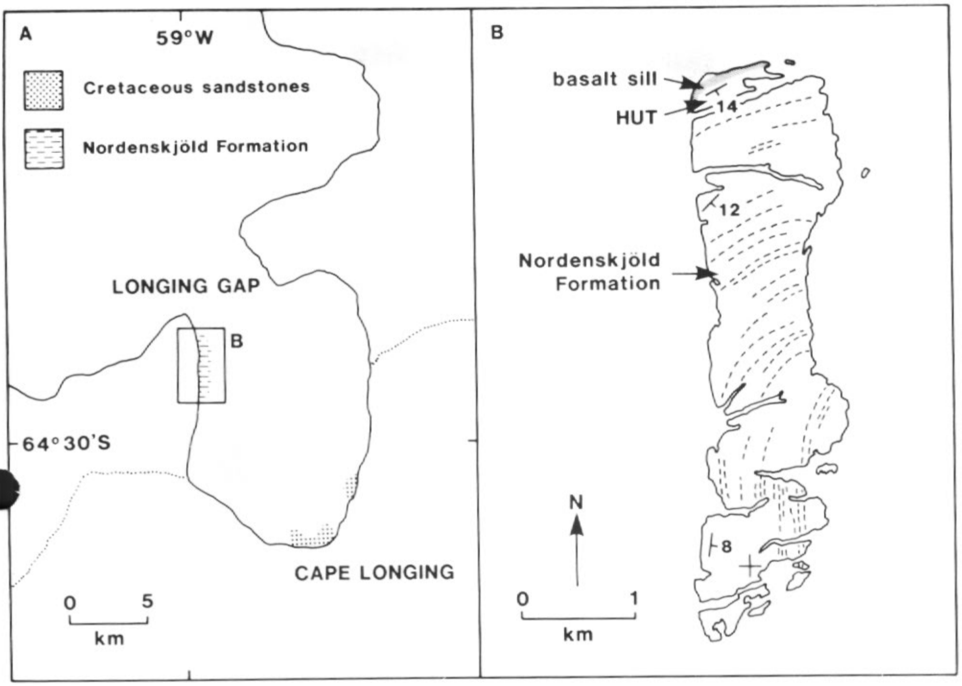


Fig. 2. Maps showing the location of the Nordenskjöld Formation outcrop at Longing Gap. The dashed lines on map B are strike lines traced from air photographs.

A section measured through the succession in the southern-most valley comprises 71 m of uniform mudstone/tuff lithology. The total thickness of strata exposed at Longing Gap can be estimated from air photographs to be 350 m. At the northern tip of the outcrop a basalt sill 4–5 m thick is concordant with the east-west striking sedimentary rocks.

Longing Gap is the most fossiliferous of the Nordenskjöld Formation occurrences, yielding fish (scales, vertebral columns and an almost complete skeleton), ammonites (usually encrusted by indeterminate oysters and oxytomid-like bivalves), belemnites, inoceramid bivalves and brachiopods.

Mount Alexander, Joinville Island 63°19'30"S, 55°47'00"W

Stratified rocks on Mount Alexander (central southern Joinville Island, Fig. 4) were first seen, but not visited, by J. A. Standring in 1954 (see Elliot, 1967). Standring suggested that the horizontally layered rocks draping the southern and eastern flanks of Mount Alexander belonged to the Upper Jurassic Volcanic Group (renamed Antarctic Peninsula Volcanic Group; Thomson, 1982*b*). However, with the aid of helicopters from HMS *Endurance*, R. D. Hamer and G. Hyden visited the area in January 1979 and found the layered succession to consist of thin-bedded, fine-grained sedimentary rocks. A further visit was made in March 1981 by the author, R. D. Hamer and M. R. A. Thomson.

A diorite-granodiorite pluton forms the central portion of Mount Alexander, whereas the Nordenskjöld Formation occurs as the country rock on the flanks of the mountain and also as large xenoliths (tens of metres across) within the pluton

Fig. 3. The type section of the Nordenskjöld Formation at Longing Gap. The section exposed in this stream-cut canyon at the southern tip of the outcrop is 70 m thick.

(Fig. 4). The dominant lithology is dense black, cherty mudstone (1–15 cm thick) interbedded with grey/green tuffaceous horizons (0.5–15 mm thick) ranging in grain size from mud to coarse sand (Fig. 5). The tuffs are typically normally graded and are always perfectly laterally continuous. The approximate ratio of mudstone to tuff is 3:1. Interspersed at fairly regular (10–20 cm) intervals within the succession are thin (0.5–1 cm) laterally continuous layers of yellow clay (? bentonites). Blue-grey diagenetic limestone occasionally forms discontinuous horizons 10–20 cm thick.

With the exception of the tilted xenolithic blocks, the sedimentary rocks dip gently towards the north-east. However, a number of slump folds disrupt this orientation. Measurements around three such folds show that they were overturned towards 180°, 202° and 215°. Thus the sediments were probably deposited on a palaeoslope dipping to the south-south-west. The sequence is cut by many dykes and transgressive sills.

Several fragments of poorly preserved perisphinctid ammonites were recovered from the succession and possible bivalve remains were seen. The trace fossil

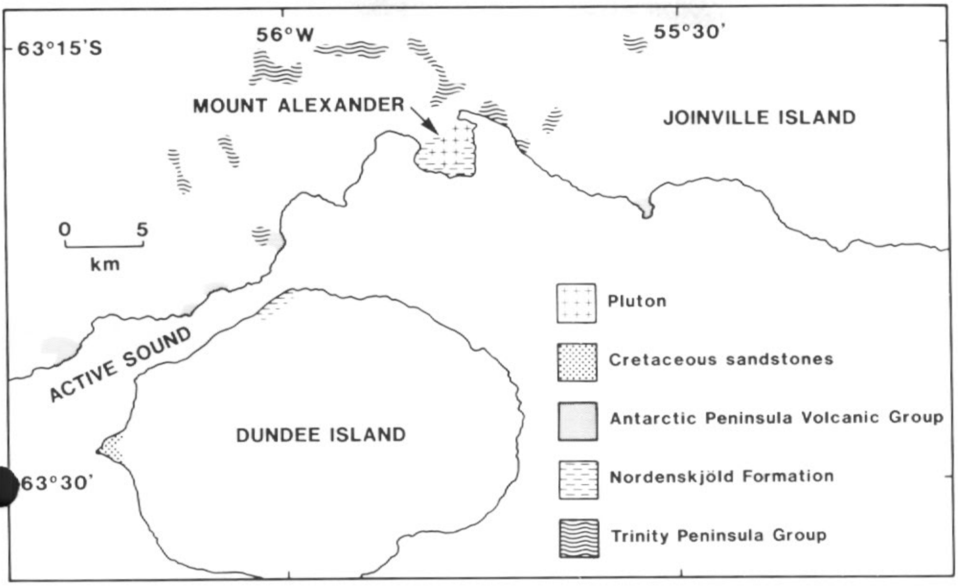


Fig. 4. Sketch map of southern Joinville Island and Dundee Island showing the two areas where the Nordenskjöld Formation is exposed.

Fig. 5. A typical exposure of Nordenskjöld Formation lithology on the southern shore of Mount Alexander, Joinville Island, clearly illustrating the alternation of mudstones (dark) and tuffs (light). Hammer is 77 cm long.

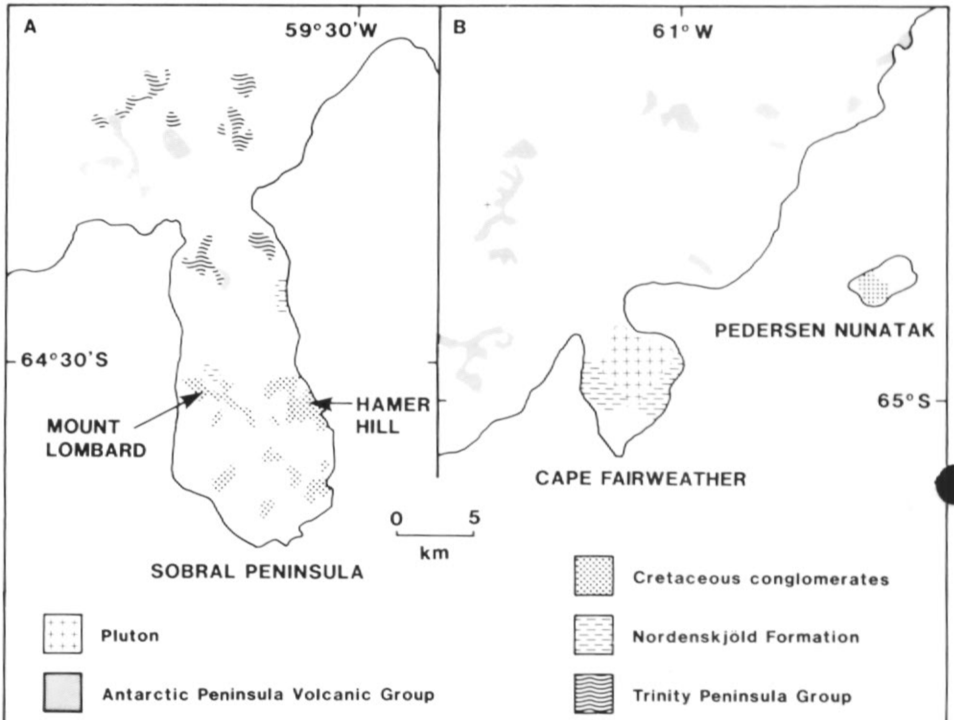


Fig.6. Geological sketch maps of A, Sobral Peninsula and B, Cape Fairweather.

Chondrites was noted on several bedding planes. The estimated stratigraphic thickness of the Nordenskjöld Formation at Mount Alexander is 250 m.

Dundee Island 63°23′50″S, 56°01′30″W

Small, inaccessible outcrops beneath the ice cliffs of nothern Dundee Island (southern shore of Active Sound, Fig. 4) were approached to within 10 m by boat and found to comprise the characteristically layered Nordenskjöld Formation. The ratio of mudstone to tuff is 6:1 and the approximate bedding orientation 20°/180° (thoughout this paper orientations of planes are expressed as dip/dip direction).

Sobral Peninsula 64°27′40″S, 59°36′30″W and 64°30′20″S, 59° 42′ 20″W

J. S. Bibby visited the Sobral Peninsula (Fig. 6a) in 1959 but only recorded outcrops of conglomerate near the southern tip of the peninsula (unpublished data). The presence of finer grained lithologies in the same general area was first noted by Elliot (1966), who described them as thin, interbedded shales and dark grey sandstones.

The Nordenskjöld Formation is exposed in two small areas; one immediately to the north of Mount Lombard, the other on the eastern side of the peninsula 7 km north of Hamer Hill (Fig. 6a). At the former locality approximately 550 m of strata is exposed as steeply dipping (55°/145°–90°/159°) beds. The basal 300 m is composed of typical Nordenskjöld Formation lithology (cherty black mudstone alternating

Fig. 7. Part of the mudstone–tuff succession exposed to the north of Mount Lombard, showing an isolated, small-scale slump. Notebook is 17 cm long.

with graded ash-fall tuffs), whereas towards the top of the sequence the ash bands and cherty nature of the mudstones disappear to give way to fissile grey mudstones and siltstones. At the eastern outcrop, 100 m of alternating mudstone and tuff is exposed with a constant bedding orientation of 85°/290°.

Synsedimentary slumping (Fig. 7) and microfaulting are common features. The slumps have amplitudes of up to 3 m and are generally overturned towards the west. A few ammonite fragments, an inoceramid bivalve, belemnite and abundant pieces of petrified wood were recovered from the formation. A feature unique to the Nordenskjöld Formation as exposed on the Sobral Peninsula is the occasional occurrence of laterally continuous medium- to coarse-grained sandstones up to 10 cm thick.

The Lower Cretaceous conglomerates that occur on the southern half of the Sobral Peninsula contain abundant clasts of mudstone/tuff lithology. These clasts are angular, up to 5 m across, and display soft-sediment deformation structures around their edges suggesting that they were unconsolidated during transport and subsequent deposition. Although not exposed, it is probable that an unconformity exists between the Nordenskjöld Formation and the volcaniclastic conglomerates on the Sobral Peninsula.

Cape Fairweather 64°59′00′′S, 61°01′00″W

The sedimentary rocks at Cape Fairweather (Fig. 6b) were initially described by Fleet (1968) who noted the presence of hornfelsed mudstones adjacent to a diorite pluton. Despite being hornfelsed, these deposits clearly belong to the Nordenskjöld Formation, comprising normally graded ash-fall tuffs interbedded with dense, black cherty material. The tuffs vary in thickness from 1 to 2.5 cm and form 50% of the lithology. Approximately 200 m of the formation are exposed. The sequence is unfossiliferous and the only age evidence comes from a K-Ar date of 100 ± 4 Ma (Rex, 1976) on the adjacent pluton, implying that the sedimentary rocks must be older than mid-Cretaceous.

Looking to the south the strata on Cape Fairweather form a large-scale S-fold. The dominant dip is 25°/280° but the common limb of the two exposed folds is overturned and has an attitude of 80°/280°. The hinges are angular and the axes plunge 8° to the north. The near-vertical strata are host to numerous leucocratic sills, 1–2 m thick.

Lithology

The Nordenskjöld Formation consists of a uniform succession of alternating Radiolaria-rich mudstones and ash-fall tuffs (Figs 8 and 9A). Distinctive features are the thinness of the beds (0.1–15 cm, though generally in the range 0.5–2 cm), the lateral persistence at constant thickness of the individual beds, and the range of weathering colours (pale blue, yellow, white and red) exhibited by the tuffs.

In outcrop, the mudstones appear as homogenous, dense black cherty layers while in thin-section the presence of recrystallized Radiolaria set within a brown very fine-grained groundmass becomes apparent (Fig. 9B). The Radiolaria comprise between 5 and 70% of the mudstone layers and where elongate sections are seen they always lie parallel to bedding. The Radiolarian tests occur as globular mosaics of quartz crystals. Growth of the quartz crystals from the test wall inwards is indicated by a rapid decrease in abundance and concomitant increase in size of the crystals from the circumference to the centre. The core is usually occupied by a single, angular opaque crystal with many re-entrant angles that accomodate the terminations of the inward facing quartz crystals. Also, the rim of the quartz mosaic

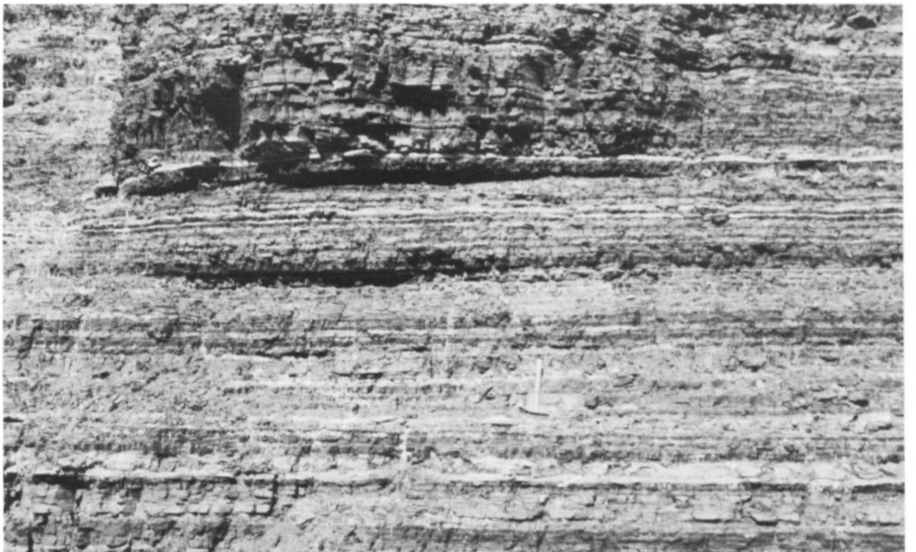
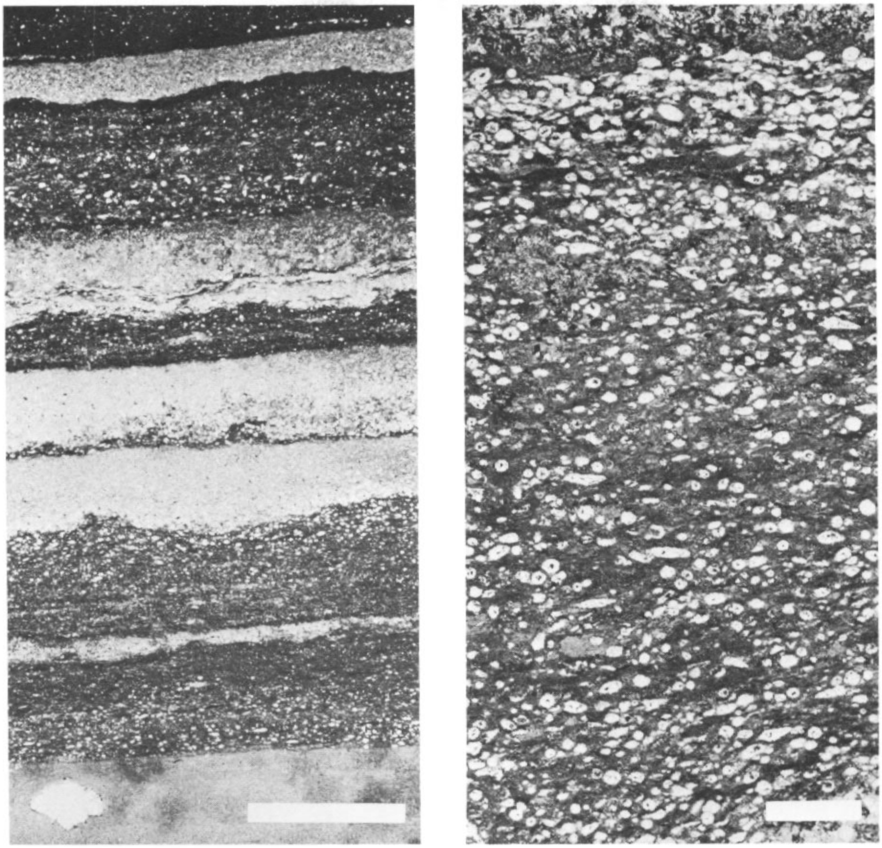


Fig. 8. The Nordenskjöld Formation at Longing Gap; note the lateral continuity and thinness of the mudstone (dark) and tuff (light) beds. Hammer is 35 cm long.



A B

Fig. 9. Photomicrographs to show characteristic features of Nordenskjöld Formation lithology. A, Dark mudstone laminae with abundant Radiolaria alternating with normally graded tuffs; Longing Gap. (R.1329.11). Scale bar is 5 mm. B, Abundant recrystallized Radiolaria within an amorphous matrix constitute the mudstone laminae; Longing Gap. (R.1329.5). Scale bar is 1 mm.

is typically studded with small opaque grains. Two distinct forms of Radiolaria can be distinguished in thin-section: a conical form *(? Dictyomitra* sp.) and a spherical one *(? Cenosphaera* sp.). Preservation of both test shape and internal structure varies considerably. The best preserved examples are from Longing Gap where the tests are commonly divided by planar partitions.

The brown amorphous groundmass within which the Radiolaria are embedded contains opaque bodies in the form of perfect spheres or aggregates of spheres. These grains commonly form stringers enclosing domains of groundmass with slight variations in colour. In the well indurated samples the stringers form tight anastomosing networks (Fig. 10A). In rare instances the mudstone laminae contain up to 10% of disseminated euhedral crystals of plagioclase feldspar, usually zoned, and quartz. Plant material with preserved cellular structure is present in very small quantities.

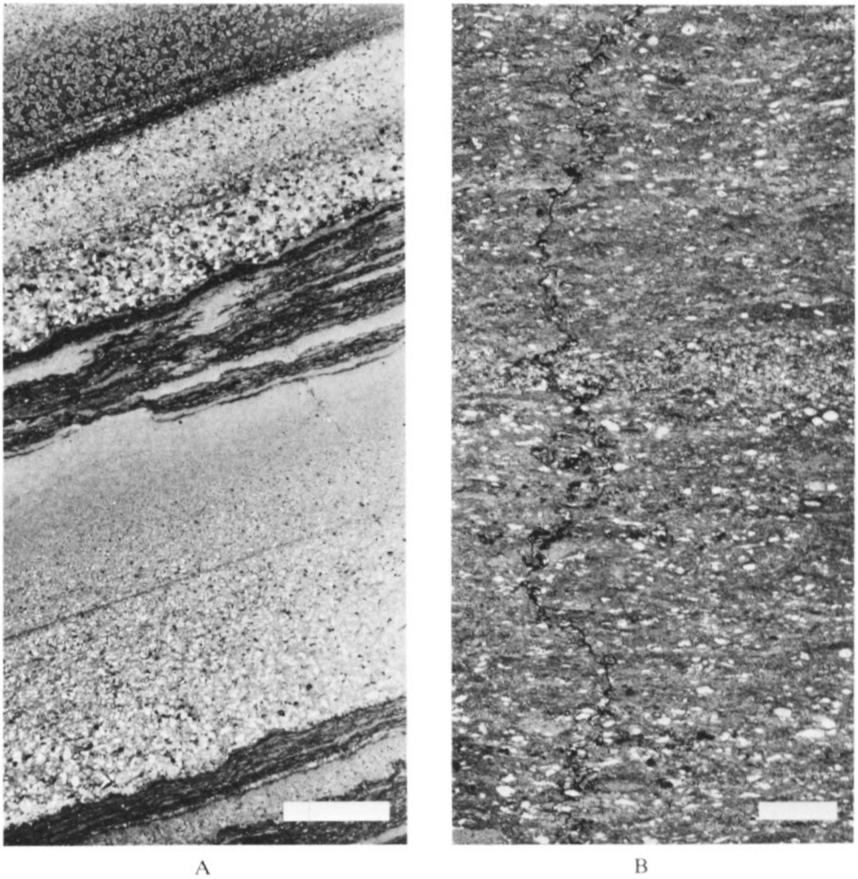


Fig. 10. Photomicrographs of typical Nordenskjöld Formation lithology. A. Illustrates the typical well developed normal grading of the ash-fall tuffs; Cape Fairweather. (R.1355.5). Scale bar is 5 mm. B. Vertical dark line is a stylolite formed by silica dissolution and the concomitant concentration of insoluble residues; Longing Gap. (R.1378.1). Scale bar is 1 mm.

Major components of the tuffaceous laminae are euhedral, zoned plagioclase feldspar (~20%) and angular, unstrained quartz crystals (~20%) up to 1 mm across. The majority of plagioclase crystals are thoroughly sericitized but optical determinations on the less altered samples indicate an andesine composition. The groundmass consists of very fine-grained quartz and feldspar. Quartzites with sutured grain boundaries, presumably derived from the Trinity Peninsula Group, and volcanic clasts having a trachytic texture are common constituents (up to 5%). Accessory minerals include zircon, opaque oxides and secondary chlorite, while the patchy development of diagenetic calcite is a common feature.

Characteristically, the tuff units display well developed normal grading (Figs 9A and 10A). A typical graded tuff may have crystals up to 0.5 mm across at the base and only 0.005 mm across at the top. The tuffs do not contain Radiolaria. Contacts between the tuffaceous and mudstone laminae are invariably sharp. The bases of the tuffs are typically loaded into the mudstone unit beneath, whereas their tops are, with rare exception, flat. Exceptions arise when Radiolaria have sunk into the very fine-grained tops of some graded tuffs. Occasionally, extreme loading of the tuffs has resulted in their complete disruption. Stylolites, truncating both the tuffaceous and Radiolaria-rich mudstone laminae, are a common secondary feature of the lithology (Fig. 10B). They take the form of thin, curvilinear concentrations of opaque minerals which presumably represent residues of insoluble material that accumulated during silica dissolution.

Blue-grey calcareous concretions are ubiquitous within the Nordenskjöld Formation, occurring as either lenticular or stratiform bodies. The diagenetic growth of calcite leading to their formation did not disrupt the primary sedimentary structures. Dimensions of the concretions are generally in the order of tens of centimetres thick and several metres long.

Sandstones are a rare feature of the formation and were only found on the Sobral Peninsula. They are medium- to coarse-grained, laterally persistent and up to 10 cm thick. Volcanic rock fragments are their main constituent along with euhedral plagioclase and clear quartz. Another minor lithological component of the formation is the thin layers of yellow clay (? bentonite) found in the succession at Mount Alexander, Joinville Island.

Sedimentology and Palaeogeography

The normal grading, planar continuity and non-erosive nature of the tuffs within the Nordenskjöld Formation indicate an origin as ash-falls from either subaerial or submarine volcanic eruptions. Deposition by micro-turbidity currents can be rejected, due to the lack of internal structures other than grading, the lack of sole marks, and the extreme angularity of the constituent grains. It is thus apparent that the distinctive lithological association of alternating Radiolaria-rich mudstones and ash-fall tuffs was generated by background sedimentation interrupted regularly by the effectively instantaneous deposition of volcanic ash layers. Comparable deposits have been studied in a succession of Palaeogene diatomites from Denmark (Pedersen, 1981) and in rocks of various ages from Japan (Kanmera, 1974).

Clasts of alternating mudstone and tuff are abundant within the Lower Cretaceous strata of north-west James Ross Island (Fig. 1). Of particular note are three blocks, the largest measuring at least 200 m thick and 800 m long, that are interpreted as isolated exotic slabs, transported to their present position by submarine sliding (Ineson, 1982; Farquharson and others, in press). Although the Nordenskjöld Formation is not exposed on James Ross Island it is clear that the formation was deposited in the Trinity Peninsula/James Ross Island region. The depositional area of the mudstone/tuff lithology must have been considerable (Joinville Island to Cape Fairweather is a distance of 325 km). Furthermore, in view of the patchy rock exposure in the Antarctic Peninsula and the number and distribution of Nordenskjöld Formation outcrops, it is likely that the formation was originally laterally continuous rather than having accumulated within several isolated basins.

The Nordenskjöld Formation possesses a number of features indicative of deposition under quiet-water conditions. These include the preservation of delicate fish remains (Fig. 11), and the absence of structures generated by currents and waves (ripples, scours, winnow lags). Deposition under anoxic conditions is indicated by perfect preservation of the fine lamination and the related absence of bioturbation. Another important feature is the virtual absence of clastic detritus

Fig.11. An almost complete fish skeleton from the Nordenskjöld Formation at Longing Gap. (R.1330.82). Natural size.

(except for the rare thin sandstones on the Sobral Peninsula). The metasedimentary and volcanic rock fragments found within the tuffaceous laminae may be assumed to be volcanic ejecta since their size varies in accordance with the grading of the tuffs and they are absent from the mudstone layers. Therefore, the Nordenskjöld Formation is incompatible with a nearby emergent arc and could not have been coeval with the Antarctic Peninsula Volcanic Group and associated non-marine sediments which represent an active and emergent magmatic arc (Farquharson, 1982*b*; Thomson, 1982*b*). It is now established that the Antarctic Peninsula Volcanic Group in northern Graham Land is probably largely of early Cretaceous age (Pankhurst, 1982; Thomson and Pankhurst, in press) and hence post-dates the Nordenskjöld Formation. The distribution of the mudstone/tuff association, together with the presence of an identical, (?) early Tithonian, lithological association on the South Shetland Islands (mudstone member, Byers Formation; Smellie and others, 1980), makes the existence of an appreciable late Jurassic emergent volcanic arc in northern Graham Land unlikely. At this time the volcanic source was probably a series of small, submarine or locally subaerial, volcanoes as opposed to an arc edifice with substantial subaerial relief (Farquharson, 1982*a*). The thin, volcaniclastic, sandstones that occur within the formation on the Sobral Peninsula appear to be the sole record, on the Antarctic Peninsula, of epiclastic sedimentation at this time.

Most of the ammonites from the formation are encrusted to varying extents by bivalves (Fig. 12). The most common epizoans are indeterminate oysters that vary in size from 1 mm or less to 2 cm. In addition to the oysters there are oxytomid-like bivalves up to 0.7 cm across. If these epizoic bivalves had become cemented on to the ammonite shells whilst the latter were lying empty on the sea floor then the ecological tolerance of the encrusting organisms would suggest that deposition occurred in a shallow marine, inner shelf setting under oxic conditions. However, this idea is incompatible with the absence of an infauna (except for rare *Chondrites* at Mount Alexander) and with the preservation of the fine lamination which indicate anoxic conditions unfavourable for the survival of oysters. It therefore seems likely that the epizoic fauna became attached to the ammonites whilst they were still floating, either alive or dead, within the water column. That this is a plausible suggestion was established by Seilacher (1960) who demonstrated from the orientation and distribution of oysters on a specimen of *Buchiceras bilobatum* that they could only have become attached while the ammonite was alive and floating clear of the sea bed (see also Meischner, 1968; Heptonstall, 1970). Due to the buoyancy effects of gas in their chambers even after death, necroplanktonic movement of cephalopods is an important consideration in their dispersal (Raup, 1973; Kennedy and Cobban, 1976). Thus the opportunity arises for colonization of

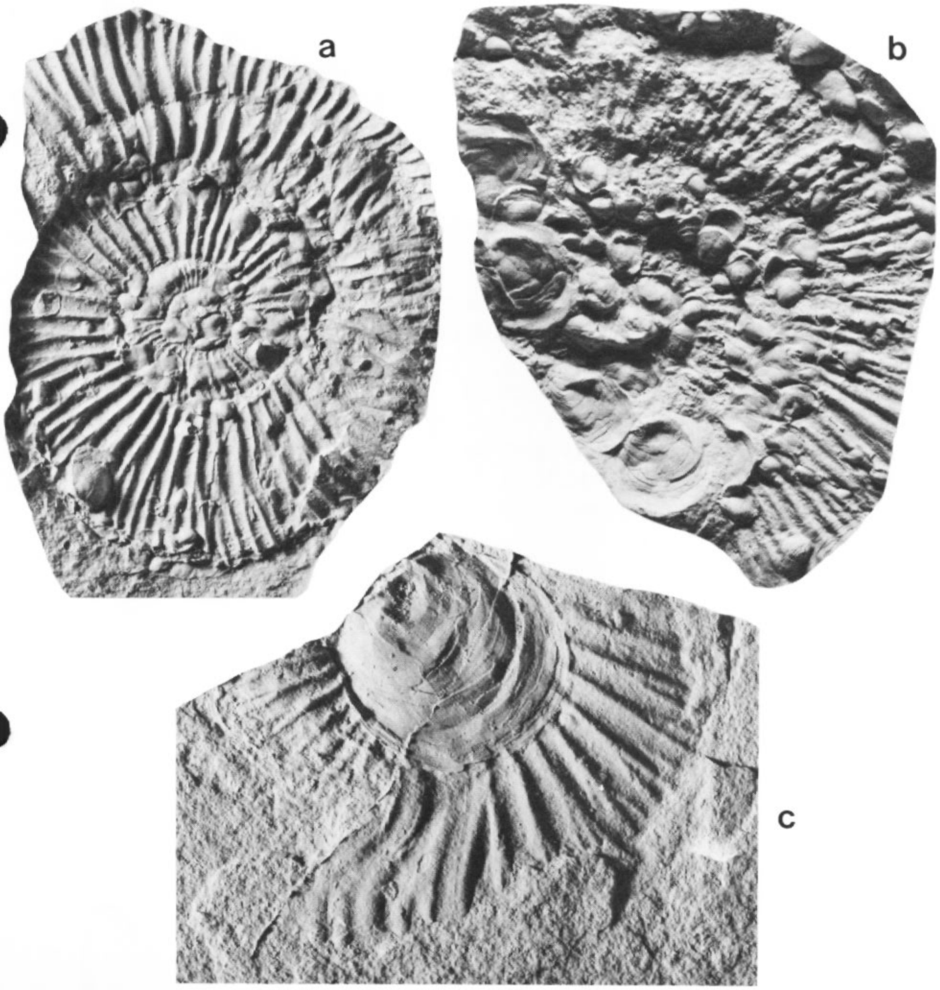


Fig.12. Ammonites (*Torquatisphinctes (?)*) encrusted to varying degrees by bivalves, from the Nordenskjöld Formation at Longing Gap. Natural sizes. a, oxytomid-like bivalve (lower left) and small oysters showing no preferred distribution. (R.1330.8). b, encrusting oysters concentrated within the umbilicus of an ammonite. (R.1330.58). c, single, large oyster sitting in the umbilicus. (R.1330.15).

the shell following death but prior to its sinking to the sea floor. An example of necroplanktonic encrustation of an ammonoid was documented by Riccardi (1980).

It is thus clear that during late Jurassic times the area presently occupied by northern Graham Land was covered by a shelf sea with anoxic bottom conditions. Two distinct models are currently envisaged for the generation of marine anoxic conditions (Thiede and Van Andel, 1977). The barred basin or 'Black Sea' model exists where density and salinity stratification in an isolated basin results in a layer of well oxygenated, low-salinity, warm water overlying anoxic deep water masses of higher salinity. In contrast, the oxygen minimum zone model allows for anoxic conditions to exist at certain depths under open oceanic conditions. This layer of low or zero oxygen content develops between the upper agitated surface waters and the deep oxygenated bottom currents as a consequence of bacterial decay of dead organisms and the concomitant consumption of oxygen (Fig. 13). The thickness and intensity (i.e. lowest oxygen content attained) of the oxygen minimum zone is dependent on many variables but particularly on planktonic productivity and the ability of bottom currents to introduce oxygen to the water column (Schlanger and Jenkyns, 1976). It is unlikely that euxinic conditions prevailing in the northern Antarctic Peninsula during the late Jurassic could have been the result of restricted circulation since, in the absence of an emergent arc, the area would have been subjected to the open oceanic conditions of the 'Pacific Ocean'. An expanded oxygen minimum zone is much more acceptable as an explanation. It is possible that enhanced planktonic production, as witnessed by the abundant Radiolaria within the Nordenskjöld Formation, resulted in the removal of much oxygen from the seas, shifting the water body towards anoxia and thereby increasing the extent of the oxygen minimum zone.

Prior to recognition of the oxygen minimum zone, euxinic conditions were always attributed to deep stagnant basins. It is now apparent that shallow epeiric seas with a high nutrient supply and high organic productivity may possess an oxygen depleted layer that intersects much of the shelf area (Jenkyns, 1980). Radiolaria, and other pelagic microfossils can occur in quite shallow water deposits

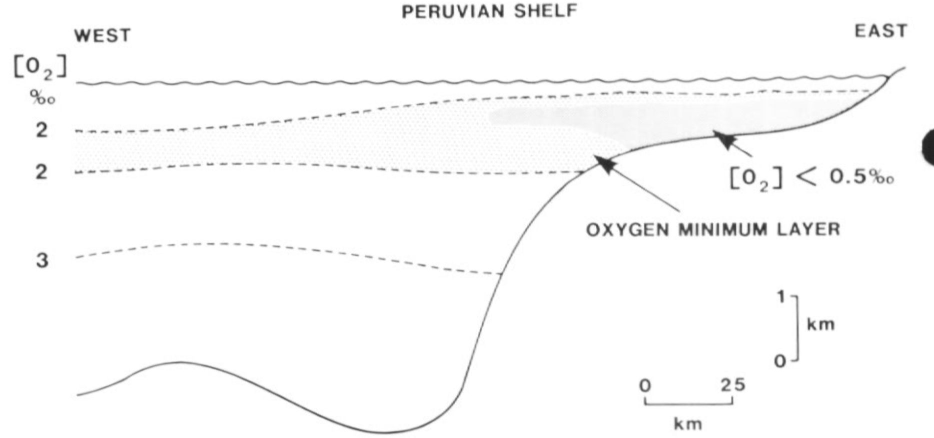


Fig. 13. An anoxic zone extends along the coast of Peru for over 1000 km. It is a useful modern example of an oxygen minimum layer caused by upwelling; in this case upwelling of the Peru Current. A comparable situation is envisaged to account for the anoxic depositional environment of the Nordenskjöld Formation. After Demaison and Moore (1980).

e.g. the Solnhofen Limestone (Kling, 1978); their distribution is in accordance with areas of high nutrient supply. These areas correspond to regions of oceanic upwelling, where the surface waters diverge and nutrient-rich deeper water ascends to the photic zone (Ramsey, 1973) (Fig. 13). Ciesielski and others (1977) have postulated that during the late Cretaceous two palaeocurrent systems converged in the region of the Falkland Plateau. The northern current would correspond to the South Atlantic gyre, whereas the current to the south would be analogous to the present West Wind Drift. There is no reason to invoke a substantially different arrangement during the late Jurassic except that the more juvenile state of the South Atlantic Ocean probably meant a less well developed circulatory system. However, it is still conceivable that convergence of two opposing currents in the region of the northern Antarctic Peninsula and Falkland Plateau would have induced nutrient upwelling and enhanced plankton productivity. In addition to, and probably more important than, this circulatory system to the east of the southern Andes – Antarctic Peninsula would be the upwelling of a westerly current against the Pacific margin of this part of Gondwana. It is believed that the main elements of oceanic circulation, westerly currents toward the poles and easterly currents in the equatorial belt, are an unchanging feature of the Earth (Ramsay, 1973). In late Jurassic–early Cretaceous times, prior to the opening of Drake Passage, the West Wind Drift would have impinged on the Pacific margin of Gondwana. Upwelling of this current as it met the continent would be analogous to the present Peru Current (Demaison and Moore, 1980) and would be accompanied by a comparable oxygen minimum layer (Fig. 13).

Correlatives and Regional Implications

Several Upper Jurassic–Lower Cretaceous successions within the Scotia arc region are lithologically similar to the Nordenskjöld Formation. They include rocks on the South Shetland Islands, South Georgia and Patagonia. A group of metasediments known as the banded hornfelses exposed on Trinity Peninsula could possibly be metamorphosed equivalents of the mudstone/tuff association.

The South Shetland Islands

Livingstone Island. Upper Jurassic (? early Tithonian) to Lower Cretaceous (? Barremian) sedimentary and volcanic rocks (Byers Formation) are exposed on Byers Peninsula, Livingston Island, South Shetland Islands (Smellie and others, 1980) (Fig. 14A). The early Tithonian mudstone member of the Byers Formation consists of alternating Radiolaria-rich mudstones and normally graded tuffs. In contrast to the Nordenskjöld Formation, parts of the succession are extensively bioturbated, and graded sandstones (thought to be storm sand layers) are occasionally interbedded with the mudstones and tuffs (Smellie and others, 1980). The age and major lithological characters of these two rock units are identical, but a less anoxic and shallower setting must be envisaged for the mudstone member to account for the bioturbation and possible storm-generated sandstones. Alternation of bioturbated and undisturbed layers indicates changing oxygen conditons resulting from a fluctuating oxygen minimum zone (cf. Pedersen, 1981). Such a setting is endorsed by the inter-tonguing of the mudstone member with terrestrial sedimentary and pyroclastic rocks (Smellie and others, 1980).

Low Island. Sedimentary rocks of late Jurassic age crop out on Low Island, the southernmost of the South Shetland Islands (Smellie, 1980) (Fig. 14A). They include both epiclastic and pyroclastic deposits and are generally well-bedded

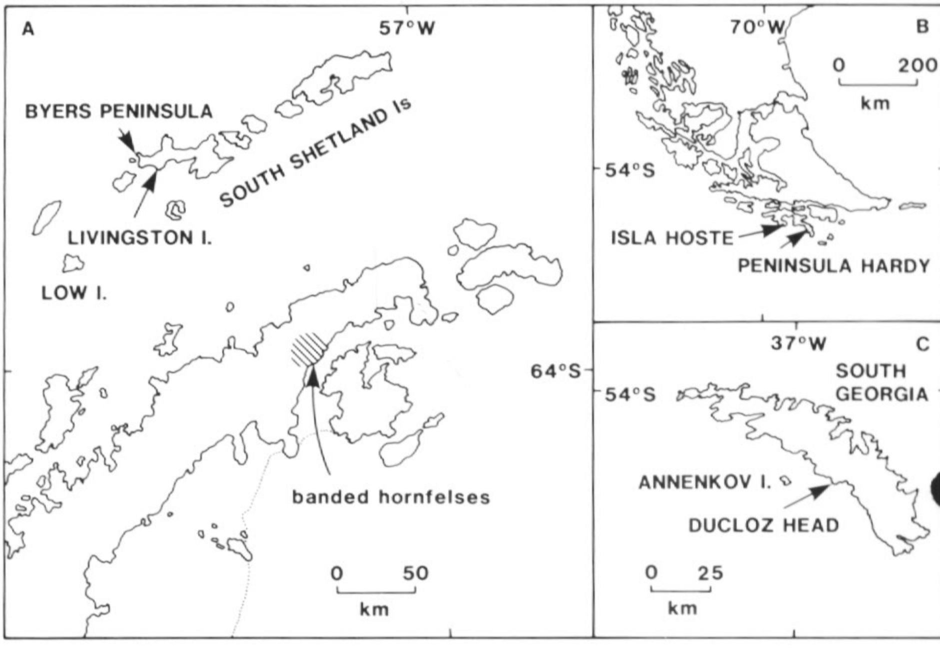


Fig.14. Maps to show the location of possible Nordenskjöld Formation correlatives in: A, the northern Antarctic Peninsula and South Shetland Islands; B, southern South America; C, South Georgia and Annenkov Island.

(beds 4–30 cm thick and laterally continuous). The predominant rock types are crystal lithic tuffs ranging in grain size from mud to pebble grade. They are composed of feldspar, quartz and volcanic rock fragments and are the product of comtemporaneous volcanism. Smellie (1980) interpreted most of the beds to be of turbidity current origin but suggested that ash-fall tuffs were also present. Accumulations of rapidly deposited ash-fall material on the flanks of the vents are thought to have been shed into deeper water as water-charged slurries that generated volcaniclastic turbidites. A subaqueous pyroclastic flow containing pumice fragments and a possible lava have been identified within the sequence.

Interbedded with the volcaniclastic layers are dark grey mudstones containing abundant Radiolaria that are presumed to represent periods of normal pelagic sedimentation. These sedimentary rocks are probably of Oxfordian age based on the occurrence of *Epimayites* aff. *transiens* (Thomson, 1982*c*). If the Low Island sequence is compared with the coeval Nordenskjöld Formation it is apparent that, whereas their background sedimentation is identical, their volcaniclastic interbeds differ considerably. It is probable that the sedimentary rocks of Low Island were deposited close to, or even on the flank of, a volcanic centre thereby explaining the presence of turbidites, a pyroclastic flow and a (?) lava within the sedimentary sequence (Smellie, 1980). This is in contrast with the purely ash-fall tuffs of the Nordenskjöld Formation and mudstone member of the Byers Formation which were deposited away from the immediate influence of a volcanic centre. Only the thin volcaniclastic sandstones within the succession on the Sobral Peninsula may be analogous to the proximal deposits of Low Island.

Isla Hoste, southern Chile

A 50-m-thick sequence of thin-bedded (less than 5 cm) fossiliferous tuffs and tuffaceous mudstones is exposed on Peninsula Hardy, Isla Hoste, southernmost South America (Suárez and Pettigrew, 1976) (Fig. 14B). The tuffs are composed of airborne vitroclastic material and Radiolaria are abundant in the mudstones. These deposits are part of the Hardy Formation which has been assigned a late Jurassic-early Cretaceous age on the occurrence of *Belemnopsis patagoniensis* and *Favrella americana*. Suárez and Pettigrew (1976) recognized that these rocks are comparable with the Lower Tuff Member of the Annenkov Island Formation.

South Georgia and Annenkov Island

Rocks identical to those of the Nordenskjöld Formation have been described from South Georgia and Annenkov Island. The Inland Member of the Ducloz Head Formation exposed in southern South Georgia (Fig. 14C) comprises thinly laminated tuffs and mudstones (Storey, in press). The tuffs are yellow to brown, laterally persistent graded units 3–12 cm thick, whereas the mudstones are black, cherty looking, rich in Radiolaria and form thin beds up to 5 cm thick. Calcareous nodules are abundant. The age of this unit is unknown.

Similar lithologies are present on Annenkov Island to the south-west of South Georgia (Fig. 14C). Here a sequence of interbedded tuffs and tuffaceous mudstones over 860 m thick is designated as the Lower Tuff Member of the Annenkov Island Formation. The tuffs are typically normally graded and the mudstones contain variable amounts of pyroclastic material and abundant Radiolaria (Pettigrew, 1981). The Annenkov Island Formation has yielded fish remains, ammonites, belemnites, bivalves and Foraminifera which indicate a Neocomian age for the Lower Tuff Member (Suárez and Pettigrew, 1976). The lithological descriptions and outcrop photographs (especially fig. 7 in Pettigrew, 1981) show a striking resemblance to the Nordenskjöld Formation. However, Storey and Macdonald (in press) favoured a turbidity current origin for the graded tuffs on the presence of mudstone intraclasts and laminations, features absent from the Nordenskjöld Formation.

South Georgia is composed largely of a volcaniclastic succession (Cumberland Bay and Sandebugten formations) of late Jurassic-early Cretaceous age that represents the flysch fill of a marginal basin (Winn, 1978; Tanner, 1982). Tanner and others (1981) have postulated that the mudstone–tuff assemblage accumulated on a narrow shelf situated between an active volcanic arc and the southwestern edge of the marginal basin. A bypass system of submarine canyons cutting through the shelf is invoked to transport detritus from the volcanic arc to the flysch basin.

Banded hornfelses of Trinity Peninsula

The banded hornfelses are a problematical group of rocks described by Elliot (1965) and Aikenhead (1975) from Trinity Peninsula (Fig. 14A). They are a monotonous succession of alternating pelitic and quartzo-feldspathic layers with bed thicknesses of 0.1–2 cm. The quartzo-feldspathic layers are occasionally graded and sometimes possess loaded bases. General sedimentary characteristics are very similar to those of the Nordenskjöld Formation and it is conceivable that the banded hornfelses are thermally metamorphosed equivalents of the mudstone/tuff facies. However, K-Ar dates of 159–174 Ma (middle Jurassic) on cross-cutting plutons and 139 and 140 Ma (late Jurassic) on the hornfelses themselves (Rex, 1976) suggest that the original sediments are older than the late Jurassic

Nordenskjöld Formation. It cannot be ruled out, however, that the mudstone/tuff facies ranges in age back to the early or middle Jurassic.

Regional implications

It is apparent that the Nordenskjöld Formation belongs to an important lithostratigraphic unit deposited in the Scotia arc region during the late Jurassic/early Cretaceous. If the mudstone member in the South Shetland Islands and the banded hornfelses are true correlatives of the Nordenskjöld Formation then it is likely that deposition of the mudstone/tuff facies occurred over the whole of the northern Antarctic Peninsula.

Legs 36 and 71 of the Deep Sea Drilling Project (DSDP) have concentrated on unravelling the evolutionary history of the South Atlantic Ocean (Barker and others, 1976; Ludwig and others, 1980). A significant result of this exploration has been the discovery of a widespread Oxfordian–Aptian euxinic facies on the Falkland Plateau (sites 327, 330 and 511) (Fig. 15). The initial transgression on the Falkland Plateau, associated with the opening of the South Atlantic, occurred in the late Jurassic bringing to a halt subaerial deposition on a gneissic basement terrain. From Oxfordian to late Aptian times euxinic conditions prevailed and were recorded by the accumulation of dark, laminated carbonaceous claystones. Normal, open-marine conditions were re-established by the early to mid-Albian times (Thompson, 1976).

The euxinic, black laminated shale facies had been encountered at several other places around the margin of the South Atlantic Ocean. These include the Cape and

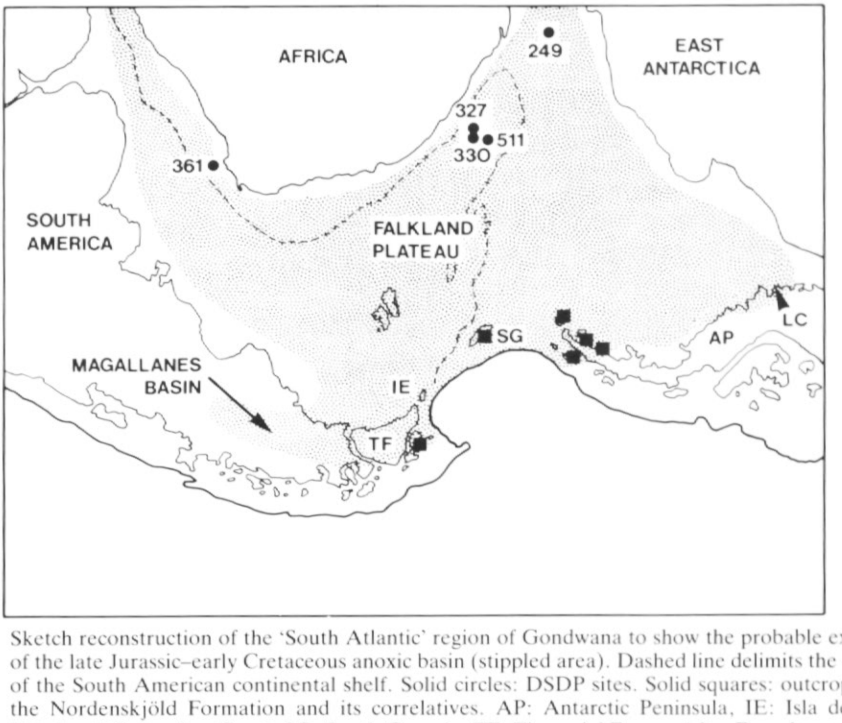


Fig.15. Sketch reconstruction of the 'South Atlantic' region of Gondwana to show the probable extent of the late Jurassic–early Cretaceous anoxic basin (stippled area). Dashed line delimits the edge of the South American continental shelf. Solid circles: DSDP sites. Solid squares: outcrops of the Nordenskjöld Formation and its correlatives. AP: Antarctic Peninsula, IE: Isla de los Estados, LC: Lassiter Coast, SG: South Georgia, TF: Tierra del Fuego. After Farquharson (In press).

Angola basins off south-west Africa (DSDP sites 361, 364, 365; Bolli and others, 1976), and the Mozambique Basin (DSDP site 249; Simpson and others, 1974). Land occurrences of late Jurassic–early Cretaceous carbonaceous shales are widespread in South America (Magallanes Basin, Katz 1963; Isla de los Estados, Dalziel and others, 1974) (Fig. 15). The largely early Cretaceous flysch of South Georgia is thought to have been deposited in a basin with low oxygen levels; a situation inferred from its low-diversity ichnofauna and opportunistic hard-bodied epifauna (Macdonald, 1982). It is now well established that the incipient South Atlantic and surrounding areas were the site of an anoxic basin during the late Jurassic and early Cretaceous (Tissot and others, 1980; Weissert, 1981) (Fig. 15). Recognition of the Nordenskjöld Formation in the Antarctic Peninsula and its correlatives in the Scotia arc extend the southern boundary of this anoxic basin into the Antarctic region. A further extension southwards can be invoked to explain the occurrence of Upper Jurassic dark carbonaceous and laminated mudstones and siltstones on the Lassiter Coast, southern Palmer Land (Latady Formation: Williams and others, 1972).

Thompson (1976) noted a progression in age of this South Atlantic euxinic facies from oldest (late Jurassic) in the south to the youngest (mid-Cretaceous) in the north and suggested a causal relationship with the fragmentation of Gondwana and the opening of the South Atlantic. It is therefore significant that the euxinic facies represented by the Nordenskjöld Formation and its correlatives conform to this age variation, being late Jurassic in the Antarctic Peninsula and late Jurassic-early Cretaceous on South Georgia and Isla Hoste. Thompson (1976) concluded that euxinic conditions in the South Atlantic were due to a combination of density stratification and deep water circulation restricted by the existence of shallow submarine ridges. The barred basin model seems applicable to the incipient South Atlantic where plateaux and ridges such as the East Falkland Plateau, Rio Grande Rise, Walvis Ridge and Mozambique Ridge could act as effective basin dividers. However, the oxygen minimum layer model cannot be ruled out as drill sites in the central, deeper, parts of the basins are lacking (Thiede and Van Andel, 1977). It is most likely that both causes of anoxic environments contributed towards formation of the South Atlantic anoxic basin, the oxygen minimum zone being most important near the Pacific boundary where unrestricted and upwelling oceanic currents resulted in high nutrient availability and high plankton productivity. Doubtless the existence of sills away from the Pacific margin restricted the circulation of bottom currents and encouraged the development of stagnant basins.

The age progression of the euxinic facies can be ascribed mainly to the gradual northward opening of the Atlantic which in any one area was characterized by a marine transgression followed some time later by the effective destruction of barriers to ocean circulation. In contrast, the cessation of anoxic conditions in South America and the Antarctic Peninsula can be related to the diachronous emergence of a volcanic arc. Uplift of this feature occurred in the earliest Cretaceous in the Antarctic Peninsula but not until the mid-Cretaceous in South America (Farquharson, 1982*a*). Such uplift would have isolated areas to the rear of the arc from the oxygen minimum layer developed as a consequence of upwelling of the West Wind Drift.

CONCLUSIONS

The Upper Jurassic Nordenskjöld Formation is exposed on Joinville and Dundee islands, at Longing Gap, the Sobral Peninsula and Cape Fairweather in the northern Antarctic Peninsula. It comprises a regular alternation between ash-fall tuffs and Radiolaria-rich mudstones that yield a marine fauna of ammonites, bivalves and fish. Deposition occurred under low energy and anoxic conditions, the background fine-grained sedimentation periodically being interrupted by the settling of ash falls. Although coeval with active volcanism, the absence of epiclastic detritus from the formation indicates that the volcanic arc lacked substantial subaerial relief at this time. Correlatives of the formation are recognized on the South Shetland Islands, Isla Hoste (southern Chile), South Georgia and Annenkov Island. The mudstone-tuff association is thus a widespread lithostratigraphic unit in the Scotia arc region. A group of banded hornfelses exposed on Trinity Peninsula may be metamorphosed equivalents of the Nordenskjöld Formation.

Euxinic sediments of late Jurassic-early Cretaceous age are commonly described from DSDP sites and onshore geology around the margins of the South Atlantic Ocean. The Nordenskjöld Formation indicates that, during late Jurassic times, anoxic conditions extended southwards into the Antarctic Peninsula region where upwelling of westerly currents against the Pacific margin of Gondwana probably resulted in high plankton productivity and an expanded oxygen minimum layer.

Acknowledgements

I wish to thank J. A. Crame, P. F. Friend, R. D. Hamer, J. R. Ineson, B. C. Storey, and M. R. A. Thomson for many useful discussions and N. St. J. Young and M. P. D. Lewis for assistance in the field.

MS received 7 February 1983; accepted in revised form 21 April 1983

References

Aitkenhead, N. 1975. The geology of the Duse Bay–Larsen Inlet area, north-east Graham Land (with particular reference to the Trinity Peninsula Series). *British Antarctic Survey Scientific Reports*, No. 51, 62 pp.

Andersson, J. G. 1906. On the geology of Graham Land. *Bulletin of the Geological Institute of Upsala*, **7**, 19–71.

Barker, P. F., Dalziel, I. W. D., *and others*. 1976. *Initial reports of the deep sea drilling project*, Volume 36, Washington (U.S. Government Printing Office) 1080 pp.

Bibby, J. S. 1966. The stratigraphy of part of north-east Graham Land and the James Ross Island group. *British Antarctic Survey Scientific Reports*, No. 53, 37 pp.

Bolli, H. M., Ryan, W. B. *and others*. 1978. *Initial reports of the deep sea drilling project*, Volume 40, Washington (U.S. Government Printing Office) 1079 pp.

Ciesielski, P. F., Sliter, W. V., Wind, F. H. *and* Wise, S. W. jr. 1977. A Cretaceous *Islas Orcadas* core from the Falkland (Malvinas) Plateau, southwest Atlantic. *Antarctic Journal of the United States*, **12**, Pt. 4, 65–7.

Crame, J. A. 1982. Late Jurassic inoceramid bivalves from the Antarctic Peninsula and their stratigraphic use. *Palaeontology*, **25**, 555–603.

Dalziel, I. W. D., Caminos, R., Palmer, K. F., Nullo, F. *and* Casanova, R. 1974. South extremity of Andes: Geology of Isla de los Estados, Argentine Tierra del Fuego. *American Association of Petroleum Geologists Bulletin*, **58**, 2502–12.

Demaison, G. J. *and* Moore, G. T. 1980. Anoxic environments and oil source bed genesis. *American Association of Petroleum Geologists Bulletin*, **64**, 1179–209.

Elliot, D. H. 1965. Geology of north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin*, No. 7, 1–24.

Elliot, D. H. 1966. Geology of the Nordenskjöld coast and a comparison with the north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin*, No. 10, 1–43.

Elliot, D. H. 1967. The geology of Joinville Island. *British Antarctic Survey Bulletin*, No. 12, 23–40.

Farquharson, G. W. 1982*a*. Late Mesozoic sedimentation in the northern Antarctic Peninsula and its relationship to the southern Andes. *Journal of the Geological Society, London*, **139**, 721–7.

Farquharson, G. W. 1982*b*. Lacustrine deltas in a Mesozoic alluvial sequence from Camp Hill, Antarctica. *Sedimentology*, **29**, 717–25.

Farquharson, G. W. In press. Evolution of late Mesozoic sedimentary basins in the northern Antarctic Peninsula. (*In* Jago, J. B. *and* Oliver, R. E. *eds. Antarctic Earth sciences.* Cambridge University Press and Australian Academy of Sciences.)

Farquharson, G. W., Hamer, R. D. *and* Ineson, J. R. In press. Proximal volcaniclastic sedimentation in a Cretaceous back-arc basin, northern Antarctic Peninsula. (*In* Kokelaar, B. P., Howells, M. F. *and* Roach, R. A., *eds. Volcanic Processes in Marginal Basins*. Geological Society of London, Special Publication.)

Fleet, M. 1968. The geology of the Oscar II Coast, Graham Land. *British Antarctic Survey Scientific Reports,* No. 59, 46 pp.

Heptonstall, W. B. 1970. Buoyancy control in ammonites. *Lethaia*, **3**, 317–28.

Ineson, J. R. 1982. Cretaceous rocks of James Ross Island and adjacent islands. *British Antarctic Survey Report* G3/1981–82/R. [Unpublished.]

Jenkyns, H. C. 1980. Cretaceous anoxic events: from continents to oceans. *Journal of the Geological Society, London*, **137**, 171–88.

Kanmera, K. 1974. Palaeozoic and Mesozoic geosynclinal volcanism in the Japanese Islands and associated chert sedimentation. (*In* Dott, R. H. *and* Shaver, R. H., *eds. Modern and ancient geosynclinal sedimentation*. Society of Economic Paleontologists and Mineralogists, Special Publication, **19**, 161–73.)

Katz, H. R. 1963. Revision of Cretaceous stratigraphy in Patagonian Cordillera of Ultima Esperanza, Magallanes Province, Chile. *American Association of Petroleum Geologists Bulletin,* **47**, 506–24.

Kennedy, W. J. *and* Cobban, W. A. 1976. Aspects of ammonite biology, biogeography and biostratigraphy. *Special paper in palaeontology* No. 17. The Palaeontological Association, London, 94 pp.

Kling, S. A. 1978. Radiolaria. (*In* Haq, B. U. *and* Boersma, A., *eds. Introduction to marine micropaleontology*. Elsevier, New York, 203–44.)

Ludwig, W. J., Krasheninnikov, V., *and others*. 1980. Tertiary and Cretaceous palaeoenvironments in the southwest Atlantic Ocean: preliminary results of Deep Sea Drilling Project Leg 71. *Geological Society of America Bulletin,* **91**, 655–64.

Macdonald, D. I. M. 1982. Palaeontology and ichnology of the Cumberland Bay Formation, South Georgia. *British Antarctic Survey Bulletin*. No. 57, 1–14.

Meischner, D. 1968. Perniciöse epökie von *Placunopsis* auf *Ceratites*. *Lethaia,* **1**, 156–74.

Pankhurst, R. J. 1982. Rb-Sr geochronology of Graham Land, Antarctica. *Journal of the Geological Society, London,* **139,** 701–11.

Pedersen, G. K. 1981. Anoxic events during sedimentation of a Palaeogene diatomite in Denmark. *Sedimentology,* **28**, 487–504.

Pettigrew, T. H. 1981. The geology of Annenkov Island. *British Antarctic Survey Bulletin*, No. 53, 213–54.

Ramsay, A. T. S. 1973. A history of organic siliceous sediments in oceans. (*In* Hughes N. F. *ed. Organisms and continents through time. Special paper in palaeontology* No. 12. The Palaeontological Association, London, 199–234.)

Raup, D. M. 1973. Depth inferences from vertically imbedded cephalopods. *Lethaia,* **6**, 217–26.

Rex, D. C. 1976. Geochronology in relation to stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin*, No. 43, 49–58.

Riccardi, A. C. 1980. Presencia de epizoos en un amonoideo heteromorfo del Maastrichtiano de Argentina: una inferencia paleoautoecologica. *Ameghiniana,* **57**, 11–14.

Schlanger, S. O. *and* Jenkyns, H. C. 1976. Cretaceous oceanic anoxic events: causes and consequences. *Geologie en Mijnbouw,* **55**, 179–84.

Seilacher, A. 1960. Epizoans as a key to ammonoid ecology. *Journal of Paleontology,* **34**, 183–93.

Simpson, E. W., Schlich, R. *and others*. 1974. *Initial reports of the deep sea drilling project*, Volume 25, Washington (U.S. Government Printing Office) 884 pp.

Smellie, J. L. 1980. The geology of Low Island, South Shetland Islands, and Austin Rocks. *British Antarctic Survey Bulletin*, No. 49, 239–57

Smellie, J. L., Davies, R. E. S. *and* Thomson, M. R. A. 1980. Geology of a Mesozoic intra-arc sequence on Byers Peninsula, Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin*, No. 50, 55–76.

Standring, A. J. 1953. Report on geological work, Hope Bay, 1952–53. Falkland Islands Dependencies Survey bureau No. 107/54. [Unpublished.]

Storey, B. C. In press. The geology of the Ducloz Head area, South Georgia. *British Antarctic Survey Bulletin.*

Storey, B. C. *and* Macdonald, D. I. M. In press. Processes of formation and filling of a Mesozoic back-arc basin on the island of South Georgia. (*In* Koklelaar, B. P., Howells, M. F. *and* Roach, R. A., *eds. Volcanic processes in marginal basins.* Geological Society of London, Special Publication.)

Suárez, M. *and* Pettigrew, T. H. 1976. An upper Mesozoic island-arc–back-arc system in the southern Andes and South Georgia. *Geological Magazine,* **113,** 305–28.

Tanner, P. W. G. 1982. The geologic evolution of South Georgia. (*In* Craddock, C., *ed. Antarctic geoscience.* Madison, University of Wisconsin Press, 167–76.)

Tanner, P. W. G., Storey, B. C. *and* Macdonald, D. I. M. 1981. Geology of an Upper Jurassic–Lower Cretaceous island-arc assemblage in Hauge Reef, the Pickersgill Islands and adjoining areas of South Georgia. *British Antarctic Survey Bulletin*, No. 53, 77–117.

Theide, J. *and* Van Andel, T. H. 1977. The paleoenvironment of anaerobic sediments in the late Mesozoic South Atlantic Ocean. *Earth and Planetary Science Letters,* **33**, 301–9.

Thompson, R. W. 1976. Mesozoic sedimentation on the eastern Falkland Plateau (*In* Barker, P. F., Dalziel, I. W. D. *et al. Initial reports of the deep sea drilling project*, Volume 36. U.S. Government Printing Office, 877–91.)

Thomson, M. R. A. 1982*a*. A comparison of the ammonite faunas of the Antarctic Peninsula and Magallanes Basin. *Journal of the Geological Society, London,* **139**, 763–70.

Thomson, M. R. A. 1982*b*. Mesozoic paleogeography of western Antarctica. (*In* Craddock, C., *e* *Antarctic geoscience.* Madison, University of Wisconsin Press, 331–7.)

Thomson, M. R. A. 1982*c*. Late Jurassic fossils from Low Island, South Shetland Islands. *British Antarctic Survey Bulletin*, No. 56, 25–35.

Thomson, M. R. A. *and* Pankhurst, R. J. In press. Age of post-Gondwanian calc-alkaline volcanism in the Antarctic Peninsula region. (*In* Jago, J. B. *and* Oliver, R. E. *eds. Antarctic earth sciences*. Cambridge University Press and Australian Academy of Sciences.)

Tissot, B., Demaison, G., Masson, P., Delteil, J. R. *and* Combaz, A. 1980. Paleoenvironment and petroleum potential of Middle Cretaceous black shales in Atlantic basins. *American Association of Petroleum Geologists Bulletin,* **64**, 2051–63.

Wiessert, H. 1981. The environment of deposition of black shales in the Early Cretaceous: an ongoing controversy. (*In* Warme, J. E., Douglas, R. E. *and* Winterer, E. L. *eds. The deep sea drilling project: a decade of progress*. Society of Economic Paleontologists and Mineralogists, Special Publication, **32**, 547–60.)

Williams, P. L., Schmidt, D. L., Plummer, C. C. *and* Brown, L. E. 1972. Geology of the Lassiter Coast area, Antarctic Peninsula: preliminary report. (*In* Adie, R. J. *ed. Antarctic geology and geophysics*. Universitetsforlaget, Oslo, 143–8.)

Winn, R. D., jr. 1978. Upper Mesozoic flysch of Tierra del Fuego and South Georgia Island: a sedimentologic approach to lithosphere plate reconstruction. *Geological Society of America Bulletin,* **89**, 533–47.