Reconstructing the Siluro-Devonian coastline of Gondwana: insights from the sedimentology of the Port Stephens Formation, Falkland Islands

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Abstract: Silurian and lower Devonian sedimentary successions are uncommon within the remnants of Gondwana. The Port Stephens Formation, the basal unit of the middle Palaeozoic West Falkland Group, presents a rare opportunity to study Gondwanan material of Siluro-Devonian age. The formation on West Falkland is c. 2560 m thick and consists of five members: Plantation, Albemarle, Mount Alice, South Harbour and Fish Creek. Thirty-five lithofacies are defined using variations in grain size and bedding characteristics. The distribution of these lithofacies and their associated ichnofacies between the various members lead us to suggest terrestrial and shallow marine deposition on an extensive, gently shelving alluvial to coastal plain. Vertical facies trends through the Port Stephens Formation, and into the base of the overlying Fox Bay Formation, record a complex superposition of subenvironments within a distinct overall transgressive–regressive–transgressive pattern, with the bulk of sediment accumulating during the regressive phase. Palaeocurrents indicate a basin to the present-day NE throughout. These results, together with lithostratigraphic correlations between the Port Stephens Formation and the Nardouw Subgroup in South Africa, are consistent with a reconstructed position of eastern South Africa and on the palaeo-Pacific margin of Gondwana, requiring a near-180° rotation of the Falkland Island microplate during break-up, in agreement with previous models. We suggest that global changes in sea level during the mid–late Silurian and early Devonian strongly influenced changes in the depositional environment. Enhanced erosion of the continental margin and extensive sediment bypass during the regressive phase of this cycle could help to explain the low abundance of preserved Gondwanan material of this age.

Keywords: Gondwana, Falkland Islands, Silurian, Devonian, sea level, lithofacies.

Current early Palaeozoic reconstructions of Gondwana place the Falkland Islands off the east coast of South Africa close to Port Elizabeth (Fig. 1). These reconstructions are based on continuity of structural trends from the Gondwanan orogeny (Curtis & Hyam 1998), palaeomagnetic reconstruction (Mitchell et al. 1986) and palaeocurrent data (Hyam 1997; Storey et al. 1999; Trewin et al. 2002), and are supported by the distribution of early Devonian marine faunas of the Malvinokaffric Province (Brashaw 1998).

Combining the distribution of marine fauna with sedimentological evidence, it is possible to distinguish between coastal and terrestrial areas and hence to plot the position of the palaeo-Pacific coastline and the positions of the smaller crustal blocks relative to it (Fig. 2) (Brashaw 1998). Unfortunately, most of the exposed Palaeozoic strata from Gondwana were deformed during the Gondwanan orogeny (latest Permian to early Triassic), thus restricting studies of Palaeozoic depositional environments along the suggested palaeo-Pacific margin. However, the sedimentary Port Stephens Formation, West Falkland Group, Falkland Islands is a thick, well-exposed and relatively undeformed Silurian-Devonian succession. In this paper, we report the first sedimentological study of this formation. A combined study of lithofacies and ichnology has been used to substantially increase confidence in the palaeoenvironmental interpretations presented and is used to suggest a depositional model for this part of the

Fig. 1. Pre-180 Ma reconstruction for the Falkland Islands off SE Africa. The islands have been rotated by 180° (from Curtis & Hyam 1998).
palaeo-Pacific margin. These results are further used to assess the reconstructed position of the Falkland Islands within Gondwana.

Stratigraphy

The Palaeozoic rocks of the Falkland Islands are divided into two groups (Baker 1924; Borrello 1963, 1972; Greenway 1972; Aldiss & Edwards 1999). The lower of the two groups, the Gran Malvina Group (Borrello 1963, 1972) or West Falkland Group (Aldiss & Edwards 1999), lies unconformably over Mesoproterozoic basement and is capped unconformably by Lower Permian glacial deposits of the overlying Lafonia Group (Aldiss & Edwards 1999). The West Falkland Group is about 5 km thick and consists of the Port Stephens, Fox Bay, Philomel and Port Stanley formations (Baker 1924; redefined by Aldiss & Edwards 1999) (Fig. 3a). Recent regional geological mapping (Aldiss & Edwards 1998) has divided the Port Stephens Formation into six members (Fig. 3b) on the basis of topographic expression and large-scale changes in lithofacies and trace fossil content. This study describes the five members of this formation exposed in West Falkland, and demonstrates a total composite thickness for the Port Stephens Formation in West Falkland of c. 2560 m.

There are no clear age constraints on the base of the Port Stephens Formation but in the southern part of West Falkland the basal unconformity truncates a mafic dyke with a minimum K–Ar whole-rock age of 422 ± 39 Ma (Thistlewood et al. 1997). The overlying Fox Bay Formation contains late Emsian (Early Devonian) Malvinokaffric fauna palynomorphs at its base (Marshall 1994). On West Falkland, the basal contact of the Port Stephens Formation is planar but marked locally by a conglomeratic unit, lying unconformably in shallow hollows on the mature palaeo-surface of the 1.1 Ga Cape Meredith Complex (Jacobs et al. 1999) (Fig. 4a). The gneissic rocks of the Cape Meredith Complex are characterized by a strong foliation, which developed before deposition of the overlying sedimentary units. Red mudstone and siltstone interbedded with poorly sorted, angular coarse sandstone to granule grade conglomerate (Plantation Member) pass upwards into trough cross-bedded sandstone rich in Skolithos burrows (Albemarle Member). These shallow marine sandstones are overlain by coarser, more poorly sorted sandstones (Mount Alice Member) with a low-diversity ichnofauna. Above this, a thick succession of palaeontologically barren sandstones (South Harbour Member) grades into muddier, finer-grained sandstones with rare plant debris at the top of the formation (Fish Creek Member).

The basal contact of the Port Stephens Formation is not exposed on East Falkland and there is no outcrop of the Plantation Member. Instead, a sandstone-dominated unit (defined as the Limpet Creek Member by Aldiss & Edwards 1999), is purported to underlie the Albemarle Member at the base of the formation (Aldiss & Edwards 1999). However, the relationship of this sandstone succession to the Port Stephens Formation is unclear, and we prefer to include these sandstones in the basal part of the Albemarle Member (see below).

Field work

The Port Stephens Formation crops out extensively in the southern part of West Falkland (Port Stephens area), the Hornby Mountain range (east coast, West Falkland) and the northern parts of West and East Falkland (Fig. 5). The study concentrated on outcrop in the Port Stephens area, where the Port Stephens Formation is exposed from its basal contact through to the upper contact with the Fox Bay Formation. There is a decrease in the intensity of the effects of Perno-Triassic deformation to the south and west across the islands (Curtis & Hyam 1998). Rocks cropping out in the Port Stephens area are relatively undeformed with a shallow angle of dip (on average only 4–10°), and low vitrinite reflectance (Hyam 1997).

In coastal areas and river estuaries exposure is good. However, high cliffs make access to the base of sections difficult and dangerous to log, and the low angle of dip minimizes the practicality of logging smaller cliffs. Inland exposure is minimal and where material is exposed, thick lichen growth and heavy weathering prevent determination of the large-scale, 3D architecture of sandstone bodies. Joints and faults in the Port Stephens
area are common, the latter offset strata by 10 m and commonly more. Several kilometres of section were measured and logged at a metre scale. Graphic logs for these sections can be obtained from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK as Supplementary Publication No. SUP 18183 (5 pages). It is also available online at http://www.geolsoc.org.uk/SUP18183.

To investigate large-scale lateral variation, data were also collected from White Rock Bay and Settlement Rocks in the northern parts of the islands (Fig. 5). Both these localities have been subjected to relatively intense deformation, resulting in almost vertical dips and pervasive shear surfaces. Finer-grained, less competent units show a strong structural overprint that hinders detailed sedimentological work, and stratal thicknesses may have been significantly affected by compressive strain. Deformation intensity is somewhat lower at White Rock Bay, where the coastal exposures display clear sedimentary features and the measured sections correlate well with the Port Stephens area. In contrast, extensive shearing and intense inland weathering at Settlement Rocks have destroyed many of the sedimentary features.

Palaeoflow data were determined from 3D orientation of trough and tabular cross bedding and, where necessary, were corrected for folding.

**Determination and interpretation of lithofacies**

The Port Stephens Formation has been divided into 35 primary lithofacies (Table 1) based purely on sedimentary structures and grain size. Marked and subtle changes in the distribution of these lithofacies between the five members of the Port Stephens Formation are illustrated using a 3D graphical approach (Fig. 6 and summarized in Table 2). The following sections describe the lithofacies present in each member and, drawing on differences in compositional maturity and ichnology, discuss likely depositional processes and palaeo-environmental settings.

**Plantation Member: description**

The Plantation Member is exposed in the south of West Falkland in the Cape Meredith region (Fig. 5), unconformably overlying the mid-Proterozoic Cape Meredith Complex (Fig. 4a). The member has an average thickness of 12 m, but shows high lateral variability and is locally absent. The upper boundary is arbitrarily taken to be the point above which mudstone is absent and is discernible by an upward colour change from purple to yellow in the coarser-grained beds.

The basal unconformity surface is marked by a thin bed of poorly sorted, coarse to very coarse sandstone with scattered granules. In places a cobble conglomerate lies in palaeo-hollows up to 1 m deep (Fig. 4a). The conglomerate is composed of well-rounded cobbles, clast-supported in a friable, poorly sorted, angular, coarse sandstone to granule grade matrix of quartz, biotite and alkali feldspar. The cobbles are dominated by pink quartzite, red sandstone and vein quartz, with minor granite clasts near the contact and rare green (meta-igneous?) clasts. Large angular, alkali feldspar clasts, derived from granitoid rocks in the underlying Cape Meredith Complex, are locally abundant.

The upper part of the member consists of plane-bedded, red, sandy mudstone (green where reduced), purple–grey granule grade to small-pebble conglomerate and minor, maroon fine-grained sandstone. Contacts between beds are distinct, and coarser-grained beds
contain clasts of the mudstone. These coarser-grained beds are laterally discontinuous, forming long thin lenses (several tens of metres in length) within the siltstone. The average bed thickness is 0.4 m, but ranges from 0.2 to 0.5 m. Both the coarser- and finer-grained beds are internally structureless, although faint cross bedding is evident in coarser beds close to the contact with the Albemarle Member. Desiccation cracks were observed in mudstone in the middle of the section. Very coarse sandstone about 9 m above the unconformity contains some simple, vertical burrows (\textit{Skolithos} Haldeman 1840), about 2 mm across.

**Plantation Member: interpretation**

The basal cobble conglomerate seems to have been partly sourced from an area lithologically similar to the underlying Cape Meredith Complex (Thomas et al. 1997). Reddened arenaceous clasts record terrestrial reworking of earlier clastic successions. The rounding of the cobbles probably records some fluvial transport but the combination of poor sorting, mixed mud–sand matrix, rounded cobbles and angular feldspar clasts suggests eventual deposition by debris flows. Structureless siltstone with
dispersed sand or granule grains higher in the Plantation Member could also be interpreted as debris flow deposits. In contrast, the interbedded lenticular sandstones and conglomerates show internal organization and evidence of erosion (mudstone clasts), and probably record streamflow processes.

Complete drying out of exposed muddy sediment is recorded by desiccation cracks, and the general red coloration of the Plantation Member suggests that early diagenesis took place in a strongly oxidizing environment. However, the presence of Skolithos burrows in the upper 2–3 m of the member testifies to the presence of persistent bodies of water, although relatively isolated Skolithos, as seen here, are not diagnostic of a specific palaeo-environment. For the Plantation Member as a whole, we can envisage a combination of ephemeral streamflow and debris flow processes on a relatively low-gradient alluvial fan system passing laterally into a body of shallow water with some connection to the sea (to allow partial colonization by Skolithos-producing organisms) (Fig. 7a).

Albemarle Member: description

The Albemarle Member is c. 800 m thick. The lower and upper contacts are conformable and gradational, except where the Plantation Member is absent and the Albemarle Member rests unconformably on the Cape Meredith Complex (Aldiss & Edwards 1999); elsewhere the base of the member is defined at the level above which red mudstone becomes absent and cross-bedding becomes prevalent. The Albemarle Member is dominated by moderately to well-sorted, red sandstone, which is mainly fine to coarse grained with dispersed granules and small to medium pebbles. Some grains have a well-rounded, spherical or ‘millet seed’ texture (Aldiss & Edwards 1999). In thin section, the sandstone is dominated by rounded quartz grains. Individual grains or small grain clusters have a thin red hematitic coating. The main accessory components are feldspar (mainly microcline), quartz-rich lithic pebbles conglomerate also forms flat-lying beds at the top of some cross-bed sets. There is little mudstone in the system, mainly present as mudstone flakes in the conglomeratic beds at the base of cross-bed sets. The mudstone is blue–grey, in contrast to the deep red of the Plantation Member, although in places it weathers to dark red iron oxide. The abundance of mudstone flakes increases up section.

The dominant sedimentary structure throughout the member is trough cross bedding (Fig. 4b), with minor tabular cross-bed sets towards the top. Foreset azimuths and trough axes indicate palaeoflow dominantly to the north or NE (Fig. 8), with minor bidirectional palaeocurrent distributions in places (see Cingolani & Varela 1976: NNW and ENE). Possible herringbone cross bedding has also been reported (Aldiss & Edwards 1999). Desiccated surfaces are present near the top of the section. Near the base of the member, poorly sorted, coarser-grained (average very coarse sandstone to granule conglomerate) cross-bed sets are 0.7–0.8 m thick. Up section, grain size decreases to fine- and medium-grained sandstone, sorting and maturity of the material increases, and cross-bed sets reduce to 0.4–0.6 m in thickness. Individual beds in cross-sets are evident from changes in grain size and vary from one clast thick (medium-pebble conglomerate lags) to c. 10 cm (fine sandstone). Thoroughgoing master or bounding surfaces occur every 2–3 m. These are generally erosive and are commonly marked by pervasive bioturbation (Fig. 4b).

Much of the Albemarle Member is highly bioturbated and the trace fossils can be grouped into two ichno-assemblages: a more abundant assemblage of Skolithos with minor Rhizocorallium-Zenker 1836, and a second consisting of Heimdallia Bradshaw 1981, Diplocraterion Torell 1870 and Didymaulichnus Young 1972. Closely spaced Skolithos burrows are by far the most distinctive and abundant form of bioturbation in the member (Fig. 9a). The burrows chiefly occur in poorly to moderately sorted, fine to medium sandstone, although they also appear in coarser material low in the section. They begin at the top of trough cross-bed sets and largely or wholly obscure the sedimentary structures. The Skolithos burrows are vertical, apart from a thin bed (2–20 m thick) just below the contact with the Mount Alice Member where burrows are inclined at an angle of up to 45° (see below). Rare, isolated burrows similar to Rhizocorallium irregulare Mayer 1952 are found in medium to coarse sandstone associated with Skolithos.

The second ichno-assemblage is commonly found in structureless to plane-bedded sandstone sheets and comprises Diplocraterion parallellum Torell 1870 together with a problematic sheeted trace (Heimdallia) and, in a few places, with traces very similar to Didymaulichnus lyelli Rouault 1850 (cf. D. lyelli Trewin & McNamara 1994, fig. 15). This latter trace is preserved as straight to gently curved epichnial grooves, which are locally very abundant on discrete bedding surfaces and commonly cross-cut each other.

The unwalled, vertical sheets possibly referable to Heimdallia occur in discrete horizons of structureless to plane-bedded, medium to coarse sandstone near the base of the member. These sheets are 1.5–4 cm wide, varying in length from 40 cm to the
scale of the outcrop (several metres) and in depth from 10 to 50 cm (Fig. 9b). These horizons are commonly associated with thick cross-bed sets of granule and pebble-rich sandstone. The sheets are bioturbated to a median furrow, visible in both vertical and horizontal sections, and form straight to gently curved, cross-cutting traces. It is not easy to reconcile vertically and horizontally bioturbated sheets with any normal mode of organism activity and it is possible that inorganic processes may have modified the structure. Curved, horizontal spreite a few millimetres apart are visible in a few specimens (Aldiss & Edwards 1999) and these have been interpreted by Buckman (1996) as a result of backfilling or passive infilling of the burrow after the constructor had withdrawn. 

Sheeted traces with curved spreite have been described as Heimdallia from mid-Palaeozoic coarse sandstone units in the Beacon Supergroup (Antarctica; Bradshaw 1981) and the Tumblogooda Sandstone (Australia; Trewin & McNamara 1994). Aldiss & Edwards (1999) have suggested that the Falkland trace may also be a species of Heimdallia but differences between the samples already described (Bradshaw 1981; Trewin & McNamara 1994) and the traces found in the Albemarle Member are significant enough to cast doubt on this assignment, and the traces require further study.

In East Falkland, the Albemarle Member is significantly thicker (over 1000 m thick) and Aldiss & Edwards (1999) suggested that it is underlain by a sixth member, the Limpet Creek Member. This member has been described from one locality on East Falkland (the Limpet Creek tidal inlet) and comprises fine-grained, plane-bedded sandstone, with minor trough and tabular cross-bedding and sedimentary structures suggestive of vigorous flow regimes (Aldiss & Edwards 1999). However, no contact is seen with the nearby Albemarle Member and the outcrop is bounded on one side by faulting. The Limpet Creek Member lacks body fossils and distinctive trace fossils, and it has been suggested that it may even be part of the overlying Fox Bay Formation (Aldiss & Edwards 1999). Combined with its structural setting, the lack of diagnostic fossils makes it difficult to define the relationship between the Limpet Creek Member and the rest of the Port Stephens Formation. However, there is no evidence for the large-scale faulting required to juxtapose the Fox Bay Formation with the Albemarle Member. Fine-grained, well-sorted, unbioturbated sandstone units are common within the Albemarle Member. For this reason, the Limpet Creek Member is considered to represent a particularly thick (up to 800 m; Aldiss & Edwards 1999) section of non-bioturbated Albemarle Member in the lower part of the East Falkland sequence.

**Albemarle Member: interpretation**

Continued sediment supply from a dominantly felsic source area (continental interior) is evident from the quartz-rich petrology. Millet-seed sand grains indicate a contribution of sediment that has experienced wind transport, although unequivocal aeolian sedimentary structures are not seen in the Albemarle Member.

![Fig. 6. Graphical summary of lithofacies present in each member. The graphs show the percentage of each lithofacies within a member based on bed thickness relative to the total measured thickness of the member. To show lateral variation, the lithofacies distributions are considered separately for localities to the NE (White Rock Bay, Port San Carlos) and the SW (Port Stephens, East Bay, Port North, Fox Bay, East Head). (See Fig. 5 for localities.) More detailed logs are available as a Supplementary Publication (see p. 461).](image-url)
Fig. 7. Sketches of the various depositional environments from the Port Stephens Formation. Summary in Table 2. (a) Rapid debris flow and ephemeral stream deposition from alluvial fans onto a coastal plain; Plantation Member. (b) Intertidal, foreshore to upper shoreface; Skolithos and trough cross bedding; Albemarle Member. (c) Coastal fluvial braidplain, possibly limited tidal flat development; Mount Alice Member. (d) Braided river system; South Harbour Member. (e) River plain with stable channels; plants become established on the flood plain; Fish Creek Member. (f) Deposition of shallow marine, offshore facies following marine transgression; Fox Bay Formation.
itself. The ichno-assemblages are consistent with marine, intertidal, foreshore to upper shoreface settings (Fig. 7b). The curious inclined *Skolithos* burrows have been attributed to later deformation (at Settlement rocks; Aldiss & Edwards 1999) but, as they appear in undeformed rocks at several other localities, the inclination is perhaps more likely to be a change in animal habit in response to different flow conditions. The general abundance of *Skolithos* as dense colonies, a positive indicator of littoral marine conditions (Bradshaw 1981; Frey & Pemberton 1984), from base to top of the member indicates marine deposition throughout, but a strongly oxidizing early diagenetic environment is suggested by the hematite cements. Hence, a high-energy clastic coastal setting is interpreted for the deposition of most of the Albemarle Member (Fig. 7b). In view of this, the thick sections of well-sorted, trough cross-bedded coarse sandstone record migration of large, 3D dunes under strong but fluctuating currents in upper shoreface settings. Unbioturbated plane-bedded to cross-bedded sandstones may record swash zone deposition, whereas finer-grained, heavily bioturbated, laminated intervals could represent more episodic reworking lower on the shoreface. Bioturbation was most likely during breaks in sedimentation, leaving bounding surfaces intact (see Bradshaw 1981; Hallam & Swett 1966). Tidal processes may be recorded locally by bimodal palaeocurrent indicators and possible herringbone cross bedding.

In detail, a large number of subenvironments are represented in this thick succession but the overall motif is a transgressive trend of upward decreasing grain sizes, decreasing bed thicknesses and increasing sediment maturity; hence, progressively increasing distality to the main sediment source areas. The greater thickness of the Albemarle Member in East Falkland and the high proportion of fine-grained, unbioturbated sandstone near the base, are consistent with a basin deepening to the NE.

**Mount Alice Member: description**

The Mount Alice Member is c. 800 m thick. The basal contact is defined by the disappearance of abundant *Skolithos* and the reappearance of granule and small to medium pebble conglomerate beds within cross-sets. The top of the member is gradational with the overlying, palaeontologically and ichnologically barren, South Harbour Member. In contrast to the reddish sandstones of the underlying Albemarle Member, Mount Alice lithologies are predominantly cream, white and grey in colour, although with some orange sandstones in the upper parts. The member is dominated by poorly sorted, cross-bedded sandstone with granule and small to medium pebble conglomerate and many mudstone clasts. The rocks are quartz rich and extremely well cemented, composed of densely packed, subangular to subrounded, non-spherical grains. The quartz grains are largely unstrained (monocrystalline), but minor ribboned quartz, characteristic of highly deformed terrains, is found as a significant detrital phase only in this member. Subsidiary detrital phases include sandstone lithic grains, sphenite, biotite, zircon and minor white mica. Heavy mineral assemblages from the Mount Alice Member are comparable with those from the Albemarle Member (Knox & Aldiss 1999). Rare, small grains of microcline were observed from...
finer-grained sandstones just above the contact with the Albemarle Member, but the coarser lithologies that dominate the member contain no feldspar. Consistent with this petrological maturity, preliminary geochemical analyses of the finer-grained Mount Alice Member lithologies indicate high values for the chemical index of alteration (CIA; Nesbitt & Young 1982) compared with typical shale analyses around the world and the rest of the Port Stephens Formation.

In the basal parts of the member, trough cross bedding is dominant, with minor tabular forms. Cross-sets are 50–70 cm thick, separated by 5–20 cm thick, discontinuous, moderately to well-sorted, claystone to siltstone or fine-grained sandstone. These discontinuous beds are plane-bedded, structureless to finely laminated, and in some cases have small-scale trough cross bedding (10–20 cm). Rare desiccation cracks and mud-draped ripples in siltstone are found in association with vertical burrows (?Skolithos). Thin pebble horizons, ranging from 5 to 30 mm thick, are concentrated at the bases of cross-bed sets. Isolated, well-rounded, medium pebble clasts are prevalent within cross-bed sets and locally abundant in granule grade conglomerate or coarse-grained horizons that are up to 50 cm thick. Minor channel structures, with widths of 2–10 m and depths of 0.5–1.5 m, are locally prominent.

Higher parts of the member are generally coarser grained, more poorly sorted and dominated by larger-scale cross-beds, ranging from medium-grained sandstone to granule conglomerate, including thin pebble lags. Trough cross-bed sets are 0.5–1.5 m thick with tangential bases and sharply truncated tops. Less abundant are tabular cross-bed sets which average a metre thick, have sharp contacts at both base and top, and in some cases, have erosive bases (Fig. 10). The sets group into planar cosets, 2–3 m thick, which from a distance give the appearance of plane-bedded sandstone. Discontinuous beds between cross-sets are composed of fine- to medium-grained sandstone with minor mudstone. Erosive-based channel fills are common amongst the trough cross-bedded horizons and cut through the finer-grained deposits. Widespread mudstone flakes and clasts are concentrated towards the bases of cosets. The upper part of the member divides into two large-scale fining-up successions. Coarse-grained, tabular cross-bedded units at the base fine into medium- to coarse-grained, trough cross-bedded sandstone. The first succession ends with 15 m of plane-bedded, fine sandstone, and is truncated by the erosive base of the second succession (Fig. 10). Palaeocurrents are to the NE throughout the member (Fig. 8).

Trace fossils are concentrated towards the base of the member, where preferential cementation of the bioturbation has resulted in prominent erosion-resistant horizons (Fig. 11a). Meandering to gently sinuous epichnial trails assignable to Taphrehelminthopsis Sacco 1888, are developed throughout the member (Fig. 11b). They appear in all grain sizes, primarily on the foresets of trough and tabular cross-bed sets, yet are also found on the surfaces of plane-bedded and structureless sandstones and in clay-rich siltstones.

Plane-bedded, fine-grained sandstone beds interbedded with heavily bioturbated sheets characterize the lower part of the Mount Alice Member (Fig. 11a) and include preferentially cemented, sheeted ?Heimdallia burrows similar to, but smaller (<1 cm wide) than those described from the Albemarle Member. These sheeted traces are closely associated with concave ellipsoidal hollows of similar size on the bedding surfaces and these hollows may be resting traces of the small arthropods responsible for the bioturbation above and below. Other, larger, crescent-

![Fig. 9](image-url)

**Fig. 9.** Trace fossils from the Albemarle Member (for localities see Fig. 5). (a) Locally abundant Skolithos, Dean River estuary, Port Stephens. (b) Horizontal section of ?Heimdallia, Cape Meredith.

![Fig. 10](image-url)

**Fig. 10.** Tabular cross-bedded, granule- and pebble-rich, very coarse-grained sandstone deposited over plane-bedded fine-grained sandstone. The contact is erosive reflecting the high energy of deposition. Mount Alice Member, Carew Harbour, Port Stephens.
shaped, epichnial hollows with lobate indentations in the lower Mount Alice Member are tentatively assigned to a small form of ?Selenichnites (see Romano & Whyte 1990) but equally they could also be resting traces.

Diplocraterion parallelum reappears at the base of the Mount Alice Member in plane-bedded, well-sorted, fine-grained sandstone boundary layers between cosets, forming dense colonies. Smaller forms of Diplocraterion are closely associated with gently curved horizontal meniscate burrows up to 15 cm long and about 2 mm wide, assigned to Beaconites coronus Keighley & Pickerill 1994. This is the first recorded example of this trace from the Siluro-Devonian. In the coarse-grained cross-bedded lithologies, cross-cutting sinuous, endichnial grooves, referable to ?Didymaulyponomos Bradshaw 1981, are numerous at the base of the member and gradually decrease in abundance up section. The grooves are generally 5–7 mm wide (up to 15 mm), and are filled with finer-grained material, ranging from mud grade to fine-grained sandstone. Coarse sandstone towards the base of the member also includes simple, branching, irregularly meandering endichnial burrows cautiously designated as a type of ?Helminthopsis.

Very fine to coarse sandstone horizons show isolated vertical burrows throughout the basal 100 m of the Mount Alice Member. In coarser-grained horizons, the vertical burrows post-date the endichnial grooves (?Didymaulyponomos). The burrows are randomly distributed and form thinly populated colonies. Some are associated with desiccation cracks. Larger vertical burrows (?Skolithos), 20–30 cm long, form crowded colonies associated with flaser bedding (Lake Ellen; Fig. 5).

Mount Alice Member: interpretation

The Mount Alice Member as a whole records a transition from the trace-fossil-rich, high-energy coastal associations of the Albemarle Member to the ichnologically barren, fluvial association of the South Harbour Member (see below). In detail, this transition involved a complex succession of depositional sub-environments but the overall trend is one of increasing fluvial influence, with decreasing preservation of fine-grained material and reduction in ichnofaunal abundance. The mix of angular and well-rounded grains in the Mount Alice Member may reflect the mixing of fluvial input with marine-derived sediment supplied by coastal processes (Fig. 7c).

In the basal part of the Mount Alice Member, small channel-fills of trough cross-bedded sandstone with mudclasts are associated with bioturbated fine-grained intervals with mud-draped ripple forms, flaser bedding and desiccation cracks. This association implies strongly fluctuating flow rates and water coverage, and is most readily interpreted in terms of tidal channels and associated tidal flats on a somewhat muddy but sand-dominated siliciclastic shoreline, perhaps interdigiting with a low-gradient alluvial system. The disappearance of Skolithos as the main form of bioturbation at the top of the Albemarle Member marks the end of high-energy deposition and reworking of relatively clean sands. In contrast, the main bioturbators at the base of the Mount Alice Member were arthropods, producing Diplocraterion, ?Didymaulyponomos, ?Heimdallia and rare arthropod resting traces and trackways. The high trace fossil abundance but low diversity in the heavily bioturbated horizons points to a relatively restricted or stressed environment. These traces and the small vertical burrows represent typical slack-water organism activity in semi-consolidated, intertidal to supratidal sediment (see Frey & Seilacher 1980).

The higher parts of the member are dominated by thick amalgamated coarse-grained successions dominated by unidirectional trough cross bedding, which are readily interpreted in terms of a sandy bedload river system. The exposed sections are referable to channel sandbodies; any associated finer-grained overbank systems are unexposed and exposure limitations preclude assessment of the overall sandbody geometries. The abundance of erosive features and lack of preservation of
argillaceous lithologies (largely restricted to mudclasts) implies high lateral channel mobility. The complex hierarchies of scour-based cross-sets record the migration of different scales of 3D dunes. Minor fining-upward packages may relate to the migration of macroforms whereas the large-scale (80–100 m) fining-up successions at Carew Harbour (Fig. 5) record reorganization of the channel system in response to climatic, tectonic or base-level change.

South Harbour Member: description

The South Harbour Member is c. 600 m thick (Aldiss & Edwards 1999). The base is gradational from the Mount Alice Member and marked by the disappearance of bioturbation and an increase in average grain size. The top passes conformably into the Fish Creek Member (Aldiss & Edwards 1999). The South Harbour Member is dominated by buff, white and grey poorly sorted, coarse sandstone to medium pebble conglomerate in mixed trough and coarser-grained tabular cross-beds. Small and medium pebbles are abundant in scours at the base of units and also within cross-bed sets. The sediment is dominantly composed of poorly sorted, non-spherical, angular to sub-angular quartz grains. Feldspar forms a minor constituent (<10%) and is mainly alkali or albitic, although prevalent clay patches suggest that feldspar was once more common. Trace amounts of quartz-rich lithic grains, zircon, apatite, large mica flakes and possible epidote are also present.

Cross-bed sets range from 0.5 to 1.5 m thick. These are grouped into planar cosets 2–3 m thick and separated by discontinuous, finely laminated, mudstone to fine-grained sandstone beds up to 50 cm thick, that grade from the underlying coarser material. The bases of the overlying cross-bed sets are commonly erosional and rich in mudstone clasts. The relative proportion of tabular to trough cross bedding is greater in the South Harbour Member than in the Mount Alice Member. Erosive channel forms about 1–2 m deep and 2–6 m wide are common. Mudstone clasts and clasts are more abundant than in the underlying members. Palaeocurrent measurements indicate flow directions varying between north and east (Fig. 8; Aldiss & Edwards 1999).

South Harbour Member: interpretation

The South Harbour Member is generally coarser grained and more texturally immature than the Mount Alice Member, suggesting that it was more proximal to the source area or that the depositional gradients were higher. The reappearance of feldspar in the detritus is also compatible with reduced transport distances (but may also indicate erosion of a less mature source area). A significant change in provenance is consistent with observed differences in the heavy mineral assemblages of the Mount Alice and South Harbour members (Knox & Aldiss 1999). The data indicate a greater affinity between the South Harbour Member and the succeeding units, whereas the assemblages from the Mount Alice Member are similar to those preceding it (i.e. the Albemarle Member). The association of lithofacies, unidirectional palaeocurrents and lack of trace and body fossils within the South Harbour Member are consistent with deposition in a large-scale, low-sinuosity fluvial system, with broad shallow channels (Fig. 7d). Trough cross-sets record the in-channel migration of 3D sandy dunes. Coarse-grained tabular cross-beds are typical of macroformal gravel bars and the common preservation of these tabular bar forms implies high net aggradation rates. Preservation of finer-grained overbank or slack-water deposits is patchy, and much of the mudstone in the system occurs as dispersed intraclasts. Overall, the South Harbour Member represents regression and fluvial progradation out over the coastal depositional systems of the Mount Alice Member (Fig. 7d).

Fish Creek Member: description

The Fish Creek Member averages 350 m thick. The member grades up from the South Harbour Member (Aldiss & Edwards 1999) and into the overlying Fox Bay Formation. The base of the Fox Bay Formation is placed at the first bioturbated horizon (see Aldiss & Edwards 1999), accompanied by a change in the colour of sandstone from orange or creamy white to yellow–brown, rich in brown or black mudstone flakes. Throughout the Falkland Islands the Fish Creek Member is marked by the reappearance of abundant feldspar in the quartz-rich sandstone. Feldspar is dominated by microcline, but plagioclase and perthitic feldspar are also present. The Fish Creek Member differs in sedimentary character between West and East Falkland.

On West Falkland, the Fish Creek Member is more mud rich and finer grained than the Mount Alice and South Harbour members. Sorting in the sandstone is moderate to poor, with coarser grain sizes being less well sorted. The mineralogy is dominated by subrounded quartz and feldspar grains of low to moderate sphericity, coated by sericite. Clay patches, interstitial clay and pockets of carbonate suggest a moderate level of alteration. Minor phases include biotite, sphene, zircon, apatite, epidote and tourmaline. Trough cross bedding in fine to coarse sandstone dominates, ranging in thickness from 0.3 to 1.5 m (Fig. 12) with consistent ENE palaeoflow directions (Fig. 8). Tabular cross-bedded units, 1–2 m thick, are constructed from

Fig. 12. Trough cross bedding in the Fish Creek Member, Port North. Hammer (40 cm) for scale.
coarse to very coarse sandstone beds, 5–10 cm thick. Medium to large pebbles, generally well rounded and 4–20 mm in size, are scattered throughout. Cross-bed sets are separated by plane-laminated fine sandstone, siltstone and black mudstone, commonly continuous on the scale of the outcrop and up to 70 cm thick. Flaser bedding and current ripples in these horizons are more abundant higher in the succession. Mudstones are commonly black or brown compared with blue–grey in the lower parts of the formation. Small upward-fining successions, 1–1.5 m thick, are common. Cross-bed sets grade up into plane-bedded, fine sandstone, then grade into siltstone or fine sandstone tops. Isolated coarse-grained channel fills (0.2–0.6 m thick) with pebbly bases and mudstone flakes are evident towards the base of the member. Average grain size decreases and sorting improves up section, concomitant with the increased proportion of fine-grained facies. Mudstone with plant debris crops out close to the contact with the Fox Bay Formation. The plants are preserved as thin black streaks or rectangles, straight or slightly curved, 2–4 mm wide and up to 25 mm long. Some specimens show branching or fine linear ornament (Aldiss & Edwards 1999).

In East Falkland the Fish Creek Member is finer grained and better sorted than its West Falkland counterpart. The constituent mineralogy is the same. The lower part of the section consists of cross-bedded, fine to medium sandstone, with scattered coarse-to very coarse-grained particles. Strong deformation has shattered quartz-rich lithologies and obscured the style of cross bedding. Cross-bed sets are up to 0.6 m thick and fine into finely laminated mudstone horizons, 0.05–0.6 m thick, and structureless black mudstone beds up to 0.4 m thick.

**Fish Creek Member: interpretation**

The unfossiliferous, unbioturbated facies of the Fish Creek Member are consistent with deposition in a low-energy fluvial system, largely as unchannelized overbank deposits (Fig. 7e). Overall fining of the lithofacies towards the north and east, together with consistent NE palaeoflow directions (Fig. 8), suggests a basin deepening (and perhaps widening) to the present-day north and east (Fig. 13). The relatively pale colour of the sandstones and increased preservation of organic matter reflect poor drainage and high water table, presumably on a low-gradient lowland plain. Increased deposition of fines encouraged the establishment of plants on the floodplain, which stabilized channel banks and hence in turn encouraged preservation of the overbank deposits. The small, sharp-based graded sandstone beds and upward-fining sandstone packages represent relatively catastrophic sheet flood or channel crevassing events. Flaser bedding and mud-draped current ripples at the top of the member record marked short-term fluctuations in current strength and are suggestive of a tidal influence. This may represent the earliest onset of marine inundation of the alluvial plain, supported by the subsequent appearance of simple burrows as the marine incursion progressed, preceding establishment of full shallow marine conditions (Fox Bay Formation; Fig. 7f; see Marshall 1994). The transition to fully marine Fox Bay Formation (Fig. 7f) is marked by a flooding surface as a consequence of a rapid rise in sea level during the Emsian (Marshall 1994). However, although the base of the Fox Bay Formation is taken at the first bioturbated horizon, the onset of bioturbated offshore mudstones, which are more typical of the Fox Bay Formation, appears lower in sections measured in the NE when compared with those in the SW. For example, simple, vertical, mudstone-filled burrows present at the base of the Fox Bay Formation at East Bay appear 110 m below the start of fully offshore shallow marine deposits (Fig. 5). This diachronity in the marine transgression concurs with the inferred deepening of the basin to the NE (see above).

Field work in the remainder of the West Falkland Group and work by Hyam et al. (2000) have shown that the Fox Bay Formation has similar alternations of sandstone–shale packages on both East and West Falkland, but that the West Falkland succession is much sandier (c. 85% compared with c. 40%). These apparent proximal–distal trends, together with palaeocurrent data (Storey et al. 1999), are consistent with basin deepening towards the present-day east or NE. Similar trends in younger formations may imply the persistence of this configuration through the Devonian.

**Discussion**

The sedimentological results presented above lead us to propose that the Port Stephens Formation was deposited on a large, long-lived, alluvial to coastal plain supplied by a mature continental basement source and experiencing gentle long-term subsidence, probably on the rifted arm of a passive margin or continental terrace. Transport of sediment was consistently towards the
present-day north and east (Fig. 13). The palaeoenvironmental record of the Port Stephens Formation further allows us to evaluate constraints on the Silurian–Devonian position of the Falkland Islands microplate relative to the Gondwanan palaeo-Pacific margin.

Initial subsidence was marked by accumulation of relatively immature alluvial fan and associated deposits in localized piedmont depocentres (Plantation Member). Subsequent widespread shallow marine deposition (Albemarle Member) records rapid creation of accommodation space relative to sediment supply and consequent transgression. In contrast, the overlying members (Mount Alice and South Harbour members) record an overall regressive trend of increasing fluviatile influence and development of a large low-sinuosity fluvial channel system. The eventual establishment of a vegetated lowland floodplain system (Fish Creek Member) with marine influence may record increased rates of accommodation space creation relative to sediment supply. This culminated in regional transgression in the Emsian (late Early Devonian), which led to the establishment of the fully marine depositional systems of the Fox Bay Formation.

Silurian–Devonian position of the Falkland Islands and comparison with South Africa

Deposition of the Port Stephens Formation along a maritime margin to the present-day NE concurs with the palaeogeographical position predicted by reconstruction models based on palaeomagnetism, structural trends and palaeontology (see Fig. 2; Bradshaw 1998), which suggest that the Falkland Islands crustal block should be reconstructed to a position off the east coast of South Africa, marginal to the palaeo-Pacific margin. Coeval deposition in southern South Africa is represented by the Nardouw Subgroup (upper part of the Table Mountain Group, Cape Supergroup). Hence the depositional environments represented by the sedimentary facies of the Nardouw Subgroup should be a lateral continuation of those interpreted for the Port Stephens Formation if the reconstruction model is correct.

The Nardouw Subgroup was deposited during the Silurian and Early Devonian (Cocks et al. 1970; Cooper 1986). With a thickness of 500–1100 m (Fig. 14; Broquet 1992), the subgroup is significantly thinner than the Port Stephens Formation (c. 2500 m). Although detailed facies analysis of the Nardouw Subgroup is lacking (Broquet 1992) and as a result the sedimentology has not yet been convincingly interpreted (Cocks & Fortey 1986), palaeoenvironments for the subgroup have been suggested (Fig. 14). The subgroup is thicker in the east than in the west and is divided into four formations: Goudini, Skurweberg and Rietvlei (west), and Bavianskloof (east). Current models favour a coastal environment for deposition of the Goudini Formation. Shallow marine systems interfinger with braided stream deposits (Malan et al. 1989), similar to the palaeoenvironment interpreted for the Albemarle and Mount Alice members in the Port Stephens Formation. The facies of the Skurweberg Formation are very similar to those seen in the South Harbour Member and are

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Fig. 14. Lithostratigraphic correlation of the Port Stephens Formation and Nardouw Subgroup. Correlation with the sea-level curve based on biostratigraphic markers in the Nardouw Subgroup. Onset of regression is identified by the transition from littoral marine to fluvial sedimentation. Transgression marked by the appearance of offshore marine deposits (Upper Emsian). Sea-level curve for the Palaeozoic from Hallam (1984); expanded area showing the mid-Palaeozoic in detail (from Johnson et al. 1991) for Silurian; from Johnson et al. 1985 for Devonian). CMC, Cape Meredith Complex; Pla, Plantation Member; PT, Pakhuis Tillite; CF, Cebarberg Formation; GF, Goudini Formation; SF, Skurweberg Formation; RF, Rietvlei Formation; BF, Bavianskloof Formation. Key to symbols is given in the Supplementary Publication.
almost 180° rotation since c. 190 Ma. This is in agreement with palaeomagnetic data (Mitchell et al. 1986), which show that the Falkland Island crustal block has undergone almost 180° rotation since c. 190 Ma.

Timing of deposition

The age of the Port Stephens Formation is constrained only at its base, where a 422 ± 39 Ma dolerite dyke is truncated by the unconformity (Thistlewood et al. 1997). Palynomorphs from the Fish Creek Member are similar to those found in the Fox Bay Formation and are probably Lower Devonian (Marshall, pers. comm.). The overlying Fox Bay Formation contains an Emsian flora and fauna at its base (Marshall 1994), deposited during the Gondwana-wide transgression (Starck 1995). The timing of deposition for the Nardouw Subgroup is better constrained: trilobites, brachiopods and spores in the underlying marine Cedarberg Formation indicate a latest Ordovician age (Cocks & Fortey 1986; Gray et al. 1986), and an Early Devonian (Pragian) fauna is present in the Baviaanskloof Formation (Tankard et al. 1982). The lithostratigraphic correlation between the two units (Fig. 14) appears to be very good, although biostratigraphic resolution is inadequate to assess the degree of diachronity. In both areas, clear internal unconformities are lacking (at least above the base of the Albeamarle Member), so these stratigraphic bodies probably represent a single major phase of basin infilling. However, these results suggest that the bulk of the Nardouw Subgroup and Port Stephens Formation was deposited during the Silurian–early Devonian, with regression probably commencing in the latter part of the Silurian and ending abruptly as a result of early Emsian transgression.

Sedimentary basin configuration

The Cambro-Ordovician successions of South Africa and Antarctica record earlier rifting of the adjacent Gondwana margin, of which there is no record in the Falkland Islands. By the Siluro-Devonian, this southern (palaeo-Pacific) margin of Gondwana would have been a mature passive margin basin with a relatively long history of thermal subsidence (Fig. 2). Hints of an approximately Silurian perturbation of this thermal history are provided by the 422 ± 39 Ma dyke ages from the Cape Meredith complex. The trace element and isotopic characteristics of these dykes imply derivation from an asthenospheric mantle source (Thistlewood et al. 1997), which is likely to occur only as a result of regional lithospheric extension. In South Africa, what altered dolerite dykes have yielded Ar/Ar ages of 418 ± 29 Ma (Hälbich et al. 1983) and ‘thermal overprint’ ages of c. 410 Ma are known from the Cape Granite (Barnett et al. 1997), which directly underlies the Table Mountain Group. The significance of these other Silurian to early Devonian dates remains uncertain but large-scale lithospheric extension is the most likely cause.

In the Falklands, the direct superposition of large-scale shallow marine successions (Albeamarle Member) onto eroded mid-Proterozoic basement (Cape Meredith Complex) implies that either the drowning of a region of subdued topography occurred without significant development of alluvial depositional systems, or the deposits of these systems were extensively reworked by marine processes during transgression. Other than the thin, laterally imperissive Plantation Member, we have no suggestion of strongly fault-controlled, compartmentalized, synrift deposition at the onset of subsidence in the Falkland Islands. Hence it is easier to envisage accumulation of the Port Stephens Formation in a broadening belt of thermal subsidence away from the main rift axis. Whether the initial transgression was the result of accelerated subsidence or eustatic sea-level rise is uncertain. In the former scenario, decreasing rates of extensional strain would gradually allow sediment supply to outpace creation of accommodation and hence lead to the fluvial progradation recorded by the Mount Alice and South Harbour members.

Previous palaeogeographical reconstructions for the Cape Supergroup (e.g. Hobday & von Brunn 1979; Tankard et al. 1982; Marshall 1994) have envisaged deposition in an elongate belt of subsidence, the Natal embayment, trending approximately parallel to the present coastline of eastern South Africa. Our findings are compatible with a relatively axial position for the Falkland Islands in this structural embayment (Fig. 15), or ‘failed arm’ of the main Gondwanan passive margin. In this context, the facies and thickness variations within the Nardouw Subgroup (generally thinning and coarsening to the north and west) and between the Nardouw Subgroup and Port Stephens Formation make sense in terms of proximity to the locus of subsidence and distality to sediment input. Restored palaeocurrent trends from both stratigraphic units also fit well with this hypothesis (Fig. 15). The landward-tapering geometry of the Natal embayment may have fixed the main sediment input point to the basin, explaining the long-term stability of palaeocurrents in the West Falkland Group. It is interesting to conjecture that this funnel-shaped geometry may also have favoured a large tidal range, which would help to account for the significant tidal influence on sedimentation in parts of the Albeamarle, Mount Alice and Fish Creek members as well as the Goudini Formation.

Source of detritus

Both the Port Stephens Formation and the Nardouw Subgroup are dominated by highly quartz-rich sandstones derived from a mature continental basement source. The volume of quartz sand involved is very large and must imply either an exceptionally quartzose provenance or intense removal of labile constituents by surface processes. As mentioned above, fine-grained lithologies from the Mount Alice Member indicate particularly high values for the chemical index of alteration (CIA; Nesbitt & Young 1982) compared with the rest of the Port Stephens Formation. These elevated values are consistent with almost total removal of feldspar from the source area before sedimentation. This suggests either a different and more weathered source area for the Mount Alice Member, or more probably extensive reworking of sediment that was itself derived from an already fairly mature source area. Heavy mineral assemblages from the Mount Alice Member
are comparable with those from the Albemarle Member (Knox & Aldiss 1999), which concurs with re-erosion of pre-existing sedimentary detritus. Deposition of texturally immature but mineralogically mature sediment suggests exposure and reworking of shelf material by fluvial processes in response to regression of the marine system.

The South Harbour Member is generally coarser grained and more texturally immature than the Mount Alice Member, suggesting greater relative proximality and/or greater depositional gradients. The reappearance of feldspar in the detritus probably indicates erosion of a less mature source area. This change could be explained either by accelerated erosion of the same source or a change in source area. However, observed differences in the heavy mineral assemblages of the Mount Alice and South Harbour members (Knox & Aldiss 1999) are more consistent with a significant change in provenance. The data indicate a greater affinity between the South Harbour Member and the succeeding units, whereas the assemblages from the Mount Alice Member are similar to those of the units preceding it (i.e. the Albemarle Member).

There is no evidence for Silurian-age collision or mountain-building in this part of Gondwana, so we infer that the detrital material originated mainly from denudation of the earlier Pan African (c. 500–550 Ma), Ross (c. 495–510 Ma) and Taconic–Ocloyic (Mid-Ordovician; Dalziel 1997) orogens. The erosional products may have been stored in shallow marine basins on the expanded shelf areas as a result of relatively high sea level during the Cambrian and Ordovician (Fig. 14). Marine strontium isotope ratios ($^{87}$Sr/$^{86}$Sr, a good tracer of the relative input of continental material to the marine realm) show a large drop during this period (Veizer et al. 1999), which indicates little continental material reaching the open ocean. In fact, extraordinarily thick alluvial to shallow marine quartzite successions of Cambro-Ordovician age are known from many parts of Gondwana (e.g. Brittany, Algeria, Oman, South Africa, Antarctica) and have evoked speculation about the unusual source, dispersal and subsidence conditions that must have prevailed (Burke & Kraus 1998; Lomas 1998; Woodcock & Rowan 2000). Although that controversy remains unresolved, it is clear that regional or local late Ordovician–early Silurian base-level fall (Fig. 14) would have made available large volumes of pre-sorted ‘clean’ sand to the subsequent river systems.

**Wider implications**

The data presented above concur with deposition of the majority of the Port Stephens Formation during a long-term marine regression (although with much low-amplitude complexity in detail) following initial transgression of the eroded hinterland. The correlative Nardouw Subgroup in South Africa is substantially thinner as a result of differential subsidence but also records the same regressive episode. Initial marine transgression led to deposition of the coastal facies of the Albemarle Member and Goudini Formation. Regression is marked by basinward progradation of fluvial systems and deposition of the Mount Alice and South Harbour members and Skurweberg Formation.

The offshore facies of the Fox Bay Formation (Marshall 1994) and Gydo Formation, Bokkeveld Group (Tankard et al. 1982) represent a flooding event that is understood to represent a Gondwana-wide rise in sea level at the beginning of the Devonian (Starck 1995).

The bulk of sediment accumulated during this main regressive phase is made up of the deposits of braided fluvial systems that prograded over the early transgressive coastal facies. Large-scale braided river systems such as these become less common after the mid-Palaeozoic. Algeo & Scheckler (1998) argued that as land plants became more sophisticated and better established in the later Palaeozoic they encouraged break-up of source rock by increased depth of root penetration, leading to greater chemical weathering and an increase in soil formation. In the Port Stephens Formation, evidence of significant vegetation appears only in the upper part of the section, concomitant with a change to a low-energy, probably meandering, fluvial system on a lowland plain. It is possible that the primary control on this transition from braidplain to low-energy fluvial system was simply the interplay between accommodation and sediment supply. However, it is interesting to speculate on the degree to which colonization and development of these new terrestrial plant ecosystems played a key role in the stabilization of river banks and hence development of meandering channels.
What is the extent and significance of this regressive episode? Inferred ‘global’ sea-level curves for the Mid-Silurian (Wenlockian) to Early Devonian (before the Emian) show a 40 Ma period of overall regression (Fig. 14; Hallam 1984, 1992; Johnson et al. 1985, 1991; Loydell 1998). This work was based principally on Northern Hemisphere successions because Gondwanan material of this age is (1) not easy to identify, as many of the mid-Palaeozoic sections are barren, and (2) where approximate ages can be assigned, the Silurian and Lower Devonian units appear to be missing. Although the age resolution is not tightly constrained, these thick records of apparently continuous deposition from the Falkland Islands and the coeval Nardouw Subgroup are evidence from the Southern Hemisphere for regression during this period, preserved in a gently subsiding extensional basin where gradual deepening might normally have been expected. Hence, a eustatic signal appears to be most likely. Falling sea levels during the Silurian exposed former shelf areas to reworking, resulting in thick fluvial successions overlying coastal and shallow marine deposits along the palaeo-Pacific margin and causing marine $^{87}$Sr/$^{86}$Sr isotopic ratios to rise (Veizer et al. 1999). The low abundance of middle–Upper Silurian and Lower Devonian material from Gondwana could be partly explained in terms of this major regression, with enhanced erosion of the continental margin sediment piles and large-scale bypass to deep water. However, the implied erosion products remain elusive and other aspects of basin configuration and sediment dispersal may also have been unusual at this time. This is a key regional problem requiring further investigation.

Conclusions

(1) The sedimentology and ichnology of the Port Stephens Formation are interpreted as the products of terrestrial and shallow marine deposition on a gently dipping alluvial to coastal plain.

(2) Although stratigraphic organization is somewhat complex in detail, overall the Port Stephens Formation records distinct trends of transgression and regression, with the bulk of sediment accumulating during the regressive phase. Sediment dispersal remained consistently towards the present-day north and east.

(3) Lithostratigraphic subdivisions of the Port Stephens Formation can be directly correlated with units of the Nardouw Subgroup in South Africa (although biostratigraphic resolution is low). A sensible palaeogeographical fit of the Nardouw and Port Stephens depositional systems is achieved if the Falkland Islands are restored to a position off the eastern margin of South Africa, particularly appreciated.

(4) Changes between terrestrial and shallow marine depositional environments were strongly influenced by global changes in sea level during the mid–late Silurian and early Devonian, culminating in a major marine transgression in the Late Emian and deposition of the offshore deposits of the Fox Bay and Gydo formations.

(5) The low abundance of Silurian and Lower Devonian material throughout Gondwana is partly an artefact of enhanced shelf erosion and bypass as a result of major regression at this time.

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