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The Port Askaig Formation, Dalradian Supergroup, Scotland

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Chapter Summary

The Port Askaig Formation is a thick glaciogenic succession within the Dalradian Supergroup that consists of over 700 m of variably dolomitic diamictite, conglomerate, sandstone mudstone and minor dolomite, and is bounded by mixed siliciclastic-carbonate successions of the Islay (Lossit) and Bonahaven Formations. These strata are exposed in the metamorphic Caledonides of Scotland, though excellent preservation of sedimentary structures can be found at several sites. An extensional setting for this succession has been proposed based on stratigraphic and structural arguments. Available chemostratigraphic data includes Chemical Index of Alteration, δ13C and strontium isotope values. Palaeomagnetic analyses have shown to be subject to post-depositional Caledonian overprinting. There is also continued debate over the regional palaeogeographic reconstructions of the Scottish promontory for this time period. The succession is chronologically poorly constrained with U-Pb analyses of stratigraphically much higher or lower deposits. The thick succession is thought to record glacially influenced marine sedimentation and reworking of unstable sediments in a tectonically active setting with evidence of ice-margin fluctuations. Alternative palaeoenvironmental interpretations that focus on glacial terrestrial processes and emphasize climatic influence instead of tectonic activity have also been proposed. The overlying carbonate is a lithologically diverse coastal complex and so does not fit
the Neoproterozoic norm. Research has to date focused on the stratigraphic and sedimentological aspects of this succession, as well as some of the broader palaeogeographic and structural features of the Dalradian basin. Future efforts should focus on the chronological, structural and palaeogeographic constraints of this succession.
Introduction

The Port Askaig Formation is exposed at several sites in Scotland including Islay, the Garvellach Islands, Schichallion, Braemar, Muckle Fergie Burn and Fordyce (Spencer & Pitcher 1968; Spencer 1971; Litherland 1980) as well as in Donegal, Mayo and Connemara in Ireland (Howarth 1971; Tanner & Shackleton 1979; Max 1981). The type section is located at Port Askaig on the island of Islay, with several good along-dip outcrops over several km of shoreline and nearby moorland (Spencer 1971). The best outcrops can be seen on the Garvellach Islands, with lateral and vertical exposures of 100s of m to several km, though only the lowermost three Members of the formation are exposed there (Fig. 1). These exposures are of phenomenal quality and, compared with other Neoproterozoic successions, relatively easy to access. They provide abundant sedimentological information as well as an excellent sense of lateral and vertical facies variability and enable relatively detailed palaeoclimatic reconstructions. Other sites in Scotland and Ireland tend to have limited outcrop exposure, complicated structural relationships, and higher degree of metamorphism. The Port Askaig Formation is also known as the Port Askaig Tillite in the literature, but this genetic term is avoided here in accordance with modern stratigraphic practice.

The Port Askaig Formation outcrops are significant in providing the first record of glacigenic deposits now known to be Precambrian (Thomson 1871). Subsequent Survey mapping and other works carried out until the early 1930s (references in Spencer 1971) provided more geological context, but with little consciousness of their international significance. Bailey (1916) was the first to use way-up indicators in these rocks and to demonstrate the simplicity of the structure. Later, the stratigraphy and origin of these deposits became the focus of several detailed studies (Kilburn et al. 1965; Spencer 1971; Eyles & Eyles 1983; Eyles 1988; Arnaud &
Eyles 2006). The most comprehensive study was Spencer’s (1971) work where the variable sedimentology and regional stratigraphy were documented at various sites in Scotland and Ireland. The majority of other studies have focused on the excellent exposures on the Garvellach Islands.

Additional papers have focused on specific aspects of this thick succession such as provenance (Anderton 1980; Evans et al. 1998; Fitches et al. 1996; Cawood et al. 2003); the sandstone intrusions or wedges (Eyles & Clark 1985), the Great Breccia (Arnaud & Eyles 2002; Benn & Prave 2006), the giant cross-bedded sandstone (Arnaud 2004) and origin of associated carbonate strata (Fairchild 1985a). Anderton (1982, 1985), Yardley et al. (1982), Harris et al. (1978, 1993) and Prave (1999) provide valuable information on the depositional setting and tectonic evolution of the Dalradian Supergroup, while discussing ongoing controversies. Harris et al. (1993) also provides a useful set of lithostratigraphic columns of the Dalradian Supergroup at selected sites in Ireland, Scotland and Shetland. Field trip guidebooks are available (itineraries I, II and III in Hambrey et al. 1991; Arnaud & Shields 2005). Sedimentological studies of the overlying Bonahaven Formation (Spencer & Spencer 1972; Fairchild 1977, 1980a, b, 1985b) have recently been supplemented with chemostratigraphic studies of the bounding formations that constrain their global context (Brasier & Shields 2000; McCay et al. 2006; Prave et al. 2009). The underlying carbonates have been described on the Garvellachs (Spencer 1971), but are less well-exposed and less-studied on Islay, although an updated map of northern Islay has been published (British Geological Survey 1994).

**Structural framework**

The Port Askaig Formation and associated strata are part of the thick Dalradian
Supergroup exposed within the metamorphic Caledonides between the Great Glen Fault and the Highland Boundary Fault. Regionally, the Dalradian Supergroup rocks were affected by several phases of deformation and folding associated with the Caledonian orogeny (Treagus 1987).

Slides or thrust faults that lie sub-parallel to bedding and are thought to have last moved in Ordovician times, and Devonian-age granitic intrusions are also present in the region (Harris et al. 1993). The outcrops at Port Askaig are exposed in the relatively structurally simple NNE-trending Islay anticline (Bailey 1916; Fairchild 1980c). On the Garvellach Islands, the beds dip uniformly to the south and south east (~35 deg.). Tertiary-age dolerite dykes cross-cut the strata.

The Argyll Group, which includes the Port Askaig Formation at its base (Fig. 2), is thought to have accumulated in an extensional basin experiencing increasing tectonic activity and development of fault-bounded sub-basins prior to the opening of the Iapetus ocean (Anderton 1982; Harris et al. 1978, 1993). Evidence that basin extension started during accumulation of Port Askaig Formation sediments includes rapid lateral thickness changes over short distances (Anderton 1982, 1985). For example, the Port Askaig Formation appears to thin rapidly westwards on Islay to the limit of its outcrop (British Geological Survey 1994) and the overlying Bonahaven Formation thins significantly west across the Bolsa fault in this region (Fairchild 1980c; Anderton 1985). There is also a coarse conglomerate facies of reworked limestone in the Lossit Limestone in the western part of its outcrop (British Geological Survey 1994). It is within this context that the Ordovician-age Grampian slides were proposed to be Proterozoic synsedimentary listric faults that were later re-activated, based on their association with rapid thickness changes at various stratigraphic levels within the Dalradian Supergroup (Soper & Anderton 1984; Anderton 1985; Anderton 1988). Most recently, some of the diamicite units as well as repeated horizons of soft sediment deformation structures have been
interpreted as additional indicators of early extensional tectonic activity in Argyll times (Arnaud & Eyles 2002, 2006).

The rocks have undergone deformation and metamorphism as a result of the Caledonian orogeny with open folding and upright cleavage developed in the least affected areas of Islay, Garvellachs and Northern Donegal (Spencer 1971; Fairchild 1980b). Locally there are high-strain areas (Borradaile 1979; Fairchild 1980c) particularly nearing bounding thrusts, re-activated faults and some major lithological boundaries (Anderton 1985; Fairchild 1985b; Treagus & Treagus 2002). Pressure-solution effects are widespread more generally with limestone and diamictite much more strongly deformed than dolostone or quartz sandstone (Fairchild 1985b). In the most-studied locations at Port Askaig and in the Garvellach Islands, sedimentary structures are well preserved, although noticeably deformed in cleaved lithologies.

Stratigraphy

The Port Askaig Formation is found within the predominantly marine succession of the Argyll Group in the Dalradian Supergroup (Fig. 2), being underlain by the Islay (Lossit) Limestone (mixed dolomitic-siliciclastic at its top) and overlain by the mixed dolomitic-siliciclastic Bonahaven Formation.

The Port Askaig Formation is over 700 m in thickness. Spencer (1971) defined five Members based on predominant facies and clast lithology (Fig. 3). Members I to III are best exposed on the Garvellach Islands, whereas Members IV and V are only exposed on the island of Islay. The lowermost member (Member I- Beannan Buidhe) consists primarily of stacked carbonate-rich diamictite with commonly discontinuous sandstone and conglomerate interbeds. Member I also contains a thick diamictite bed called the Great Breccia with very large clasts in a
muddy sandstone matrix and a series of folded and boudinaged interbedded units of variable lithologies (mudstone, sandstone, dolomite, and diamictite) commonly referred to as the Disrupted Beds. Member II (An Tamhanachd) consists of diamictite associated with sandstone and mudstone interbeds with a base defined by the appearance of extra-basinal clasts. Member III (Creagan Loisgte) consists of thick packages of laterally continuous sandstone interbedded with diamictite. Member IV (Ruahd Phort Beag) is again dominated by diamictite, whereas Member V (Con Tom) is dominated by sandstone with minor diamictite.

Significant lateral changes to the west on Islay were mentioned in the previous section. Within the Port Askaig Formation, the succession on the island of Islay is thin at the base with the unique facies of the overlying Disrupted Beds being the first unequivocal lithostratigraphic tie to the Garvellachs, but which is separated from the underlying carbonates by <6 m of sandstone and dolomitic conglomerate correlated with the Great Breccia by Spencer (1971). The remainder of members I, II and III are broadly similar between Islay and the Garvellachs.

**Glacigenic deposits and associated strata**

*The Port Askaig Formation*

The following is a summary of a relatively thick, complex and superbly exposed succession based on work by Kilburn *et al.* (1965); Spencer (1971); Eyles & Clark (1985); Eyles (1988); Arnaud (2002); Arnaud & Eyles (2002, 2006); Arnaud (2004) and Benn & Prave (2006). The Port Askaig Formation consists of a thick succession of diamictite (44 distinct units), interbedded with sandstone and minor units of mudstone and conglomerate. Diamictite are massive to stratified with clasts up to several m in diameter floating in a siltstone to silty sandstone matrix. Some diamictite beds exhibit coarse-tail inverse grading, and many contain
sandstone stringers or inclusions of variable lithologies (Arnaud & Eyles 2006). Some of the
diamictite units contain lenses of bedded siltstone sandstone and/or conglomerate (Spencer 1971). Clast and matrix lithology change up section from predominantly intrabasinal and
dolomitic at the base to extrabasinal and siliciclastic at the top. Pink granitoid extrabasinal clasts
appear to have come from Palaeoproterozoic plutonic rocks of the Svecofennian-Makkovik-
Ketilidian province (Evans et al. 1998). Beds are typically several to 10 m in thickness with
sharp conformable to erosional basal contacts. Some basal contacts are gradational with
associated laminated mudstone (Arnaud 2002; Arnaud & Eyles 2006). The Great Breccia is a
particularly thick diamictite unit (up to 50 m) with megaclasts ranging from several m to over
100 m in diameter (see Spencer 1971; Arnaud & Eyles 2002; Benn & Prave 2006 for detailed
descriptions).

Sandstone in the Port Askaig Formation exhibits a variety of characteristics including a
wide range of textures (fine to very coarse), sorting (poorly to well sorted), lithologies (dolomitic
to quartzitic), and structures (massive, horizontally-bedded, cross-bedded, and deformed). Thick
packages of sandstone within Member III are particularly notable as they contain thick to very
thick sets of cross-bedded sandstone (individual set thickness average 3 m; maximum is 11 m;
Arnaud 2004). The lowermost package of these giant cross-bedded sandstone exhibits a
preferred southerly palaeocurrent direction; while cross-bedded sandstone in the rest of the
succession are more variable (Spencer 1971; Arnaud 2004). Other interbeds within the Port
Askaig Formation include finely laminated mudstone (rhythmites), (elastic) dolomite, and
massive to stratified conglomerate. Conglomerate often overlies and loads into diamictite,
though some also occur interbedded with sandstone and mudstone. Outsized clasts in laminated
mudstones or diamictites occur at various horizons, but only limited examples displaying clear
deflection of underlying laminae occur, especially in the Disrupted Beds (Spencer 1971; Hambrey et al. 1991). Petrographic study of the carbonate in the Port Askaig Formation indicates that it appears to be largely detrital in origin, with that in the rhythmite facies being secondary (Fairchild 1985a; Hambrey et al. 1991, p. 27, 34).

Deformation structures have been documented at multiple distinct stratigraphic horizons. Several of these, namely sandstone wedges, sandstone dykes and sandstone downfold structures, were examined in detail (Spencer 1971; Eyles & Clark 1985). The sandstone wedges are predominantly < 10 cm wide, have sharp irregular outer geometries and commonly penetrate up to several metres downward into diamictite units or into carbonate units within the underlying Islay Limestone. Some exhibit branching or polygonal patterns on bedding plane surfaces. Sandstone dykes are more tabular in form and intrude diamictite and siltstone. Sandstone downfold structures, referred to as load casts or ball and pillow structures by Arnaud & Eyles (2006), are also common on top of diamictite units or within interbedded sandstone and mudstone. These features, together with horizons of convolute and contorted bedding and pseudonodules, were shown to be found most commonly within Member II sediments on the Garvellach Islands (Arnaud & Eyles 2006).

The Lossit Limestone

Strata underlying the Port Askaig Formation have been known as the Islay Limestone and on the Garvellachs a succession of 72 m, predominantly mixed dolomitic-siliciclastic sediments with some stromatolitic and other limestone is present (Spencer 1971). There are some pure dolomicrite and dolomitic stromatolites, but for the most part the facies contain both terrigenous debris and reworked intrabasinal carbonate (Hambrey et al. 1991). The most interesting
structures are crystal pseudomorphs originally illustrated by Spencer (1971). Similar structures from the Irish Dalradian were interpreted as glendonites, which are pseudomorphs after ikaite (Johnston 1995).

On Islay, the top 300 m of the "Islay Limestone" have been redesignated as the Lossit Limestone Formation (British Geological Survey 1994) of which the topmost (Persabus) member (c. 80 m thick) consists of interbedded dolostone (locally stromatolitic or intraclastic), quartzite, slate and mixed lithologies and overlies a c. 70 m pure (Kiells) limestone member, locally oolitic, which in turn overlies several thick slate and limestone units.

The Bonahaven Formation

The lithostratigraphy and geological context of the overlying mixed carbonate-siliciclastic Bonahaven Formation has been documented by Spencer & Spencer (1972) who divided it into four members, Fairchild (1977, 1980a, b, 1985) and Hambrey et al. (1991). On the east coast of Islay, the sub-arkosic arenite at the top of the Port Askaig Formation is succeeded by around 65 m of sandy facies with mudstone and local dolomite at the top (member 1), 25 m of quartzite (member 2), c. 200 m of dolomitic sandstone, oolitic facies and mudrock (member 3) and 55m of heterolithic siliclastic rocks with a central 12 m pure dolostone (member 4). In turn this is succeeded by several kilometres of pure quartzite (Jura Quartzite).

The structures at the base of the Bonahaven Formation, taken by previous workers to be desiccation cracks, have been reinterpreted as interstratal dewatering features by Tanner (1998). Primary carbonate is first encountered near the top of member 1 where displacive dolomite fabrics in terrigenous mudstone with genuine desiccation cracks (Fairchild 1977, 1980b) are suggestive of dolocrete. The main carbonate unit (member 3) consists dominantly of three
dolomite facies (stromatolitic, bimodally cross-stratified intraclastic and/or oolitic sandstone, and mudstone with thin graded and/or wave-rippled sand) (Fairchild 1980a).

**Boundary relations with overlying and underlying non-glacial units**

In eastern Islay, basal sandstone, clastic dolostone and diamictite of the Port Askaig Formation variably rest erosionally on the underlying dolomite (at times stromatolitic) and thin-bedded quartzite and shale, which in turn rest on pure limestone (Spencer 1971; British Geological Survey 1994). Over 90 m of Member I exposed on the Garvellachs is missing here on Islay. Further west, Port Askaig formation diamictite units are less poorly exposed, but commonly are limited by sedimentary limestone breccias (British Geological Survey 1994). On the Garvellach Islands, diamictite sharply and erosionally overlies the Islay Limestone in places (Spencer 1971). In other areas of the Garvellach Islands (Dun Chonnuill & Garbh Eileach), the contact is gradational as shown by the appearance of rare clasts and the presence of siltstone (typical of the siltstone matrix of the overlying diamictite) interbeds in the upper part of the Islay limestone (Spencer 1971; Arnaud 2002; Arnaud & Eyles 2006).

The upper contact of the Port Askaig Formation is seen on Islay, where it is conformable with the Bonahaven Formation, but it is difficult to define where the last evidence of glacial phenomena occur as the dominant facies near the top is quartzite, with only rare thin diamictite horizons. The highest occurrence of chess-board albite, which is diagnostic of the granitic pebbles of the Port Askaig Formation (Spencer 1971), is within a channelled conglomerate horizon, located approximately 25 m above the base of the Bonahaven Formation (Hambrey *et al.* 1991, p. 39-40). The first occurrence of dolomite is found near the top of member 1 of the Bonahaven Formation where it occurs in tidal flat facies (Fairchild 1977, 1980c) and is
succeeded by more extensive dolomite facies in member 3, with local undolomitized oolitic and micritic limestone (Fairchild 1980a).

**Chemostatigraphy**

Panahi & Young (1997) carried out a study of major and trace element geochemistry, specifically utilizing the Chemical Index of Alteration (CIA). Most of the 21 samples were taken from the matrix of diamictite exposed on Garbh Eileah, Garvellach Islands. Analysis showed a decrease in CIA values from the base of the Port Askaig Formation (values range from 68 to 77) to the upper part of Member III (values range from 60-68). The CIA values are an indication of the extent of weathering based on the relative proportions of alkali and alkaline earth elements and thus the decrease was interpreted as indicating a change in sediment source. The high CIA values reflect erosion of underlying sedimentary rocks, which had already experienced weathering, whereas the lower CIA values at the top of the section indicate incorporation of sediments from relatively unweathered basement rocks (Panahi & Young 1997). In addition, analysis of the trace element geochemistry suggests erosion of shale developed on a post-Archean crystalline basement, though a specific source area could not be identified.

Brasier & Shields (2000) provided the first isotopic chemostratigraphic constraints, with reliable Sr isotope values as low as 0.7067 being obtainable from the Sr-rich facies of pure Lossit (Islay) Limestone underlying the Port Askaig Formation. These Sr isotope values are comparable with facies underlying the earliest evidence of Neoproterozoic glaciation in other regions. Thomas et al. (2004) verified this result at a slightly lower horizon in the Islay limestone (Storakaig limestone of Ballygrant) (0.706651–0.706902) using a slightly more careful sample preparation protocol. Sawaki et al. (2010) carried out a careful chemostratigraphic study
on both Islay and the Garvellachs. The samples closest to the onset of glaciation, which also passed a stringent test for preservation (Mn/Sr < 0.2) were found 40 m below the base of the Port Askaig Formation on Garbh Eilach with values as low as 0.70640. These are close to the lowest values found in East Greenland immediately prior to glaciation (Fairchild et al. 2000) and suggest that the Garbh Eilach section is similarly complete.

McCay et al. (2006) described evidence for a third Dalradian glacial from Ireland and also built on earlier $\delta^{13}$C results of Brasier & Shields (2000). Values of +5‰ PDB in a lower (Ballygrant) limestone were followed by a decline to weakly positive to negative values in the Lossit Limestone (Brasier & Shields 2000). McCay et al. (2006) and Prave et al. (2009) show that in the Garvellachs section, both dolomitic and limestone facies show a change upwards from negative values (-4 to -6) in the strata that Sawaki et al. (2010) measured the lightest Sr isotope signatures, to weakly positive values. In terms of the carbonate rocks overlying the Port Askaig Formation, all these publications show that the main ferroan dolomitic part (member 3) of the Bonahaven Formation displays negative values and Brasier and Shields (2000) document values in the member 4 dolomite horizon exceeding +10‰.

Other characteristics (e.g. economic deposits, biomarkers)

Mining of zones of epigenetic Pb-Zn mineralization formerly occurred on Islay in the Ballygrant and Lossit limestones (British Geological Survey 1994). The Port Askaig Formation is locally rich in detrital magnetite and in the Disrupted Beds there are occasional massive layers of magnetite.

Spencer (1971) reported possible organic traces in member 1 (Spencer & Spencer 1972) of the Bonahaven Formation. A detailed description of sole structures interpreted as representing
chains of faecal pellets was made by Brasier & McIlroy (1998), although Brasier and Shields (2000) conceded that they could well be of inorganic origin.

Fairchild (1977) described clear 0.1 mm-sized mica spheres within a 2 m stratigraphic interval of carbonaceous mudstones near the top of member 1 of the Bonahaven Formation. Petrographic evidence indicates that they were delicate enough to collapse when mud desiccated, yet were mineralized (perhaps by glauconite) when eroded as intraclasts. They were interpreted as an unusual form of preservation of acritarch fossils. However, their great similarity with Triassic mica spheres from SW England was noted and the latter were subsequently interpreted as tektites by Walkden et al. (2002); this seems a more likely explanation for the Islay occurrence. Only one other example of impact-related phenomena has been reported in the Neoproterozoic of the British Isles (Amor et al. 2008).

**Palaeolatitude and palaeogeography**

Earlier palaeomagnetic work by Tarling (1974) and Urrutia-Fucugauchi & Tarling (1983) based on large sample suites on the Garvellachs appeared to be consistent with low palaeolatitudes, although difficulties were encountered due to the unknown age of the deposits and the inability to eliminate the possibility of Caledonian overprinting. Stupavsky et al. (1982) specifically addressed the overprinting issues using clasts (79 specimens from 36 cores) and matrix (2 to 3 specimens from 20 cores) of the diamictite units as well as siltstone (2 to 3 specimens from 6 cores) from Garbh Eileach, Garvellach Islands. Remanent magnetisation measurements were used to calculate remanence angular standard deviation in order to evaluate within-specimen homogeneity and reliability of specimens that were sampled. Specimens were also subjected to alternating field and thermal demagnetisation. All samples yielded similar
results, thus failing the conglomerate test, and suggesting that these deposits have been remagnetized by Ordovician-age overprinting (Stupavsky et al. 1982).

The Dalradian Supergroup is generally associated with the Proto-Iapetus Ocean although palaeogeographic reconstructions are uncertain, in part because of an incomplete understanding of Dalradian basin development (Soper 1994; Tanner & Bluck 1999; Prave 1999; Dalziel & Soper 2001; Dempster et al. 2002; Hutton & Alsop 2004; Tanner et al. 2005). Some have suggested the Dalradian experienced orogenesis prior to rifting and opening up of the Iapetus Ocean in Argyll-Southern Highland times. Such an orogenic event would suggest an affinity with Gondwana and a palaeogeographic location either off of NW Gondwana (Bluck & Dempster 1991) or off of Amazonia (Dalziel 1994). Others have suggested the Dalradian experienced prolonged rifting and extension throughout its history consistent with a palaeogeographic location on the margin of Laurentia (Dalziel & Soper 2001). Others still have suggested the Dalradian was an extension of Baltica (Greiling & Smith 2000) based on the similarity between granitic clasts in the Port Askaig Formation and Scandinavian intrusions. Recent work by Cawood et al. (2003) demonstrates the similar characteristics of the detrital zircon populations throughout the Dalradian and their close match to Laurentian sources, with the Port Askaig Formation clasts having closest matches in the North Atlantic Borderlands (Makkovik, Ketilidian and Svecofennian provinces). In this viewpoint, the distinctive provenance represents along-basin rather than cross-basin transport.

**Geochronological constraints**

Radiometrically, the Port Askaig Formation is relatively poorly constrained. A maximum age of c. 806 Ma comes from the underlying Grampian Shear Zone located at the base
of the Dalradian Supergroup (Noble et al. 1996). This finding is based on three dates (806 +/- 3; 808 +11/-9; 804 +13/-12 Ma) obtained from U-Pb isotope analyses of primary monazite in pegmatite and neo-crystalline monazite associated with mylonitic host rocks. Samples were collected from the Grampian Shear Zone at Lochindorb and A’Bhuidheanaich, East of the Great Glen Fault and Inverness, Scotland.

A minimum age for the Port Askaig Formation is provided by two dates from the Tayvallich volcanic rocks, which are stratigraphically, 8 km above the Port Askaig Formation at the top of the Argyll Group in SW Scotland (Fig. 2; Prave 1999). Halliday et al. (1989) present various data from U-Pb, $^{207}$Pb/$^{206}$Pb and Sm-Nd isotopic analyses of zircons from a keratophyre sampled from a small laccolithic body on the Tayvallich Peninsula. They conclude that the most likely age of the keratophyre is 595 +/-4 based on their Pb-Pb analyses. Field relationships between the small laccolithic body and the Tayvallich volcanic rocks are somewhat unclear and Dempster et al. (2002) have suggested that this age may be younger than the Tayvallich volcanic rocks. In an attempt to refine this age, Dempster et al. (2002) analysed fourteen zircons from a felsic tuff collected at Port a’ Bhualteir on the Tayvallich Peninsula. Concordia diagrams show a mean $^{206}$Pb/$^{238}$U age of 601.4 +/- 3.7 Ma (n=13/14; 2σ; MSWD = 0.82).

Lithological comparisons with other diamicite-bearing succession in Scotland and Ireland and throughout the North Atlantic as well as chemostratigraphic studies has led to various regional and global stratigraphic correlation schemes (Spencer 1975; Hambrey 1983; Prave 1999; Brasier & Shields 2000; Halverson et al. 2005; McCay et al. 2006), with the most recent work suggesting that the Port Askaig Formation likely represents the oldest of several Neoproterozoic glacial periods within the Dalradian basin and the North Atlantic region. A particularly distinctive attribute is the low Sr isotope ratios of the underlying limestone (Brasier

Discussion

Although there is broad agreement that the Port Askaig Formation records environmental conditions during one of the Neoproterozoic glacial periods, several palaeoenvironmental models have been proposed with differences hinging largely on the interpretation of diamictite units as directly deposited by ice (Kilburn et al. 1965; Spencer 1971; Benn & Prave 2006) or as primarily deposited in a marine setting influenced by ice rafting and tectonic instability (Eyles 1988; Arnaud & Eyles 2006).

In the models that emphasize a subglacial or ice marginal origin, diamictite units are interpreted as tills recording multiple grounded ice advances based on the lateral extent of diamictite, the discontinuous nature of some of the interbeds in the lower members, the presence of large extra-basinal clasts and faceted clasts, the sandstone wedges that are interpreted as periglacial and the siltstone with outsized clasts that are interpreted as varves with ice rafted debris. In these models, the Great Breccia is thought to record glacitectonic deformation of sediments based on its similarity to deformed chalk rafts in tills of Norfolk (U.K.) and its correlative erosional unconformity on Islay. The sandstone wedges are thought to be periglacial because of their similarity to those formed by repeated freeze and thaw. The associated interbeds are thought to record either terrestrial or marine depositional conditions preserved between successive ice advances.

Benn & Prave (2006) took this argument further by suggesting that the Great Breccia and associated Disrupted Beds recorded proglacial and subglacial phases of a single glacitectonic deformation cycle. Although they acknowledged that the sedimentary characteristics of the
Great Breccia were consistent with either a glacitectonic or a non-glacial sediment gravity flow origin, they preferred a glacial origin based on their interpretation of several features within the associated Disrupted Beds as indicative of subglacial deformation; namely laminae that resemble glacitectonic laminae, deformation indicative of shear, an increase upsection in the number of extra basinal clast and evidence of increasing upwards cumulative strain in diamicite.

In the tectonically-influenced glaciomarine models, many diamicite units are thought to record sediment instability associated with basin development, whereas diamicite units in the uppermost part of the succession are thought to record reworking of sediments and rainout of fine-grained sediments and ice-rafted debris in a glacially-influenced basin (Arnaud & Eyles 2006). This interpretation is based on the presence of coarse-tail inverse grading, gradational basal contacts and the close association with other sediment gravity flow deposits (Boulton 1972; Nardin et al. 1979; Mulder & Alexander 2001; Arnaud & Eyles 2006). The Great Breccia is interpreted as a catastrophic subaqueous landslide associated with local tectonic activity (Arnaud & Eyles 2002) based on mapping that revealed i) the Great Breccia to be a ‘composite graded sequence’, ii) an intimate association with undeformed subaqueous sediment gravity flow and traction current deposits, and iii) a similarity to published studies of allochthonous carbonate megabreccia (Arnaud & Eyles 2002). The stratigraphic horizons of deformation structures, including the overlying Disrupted Beds, are interpreted as seismites indicative of local tectonic instability based on their form, geographic extent, and tectonic setting in which they are found (Arnaud & Eyles 2006). Stratigraphic analysis of the sedimentary facies and indicators of glacial and tectonic activity suggests repeated ice-margin fluctuation and tectonically quiet conditions occurred during deposition of Member III sediments (Arnaud & Eyles 2006).
The sandstone, mudstone and conglomerate interbeds record shallow marine conditions affected by sediment gravity flows and traction currents (Arnaud & Eyles 2006). The giant cross beds are thought to result from the migration of large dunes under strong tidal currents considering the Dalradian basin is thought to be narrow at this time (Eyles 1988; Arnaud 2004). In terms of the dolomite interbeds, there is no specific evidence of chemical deposition and much evidence of detrital dolomite (Fairchild 1985a, Hambrey et al. 1991).

The superb exposures in the Garvellach Islands have resulted in numerous detailed studies and yet the resulting depositional models proposed for the Port Askaig Formation have some significant differences in their climatic and palaeoenvironmental implications. A full discussion of these models is beyond the scope of this paper and the reader is referred to the original works for more details. While recent developments in glacial geology have allowed some of the earlier interpretations to be discounted, there are still instances where the exact nature of glacial influence over these deposits is debatable and difficult to establish unequivocally.

The carbonate succession underlying the Port Askaig Formation on Islay is consistent with marine regression from offshore shale to coastal facies. On the Garvellachs, the mixed carbonate-siliciclastic sediments bear local probable ikaite pseudomorphs near the top, suggestive of cool marine conditions. Facies resembling modern carbonate tropical platforms are limited to local intraclastic dolostones in parts of the Persabus Member at the top of the Lossit Limestone, whereas more distinctive oolitic limestone facies occur below in the Kiells member. The relative stratigraphic positionings of these occurrences between the Garvellachs and Islay cannot be resolved because of the lack of marker horizons between the two.

The mixed carbonate-siliciclastic succession that overlies the Port Askaig Formation is
thought to record shallow marine sedimentation. No climatically-distinctive facies occur in the basal part of the Bonahaven Formation. The most prominent carbonate (member 3 of the Bonahaven Formation) records a lagoonal and tidal complex (Fairchild 1980a). It is generally agreed that the Bonahaven Formation is not a typical cap carbonate sequence (Halverson et al. 2005; McCay et al. 2006). It is hard to pinpoint the last glacial influence (the highest characteristic conglomerate is argued to be reworked and represents a tidal channel deposit, Hambrey et al. 1991) and the facies succession does not resemble that of carbonate successions found elsewhere. Member 3 carbonates have only one exact facies counterpart in the geological record – the upper Canyon Formation of East Greenland – and the latter occurs some distance above the upper of two glacial deposits in that area (Fairchild 1989).

A difference of viewpoint exists about the significance of the negative carbon isotope anomalies below the Port Askaig Formation and in the overlying Bonahaven Formation. Prave et al. (2009) argue that the carbon isotope stratigraphy recorded in the Dalradian succession as a whole bears close comparison with global trends and that the published signatures can be taken at face value as primary signatures. The alternative view is that wherever impure ferroan dolomites are present, it would be expected that negative deviations from marine signals would be present. This applies to some (but not all) of the pre-glacial facies of the Lossit Limestone on the Garvellachs and to the samples of member 3 of the Bonahaven Formation that have been studied so far. The exact facies equivalents of the Bonahaven rocks in East Greenland show coherent variations in negative $\delta^{13}C$ values over vertical distances of 10-20 m (Fairchild 1991). There are limestone facies in the Bonahaven Formation that could be studied to help resolve this issue. The extraordinarily high $\delta^{13}C$ signature in the pure dolostone of member 4 is an enigma; a similar strong signal appears rather soon after glaciation in deposits of NW Canada, known as
the Keele peak (McCay et al. 2006). Whereas Halverson et al. (2005) chose to trust the pre-
Port Askaig δ¹³C negative anomaly to correlate with late Cryogenian glaciations elsewhere, it is
now clear that such an anomaly is present below both early and late Cryogenian glacial (Prave et
al. 2009). Most authors believe that the low Sr isotope ratio is a more specific feature to
establish an early- to mid-Cryogenian age for the Port Askaig Formation. The minimum value
obtained a short distance below the Port Askaig Formation of 0.70640 (Sawaki et al. 2010) is
close to the lowest value of 0.7063 found in East Greenland immediately prior to glaciation
(Fairchild et al. 2000), and suggest that the Garbh Eilach section is similarly complete. There are
difficulties in reconstructing stratigraphic profiles through the entire thickness of the Dalradian
succession and there is also evidence of diachroneity of widely distributed glacial deposits
thought previously to be correlative (e.g. Kendall et al. 2006; Fanning & Link 2004), but Prave
et al. (2009) were optimistic that there are sufficient diagnostic chemostratigraphic results to
allow the global stratigraphic context of the Port Askaig Formation as early- to mid Cryogenian
(Sturtian in their terminology) to be confirmed.

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Figures:

Fig. 1. Map showing location of Port Askaig Formation outcrops on the Garvellach Islands (modified from Spencer 1971). Detailed map of outcrops on Islay can be found in Spencer (1971) and Hambrey et al. (1991). Note the lithology "sandstone" includes from 0 to 90+% dolomite at different horizons.

Fig. 2. Generalized stratigraphy and tectonic setting of the Port Askaig Formation and associated strata. P-Port Askaig Formation; I-Islay Limestone; B-Bonahaven Formation; J-Jura Quartzite; S-Scarba conglomerate; *-earthquake-induced liquefaction features (modified from Arnaud & Eyles 2006)

Fig. 3. Stratigraphic log of the Port Askaig Formation based on outcrops on the Garvellach Islands (Member I to III) and on the island of Islay (Member IV and V). GB-Great Breccia; DB-Disrupted Beds; and XB-Giant cross-bedded sandstone (modified from Arnaud & Eyles 2002). Note the dolomite interbeds are considered detrital in origin (see text for discussion).
Arnaud and Fairchild, Fig. 2
Arnaud and Fairchild, Fig. 3