NEOPROTEROZOIC ENVIRONMENTAL CHANGE

RECORDED IN THE PORT ASKAIG FORMATION, SCOTLAND:

CLIMATIC VS TECTONIC CONTROLS

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ABSTRACT

The snowball Earth hypothesis suggests that the Neoproterozoic was characterized by several prolonged and severe global glaciations followed by very rapid climate change to ‘hot house’ conditions. The Neoproterozoic Port Askaig Formation of Scotland consists of a thick succession of diamictite, sandstone, conglomerate and mudstone. Sedimentological and stratigraphic analysis of Port Askaig deposits exposed on the Garvellach Islands was carried out to establish the nature of Neoproterozoic palaeoenvironmental change preserved in this thick succession. Particular emphasis was placed on identifying and distinguishing between climatic and tectonic controls on sedimentation.

Port Askaig Formation diamictite units are attributed to deposition by sediment gravity flow processes or ‘rainout’ of fine-grained sediment and ice-rafted debris in a glacially-influenced marine setting. Associated facies record various depositional processes ranging from sediment gravity flows (conglomerate, massive sandstone and laminated mudstone) to deposition under unidirectional currents (cross-bedded and horizontally-laminated sandstone). The Port Askaig Formation is also characterized by abundant soft sediment deformation features which occur at discrete intervals that are interpreted to record episodic seismic activity.

Stratigraphic analysis of the Port Askaig Formation on the Garvellach Islands reveals three phases of deposition. Phase I was dominated by sediment gravity flow processes and sedimentation was primarily tectonically-controlled. Phase II was a transitional phase characterized by continued tectonic-instability, an increased supply of sand to the basin and the preservation of current-generated facies. In the third and final phase of deposition, the interbedded units of sandstone and diamictite are interpreted to reflect development of large sandy bedforms and ice margin fluctuations.
in a tectonically-stable marine setting.

Sedimentological and stratigraphic analysis of the Port Askaig Formation demonstrates that tectonic activity had a significant influence on development of the lowermost parts of the succession. Climatic influences on sedimentation are difficult to identify during such phases of tectonic activity but are more easily discerned during episodes of tectonic quiescence (e.g. Phase III of the Port Askaig Formation). The thick succession of diamictite interbedded with current-deposited sandstone preserved within the Port Askaig Formation is not consistent with deep freeze conditions or rapid deglaciation proposed by the snowball Earth hypothesis.

Keywords: Neoproterozoic glaciation, paleoclimatology, snowball Earth, gravity flows, Dalradian, Port Askaig Formation
1. INTRODUCTION

The geologic record suggests significant palaeoenvironmental changes occurred during the Neoproterozoic including several widespread glaciations followed by relatively warm climatic conditions, and severe fluctuations in the global carbon cycle. These changes are recorded in Neoproterozoic sedimentary successions, many of which contain diamictites. Diamictites are poorly-sorted coarse-grained deposits commonly interpreted as glacigenic or debris flow deposits. They are found in Neoproterozoic successions on every continent, including some thought to have been in equatorial regions at their time of deposition (Harland, 1964; see most recent reviews in Evans, 2000; Eyles and Januszczak, 2004). Many Neoproterozoic diamictites are closely associated with carbonates (Fairchild, 1993), which are thought to have formed under relatively ‘warm’ depositional conditions, suggesting extreme and rapid palaeoclimate changes. These carbonates exhibit unprecedented negative and positive excursions in $^{13}$C (e.g. Knoll et al., 1986; Kaufman et al., 1997, Halverson et al., 2002) unlike those recorded during other periods in Earth history. In addition to these lithological and geochemical changes, metazoans first appear in sedimentary rocks overlying Neoproterozoic diamictites and carbonates (see review in Narbonne, 1998) and record a significant stage in the evolution of eukaryotes.

The snowball Earth hypothesis is one of the more recent, non-uniformitarian models proposed to explain the nature of the Neoproterozoic geological record (Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002). In this model, global-scale glaciation, with ice reaching into equatorial latitudes, is argued to account for the widespread distribution of Neoproterozoic glacial deposits. Rapid climate change in the aftermath of such ‘global’ glaciations is proposed to explain the close association of glacial and carbonate deposits; reduced organic productivity under
snowball Earth conditions, combined with extreme weathering in its aftermath, is used to explain the unusual $^{13}C$ excursions in ‘cap’ carbonates overlying diamictites. These dramatic fluctuations in environmental conditions are also hypothesized to have played a role in the evolution of early biota (Hoffman et al., 1998; Runnegar, 2000). While the snowball Earth hypothesis attempts to explain features that have been considered enigmatic, the environmental conditions and changes it proposes are extreme and highly controversial (e.g. Kennedy et al., 1998; Christie Blick et al., 1999; McMchan, 2000; Williams and Schmidt, 2000; Hoffman and Schrag, 2002; Jiang et al., 2003).

Neoproterozoic glacigenic sedimentary successions have the potential to provide important data regarding the nature and severity of palaeoenvironmental change during this critical time period. Many of these successions are preserved in tectonically-active marine basins, some of which are associated with the break up of the supercontinent Rodinia (Young, 1995). In these basins, diamictite can form as a result of glacially-influenced deposition and/or tectonically-controlled sediment instability. Many of the extreme climatic and environmental changes inferred to have occurred during the Neoproterozoic depend on interpretation of diamictite deposits as representing fully glacial and extremely cold conditions. However, these deposits can form under a range of climatic and tectonic conditions and it is essential to firmly establish the origin of diamictites and associated deposits prior to making interpretations about the severity of palaeoclimatic change recorded by Neoproterozoic successions.

This paper presents a sedimentological and stratigraphic analysis of the Neoproterozoic Port Askaig Formation exposed on the Garvellach Islands of Scotland (Fig. 1) in order to reconstruct changes in depositional conditions that occurred during sediment accumulation and to evaluate the relative importance of climatic and tectonic controls on these changes. Previous studies of the Port
Askaig Formation have focused on establishing the glacial origin of the diamictites and details of the regional stratigraphy (Fig 2; Kilburn et al., 1965; Spencer, 1971; Eyles, 1988). This paper describes the nature and stratigraphic distribution of diamictites and associated deposits and interprets their depositional origin as a means to better understand Neoproterozoic environmental conditions and the severity of climatic change at that time.

2. GEOLOGICAL BACKGROUND

The Port Askaig Formation is a diamictite-bearing unit within the predominantly marine succession of the Argyll Group and the Dalradian Supergroup (Fig. 2A, Kilburn et al., 1965; Spencer, 1971). As in many other Neoproterozoic successions, the glacigenic Port Askaig Formation is associated with carbonate deposits; it is underlain by the Islay Limestone and overlain conformably by the mixed carbonate-siliciclastic Bonahaven Formation, both of which record shallow marine sedimentation (Spencer, 1971; Spencer and Spencer, 1972; Fairchild, 1980). The palaeolatitude of the Dalradian Basin is the subject of some debate due to remagnetization of deposits during the Caledonian orogeny (Stupavski et al., 1982), uncertainty about the location of the Scottish Promontory relative to Laurentia at this time (Evans, 2000) and limited well-dated palaeomagnetic data for the Neoproterozoic (van der Voo and Meert, 1991; Meert and Torsvik, 2003). Hence, it is not currently possible to ascertain whether the Port Askaig Formation was deposited in low or high palaeolatitudes.

The Dalradian Supergroup is thought to record sedimentation in an extensional basin prior to the opening of the proto-Iapetus Ocean (Harris et al., 1978; Anderton, 1982; Harris et al., 1993). Although an extensional setting has been disputed for the early part of the Dalradian Supergroup
(Tanner and Bluck, 1999; Prave, 1999; Dalziel and Soper, 2001), the Argyll Group and the Port Askaig Formation sediments accumulated at a time of increasing extensional tectonic activity. This is first indicated by significant lateral thickness changes in the uppermost part of the Appin Group. Extensional tectonic activity was sustained and intensified through the Argyll Group as evidenced by increasing volcanic activity, abrupt facies changes interpreted as rapid deepening events related to synsedimentary faulting, faulting associated with a fining upward basin fill (Easdale Subgroup), and abundant earthquake-induced liquefaction features in the Jura Quartzite and at the top of the Easdale Subgroup (Anderton, 1976; Harris et al., 1978; Anderton, 1985; Harris et al., 1993). Rapid thickness changes in stratigraphic units (Islay and Easdale subgroups) are also documented in the Argyll Group, some of which have been linked to synsedimentary listric faults that were later reactivated during the Grampian orogeny (Soper and Anderton, 1984; Anderton, 1988). Deposition of the Great Breccia, a subaqueous landslide deposit within the Port Askaig Formation, has also been related to localized faulting (Arnaud and Eyles, 2002). The subsequent opening of the Iapetus Ocean is thought to be recorded by the formation of the Tayvallich Volcanics at the top of the Argyll Group (Fig. 2A; Harris et al., 1978; Anderton, 1982).

The Port Askaig Formation is broadly constrained chronometrically by a date of 806 Ma from the underlying base of the Dalradian Supergroup (U-Pb date on primary monazites from pegmatites of the Grampian Shear Zone) and dates of 595 ± 4 and 601 ± 4 Ma from the overlying Tayvallich Volcanics (Fig. 2A, Halliday et al., 1989; Noble et al., 1996; Dempster et al., 2002). Based on lithology, the Port Askaig Formation was initially correlated with other Varangian-age (c. 600 Ma; Knoll, 2000) glacigenic successions in the North Atlantic region (Spencer, 1975; Hambrey, 1983). Subsequently, others have suggested that the Port Askaig Formation may represent an older
glaciation, possibly equivalent to Sturtian-age deposits elsewhere (e.g. Ghubrah glacial deposits, Oman, 723 Ma; Brasier et al., 2000). This was based on the stratigraphic position of the Port Askaig Formation approximately 8 km below the Tayvallich Volcanics dated at c. 600 Ma (Prave, 1999), geochemical characteristics of associated carbonate deposits of the Bonahaven Formation, which are consistent with Sturtian-age geochemical signatures (Brasier and Shields, 2000), and the presence of a younger glacigenic unit in Dalradian sediments of Ireland, which was argued to represent a Marinoan/Varangian age glaciation c. 590-570 Ma (Condon and Prave, 2000).

A Sturtian age for the Port Askaig Formation is problematic in the context of the overall tectonic development of the Dalradian Basin as it would suggest extensional conditions prevailed for over 100 Ma before the creation of the Iapetus Ocean at c. 595 Ma (Tayvallich volcanics). There is also growing evidence that the younger glacigenic unit in Ireland as well as its correlative in Scotland (the Loch na Cille Boulder Bed) is not likely Marinoan/Varangian in age. Glacial deposits of the Ghaub Formation, long considered to represent a ‘Marinoan’ glaciation, have now been dated at 635.5 +/- 1.2 Ma (U-Pb zircon; Hoffmann et al., 2004). In addition, a third Neoproterozoic glacial period is now suggested based on a U-Pb zircon date of c. 580 Ma on volcanic ash associated with the glacigenic Gaskiers Formation in Canada (Bowring et al., 2003).

The initial correlation of the Port Askaig Formation with other Varangian/Marinoan age deposits in the North Atlantic region may therefore prevail. However, there is much debate about the number of glacial periods within the Neoproterozoic, such that lithostratigraphic correlation to a few well-dated sections is tenuous. Therefore, the age of the Port Askaig Formation remains poorly constrained and requires further study.
The Port Askaig Formation consists of a thick conformable succession of diamictite interbedded with sandstone, conglomerate and mudstone (Fig. 2B; Kilburn et al., 1965; Spencer, 1971). Spencer (1971) defined five stratigraphic members within the Port Askaig Formation based on changes in clast lithology and dominant facies types (Fig. 2B). Clast lithologies change from predominantly intrabasinal dolomitic and other detrital dolomitic lithologies in the lower part of the Port Askaig Formation, to increasingly extrabasinal types up-section, including granites, quartzites, schist, gneisses and other igneous rocks (Kilburn et al., 1965; Spencer, 1971).

This paper is based on sedimentological and stratigraphic analyses of 11 sections (total thickness of 825 m; Figs. 1, 3) through the Port Askaig Formation on the Garvellach Islands, where excellent exposures allow high-resolution analyses of lateral and vertical facies changes through the lower 445 m of the formation (Members I-III; Figs. 1 and 2B).

3. SEDIMENTARY FACIES

Diamictite (55%) and sandstone (35%) comprise the bulk of the total succession thickness, whereas relatively thin units of mudstone (6%) and conglomerate (4%) form the remainder (Fig. 3). Each of these facies types is described below together with interpretations of their depositional origin. Soft sediment deformation features, which are common throughout the Port Askaig Formation, are also described in an attempt to establish their origin and palaeoenvironmental significance. Diamictites are numbered D1 through D47 (Figs. 2B and 3) following the original identification scheme of Kilburn et al. (1965) and Spencer (1971).

3.1. Diamictite
3.1.1. Description

Diamictite units are matrix-supported, massive or stratified and contain clasts up to several metres in diameter within a siltstone to silty sandstone matrix (Fig. 4). Clasts are subangular to rounded and are present in variable abundance. In places, clast fabric has been affected by tectonic cleavage so that it is difficult to determine if clasts ever had a preferred orientation (Spencer, 1971). Coarse-tail inverse grading was noted in some diamictite units (e.g. D15 on Eileach an Naoimh).

Stratification in diamictite units is defined by changes in matrix texture or clast characteristics, inclusions of other rock types, or discontinuous sandstone stringers (Fig. 4). Inclusions are irregular and discontinuous bodies, up to several m², of dolomitic conglomerate, sandstone, siltstone or diamictite with different matrix texture or clast abundance that are contained within a diamictite unit (Figs. 4C). They commonly show evidence of soft sediment deformation, with contorted and convoluted internal structure and/or outer margins, and impart a chaotic internal structure to the hosting diamictite. Outer margins of inclusions are either well defined, or poorly defined and gradational with the host diamictite. Discontinuous stringers of deformed sand (with or without clasts <3 cm in diameter), several cm thick and up to several m in length, commonly have flame-like irregular margins (Fig. 4B).

Diamictites most commonly form relatively tabular beds, 10 m thick on average (Fig. 3), although the Great Breccia is a distinctive diamictite unit, up to 50 m thick, that contains much larger clasts than the other diamictites (Spencer, 1971; Arnaud and Eyles, 2002; Fig. 3A). Most diamictites can be traced up to several kilometres across the Garvellach Islands. Several diamictite beds are laterally discontinuous over 100's of metres (e.g. D26, D31 and D32; Fig. 5), and others amalgamate as interbedded sediments thin out laterally (e.g. D2/3, D5-12, D16-18, D20-22, D27-29;...
Fig. 1). Upper and lower contacts of diamictite units are commonly sharply defined: lower contacts are conformable to erosional, with some gradational contacts, whereas upper contacts are loaded or conformable. Diamictite is commonly overlain by conglomerate, but is also associated with sandstone and mudstone (Fig. 3).

3.1.2. Interpretation

Diamictite can form as a result of many different processes including subglacial lodgement, deformation or meltout in ice-contact and ice-marginal settings, ‘rainout’ of fine grained sediments and ice rafted debris in glacially-influenced marine settings, and sediment gravity flows in glacial and non-glacial settings. It is important to distinguish among these various processes in palaeoenvironmental analyses as each indicate significantly different ice cover and palaeoclimatic conditions. Recent experimental studies, field-based sedimentological analyses, and offshore seismic data have documented the sedimentary characteristics and geometry of many diamictite deposits (e.g. Pickering et al., 1989, Colella and Prior, 1990; Lønne, 1995; Anderson, 1999; Mohrig et al., 1999; Sohn, 2000; Laberg and Vorren, 2000; Eyles and Eyles, 2000; Ó Cofaigh and Dowdeswell, 2001; Mulder and Alexander, 2001; Ghienne, 2003). These sedimentological data can be used to help differentiate ice-marginal from glacially-influenced or non-glacial diamictites (Fig. 6).

The Port Askaig Formation diamictites were originally interpreted as subglacial deposits by Spencer (1971). However, the absence of striated and faceted clasts, bullet-shaped boulders and boulder pavements, the lack of organized conglomerate and sandstone deposits typical of outwash fans found at ice margins, and the absence of glacitectonic deformation features, renders this
interpretation unlikely (Fig. 6; Eyles, 1988). The Port Askaig diamictites do not show evidence of shear deformation typical of subglacial tills (Benn and Evans, 1996), or of faulting, deformation and collapse of sediments typical of meltout and resedimented deposits at stagnant ice margins (Boulton, 1972). The lateral continuity and planar tabular geometry of the diamictite units also contrasts markedly with the chaotic outcrop geometry and rapid lateral facies changes that characterize ice-marginal terrestrial and marine deposits (cf. Boulton, 1972; Eyles and Eyles, 1984; Hart and Roberts, 1994).

Several of the diamictite units of the Garvellach Islands (e.g. D15, D26a, D28/29, D30, D31, Fig. 3) closely resemble poorly sorted deposits formed as a result of subaqueous sediment gravity flows (cohesive debris flows or non-cohesive hyperconcentrated density flows using terminology of Mulder and Alexander, 2001). Subaqueous sediment gravity flow deposits may be massive, graded or stratified, with sharp and conformable or erosional basal contacts, planar tabular or lenticular outcrop geometries, and they may contain inclusions of deformed sediment and sandstone stringers (Fig. 6B). These are all features shown by the diamictite units listed above. The Great Breccia (Fig. 3) is also interpreted as a sediment gravity flow deposit, although its characteristics suggest it was the product of a catastrophic subaqueous mass failure along a fault scarp (Arnaud and Eyles, 2002).

Inclusions in these diamictite beds result from incomplete mixing of heterolithic source sediment or incorporation of underlying materials during downslope transport (Nardin et al., 1979; Eyles and Eyles, 2000; Mulder and Alexander, 2001). Sandstone stringers in diamictites form by incomplete mixing of heterolithic sediment, or winnowing of the diamictites by traction currents (Powell and Molnia, 1989; Eyles and Eyles, 2000). Coarse-tail inverse grading may be the result
of various factors including surging within the flow (Major, 1997), a lag in the transport of the
coarsest size fraction (Hand, 1997), or clay rheology and a decrease in shear strength towards the
base of the debris flow (Naylor, 1980).

Although many diamictite units show characteristics consistent with a sediment gravity flow
origin, others show features that indicate an alternative mode of subaqueous deposition. Diamictite
units D20 and D35 (Fig. 3) are massive to stratified, contain clast clusters, show disruption of
laminae below large clasts and have tabular and blanket-like geometries with gradational to
conformable basal contacts. These characteristics are typical of diamictite formed as a result of
‘rainout’ of suspended fine-grained sediment and ice-rafted debris (Thomas and Connell, 1985;
Eyles et al., 1985; Hart and Roberts, 1994; Lønne, 1995; Crowell, 1999; Fig. 6C). Diamictite units
D20 and D35 also contain inclusions of deformed sediment, which may be attributed to the post-
depositional gravity-induced deformation of ice-berg dump deposits (Söhnge, 1984; Lønne, 1995;
Crowell, 1999). Sandstone stringers in these diamictite units probably result from winnowing of
sediment by traction currents.

Many diamictite units within the Port Askaig Formation do not show specific characteristics
that allow differentiation of either ‘rainout’ or sediment gravity flow depositional processes. These
diamictite types may have originated as a result of one or the other process or a combination of both.
Several Port Askaig diamictite units (e.g. D36-D38) show characteristics indicative of both
processes and suggest that diamict originally formed by ‘rainout’ processes may have been
subsequently remobilized on subaqueous slopes.

3.2. Sandstone
3.2.1. Description

Sandstone units are fine- to coarse-grained in texture and poorly- to well-sorted. Their lithology changes upsection from dolomitic sandstone at the base to quartzitic sandstone at the top of the succession. Whereas the quartzitic sandstone visually appears more mature than the dolomitic sandstone, both can be considered mineralogically immature based on petrographic work by Spencer (1971). Rare isolated outsized clasts can be found within sandstone units; they are generally less than 5 cm in diameter.

Sandstones include massive, deformed, laminated (horizontally, wavy or irregular), rippled, and cross-bedded facies of various scales (Figs. 3, 5, and 7). Deformed sandstone shows loaded basal contacts and/or convoluted or contorted internal laminations disrupted on cm to m scales. Asymmetrical ripples have heights and lengths of several cm. Cross-bed sets are between 0.2 and 11 m thick (small to very large using the terminology of Ashley, 1990). Cross-bedded sandstone units have planar and trough-shaped foresets with simple and compound internal structure. Foresets dip either randomly or in a preferred southerly direction (Spencer, 1971; Eyles, 1988; Arnaud, 2004).

All sandstone facies are present as relatively tabular units with sharp, planar, undulating or loaded basal contacts (Figs. 1 and 5). Individual sandstone beds range from centimetres to metres in thickness. Sandstones are most commonly found in association with diamictite, although they also occur interbedded with mudstone (Fig. 3). In the upper part of the succession, individual sets of giant (> 5m thick) cross-beds (e.g. Fig. 7D) occur stacked one on top of each other in successions up to 70m thick (Fig. 3).
3.2.2. Interpretation

Sandstone of the Port Askaig Formation appears to have accumulated in open marine conditions supplied from both dolomitic and siliciclastic sediment sources. Individual sandstone units record a number of different processes including deposition under upper flow regime plane bed conditions or from suspension (horizontally-laminated facies), and deposition under other unidirectional currents of varying velocities (rippled and cross-bedded facies). Thick successions of giant cross-beds in sandstone are interpreted to record the migration of large tidal bedforms in a marine setting based on their sedimentary characteristics, internal structure and facies associations (see Arnaud, 2004 for a detailed analysis). Disruption of sedimentary structures within deformed sandstone is indicative of liquefaction and loading. Internal structure may not be visible in outcrop in some cases or may have been lost by dewatering and liquefaction (massive facies). However, most massive sandstones are interpreted as resulting from rapid deposition by hyperconcentrated or concentrated sediment flows (terminology of Mulder and Alexander, 2001), based on their association with other sediment gravity flow deposits.

3.3. Conglomerate

3.3.1. Description

The conglomerates of the Port Askaig Formation are massive to crudely stratified and poorly-sorted with clasts up to 1 m in diameter in a fine- to coarse-grained sandstone matrix (Fig. 8). Conglomerate units range from centimetres to metres in thickness; thicker units commonly show a chaotic internal structure defined by contorted stringers of sandstone and variable clast content (Figs. 3 and 8). Crude inverse grading is observed at the base of some conglomerate beds. Clast
lithologies are similar to those found in diamicite and pass from dolomitic at the base to more granitic up-section.

Conglomerate beds are found most commonly as relatively tabular units with loaded (up to several m of relief), erosional, and/or sharp and conformable lower contacts (e.g. above diamicites D2, D22, D26, D31, D34; Figs. 3 and 8A). Conglomerate commonly overlies and loads into underlying diamicite, but is also associated with massive and horizontally-laminated sandstone; thin clast layers are occasionally present within mudstone facies (Fig. 8D).

3.3.2. Interpretation

Thin conglomerate units within the Port Askaig Formation were previously interpreted as lags, recording strong current winnowing of underlying diamicite (Spencer, 1971; Eyles, 1988). Conglomerates overlying diamicite units D6, D26a, and D35 form a thin surface veneer (one-clast thick) and are immediately overlain by cross bedded sandstone (e.g. Fig. 8B); these are likely to be lag deposits. However, the thicker beds of conglomerate that overlie diamicite units D2, D22, D26, and D34, with their poorly-sorted and matrix-supported nature, chaotic internal structure, erosional and loaded lower contacts, and the presence of some inverse grading, are most consistent with rapid deposition by hyperconcentrated density flow (e.g. Fig. 8A; Walker, 1975; Nemec et al., 1984; Nemec and Steel, 1984; Mulder and Alexander, 2001). Slightly thinner conglomerate layers associated with sandstone and mudstone are also interpreted as the product of hyperconcentrated density flows.

3.4. Mudstone
3.4.1. Description

Mudstone is most commonly horizontally-laminated, with laminae defined by slight changes in grain size; in places normal grading from fine sand to silt can be observed (e.g. Log GE-3, at 30-35 m, Fig. 5). Several mudstone units are massive or contain lenses of sandstone with weakly defined ripple structures. Although one mudstone unit at the top of Member II appears to be rhythmically laminated, no cyclical periodicities have been identified (Spencer, 1971). Outsized clasts (< 10 cm) or limestones within finely-laminated mudstone are either rare and randomly distributed, or are found concentrated in clast-rich layers (up to 5 cm thick; Fig. 8D; Spencer, 1971; Eyles, 1988). Soft sediment deformation is observed in fine-grained facies and includes convoluted or contorted laminations, pseudonodules, and rare water escape structures.

Mudstone units range from 0.25 to 8 m in thickness (Fig. 3). Lower contacts are either sharp and relatively planar or gradational. Upper contacts are commonly sharp, gradational or loaded showing flame structures. Mudstone is commonly associated with sandstone and diamictite, and is mostly found within Member II (Fig. 2B).

3.4.2. Interpretation

Eyles (1988) suggested that finely-laminated mudstones of the Port Askaig Formation accumulated as turbidites produced by sediment instability at the basin margin or by quasi-continuous sediment-laden underflows. The graded nature of some of the mudstone and its common association with other sediment gravity flow deposits is consistent with a turbidite origin. Low-density turbidity currents often result in the formation of Td-Te Bouma divisions and do not always lead to the development of current structures (Stow et al., 1996); this is thought to be particularly
common for surges and surge-like turbidity flows (Mulder and Alexander, 2001). Laminated mudstone may also have formed by the passive settling of suspended fines under quiet water conditions (Mulder and Alexander, 2001; Ó Cofaigh and Dowdeswell, 2001).

Few of the rare lonestones found within finely-laminated mudstone (3 out of approximately 30 observed in the 800 m of section measured for the study) show evidence of the bending, or piercing of underlying laminae, indicative of dropstones released by floating ice (Thomas and Connell, 1985). The palaeoclimatic significance of these three dropstones remains unclear given that they are small (on average less than 5 cm) and very rare. The presence of dropstones may indicate proximity to a glacial ice margin, although they may also have been derived from seasonal sea ice or icebergs far-removed from an ice margin (Crowell, 1964; Gilbert, 1990; Eyles et al., 1997). Other outsized clasts found in clast layers within mudstone are likely to have accumulated as thin hyperconcentrated density flows that reworked a heterogeneous sediment source area (see section 3.3.2).

3.5. **Soft sediment deformation features**

3.5.1. **Description**

Horizons displaying soft sediment deformation on cm to m scale and bounded by undeformed sediment are found at several distinct stratigraphic intervals within the Port Askiaig Formation (Figs. 9 and 10). Although some soft sediment deformation features are found only at specific localities, others affect laterally continuous sedimentary units that are traceable over several km along strike (Fig. 9). The distinctive blue-grey mudstone of the Disrupted Beds is laterally traceable from the Garvellach Islands to Islay, a distance of 48 km (Spencer, 1971), although the
most pervasive and large-scale deformation in the Disrupted Beds is restricted to outcrops in the
Garvellach Islands.

The stratigraphic interval known as the Disrupted Beds is associated with the Great Breccia
(see Fig. 2B) and exhibits particularly pervasive soft sediment deformation, including convolute and
contorted bedding at cm to m scales, and sedimentary boudinage (Kilburn et al., 1965; Spencer,
1971; Arnaud and Eyles, 2002).

Synsedimentary sandstone dykes up to 30 cm wide and 4 m long (the ‘sandstone wedges’
of Spencer, 1971) have been described in detail by Eyles and Clark (1985). They are commonly
found as randomly oriented and isolated features, but also occur arranged in polygonal nets on
bedding planes (e.g. D22, D35, Figs. 9, 10A and 10B). These dykes penetrate unconsolidated finer-
grained facies such as diamictite and mudstone of the Port Askaig Formation (Fig. 9), or dolomites
of the underlying Islay Formation, 20 to 25 m below the base of the Port Askaig Formation
(Spencer, 1971; Eyles and Clark, 1985). The nature of the contacts between dykes and the hosting
sediment ranges from sharp to poorly defined and regular to irregular with flame structures.

Other stratigraphic intervals within the Port Askaig Formation exhibit soft sediment
deformation features that affect individual beds and include convoluted or contorted bedding in
sandstone and mudstone, load casts (the sandstone downfolds structures of Spencer, 1971), ball and
pillow structures and pseudonodules of sandstone in mudstone (Figs. 9,10C-F).

3.5.2. Interpretation

The close stratigraphic association of deformed and undeformed sediment and the erosional
truncation of some of the deformed strata indicate repeated synsedimentary disturbance of
unlithified sediment, rather than post-depositional tectonic deformation of the entire stratigraphic unit (Spencer, 1971; Maltman, 1994).

Sandstone dykes of the Port Askaig Formation have been interpreted as subaqueous deformation features resulting from reverse-density loading and intrusion of sand into finer-grained facies (Eyles and Clark, 1985). The sandstone dykes are not likely to be periglacial ice-wedge casts as originally proposed by Spencer (1971) due to the absence of other periglacial indicators in the deposits (cf. Williams, 1994), the subaqueous origin of the diamictite, the close association of sandstone dykes with other soft sediment deformation structures, and their presence in marine non-glacial Islay Formation dolomite (Eyles and Clark, 1985). Eyles and Clark (1985) suggested that the dykes may have formed as a result of rapid sedimentation or seismic shaking, although they favoured a seismic origin based on the tectonic setting of the Port Askaig Formation. Downward-injected sandstone dykes with polygonal surface expressions have been documented elsewhere and interpreted as resulting from fluid injection into seismically-generated fissures (e.g. Söhnge, 1984; Aspler and Donaldson, 1986).

Contorted and convoluted laminations, sedimentary boudinage, ball and pillow structures, load casts and pseudonodules within the Disrupted Beds and the rest of the Port Askaig Formation are attributed to sediment liquefaction processes (deformation mechanism sensu Owen, 1987) and gravitational instabilities or unstable density gradients (driving force sensu Owen, 1987; Moretti et al., 1999). These soft sediment deformation features can form as a result of wave action, groundwater movements, slumping, rapid deposition of sediment with slightly different density characteristics, and/or seismic shaking (trigger mechanism sensu Owen, 1987; Obermeier, 1996; Molina et al., 1998; Jones and Omoto, 2000). Although other mechanisms cannot be completely
discounted, a seismic origin is preferred based on the following four criteria established in previous palaeoseismic studies (Sims, 1975; Obermeier, 1996; Pope et al., 1997; Moretti et al., 1999; Rosetti, 1999; Jones and Omoto, 2000).

1. **Active tectonic setting.** The Port Askaig Formation accumulated in the extensional Dalradian Basin at a time of increased tectonic activity (Harris et al., 1978, 1993; Anderton, 1982, 1985). The Great Breccia, a diamictite unit within the Port Askaig Formation, which formed as a result of catastrophic slope failure, suggests localized tectonic activity at this time (Arnaud and Eyles, 2002). The Disrupted Beds have been interpreted to indicate continued sediment instability following localized tectonic activity associated with deposition of the Great Breccia (Arnaud and Eyles, 2002). Recurring seismic activity following this initial faulting and instability is likely in the context of the regional tectonic setting of the Port Askaig Formation.

2. **Form.** Dykes, convoluted and contorted bedding, load casts, ball and pillow structures and pseudonodules of the Port Askaig Formation are similar to deformation features attributed to palaeoseismic events elsewhere (Söhnge, 1984; Aspler and Donaldson, 1986; Mohindra and Bagati, 1996; Bose et al., 1997; Lignier et al., 1998; Bhattacharya and Bandyopadhyay, 1998; Rosetti, 1999; Jones and Omoto, 2000), or to seismites produced experimentally with a shaking table (Moretti et al., 1999).

3. **Extent.** Deformation in the Port Askaig Formation is common and observed at distinct stratigraphic levels separated by intervals with no soft sediment deformation. This is consistent with the sporadic nature of seismic events in tectonically-active areas. In addition, the deformation features can be traced over a wide area (100's of m to km and up to 48 km for the Disrupted Beds; see Fig. 9). Decreasing amounts and complexity of deformation within the Disrupted Beds between
outcrops on the Garvellach Islands and Islay is consistent with regional trends shown by other seismites, where the strength of seismic waves and the resulting deformation decreases away from an epicentre (Obermeier, 1996).

4. Alternative mechanisms are unlikely. Soft sediment deformation is unlikely to have been the result of wave action and wave loading as there is no evidence for large storm waves affecting the substrate (e.g. HCS), and deformation is rarely associated with current-generated features (cf. Pratt, 1994; Molina et al., 1998). The deposition of the Great Breccia and the pervasive deformation reported within the Disrupted Beds suggest slumping and tensioal stresses along a localized palaeoslope. However, this mechanism is unlikely to explain the smaller scale and discrete intervals of soft sediment deformation features found at other stratigraphic levels. Based on the highly variable palaeocurrent directions derived from cross-bedded sandstone higher up in the succession, Spencer (1971) concluded that there was no evidence for a palaeoslope of regional extent within the upper part of the Port Askaig Formation. It also seems unlikely that the deformation was a result of groundwater movements, because of the lack of topography or geological structure required to create artesian conditions.

It is difficult to completely discount rapid deposition as a trigger mechanism for soft sediment deformation due to the abundance of sediment gravity flow facies within the Port Askaig Formation. However, soft sediment deformation features are found throughout the succession despite changes in dominant facies types and depositional processes. For example, deformed units are closely associated with mudstones in the lower part of the succession, which have been interpreted as recording fine-grained turbidite deposition (e.g. between Disrupted Beds and D26; Fig. 9); other deformation features higher in the succession are associated with cross-bedded and
rippled sandstone (e.g. between D26 and giant cross-beds-XB, Fig. 9). This suggests that the mechanism responsible for the deformation may be independent of depositional process and therefore not necessarily connected to rapid deposition. Other indicators of rapid deposition such as climbing ripples in sandstone are also conspicuously absent from the succession.

In conclusion, based on the above four criteria, it is proposed that the Disrupted Beds, the clastic dykes, and other soft sediment deformation features within the Port Askaig Formation represent intervals of deformation primarily related to episodic seismic activity.

4. STRATIGRAPHY

Sedimentological analysis of individual facies types found within the Port Askaig Formation suggests deposition by a variety of processes in a marine environment that was supplied with large amounts of poorly-sorted sediments and was periodically prone to seismic activity. Establishing the nature and scale of changing palaeoenvironmental conditions through time requires analysis of facies types in their stratigraphic context. Seven stratigraphic units can be identified within the succession, each consisting of a distinct assemblage of facies types (Table 1, Fig. 9).

4.1. SU1: dolomitic diamictite (95 m thick)

This lowermost stratigraphic unit overlies the upper dolomitic member of the Islay Formation, the upper 36 m of which is characterized by interbedded dolomite, dolomitic sandstone and pelites (Spencer, 1971). The basal contact of SU1 is gradational on the Garvellach Islands and erosional on Islay (Spencer, 1971). SU1 is characterized by massive dolomitic diamictite interbedded with discontinuous units of dolomitic sandstone (massive, deformed or horizontally-
laminated), conglomerate, and siltstone (Fig. 9, Table 1). Soft sediment deformation features are not common in SU1. Massive diamicrite units are interpreted as debris flow deposits due to the absence of ice-rafted debris in associated deposits, although a ‘rainout’ origin cannot be completely ruled out. Associated conglomerate, sandstone and siltstone are also interpreted as the product of hyperconcentrated density flows and turbulent flows.

The transition from increasingly siliciclastic sediments of the upper Islay Formation to the diamicrite-bearing SU1 of the Port Askaig Formation heralds a major change in sediment supply and depositional conditions in the basin. SU1 appears to record reworking of local coarse-grained dolomitic sediment. The predominance of sediment gravity flow facies suggests an unstable depositional environment, possibly on or adjacent to a marine slope. The predominance of sediment gravity flow facies and absence of ice-rafter debris make it difficult to identify a distinct glacial influence on sedimentation.

4.2. SU2: the Great Breccia (40-60 m thick)

SU2 is bounded by an erosional surface at its base and comprises the Great Breccia and immediately overlying massive to stratified conglomerate and sandstone units (Fig. 9, Table 1). SU2 constitutes a crudely fining-upward succession, recording initial catastrophic failure of lowermost Port Askaig Formation and Islay Formation deposits along a localized active fault scarp, and subsequent retrogressive failure of unstable sediment exposed along steep subaqueous slopes (Arnaud and Eyles, 2002).

4.3. SU3: the Disrupted Beds (25 m thick)
Mudstone of the Disrupted Beds (SU3) sharply overlies conglomerate of SU2 (Fig. 9). This stratigraphic unit consists of blue-grey mudstone interbedded with dolomitic sandstone, conglomerate and diamicite. It is pervasively deformed at the scale of individual beds as well as over 10's of m of lateral and vertical exposure (Table 1). Lateral changes from boudinaged sandstone beds to chaotically stratified and massive diamicite are interpreted as recording increasing deformation and homogenization by slumping of sandstone, conglomerate and mudstone (Arnaud and Eyles, 2002; Table 1). SU3 marks the first appearance of extrabasinal clasts in the Port Askaig Formation (10-15% of all clasts in 0.1 m$^3$; data from Spencer, 1971); rare limestones in mudstone facies show disruption of underlying laminae and are interpreted as dropstones.

The base of SU3, where mudstone sharply overlies conglomerate, is interpreted as a flooding surface. The predominance of siltstone and siltstone-rich diamicite within this stratigraphic unit also suggests a change to relatively deep and quiet water depositional conditions. The Disrupted Beds indicate continued sediment instability in the basin, following deposition of the Great Breccia (Arnaud and Eyles, 2002). While the palaeoclimatic significance of rare dropstones in SU3 is difficult to establish, their presence and the first appearance of extrabasinal clasts may constitute the first indication of glacial influence on sedimentation.

4.4. SU4: diamicrite and mudstone (55 m thick)

The lower contact of SU4 with the underlying Disrupted Beds is sharp to gradational. This stratigraphic unit consists of interbedded diamicrite, finely-laminated mudstone with common clast layers, and dolomitic to quartz-rich sandstone that is predominantly massive, deformed or laminated (Fig. 9, Table 1). Soft sediment deformation is observed at several discrete horizons separated by
significant thicknesses of undeformed sediment (Fig. 9). Diamictite in SU4 is interpreted as the product of debris flow processes (D15), ‘rainout’ processes (D20) or a combination of both. Associated facies are interpreted as the products of hyperconcentrated or concentrated flows, turbidity currents or settling of fine-grained sediment from suspension. Rare lonestones were observed, but only one shows clear disruption of underlying laminae. The ‘rainout’ diamictite and the single dropstone suggest a possible glacial influence on sedimentation. Intervals characterized by soft sediment deformation structures indicate intermittent but continued sediment instability, primarily related to episodic seismic shaking.

SU4 deposits thus record the continued domination of sediment gravity flow processes, reworking of both intrabasinal and extrabasinal material, and some glacial influence on sedimentation. The continuation of unstable depositional conditions is likely related to ongoing tectonic activity, which may have been augmented by high influxes of coarse-grained glacigenic sediment to the basin margin. However, it should be noted that evidence for glacial conditions is relatively weak and that the presence of a significant ice margin in the Dalradian basin at this time is uncertain.

4.5. SU5: diamictite and sandstone (65 m thick)

The basal contact of SU5 is conformable and stratified diamictite and horizons of deformation features are still common (Fig. 9, Table 1). However, SU5 is defined by the appearance of current-generated structures and relatively thick interbedded sandstone and mudstone separating diamictite units (Fig. 9). Sediment gravity flows continue to dominate (D26A, 28/29, 30 and 31, siltstone and massive sandstone, Figs. 3 and 5) other sandstone facies indicate deposition under other
unidirectional currents and upper flow regime conditions.

The appearance of current-generated structures and the increasing importance of sandstone facies in SU5 indicate a significant change in the nature of sediment supply and depositional conditions within the basin. Soft sediment deformation features between D30 and D31, together with horizons of sandstone dykes (Fig. 9), indicate continued sediment instability and intermittent seismic shaking. Evidence for glacial influence on sedimentation within SU5 is very limited; only the uppermost laminated mudstone unit contains rare dropstones. SU5 exhibits a fining-upward trend, passing from a diamicite-sandstone association at the base to a diamicite-siltstone association at the top (Fig. 9). The fining upward trend may be a function of a variable supply of sand and/or increasing water depths caused by basin subsidence.

4.6. SU6: cross-bedded sandstone (100 m thick)

The base of SU6 is sharp and appears conformable with underlying sandstone of SU5 (Fig. 9). SU6 consists of thick packages of quartz-rich giant cross-beds in sandstone and thinner units of diamicite and conglomerate (Fig. 9, Table 1). The giant cross-beds at the base of SU6 mark a significant change in depositional conditions characterized by an ample supply of well-sorted quartz-rich sediment and the migration of large subaqueous dunes in a current-dominated setting. Diamictite units show characteristics typical of deposition by either ‘rainout’ processes (D35), or a combination of sediment gravity flow and ‘rainout’ processes (D33 and D34). Conglomerate is the product of both hyperconcentrated density flows (overlying D34) and winnowing of underlying diamicite (overlying D35). Soft sediment deformation features are a minor component of SU6, suggesting more tectonically-stable depositional conditions than those previously existing. Rare
outsized clasts in cross-bedded sandstone immediately below diamictite D36 were interpreted as ice-rafted clasts by Spencer (1971).

The thickness (up to 70 m) and unchanging nature of the sandstone units suggests that the balance between sediment supply and creation of accommodation space was maintained; depositional conditions appear to have remained unchanged for significant periods of time. A single interval of diamictite deposition by glacially-influenced mass-flow and/or ‘rainout’ processes within SU6 (Fig. 9) indicates an abrupt shift to a relatively coarse-grained and poorly-sorted sediment supply, which may relate to the onset of glacially-influenced conditions and/or shallower water conditions in the basin. The thick successions of sandstone recording the development of large subaqueous bedforms otherwise suggest persistent ice-free conditions during deposition of SU6.

4.7. SU7: sandstone and diamictite (55 m thick)

The base of SU7 is marked by an erosional surface. This stratigraphic unit is characterized by interbedded sandstone and diamictite, and is distinguished from the underlying SU6 by relatively thin packages of quartz-rich cross-bedded sandstone, smaller cross-bed sets (<50 cm thick), variable palaeocurrent directions (Spencer, 1971; Eyles, 1988) and the presence of climbing and mud-draped ripples and soft sediment deformation features (Fig. 9, Table 1). Cross-bedded sandstone units within SU7 are indicative of weaker and more variable traction currents than those that formed the larger bedforms preserved in SU6. The presence of massive sandstone, climbing ripples and soft sediment deformation features suggests rapid sedimentation in the uppermost part of SU7. Diamictite units D36-38 have characteristics indicating that both sediment gravity flow and ‘rainout’ processes were important in their formation. SU7 thus represents deposition under variable currents
in an open marine setting, separated by intervals of glacially-influenced conditions (Fig. 9).

5. BASIN DEVELOPMENT AND CONTROLS ON SEDIMENTATION

The seven stratigraphic units identified show a progressive upward change from a predominantly coarse-grained facies association at the base, through a diamictite-mudstone association, into a sandstone-diamictite association at the top of the succession. This stratigraphy reflects changing environmental conditions over time and allows three major phases of Port Askaig deposition to be defined (Fig. 11). Each of these phases represents a different stage of development of the sedimentary basin and records changing controls on sedimentation patterns with time.

5.1. Phase I (SU1-SU4)

Phase I (Fig. 11A; Table 1) of Port Askaig deposition is a fining-upward succession that consist predominantly of carbonate-rich sediment gravity flow facies that record reworking of locally-derived sediment in a tectonically-active depositional environment. The Great Breccia and common horizons of soft sediment deformation within SU3 and SU4 provide evidence for tectonic influences on sedimentation. These deposits contain very few current-generated structures, which suggests either reworking of current-generated deposits during slumping, or accumulation of sediment below wave base in relatively deep water.

The increased delivery of coarse-grained debris to the basin margin and the abundance of sediment gravity flow facies may have been controlled by climatic or tectonic factors, or a combination of both. Glaciation of basin margins can contribute large volumes of coarse-grained debris to the marine environment. Rapid glaci-eustatic sea level changes and depositional
oversteepening caused by high sedimentation rates at the basin margin may have triggered
reworking of coarse-grained debris downslope as sediment gravity flows. However, a distinct
glacial influence on sedimentation is difficult to confirm in this earliest phase of Port Askaig
deposition as sedimentation was dominated by sediment gravity flow processes and evidence for the
presence of ice is limited to a single diamictite formed by ‘rainout’ processes (D20) and rare
dropstones and extrabasinal clasts found within SU3 (the Disrupted Beds) and SU4. Given the clear
evidence for faulting and tectonic instability, it is most likely that the onset of coarse-grained
sediment deposition at the base of the Port Askaig Formation is at least in part related to local
tectonic activity. In this context, the fining-upward trend that characterizes Phase I can be
interpreted as driven by fault-related subsidence outpacing sediment supply.

5.2. Phase II (SU5)

Phase II records the transition from sediment gravity flow dominated deposition of locally-
derived materials in Phase I to the predominance of current-deposited sandstone facies and farther-
travelled materials in Phase III (Fig. 11B; Table 1). The appearance of current-generated structures
in sandstone of SU5 suggests that Phase II was characterized by relatively shallow-water conditions
and/or more stable substrates (lower slopes?), where sandy bedforms could develop and be
preserved. The presence of relatively thick units of sandstone marks the onset of a coarsening
upward trend passing from the diamictite-mudstone association of SU3 and SU4 to the sandstone-
diamictite association of SU6 and SU7. There is continued but intermittent tectonic activity within
the basin based on soft sediment deformation horizons and limited glacial influence on
sedimentation (Figs. 9 and 11B).
5.3. Phase III (SU6-SU7)

Phase III deposition is characterized by the migration of large subaqueous dunes in an ice-free open marine setting as well as intervals of glacially-influenced deposition by ‘rainout’ and sediment gravity flow processes (Fig. 11C, Table 1). The overall coarsening upward trend from Phase I to Phase III sediments is likely related to an increase in sediment supply and a decrease in fault-related subsidence. The abundant supply of well-sorted quartz-rich sand during Phase III probably reflects development of a major fluvial (glaciofluvial?) feeder system on the basin margin and delivery of sand to the basin by seaward-returning relaxation flows, flood discharge jets or rip currents (Johnson and Baldwin, 1996).

Soft sediment deformation features are rare in SU6 and SU7 and are associated with indicators of rapid sedimentation such as climbing ripples and massive sandstone; the sediment disturbance by faulting and seismic shaking that predominates in the previous two phases appears to have ceased by Phase III. Given this relative tectonic quiescence, the diamictite deposited by sediment gravity flow processes during Phase III is most likely the result of glacially-influenced sediment instability. As a result, interbedding of thick sandstone with glacially-influenced diamictite is interpreted to reflect ice margin fluctuations during Phase III (Fig. 11C). Unlike diamictite deposited during Phase I and II, a climatic signal can be inferred from the delivery of coarse-grained sediment and formation of diamictite under the relatively quiet tectonic conditions of Phase III.

6. DISCUSSION

The Great Breccia, the Disrupted Beds and the repeated intervals of synsedimentary soft
sediment deformation features within the succession, strongly suggest that localized tectonic activity played a significant role in controlling the nature of sedimentation. No faults or fault traces have been identified on the Garvellach Islands. However, this is probably due to the limited outcrop and the coarse-grained nature of the sediment. On a regional scale, there are significant thickness changes between various outcrops of the Port Askaig Formation in Scotland, which provide further evidence for tectonic controls on succession development (Anderton, 1982, 1985). For example, over 100 m of the Port Askaig and Islay formations exposed on the Garvellach Islands below the Great Breccia are absent on Islay, where the Great Breccia unconformably overlies carbonate deposits of the Islay Formation (Figs. 1 and 2; Spencer, 1971). The thickness of the Great Breccia itself varies from 50 m on the Garvellach Islands to only 4 m on the island of Islay, which lies 48 km to the southwest (Spencer, 1971; see Fig. 1 inset).

This sedimentological and stratigraphic evidence is consistent with existing models for the Dalradian Basin, which identify an extensional basin on continental crust (Harris et al., 1978; Anderton, 1982; Harris et al., 1993). The changing facies associations and tectonic conditions reported in this paper are also consistent with those reported in other extensional settings (Schermerhorn, 1974; Nystuen, 1985; Young, 1988; Eyles, 1993; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). Initial fault activity and basin differentiation is recorded by deposition of coarse-grained sediment gravity flow deposits (e.g. diamicrites and conglomerates) followed by tectonic quiescence and basin infilling with marine strata (e.g. turbiditic mudstones and tidally-influenced sandstones).

The presence of several diamicrite beds on the Garvellach Islands interpreted as the product of ‘rainout’ processes, rare dropstones and the presence of far-travelled clasts in several stratigraphic
units, suggests glacial conditions may have had some influence (albeit weak) on sedimentation during early Port Askiaig times (Phase I and II). The relative importance of a climatic control in this early part of the succession is difficult to assess due to the predominance of sediment gravity flow deposits and tectonic activity in most of Phase I and II. Considering the tectonically-quiescent conditions of Phase III, the sediment gravity flow diamictite in this part of the succession is most likely related to glacially-induced instability and fluctuations of an ice margin. A glacial influence on sedimentation and significant climatic control in this later phase of deposition is also likely as it can explain the continued delivery of poorly-sorted coarse-grained sediment to the basin margin, the high rates of sediment supply that kept pace with local subsidence rates and the resulting fining-upward to coarsening upward architecture of this succession.

Schermerhorn (1974) argued that tectonic activity was much more important than climate change in controlling the nature of Neoproterozoic successions; he attributed evidence for limited glacial influence in some successions to localized mountain glaciation of uplifted basin margins. Given the evidence for tectonic activity and the limited evidence for glacial influence on sedimentation in the Port Askiaig Formation, this study appears to support some of Schermerhorn’s (1974) contentions. The diamictite of the Port Askiaig Formation most likely records sediment instability related to tectonic activity and basin development, and localized glaciation of basin margins.

The snowball Earth hypothesis suggests Neoproterozoic glaciations were global, lasting between 4-30 Ma, with thick ice covering the oceans (Hoffman et al., 1998). This study has shown that diamictite cannot be presumed to represent severe glacial conditions. None of the Port Askiaig diamictite units analysed in this study records subglacial deposition. Some are a result of glacially-
influenced ‘rainout’ processes, which implies floating ice rather than completely frozen oceans, and many other diamicrites formed by sediment gravity flow processes, most likely associated with tectonic activity in the basin.

Deposition and preservation of thick and variable sediment types in a marine setting, as well as evidence for alternating ice-free and ice-influenced depositional conditions in SU6/SU7 deposits, are incompatible with a completely frozen Earth as proposed in the snowball Earth hypothesis (Hoffman et al., 1998; Hoffman and Schrag, 2002). While glaciation may have had an influence on sedimentation of the Port Askaig Formation, there does not appear to be any evidence for climatic conditions as severe as those proposed by the snowball Earth hypothesis.

7. CONCLUSIONS

The Neoproterozoic Sub-Era appears to record significant palaeoenvironmental changes, many of which have been considered paradoxical and enigmatic. The Port Askaig Formation exposed on the Garvellach Islands in Scotland contains a wealth of information about the nature of palaeoenvironmental change at this time. This thick succession consists of diamicrite interbedded with conglomerate, sandstone and mudstone, which accumulated by various processes in a tectonically-active and glacially-influenced marine setting.

Detailed sedimentological analysis has shown that many diamicrite units were formed by subaqueous debris flows, where a distinct glacial influence on their formation cannot be discerned. Relatively few of the diamicrite beds are interpreted as glacially-influenced ‘rainout’ deposits, which together with rare dropstones, record the presence of floating ice in the basin. Associated sandstone and mudstone facies were deposited as sediment gravity flows or under current-dominated
subaqueous conditions. Giant cross-beds in the upper part of the succession formed as a result of
the migration of large subaqueous sand dunes; these most likely accumulated under the influence
of tidal currents in open marine waters. Localized tectonic activity is inferred from the Great
Breccia, the Disrupted Beds and horizons of abundant soft sediment deformation features, which are
interpreted to record episodic seismic activity.

Stratigraphic analysis has allowed 3 phases of deposition to be identified with an early stage
dominated by sediment gravity flow processes (Phase I and II) and a later stage characterized by ice-
free, current-dominated conditions alternating with glacially-influenced sedimentation (Phase III).
The first two phases appear to be controlled by tectonic influences, although climatic influences on
sedimentation may have been obscured by the predominance of sediment gravity flow processes.
Glacial influence on sedimentation can only be unambiguously identified in Phase III, where
conditions appear to be tectonically stable and diamictite interbedded with cross-bedded sandstone
most likely records changes in sea level and sediment supply associated with ice margin fluctuations.

This study has shown that many Port Askaig diamictite units record sediment instability
related to tectonic activity and basin development rather than severely cold conditions as postulated
by the snowball Earth hypothesis. The thick succession of sediments preserved within the Port
Askaig Formation also indicates abundant sediment delivery to the Dalradian Basin, deposition
under strong tidal currents and ice margin fluctuations. These characteristics are inconsistent with
the deep freeze conditions of a snowball Earth.

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FIGURE CAPTIONS

Fig. 1: The Garvellach Islands, Scotland. A) geological map showing Islay Formation and various facies types in the Port Askaig Formation (modified from Spencer, 1971). Dip of beds is towards the south/southeast at 35°; beds ‘young’ towards the south; B) map showing sections logged in this study. Triangles on inset map of Scotland show other outcrops of the Port Askaig Formation (modified from Spencer, 1971).

Fig. 2: A) The Dalradian Supergroup and stratigraphic position of the Port Askaig Formation. Total stratigraphic thickness is approximately 25 km (modified from Anderton, 1985; Eyles, 1988; Prave, 1999). Date for the Grampian Group is from Noble et al. (1996). The Tayvallich Volcanics have been dated at 595 ± 4 Ma by Halliday et al. (1989) and at 601 ± 4 by Dempster et al. (2002). See text for discussion. J, Jura Quartzites; B, Bonahaven Formation; I, Islay Limestone. B) Schematic log through the Port Askaig Formation showing Members (I-V; Spencer 1971), phases (I-III; this study) and stratigraphic units (1-7; this study); base is at lower left, top at upper right. It should be noted that phases I-III are broadly equivalent to the Members defined by Spencer, although there is a significant difference in the definition of Member II and Phase II (Fig. 2B). Member II was defined by Spencer (1971) on the basis of the first appearance of significant amounts of extrabasinal clasts and the predominance of mudstone facies in the interval between the Disrupted Beds and the giant cross-beds of Member III (Fig. 2B). In contrast, the base of Phase II is defined here as beginning higher up in the succession and is characterized by the first appearance of current-generated structures, which replace the sediment gravity flow facies typical of Phase I deposits (Fig. 2B). The stratigraphic log of Members I through III is based on analysis of outcrops on the
Garvellach Islands; the stratigraphic log of Members IV and V is modified from Spencer (1971) and
based on outcrops from Islay. Numbering of diamictite units (D1-D47) first established by Kilburn
et al., (1965) and used later by Spencer (1971) is retained here. Formal member names are as
follows I-Beannan Buidhe, II-An Tamhanachd, III-Creagan Loisgte, IV-Ruadh-Phort Beag, V-Con
Tom (Spencer, 1971); roman numerals are used throughout the paper for the sake of brevity. GB
is Great Breccia; DB is Disrupted Beds; XB is giant cross-beds.

Fig. 3: A) Generalized graphic log of the Port Askaig Formation exposed on the Garvellach Islands
based on 11 detailed graphic logs (e.g. EN-2, GE-3) measured for this study (see Fig. 1B for their
location). Note the lithology of clasts within diamictite is undifferentiated in this log; B) symbols
and lithofacies codes used in this study. Abbreviations and numbering of diamictite units as in Fig.
2.

Fig. 4: Diamictite facies. A) massive diamictite D28/29, log GE-3; B) sandstone stringer within
diamictite D26, log AC-2. Note the soft-sediment deformation of the outer margin of the sandstone
stringer; C) deformed sandstone inclusion within diamictite D30, log GE-3. See Fig. 1 for location
of logs and Fig. 3 for stratigraphic location of diamictite units.

Fig. 5: Partial graphic logs at selected sites showing the interval between diamictite D30 to the base
of the giant cross-beds. Note the lateral facies changes shown by diamictite D31 and D32, the
horizons of deformation features in associated sandstone and mudstone facies, the sandstone dykes
penetrating mudstone in the uppermost part of logs GE-3 and GE-8 and the presence of current
generated structures typical of Stratigraphic Unit 5. See Fig. 1 for location of logs and Fig. 3B for symbols and lithofacies codes. Numbers in brackets represent distance between logs; the facies code “Flent.d” corresponds to pseudonodules (deformed lenses of sandstone within mudstone).

Fig. 6: Idealized graphic log, sedimentary characteristics, outcrop geometry and associated facies that can help distinguish diamictite deposited by A) subglacial lodgement and deformation processes in ice-marginal settings (see text for additional comments on meltout processes); B) subaqueous sediment gravity flow processes in glacial and non-glacial settings; and C) ‘rainout’ processes in glacially-influenced marine settings. See text for explanation. Lithofacies codes as in Fig. 3B; ‘FA’ stands for Facies Association. No particular clast lithology is inferred. Deposition by subglacial lodgement or deformation processes can result in diamictite units up to 10's of m, whereas deposition by sediment gravity flow and ‘rainout’ processes can result in units up to 100's of m in thickness.

Fig. 7: Sandstone facies. A) deformed and horizontally-bedded sandstone with minor units of mudstone and rippled sandstone lying between diamictite units D30-31, log EN-2 (person arrowed for scale). Note the cross-bedded sandstone in the lower part of the photograph, which records deposition under unidirectional currents (see Fig 5 for detailed stratigraphic log); B) close up view of horizontally-bedded and deformed sandstone shown in (A); C) rippled sandstone facies above diamictite D38, log GE-2, Stratigraphic Unit 7. These symmetrical ripples suggest limited wave action influenced sediment deposition. Note that rippled sandstone in other Stratigraphic Units are asymmetrical, suggesting deposition under unidirectional currents; D) giant cross-beds, log GE-8
(person circled for scale). See Fig. 1 for location of logs and Fig. 3 for stratigraphic locations of units.

Fig. 8: Photographs and graphic logs showing typical stratigraphic relationships and characteristics of conglomerate facies A) loaded and deformed contact of conglomerate with underlying diamictite (D26), log GE-3; B) one-clast thick conglomerate bed (arrowed) separating underlying diamictite (D26A) from overlying cross-bedded sandstone, log EN-2; C) channelized conglomerate within interbedded sandstone and mudstone, log EN-2; D) finely-laminated siltstone with thin clast layers (arrowed), below diamictite D16, log EN-3. See Fig. 1 for location of logs and Fig. 3 for overall stratigraphic position, symbols, and lithofacies codes.

Fig. 9: Summary composite log for the Port Askaig Formation on the Garvellach Islands showing intervals characterized by synsedimentary deformation, horizons of sandstone dykes and stratigraphic levels where rare outsized clasts were observed (this study and additional data from Spencer, 1971; Eyles and Clark, 1985; Eyles, 1988). Stratigraphic units 1 through 7 are also identified. GB is Great Breccia; DB is Disrupted Beds; XB is giant cross-beds. Numbering of diamictite units as in Fig. 2B. Note the deformation of the Disrupted Beds can be traced along strike to the island of Islay, 48 km SW of the Garvellach Islands.

Fig. 10: Synsedimentary deformation features. A) polygonal array of sandstone dykes on the surface of diamictite D22, Eileach an Naoimh; B) sandstone dykes (arrowed) penetrating into diamictite D22, east Garbh Eileach. Note sandstone dyke that is connected to overlying deformed sandstone
and conglomerate bed; C) loaded lower bed contact in interbedded sandstone and mudstone above diamicite D30, log GE-3; D) folded and convoluted sandstone above diamicite 38, log GE-2; E) general view of deformed pseudonodules (sandstone in mudstone) found above D30 (see log EN-2, Fig. 5). Regional dip to the lower left; F) close up view of pseudonodules shown in (E). See Fig. 1 for location of logs and Fig. 9 for stratigraphic location of deformation features.

Fig. 11: Model showing depositional environments for different phases of Port Askaig deposition on the Garvellach Islands. A) Phase I; B) Phase II; C) Phase III. Circled numbers refer to stratigraphic units. ‘G’ denotes the position of the Garvellach Islands sections. See text for explanation.
<table>
<thead>
<tr>
<th>Phase</th>
<th>Stratigraphic Unit</th>
<th>Dominant Facies</th>
<th>Depositional process</th>
<th>Depositional Setting</th>
<th>Control on sedimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>St, Sh, Dms</td>
<td>Sediment gravity flow, and/or ‘rainout’, unidirectional currents</td>
<td>Tidally- and glacially-influenced offshore marine setting under relatively stable tectonic conditions</td>
<td>Tectonic</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td>Very thick St, Sh, Dms</td>
<td>Tidal currents, Sediment gravity flow and/or ‘rainout’</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sh, Sd, St, Sr, Fl, Dms, (def)</td>
<td>Sediment gravity flow, unidirectional currents</td>
<td>Transitional between Phase I and Phase III</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td>Dms,Dmm Fl, Fd, (def)</td>
<td>Sediment gravity flow, and/or ‘rainout’</td>
<td>On or adjacent to a slope in a marine setting and dominated by sediment instability, slumping and sediment gravity flow processes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fl, Sd, Dms, Gms (def)</td>
<td>Sediment gravity flow, tensional stress and downslope remobilization</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Mega-Br, Dms, Gm, Fl, Sh, Sm, Sd</td>
<td>Catastrophic and retrogressive mass failure from fault-bounded scarp</td>
<td>Localized tectonic activity in SU2, episodic seismic activity in SU4</td>
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</tr>
<tr>
<td>I</td>
<td></td>
<td>Dms, Dmm Gms, Sd, Sm, Sh</td>
<td>Sediment gravity flow, ‘rainout’ of fine sediment and ice-rafted debris possible</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Conglomerate facies

- Gm: matrix-supported, massive
- Gms: matrix-supported, stratified
- Br: breccia

## Sandstone facies

- Sd: deformed
- Sh: horizontally laminated
- Sr: rippled
- St: trough cross-bedded
- Sp: planar cross-bedded
- Sm: massive

## Fine-grained facies

- Fl: laminated
- Flc: laminated, with clasts
- Fld: laminated, deformed
- Fd: deformed
- Fm: massive

## Diamictite facies

- Dmm: matrix-supported, massive
- Dms: matrix-supported, stratified
- D12: diamicite #12

### Symbols:
- Laminated
- Deformed
- Rippled
- Cross-bedded, planar foreset
- Cross-bedded, tangential foreset
- Diamictite, massive
- Diamictite, stratified, with inclusions
- Conglomerate
- Breccia
- Granitic
- Dolomitic
- Polymictic
A

Subglacial lodgement and deformation

- Typical succession consists of erosional to deformed basal contact, deformed, and sheared glaciteconite and massive diamicite
  - Massive or chaotically stratified
  - Inclusions (can be deformed and/or well sorted) from outwash sediments?
  - Boulder pavements, bullet-shaped boulders
  - Erosional or deformed contact
  - Thin, tabular geometry
  - FA: outwash conglomerates and sandstones

B

Sediment gravity flow

- Massive, stratified or graded
  - Inclusions and stringers (deformed) from incomplete mixing of sediment rafts eroded into or carried by the debris flow
  - Sharp, conformable or erosional contact, deformation at base of unit
  - Lenticular, channelized or tabular geometry
  - FA: other sediment gravity flow facies

C

‘Rainout’

- Massive or stratified with horizontal stratification from winnowing
  - Dropstones, clast clusters, diamicct pellets
  - Variable clast content from changes in sediment accumulation rates or supply of IRD
  - Gradational basal contact
  - Blanket-like, draped geometry
  - FA: outwash sediments (ice proximal), sediment gravity flow facies and laminated mustones with dropstones (ice distal)

Powell, 1981; Eyles et al., 1985; Powell and Molnia, 1989; Hart and Roberts, 1994; Lønne, 1995; Benn and Evans, 1996; Hambrey and McKelvey, 2000

Nardin et al., 1979; Prior et al., 1984; Eyles et al., 1985; Postma et al., 1988; Powell and Molnia, 1989; Prior and Bornhold, 1990; Aksu and Hiscott, 1992; Eyles, 1993; Eyles and Eyles, 2000; Hambrey and McKelvey, 2000; Lowe and Guy, 2000; Laberg and Vorren, 2000; Mulder and Alexander, 2001

Ó Cofaigh and Dowdeswell, 2001