**Cryogenian glaciation: the extraordinary Port Askaig record**

*Virtual conference via Zoom 26-27 May 2021*

# Programme and Abstracts

This international workshop is in association with the Cryogenian Working Group of the International Stratigraphic Commission

This workshop is designed to allow in-depth presentations of the results of a long-term field campaign on the 1100 m thick Port Askaig Formation focussed on the extraordinarily complete exposures in the Garvellach Islands and Islay.

# Programme

**This is the second updated version (18th May) of the programme. A recording will be made of each of the four sessions and posted to a Youtube channel by David Webster by the morning of 28th May. The address for the channel is:** https://www.youtube.com/channel/UCnvq23gfJdfTtghqq4REw7Q

| Topic | Speaker(s) | Timing |
|---|---|---|
| **Session A. 26th May Start 12 noon** | | |
| **Welcome** | **David Webster (Geological Society of Glasgow)** | 12.00 |
| 0. Use of drone technology on the Garvellach Islands | Jordan Mertes and Doug Benn | 12.05 |
| 1. Port Askaig Fm: context & history of research | Anthony Spencer | 12.10-12.30 |
| 2. Carbonate substrata – Garbh Eileach Fm & Cryogenian correlation | Ian Fairchild | 12.30-13.00 |
| 3. Stratigraphic architecture of the PAF | Roger Anderton | 1.00-1.20 |
| Discussion of topics 1 to 3 (contribute via chat function) | | 1.20-1.45 |
| **Session B. 26th May Start 2 p.m.** | | |
| 4. Glacial geology – grounded and floating ice | Doug Benn, Mike Hambrey and Jordan Mertes | 2.00-2.35 |
| 5. Periglacial geology | Richard Waller and Mike Hambrey | 2.35-3.05 |
| 6. Identifying detailed events: example of D26 | Dilshad Ali | 3.05-3.15 |
| Discussion of topics 4 to 6 (contribute via chat function) | | 3.15-3.45 |
| **Session C. Non-glacial environments 27th May Start 12 noon** | | |
| 7. Origins of dolomite | Ian Fairchild | 12.00-12.30 |
| 8. Marine environments | Roger Anderton | 12.30-1.00 |
| 9. Continental environments | Bruce Levell | 1.00-1.30 |
| 10. Virtual field trip to Sgeir Leth a Chuain (Continental environments, Member 2) | Bruce Levell, Doug Benn and Jordan Mertes | 1.30 - 1.40 |
| Discussion of topics 7 to 10 (contribute via chat function) | | 1.40-2.00 |
| **Session D. 27th May Start 2.15 p.m.** | | |
| 11. Environmental changes – Members 1 and 2 | Doug Benn and Bruce Levell | 2.15-2.45 |
| 12. Environmental changes – Members 3 to 5 | Anthony Spencer | 2.55-3.20 |
| 13. Capturing the Port Askaig Formation | The research team | 3.20-3.40 |
| General discussion (contribute via chat function) | | 3.40-4.15 |

# 1. Port Askaig Formation: context & history of research

Anthony Spencer

The Port Askaig Formation (PAF) lies in the approximate stratigraphic centre of the ~25km thick Dalradian Supergroup. The latter has been the subject of a huge research effort, now spanning 200 years, that has focused on structural and metamorphic history and on the character of the large number of igneous intrusions. As a result of these research efforts, the overall stratigraphy of the Supergroup was slowly understood and one of the horizons critical to that was the "Boulder Bed". This was first recognized in the starting phase of Scottish geology (MacCulloch 1819) and a glacial origin was proposed by Thomson in 1871 - the first Cryogenian tillite to be recognized. The study of the PAF as a sedimentary formation started much later, when Pitcher & Shackleton visited the Garvellach Islands in 1961 and measured the ~600m stratigraphic column there and identified 38 diamictite beds. This led on to my own PhD research on the Garvellachs and Islay, resulting in the publication of the Memoir 'Late Pre-Cambrian glaciation in Scotland' (1971), which proposed that the PAF recorded 17 largely terrestrial glacial advances and recessions. Research on the Garvellachs in the period 1983-2006 by the Eyles' and Arnaud suggested that the diamictites were marine mass-flow deposits, some with a glacial influence, whilst Benn & Prave (2006) returned to a largely terrestrial glacial interpretation.

The PAF is seen in ~20 outcrops from western Ireland to northeast Scotland. The name comes from Port Askaig on the Isle of Islay in Argyll, Scotland. The best outcrops are on the group of four islands and 20 skerries and tidal rocks in the Garvellach Islands 50km to the north. It is in these outcrops in Argyll that the PAF is least metamorphosed (to greenschist facies) and least deformed and can be studied as 'normal' sedimentary strata. In addition, in the Garvellachs, the 8m raised rock platform around all the islands (due to isostatic uplift following Quaternary glaciation), the 4m tidal range and the frequent Atlantic storms provide bare rock outcrops around all the coasts that are safe to work on. All 600m of strata are completely exposed, in up to 7 dip sections along the strike of the islands.

Members 1 to 3 (~600m) are exposed on the Garvellach Islands. On Islay Members 1 to 5 are exposed, although the succession in Member 1 is truncated at the base. In the 1100m of the PAF as a whole 47 diamictite beds have been identified, building on the 1961 scheme of Pitcher & Shackleton. Since 2012 these strata have been studied by a team totalling 55 geologists and involving ~1100 geologist days in the field. Many new findings have been made: e.g. boulder pavements, imbricated rafts, abundant evidence of glaciotectonism etc (providing evidence of grounded ice); frost-shattered stones, frozen sand slabs etc (evidence of periglacial conditions); fluvial conglomerates, debris flows etc (evidence of continental environments). Based on observations from the 1960s and from the 2010s, we now propose that the PAF records 76 climatically related episodes: 28 glacial, 25 periglacial and 23 non-glacial.

This series of presentations on our observations and results is organized around three themes:

Stratigraphy: **2** Carbonate substrata; **3** Stratigraphic architecture; **10** Members 1-2; **11** Identifying events; **12** Members 3-5

Mechanisms / environments: **4** Glacial; **5** Periglacial; **6** Dolomite; **7** Marine; **8** Continental.

Virtual field trip: **9** Sgeir leth a Chuain.

The 12 presentations will cover much of our research, but not all. Important topics we will not have time to present include research on: geochemistry of the sedimentary rocks (Martin Dahlgren); pattern of the stone suites (Anthony Spencer, Ken Chew); provenance of the sediments and clasts (Martin Dahlgren, Catherine Rose); geochemistry of the ironstones (Patrick Casey); glaciotectonics of Member 1 in Islay (Ian Fairchild, Anthony Spencer); geology of the PAF outcrops in Ireland and mainland Scotland etc

# 2. Carbonate substrata – Garbh Eileach Fm & Cryogenian correlation

Ian Fairchild

The lower contact of the Port Askaig Formation (PAF) has international significance in respect of a potential boundary section of the base of the Cryogenian System. The PAF possesses typical features of the early Cryogenian Sturtian panglaciation such as great thickness, relatively high inferred sea level, presence of iron formation, and a newly recognized cap carbonate with composition of -5 ‰. In the Garvellachs, there is an overall transition between overlying glacial facies and underlying non-glacial facies including carbonates with low Sr isotope signatures typical of pre-Sturtian strata. We proposed (Fairchild et al., *Precambrian* Research, 2018) defining the Tonian-Cryogenian System boundary within this section at the point where carbon isotope values cross over from negative to positive and a few metres below the first evidence for ice.

The putative Global Stratotype Section and Point (GSSP) lies within the recently defined Garbh Eileach Formation (GEF), a 70 m-section of carbonate rocks with 100% exposure. The basal 50 m has a carbon isotope composition of around -4 ‰, rising to zero in the 60-61 m interval with positive values (0 to +1 ‰) above. Lithologically, carbonate mudstones dominate. In the interval up to 35 m, these are predominantly limestone (with $^{87}Sr/^{86}Sr$ = 0.7064-0.7066) and interlaminated limestone and dolomite with some stromatolite bioherms and associated flake breccias. In the 35-50 m interval strata are dolomitic siltstones and sandstone with localized wave ripples and evidence for subaerial exposure. Above 50 m, lithologies are consistently dolomitic and contain discrete sandstones with wave-generated structures. Several horizons of silicified gypsum pseudomorphs occur together with evidence for subaerial exposure. At the proposed GSSP at 61 m a dolomitic sandstone bed overlies a massive dolomite bed, whilst the first evidence for ice-rafting of sand and granule grains is at 65 m. The base of the Port Askaig Formation at 70 m is a laterally discontinuous diamictite, up to 10 m thick, with evidence for subglacial deposition. Gypsum pseudomorphs grow on its top surface and it is overlain by 2 m of silty dolomite similar to those at the top of the GEF.

Regarding the suitability for a GSSP, weaknesses are the lack of constraints from radiometric dating or palaeontology. However, a combination of climatostratigraphy and chemostratigraphy should be decisive for this GSSP. The Garbh Eileach section is regarded as having the qualities required for a GSSP because of:
a) complete exposure in an accessible, but not routinely visited location
b) the unusual relationship of a transitional base to glacial conditions
b) carbon and strontium isotope signatures
c) potential for extending the section downwards by offshore or onshore drilling and by further study of rafts in a megabreccia within the Port Askaig Formation.

On Islay, the PAF rests unconformably on the Lossit Formation (LF). In the southern (Lossit) area a sandy dolomitic breccia resting on a periglaciated dolomite surface of the top Lossit Formation member (L5), but rests on the older siliciclastic member L4 across a newly recognized pre-PAF fault to the NE. In the northern (Persabus) area, member L4 (and locally L5) is overlain by a recently recognized glaciotectonic complex including both LF and basal PAF clasts and rafts.

# 3. Stratigraphic architecture of the PAF

Roger Anderton

The Port Askaig Formation (PAF) lies roughly in the middle of the very thick Dalradian Supergroup which was deposited near the edge of the Rodinian Supercontinent in a rift zone, which subsequently ruptured to form the Iapetus Ocean. The tectonic context of PAF deposition was, therefore, one of crustal extension and thinning producing extreme basin subsidence over a long period (c.200 Ma).

The PAF can be recognized at the same stratigraphic level in the Dalradian but forming discontinuous outcrops for 700 km from western Ireland to northeast Scotland. The PAF has the same overall internal stratigraphic pattern throughout the extent of its outcrop: dolomitic diamictites are succeeded by arenaceous diamictites; dolomites and dolomitic sandstones are succeeded by sub-arkoses; clasts change progressively from dolomite/limestone to quartzite/granite. These stratigraphic changes reflect the evolution of the sediment source area and show that the area of Dalradian deposition was small compared with the glacial erosion and transport system. These changes also allow five lithostratigraphic members to be defined in the Garvellachs – Islay – north Donegal area (over a distance of 170 km), but not elsewhere.

The PAF is thickest in the Garvellachs and the Port Askaig area of Islay (c. 1 km). Elsewhere, it can be much thinner but still shows the same dolomitic to arenaceous upward trends. Most of the 38 numbered diamictite beds first recognized on the east coast of Garbh Eileach can be traced along the 5 km of the Garvellach islands, but a few thin out laterally and others appear. None of these individual diamictite beds can be identified with certainty on Islay, 50 km away.

How far are these lateral changes in stratigraphy due to underlying tectonics rather than a complex depositional environment? The stratigraphic units overlying the PAF show clear evidence for differential subsidence along major basin-bounding faults leading to lateral thickness and facies changes. Although one of these faults, the Insh Fault, lies just to the east of the Garvellachs, it does not appear to have been active during PAF times but came into existence during a later crustal-stretching event. This later event may have produced the small faults between the individual islands of the Garvellachs. Stratigraphic profiles along the Garvellachs chain show little evidence for any fault control during sedimentation and the PAF in this area seems to have been deposited well away from any basin-margin complexities, shows a gradational contact with the underlying unit and a continuously-deposited, ‘layer-cake’ type of architecture.

However, the situation on Islay is quite different. Here, complex folding renders stratigraphic analysis much more difficult. These complexities result from the presence of a major syn-depositional fault zone running through Islay, which affected post-PAF units, together with complex oblique compression during the Grampian Orogeny. The lower part of Member 1 of the PAF is missing around Port Askaig, the upper part appearing to overstep onto an erosional unconformity beneath which ~130 m of the Lossit Limestone Formation has been eroded. This shows that the subsidence history here is different from that on the Garvellachs. Also, although the overall PAF thicknesses are similar at Port Askaig and on the Garvellachs, there are thickness variations at a Member level. Finally, in SW Islay on the Mull of Oa, both the PAF and the overlying units are a fraction of their thicknesses in eastern Islay. There are no obvious unconformities but the whole succession appears to be condensed. The Mull of Oa succession accumulated in a different basin from that at Port Askaig.

The Garvellachs PAF accumulated in the central part of a rapidly subsiding basin. The Mull of Oa succession was deposited in a different basin with much slower subsidence. The Port Askaig area lies at the edge of the rapidly subsiding Garvellachs basin in what, at least subsequently, was a syn-depositional fault zone. One would not be surprised to see facies and thickness variations here. Unfortunately, in this area the PAF is both poorly exposed and structurally complex.

# 4. Glacial Geology

Doug Benn, Mike Hambrey, Jordan Mertes

A glacial origin for diamictite strata at Port Askaig was first proposed as early as 1871, but in the ensuing 150 years there has been much disagreement about the precise mode of origin of these distinctive rocks. Interpretations have ranged from subglacial, through glaciomarine, to non-glacial mass flows. In part, this reflects the apparently massive, structureless character of the diamictites in many easily accessible exposures, which have provided a temptingly blank canvass upon which ideas could be projected. The extent and quality of the outcrop on the Garvellach Islands, however, is such that all horizons are very well exposed in at least one (and often several) localities, allowing both sedimentary structures and large-scale architecture to be studied in detail. Using a combination of detailed field logging and drone-based air photo surveys over many field seasons, we have systematically documented all diamictites and associated facies in Members 1-3 on the Garvellach Islands, and parts of Members 4 and 5 on Islay. This work reveals that the Port Askaig Formation contains a rich diversity of facies indicating the direct presence or close proximity of glacier ice. These can be grouped into four genetic facies associations, recording deposition in subaqueous, terrestrial ice-marginal, subglacial, and proglacial tectonic settings.

Subaqueous facies associations record both ice-distal and ice-proximal environments. Ice-distal sediments take the form of laminated silts with outsized clasts (dropstones); well-exposed examples occur within the Disrupted Beds on A'Chuli and in the upper part of Member 2 on Garbh Eileach. Ice-proximal sediments are more variable and include: massive diamictites with interbeds of silt and/or sand (dropstone muds); complexly interbedded conglomerates, sandstones and diamictites (subaqueous fans); and massive pebbly sandstones (mass flows). These occur at several levels in Members 1 and 2, and possibly also make up the bulk of Member 4 and parts of Member 5 on Islay.

Compelling evidence for terrestrial environments is provided by periglacial phenomena such as frost-shattered stones, involutions, and ice-wedge polygons. In a small number of cases, the close proximity of glacier ice is recorded by terrestrial ice-marginal facies associations, consisting of complexly interbedded diamictites and sorted sediments, with characteristic irregular bedding and evidence for slumping. Examples include D34 or Garbh Eileach, where there is evidence for reworking of frost-shattered stones.

Subglacial deposition and deformation is recorded at over a dozen horizons in Members 1-3. Several of the diamictites contain signatures typical of subglacial traction tills, including strong a-axis fabrics, boulder pavements, and imbricated (ploughed and lodged) boulders. In many cases, these occur in conjunction with evidence for deformation and erosion of the underlying sediments, such as shear deformation, recumbent folds, injection of till around blocks, and transport of rafts. Finally, stratified fracture fills (hydrofractures) are seen to penetrate sub-till sediments at several localities, most notably beneath D32 on Holy Isle.

Proglacial glaciotectonic structures occur at two levels in Member 1: D13 (the Great Breccia) on the Garvellach Islands and in a thrust complex at the base of the Formation in the Persabus-Torrabus area on Islay. Of these, the Great Breccia is by far the better exposed. The Great Breccia typically consists of two main facies, although either may be absent at some localities: 1) large imbricated and/or folded and thrust-faulted rafts, some of which are tens of metres across; and 2) an upper 'sheared boulder facies' consisting of innumerable edge-rounded boulders (typically up to 1 m) within a sheared matrix of silt- to pebble-sized material. These facies record excavation, thrusting and proglacial emplacement of pre-PAF rocks, and their subsequent over-riding by advancing ice. Particularly fine examples of over-ridden rafts occur on A'Chuli and at 'The Bubble' on Holy Isle, which are closely similar to sediments exposed in Quaternary thrust moraine complexes.

# 5. Evidence for Periglacial Processes in the Port Askaig Tillite Formation

Richard Waller, Michael Hambrey, Anthony M. Spencer

Periglacial and other permafrost-related features in Neoproterozoic glacially influenced successions offer supporting evidence of associated climates. However, such features are commonly subtle and good rock exposure, both stratigraphically, vertically and laterally, optimizes their identification and the chances of deciphering the palaeoenvironment and palaeoclimate of the succession.

The Port Askaig Formation on the Garvellach Islands offers an exceptionally well-exposed succession for investigating Neoproterozoic frost-related features in association with established glacigenic deposits. Some of these features, notably sandstone wedge structures and cryoturbation features, were originally described by Spencer (1971). However, a periglacial origin was dismissed by Eyles & Clark (1985), who argued they were gravity-induced soft-sediment deformations triggered by seismic shocks, thereby not conflicting with their preferred model of glaciomarine environments.

Using a range of field techniques, including localised mapping, lithological logging, analysis of clast roundness and their fracture characteristics and 3-D drone images, we reaffirm that the evidence for periglacial terrestrial environments is unequivocal and present at around 25 horizons throughout the Formation. This evidence includes:

(1) Sandstone wedges at the top of diamictite beds which, in plan view, are often in branching or polygonal networks (11 stratigraphic horizons) or isolated (a further 9 horizons). These are interpreted as sand-wedge casts formed in regions with continuous permafrost where the mean annual air temperatures are significantly below 0ºC.
(2) Syn-sedimentary sandstone “vein-like” features and sandstone-filled hydrofractures formed by injection of meltwater into sediment under high pressure beneath a grounded ice mass (3 to 4 horizons).
(3) Downfolds of gravel and sand, which resemble periglacial involutions and patterned ground (3 horizons).
(4) Brecciated dolomitic horizons indicative of freeze-thaw processes at the top of a bed (2 to 3 horizons).
(5) Fractured clasts of various rock types at the top of diamictite beds - notably granite cobbles and boulders disaggregated along crystal boundaries - interpreted as subaerial frost-shattering of stones on exposed till surfaces (7 horizons).
(6) Local accumulation of breccia on dolomitic beds, indicative of frost-shattered regolith (“head” deposits), named here as gelifluctite (1 horizon).
(7) Angular sandstone intraclasts in conglomerate, interpreted as frozen fragments resulting from river-bank collapse (3 horizons).
(8) Sandstone intraclasts in diamictites, indicative of glacier-permafrost interaction (<5 horizons).

Apart from the “vein-like” and hydrofracture features (which formed subglacially), all these features of the Port Askaig Formation are complementary to the evidence for subglacial depositional and glaciotectonism and consistent with subaerial conditions. Periodic ice recession, which left behind till and associated sediments on low-lying land, revealed proglacial areas that were then exposed to periglacial processes and permafrost aggradation.

In summary, from our renewed fieldwork, we find no evidence of predominantly submarine conditions, but envisage repeated terrestrial landscapes under the influence of climates that resembled those of the High-Arctic today.

# 6. Identifying detailed events: example of D26

Dilshad Ali

The excellent rock outcrops in the Garvellach islands have allowed us to identify a total of 60 climatically-related episodes in the ~520m thick succession of Members 1 to 3 there. These are the large-scale changes recorded by the strata. When we examine the horizons marking the changes from glacial to periglacial to non-glacial conditions – typically the top surfaces of the diamictite beds – we often find evidence of sets of more detailed events marking stages in the changeover. To illustrate this we have chosen one horizon - the top of Diamictite 26 – to show how these events can be analysed.

Diamictite 26 is overlain by a periglacial horizon with sandstone wedges, cryoturbations and frost-shattered stones, which in turn is succeeded by non-glacial sandstones. Detailed analysis of the geometry of the outcrop on the east of Garbh Eileach, plus the stratigraphy in 11 other outcrops along the 5km chain of islands, allows 9 depositional events to be distinguished within the <5m of strata. The full set of events – including the time gaps – is demonstrated on a Wheeler diagram.

The presence of such sets of detailed events at many of the horizons of climatic changeover is a major example of the remarkable preservation potential in the Port Askaig Formation in the Garvellach islands.

# 7. Non-glacial geology – origins of dolomite

Ian Fairchild

In the Port Askaig Formation (PAF) we can now demonstrate the chemostratigraphic potential of Cryogenian marine dolomite precipitates. The co-occurrence of glacial deposits and dolomite was formerly supposed to be a palaeoclimatological paradox since most sedimentary dolomite is associated with warm shallow seas. The paradox is solved by recognition of marine authigenic dolomite precipitation, regardless of depositional temperature, combined with extensive reworking as detritus of both pre-glacial and syn-glacial dolomite.

Detrital dolomite, derived from lateral equivalents of the underlying platform sediments, is the dominant carbonate rock type glacially reworked into diamictites in the PAF. It is accompanied by limestone in the first 12 diamictites on Garbh Eileach where carbon isotope shifts demonstrate an unroofing of equivalents of the underlying succession (Ali et al., 2018, *Precambrian Research*). Above diamictite 13, a megabreccia, is a terrestrial unconformity overlain by gelifluction deposits then fluvially transported iron-poor dolomite revealing another upward reversing carbon isotope shift in iron-poor dolomites.

Dolomite is a widespread precipitate in Neoproterozoic marine rocks and nearly ubiquitous in peritidal facies. There is a consensus that Mg/Ca in solution at that time was much higher than in modern seawater. With rare exceptions, terrestrial freshwaters do not have sufficiently high Mg/Ca to favour dolomite formation. Continental occurrences of dolomite are thus of evaporative origin and result from extensive prior precipitation of $CaCO_3$. Oxygen isotope data clearly show this to be the case in non-marine environments of the Marinoan glacial in Svalbard. Conversely, in the absence of evidence for high salinity, dolomite can be regarded as a marine mineral. Dolomite precipitates have been identified at many stratigraphic levels in the PAF, but evidence of evaporites is absent above diamictite 2, and so we use their occurrence here as a marine indicator.

Precipitated ferruginous dolomite in Sturtian glacimarine deposits was first identified 30 years ago in Svalbard. It is of early diagenetic concretionary origin and such dolomite is prominent high in member 1 of the PAF (locally associated with iron formation), nucleating preferentially within non-ferroan dolomite breccia horizons (mass flows basinward of a glacier grounding line). The deltaic deposits of Member 2 have dolomite precipitates only at specific low-energy stratigraphic horizons where they are also reworked as intraclasts: these are interpreted as proglacial marine bands. Tidal sandstones near the base of Member 3 locally have dolomite concretions displaying displacive growth textures and are reworked into intraclasts Ferroan dolomite patches occur at the top of Diamictite 35, interpreted as reflecting patchy dolomite concretion formation following marine transgression of the periglaciated upper surface of the till. Some other diamictites, interpreted as marine, have concretionary dolomite throughout. More extensive development of dolomite as fine-grained beds (and associated intraclasts) is focused at three levels. 1) Between diamictites 1 and 2 on the Garvellachs there is a continuation of the peritidal facies found near the top of the underlying Garbh Eileach Formation. 2) at the top of member 1 a bedded dolomite unit includes local low-domal stromatolites, and evidence of reworking by wave action to form wave-dominated peloidal dolomites 3) In Member 5 turbiditic peloidal carbonates interbedded with mass flow deposits were dolomitized contemporaneously and extensively disrupted by downslope movement. This is the only deep-water dolomite in the succession and is interpreted as the cap carbonate following glaciation and, like other Sturtian caps, has a $\delta^{13}C$ value around -5 ‰.

A dichotomy between regular marine carbonate (whose carbon isotope composition reflects marine dissolved inorganic carbon) with concretionary carbonate, with carbon isotope shifted to extreme values by incorporation of organically derived carbon, does not apply in the Cryogenian. In the case of the PAF, the carbon isotope composition of dolomite precipitates shows a scatter of 2 to 3 ‰ at any one horizon which may reflect varying contributions from organic matter diagenesis. However, the most remarkable feature is a systematic steady shift from close to zero high in Member 1 to the -5 ‰ value in the cap carbonate of Member 5. This offers potential for a chemostratigraphic subdivision of the Sturtian glaciation.

# 8. Non-glacial geology – marine environments

## Roger Anderton

Whereas the lower parts of the PAF exhibit a variety of interbed lithologies, Members 3, 4 and 5 are characterised by white quartzites which are interpreted as various types of marine facies. Quartzites are often interpreted as shallow marine, tidal sandbodies, their textural and mineralogical maturity being an indication of high energy depositional environments and much reworking, The PAF quartzites exhibit an assortment of structures, cross bedding with variable, and sometimes bipolar, palaeocurrent orientations being the most common. On Garbh Eileach there are four distinct interbeds in Member 3 which are each well exposed in two coastal sections allowing lateral variations to be demonstrated. Member 4 and 5 interbeds are only exposed on Islay. Member 4 interbeds are very patchily exposed but there is a large, rather inaccessible, outcrop of Member 5 on the Sound of Islay.

The four quartzite interbeds on Garbh Eileach make up about 65% of the total Member 3 thickness of 150-200 m. They are all slightly different. The lowest one shows giant cross beds up to 7 m thick suggesting some kind of tidal delta or estuarine environment. There appears to be significant topographic relief on the base of the unit implying subaerial erosion followed by a transgression along the resulting incised palaeovalley. The upper part of the unit looks like a more open marine facies. The second unit also shows giant cross beds but there is no evidence for erosion of the base, but rather a low energy transgression. The third unit only has smaller-scale cross bedding but two conspicuous granite dropstones and a lot of liquefaction structures. The fourth unit includes thin, sheet-like beds with climbing ripples suggesting storm deposition.

In all the cases where it is possible to see the contact between an interbed and the overlying diamictite, this is a sharp erosional truncation. Contacts with underlying diamictites are more variable. There are cases of subaerial erosion followed by a high-energy transgression, a low-energy transgression across a winnowed periglacial surface and an entirely marine transition. The alternation of diamictites and quartzite interbeds in Member 3 does indicate relative changes in sea level as one would expect during successive periods of ice advance and retreat.  However, the indicated changes are not large suggesting oscillation of the ice margin rather than periods of total deglaciation.

The quartzite interbeds on Islay are more difficult to interpret. Sections of uncertain stratigraphic affinity around the ferry terminal at Port Askaig could be delta distributary and mouth bar facies. North of Caol Isla a quartzite section in Member 4 could also be a delta mouth bar. The Member 5 section at Con Tom is composed of decimetre-thick beds showing a variety of structures, but no vertical organisation or large-scale bedding architecture. This, together with the well-sorted, mature texture of the sediment is consistent with a shallow marine origin. In that respect, it has many similarities with the stratigraphically higher and better known Jura Quartzite which is interpreted as a tidal delta deposit. In spite of the uncertainties in the facies interpretation, it is likely that the diamictites in Member 3 to 5 are largely of shallow marine origin.

# 9. Non-glacial geology – continental environments

Bruce Levell

This work is based predominantly on Member 2. The Inter-diamictite units of Members 1 and 2 are interpreted as largely non-marine. Four facies associations are recognised: (1) lenticular sandy conglomerates, (2) 2-3 m thick units coarsening-upwards from siltstone to coarse sandstone (3) 5-10 m thick units irregularly coarsening-upwards from siltstone to erosionally-based conglomerate and (4) up to 5 m thick moderately-sorted, mostly pebble-free sandstones. These are interpreted collectively as deposits of streams, and minor deltas in a mosaic of small, shallow lakes or embayments. Diamictite thickness changes probably complicated topography. Limited evidence of waves suggests limited fetch. Marine pore-water is suggested by dolomite and pyrite. Lakes, lagoons or marine embayments are all possible.

Member 1 and 2 diamictites were deposited in continental or very shallow water settings. Winnowed top-surface lags occur on just 4 of the 32 numbered diamictites. However, common preservation of wedges and aeolian sands on top surfaces immediately below deltaic units demonstrates an absence of transgressive reworking. Furthermore two laminated diamictites (D23 and D25), are succeeded gradationally, through laminated siltstones with dropstones, by fluvio-deltaic deposits. Base level changes between diamictites and inter-diamictite units appear to have been both minor and low energy.

Both ice-marginal and non-ice marginal settings are suggested by the highly variable sorting and angularity.

Erosion and thickness changes during inter-diamictite times (D26-D27) demonstrate tilting and active syn-depositional faulting. This faulting controlled the vertical stacking of incised fluvial channels in one spot at five stratigraphic levels.

# 10. Virtual field trip to Sgeir Leth a Chuain

## Doug Benn, Bruce Levell and Jordan Mertes

The strata of Member 2, from Diactite 25 up to above Diamictite 30 (80 m of succession) are completely exposed on Sgeir leth a'Chuain. Orthorectified drone imagery supplemented by detailed outcrop photographs will be used to guide participants around this fascinating skerry without getting wet. Correlation, facies variety, and the stacking of channelised fluvial-deltaic conglomerates in this small area are interpreted in terms of active syn-depositional faulting.

# 11. Environmental changes – Members 1 and 2

## Doug Benn and Bruce Levell

Members 1 and 2 record a sequence of major environmental changes in extraordinary detail, allowing detailed reconstruction of ice-margin and sea-level fluctuations and climate change during the Sturtian panglaciation. Here we summarise those changes then consider the regional (and possibly global) implications.

*Member 1*
Indicators of cooling and proximity of glacier ice appear near the top of the Garbh Eileach Formation. Evidence for grounded ice appears emphatically at the base of the Port Askaig Formation (PAF) on the Garvellach Islands in the form of glaciotectonism and subglacial traction tills, with three ice advances recorded by D1, D2 and D5-D6. Glacially influenced subaqueous conditions then prevailed until a major ice advance emplaced D13, the Great Breccia with spectacular glaciotectonics. The following deglaciation occurred in a cold, terrestrial environment, with no evidence for flowing water. Reactivation of the hydrological cycle is recorded by the fluvial sandstones and conglomerates of the Main Dolomite, with evidence for increasing discharge and deepening water. On Islay, this entire interval of time is represented by an erosional unconformity and periglacial horizon. Following a marine transgression, the Disrupted Beds record glaciomarine deposition, culminating with renewed ice advance (D14-D15). Member 1 ends with a transition to non-glacial conditions (Upper Dolomite) and a period of erosion.

*Member 2*
The thick diamictite beds that make up most of Member 2 record alternating subaqueous and subglacial deposition. An irregular trend of increased thickness of inter-diamictite units and increasing deltaic fluvial deposition suggests gradually rising relative base level over the duration of Member 2 deposition. Periglacial horizons (wedge polygons, involutions, shattered stones) indicate episodes of subaerial emergence, and fluvial channels are incised metres into subaqueous sediments at several levels. Towards the top of Member 2, glacial and glaciofluvial transport systems were augmented by a fluvial system draining a mature pebble-free, quartz-rich source area. Where the succession is most complete, Member 2 ends with deposition of non-glacial rhythmites. Elsewhere, erosion removed 40-60 m of sediment prior to deposition of Member 3.

*Subsidence and base level:*
Relative base level changes comprise rift-basin subsidence, upon which presumably were superimposed glacio-eustatic and glacio-isostatic sea-level fluctuations. We infer the following sequence of changes. 1) The base of the PAF was deposited close to sea level, and tidal flat conditions occurred in the interval between D1 and D2. 2) The subaqueously deposited sediments D7 - D12 lack dolomite cements and sometimes contain calcite cement, indicating freshwater conditions. This is consistent with a eustatic drop in sea level consequent

on ice-sheet growth, as indicated in other Sturtian successions. 3) Terrestrial conditions post-Great Breccia additionally reflect creation of relief by glaciotectonics, further offsetting the effects of basin subsidence. 4) The subsequent marine transgression suggests a reduction in clastic sediment supply, and subsidence becoming the dominant influence of relative sea level. 5) Dolomite cements occur in the Disrupted Beds, D15, the Upper Dolomite (Member 1), in D22, D26 and in the interval D30 - D31 (Member 2), indicating marine waters, while periglacial horizons record intermittent emergence. (6) In Member 2, the presence of deltaic and subaqueous sediments, emergence horizons and fluvial incision indicates minor fluctuations in local base-level. However, sediment supply and accommodation space creation (subsidence, and isostasy and eustasy) remained surprisingly well-balanced. 7) Syn-depositional faulting caused tilting and erosion (demonstrated in the Sgeir Leth a' Chuain area in late Member 2 time).

*Climate:*

Periglacial conditions with cryogenic structures occurred at many levels when grounded ice was not present, indicating persistently cold conditions throughout deposition of Members 1 and 2. Glacier ice was either present or close to the basin for much of the succession, although sediment maturity suggests that some inter-glacial deltaic sequences in Member 2 were not ice-marginal. It is abundantly clear that Member 2 documents an active hydrological cycle, open to the atmosphere, interspersed with ice advances. However, there evidence for arid periglacial conditions at times, e.g. the periglacial horizon above the Great Breccia (Member 1) and wind-blown sands above D24 (Member 2). We found no evidence that requires 'hard Snowball' conditions; indeed, it is difficult to find anywhere in the succession into which prolonged deep Icehouse conditions could be fitted. Instead, the conditions are consistent with those found during Phanerozoic glaciations.

# 12. Environmental changes – Members 3 to 5

Anthony Spencer

Members 3, 4 and 5 form the upper two-thirds of the Port Askaig Formation and contain Diamictites 33 to 47. The best outcrops of Member 3 are in the Garvellach islands, but other outcrops have been recognized and measured in Islay and in north Donegal. Members 4 and 5 are not exposed in the Garvellach islands and their stratigraphy has been measured following geological mapping in Islay and north Donegal. The three Members are easy to distinguish because of their different stratigraphies: Member 3 contains thick tidal sandstones alternating with diamictite groups D33-35, D36 and D37-38; Member 4 contains thick diamictites (D39-D44) separated by thin sandstones; Member 5 contains dominantly sandstones with thin diamictite/conglomerate levels (D45-D47 on Islay).

Member 3 in the Garvellachs is ~200m thick and contains features recording alternating non-glacial (tidal sandstones), periglacial (sandstone wedges, cryoturbations, frost-shattered stones) and glacial (grounded and floating ice) episodes, totalling 18 in all. Many of these features have been described by earlier speakers – glacial (Doug Benn), periglacial (Richard Waller, Mike Hambrey), marine environments (Roger Anderton) and continental environments (Bruce Levell). So in this talk I will illustrate two special features: a rare occurrence of iceberg rafting in the marine sandstones and the remarkable preservation of periglacial features beneath Diamictite 33. There tidal sandstones are overlain by <7m of sandstones containing cryoturbations, in turn succeeded by Diamictite 33 with a boulder pavement at its base and related glaciotectonic shearing below. This is another example of the remarkable preservation potential exhibited by the Garvellachs strata – marine conditions changed to subaerial, periglacial conditions and then a grounded ice sheet advanced over the top, burying and gently deforming – but not eroding – the earlier record.

Member 4 is defined on Islay where it is ~250m thick. The quality of the outcrops is poor compared to the Garvellachs and geological mapping at scales of 1:1000 to 1:3000 using air photos has been undertaken to improve the basis for the stratigraphy. The coastal cliffs from Port Askaig to Caol Ila provide a stratigraphic column which has been measured; other columns are constructed from geological profiles. Sandstone wedges occur at the tops of three diamictites and provide firm environmental indicators there. Both the thick, massive diamictites and the thin sandstone interbeds lack the numerous distinctive features seen in Members 1 to 3 in the Garvellachs and so provide no firm evidence of their environments.

Member 5 is also defined on Islay where it is ~300m thick. The coastal cliffs at Con Tom provide the best stratigraphic column, but only expose the top two-thirds of the Member. Most of the column there is made up of marine sandstones, with three thin numbered horizons. D45 is poorly exposed in the cliff (~11m thick) but fallen blocks on the beach provide examples of diamictites, granitic conglomerates and dolomite breccias: the slope facies dolomites have $\delta^{13}C$ values of -5.3±0.4 ‰ suggesting this may be the 'cap carbonate'. D46 and D47 are thin granitic conglomerates. More work is planned on inland outcrops of Member 5.

Members 3, 4 and 5 show a total of 12 glacial, 10 periglacial and 12 non-glacial episodes, totalling 34 climatically-related episodes, almost half of all of the episodes recorded in the Port Askaig Formation.

# 13. Significance of the Port Askaig Formation

## The research team

Four five-minute personal reflections by Tony Spencer, Ian Fairchild, Bruce Levell and Doug Benn about their understanding of its significance will be followed by a general discussion moderated by David Webster.