

Indicators of relative completeness of the glacial record of the Port Askaig Formation, Garvellach Islands, Scotland

Dilshad O. Ali¹, Anthony M. Spencer², Ian J. Fairchild³, Ken J. Chew⁴, Roger Anderton⁵, Bruce K. Levell⁶, Michael J. Hambrey⁷, Dayton Dove⁸, Daniel P. Le Heron¹

1. Department of Earth Sciences, Royal Holloway, University of London, Egham, Surrey TW20 OEX, UK (dilshad_umer@yahoo.com)
2. Madlavollveien 14, 4041 Hafslund, Norway
3. School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, UK
4. Morenish Mews, By Killin, Perthshire FK21 8TX, UK
5. Kilmichael House, Kilmichael Glassary, Lochgilphead, Argyll, PA31 8QA, UK
6. Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK
7. Centre for Glaciology, Department of Geography & Earth Sciences, Aberystwyth University, Aberystwyth, Ceredigion, SY23 3DB, UK
8. British Geological Survey, Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK

Abstract

The Port Askaig Formation (PAF) is a diamictite-bearing succession in the Dalradian Supergroup of Scotland that provides an excellent archive of a Cryogenian glaciation in the Garvellach Islands and Islay, Argyll. The formation is ~1100 m thick, comprises 5 members and includes 47 diamictite beds, interbedded with siltstones, dolostones and sandstones. Here we document seven features of the PAF that indicate its relative stratigraphic completeness. There are gradual, progressive changes up-section in the lithologies of the diamictites, their interbeds, and clast lithologies. The sharp basal surfaces of the diamictites each show the same, repeated pattern of environmental change, from non-glacial to glacial. Many of the top surfaces of the diamictites show evidence of periglacial conditions. The succession in the PAF records a total of 76 climatically-related stratigraphic episodes: 28 glacial episodes, 25 periglacial episodes and 23 non-glacial episodes. Parts of Member 1 (Diamictites 1 to 12 and Diamictites 16 to 18) and Member 2 (Diamictite 31 to the base of Member 3) are most complete on the east coast of Garbh Eileach. The PAF in the Garvellach Islands occurs within a succession that is several kilometres thick, as newly revealed by sea-floor mapping. Compared with other Cryogenian and Phanerozoic glacial successions, the PAF is exceptional in its combination of formation thickness, the number of climatically-related stratigraphic episodes, and the considerable thickness of its host supergroup. Furthermore, these indicators of relative stratigraphic completeness provide evidence that the base of the PAF on the east coast

34 of Garbh Eileach is a succession without a major break in deposition, supporting the account of the strata at and
35 below the base of the PAF in the companion article by Fairchild et al. (this volume).

36 1. Introduction

37 This paper provides the first detailed analysis of ‘indicators of relative stratigraphic completeness’ in a
38 Neoproterozoic glacial succession. These ‘indicators’ allow us to re-affirm that the Port Askaig Formation (PAF)
39 in the Garvellach Islands is a succession containing an exceptional archive of climatically-related depositional
40 episodes. Our main aim, however, in the context of this special issue on the Tonian-Cryogenian boundary, is to
41 show that they are entirely consistent with the inferred lack of a stratigraphic break at the base of the formation
42 (Fairchild et al., this issue). Thus they add to the case presented in that companion article - that the rock
43 succession of the Garvellach Islands is a candidate to host the basal Cryogenian Global Boundary Stratigraphic
44 Section and Point (GSSP).

45 The Port Askaig Formation occurs near the middle of the ca. 25 km thick Dalradian Supergroup, a largely
46 Neoproterozoic succession which may extend upwards into the Early Cambrian (Stephenson et al. 2013). The
47 stratigraphic position of the PAF in the Dalradian and as a representative of the Sturtian glaciation in the
48 Cryogenian System is shown in Fairchild et al. (this volume, their fig. 2). It crops out at approximately 30
49 localities from western Ireland to northeast Scotland and is generally between 100 m and 500 m thick but is
50 thickest, least metamorphosed and deformed and best preserved in Argyll, where it is ~1100 m thick (Fig. 1).
51 There the complete succession has been established by mapping around Port Askaig, on Islay, but the finest
52 outcrops are in the Garvellach Islands, where the combination of a raised rock platform and a uniform dip
53 continuously expose 550m of strata (Fig. 2).

54 A glacial origin for granite-boulder-bearing strata at Port Askaig was suggested by Thomson (1871) – making
55 this the first Cryogenian glacial deposit to be recognized. The remarkable nature of the stratigraphy was first
56 revealed by Kilburn et al. (1965), who measured the section in the Garvellachs, recognizing 38 diamictite beds. A
57 comprehensive study of the Garvellachs and Islay was reported by Spencer (1971), who recognized five members
58 and a total of 47 diamictite horizons in the ~1100 m-thick PAF; this succession was interpreted to record 17
59 glacial episodes, 27 periglacial episodes and 17 non-glacial periods. The latter author recognised the same 38
60 diamictite beds as Kilburn et al. (1965) and added a further nine; in this study, we follow this nomenclature, and
61 abbreviate accordingly (e.g. Diamictite 1 is abbreviated to D1). Study of the Garvellach outcrops was next

62 reported in a series of papers in which the diamictites were interpreted to have arrived as material from floating
63 ice and down-slope mass flows (Eyles & Eyles 1983; Eyles & Clark 1985; Eyles 1988; Arnaud & Eyles 2002).
64 Benn & Prave (2006) produced new evidence for glaciotectionic deformation in the Garvellachs, and new
65 fieldwork there in the last five years – by most of the authors of this article - has added greatly to the evidence for
66 grounded ice and emergent conditions. This article outlines some of these new data but full accounts will be
67 published in a planned, comprehensive memoir. We do not discuss the full palaeoclimatic implications of the
68 PAF here or its relevance to the Snowball Earth hypothesis.

69 One aspect of the succession has not been made clear in previous publications: the significance of the many
70 ‘indicators of relative stratigraphic completeness’ that are present. In this article we aim to document seven types
71 of ‘indicators’: (i) that the overall stratigraphic pattern of the formation shows gradual, progressive changes in the
72 lithologies of the diamictites and the interbeds and of the clast types: (ii) that the basal contacts of the diamictites
73 each show the same, repeated pattern of environmental change; (iii) that the top surfaces of most of the
74 diamictites show consistent patterns of detailed environmental change, from glacial to periglacial to non-glacial
75 conditions; (iv) that the succession in the PAF records a total of 76 climatically-related stratigraphic episodes; (v)
76 that the east coast of Garbh Eileach – where the base of the PAF is best exposed – shows a thicker and more
77 complete succession at three separate stratigraphic levels; (vi) that the PAF in the Garvellach Islands occurs
78 within a succession that is several kilometres thick, as now shown by new sea-bed geological mapping; and (vii)
79 that, at the largest scale, the PAF and the major part of the enclosing Dalradian Supergroup are amongst the
80 thickest Neoproterozoic successions anywhere. The seven ‘indicators’ show that the PAF succession is
81 stratigraphically more complete on the east coast of Garbh Eileach – compared with exposures to the west - and
82 contains a record of climatically-related stratigraphic episodes which is exceptionally rich when compared to
83 other Cryogenian and Phanerozoic glacial successions.

84 **2. Overall stratigraphic pattern**

85 The diamictite beds in the Garvellachs were numbered 1 to 38 by Kilburn et al. (1965, their fig. 3) and they
86 marked there the gradual upward change in clast types, from carbonate fragments to granite fragments. Spencer
87 (1971, plate 10) erected five members in the formation: members 1-3 in the Garvellachs and members 4-5 on
88 Islay, which contained a further 9 diamictites, making 47 in total (labelled D1 to D47 in this article).

89 The lithological composition of the matrix of these 47 diamictites changes progressively upwards through the
90 PAF. In Member 1 they are dolomitic siltstones (Fig. 3, D7, D15); in Member 2 they change from sand-rich
91 dolomitic siltstones (D19-22) to dolomitic, silty arenites (D26, D29); in Member 3 (D35, D38) and Member 4
92 (D40, D42, D45) they are silty arenites. Modal analyses showing these changes are given in Spencer (1971, fig.
93 28b).

94 The gradual upward change in clast types was also noted by Spencer (1971, plate 10), expressed then as “the ratio
95 of dolomite to granite stones”. New, systematic, measurements of clast type have been made, by counting stones
96 larger than 1cm in a 50 x 50 cm square and marking their outlines onto tracing film. Seven clast types have been
97 counted: dolomite, limestone, intrabasinal unknown, granite, quartzite, extrabasinal unknown and unknown. Here
98 we illustrate the extrabasinal clasts (i.e. granite + quartzite + extrabasinal unknown) (Fig. 4), which show there is
99 a steady, progressive change in clast types upwards through the PAF. In the lowest diamictites of Member 1, only
100 intrabasinal clasts are present (Fig. 3, D7). Extrabasinal clasts first become predominant towards the top of
101 Member 2 (Fig. 3, D29). At the top of Member 4 there are almost no intrabasinal clasts (Fig. 3, D42). The
102 percentages of the seventh clast type (‘unknown’) are small and do not affect the trend shown in Fig. 4 (0%
103 unknown in 106 measurements; 1-10% in 50; 11-20% in 15; 21-42% in 13).

104 The stratified sedimentary rocks separating the diamictites show a similar, progressive, upward change in
105 lithology, from dolostones to white sandstones. Beds of dolostone are only present in members 1 and 2 (Fig. 2).
106 The sandstone interbeds are dolomitic in members 1 and 2, but more arenaceous in Member 3 and highly
107 arenaceous in Member 5; modal analyses showing these changes are given in Spencer (1971, fig. 28a). These
108 lithological trends of the stratified sedimentary rocks in the PAF fit with the overall litho-stratigraphic
109 progression of the formations in this part of the Dalradian Supergroup, from the carbonate rocks of the Lossit
110 Limestone and Garbh Eileach formations up to the monotonous sandstones in the Jura Quartzite; only the
111 Bonahaven Dolomite interrupts this uniform progression.

112 **2.1. Isotope data**

113

114 Further insight into the progressive changes represented by the succession is provided by carbon isotope analyses
115 of clasts of dolomite (common) and limestone (rarer) in the basal diamictite units. These analyses were made as
116 part of a wider study (Fairchild et al., this issue) which established that the $\delta^{13}\text{C}$ values in the studied section were

117 virtually unaffected by diagenetic and metamorphic change. The clasts are lithologically similar to the underlying
118 Appin Group succession, 70 m of which is exposed on Garbh Eileach (Fig. 5). This succession is described in
119 detail in Fairchild et al. (this issue) and there re-named the Garbh Eileach Formation (GEF); it was formerly
120 called the Islay Limestone. It is younger than the sub-PAF Lossit Limestone of Islay. The GEF broadly consists
121 of microsparry limestones and dolomicrites, locally interlaminated and typically containing siliciclastic
122 impurities. Lithologies become consistently dolomitic upwards and contain siliciclastic sand. Carbon isotope
123 characteristics of dolomite and limestone beds from similar horizons are indistinguishable and define a distinct
124 negative anomaly, the *Garbh Eileach anomaly*, which passes smoothly up into $\delta^{13}\text{C}$ values close to zero above the
125 60 m level (Fig. 5). Bedded dolomites are also found between some of the lower diamictite beds and have similar
126 lithological and carbon isotope characteristics to those at the top of the GEF. Evidence for gypsum formation and
127 for ice-rafting is found in both the topmost GEF beds and up to the base of D2 in the PAF, indicating an overall
128 environmental transition at the base of the PAF, despite the sharp bases of individual diamictite beds.

129 Specific evidence of erosion of the lateral equivalents of the underlying succession is found in the Great
130 Breccia where rafts of sediment, up to tens of metres across, include those with an internal stratigraphy that can
131 be closely matched with sediments across the GEF-PAF boundary (Fairchild et al., this issue). Erosion of the
132 lateral equivalents of immediately underlying strata is also indicated by the identical $\delta^{13}\text{C}$ values of dolomite
133 clasts in the basal two diamictites (Fig. 5). Clasts in higher diamictites display a wider range, including many
134 dolomite clasts with values as low as -3 ‰ which must be sourced at deeper levels of erosion. Although
135 limestone clasts are much rarer, a minimum of five were analyzed from each of several diamictite beds. They
136 display consistently negative $\delta^{13}\text{C}$ values with gradual shifts in mean composition from a minimum of around -4
137 ‰ to a value close to zero in D12 (Fig. 5). Comparison with the underlying GEF shows little overlap with the -4
138 to -7 ‰ values of the exposed Garbh Eileach anomaly, so derivation from limestone beds forming the lower,
139 descending limb of the anomaly at deeper erosional levels is implied. Since the next oldest exposed strata (on
140 Islay) have weakly positive carbon isotope signatures (Fairchild et al., this issue), it is logical to interpret the
141 values around zero in limestone clasts in D12 as indicating that erosion reached limestone beds beneath the Garbh
142 Eileach anomaly.

143

144

3. Basal surfaces of diamictite beds

Almost all diamictites in the PAF have sharp bases on dolomites, siltstones and sandstones. None of the diamictites have gradual, transitional bases and no examples have been observed where stratified sedimentary rocks lacking clasts pass gradually upwards, through stratified sedimentary rocks with clasts, into stratified diamictite and finally into unstratified diamictite. Also, none of the basal surfaces of the diamictites show angular discordance or erosional geometries. Instead the basal surfaces are always parallel with the layers of the strata below. These sharp basal contacts – and the lack of gradual transitions - were first noted by Kilburn et al. (1965, p. 351) and highlighted by Spencer (1971, p. 11), but were not emphasized by subsequent observers (e.g. Eyles & Eyles 1983; Eyles 1988; Arnaud & Eyles 2006).

Figure 6 shows selected examples of well-exposed, sharp basal contacts of the diamictites observed throughout members 1 to 3 in the Garvellachs. In Member 3, the diamictites overlie tidal sandstones (Fig 6 a-c). The sandstones lack any clasts and the diamictites are massive. In places, the topmost metre of the sandstone has poorer stratification (but normally no clasts); in places, the lowest metre of the diamictite has homogeneous sandstone lenses with few clasts (e.g. Spencer 1971, his fig. 3), but mostly the basal contacts of these diamictites are knife-sharp. In Member 2, D30 has a sharp base (Fig 6 d). D23 is laminated and contains sparse outsized stones which may represent ice-rafted debris (IRD). Nevertheless, it has both a sharp base and a sharp top beneath the unstratified D24 (Fig. 6 e).

As has been noted by all observers in the Garvellachs, the basal contacts of the diamictites normally show no evidence of glaciotectionic disturbance (e.g. Fig 6 f). However, recent observations suggest that there are subtle, small-scale, disturbance structures whose significance may have been overlooked (e.g. Spencer 1971, his figures 3, 6 b, c, f, g). Here we illustrate another example: the dolomite breccia present at the base of D19, which appears to be composed of ripped-up fragments of the Upper Dolomite (Fig 6 g). Note, however, that the base of D19 in an exposure 2 km farther west shows no signs of glaciotectionism (Fig. 6 h).

These sharp basal contacts to the diamictite beds must record abrupt changes from non-glacial to glacial conditions. That such contacts are repeated at least 25 times in the PAF implies that such switches occurred - and were preserved - at least 25 times.

174 The top surfaces of the diamictite beds in the PAF are also sharp, but exhibit many more depositional structures
175 than the basal surfaces. Involution structures and polygonal wedges in the tops of the diamictites were first
176 recognized by Kilburn et al. (1965, their fig. 4). These were illustrated and documented by Spencer (1971), who
177 recognized many levels of “sandstone downfolds” and recorded sandstone wedges at 27 horizons, interpreting the
178 latter as periglacial structures. This interpretation was disputed by Eyles & Clark (1985), who argued more
179 evidence was required to invoke a periglacial origin. New fieldwork has, we believe, provided this evidence and
180 will be published in full elsewhere. Here we illustrate some examples of the depositional structures of the top
181 surfaces of the diamictites, because they provide some of the best data on the repeated preservation of detailed
182 environmental changes.

183 Frost-shattered clasts have been found at six stratigraphic levels in members 2 and 3 in the Garvellachs (Fig. 2);
184 five of these are at the tops of diamictites. Coarse-grained granite clasts, up to boulder size, have been seen which
185 appear to have disintegrated *in situ*, with the gaps between the fragments filled with the normal diamictite matrix
186 (Fig. 7 a). At other levels, quartzite clasts appear to have shattered into angular fragments, with normal diamictite
187 matrix between the separated parts of the clast (Fig 7 b); this photograph also shows angular quartzite debris to
188 the right of the clast. These newly discovered frost-shattered clasts provide the supporting evidence for periglacial
189 conditions.

190 The “sandstone downfolds” of Spencer (1971) have been re-studied and three levels are now interpreted as
191 periglacial cryoturbations (Fig. 2). One of these (Fig 7 c) affects sandstones at the top of D26. This exposure is
192 sketched in Fig. 8 a, which also shows the detailed stratigraphic column 2 km to the west (Fig. 8 b); there the
193 cryoturbated horizon contains frost-shattered clasts and is 5 m above the top of D26.

194 The sandstone wedges have been re-studied and are now confirmed at 23 stratigraphic levels, 18 of which are in
195 the tops of diamictite beds. The best developed polygonal system of wedges is in the top of D22, on the west
196 coast of Eileach an Naoimh (Fig. 7 d). On the east coast of the island, one kilometre away, polygonal wedges are
197 again exposed at this horizon (Fig. 7 e) and are there associated with a thin breccia bed containing angular
198 fragments, mostly of quartzite (Fig. 7 f). Sandstone wedges also occur penetrating stratified sedimentary rocks
199 (Fig. 7 g). A general observation in cross-section is that the tops of the wedges are always truncated at erosion

200 surfaces, commonly beneath lag conglomerates (Fig. 7 g, h). In one exceptional case, a system of polygonal
201 wedges is truncated beneath a thin overlying diamictite bed (Fig. 7 i).

202 Four conclusions can be listed with respect to these features at the tops of diamictite beds. Firstly, they show that
203 many detailed events are preserved in the rock record (e.g. Fig. 8), at numerous horizons (Fig. 2). Secondly, the
204 association of sandstone wedges, frost-shattered clasts and cryoturbations records periglacial environments
205 transitional between the (glacial) diamictites and the succeeding (non-glacial) stratified sedimentary rocks.
206 Thirdly, they imply that any erosion was minor. Fourthly, taking the record of these periglacial horizons in the
207 PAF as a whole, such conditions are preserved at 25 levels in the ca. 1100 m thick-stratigraphic column (Table 1).

208 **5. Climatically-related depositional episodes**

209 The diamictite bed numbers 1 to 38 of Kilburn et al. (1965) were assigned by W. S. Pitcher and R. M. Shackleton
210 when they measured the section on the east and south coasts of Garbh Eileach in 1962. All subsequent authors
211 have retained and built on this numbering system (e.g. Spencer 1971; Eyles & Clark 1985; Arnaud & Eyles
212 2006). Nevertheless, some of the beds that Pitcher and Shackleton measured between the numbered diamictites
213 are only centimetres thick and have been shown to be absent laterally (Spencer 1971, plate 11a). Clear examples
214 in the Garvellachs where the numbered diamictites are best grouped together are: D14-15, D19-22, D27-29, D33-
215 35, D37-38. Some of the diamictites in Member 4 on Islay are also best grouped together.

216 The PAF succession consists of diamictite beds containing far-travelled clasts, alternating with beds of sandstone,
217 siltstone and dolomite which lack such clasts. Using the diamictite groups, most of which are shown on Fig. 2, we
218 have tallied three types of episode represented in the PAF: glacial, periglacial and non-glacial (Table 2).
219 Diamictites 1 to 12 are there treated as one group, but require further study. The 26 diamictite groups, plus two
220 beds of laminated siltstones with ice-rafted debris (IRD) in Member 2 (one shown in Fig. 7 g), add up to a total of
221 28 glacial episodes. The horizons with periglacial features total 25. These glacial plus periglacial episodes are
222 separated by 23 non-glacial episodes. Thus in the ~1100 m of strata of the PAF there are a total of 76
223 climatically-related depositional episodes preserved.

224 **6. Relative completeness of east Garbh Eileach section**

225 The stratigraphic section of members 1 and 2 on the east coast of Garbh Eileach is the most complete in the
226 Garvellach Islands. It is also the most accessible and the easiest in terms of terrain because it is exposed on a
227 continuous raised rock platform. Recent work has shown that this section preserves the most episodes, with extra

228 strata (when compared with other sections in the Garvellachs and Islay) present at three levels: in the lowest and
 229 uppermost parts of Member 1 and in the uppermost part of Member 2.

230 Sedimentological evidence presented in Fairchild et al. (this issue) indicates that there is an environmental
 231 transition at the base of the PAF, with dolomites locally containing gypsum pseudomorphs (arid tidal flat
 232 environment) that are interstratified with sediments with IRD (shallow water environment liable to ice-
 233 rafting); the first diamictite (D1) occurs within this transition zone. In that paper, the smoothly varying nature of
 234 the carbon isotope profile from the Garbh Eileach Formation and upwards into D1 and D2 (on both Garbh
 235 Eileach and Dun Chonnuill) is viewed as consistent with the apparently conformable contact between the two
 236 formations. Herein, we also show that the carbon isotope composition of limestone clasts from D1 to D12 show
 237 smooth changes over 100 m of stratigraphic height (Fig 5), also consistent with a lack of significant stratigraphic
 238 breaks within this interval. It should be noted that D1 to D12 are only present in the Garvellachs (Fig 9). On Islay,
 239 where D1 to D12 are missing, conglomeratic sandstones (traditionally labelled the ‘Great Breccia’) overlain by
 240 Disrupted Bed lithologies, rest erosionally on underlying pre-glacial carbonates (Spencer, 1971; Fairchild et al.,
 241 this issue). In the Garvellachs, the interval from the top of the Great Breccia to the base of the Disrupted Beds
 242 consists dominantly of arenites and conglomerates composed largely of detrital dolomite. Such lithologies are
 243 atypical of the PAF as a whole and may reflect a discontinuous record of sedimentary events.

244 New fieldwork has revealed more details of the stratigraphic relationships at the top of Member 1. Spencer (1971,
 245 plate 11a) inferred an unconformable relationship between D18 and the overlying Upper Dolomite on Garbh
 246 Eileach. These strata have been followed in detail across the island (Fig. 10), revealing that the base of the Upper
 247 Dolomite is indeed an unconformity. Beneath it, the 18 m of strata from D18 down to D16 on the east coast are
 248 progressively cut out by subcrop towards the west.

249 Similar work at the top of Member 2 on Garbh Eileach was undertaken to check the unconformable relationship
 250 beneath Member 3 shown by Spencer (1971, plate 11a). This new investigation has confirmed that 20 m of strata,
 251 present on the east coast from D31 up to the top of Member 2, are progressively cut out by subcrop beneath the
 252 sandstones of Member 3 over a distance of 1.5 km to the west (Fig. 11).

253 These three intervals show that more stratigraphic units are preserved in the outcrops on the east coast of Garbh
 254 Eileach than further to the west. If we express this in terms of the ‘depositional episodes’ of the previous section,
 255 then the east coast section contains four more diamictite episodes (D1 to D12, D16-18, D31, D32) and four more

256 periglacial episodes (wedges above D18, D31, D32 and above the overlying ‘rhythmically laminated siltstones’).
257 These eight episodes amount to about 10% of all of the 76 ‘depositional episodes’ present in the whole of the
258 PAF. This is a direct indicator of the relative completeness of the stratigraphic section on the east coast of Garbh
259 Eileach.

260 **7. Accommodation space and subsidence.**

261 In comparison with other Neoproterozoic glacial successions, the PAF in the Islay-Garvellachs region of Argyll is
262 unusually thick (Fig. 13). As both under- and overlying formations were deposited close to sea level, its total
263 thickness of ~1100 m must be close to the amount of tectonic subsidence experienced during its deposition.
264 Assuming that the boundaries of the formation are defined by the same climatic changes that were responsible for
265 defining other Sturtian glacial units, then the unique character of the PAF is a consequence of what, for
266 Neoproterozoic glacial deposits, was a fortuitous tectonic context.

267 The PAF lies near the middle of the thick Neoproterozoic part of the Dalradian succession that was deposited in a
268 continental rift, within the supercontinent of Rodinia, which eventually split apart and became a passive margin to
269 the expanding Iapetus Ocean (Daly 2009). Such rift environments can produce thick successions accommodated
270 by rapid subsidence as compared with continental interior or cratonic regions. However, these successions are
271 commonly strongly deformed and metamorphosed, as their eventual position at continental margins means that
272 they inevitably become involved in subsequent plate collisions. Although the Dalradian Supergroup was
273 deformed during the Grampian Orogeny in early Ordovician times, it escaped the intense deformation, at least in
274 the Garvellachs/Islay area, that would have obliterated the exquisite depositional features discussed above.

275 Below the PAF lies the Appin Group, which on Islay and in the Appin area (40 km NE of the Garvellachs)
276 comprises ca. 7 km of largely shallow marine sediments. Only the top of this succession is exposed on the
277 Garvellachs, the deeper levels underlying the sea bed to the NW (Fig. 12). Above the PAF lies the Bonahaven
278 Formation, also well exposed on Islay but lying offshore to the SE of the Garvellachs. Above this is the Jura
279 Quartzite (Fig. 1b), a shallow-marine sandstone deposited under tidal and storm conditions that reached a
280 remarkable 5.3 km in thickness (Anderton 1976). Although it shows lateral and vertical facies variations,
281 nowhere does it show evidence of having been deposited either above sea level or at depths greater than a few
282 tens of metres (Anderton 1976). The coarseness of the formation necessitates that a large amount of finer
283 sediment was bypassed across the Jura Quartzite shelf into deeper, lower energy environments. The abundant

284 supply of sediment, presumably transported from distant sources by large rivers, was effectively dispersed by
285 shelf processes so that any tectonically produced accommodation space was constantly filled. For such a thick,
286 relatively uniform succession to accumulate, the palaeogeography responsible for creating this transport system
287 must have persisted for a remarkably long time. One can make the same argument about subsidence for the PAF.
288 The sediment supply was more than adequate to fill the accommodation space and the shallow marine dispersal
289 system that reworked the area returned the environment to near base-level between each glacial episode.

290 It seems likely that during the period from the deposition of the Appin Group through the PAF to the end of Jura
291 Quartzite times, the area around the Garvellachs was undergoing steady, moderately fast subsidence. Sediment
292 supply was capable of filling the resulting accommodation space and shallow marine dispersal systems
293 distributed the sediment so that it did not, in the long term, build up above base level. During PAF times, the
294 situation would have been complicated by eustatic sea-level changes and ice-loading; however, the interaction
295 between subsidence, sediment supply and dispersal kept the position of the sediment surface within a few tens of
296 metres of sea-level during the period from well before to well after PAF times.

297 Although data on the timing of Dalradian events is sparse, some inferences can be made about subsidence rates.
298 The lower three groups in the Dalradian Supergroup (the Grampian, Appin and Argyll Groups) span about 200
299 Ma, based on an estimated age for the base of the succession at around 800 Ma (Noble et al. 1996) and the ca.
300 600 Ma date for the Tayvallich Volcanics (Dempster et al. 2002) (Fig. 1b). Together, these three groups are
301 around 20-25 km thick which gives a long-term subsidence rate of 100-125 m/Ma, a figure that is typical for
302 sediment accumulation rates measured over millions of years (e.g. Partin & Sadler 2016). Such a subsidence rate
303 would suggest a duration of ca. 10 million years for the Port Askaig Formation.

304 **8 Comparison with other glacial records**

305 Here we give lithostratigraphic information on other thick, relatively complete, Cryogenian and Phanerozoic
306 glacial successions to compare with the PAF. We have used comprehensive compilations as the main sources of
307 information on pre-Pleistocene successions (Arnaud et al. 2011; Hambrey & Harland 1981).

308 **8.1. Cryogenian successions**

309 The 59 chapters in Arnaud et al. (2011) describe glacial successions of Neoproterozoic age to compare with the
310 PAF in respect of thickness and relative completeness. Many successions rest unconformably on basement rocks

311 (18 chapters) and so are quite different from the PAF. Other chapters have insufficient thickness data. For the
312 remaining 32 chapters the thickness data are plotted in Figure 13. The 16 thickest sections are named and are the
313 principal examples that bear comparison with the PAF.

314 The Port Askaig Formation forms part of the thickest Neoproterozoic succession; only seven others are thicker
315 than 10 km (Fig. 13 b). Also, the formation has the third largest sub-tillite Neoproterozoic thickness, only
316 exceeded by those in NW Tasmania and East Greenland (Fig. 13 a). Many glacial successions exceed the Port
317 Askaig Formation in thickness (Fig. 13 b) but some of these include more than one tillite formation. Just
318 considering the 'basal' tillite unit (Fig. 13 a), there are five localities thicker than the PAF and which have >10
319 diamictite beds. These are as follows (thickness; number of diamictites; figure number in Arnaud et al. 2011):
320 Yangtze region, 2.7 km, approximately 14, fig. 32.2A; Macaúbas Group, Brazil, 2.2 km, approximately 22, fig.
321 49.5; East Tianshan, 1.7 km, approximately 12, fig. 33.7; Lena River, 1.1 km, approximately 17, fig. 27.3;
322 Mackenzie Mountains, 1.0 km, approximately 30, fig. 36.3 . In addition, two other localities, which are not shown
323 on Fig. 13, are thicker than the PAF and have many diamictite beds: Oman, <3 km, 9, fig. 20.1; Southern
324 Canadian Cordillera, <2.5 km, approximately 31, fig. 37.4. The Oman succession rests unconformably on
325 basement rocks.

326 These seven successions, which range from 1.0 km to 3.5 km in thickness and contain from 9 to approximately 30
327 diamictite beds, are most similar to the PAF but, so far, none has been shown to contain so many climatically-
328 related depositional episodes as the latter (Table 2 – 76).

329 As an illustration of the difficulties in assessing the number of depositional / climatic episodes for the seven
330 successions, we provide a brief account of another thick example. In the Death Valley area of California, multiple
331 outcrop belts of Cryogenian strata occur. Correlation between them is challenging, and it is difficult to determine
332 which, if any, of them is representative of the entire glacial record. Miller (1985) proposed a two-fold glaciation
333 in the Panamint Range, and the separation of these by non-glacial carbonate rocks led Prave (1999) to propose
334 that this range contains the full record of two rift-related (Sturtian and Marinoan) glaciations. This succession,
335 which is up to 1200 m thick (Miller, 1985) was thus posited to be the most complete in the Death Valley area
336 (Pettersen et al., 2011). The diamictites rest with sharp contact on the underlying Beck Spring Dolomite
337 (Pettersen et al., 2011). However, other outcrop belts have subsequently been shown to be thicker, including the
338 2500 m-thick southern Kingston Range transect (Le Heron et al., this volume), and the almost 1400 m-thick
339 interval in the Silurian Hills (Le Heron et al., 2017). This latter mountain range also contains an excellent record

340 of a mixed siliciclastic-carbonate preglacial shelf system (Smith et al. 2016), where field observations suggest
341 that there is a probable gradational relationship between the pre-glacial deposits and diamictites of the syn-glacial
342 interval (Kupfer, 1960; Basse, 1978). If correct, this relationship may, like the PAF succession, imply an
343 excellent and full record of events preserved in the overlying succession.

344 **8.2. Cenozoic and Palaeozoic successions**

345 Contemporary analogues for the PAF should be sought in modern rift basins with thick glacial
346 sequences. Few such settings exist, but we identify two possible analogues.

347 Firstly, in the West Antarctic Rift System of the Ross Sea region of Antarctica, scientific drilling has
348 achieved outstanding (>95%) core recovery and allowed detailed multi-disciplinary studies (Hambrey et
349 al. 2002; Barrett 2009; Wilson et al. 2012). Three programmes – CIROS in the 1980s, CRP in the 1990s
350 and ANDRILL in the 2000s – have yielded a proximal record of glaciations with sequences on the order
351 of a kilometre thick and spanning up to 34 million years. The records demonstrate glacial processes at
352 the marine-terrestrial transition and are temporally complete for large parts of the Cenozoic. The facies
353 associations, thicknesses and cycles cored resemble those of the PAF.

354 The principal similarities are:

355 (i) The presence of numerous diamictite beds, including 49 in the 702 m CIROS 1 core, the main
356 ones being shown in Fig. 14 (Barrett, 1989); and over 50 in the 1285 m deep AND-1B core
357 (Wilson et al. 2012).

358 (ii) Sequence boundaries or “glacial surfaces of erosion” (GSE) at the base of many diamictite units
359 (Fielding et al. 2000; Naish et al. 2001).

360 (iii) Strong evidence for grounded ice, notably glaciotectonically deformed layers occurring
361 below diamictites, micromorphological investigations of thin sections of diamictites and
362 evidence for shearing within them. In addition, there are strong clast orientation fabrics. This
363 evidence leads to the interpretation of this facies being a basal till (Hambrey et al., 2002;

364 Barrett 2009, Wilson et al. 2012).

365 (iv) A lack of angular stones in diamictite, indicating ice sheet-scale glaciation with most glacial
366 sediment produced at the ice/bed interface (Hambrey et al., 2002; Barrett 2009, Wilson
367 2012).

368 (v) distinct depositional cycles, each 10-25 m-thick in the AND-1B core and comprising, from
369 bottom to top: a glacial surface of erosion, massive diamictite, stratified diamictite, stratified
370 sand, diatomite. These cycles indicate transitions from grounded ice to glaciomarine, then
371 open marine conditions and are believed to be orbitally controlled (Naish et al. 2001; Wilson
372 et al., 2012)

373 Barrett (2009) further analysed the proportions of facies and thickness of the cycles in CRP-1 and -2A
374 using the high-resolution chronology that has been obtained from these cores. Focusing on the interval
375 from 33 to 17 Ma, grounded ice extended across the CRP-2A drill site over 50 times, producing
376 significant unconformities at 29 Ma (443 metres below sea floor (mbsf), 25 Ma (307 mbsf) and 23 Ma
377 (130 mbsf), as well as multiple less pronounced GSEs. Such data are an indication of time intervals and
378 sedimentation rates that are realistic for deposition of the PAF.

379 A second example is the long Plio-Pleistocene record, with many diamictites, preserved at Tjörnes in
380 northeast Iceland, which resulted from subsidence adjacent to the Mid Atlantic Ridge (Eiríksson 2008).
381 This 600 m thick sequence records 14 glaciations with terrestrial glacial deposits interbedded with lavas
382 and tuffs.

383 Are there thick Palaeozoic glacial successions with lithostratigraphic patterns comparable to the PAF? Of the 52
384 chapters in Hambrey & Harland (1981) describing Permo-Carboniferous tillites, many have sections which are
385 thin and rest unconformably on older rocks, commonly striated basement. Only nine chapters described thick
386 tillite-bearing sections, ranging from 500 m to 2500 m (papers A10, B14, D4, D11, G7, G9, G12, G14, G15 in
387 that volume), and of these only one has more than 10 diamictites: the Carnarvon Basin in Western Australia (D4),
388 where mapping of the desert outcrops has suggested that the succession is 1250-2500 m-thick, contains 20-25

diamictites and records 4-5 glaciations (van de Graaff 1981). For the Ordovician glaciation there are 17 chapters in Hambrey & Harland (1981). Again many of the sections are thin and have tillites resting unconformably on older rocks. Two chapters have thicker sections: the Amazon region of Brazil which is 650 m-thick and contains 9 diamictites; and Argentina-Peru, which is 150-1000 m-thick and contains <5 diamictites. Few of these Palaeozoic examples appear to be as thick and show as many climatically-related stratigraphic episodes as the PAF.

8. Conclusions

The ~1100 m thick succession of the PAF contains 47 diamictites and there is a gradual, progressive evolution upsection in the lithologies of the diamictites, of the interbeds and of the clast types. The diamictites are interpreted as tillites, and their basal surfaces are almost always sharp, recording the change from non-glacial to glacial environments; such environmental switches occur at 25 levels in the PAF. Evidence of periglacial environments occurs at 25 horizons in the PAF; most are at the top of diamictite beds. Sandstone wedges of periglacial origin occur at 23 levels, cryoturbations at 3 levels and frost-shattered stones at 6 levels. The succession in the PAF records 28 glacial, 25 periglacial and 23 non-glacial episodes, thus representing a total of 76 climatically related depositional episodes.

The most complete succession in the PAF occurs on the east coast of Garbh Eileach. Carbon isotope data show no sign of a stratigraphic break at the base of the formation. Additional section is preserved there at three levels – from D1 to D12, from D16 to D18 and from D31 to the base of Member 3.

The PAF in Argyll lies near the middle of a 20-25 km-thick Neoproterozoic sequence. It is underlain by 7 km of largely shallow marine sedimentary rocks and overlain by 6 km of shallow marine and tidal sedimentary rocks. The long-term subsidence rate over these intervals, based on only sparse datings, may have been ca. 100-125 m/Ma. A comparison of the PAF with other thick, relatively complete Phanerozoic and Cryogenian glacial successions suggests that the PAF is exceptional in its combination of formation thickness (~1100 m), the number of climatically-related depositional episodes (76) and the huge thickness of the Neoproterozoic succession within which it lies.

These indicators of relative stratigraphic completeness provide supporting evidence (to the case made in the companion article by Fairchild et al. this volume) that the Garbh Eileach Formation and the base of the PAF

on the east coast of Garbh Eileach is a succession without a major break, and so is a candidate for the basal Cryogenian GSSP.

Acknowledgements. The authors thank Hugh Rice, Galen Halverson and two anonymous referees for their thorough comments which resulted in considerable improvements to the article. David Stephenson is thanked for reviewing the article. We are grateful to Alasdair MacLachlan and family of Cullipool, Luing for expert boat services in the Garvellachs. Dilshad O. Ali wishes to thank the Earth Sciences Department, Royal Holloway University of London for encouragement and support during his PhD studentship there.

9. References

- Anderton, R. 1976. Tidal-shelf sedimentation: an example from the Scottish Dalradian. *Sedimentology* 23, 429-58.
- Arnaud, E., Halverson, G.P. & Shields-Zhou, G. (eds) 2011. The geological record of Neoproterozoic glaciations. Geological Society, London, Memoirs, 36.
- Arnaud, E. & Eyles, C. 2002. Catastrophic mass failure of a Neoproterozoic glacially influenced continental margin, the Great Breccia, Port Askaig Formation, Scotland. *Sedimentary Geology* 151, 313-333.
- Arnaud, E. & Eyles, C. 2006. Neoproterozoic environmental change recorded in the Port Askaig Formation, Scotland: Climatic vs tectonic controls. *Sedimentary geology* 183, 99-124.
- Barrett, P. J. (ed.) 1989. Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. DSIR Bulletin 245, Wellington, New Zealand, 254 pp.
- Barrett, P. J. 2009. Cenozoic climate and sea level history from glaciomarine strata of the Victoria Land coast, Cape Roberts Project, Antarctica. In: Hambrey, M. J., Christoffersen, C., Glasser, N.F. and Hubbard, B. (eds.) Glacial sedimentary processes and products. International Association of Sedimentologists, Special Publication, No. 39, 259-287.
- Basse, R.A. 1978. Stratigraphy, Sedimentology and Depositional Setting of the Late Precambrian Pahrump Group, Silurian Hills, California. MS Thesis, Stanford University, 86p.
- Benn, D. I. & Prave, A. R. 2006. Subglacial and proglacial glaciotectionic deformation in the Neoproterozoic Port Askaig Formation, Scotland. *Geomorphology*, 75, 266-280.
- Daly, J.S. 2009. Precambrian. In Holland, C.H. & Sanders, I.S. (eds), The Geology of Ireland (2nd edition), Dunedin Academic Press, Edinburgh, 7-42.

444 Dempster, T.J., Rogers, G., Tanner, P.W.G., Bluck, B.J., Muir, R.J., Redwood, S.D., Ireland, T.R. & Paterson,
445 B.A. 2002. Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints
446 from U-Pb zircon ages. *Journal of the Geological Society, London* 159, 83-94.

447 Eiríksson, J. 2008. Glaciation events in the Pliocene – Pleistocene volcanic succession of Iceland. *Jökull* No. 58,
448 315-329.

449 Eyles, C.H. 1988. Glacially- and tidally-influenced shallow marine sedimentation of the late Precambrian Port
450 Askaig Formation, Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 68, 1-25

451 Eyles, C. & Eyles, N. 1983. Glaciomarine model for upper Precambrian diamictites of the Port Askaig
452 Formation, Scotland. *Geology* 11, 692-696. Comment by I. J. Fairchild & reply by C. H. Eyles & N. Eyles.
453 *Geology*, 13, 89-90.

454 Eyles, N. & Clark, B.M. 1985. Gravity-induced soft-sediment deformation in glaciomarine sequences of the
455 Upper Proterozoic Port Askaig Formation, Scotland. *Sedimentology* 32, 789-814.

456 Fairchild, I.J., Spencer, A.M., Ali, D.O., Anderson, R.P., Anderton, R., Boomer, I., Dove, D., Evans, J.D.,
457 Hambrey, M.J., Howe, J., Sawaki, Y., Wang, Z., Shields-Zhou, G., Shields-Zhou, Y., Skelton, A. and Tucker,
458 M.E. 2018. Tonian-Cryogenian boundary sections of Argyll, Scotland. *Precambrian Research*. This volume.

459 Fielding, C.R., Naish, T. R. & Woolfe, K.J. 2000. Facies analysis and sequence stratigraphy of CRP-2/2A,
460 Victoria Land Basin, Antarctica. *Terra Antarctica* 7, 323-338.

461 Hambrey, M. J., Barrett, P. J. & Powell, R.D. 2002. Late Oligocene and early Miocene glaciomarine sedimentation
462 in the SW Ross Sea, Antarctica: the record from offshore drilling. In: Dowdeswell, J.A. & Ó Cofaigh, C. (eds.),
463 Glacier-influenced sedimentation in high-latitude continental margins. Geological Society, London, Special
464 Publications, 203:105-128.

465 Hambrey, M. J. & Harland, W. B. 1981. Earth's pre-Pleistocene glacial record. Cambridge University Press.

466 Kilburn, C., Pitcher, W.S. & Shackleton, R.M. 1965. The stratigraphy and origin of the Port Askaig Boulder Bed
467 Series (Dalradian). *Geological Journal*. 4, 343-60.

468 Kupfer, D.H., 1960, Thrust faulting and chaos structure, Silurian Hills, San Bernadino County, California.
469 *Geological Society of America Bulletin*, 71, 181-214.

470 Le Heron, D.P., Busfield, M.E., Ali, D.O. & Tofaif, S. This volume. Glacial cycles in the thickest Cryogenian
 471 succession of Death Valley, California. *Precambrian Research*.

472 Le Heron, D. P., Tofaif, S., Vandyk, T., & Ali, D. O. 2017. A diamictite dichotomy: Glacial conveyor belts and
 473 olistostromes in the Neoproterozoic of Death Valley, California, USA. *Geology*, 45(1), 31-34.

474 Miller, J.M.G., 1985, Glacial and syntectonic sedimentation: The upper Proterozoic Kingston Peak Formation,
 475 southern Panamint Range, eastern California. *Geological Society of America Bulletin*, v. 96, p. 1537-1553.

476 Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S. and 29 others. 2001? Orbitally induced oscillations in the
 477 East Antarctic Ice Sheet at the Oligocene-Miocene boundary. *Nature*, 413, 719-723.

478 Noble, S.R., Hyslop, E.K & Highton, A.J. 1996. High precision U-Pb monazite geochronology of the c.806 Ma
 479 Grampian Shear Zone and the implications for the evolution of the Central Highlands of Scotland. *Journal of the*
 480 *Geological Society, London* 153, 511-514.

481 Partin, C. A. & Sadler, P. M. 2016. Slow net sediment accumulation sets snowball Earth apart from all younger
 482 glacial episodes. *Geology*, 44, 1019-1022.

483 Petterson, R., Prave, A.R. & Wernicke, B.P. 2011. Glaciogenic and related strata of the Neoproterozoic Kingston
 484 Peak Formation in the Panamint Range, Death Valley region, California. In: *The Geological Record of*
 485 *Neoproterozoic Glaciations* (Eds E. Arnaud, G.P. Halverson and G. Shields-Zhou). Geological Society, London,
 486 *Memoirs*, 36, p. 449-458.

487 Prave, A.R. 1999. Two diamictites, two cap carbonates, two $\delta^{13}\text{C}$ excursions, two rifts: the Neoproterozoic
 488 Kingston Peak Formation, Death Valley, California. *Geology*, v. 27, p. 339-324.

489 Rooney, A. D., Strauss, J. V., Brandon, A. D. & Macdonald, F. A. 2015. A Cryogenian chronology: two long-
 490 lasting synchronous Neoproterozoic glaciations. *Geology*, 43, 459-462.

491 Sawaki, Y., Kawai, T., Shibuya, T., Tahata, M., Omori, S., Komiya, T., Yoshida, N., Hirata, T., Ohno, T.,
 492 Windley, B. F. & Maruyama, S. 2010. $^{87}\text{Sr}/^{86}\text{Sr}$ chemostratigraphy of Neoproterozoic Dalradian carbonates
 493 below the Port Askaig Glaciogenic Formation, Scotland. *Precambrian Research*, 179, 150-164.

494 Smith, E.F., Macdonald, F.A., Crowley, J.L., Hodgins, E.B. & Schrag, D.P. 2016. Tectonostratigraphic evolution
 495 of the ~780-730 Ma Beck Spring Dolomite: Basin Formation in the core of Rodinia. In: Li, Z. X., Evans, D. A. D.
 496 & Murphy, J. B. (eds). *Supercontinent cycles through Earth history*. Geological Society, London, Special
 497 Publications 424, 213-239.

498 Spencer A. M. 1971. Late Pre-Cambrian glaciation in Scotland. Memoirs of the geological Society, London. No.
 499 6.

500 Spencer, A. M. & Spencer, M. O. 1972. The late Pre-cambrian/ Lower Cambrian Bonahaven Dolomite of Islay
 501 and its stromatolites. *Scottish Journal of Geology*. 8, 269-282

502 Stephenson, D, Mendum, J. R., Fettes, D. J. & Leslie, A. G. 2013. The Dalradian rocks of Scotland, an
 503 introduction. *Proceedings of the Geologists' Association* 124, 3-82.

504 Thomson, J. 1871. On the occurrence of pebbles and boulders of granite in schistose rocks in Islay, Scotland. *40th*
 505 *meeting British Association, Liverpool Transactions*. P. 88 only.

506 Van de Graaff, W. J. E. 1981. D4 Early Permian Lyons Formation, Carnarvon Basin, Western Australia. In:
 507 Hambrey, M. J. & Harland, W. B. (eds) *Earth's pre-Pleistocene glacial record*. Cambridge University Press, pp.
 508 453-458.

509 Wilson, G.G. and 63 others, 2012. Neogene tectonic and climatic evolution of the Western Ross Sea, Antarctica
 510 — Chronology of events from the AND-1B drill hole. *Global and Planetary Change* 96–97 (2012) 189–203

511 **Figure captions**

512 **Fig. 1** Location maps. (a) Outcrop of the Dalradian Supergroup and main localities of the Port Askaig Formation.
 513 (b) Main outcrops of the Lossit Limestone, Port Askaig, Bonahaven Dolomite and Jura Quartzite formations from
 514 Islay to the Garvellachs. (c) Port Askaig Formation members in the Garvellachs; sea-floor geology inferred from
 515 marine bathymetry data.

516 **Fig. 2** Compiled stratigraphic column from the Lossit Limestone to the base of the Jura Quartzite for Islay and the
 517 Garvellachs. Locations and sources: lower Lossit Limestone – south of Beannan Buidhe, Islay (new compilation);
 518 Garbh Eileach Formation and Members 1-3 – east coast of Garbh Eileach (Spencer 1971, plate 10A); Members 4
 519 and 5 – Port Askaig to Caol Ila and Con Tom (Spencer 1971, plate 10 G, H); Bonahaven Dolomite - north Islay
 520 (Spencer & Spencer 1972, fig 2, B, C). Note that the Lossit Limestone of Islay unconformably underlies the PAF,
 521 whereas the GEF on the Garvellachs conformably underlies the PAF. Given also chemostratigraphic differences
 522 (Fairchild et al. this issue), a gap is shown between the GEF and the Lossit Limestone. Similarly, the exact
 523 correlation of the top of Member 3 on the Garvellachs with the base of Member 4 on Islay is unknown (shown as
 524 a gap). S=Shallow marine; T=Tidal.

525 **Figure 3.** Evolution of the lithologies of the diamictites of the PAF. All photographs are of 50 x 50 cm areas. The
526 lowest diamictite (D7) is a dolomitic siltstone, here showing grey colour because of weathering in the inter-tidal
527 zone; D15 and D19-22 are sand-rich dolomitic siltstones; D26 to D45 are silty arenites with progressively less
528 dolomite. The clast contents show a similar gradual change from dolomite and limestone clasts (D7), to dolomite
529 and crystalline clasts (D15 and D19-22), to crystalline and progressively less dolomite clasts (D26-45). In D26-45
530 the dolomite clasts weather as holes. These photographs show ten of the diamictite measurement sites plotted in
531 Fig 4 and identified there by red dots.

532 **Figure 4.** Evolution of extrabasinal clasts in the diamictites of the PAF, based on a 184 measurements of clasts
533 >1 cm in 50 x 50 cm sized outcrops. The stratigraphic position of each of the 47 diamictites has been plotted
534 according to their percentage height within the 1100 m thickness of the formation. The percentage of extrabasinal
535 clasts is the sum of the granite + quartzite + extrabasinal unknown clasts and excludes intrabasinal clasts
536 (dolomite, limestone, intrabasinal unknown). The red dots are the measurements of the 10 exposures shown in
537 Fig.3. The diagram shows the remarkably gradual change in clast types upwards through the formation.

538 **Figure 5.** Carbon isotope profiles of carbonate clasts in diamictites 1 to 12 in relation to bedded carbonates in the
539 Garbh Eileach Formation (GEF). Samples are mainly from east Garbh Eileach, although some close to the base
540 of the PAF were taken from the equivalent sections in Dun Chonnuill and north Garbh Eileach. The standard
541 deviation at each level is also shown for limestones, but not for dolomite as they are not apparently unimodal. A
542 distinct negative carbon isotope anomaly (the Garbh Eileach anomaly) in the GEF is succeeded by values close to
543 zero. The presence of dolomite clasts identical in composition to underlying beds at the top of the GEF and base
544 of the PAF indicates erosion of lateral equivalents of these beds. The presence of limestone and dolomite clasts
545 with negative $\delta^{13}\text{C}$ indicates derivation from a deeper level of erosion and the gradual pattern of change shown by
546 the limestone clasts is suggestive of progressive unroofing of the Appin Group carbonate strata during Port
547 Askaig times. Analytical methods and full data listing are given in Fairchild et al. (this issue). Data on bedded
548 carbonate strata include those published in Sawaki et al. (2010).

549 **Fig 6.** Examples of the sharp basal contacts of diamictite beds in Member 3 (a-c) and Member 2 (d-f) in the
550 Garvellachs. (a-c) show diamictites which overlie tidal sandstones. (d) D30 overlies a 2m tidal/fluvial sandstone
551 whose base cuts across the sandstone wedge (yellow lines) penetrating the top of D29. (e) The massive, clast-rich
552 D 24 overlies sharply the laminated, clast-poor D23 (ice-rafted?), which rests on tidal/fluvial sandstones. (f) D19
553 has a sharp, undulating base above a siltstone. (g) D19 overlies, with an irregular contact, a 2 m dolomite breccia

554 (glaciotectonic?); this overlies sharply the Upper Dolomite; the contact of members 1 and 2 of the PAF is here at
555 the top of the Upper Dolomite beneath the dolomite breccia. Localities: a – south coast of Garbh Eileach; b-e –
556 east coast of Garbh Eileach; f – southwest coast of Eileach an Naoimh; g – west cliff of A'Chuli. Scales: a and b
557 – 2 m ruler; c-f – person.

558 **Fig 7.** Examples of the upper contacts of diamictite beds in members 3 (a, b, h) and 2 (c, d-g, i) in the
559 Garvellachs. (a, b) Frost-shattered stones in the tops of diamictites; the white outlines enclose the fragments of a
560 former granite boulder (a) and a former quartzite pebble (b). (c) Cross-section view of sandstone downfold
561 structures (cryoturbations) affecting a pebbly sandstone above D26. (d, e) Polygonal sandstone wedges seen
562 looking down on the top surface of D22. (f) An angular breccia (due to frost-shattering?) occurs as a 5cm-thick
563 layer overlying D22, within the outlines of the wedge polygons; for location - see the red rectangle on (e). (g)
564 Cross-sectional view of a sandstone wedge penetrating laminated siltstones, which contain dropstones in this
565 locality; the wedge is capped by a pebble lag (red line) and overlain by more laminated siltstones. (h) View
566 looking down on branching sandstone wedges penetrating the top of D35; both are overlain unconformably by a
567 granitic lag conglomerate. (i) Cross-sectional view of branching sandstone wedges penetrating D26; these are
568 truncated by a bedding plane (red line), above which lies a 50 cm-thick bed of diamictite (labelled D26').
569 Localities: (a, b) – west coast of Garbh Eileach; (c) – east coast of Garbh Eileach; (d) – southwest coast of
570 Eileach an Naoimh; (e, f) – northeast coast of Eileach an Naoimh; (g) – laminated siltstones at top of Member 2,
571 west coast of Garbh Eileach; (h) – south coast of Garbh Eileach; (i) – east coast of A'Chuli.

572 **Fig. 8.** Examples of the many events implied by the periglacial features at the top of D26: (a) measured profile,
573 east coast of Garbh Eileach; (b) stratal column, east coast of A'Chuli. The cryoturbated sandstone bed is present
574 along all of the outcrops for 5km throughout the Garvellachs. See Figure 7 (c) for a photograph of (a) in outcrop.
575 See Figure 7 (i) for a photograph showing the events (1) to (8) of (b) in outcrop.

576 **Fig 9.** Comparison of the Lossit Limestone to Disrupted Beds sections of the Garvellachs (left) and Islay (right).
577 Two distinctive units – the Great Breccia and the Disrupted Beds – can be recognized in both localities, but are
578 thicker in the Garvellachs. Diamictites 1 to 12 are missing on Islay: there the Great Breccia rests unconformably
579 on the dolomite bed at the top of the Lossit Limestone (Spencer 1971, fig. 43).

580 **Fig. 10.** Correlation of the uppermost beds of Member 1 in the Garvellachs (Fig 1c), showing their subcrop at the
581 unconformity below the Upper Dolomite, which is drawn as a horizontal datum. The section on the east coast of
582 Garbh Eileach contains 18 m of strata that are progressively cut out when traced 5 km to the west. Thus on the

583 east coast the section records more events: three diamictites (D16 to D18), the intervening sandstones and
584 siltstones and a sandstone wedge horizon (top of D18).

585 **Fig. 11.** Correlation of the uppermost beds of Member 2 on Garbh Eileach (Fig 1c), showing their subcrop at the
586 unconformity below Member 3, which is drawn as a horizontal datum. The section on the east coast of the island
587 contains 20 m of strata which are progressively cut out when traced 1.5 km to the west. Thus on the east coast the
588 section records several more events: two diamictites (D31, D32), three horizons of sandstone wedges and the unit
589 of 'varved' siltstones.

590 **Fig 12.** Outline geological map of the Garvellachs to Jura region superimposed on images of offshore swath
591 bathymetry data and terrestrial airborne radar altimetry data. The relative absence offshore of Quaternary
592 overburden allows the relief of the Dalradian seabed ridges, formed by the more-resistant Dalradian rocks, to be
593 clearly seen. Note the relatively uniform dip angles and directions (35-36 degrees towards the S and SE) in the
594 Garvellach Islands and Jura. Bathymetry data provided courtesy of the Maritime Coastguard Agency's UK Civil
595 Hydrography Programme – Crown Copyright. Terrestrial topography data derived from Intermap Technologies
596 NEXTMap Britain elevation data.

597 **Fig 13.** Overviews of thickness data for 33 relatively complete Neoproterozoic glacial successions - the 17
598 thickest are named. (a) Maximum basal tillite unit thickness versus maximum thickness of underlying
599 Neoproterozoic strata. (b) Maximum tillite-bearing interval thickness versus maximum Neoproterozoic thickness.
600 The data for 32 successions are from the chapters in Arnaud et al. (2011). Where all relevant data are available
601 within a chapter we have accepted the contents of that chapter without further research. For a number of chapters
602 in which key age and / or thickness data are ambiguous or absent we have sought out the most recent authoritative
603 source of the information required (e.g. for NW Tasmania the age / thickness data for the lower Neoproterozoic
604 have been sourced from the Australian Stratigraphic Units Database). In interpreting the contents of the 32
605 chapters in Arnaud et al. (2011); we have attempted to record in a consistent manner the maximum observed
606 stratal thickness of each of the units reported (Total Neoproterozoic; Sub-tillite Neoproterozoic; Tillite-bearing
607 interval; Basal tillite unit). For the PAF, the values are based on the regional maximum thickness for the
608 Dalradian of 15km given by Stephenson et al. (2013). Note that two important areas are missing due to our lack
609 of overview data: Central and South Australia.

610 **Fig. 14.** Summary lithological log of the CIROS-1 drill hole, Ross Sea region, Antarctica. Reproduced from
611 Barrett (1989, fig. 1). Abbreviations: m – marine; d – distal glaciomarine; p – proximal glaciomarine; w –

612 waterlain till (continuous rainout of glacigenic sediment); l – lodgement till (now known as subglacial traction
613 till); O-offshore; N-nearshore; S-shoreface; B-beach; F-fluvial.

614 **Tables**

615 **Table 1.** Statistics of periglacial features in the Port Askaig Formation. The 47 numbered diamictites in the
616 formation belong to at least 26 groups of diamictites. These groups often show periglacial features at their top: 18
617 tops have sandstone wedges; 5 tops have frost-shattered clasts; one top has cryoturbations. Most of these tops
618 show only wedges (13), but at 4 tops there are wedges and frost-shattered clasts and at one top all three features
619 are present. More horizons of periglacial features occur within bedded sedimentary rocks in the Formation:
620 wedges (5), frost-shattered clasts (1), cryoturbations (2) and frozen sedimentary fragments (2). The data from
621 members 1-3 are from the Garvellachs; those from members 4-5 are from Islay. The total of 25 periglacial
622 horizons is the sum of 23 horizons with wedges and two horizons where there are cryoturbations but no wedges
623 (above D26; below D33).

624 **Table 2.** Summary of the main climatically-related depositional episodes represented in the Port Askaig
625 Formation. The members, diamictite groups and periglacial horizons in the PAF are shown on Fig 2.

626

627 Suggested sizes of figure when printed: Fig 1 – page width. Fig 2 – column width. Fig 3 – column width. Fig 4 –
628 column width. Fig 5 – column width. Fig 6 – 120mm. Fig 7 – page width. Fig 8 – page width. Fig 9 – 120mm.
629 Fig 10 – page width. Fig 11 – 150mm. Fig 12 – column width. Fig 13 – page width. Fig 14 – column width.