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Ice-Rafting in Lakes in the early Neoproterozoic: Dropstones in the Diabaig Formation, Torridon Group, NW Scotland

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Abstract

A dropstone horizon is described from lake deposits in a paleo-valley from the ~1000 Ma Diabaig Formation, Torridon Group, NW Scotland. Dropstones occur in wave-rippled, fine grained sandstones and siltstones that contain desiccation and syneresis cracks indicative of fluctuating lake levels. Five locally-derived dropstones occur at the same horizon over lateral distance of 250 m and display clear evidence of deflection and penetration of laminae at the base, with thinning, onlap and draping of laminae onto clast margins and tops. Mechanisms of dropstone formation are discussed with ice-rafting considered the most likely explanation. It is suggested that rafting was promoted by cold winters at 35˚S in the early Neoproterozoic, possibly in an upland setting. Interpretation of the dropstones as ice-rafted debris provides the first physical record of evidence for ice at the Earth's surface during the late Mesoproterozoic to early Neoproterozoic.

Introduction

The Neoproterozoic Torridon Group outcrops throughout NW Scotland (Fig. 1). It unconformably overlies Lewisian Gneiss and Mesoproterozoic Stoer Group sediments and is unconformably overlain by Lower Cambrian quartzites (Stewart 2002; Fig. 2). The Torridon Group comprises four formations: the basal Diabaig overlain by the Applecross which is in turn overlain by the Aultbea and Cailleach Head formations (Fig. 2). The approximately 1000 Ma Diabaig Formation has been studied extensively by previous authors who have provided a framework for understanding both the depositional setting and controls on the distribution of the formation (Stewart 1972, 1988, 2002; Stewart and Parker 1979; Rodd and Stewart 1992; Turnbull et al., 1996; Park et al. 2002; Prave 2002; Kinnaird et al. 2007; Callow et al. 2011; Parnell et al., 2011). The thickness and distribution of the Diabaig Formation is strongly influenced by the underlying palaeo-topography developed on the Stoer Group and Lewisian Gneiss (Stewart 1972; Fig. 2). In contrast the overlying sandstones of the Applecross Formation show little influence of underlying topography on sedimentation and record the development of extensive fluvial systems that drained to the southeast across the entire Torridon group outcrop belt (Stewart 2002).

In the eastern and southern part of the Torridon group outcrop, the Diabaig Formation records deposition within a series of up to 600 m deep palaeo-valleys cut into the Lewisian Gneiss (Stewart 1972; 1988, 2002; Rodd and Stewart 1992; Park et al. 2002; Kinnaird et al. 2007). Along palaeo-valley margins, locally derived angular breccias record alluvial fan/fan-delta development (Stewart 1988, 2002). These proximal deposits pass both laterally and vertically into tabular sandstones and siltstones which in turn transition into interbedded grey siltstones, claystones and thin fine-grained sandstones (Stewart 1988, 2002; Park et al.

2002). The sandstones and siltstones display ubiquitous desiccation cracks and wave ripples, with syneresis cracks and microbial structures also documented (Prave 2002; Callow et al. 2011). The Diabaig Formation is interpreted to record shallow siliciclastic lake deposition with fluctuating water levels (Stewart 1988, 2002; Callow et al. 2002). Here we present new field observations that describe an additional depositional component of the Diabaig Formation which we interpret to represent ice-rafted dropstones. Following this, we discuss the significance of this interpretation within the context of the early Neoproterozoic climate and highlight the possibility that the dropstones provide the first affirmative physical evidence for ice at the Earth's surface in the Tonian.

Description

The studied section in the Diabaig Formation is exposed on the southern shore of Upper Loch Torridon in Ob Mheallaidh Bay (Fig. 1) at the high tide mark (NG 83055375). It has been described previously by Stewart (2002) and Callow et al. (2011) and is located in the centre of what is referred to as the Shieldaig palaeo-valley (Fig. 3). The paleo-valley is oriented north-south and present day exposure indicates a minimum erosional relief of 200 m during Diabaig deposition although this depth could be considerably greater as the base of the valley is not exposed.

The studied section is exposed in the centre of the palaeo-valley over a distance of 300 m along the shoreline and comprises 2.2 m of very fine to fine grained sandstones interbedded with siltstones and subordinate red claystones (Figs. 3 and 4). Occasional thin (up to 3 mm) lenses of medium sandstone are present in some horizons. Sedimentary structures are dominated by short-wavelength, symmetrical to asymmetrical wave ripples (3-7 cm wavelength), 0.5 to 4 cm thick and mm scale horizontal to slightly undulose laminae.

Occasional desiccation cracks and syneresis cracks are visible on bedding plane surfaces. The logged section is interpreted to record deposition in a relatively low energy, shallow, siliciclastic lake with fluctuating lake levels as indicated by the syneresis and desiccation cracks (Callow et al. 2011).

Dropstones

A 20 cm thick package of very fine to fine grained wave-rippled sandstones 1.2 m above the base of the section contains at least 5 outsized clasts (Fig. 4). Clast bases show clear evidence of deflection and penetration of laminae with thinning, onlap and draping of laminae onto clast margins and tops, with sediment compaction strain shadows at clast edges (Fig. 5). The clasts are isolated, restricted to a single horizon and occur over a lateral distance of 250 m. Clast long axes range in length from 3.5 to 9 cm. Of the clasts, four have long axes that lie parallel to bedding with one clast long axis oriented at 60 degrees to bedding (Fig. 5). Clasts range in shape from subangular to subrounded. Two clasts comprise Lewisian gneiss, two comprise amphibolite and one includes both lithologies. The amphibolite occurs as dykes within the gneiss in the adjacent area (Sutton and Watson 1950). The clast compositions, size and shape suggest local derivation.

Interpretation of dropstones

A dropstone is defined as a clast of anomalous size, and/or lithology, indicative of vertical or oblique introduction into the host sediment (Bennet et al. 1996; Le Heron 2015). The outsize nature and occurrence within very fine to fine wave-rippled sandstone, the depression and piercing of laminae beneath clasts and the thinning, onlap and draping of laminae above the clasts suggest that they represent dropstones.

Four main processes of transport and formation of dropstones have been documented (Bennet et al. 1996): biological rafting, flotation, ice rafting and projectiles. Whilst algal mat development has been identified in the Diabaig Formation and the older Stoer Group (Upfold 1984; Prave 2002; Callow et al 2011), it seems unlikely that floating algal mats would be capable of transporting large pebbles of relatively dense amphibolite and gneiss. Similarly, the clast types are too dense for floating to be an appropriate transport mechanism which is normally associated with coral (Kornicker & Squires 1962), pumice (Whitham & Sparks 1986) or very small flat shale clasts (Nordenskiold, 1900; Hume 1964). An origin as projectiles in the form of volcanic bombs or meteorites is also inappropriate given the clast composition.

An additional alternative explanation for dropstone formation which was not considered in the review of Bennet et al (1996) is as possible out-runner clasts that occur at the front of mass flow deposits (Postma et al. 1988; Nemec 1990). These have been described from subaqueous debris fall and flow deposits (Postma et al. 1988; Nemec 1990) and occur at the base of steep slopes in relatively deep water (below storm wave-base) and result in clasts often with load structures isolated within finer grained sediment. They are commonly related and/or interbedded with coarse-grained debris flow deposits (e.g. Eyles & Januszczak 2007). Whilst it is possible that coarse grained material could have been introduced into the Diabaig palaeo-valley via gravity flow processes particularly as breccias are commonly described from the base and margins of the Diabaig paleo-valleys (Stewart 1988, 2000; Kinnaird et al. 2007), we do not favour this interpretation for the following reasons. The dropstones occur within fine-grained, shallow water lake deposits and no coarse-grained or debris flow deposits occur within, or are present above or below the section elsewhere in the bay (see Stewart 2002 for a detailed description of the Torridonian succession in the area). The fine-grained character and lack of syn-sedimentary deformation such as preferred slump or flow directions in the lake deposits (e.g. Moretti and Sabado 2007) also suggests there was no significant depositional slope at the time of deposition.

If biological, projectile, floating and out-runner clast origins are excluded as an origin for the Diabaig dropstones then the most likely explanation for their presence, is that they represent ice-rafted material. Ice-rafted dropstones are well known from Quaternary glacial lake (Carrivick & Tweed 2013) and shallow marine glacial deposits (e.g. Lønne & Mangerud 1991) and in the rock record from shallow water glacio-marine (e.g. Eyles 1988) and proglacial or ice-contact lake deposits (e.g. Limarino & Cesari 1988; Buatois & Mangano 1995; Netto et al. 2009). Studies of the Late Carboniferous and Permian glacial lakes of Argentina are particularly noteworthy in that they contain dropstones that occur in wave-rippled and desiccated shallow water siliciclastic glacial lake deposits that infill a series of paleo-valleys (Limarino & Cesari 1988; Netto et al. 2009).

Discussion

If an ice-rafted origin for the Diabaig dropstones is accepted, then the implications of ice presence in the Diabaig paleo-valleys in the early Neoproterozoic requires explanation. The absence of any associated glacial deposits together with the small number (density) of dropstones and the early Neoproterozoic age of the Diabaig Formation suggest that the dropstones do not record a period of extensive glaciation. Whilst extensive glacial deposits are known from the Neoproterozoic, they occur some 300 million years after deposition of the Diabaig Formation in the Cryogenian (e.g. Spence et al. 2016), and the early Neoproterozoic Tonian time period is considered to be devoid of glacial activity (Young

2018). Whilst the precise age of the Diabaig Formation is uncertain, the only available date of 994+/- 48 Ma being derived from a Rb-Sr whole rock isochron on diagenetic phosphate (Turnbull et al. 1996), it is likely that dropstones in the Diabaig Formation record the only direct evidence for ice presence at the Earth’s surface between the late Mesoproterozoic (Stenian) and early Neoproterozoic (Tonian).

An alternative ice-rafted interpretation for the dropstones could be related to cold winter temperatures and formation of ice floes on the Diabaig lakes (Fig. 6). In this scenario, such outsized clasts could be incorporated into lake ice either by basal freeze-on near the lake shore or supplied by snow and debris avalanches reaching the frozen lake surface (Luckman, 1975). This debris-rich ice floe, during melt season, could be moved by winds and waves releasing dropstones in more distal parts of the lake.

During deposition of the Diabaig Formation, NW Scotland is considered to have been positioned in the southern hemisphere at a latitude of approximately 35˚S, although this is poorly constrained and could range between 30˚S and 50˚S (Stewart 2002). The presence of topographic relief of up to 600 m at the base of the Diabaig Formation could indicate that lacustrine deposition took place in an upland setting at altitudes favouring winter ice formation.

Conclusions

Dropstones are described from a palaeo-valley in the Diabaig Formation of the Torridon Group located on the southern shore of Upper Loch Torridon. The dropstones occur within very fine to fine grained wave-rippled sandstones displaying desiccation and syneresis cracks and which are interpreted to represent shallow lacustrine sedimentation. The origin of the dropstones is ascribed to ice-rafting as alternative explanations such as out-runner clasts at the end of debris flows, floatation, biological rafting and projectiles can be excluded. Whilst the dropstones are considered to record ice rafting, they are not thought to represent a period of glaciation due to the lack of associated glacial deposits and the absence of late Mesoproterozoic early Neoproterozic glacial deposits in general. It is suggested that the dropstones provide a transient record of cold winters at 35˚S in the late Mesoproterozoic to early Neoproterozoic promoting ice rafting within valley confined (upland?) lakes.

Acknowledgments

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List of Figures

Figure 1 Location map showing the distribution of the Diabaig Formation in the Torridon area and location of the studied section. Map based on Stewart (2002) and Callow et al. (2011).

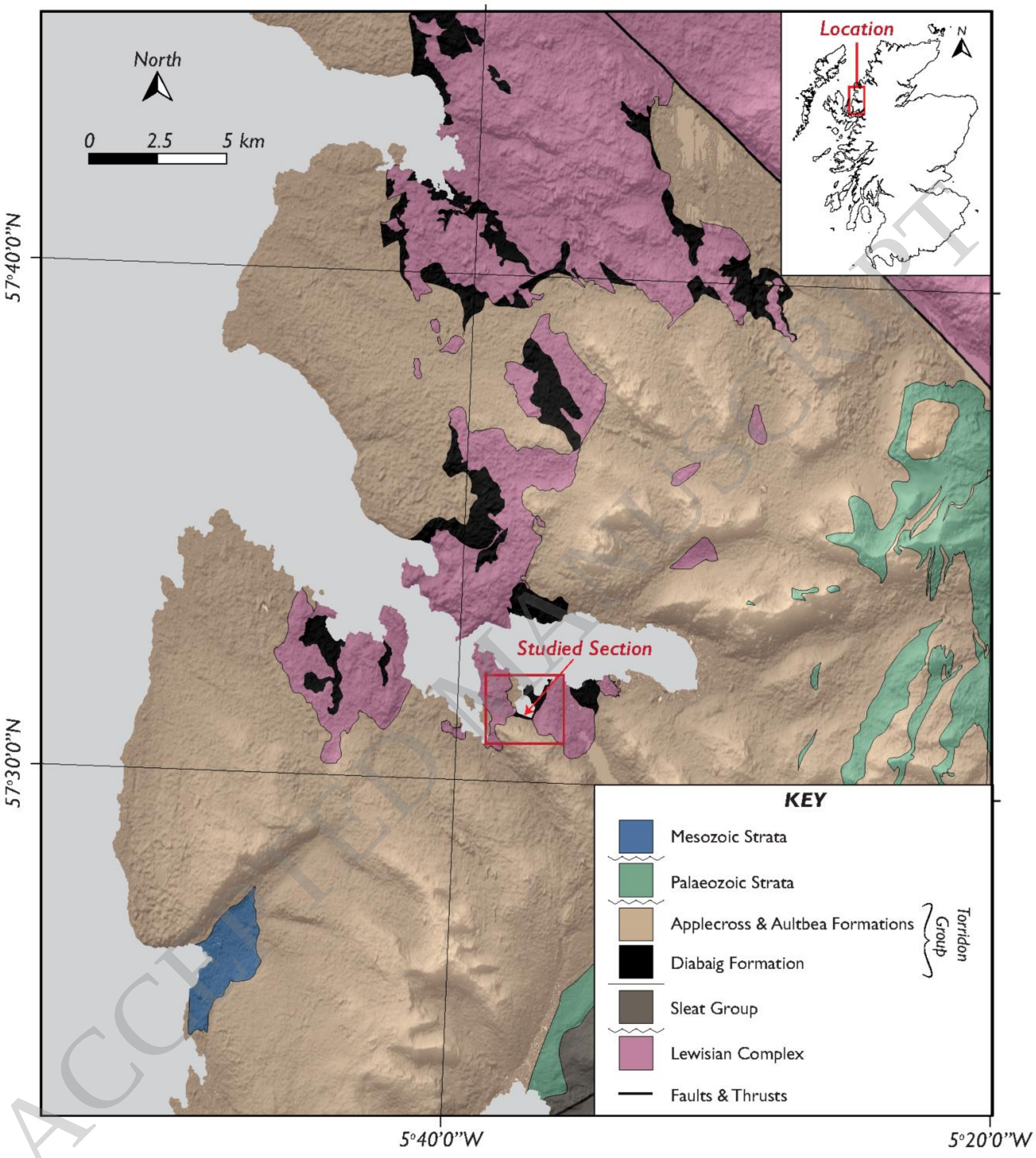
Figure 2 Generalised lithostratigraphy of the Torridonian succession in NW Scotland showing the stratigraphic position of the Diabaig Formation. Radiometric dates from (1) Turnbull at el. (1996) and (2) Parnell et al. (2011). Based on Lawson (1965), Stewart (1966, 2002), Williams (1966), and Callow et al. (2011).

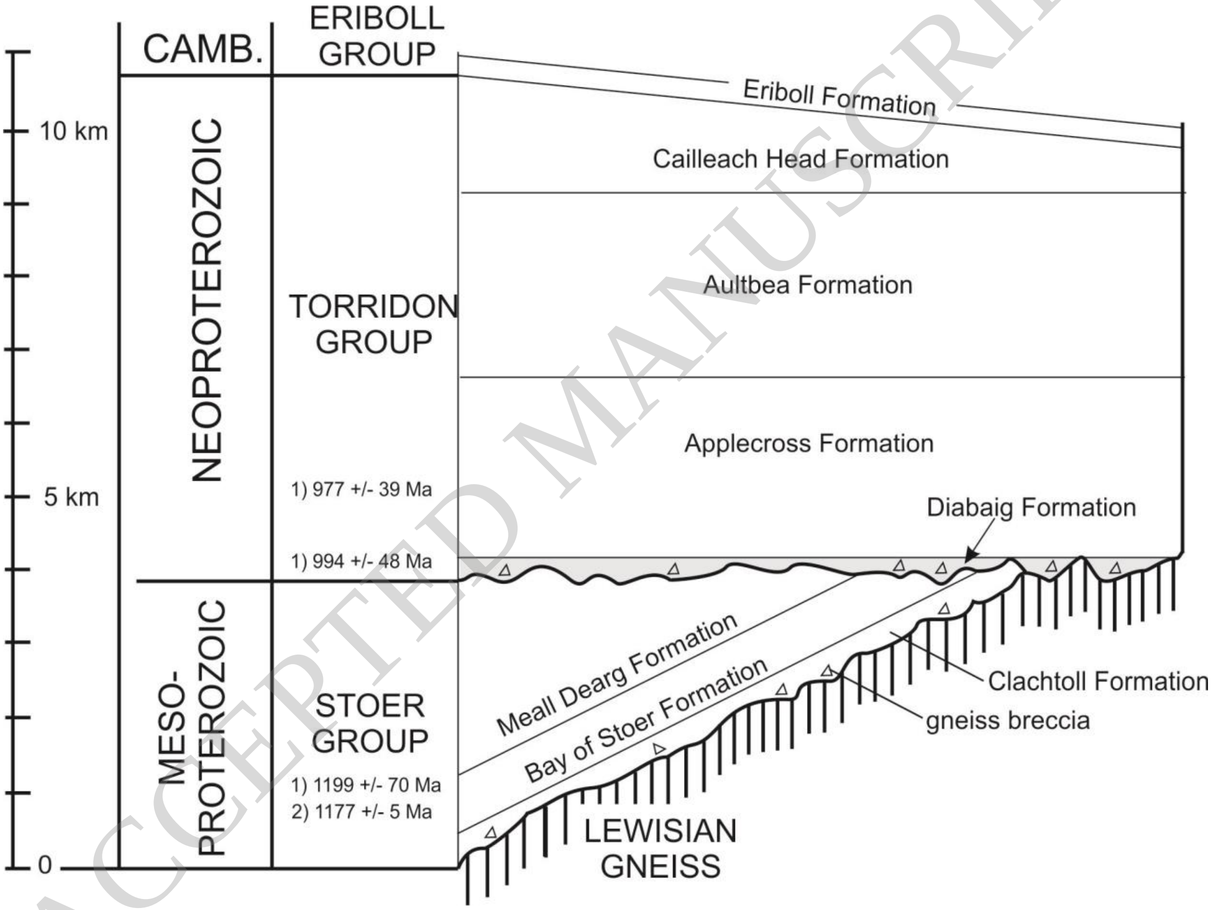
Figure 3 Annotated Googlearth image (Image Landsat/Copernicus, copyright 2019 Getmapping plc, ©2018 Google) illustrating the Sheldaig palaeo-valley cut into the Lewisian basement and infilled with the Diabaig Formation overlain by the Applecross Formation. The studied section is in the centre of the palaeo-valley. View to south.

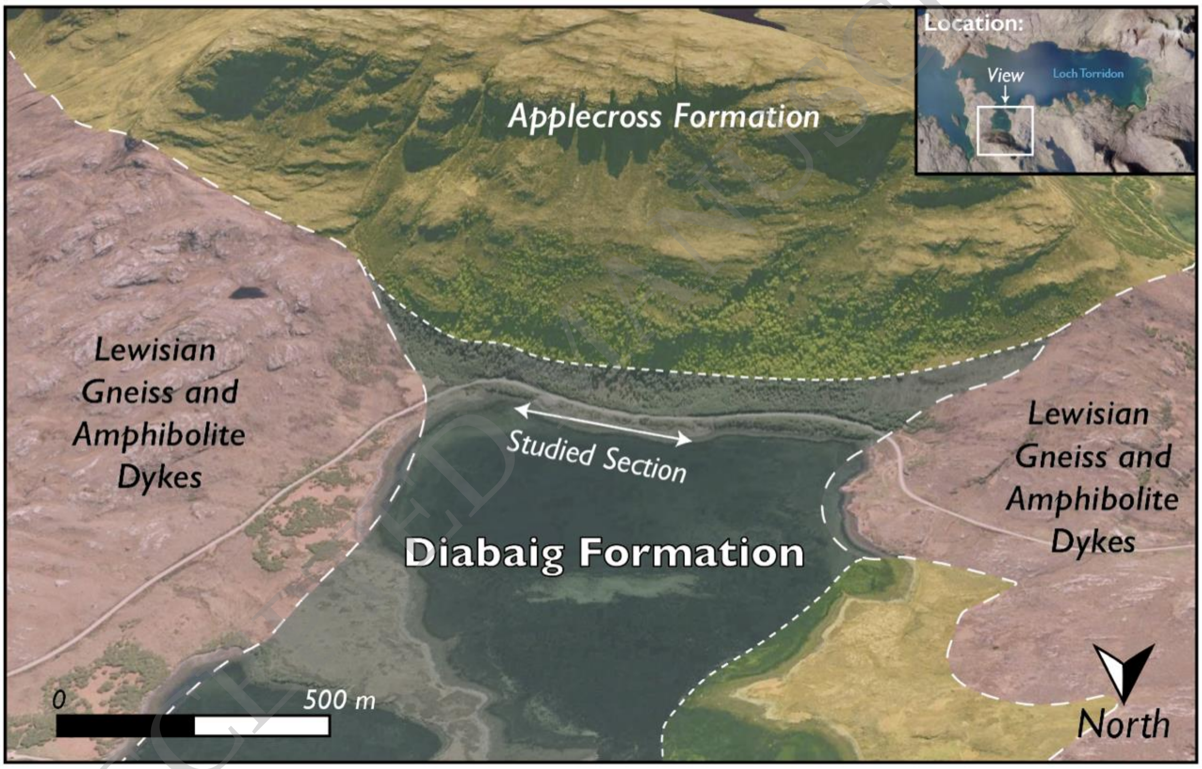
Figure 4 Logged section and photograph of the section illustrating the sedimentological character of the Diabaig Formation. Note the presence of the dropstone.

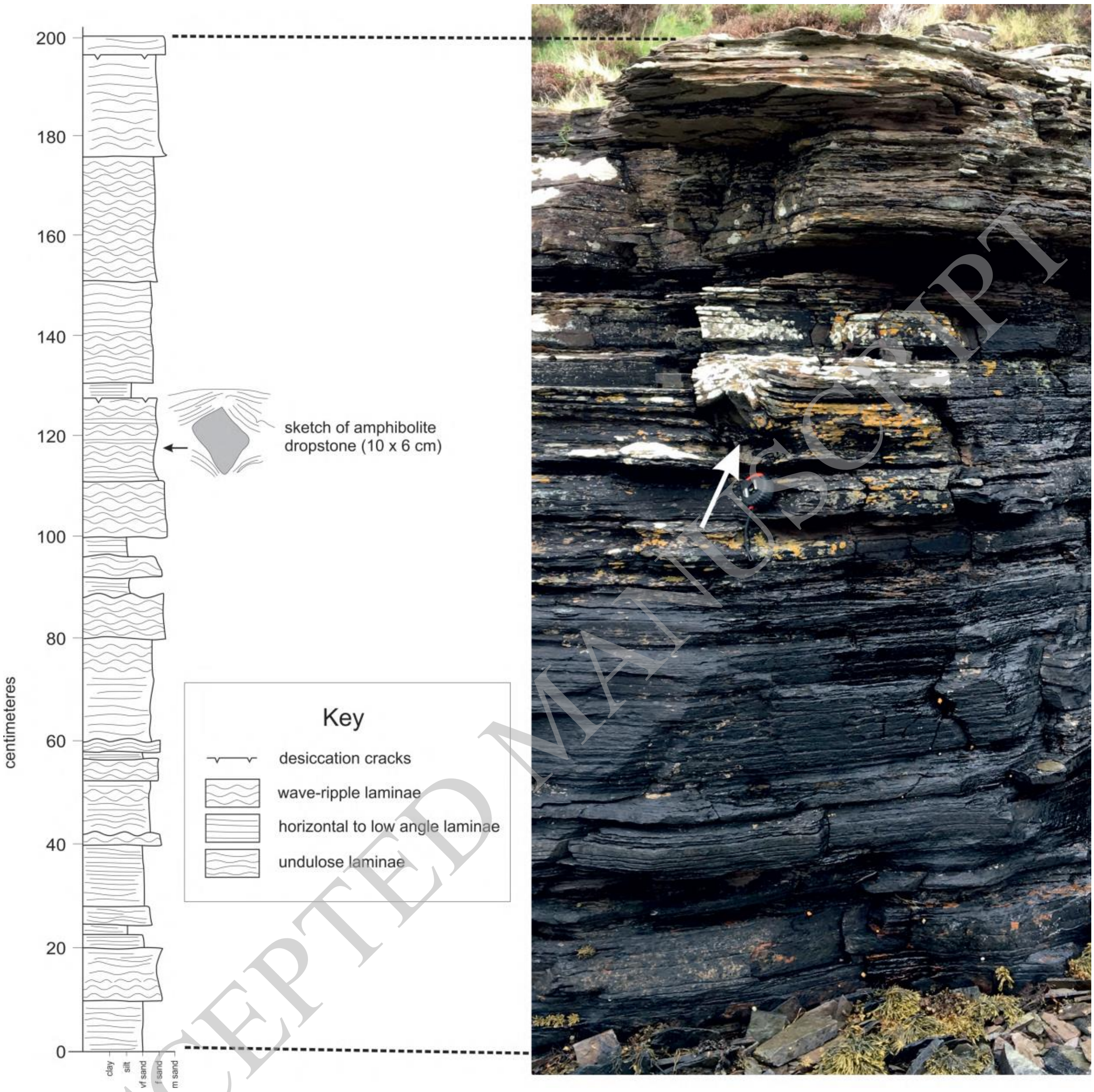
Figure 5 Examples of dropstones located at the same horizon across the outcrop over 250 m. Note the deflection of laminae above and below the clasts and the variations in size, shape and composition.

Figure 6 Schematic diagram illustrating seasonal ice-rafting mechanism for dropstone emplacement in Diabaig Fm; A – Summer/Autumnal - background deposition, no lake ice; B – Winter – marginal to extensive lake ice formation with clast incorporation; C – Spring – melting of seasonal ice, ice-rafting and flotation, dropstone deposition in deep lake.


North
0
2.5
5 km
Location
N
57°40'0"N
57°30'0"N
Studied Section
KEY
Mesozoic Strata
Palaeozoic Strata
Applecross & Aultbea Formations
Diabaig Formation
Torridon Group
Sleat Group
Lewisian Complex
Faults & Thrusts
5°40'0"W
5°20'0"W


CAMB.
ERIBOLL GROUP
10 km
NEOPROTEROZOIC
TORRIDON GROUP
5 km
1) 977 +/- 39 Ma
1) 994 +/- 48 Ma
MESO-PROTEROZOIC
STOER GROUP
1) 1199 +/- 70 Ma
2) 1177 +/- 5 Ma
0
Eriboll Formation
Cailleach Head Formation
Aultbea Formation
Applecross Formation
Diabaig Formation
Meall Dearg Formation
Bay of Stoer Formation
Clachtoll Formation
gneiss breccia
LEWISIAN GNEISS


Location:
View
Loch Torridon
Applecross Formation
Lewisian Gneiss and Amphibolite Dykes
Studied Section
Lewisian Gneiss and Amphibolite Dykes
Diabaig Formation
0
500 m
North


200
180
160
140
120
100
80
60
40
20
0
centimeteres
clay
silt
vf sand
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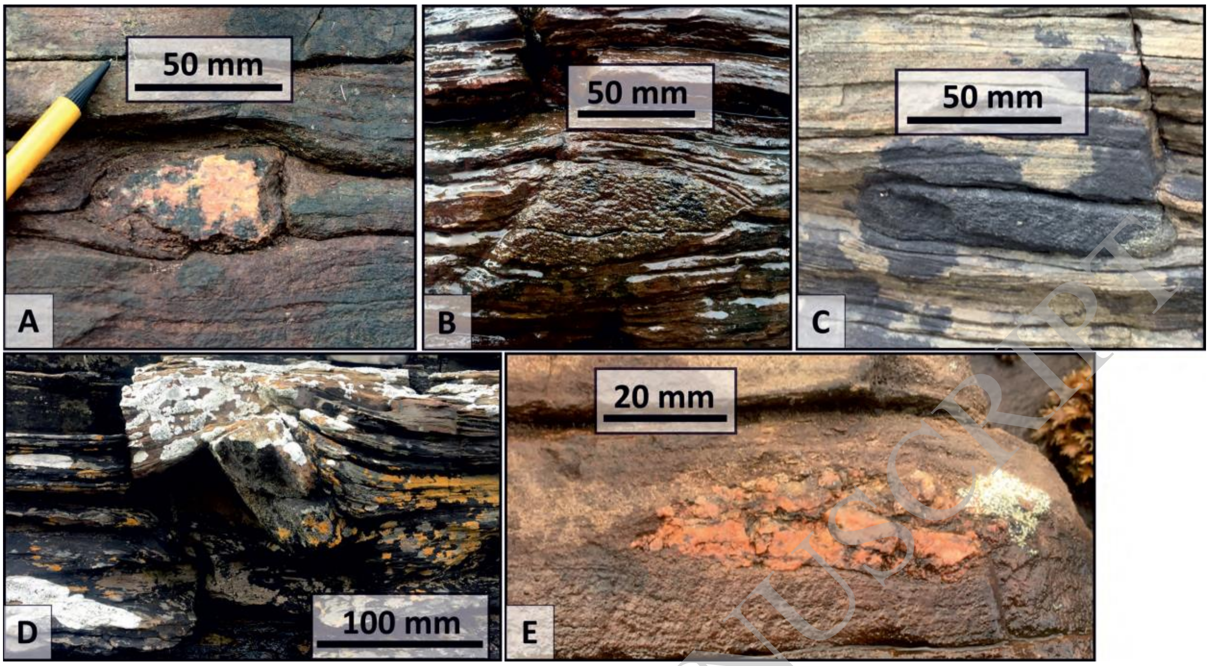
m sand
sketch of amphibolite dropstone (10 x 6 cm)
Key
desiccation cracks
wave-ripple laminae
horizontal to low angle laminae
undulose laminae


50 mm
A
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D
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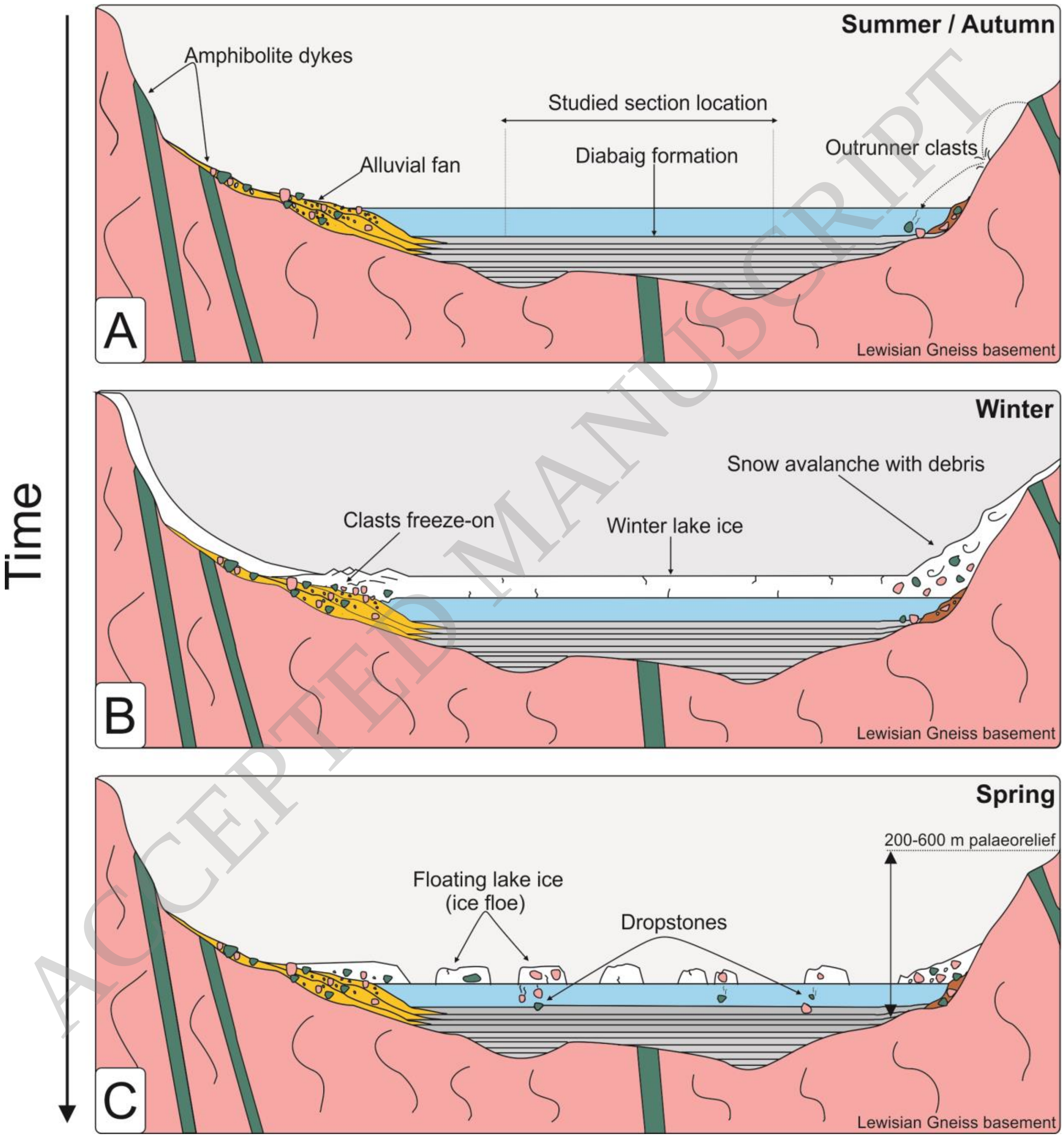
Time
Summer / Autumn
Amphibolite dykes
Studied section location
Diabaig formation
Outrunner clasts
Alluvial fan
A
Lewisian Gneiss basement
Winter
Snow avalanche with debris
Clasts freeze-on
Winter lake ice
B
Lewisian Gneiss basement
Spring
200-600 m palaeorelief
Floating lake ice
(ice floe)
Dropstones
C
Lewisian Gneiss basement