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1 **Highlights**

- 2 • First description of a Precambrian heterolithic meandering fluvial system.
- 3
- 4 • Challenge current paradigms regarding Precambrian alluvial environments.
- 5
- 6 • Novel insights on the Precambrian depositional dynamics.
- 7
- 8 • Depositional environment of the Torridonian succession (Neoproterozoic, NW
- 9 Scotland).

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1 **Heterolithic meandering-channel deposits from the Neoproterozoic of**
2 **NW Scotland: implications for palaeogeographic reconstructions of**
3 **Precambrian sedimentary environments**

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9

10 ABSTRACT

11 Pre-Silurian fine-grained meandering river deposits are apparently rare in the rock
12 record. Most modern-day river dynamics are influenced by vegetation through bank
13 stabilization, fine-grained sediment production and retention, and runoff control,
14 leading to the development of highly sinuous, single-channel systems. In contrast, pre-
15 vegetation river dynamics are poorly understood, in part because there are no modern-
16 day analogues for completely non-vegetated meandering river systems, particularly
17 under humid climates. Some models attribute the paucity of fine-grained sediments
18 described from studies of pre-vegetation fluvial deposits to lower rates of chemical
19 weathering in the absence of land plants. The architecture of precambrian, fine-grained
20 meandering stream deposits is here described for the first time.

21 The Allt na Béiste Member at the base of the Applecross Formation of the Torridon
22 Group (Neoproterozoic, NW Scotland) is characterized by heterolithic deposits,
23 preserving a varied suite of fluvial forms including inclined heterolithic strata, lateral-
24 accretion sets, up to 8 m-thick muddy floodplain deposits with preserved crevasse-

1 splays. Successions of laterally-accreting strata are interbedded with metre-scale
2 channel-fill sandstones, in a succession up to 190 m-thick related to the early stages of
3 the Applecross Formation fluvial system, as large-scale rivers buried the Lewisian
4 palaeovalleys over which fluvial and lacustrine sediments of the Diabaig Formation had
5 been deposited. The lacustrine fine-grained sediments, coupled with relatively low
6 gradients of the shallow lacustrine environments and denuded, highly weathered
7 Lewisian basement, apparently provided considerable amounts of fine-grained sediment
8 which added sufficient cohesion to this fluvial system to induce the adoption of
9 laterally-migrating, meandering channel planforms at the expense of multi-thread
10 braided channels.

11 Our data suggest that, given appropriate conditions, pre-vegetation meandering channel
12 planforms were indeed able to develop, without the buffering effects of land plants. The
13 paucity of fine-grained sediments in the pre-vegetation rock record may be more a
14 consequence of preservation-related issues than the actual paucity of such sediments.
15 These results provide novel insights into the characteristics of Earth's landscape prior to
16 the Silurian, and provide potential analogues for meandering channels interpreted from
17 satellite imagery of Mars.

18

19 *Keywords:* Fluvial deposits, meandering rivers, Precambrian, pre-vegetation, Neoproterozoic, Torridonian, Scotland.

20

21

22 **1. Introduction**

23

1 Precambrian rivers functioned in the absence of significant interaction between
2 sedimentological processes and biological activity on land. Deposits of pre-vegetation
3 fluvial systems share many characteristics with those of post-vegetation fluvial systems
4 developed under arid climates (Schumm, 1968), since these are the only modern
5 climatic conditions in which vegetation is sparse or mostly absent. Pre-vegetation rivers,
6 however, are interpreted to have developed within relatively barren continental
7 environments under a wide variety of climatic and hydrological conditions (Long, 1978,
8 2004, 2006, 2011; Eriksson et al., 1998, 2006, 2013). Vegetation appeared in alluvial
9 environments in the Mid-Palaeozoic and is a major control in most modern-day
10 depositional systems (Corenblit and Steiger, 2009), influencing soil production, run-off
11 control, surface roughness and bank stabilization, and allowing the development and
12 preservation of stable floodplain deposits (Cotter, 1978; Gibling et al., 2014). The
13 interpretation of pre-vegetation fluvial systems is therefore a challenge for
14 sedimentologists since there are no modern analogues for non-vegetated alluvial
15 systems under most climatic settings, and there is a lack of specific analytical methods
16 and criteria to account for the particular features of these systems. Their interpretation
17 consequently requires detailed architectural modelling, including the collection of large
18 datasets recording the orientations of different sedimentary surfaces in relation to each
19 other (Long, 2011). Recent detailed studies on the precambrian Ellice Formation
20 demonstrated higher geomorphic variability than envisaged by current models for pre-
21 vegetation fluvial systems (Ielpi and Rainbird, 2015).

22 According to present models for pre-vegetation fluvial systems, most were
23 multi-channel, braided streams (Schumm, 1968) which rapidly widened in response to
24 increasing discharge due to the lack of sediment cohesion (Wolman and Brush, 1961).
25 This behaviour resulted in channels with high width-to-depth ratios, classified as the

1 sheet-braided fluvial style (Cotter, 1978; Fuller, 1985). Most published studies of pre-
2 vegetation fluvial systems describe a paucity of fine-grained sediments, and most
3 sedimentary structures and facies associations are attributed to bedload transport in
4 braided streams (Hjellbakk, 1997; Long, 2006, 2011; Marconato et al., 2014; Røe,
5 1987; Røe and Hermansen, 1993; Santos et al., 2014; Selley, 1969; Sønderholm and
6 Tirsgaard, 1998; Tirsgaard and Øxnevad, 1998; Went, 2005, 2013; Williams and Foden,
7 2011; Winston, 1978). Published interpretations of fine-grained meandering systems are
8 based primarily on supposed fining-upwards trends in channel deposits (e.g. Sweet,
9 1988). Depositional models for non-vegetated meandering river deposits are scarce, no
10 fine-grained meandering river deposits have been described in the literature, and
11 examples of sandy and gravelly meandering systems are very rare (Long, 2011).
12 Crevasse-spay deposits are also very rare, and have been recorded adjacent to
13 ephemeral sandy-meandering systems (Long, 2011). Braided systems with deep
14 channels and well-developed levées have been described in the upper successions
15 Applecross Formation (Ielpi and Ghinassi, 2015).

16 Interpretations of meandering channel planforms from outcrop studies are
17 largely based on the recognition of laterally accreted fluvial forms and their abundance
18 in relation to other forms (Allen, 1964; Miall, 1996). Lateral accretion sets are typically
19 heterolithic and characterized by sigmoidal profiles with a basal scoured surface.
20 Fining-upward cycles are common, grading upward into siltstones and heterolithic strata
21 (Allen, 1965; Leeder, 1973). Studies of modern and ancient strata suggest that such
22 features form through the lateral growth of point bars in high-sinuosity channel systems
23 of various scales and settings (Thomas et al., 1987). A sharp increase in the reported
24 frequency of preservation of inclined heterolithic stratification in lateral accretion sets in
25 fluvial deposits from the Silurian onwards suggests that meandering river systems

1 become more frequent during the Palaeozoic, at the same time as land plants colonized
2 the continents (Cotter, 1978; Davies and Gibling, 2010). Those data suggest that
3 meandering channel planforms are closely linked to the presence of vegetation in the
4 alluvial environment, and that prior to the development of vegetation on the continents
5 there was little variation in river characteristics. Interestingly, meandering channel
6 planforms have recently been described from Mars (Nußbaumer, 2009; Schon et al.,
7 2012), adding a range of possible scenarios for pre-vegetation river systems.

8 We present here the results of detailed outcrop studies from the Allt na Béiste
9 Member at the base of the Neoproterozoic Applecross Formation of the Torridonian
10 succession in NW Scotland, UK (Stewart, 2002; Owen and Santos, 2014). These fluvial
11 deposits display a range of depositional architecture including lenticular bedding with
12 lateral accretion surfaces, and macroforms characterized by inclined heterolithic strata.
13 Fine-grained deposits are thick (up to 8 m) compared with other pre-vegetation fluvial
14 deposits and incorporate several facies associations, crevasse-channel and -splay
15 deposits, and a range of soft-sediment deformation features. These characteristics
16 indicate that parts of the river system formed discrete channel and floodplain elements,
17 and that some channels had meandering planforms, results that contrast with other pre-
18 vegetation fluvial systems described in the literature to date.

19 The object of this paper is to present the first description of the depositional
20 architecture of Precambrian heterolithic meandering fluvial channels, and suggest local
21 and regional controls that enabled rivers to meander in the absence of land plants. These
22 observations provide novel insights into aspects of Earth's landscape prior to the early
23 Palaeozoic, and represent potential field-based analogues for recently-interpreted
24 channels on Mars. This work contributes to the understanding of pre-vegetation fluvial
25 systems, and contributes to developing a methodology for the study of precambrian

1 fluvial deposits. The description of the geometry of the heterolithic facies association
2 contributes to understanding the nature of barriers to fluid migration in precambrian
3 rocks.

4

5

6 **2. Geological setting**

7

8 The Mesoproterozoic to Neoproterozoic “Torridonian” rocks of NW Scotland,
9 UK, comprise a >11 km-thick continental siliciclastic succession limited to the East by
10 the Moine Thrust and to the West by the Outer Hebrides Fault Zone, and
11 unconformably overlain by Cambrian rocks (Fig. 1). “Torridonian” is an informal
12 stratigraphical unit comprising the Stoer, Sleat and Torridon Groups (Stewart, 2002),
13 sometimes referred to as the Torridonian Supergroup (e.g. Williams and Foden, 2011).
14 The Mesoproterozoic Stoer Group (up to 2 km thick) unconformably overlies Archean
15 to Lower Proterozoic Lewisian Gneiss and is separated by an angular unconformity
16 from the more widespread Neoproterozoic Torridon Group (Stewart, 1969). This is up
17 to 7 km thick and comprises the Diabaig, Applecross, Aultbea and Cailleach Head
18 Formations (Selley, 1965, 1969; Williams, 1969, 2001; Owen, 1995, 1996). The
19 original size and shape of the Torridon Group basin is impossible to constrain because
20 its present-day extent is bounded by post-depositional faults (Krabbendam et al., 2008)
21 and its syn-depositional limits are concealed or eroded. Its tectonic setting is disputed;
22 interpretations include an asymmetrical rift basin with a faulted margin near the present-
23 day Outer Hebrides (Stewart, 1982, 2002; Williams, 1969, 2001), a thermal sag basin

1 (Nicholson, 1993), a post-Grenvillian extensional collapse basin (Turnbull, 1996;
2 Williams and Foden, 2011), and a Grenville Orogeny-related foreland basin (Rainbird et
3 al., 2001; Kinnaird et al., 2007; Krabbendam et al., 2008).

4 Massive, coarse-grained breccias at the base of the 600 m-thick Diabaig
5 Formation pass laterally and upwards into grey shales, silty mudstones and rippled,
6 tabular-bedded red sandstones (Stewart, 1988). The depositional setting was the
7 infilling of Lewisian palaeovalleys, initially by locally derived, coarse-grained
8 sediments, followed by deposition in shallow lakes and rivers (Stewart, 2002). Zircon
9 provenance analysis shows the youngest grains to be of late Mesoproterozoic age (1093
10 ± 34 Ma, Kinnaird et al., 2007), while Rb-Sr whole-rock isotopic determination gives a
11 depositional age of 994 ± 48 Ma (Turnbull et al., 1996). Tabular centimetre- to
12 decimetre-scale beds of symmetrically rippled sandstone alternating with mudstone pass
13 upward into tabular sandstone beds with small- to large-scale cross-bedding at the base
14 of the Applecross Formation, recording a change from event deposition in a shallow
15 lake to the onset of a large-scale fluvial system.

16 The Applecross Formation includes over 3,000 m of predominantly red, coarse-
17 grained arkosic sandstones and pebble conglomerates, with very rare fine-grained
18 deposits (Stewart, 2002). Rb-Sr whole-rock isotopic analysis has yielded a depositional
19 age of 977 ± 39 Ma (Turnbull et al., 1996) and youngest detrital zircon data give $1060 \pm$
20 18 Ma (Rainbird et al., 2001). These sediments have been interpreted by some as
21 transversal fluvial megafan systems draining supracrustal and crystalline terrains of
22 mainly late Palaeoproterozoic age to the West of the present-day outcrop, forming a
23 broad alluvial plain related to a post-Grenvillian extensional basin (Williams, 1969,
24 2001; Williams and Foden, 2011). The depositional architecture is typified by laterally-
25 extensive tabular sandstone bodies with high width-to-depth ratios which resemble the

1 typical pre-vegetation architecture classified by Cotter (1978) as sheet-braided.
2 Williams (1966), working in the NW of the outcrop, described pebbly sandstone and
3 conglomerate in laterally-accreted cross-sets up to 2 m thick with moderate dip and
4 internal cross-stratification related to channel bars or point bars of migrating braided
5 channels, and inferred that flow conditions were very variable. He proposed periods of
6 quiet water when mud cross-strata and low-dipping, fine-grained sands filled channels
7 and were later removed by recurring strong currents, and noted point bars with
8 relatively low dips which rarely reached the angle of repose of saturated sands.
9 Nicholson (1993), working over most of the Applecross Formation extent, found
10 evidence for channels of the order of 10 m deep and related these to longer, deeper,
11 perennial river systems. The architectural characteristics of the upper parts of the
12 Applecross Formation, in the Stoer Peninsula, are interpreted as channelized gravelly-
13 sandy braided systems, and include local non-heterolithic lateral accretion elements,
14 interpreted as parts of inchannel braid bars (Ielpi and Ghinassi, 2015).

15 The object of this study is the Allt na Béiste Member at the base of the
16 Applecross Formation. Restricted to the Allt na Béiste Member are relatively thick units
17 of fine-grained and heterolithic deposits, as described by Peach et al. (1907), which
18 suggest continuity of deposition from the underlying Diabaig Formation. A fluvial
19 origin for the Allt na Béiste Member was proposed by Stewart (2002), who redefined
20 the base of the Applecross Formation to the base of this member. The differences
21 between the Allt na Béiste Member and the underlying Diabaig Formation were
22 described by Stewart (2002), including: (1) modal mineralogy of sandstones (similarity
23 of the Allt na Béiste Member deposits to those preserved in the Applecross Formation
24 but different from those preserved in the Diabaig Formation); (2) provenance analyses
25 (presence of distantly-sourced chert and porphyry pebbles in the Allt na Béiste Member

1 and Applecross Formation, as opposed to the proximal-sourced Diabaig Formation); (3)
2 feldspar content (content around 25% and mostly potassic composition in the Allt na
3 Béiste Member as opposed to the content of up to 40% and mostly by plagioclases
4 derived from local basement gneiss); and (4) colour (shales in the Allt na Béiste
5 Member being reddish-brown and greyish red, as opposed to the Diabaig Formation's
6 grey shales). The type section near the Allt na Béiste stream at Lower Diabaig, on the
7 north side of Loch Torridon, is approximately 25 m thick, but the thickness is highly
8 variable, reaching almost 200 m near Gairloch (Stewart, 2002). Although Kinnaird et al.
9 (2007) suggested on the basis of zircon geochronology that the Diabaig–Applecross
10 contact represents a hiatus of the order of a few million years, detailed sedimentological
11 studies point to a transition from the Diabaig lacustrine shales and basin-border
12 fanlomerate system to the large-scale fluvial system of the Applecross Formation
13 (Selley, 1965; Stewart, 2002; Williams and Foden, 2011). It is distinguished from the
14 remainder of the Applecross Formation by finer grain-size, fewer pebbles, abundance of
15 preserved mudstone, and includes heterolithic deposits with apparent fining-upward
16 cycles as well as units with distinctive lenticular bedding geometries (Stewart, 2002).

17

18 **3. Methodology**

19

20 Stratigraphical sections in the Allt na Béiste Member were logged at the type
21 section are at Diabaig and near Big Sand fishing station W of Gairloch, and
22 photomosaics of key architectural panels were annotated in the field at Diabaig. The
23 classification of fluvial forms is based on the relationship between external form and
24 internal structures (Miall, 1996; Long, 2006). Palaeoflow indicators from cross-

1 stratification (0th-order) were measured and compared with the dip directions of major
2 internal surfaces (2nd- to 3rd-order) and lower bounding surfaces (4th- to 5th-order). The
3 data are plotted as rose diagrams and analysed along with photographic panels and field
4 sketches to identify different fluvial forms, each characterized by distinct characteristics
5 of sedimentary facies associations (Table 1) and external geometries. Characterization
6 of architectural elements was based on the relationship between external and internal
7 surfaces (Table 2). Although Stewart (2002) describes a regional dip of 20° to 300°,
8 local dips measured from interbedded mudstones and sandstones at Diabaig were much
9 lower, measured at 2–4° to 340°. Due to these low values, no adjustments were made for
10 tectonic tilt for the data from Diabaig. Regional tilt values quoted by Stewart (2002)
11 were, however, applied to data from other localities, such as Gairloch, as described
12 below.

13

14

15 **4. Results: Sedimentology of the Allt na Béiste Member**

16

17 The Allt na Béiste Member comprises red to brown, fine- to coarse-grained
18 arkosic sandstones and granule to pebble conglomerates interbedded with red to dark
19 grey siltstones and mudstones with lenticular to tabular bedding (Fig. 2). In the type
20 section, the transitional relationship with the underlying Diabaig Formation is clear in
21 an almost continuous succession. Cross-stratified sandstones are generally organized in
22 lenticular bodies alternating with laterally-extensive units of siltstone and shale
23 approximately 5-8 m thick. It shares with the remainder of the Applecross Formation

1 the dominance of red trough cross-stratified coarse-grained sandstones with pebbles of
2 various lithologies, and the presence of soft-sediment deformation in the coarser
3 members (Owen, 1995, 1996), but lacks the dominantly tabular geometry of sandstone
4 units, the large-scale fluvial forms, and large-scale, complex forms of soft-sediment
5 deformation (e.g. Nicholson, 1993; Owen, 1996; Selley, 1969; Williams, 1969). Our
6 data supports the fluvial origin for the Allt na Béiste Member, proposed by Stewart
7 (2002), based on a number of evidences, including: palaeocurrent directions (not
8 bimodal), bedform types (no symmetrical ripples, predominance of cross-stratification),
9 well-rounded pebbles, and continuous gradation to the typical Applecross Formation
10 lithofacies.

11 Two distinct facies associations represent different depositional elements: (1)
12 sandstone-dominated facies characterized by cross-stratified sandstones organized in
13 laterally extensive sandbodies and inclined heterolithic bodies, interpreted as channel
14 complexes; and (2) fine-grained facies organized in complex and varied depositional
15 architectures, interpreted as floodplain units. These distinct depositional elements are
16 unique to the Allt na Béiste Member; in the rest of the Applecross Formation the
17 distinction between channel and floodplain deposits is not straightforward, due to
18 intense amalgamation of channel deposits, paucity of preserved fine-grained sediments,
19 and reworking of floodplain deposits.

21 4.1. Sandstone-dominated facies association: channel complexes

22

23 *4.1.1. Sedimentary Facies.* These intervals are characterised by well-cemented,
24 medium- to coarse-grained arkosic sandstones and pebbly sandstones that are reddish-

1 brown when weathered and dark red to pale grey when fresh, with subordinate cm-thick
2 siltstone lenses and mm- to cm-thick red and grey shale partings (Table 1). The
3 sandstones contain trough and planar cross-stratification with some synsedimentary
4 soft-sediment deformation (Fig. 3A), although not on the frequency or scale typical of
5 most of the Applecross Formation (e.g. Selley, 1965; Owen 1995, 1996b; Owen and
6 Santos, 2014). Fine-grained sandstone and silty mudstone occur as cm- to dm-thick
7 lenses, commonly preserving depositional forms in underlying beds (Fig. 3A, 3B).
8 Extraformational granules and pebbles are well-rounded and polymictic.
9 Intraformational mudclasts mm to cm long are concentrated at the bases of many sets
10 (Fig. 3C). Horizontal and low-angle cross-stratification occur in fine- to coarse-grained
11 sandstones (Fig. 3D). Fine-grained sediments comprise laminated and cross-laminated
12 fine-grained sandstone to silty mudstone. Lenticular heterolithic intervals (Fig. 3E) are
13 characterized by cm-thick couplets of fine- to coarse-grained sandstone intercalated
14 with silty mudstone, which pinch out laterally (Fig. 3F). Although most set bounding
15 surfaces are erosional, some preserve the shape of underlying bedforms, from which
16 they are usually separated by a thin layer of finer-grained sediment that commonly
17 weathers out (Fig. 3G).

18

19 *4.1.2. Depositional Architecture.* Sandstone-dominated facies associations are organized
20 into laterally-extensive lenticular and tabular bodies decimetres to metres thick and
21 metres to 10s of metres wide. The geometry of basal bounding surfaces is varied,
22 including wavy, dipping, concave-upward, convex-upward, and horizontal planar
23 surfaces (Fig. 4). Fine-grained drapes (siltstone and silty-mudstone) a few millimetres
24 thick and tens of centimetres wide with lenticular and wavy geometry cover bedforms in
25 underlying units. Concave-upward scour geometries are typically filled by trough cross-

1 stratified sandstones and intraformational conglomerates. Trough cross-stratified
2 sandstones and pebbly sandstones are commonly organized in multi-storey, multi-lateral
3 sandstone bodies with wavy geometry as a result of erosion of the underlying beds (Fig.
4 5).

5 Heterolithic strata occur in lenticular bodies up to 2 m thick (Fig. 4)
6 characterized by inclined beds comprising coarse-to-fine couplets (cf. Thomas et al.,
7 1987) in which sandstone cosets are characterised by low-angle planar cross-
8 stratification (Fig. 6). These forms commonly pinch out laterally over 4 - 5 m (Fig. 7)
9 and their internal structures indicate palaeoflow parallel to the dip direction of the bed.
10 Associations of planar cross-stratified sandstones with trough cross-stratified sandstones
11 are organized in various forms, including: (1) wedge-shaped bodies with convex-
12 upward upper bounding surfaces and internal palaeoflow indicators dipping at oblique
13 to high angles ($> 30^\circ$) relative to the flat lower bounding surfaces; (2) lenticular bodies
14 with palaeoflow indicators dipping in the opposite direction to dip of the lower
15 bounding surface; and (3) bodies with concave-upward lower bounding surfaces and
16 relatively flat upper bounding surfaces. Cosets of low-angle planar cross-stratification
17 are typically organized into tabular geometries.

18

19 *4.1.3. Interpretation.* These sandstone-dominated intervals are interpreted to represent
20 channel complexes. Their internal architecture and the dip data indicate a variety of
21 channel geometries. The sandstone-dominated intervals therefore record a range of
22 channel forms, including evidence of laterally-accreted channels, which are typically
23 related to meandering-channel planforms. Architectural elements identified in the
24 channel deposits include (Table 2): point bars, downstream accretion, upstream

1 accretion, sandy bedforms, laminated sandstone sheets, and scour-fill. Abundant
2 intraformational mudclasts provide evidence of intense reworking of fine-grained
3 sediments deposited during periods of quiet conditions, possibly on mud flats,
4 indicating variable flow regimes and/or floodplain reworking. Inclined heterolithic
5 strata with palaeoflow indicators parallel to the dip directions of lower bounding
6 surfaces are interpreted as point-bar deposits (PB1) that accumulated in the downstream
7 part of the bar, with intercalation between traction and suspension deposition as a result
8 of fluctuations in flow discharge (Fig. 4). Planar cross-stratified sandstones with
9 palaeoflow indicators dipping at oblique angles ($\sim 45^\circ$) to the dip direction of inclined
10 planar lower bounding surfaces, and convex-upward upper bounding surfaces are
11 interpreted as lateral-accretion deposits recording deposition on the apex of point bars
12 (PB2). Multi-storey, multi-lateral sandstone bodies with palaeoflow indicators that dip
13 at right angles to the dip of wavy lower bounding surfaces, convex-upward upper
14 bounding surfaces and abundant intraformational clasts are interpreted as sandy
15 bedforms (SB), representing in-channel deposition of 3D dunes with transport at right
16 angles ($\sim 90^\circ$) to the lower bounding surface dip of the underlying point bar. Intervals
17 with lower bounding surfaces that dip in the same direction as palaeoflow indicators in
18 surrounding fluvial forms, but in the opposite direction to the internal palaeoflow
19 indicators are interpreted as upstream accretion (UA) forms deposited on the upstream
20 margins of bars as a result of upstream flow. Cosets of planar cross-stratified sandstones
21 characterized by lower bounding surfaces and 2nd- and 3rd-order surfaces that dip
22 concordantly with the internal palaeoflow indicators are interpreted as downstream-
23 accretion macroforms (DA), recording bar accretion during peak flow (Fig. 6). Tabular
24 sandstone bodies composed of medium- to coarse-grained sandstones with low-angle to

1 horizontal stratification represent laminated sandstone sheets (LS), recording deposition
2 during waning flow stages in shallow streams or during peak discharges.

3

4

5 4.2. Fine-grained facies association: floodplain units

6

7 *4.2.1. Sedimentary facies.* A wide range of mudstone-dominated and heterolithic facies
8 are present (Table 1). Silty mudstone, and laminated and cross-laminated fine-grained
9 sandstone (Fig. 8A) alternate with cm-thick lenses of coarser sediment. Other facies are
10 characterized by m-thick laminated and massive units of mudstone (Fig. 8B) that are red
11 to dark grey when fresh and pale red when weathered. Coarser-grained lenses include
12 beds of sandstone or granules with horizontal lamination, fine-grained sandstones with
13 asymmetric- to wavy climbing-ripple cross-lamination (Fig. 8C, 8D), fine- to coarse-
14 grained sandstone with horizontal to low-angle stratification, and coarse-grained
15 sandstone and granulestone with planar cross-stratification (Fig. 8E, 8F). These
16 commonly include intraformational mudclasts up to 20 cm long (Fig. 8E) which are
17 darker in colour than the surrounding mudstones. Some lenses of poorly-stratified to
18 massive granule to pebble conglomerate are only as thick as the clasts they contain.
19 Other lenses of pebbly sandstone contain soft-sediment deformation ranging from
20 smooth synclines with wavelengths of a few centimetres (Fig. 8G) to complete
21 disruption into pseudonodules (Fig. 8H). Some of the horizontally bedded sandstones
22 dip gently in the opposite direction to laterally-related sandstone (channel) deposits
23 (Fig. 9). Clastic dykes of medium- to coarse-grained sandstone are common and are up
24 to a few centimetres thick and wide. Some originate in the upper regions of lenticular

1 sandstone bodies and some are tightly folded. Other dykes are just a few millimetres
2 wide and filled by granules.

3

4 *4.2.2. Depositional Architecture.* Fine-grained facies are organized into a range of
5 depositional forms. Some bodies of heterolithic strata are tabular over metres to tens of
6 metres, with flat to wavy lower bounding surfaces and convex upper bounding surfaces.
7 They pinch out rapidly at their margins. Others incorporate beds that dip at a high angle
8 away from laterally-equivalent sandstone (channel) bodies (Fig. 9). Mudstone-filled
9 lenticular bodies are characterized by concave-upward lower bounding surfaces and flat
10 upper bounding surfaces. Some massive mudstone units are characterized by irregular,
11 wavy lower bounding surfaces and relatively flat upper bounding surfaces (Fig. 10).
12 These are laterally related to point bars of channel deposits, while other mudstone-filled
13 bodies are tabular with very thin lenses of sandstone and granulestone. Some planar
14 cross-stratified sandstone lenses also occur within mudstone bodies, and pinch out
15 laterally at both ends, being characterized by flat lower bounding surfaces and convex-
16 upward upper bounding surfaces (Fig. 9), commonly with a pebble lag and tool marks at
17 their base. Other cross-stratified sandstone lenses are characterized by concave-upward
18 lower bounding surfaces and flat upper bounding surfaces.

19

20 *4.2.3 Interpretation.* These heterolithic bodies represent floodplain deposits (Table 2).
21 Tabular bodies of mostly muddy heterolithic strata (Fig. 10) are interpreted as overbank
22 fines which accumulated in long-lived floodplains (OF). Heterolithic beds that dip away
23 from laterally-equivalent sandstone (channel) bodies (Fig. 9) are interpreted as possible
24 channel levées (LV), similar to the ones described in Miall (1979), but smaller in scale,

1 and these are different from those described in younger successions of the Applecross
2 Formation (Ielpi and Ghinassi, 2015). Planar cross-stratified sandstone lenses in
3 mudstone that pinch out laterally, with flat lower bounding surfaces represent crevasse-
4 splay deposits (CS). Intraformational mudclasts indicate re-working of previously
5 deposited overbank fines. Mudstone-filled lenticular bodies with concave-upward lower
6 bounding surfaces and flat upper bounding surfaces which are associated with CS forms
7 are interpreted as crevasse channels (CC). Finally, mudstone-filled lenticular bodies
8 with concave-upward lower bounding surfaces and which are truncated upwards are
9 interpreted as abandoned channels (AC). Tightly folded dykes indicate compaction of
10 the enclosing fine-grained sediment after dyke injection.

12 4.3. Palaeocurrents

14 Orientations of 347 surfaces were measured, including 194 palaeocurrent
15 readings from cross-sets and 153 measurements of higher-order (1st- to 4th-order)
16 surfaces (set and coset bounding surfaces and major erosional surfaces). The data are
17 plotted as rose diagrams with an equal-area frequency scale (Nemec, 1988; Baas, 2000;
18 Fig. 11). Palaeoflow indicators show mean transport towards 334° (angular deviation
19 39°, largest frequency 26%). Higher-order surfaces show mean dip towards 336°
20 (angular deviation 30°, largest frequency 46%). Relationships between depositional
21 surfaces and higher-order surfaces (Fig. 4, Fig. 6, Fig. 9) are characterized by deviations
22 of up to 99° in sandy bedforms and up to 160° in upstream accretion forms, both
23 clockwise and anticlockwise. Sandy bedforms present the largest observed range of
24 directions, with angular deviations up to 48° and largest frequency of 32% (Fig. 4).

1 Crevasse splays present deviation of palaeocurrent in relation to higher-order surfaces,
2 which are concordant with the overall sediment transport direction, of up 81°. Sediment
3 transport indicated by 0th-order surfaces varies from 304° to 070° in Figure 4 and 318° to
4 125° in Figure 6. Crevasse splay depositional transport is consistently to the west, and
5 perpendicular to the overall sediment transport of the inchannel deposits. The mean
6 transport to NNW (335°) contrasts with results from studies of successions higher in the
7 Applecross Formation, which show mean transport to the SE (e.g. Nicholson, 1993;
8 Stewart, 2002; Williams, 2001; Williams and Foden, 2011). This may reflect a contrast
9 in sediment transport with the overlying successions of the Applecross Formation as a
10 result of coeval channels flowing into Lewisian palaeovalleys before the establishment
11 of the main fluvial system represented by the typical Applecross Formation.

12

13 4.4. Sandstone dykes and fractures

14

15 Sandstone-filled fissures and associated fractures are common in the fine-
16 grained and heterolithic facies in Diabaig, near the type-section of the Allt na Béiste
17 Member. Some sandstone-filled fissures are connected to an overlying sandstone bed
18 (Fig. 12A) and may represent infilled desiccation cracks. Others are connected to
19 underlying beds or are isolated within mudstone (Fig. 12B). Several are contorted by
20 soft-sediment deformation. These varieties are likely to represent sandstone dykes
21 injected through the fluidization of water-saturated sediments (Lowe, 1975; Owen,
22 1996). Orientation data show a consistent NE-SW strike (042°-222°; Fig. 9), similar to
23 dykes described by Stewart (2002). This uniform trend indicates a NW-SE extensional
24 palaeostress field shortly after deposition, most likely related to basin extension and,

1 together with the palaeocurrent data, this is consistent with models of an extensional
2 basin with a NE-SW axis, infilled by transverse alluvial systems (e.g. Williams, 2001).
3 The injection features may indicate enhanced seismic activity associated with deposition
4 of the Applecross Formation, culminating in the abundant large-scale soft-sediment
5 deformation higher in the succession (e.g. Owen, 1996). Some of the observed dykes
6 originated in underlying and overlying crevasse splays, while others seem to be
7 unconnected with any particular sandstone body, being characterized as isolated
8 features of sandstone between the mudstone. This is inferred after the structural analysis
9 of fractures in the studied deposits: clastic dyke orientations are strongly concordant
10 with joints, indicating that the deposits were well lithified before such brittle
11 deformation occurred. Along the Diabaig shoreline, a prominent fault cutting through
12 floodplain and channel deposits with displacement up to 30 cm and a strike oblique to
13 the sandstone-filled fissures and fractures (Fig. 10) is interpreted as a later, tectonic
14 feature. An alternative interpretation of these sandstone dykes is that they may reflect
15 variable compaction of muds in the underlying Diabaig Formation leading to
16 contrasting rates of local subsidence and promoting the development of lower-lying
17 areas prone to the development of floodplain ponds.

18

19

20 **5. Discussion**

21

22 5.1. Fluvial styles in the Allt na Béiste Member and their significance

23

1 The Allt na Béiste Member records variable channel style, including both
2 meandering planforms with coeval deposition of crevasse splays and crevasse channels
3 (Fig. 9), and multi-storey, multi-lateral sets (Fig. 5). The identified architectural
4 elements are summarized in Fig. 13. The laterally accreted units (Fig. 4, Fig. 6) share
5 many features with lateral accretion attributed to meandering sand-bed streams by Allen
6 (1963, 1964) and Jackson (1978): heterolithic sand-mud stratification, cross-
7 stratification dipping at oblique angles to basal bounding surfaces; fining-upward
8 successions (Fig. 2), steep ($> 20^\circ$) point-bar slopes, and comparable thickness of coarse
9 and fine intervals. Although river systems characterized by laterally accreting channel
10 banks and regularly inundated floodplains were apparently rare during the Precambrian,
11 the data from the Allt na Béiste Member indicate that meandering channels could
12 develop if river banks could be stabilized by the presence of fine-grained sediment. Mud
13 was abundant enough in the Allt na Béiste palaeoenvironment to provide the necessary
14 cohesion (e.g. Peakall et al, 2007; van Dijk et al, 2013) that is typically provided in
15 more recent times by land plants and the supposedly more abundant fine-grained
16 sediments. A possible mechanism with which to retain fine-grained sediments in the
17 Allt na Béiste Member may have been the development of floodplain ponds promoted
18 by local subsidence as a result of the compaction of the underlying lacustrine, fine-
19 grained deposits of the Diabaig Formation. These were sandwiched between the
20 underlying Lewisian basement and the overlying Applecross Formation, with such
21 compaction potentially having triggered the mobilization of sandstone dykes. The
22 development of such floodplain ponds may have promoted suspended load deposition,
23 leading to higher proportion of fine-grained sediments in the alluvial plain, with
24 consequent increase in cohesion.

1 The specific characteristics of the Allt na Béiste Member sedimentology suggest
2 some differences from systems where channel stability is contributed by the stabilizing
3 effects of roots. The common occurrence of small-scale crevasse-splay deposits (Fig. 9)
4 suggests that levée ruptures may have been more frequent. The common occurrence of
5 fine-grained drapes preserving three-dimensional dune bedforms in channel deposits,
6 together with abundant intraformational mudclasts, indicates frequent flow-regime
7 fluctuations, which may have resulted from reduced runoff control compared to
8 modern-day systems. Flat-bedded depositional surfaces are, however, rare, indicating
9 that in-channel flow was rarely shallow or fast enough to produce and preserve them.
10 Extreme flow-regime fluctuations represent a possible trigger for liquefaction and soft-
11 sediment deformation in the upper successions of the Applecross Formation (see Owen
12 and Santos, 2014).

13 Our data suggest that floodplains during the deposition of the Allt na Béiste
14 Member were repeatedly combed by sinuous channels, the abandonment of which was
15 probably cyclic, as recorded by the juxtaposition of floodplain deposits on channel
16 deposits, as observed in Figs. 4 and 9, with erosional channel sandbodies at the base
17 grading upwards to floodplain fines and splay sandstones. The absence of in-situ
18 mudcracks suggests a possible humid climate, or lack of subaerial exposure due to the
19 presence of flooded regions of the alluvial plain. The preservation of numerous small-
20 scale crevasse splays, channels and levées - architectural elements that are under-
21 represented in pre-vegetation compared with post-vegetation river deposits (O'Brien
22 and Wells, 1986; Long, 2011) - may indicate that non-vegetated point-bars were so
23 poorly-stabilized that they were relatively low in height and slope, allowing the more
24 frequent development of smaller crevasse channels. Either this situation was very rare in
25 the Precambrian, or its preservation potential was very low. In fact, the ~190 m

1 thickness of such deposits in comparison with the overlying > 6 km of Applecross
2 Formation reflects the difficulties of preserving Precambrian heterolithic fluvial
3 deposits. Pre-Silurian crevasse-splay deposits have not previously been positively
4 identified (Long, 2011). Pre-vegetation levées were probably highly prone to erosion, so
5 that crevasses could occur more readily, but the non-stabilized nature of the floodplains
6 meant that crevasse splays could rapidly be eroded during floods so that their
7 preservation potential was very low. Because thin soils are characterized by low total
8 water storage capacity, runoff hydraulics are controlled by surface roughness, and
9 Hortonian flows are controlled by infiltration rate and precipitation rate (North and
10 Davidson, 2012), it is accepted that the paucity of well-developed soils in pre-Silurian
11 fluvial deposits (Long, 2011) implies rapid runoff flow and fast erosion of hinterland
12 (e.g. Long, 2006; Eriksson et al., 2006). But soils were preserved along the
13 unconformity between the Torridonian sandstones and the Lewisian metamorphic rocks
14 despite the absence of land plants acting as chemical-weathering agents (Retallack and
15 Mindszenty, 1994). These palaeosols are the oldest known palaeosols in the British Isles
16 and developed penecontemporaneously with the deposition of the Applecross Formation
17 (Williams and Schmidt, 1997). They present chemical characteristics similar to modern-
18 day soils developed under moderately humid climate (Williams, 1968). These
19 conditions potentially influenced the nature of runoff rates after precipitation events,
20 may have provided additional fine-grained sediments, and further contributed to
21 buffering discharge rates in the Allt na Béiste river system. Other potential control may
22 include influences of microbial mats (Noffke, 2009), which although no evidence of
23 these were observed in this study, they have been described near the present study area
24 in the underlying Diabaig Formation in fresh-water lake system deposits (Prave, 2002)
25 and such microbial ecosystems were already adapted to low light levels and prolonged

1 exposure to the air (Callow et al., 2011), and studies on microfossil assemblages from
2 suggest that non-marine eukaryotes were thriving in subaerial and freshwater aquatic
3 habitats during the deposition of the Torridon Group (Strother et al., 2011).

4

5 5.2. Implications for fluvial style in the Precambrian: causes of meandering in pre-
6 vegetation river systems

7

8 The largest interval of the continental sedimentary environment's record was
9 characterized by relatively discrete interactions between life and continental
10 sedimentary processes (e.g. Gehlin, 1999; Bouougri & Porada, 2007; Noffke, 2009;
11 Parizot et al., 2005), while facies models to account for the interpretation of different
12 fluvial styles are largely based on modern day analogues (e.g. Jackson, 1978; Miall
13 1996, 2013; Bridge, 2003). The behaviour of river systems can be influenced by
14 vegetation density (Braudrick et al., 2009; Tal and Paola, 2007) and other interactions
15 between geomorphic processes and ecosystems (Rice et al., 2012, Stoffel et al., 2013),
16 to the extent that they do not provide reliable analogues for river systems that pre-date
17 the advent of land vegetation. Land vegetation only developed significantly after the
18 Ordovician (Wellman, 2010), and probably did not impact significantly on sedimentary
19 processes until the Late Devonian, when roots were able to penetrate considerable
20 depths into the substrate (Algeo et al., 1998), becoming an important control on
21 sedimentary processes by Carboniferous times (Gastaldo and Degges, 2007; Gibling et
22 al., 2010; Davies and Gibling, 2013). The presence of laterally-accreted heterolithic
23 point bars and relatively thick overbank fine-grained deposits in the Allt na Béiste
24 Member indicates that sinuous, meandering channels were able to comb stable

1 floodplains at that time. A variety of controls can induce rivers to develop sinuous,
2 single-thread channels, including: (i) the presence of vegetation (Schumm, 1968; Tal
3 and Paola, 2007); (ii) the availability of fine-grained sediment, adding cohesion to the
4 depositional system (Sweet, 1988; Peakall et al., 2007; van Dijk et al., 2013); and (iii)
5 dynamics between discharge rates, sediment supply and alluvial-plain gradients
6 (Nanson and Huang, 2008; Lazarus and Constantine, 2013). Recent observations of
7 meandering palaeochannel planforms on Mars (e.g. Nußbaumer, 2009; Schon et al.,
8 2012; Matsubara et al., 2015) demonstrate that meandering channel systems are not
9 exclusively linked to the interaction of alluvial processes with terrestrial life.

10 Several factors may have contributed to the availability of fine-grained, cohesive
11 sediment that enabled the development of isolated, meandering channels and stable
12 floodplains in the Allt na Béiste Member. (1) Legacy of the Diabaig Formation.
13 Lewisian palaeovalleys filled by Diabaig Formation sediments resulted in low-gradient
14 alluvial plains. Localised subsidence that may have been driven by differential
15 compaction of the underlying lacustrine sediments promoted the development of
16 floodplain ponds on the alluvial plain, providing environments that allowed for
17 suspended-load deposition, resulting on relatively-large amounts of fine-grained
18 sediment available for reworking. This setting is similar to that inferred for meandering
19 channels in the Jezero crater on Mars (Schon et al., 2012). (2) Climate-related enhanced
20 weathering. Enhanced chemical weathering under warm, wet climates may have
21 increased the availability of fine-grained sediment. This is consistent with the sub-
22 humid and seasonal palaeoclimate inferred for the basal Torridon Group from palaeosol
23 analysis of the unconformity between Lewisian metamorphic rocks and the Applecross
24 Formation (Retallack and Mindszenty, 1994). (3) Basin evolution. High subsidence
25 rates and/or high base levels may have led to the development of isolated channels and

1 relatively thick floodplain deposits (e.g. Allen, 1974; Wright and Marriott, 1993). These
2 factors did not persist into the deposition of the main Applecross Formation, which was
3 influenced by the low availability of fine-grained sediments and/or environmental
4 conditions leading to the by-passing of such sediments to extrabasinal areas.

5 Laterally extensive silt and clay deposits in the Mesoproterozoic Belt
6 Supergroup were interpreted as distal low-gradient, fine-grained floodplain deposits by
7 Winston (1978). They accumulated on the hanging-wall of the basin in an unconfined
8 setting, and their preservation was controlled by sea-level fluctuations, demonstrating
9 that mud could accumulate in pre-vegetation times under appropriate conditions. Other
10 examples include fining-upward cycles and lateral accretion surfaces interpreted as
11 meandering fluvial and fluvio-volcanic deposits from the Early Proterozoic Hatches
12 Creek Group in central Australia (Sweet, 1988).

13 The Allt na Béiste Member of the basal Applecross Formation represents an
14 example of a rarely preserved pre-vegetation palaeoenvironment. One comparable
15 example is the 1.4 Ga Sibley Group in Canada (Fralick and Zaniwski, 2012), although
16 that study is not based on three-dimensional analysis. The preservation of such fine-
17 grained alluvial deposits confirms interpretations by Ronov (1964) and Dalrymple et al.
18 (1985) that other environmental controls are responsible for the uncommon preservation
19 of fine-grained sediments in pre-vegetation alluvial environments, and that fine-grained
20 sediment was available despite the lower chemical weathering rates due to the absence
21 of vegetation.

22

23 5.3. Significance of soft-sediment deformation structures

24

1 Synsedimentary soft-sediment deformation structures in channel deposits,
2 observed in series of cosets with upwardly-increasing deformation disrupted by
3 erosional surfaces (Fig. 3A; cf. Santos et al., 2012), point to liquefaction driven by
4 sudden pore-pressure build-up enabling deformation by current shear. Other examples
5 relate to upwardly directed stresses deforming previously deposited, saturated sediments
6 that were buried prior to deformation, which indicate a fluctuating water table and may
7 have been triggered by flash-floods, sudden variations in flow regime or seismic activity
8 (Owen et al., 2011; Owen and Moretti, 2011). Soft-sediment deformation structures in
9 floodplain deposits are commonly related to the interruption of upward-directed pore-
10 fluid flow by permeability barriers. This scenario may have triggered fluidization events
11 recorded by small-scale clastic dykes. Their abundance suggests intense tectonism
12 immediately after deposition and before diagenesis, and structural analysis indicates a
13 NW/SE extensional palaeostress field. These dykes may also indicate compaction of the
14 underlying Diabaig Formation contemporarily to the Allt na Béiste Member deposition.

15 Although soft-sediment deformation structures are much less abundant and smaller in
16 scale in the Allt na Béiste Member than in the overlying part of the Applecross
17 Formation (e.g. Owen, 1995, 1996), their presence, particularly in the floodplain facies,
18 points to a near-surface water table (cf. Fralick and Zaniwski, 2012), supporting the
19 interpretation of a wet palaeoclimate inferred from the absence of in situ mudcracks.

20

21 5.4. Significance of the Diabaig-Applecross boundary

22

23 Kinnaird et al. (2007) noted that the contact between the Diabaig and Applecross
24 Formations “commonly displays erosive channelling and marks a sharp increase in

1 grain size” and suggested that it represents an unconformity. Most basal bounding
2 surfaces in the Applecross Formation are erosional, however (cf. Williams, 1966), and
3 in the Allt na Béiste Member they represent contacts between channel and floodplain
4 deposits. We therefore find no evidence in the Diabaig section for a significant
5 unconformity at this stratigraphical level. On the contrary, the sedimentary facies are
6 entirely consistent with a gradational succession of palaeoenvironments from mudstone-
7 dominated lacustrine deposits in the Diabaig Formation through the heterolithic
8 meandering fluvial systems of the Allt na Béiste Member to the braided fluvial systems
9 represented in the pebbly sandstones of the main part of the Applecross Formation.

10

11 5.5. Study of fluvial architecture in areas of limited exposure

12

13 Techniques for the reconstruction of fluvial dynamics in conglomeratic and
14 sand-prone deposits involving mapping sedimentary features onto multi-photograph,
15 high-resolution mosaics (Allen, 1963; Miall, 1996, 2013) are not readily applied to
16 mud-prone successions that are typically less well exposed, particularly away from
17 coastlines in areas such as the glacially eroded northwest of Scotland, where finer
18 grained and heterolithic facies may be obscured by soil and bog. This highlights the
19 need for new studies of pre-Silurian (pre-vegetation) heterolithic fluvial deposits
20 preserved in scattered outcrops. Not surprisingly, the most detailed description of pre-
21 vegetation floodplain deposits to date (Fralick and Zaniewski, 2012) is from borehole
22 core analysis.

23

1

2 **6. Conclusions**

3

4 The Allt na Béiste Member differs from the overlying successions of the Applecross
5 Formation in preserving many fluvial forms that are uncommon in Precambrian, pre-
6 vegetation fluvial deposits, including point-bar deposits and relatively thick floodplain
7 deposits, indicating that channels with sinuous planforms migrated laterally across
8 stable floodplains. These floodplain deposits offer a glimpse of the depositional
9 processes that prevailed on barren floodplains and indicate the presence of more
10 complex alluvial environments than previously envisaged for Precambrian and pre-
11 Silurian depositional systems. Possible controls for the preservation of such architecture
12 include the presence of palaeovalleys filled by previous lacustrine and fluvial systems
13 leading to low gradients, the availability of fine-grained sediment from highly-
14 weathered basement with well-developed soils which also contributed to lower rates of
15 runoff, and local subsidence resulting from differential compaction of previously
16 deposited sediments. Structural data on fractures and associated soft-sediment
17 deformation structures reveal an overall NW/SE extensional palaeostress field during
18 the deposition of the Applecross Formation.

19 Pre-vegetation sinuous channel systems could develop as long as silt and mud
20 provided sufficient channel cohesion and/or gradients and discharges were low. The
21 point bar deposits coupled with the preservation of relatively thick floodplain deposits
22 described here from the Allt na Béiste Member suggest that discharge rates prior to the
23 Silurian were not restricted to the higher values proposed by previous works on pre-
24 vegetation fluvial deposits (Schumm, 1968). Flows were not necessarily restricted to

1 poorly-confined channels, and channel bank cohesion was sufficient to stabilize single
2 channels. Although meandering rivers were able to develop, they were potentially short-
3 lived and had low preservation potential. This can be observed when comparisons are
4 made between the thickness of the Allt na Béiste Member (max. 190 m) and the main
5 Applecross Formation (>3 km), in which the depositional architecture and facies are
6 similar to most pre-vegetation fluvial systems described in the literature.

7 These results indicate that pre-vegetation alluvial environments were more
8 complex than predicted by current models, in agreement with recently published papers
9 (e.g., Long, 2011; Santos et al., 2014; Ielpi and Ghinassi, 2015; Ielpi and Rainbird,
10 2015). Importantly, they could present more fine-grained sediments than previously
11 envisaged. The limited thickness of the Allt na Béiste Member with its unusual
12 architecture in comparison with the thicker upper successions of the Applecross
13 Formation suggests that in non-vegetated systems such fluvial styles were unlikely to be
14 preserved or were highly unstable and short-lived.

15 These findings contribute to the understanding of fluvial processes prior to the
16 evolution of land plants. The availability of fine-grained sediments was probably related
17 to enhanced weathering, and their paucity in most Precambrian fluvial systems is
18 probably related to controls such as sediment bypass to distal areas and flashy floods.
19 The preservation of heterolithic and fine-grained sediments in pre-vegetation fluvial
20 systems is more likely to be related to factors such as low-gradient fluvial profiles, mud-
21 prone source rocks, and suspended-load. Further detailed outcrop-based studies on pre-
22 vegetation heterolithic fluvial deposits are needed to widen the spectrum of pre-
23 vegetation fluvial deposits to a more comprehensive and representative data set with
24 which to develop further understanding of the evolution of rivers through geological

1 time. We suggest that it is still too early to establish robust models for such a large
2 period of time when continental environments were barren of macroscopic life.

3

4

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6

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13

14

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- 12

1

2 **FIGURE AND TABLE CAPTIONS**

3

4 **Figure 1:** Map of the study area showing the outcrop of the Torridon Group and older
5 rocks in the coastal sections of Loch Torridon and Loch Gairloch (NW Highlands,
6 Scotland). The Allt na Béiste Member comprises the basal part of the Applecross
7 Formation which overlies the Diabaig Formation. (1-column)

8

9 **Figure 2:** Sedimentary logs of the Allt na Béiste Member in its type area in the coastal
10 cliffs of Diabaig (see location on Fig. 1). Distance between measured sections is 10 m.

11

(1.5-column)

12

13 **Figure 3:** Main sedimentary facies of channel deposits: (A) trough cross-stratified
14 sandstone with soft-sediment deformation (hammer, 385 mm); (B) coset of trough
15 cross-stratified sandstone (hammer, 280 mm); (C) intraformational mudclasts in trough
16 cross-stratification; (D) horizontally-stratified, medium-grained sandstone; (E) laterally-
17 accreted, convex-upward lenticular forms; (F) inclined heterolithic stratification; (G)
18 three-dimensional dune deposits (indicated by hammer) overlain by siltstone and silty-
19 mudstone. (2-column)

20

21 **Figure 4:** Interpretation of depositional architecture and relationship between
22 palaeocurrent directions and bounding surfaces for individual forms. A-F refer to the

1 rose diagrams shown in boxes. Rose diagrams: Black petals represent 3rd-order surface
2 dip direction; dark grey, 2nd-order surface dip direction; light grey, depositional
3 surfaces.

4 (2-column)

5 **Figure 5:** Multi-storey, multi-lateral sets of sandbodies (lower part of the picture) and
6 laterally-accreting point bar (upper right of the picture). (2-column)

7

8 **Figure 6:** Inclined heterolithic strata in channel deposits. B-E refer to the rose diagrams
9 shown in boxes. Legend as Fig. 4. (2-column)

10

11 **Figure 7:** Laterally-accreted channel deposits pinching out laterally. Horizontal and
12 vertical scale bar (white circle) is 20 cm long. (2-column)

13

14 **Figure 8:** Main sedimentary facies of floodplain deposits: (A) cross-laminated fine-
15 grained sandstone; (B) silty-mudstone; (C) levée deposits; (D) crevasse-splays; (E)
16 detail of crevasse-splay with intraformational mudclasts; (F) planar cross-stratified
17 sandstone in crevasse; (G) tool marks at the bottom of crevasse deposits; (H) soft-
18 sediment deformation: pseudonodules in mudstone. (2-column)

19

20 **Figure 9:** Crevasse-splays in the Allt na Béiste Member and associated forms such as
21 SB and PB2. (A)-(E) rose diagrams shown in boxes; legend as Fig. 4. (C) levée
22 deposits; (F) point bar similar to the one depicted in Fig. 4.

1 (2-column)

2

3 **Figure 10:** Examples of point bars (PB1 and PB2), sandy bedforms (SB), and overbank
4 fines (OF). The variance of palaeocurrent directions reflects highly-sinuuous channels.
5 Rose diagrams: Black petals represent 3rd-order surface dip direction; white,
6 depositional surfaces; red arrows, mean vector. Normal fault and associated kinetics are
7 represented are represented in dashed white lines. Person as scale: 1.72 m. (2-column)

8

9 **Figure 11:** Palaeocurrent data for the Allt na Béiste Member. Blue petals, all data; light
10 grey, cross-set data; dark grey, main bounding surfaces. (1-column)

11

12 **Figure 12:** Structural data for clastic dykes and fault plane. (A) downwardly-directed
13 sandstone dyke originated in sandstone body (coin diameter 20 mm); (B) isolated dykes
14 in mudstone deposits (pencil metallic part is 20 mm). Grey arrow represents main
15 extensional stress field. (1-column)

16

17 **Figure 13:** Summary of the main architectural elements found on the Allt na Béiste
18 Member in this study. Grey lines are 0th- to 1st-order surfaces; blues lines, 2nd-order;
19 black lines, 3rd- to 5th-order surfaces. (2-column)

20

21 **Table 1:** Main facies associations. (2-column)

1

2 **Table 2:** Main architectural elements.

(2-column)

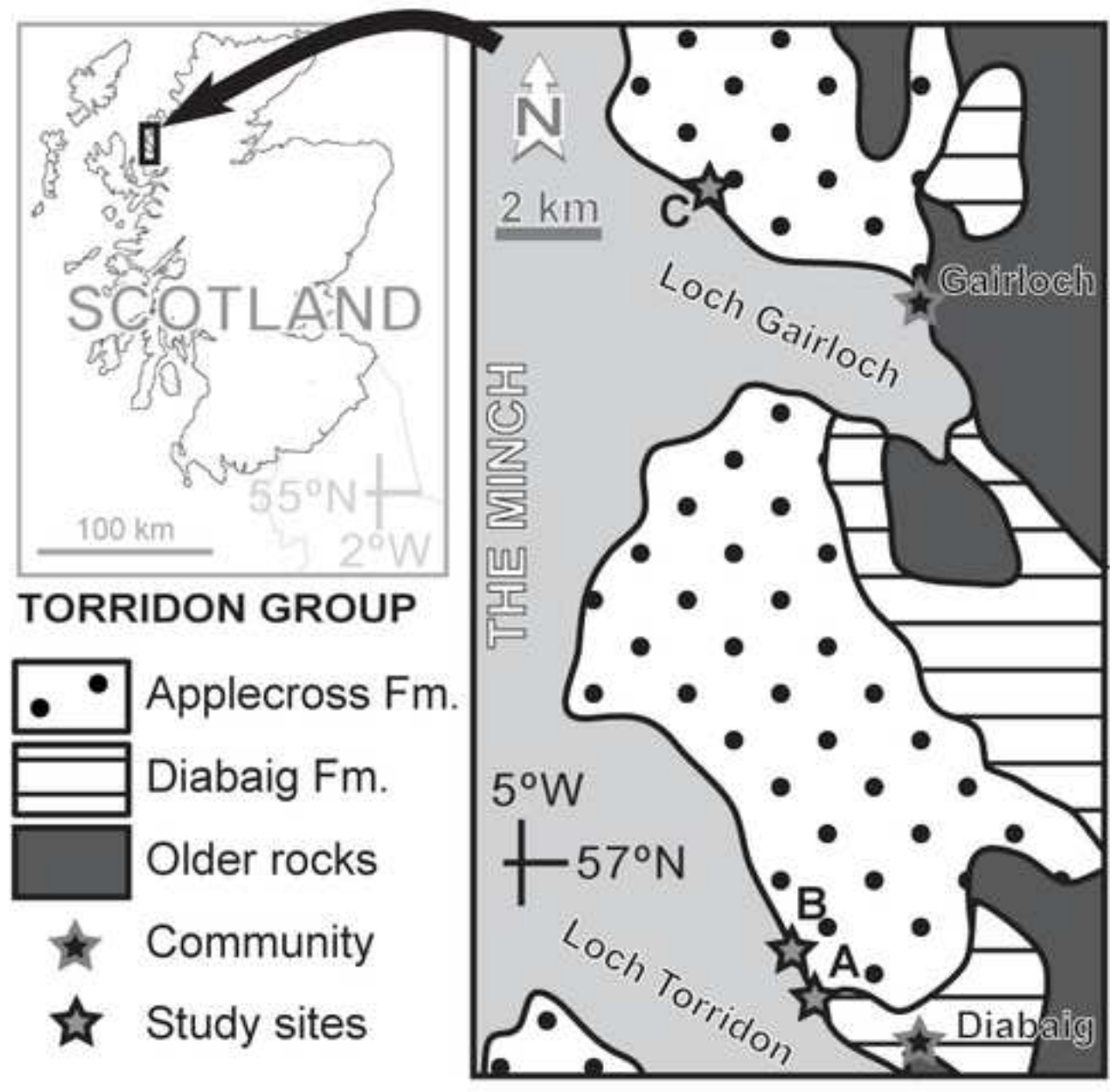
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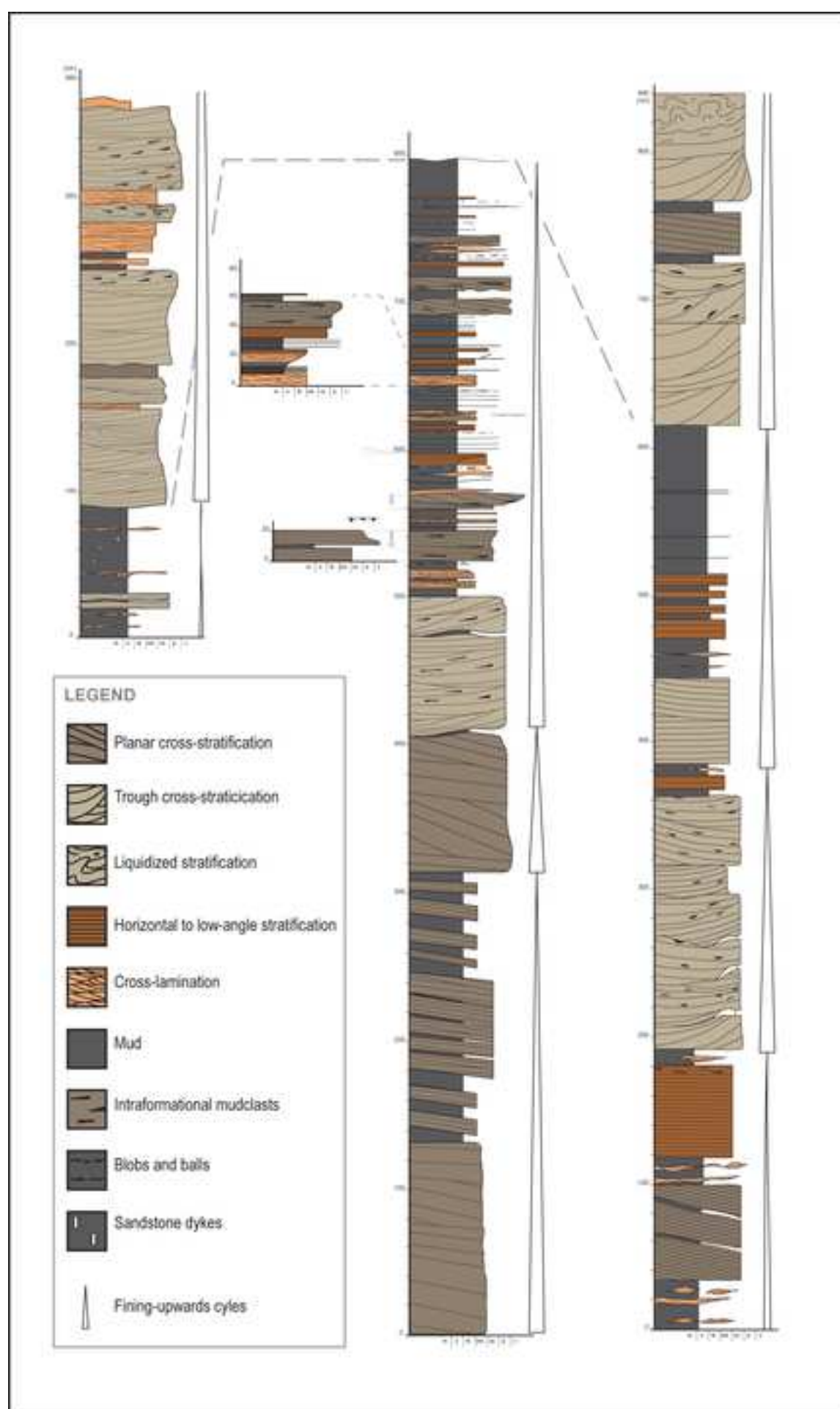
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FAC02	planar cross-stratified sandstone lenses.	with fine-grained sediments settling out during peak flow energy.
FAC03	Planar cross-stratified, medium- and coarse-grained sandstones preserved in 20 to 80 cm-thick cosets laterally associated with up to 20 cm to 130 cm-thick cosets of trough cross-stratified coarse-grained sandstones with granules and scattered extraformational pebbles up to 3 cm (mostly of vein quartz and k-feldspar; angular to sub-angular). Abundant intraformational mudclasts. Some of the trough cross-stratified sandstones are capped by undulated lenses of fine-grained sandstone at upper part preserving upper part of dune; they are 1 cm to 8 cm thick and up to 30 cm long.	Migration of two- and three-dimensional dunes interpreted as to record waning flow after peak discharge.
FAC04	Horizontally stratified coarse-grained sandstones in 30-120 cm-thick, laterally-extensive sandstone lenses.	Channel shallowing, with deposition of low-relief regime.
FAC5	Soft sediment deformation features consisting of unharmonic folds with chaotic organization. Deformation disrupts series of sets of coarse-grained to pebbly sandstones presenting trough cross-stratification and may be truncated by overlying erosional surface or diminishes upwards. Deformation occur in isolated, deformed sets or may include a large, > 5 sets and cosets; overlying sediments are typically non-deformed.	Liquefaction occurring in two different settings: on influence of river flow, and on buried sediments. current-shear drag and liquefaction, while the latter up-welling.
FAC6	Heterolithic deposits characterized by reddish brown, 20 cm- to 1 m-thick planar-cross-stratified, coarse-grained sandstones alternated with 1 to 10 cm-thick lenses of dark grey mudstone. Such facies association is characterized by inclined beddings which dip in the direction of lateral channel migration.	Point bar deposits related to the apex of such fluvial accumulation indicates avalanching of such deposits.
FAC7	Medium-grained sandstone with climbing ripples, 4-8 cm, asymmetrical ripples and sparse granules associated with laminated, rippled siltstone and mudstone. Basal surface preserves bedform relief of dunes.	Low-energy flow periods and possible flow cessation. mudstone drapes were preserved.
FAF01	Laminated mudstone, grey colour, 15-200 cm thick, presenting 2 mm- to 4 cm-thick medium- to very coarse-sandstone with low-angle ripple lamination in tabular to lenticular bodies; sandstone lenses are locally characterized by pinch and swell structures representing low-amplitude ripples and may present rippled top; blobs of granules and small pebbles (up to 4 cm) blobs up to 5 mm; upper part of thin unit is mainly coarse Sst, very poorly sorted; very coarse Sst 1 granule laminae; (+) mm-thick laminae of coarse Sst, CU; (+) load casts.	Settling out of fine-grained sediments during late lenses are interpreted as the result of unconfined flooding.
FAF02	Heterolithic strata consisting of 18-25 cm-thick tabular strata characterized by crudely stratified, low-angle planar-stratified, medium- to fine-grained sandstone, horizontal lamination and ripple cross-lamination, rippled at base, horizontal at top; rippled top erosional surface; finning-upward to silty mudstone alternated with millimetres to a few centimetres-thick laminated mudstones. The sandstone lenses dip outwards the main channel deposits.	May record levee deposits or unconfined flow deposits.
FAF03	Soft-sediment deformation features characterized by pseudo-nodules which present typical ductile deformation including folding and boudinage. Clastic dykes characterized by coarse-grained sandstone emplaced vertically, both downwards and upwards, in the mudstone.	Their origin is potentially related to differential compaction sediment load following crevasse splay deposits in mudstone.
FAF04	10 to 30 cm thick, brownish coarse-grained sandstones with well-rounded granules and pebbles presenting planar cross-stratification in sets or cosets. It coarsens upwards from sandstone at the base, then granules and finally lag of pebbles at the top. These sandstones commonly present mm- to a few cm-thick lamina of mudstone. Intraformational mudclasts are common with dimensions of up to 20 cm x 2 cm dimensions. These facies commonly pinch-out and coarsens laterally to thin layers of well-sorted granules. Tool-like marks are commonly observed at the set base.	Unconfined flow originated from river-bank rupture stream over floodplain deposits, similar to small-scale. Mudstone lenses indicate pause between splay re-deposition.
FAF05	Up to 25 cm-thick reddish medium- to coarse-grained sandstones presenting horizontally-bedded stratification and asymmetrical ripples organized in lenticular geometry which pinch out laterally.	Early phases of unconfined flow over floodplain deposits.
FAF06	Internally-bedded, 10 to 30 cm-thick mudstone with laminae 1-5 mm to 1 cm of very poorly-sorted coarse-grained sandstone and granules, and also scattered blobs and balls. Apparently CU to next unit.	Soft sediment deformation due to burial pressure between mudstone and sandstone.
FAF07	Fine-grained sandstone, horizontal lamination and ripple cross-lamination; 3-20 cm; rippled at base, horizontal at top; rippled top erosional surface; finning-upward to silty mudstone;. pinches out laterally.	Unconfined flow deposition on floodplain during

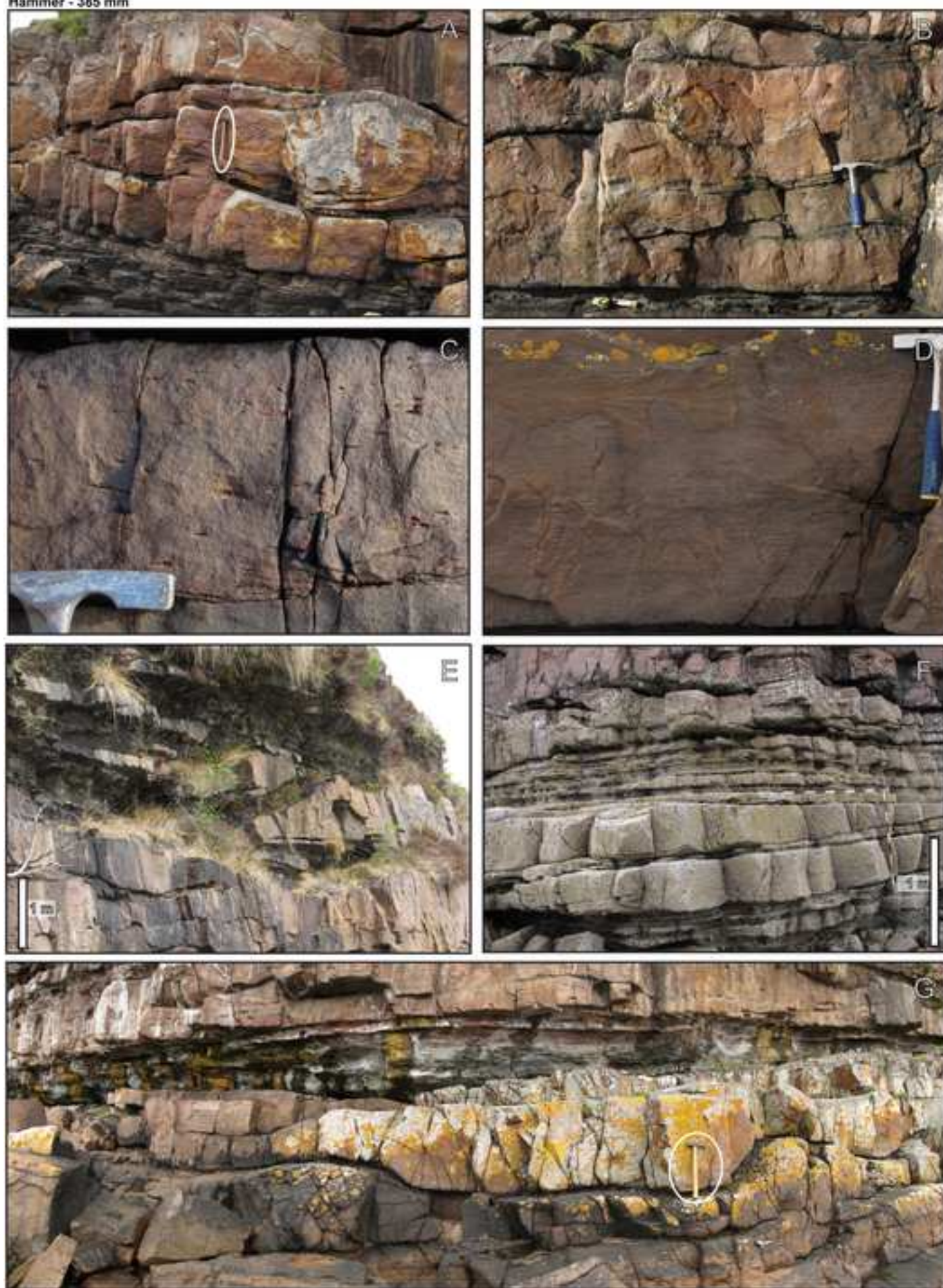
	m thick and several metres wide.	
SB	Multi-story, multi-lateral sandstone bodies with laterally accreting sets and cosets, and scouring sets. The external geometry of such forms is characterized by tabular forms presenting undulating surfaces (Fig. 3G) commonly eroding floodplain fine-grained sediments. Scouring features filled by cosets of trough-stratified sandstones is locally present.	Sandy-bedforms. Subaqueous dunes and low amplitude deposition in channel.
PB1	Inclined heterolithic strata presenting downstream accretion: cm-thick, crudely-stratified fine- to medium-grained sandstones alternated with mm- to cm-thick clayey siltstone, in coarse-to-fine couplets separated by inclined surfaces. Thickness vary from 60 cm to 2.0 m. The relationship between lower bounding surface and internal strata is characterized by parallel dip directions.	Point bar 1: Deposition on downstream part of point bar result of fluctuations in flow discharge.
PB2	Wedge-shaped lenticular bodies of coarse-grained sandstone with convex-upward upper bounding surface, accreting laterally to mean palaeocurrent direction, which is more varied than PB1. Internal stratification dips at right angles to main bounding surfaces; internal cosets may be separated by mud drape; these sandstone bodies pinch-out both upwardly and downwardly. Lateral accretion macroforms.	Point bar 2: Deposition on apex of point bars record lateral accretion.
UA	Lenticular bodies composed of series of cosets characterized by planar and trough cross-stratified sandstone with lower bounding-surface that dips averagely in the opposite direction of cross-sets. The latter typically dips in the opposite direction of the surrounding cross-sets related to other fluvial forms. Intraformational mudclasts are common.	Upstream accretion: Deposition on upstream margin of point bar result of upstream flow caused by flow separation.
LS	Tabular-geometry sandstone bodies characterized by internal stratification of low-angle cross-stratification to horizontal stratification.	Laminated sandstone sheets. Such deposits record channel bank accretion during waning flow stages in shallow streams or channels during high discharges.
SF	Sandstone bodies characterized by cosets of trough cross-stratified, coarse-grained to pebbly-sandstones presenting concave-up bounding surface and relatively flat upper bounding-surface.	Scour fill. Deposition in small secondary channels during high flow stages of avulsion.
OF	Horizontally laminated siltstone and mudstone organized in tabular bodies. In some of the studied examples it pinches-out laterally. Such forms are up to 2 m thick and several tens of metres wide.	Overbank fines. Overbank fines deposited in long levee channels.
CS	Lenticular bodies comprising medium- to coarse-grained sandstone and granules with medium- to low-angle planar cross stratification. Lower bounding surface is usually erosive and commonly irregular, sometimes presenting lag of pebbles and tool marks. Convex-upward to slightly planar upper bounding surfaces.	Crevasse-splays.
CC	Lenticular bodies of concave-upward lower bounding surface and flat upper bounding surfaces. They occur laterally-related or above crevasse-splay forms. Dimensions are of 15 to 30 cm thick, 30 cm to a couple of metres wide.	Crevasse channels.
LV	Tabular-shaped lenses of well-sorted, medium- to coarse-grained sandstones in laterally extensive bodies 5-10 cm thick (check) overlain by cm-thick, tabular bodies of mudstone and siltstone.	Channel levees, characterized by deposition of fine-grained deposits related to channel-bank deposition during high flow stages.
AC	Lenticular bodies characterized by concave-up lower bounding surface and truncated on top, filled by laminated mudstone.	Abandoned channel deposits.

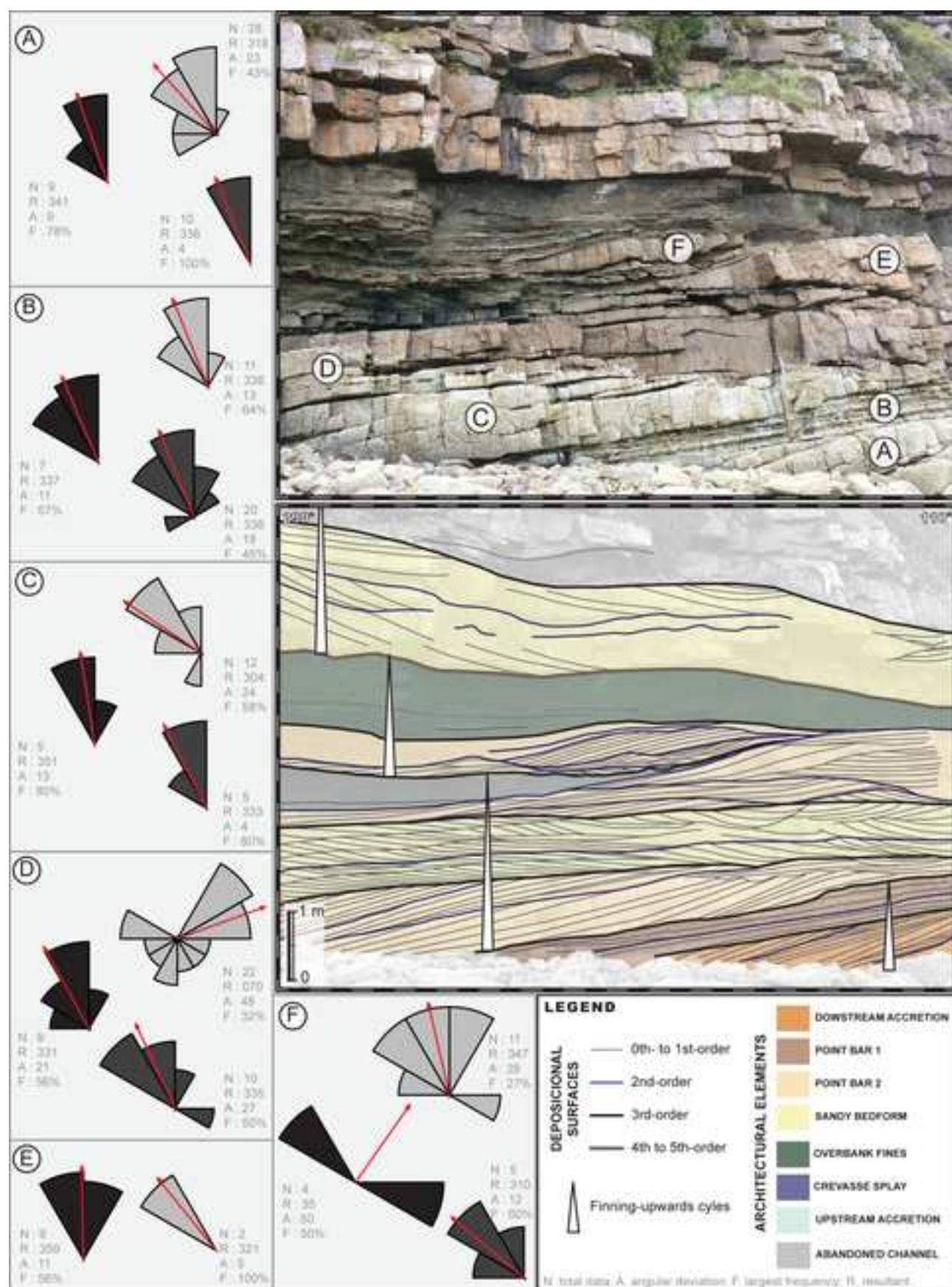
Figure





Hammer - 385 mm



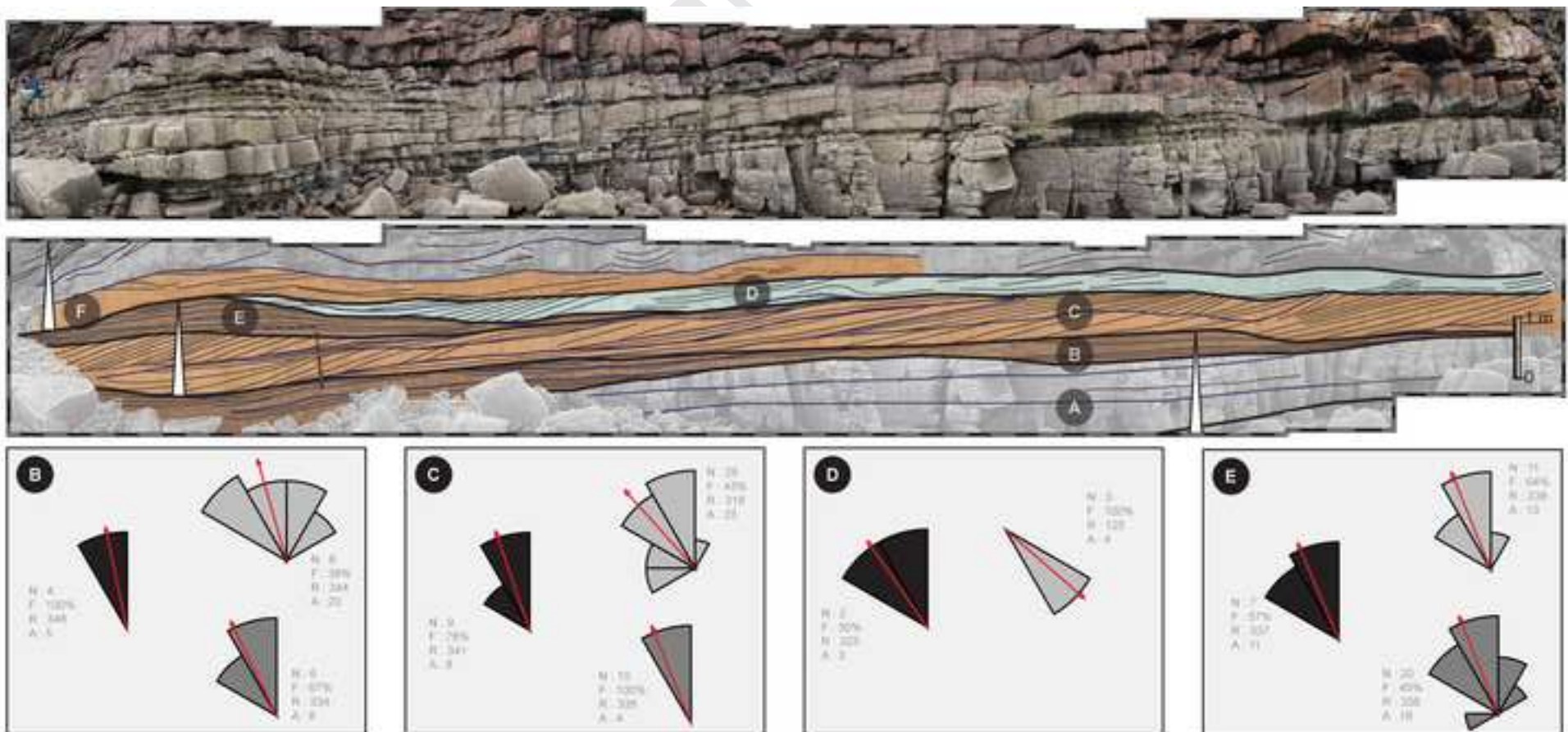


Figure



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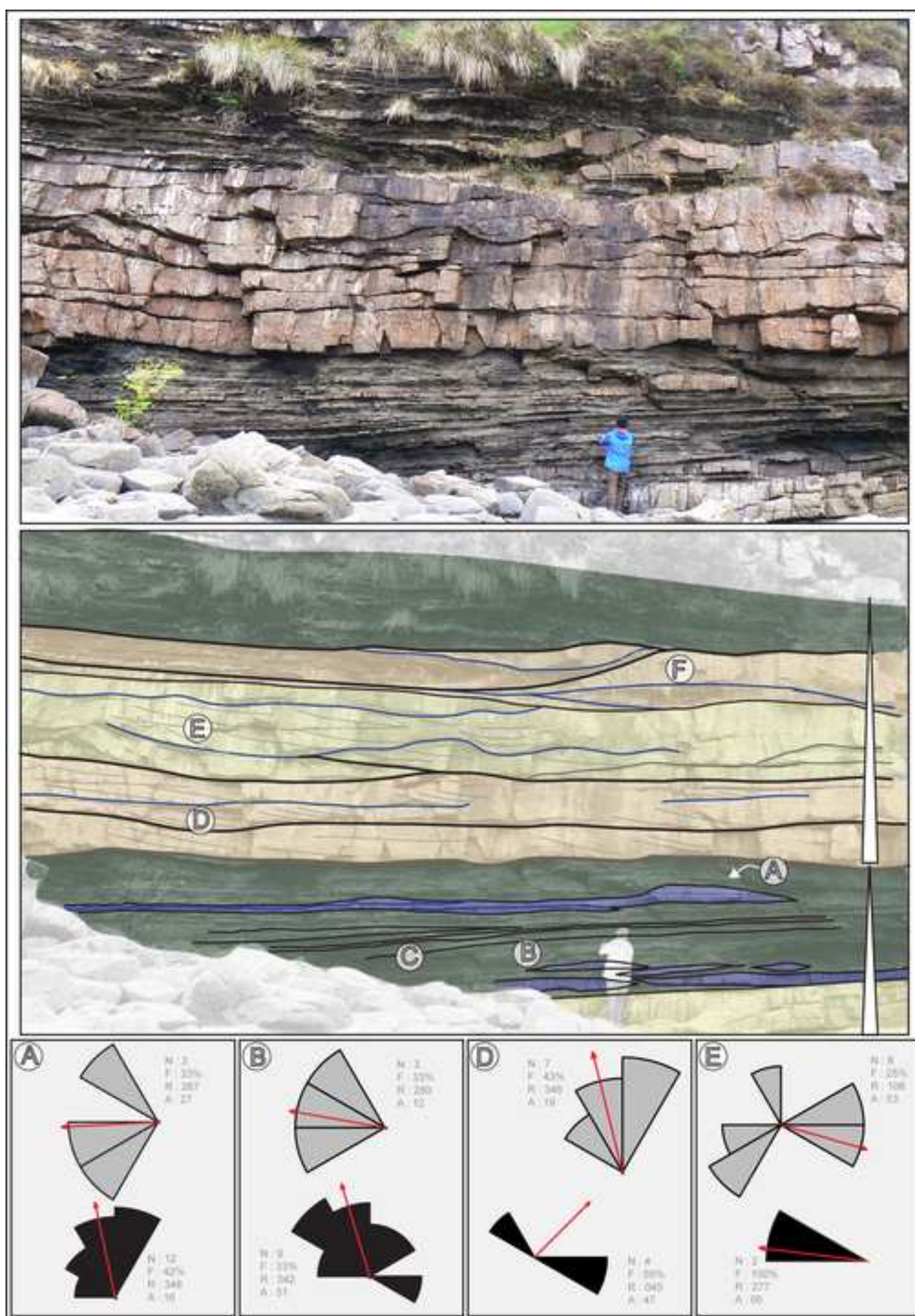


Figure

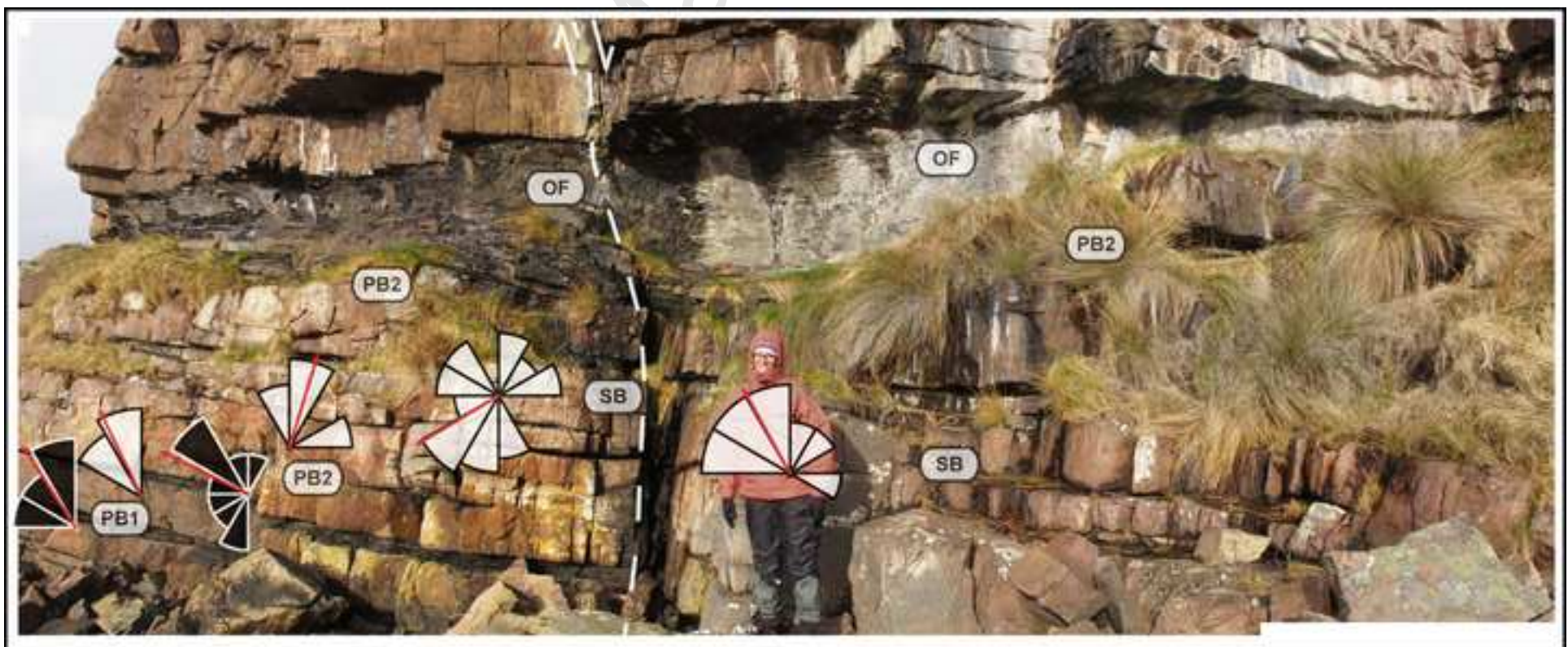
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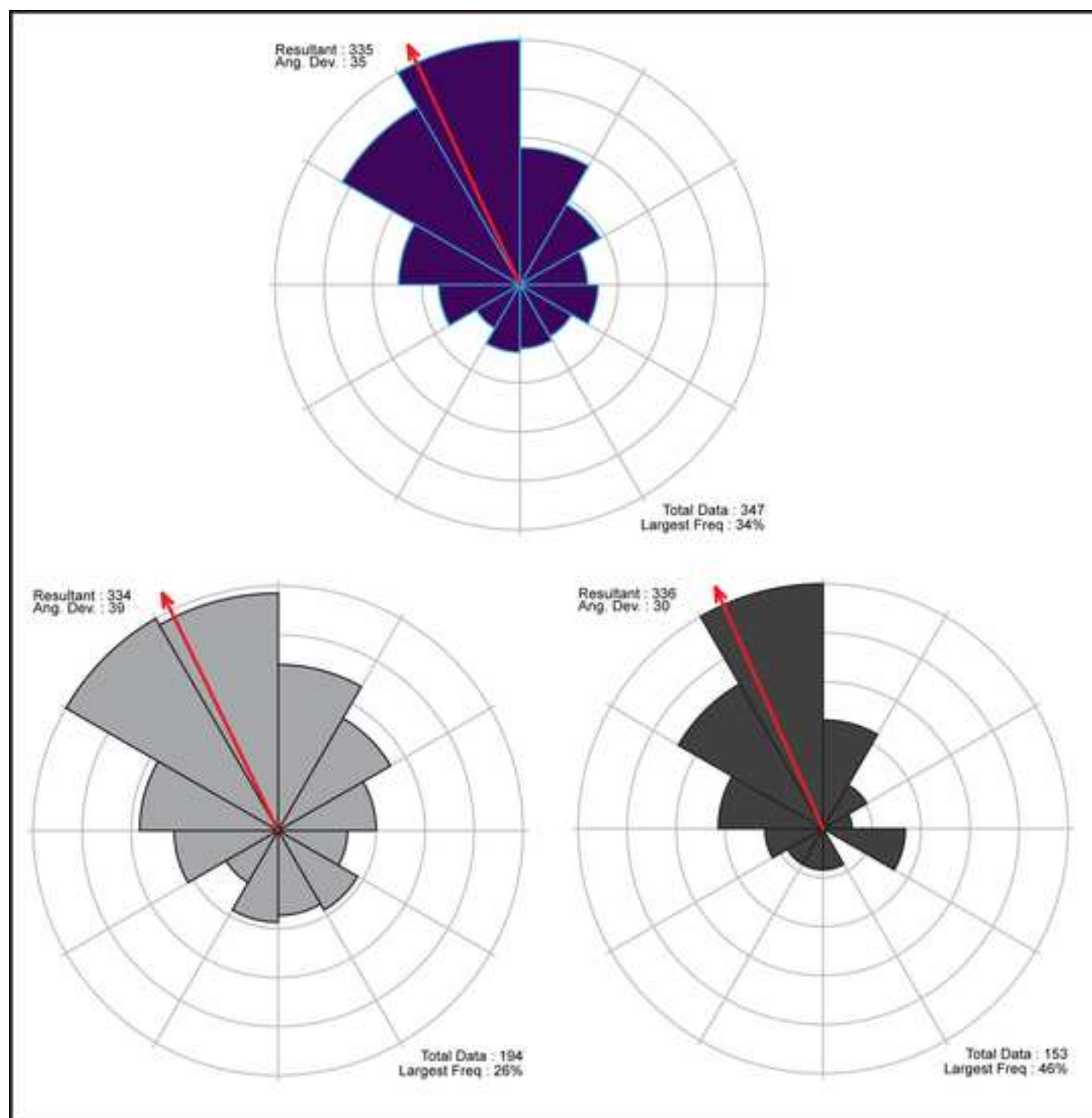




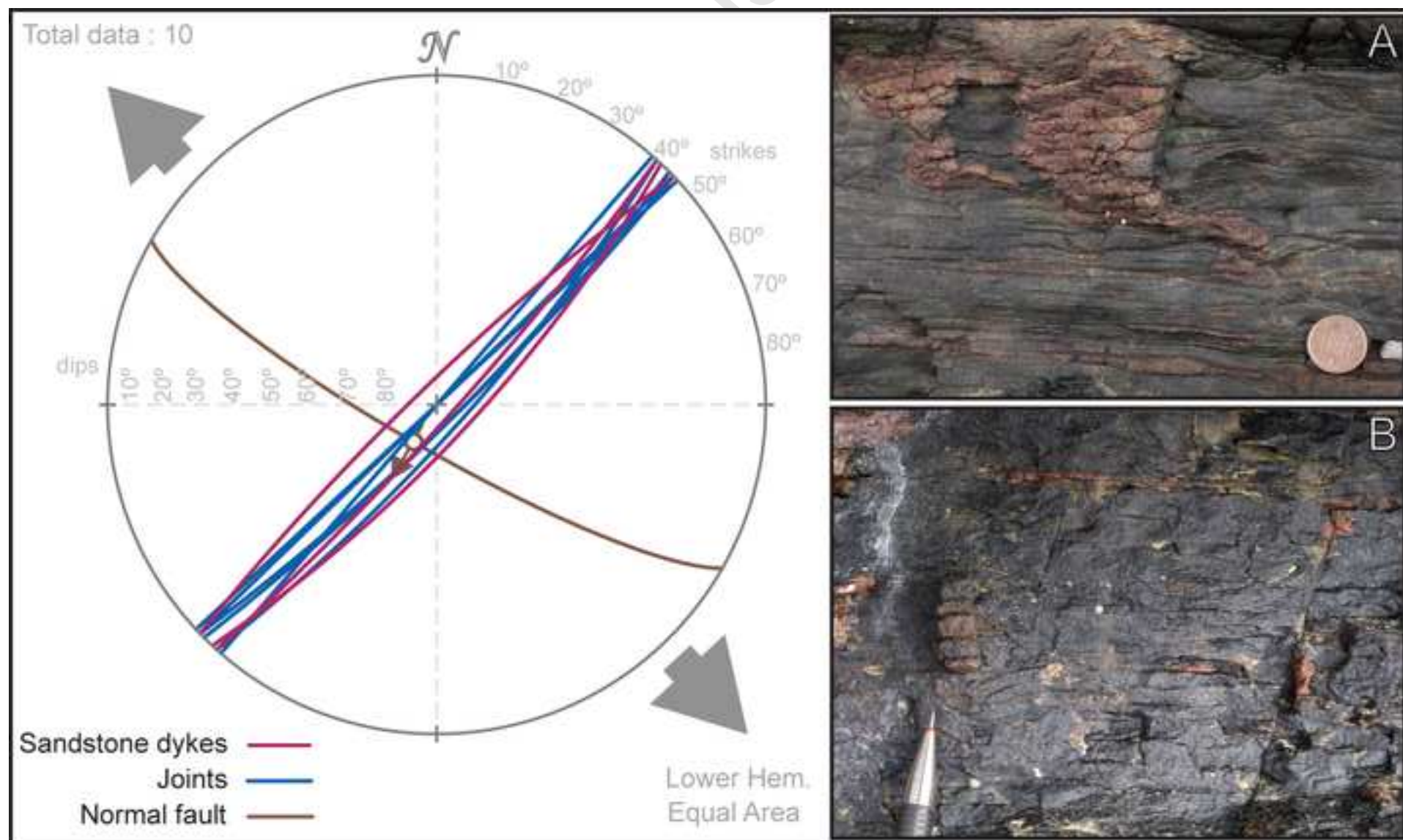


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