Sedimentological constraints on the late Silurian history of the Highland Boundary Fault, Scotland: Implications for Midland Valley Basin development

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Abstract

The relationship between movement on the Highland Boundary Fault (HBF) and deposition of the Lower Old Red Sandstone (LORS) in the Midland Valley Basin, Scotland is controversial. Most models favour mid-Silurian to early Devonian sinistral movement on the HBF and development of a transtensional Midland Valley Basin. To constrain HBF movement during the late Silurian, we examine the basal LORS alluvial succession exposed adjacent to the HBF. A lack of syn-sedimentary fault movement indicators coupled with an increase in stratal thickness across the fault, indicates the HBF was not active during LORS sedimentation. A transtensional basin model cannot be sustained.

The Highland Boundary Fault (HBF) is a steeply-dipping reverse fault that juxtaposes Dalradian metasediments of the Grampian Terrane (GT) onto Highland Border Complex and Lower Old Red Sandstone rocks (LORS) of the Midland Valley Terrane (MVT) (Barrow 1901; Campbell 1913; Anderson 1946; Strachan et al. 2002; Tanner 2008; Figs. 1a). The main phase of reverse movement on the fault took place in the Middle Devonian between deposition of the Lower and Upper Old Red Sandstone, yet the timing and nature of pre Mid-Devonian movement on the HBF remains controversial (e.g. Tanner 2008, 2011; Bluck 2010). Marked differences in late Precambrian to Lower Palaeozoic development of the GT and MVT have suggested to some workers that the HBF represents a terrane boundary separating the GT (Laurentia) from the MVT with extensive (> 500 km) sinistral strike-slip movement in Silurian to early Devonian times (e.g. Harte et al. 1984; Bluck 2002; Strachan et al. 2002; Dewey & Strachan 2003). In contrast, others believe there has been limited post-mid-Silurian strike-slip movement and that the GT and MVT blocks were amalgamated by the early Silurian (Oliver 2001; Tanner 2008). Bluck (2002, 2010) suggested that the northern edge of the MVB lay north of the current location of the HBF and that it migrated southwards during the early Devonian. He stressed that the notion that the LORS basin was continuous across the HBF could not be reconciled with provenance data, favouring deposition in a series of small strike-slip basins. In palaeogeographic reconstructions, the HBF also forms the northern, fault-bounded margin to the late Mid-Silurian LORS Midland Valley Basin (MVB), with, sediment shed southwards across the active fault into the basin (e.g. Bluck 1983; Haughton 1989; Trewin & Thirlwall 2002).

To constrain the timing and nature of mid Silurian to early Devonian movement on the HBF, we examine sedimentological and stratigraphic evidence from the Cowie Sandstone Formation, the oldest sedimentary unit in the northern part of the MVB. The formation unconformably overlies the Ordovician Highland Border Complex and is juxtaposed against the HBF, consequently sedimentological analysis should allow constraints to be placed on any syn-sedimentary fault activity during basin formation. Results suggest that the HBF was not active during deposition of the LORS and this observation is discussed within the context of the late Silurian to early Devonian development of the MVB.

Sedimentology of the Cowie Sandstone Formation

The sandstones of the LORS which unconformably overlie the pillow lavas of the Highland Border Complex and are truncated by the HBF are referred to as the Cowie Sandstone Formation and together with the overlying Carron Sandstone Formation form the Stonehaven Group (Fig. 2; Browne et al. 2002). The Cowie Sandstone Formation is dated as Wenlock in age on the basis of spores (Marshall 1991; Wellman 1993). A measured section through the 430 m thick formation is presented in Fig. 2. It comprises coarse grained, moderate to poorly sorted, trough cross-stratified sandstones interbedded with horizontally laminated mudstones, rippled and horizontally laminated siltstone and fine sandstones. Pebbly sandstones and occasional well rounded clast-supported conglomerates occur towards the top of the formation. Desiccation cracks are present in some mudstone intervals, freshwater fish, arthropod and millipede remains have been found in a siltstone unit towards the top of the formation (Westoll 1977). Sandstone bodies range from 1 m thick, single story, channel-fill packages to amalgamated channel-belt bodies up to 60 m thick interpreted to represent the deposits of medial and lateral bars developed in a large-scale, low sinuosity fluvial system. Tilt-corrected palaeocurrent data measured from trough cross-strata are presented for a number of stratigraphic units within the Cowie Sandstone

Formation and summed for all units in Fig. 2. A consistent transport direction towards the west is clearly illustrated with a WNW component dominant in the lowermost units.

Highland Boundary Fault: Field Relationships

Field relationships associated with the HBF have been described in detail previously (e.g. Barrow 1901; Campbell 1913; Anderson 1946; Tanner 2008) and a brief summary relevant to the study area is presented here. The HBF is exposed on the coastline at Cowie (Fig. 2), where it forms a high angle reverse fault that dips steeply to the north, placing late Precambrian to Cambrian Dalradian metasediments of the GT onto Ordovician pillow lavas (Highland Border Complex) of the MVT and LORS sandstones (Campbell 1913). An unconformity dipping 51° to the south, separates the pillow lavas from sandstones of the LORS (British Geological Survey 1999). Strata above the unconformity show a progressive increase in dip south of the unconformity from 51° to close to vertical over a horizontal distance of 500 m. Dips remain close to vertical south of this point for a further 4 km. The unconformity between the LORS and the Highland Border Complex is only seen at Cowie. Elsewhere the LORS is always in fault contact with either Dalradian metasediments or the Highland Border Complex.

The LORS sucession at Cowie forms part of the northern limb of the Strathmore Syncline (Fig. 1) - a Middle Devonian structure truncated prior to deposition of the Upper Devonian Upper Old Red Sandstone (Bluck 2000). The syncline can be traced for >200 km across the Midland Valley Basin where it runs parallel to the HBF and is thought to have developed during the main phase of movement on the HBF (Tanner 2008)

Discussion

Palaeocurrent data from the Cowie Sandstone Formation do not support evidence for syn-sedimentary movement on the HBF. Fluvial channel deposits located immediately adjacent to the HBF flowed either directly or obliquely towards the present day location of the fault. In addition, if the HBF had been active during LORS deposition, as suggested in reconstructions (e.g. Bluck 1983; Haughton 1989; Trewin & Thirlwall 2002), then thick packages of coarse grained, angular, poorly sorted alluvial fan deposits that dipped southwards off the active fault scarp should be preserved. No evidence for alluvial fan deposits such as are commonly observed along active fault scarps (e.g. Blair & McPherson 1994) are present in the Cowie Sandstone Formation (Fig 2). Palaeocurrent data from strata overlying the Cowie Sandstone Formation also indicate no evidence for transport of material southwards across the HBF in the LORS. For example, fluvial sandstones in the overlying Carron Sandstone Formation show westerly directed palaeoflow (Haughton 1989; Davidson & Hartley 2010). Haughton (1989) described complex palaeocurrent patterns from conglomerates of the 1500 m thick Dunnottar Group (Fig. 2) which overlies the Stonehaven Group, and which also display predominantly southwesterly directed palaeoflow. This indicates that for at least the lower 2500 m of LORS deposition, sediment was consistently sourced from the east with no input from the north.

Unfolding of the Strathmore Syncline and restoration of depositional dip to palaeo-horizontal (Fig. 3), shows that the Cowie Sandstone Formation thickened northwards towards what is the present day location of the HBF. Assuming an equivalent thickness of LORS overlay the GT prior to post-Lower Devonian movement on the HBF, estimates of displacement on the HBF at Cowie would include the full thickness of the LORS on the northern limb of the syncline of at least 4500 m. Although fault-bounded on the BGS section (Figs. 1 and 2), this still provides a minimum value for post-Lower Devonian displacement and erosion prior to UORS deposition. Elsewhere adjacent to the HBF across Scotland, thick (>5 km) sections of LORS strata are affected by the Strathmore Syncline (Fig. 2), with the implication that up to 5000 m of LORS overlay much of at least the southern part of the GT prior to movement on the HBF in the Mid Devonian.

Evidence for LORS sedimentation across the GT is provided by a regional base-LORS unconformity that can be reconstructed across much of the GT using numerous scattered LORS outliers (Watson 1985; Stephenson & Gould 1995; Bluck 2000; Macdonald et al. 2000). North of the HBF, thick accumulations of sediments and interbedded lavas (800 to 1440 m) of late Silurian to earliest Devonian age are recorded for example at Lintrathen, Glen Turret, Lorne, Oban and Kintyre (Bluck 2000; Browne et al. 2002; Trewin & Thirlwell, 2002; Fig. 1). The preservation of a base-LORS unconformity and LORS outliers of Silurian age north of the HBF support the idea that the GT did not form a topographic high during LORS deposition, but rather was buried by LORS sediment at least partially by the late Mid-Silurian and certainly by the Late Silurian (Fig. 3),

The palaeocurrent data from the Cowie Sandstone Formation, the projected increase in LORS thickness across the HBF and the absence of any significant accumulations of alluvial fan deposits adjacent to the fault have a number of significant implications: 1) the HBF was not active during deposition of the LORS, 2) the LORS basin margin lay significantly north of the present day location of the HBF (Bluck 2000), 3) sedimentation was continuous across the HBF,

4) a significant thickness of LORS (4500 m) directly overlay GT Dalradian basement and was subsequently uplifted and exhumed in relation to post-LORS reverse HBF movement, 5) any strike-slip movement on the HBF must have occurred prior to the Wenlock such that there is no evidence for large scale sinistral strike-slip movement on the HBF in late Silurian to early Devonian times (see also Tanner 2008).

Bluck (1978) suggested the LORS was deposited in a series of linked transtensional sub-basins which together formed the MVB. In these models the northern margin of the basin was represented by an active HBF which separated an uplifted GT from the MVB. The evidence from the Cowie Sandstone Formation and overlying strata suggest that this model cannot be sustained, with no indication of syn-sedimentary relief on the HBF during LORS deposition, sediment extending northwards over the subdued relief of the GT and at least the lower 2500 m of the basin-fill derived from an elevated area to the east of the basin. Other features that are commonly associated with active strike-slip basin margins (e.g. Miall 2000) such as angular unconformities within the basin-fill adjacent to the basin-bounding fault and rapid along strike changes in true stratigraphic thickness have not been documented within the LORS succession (e.g. Browne et al. 2002),

To assess the significance of these observations within a wider context, it is necessary to place the HBF within the late Lower Palaeozoic tectonic framework. In the early to Mid Silurian (435-425 Ma), to the east and north of the GT and MVT, collision between Laurentia and Baltica resulted in the Scandian deformation phase of the Caledonian Orogeny (Coward 1990). Scandian deformation affected western Norway, east Greenland and the Northern Highland

Terrane (NHT) of Scotland, and was responsible for large-scale nappe emplacement including development of the Moine Thrust. The GT which is separated from the NHT by the Great Glen Fault (Fig. 1) has no record of significant Scandian deformation. To explain the present day juxtaposition of these crustal blocks, it has long been inferred that significant (possibly >500 km) late Silurian to early Devonian sinistral strike-slip movement took place on the Great Glen Fault (Strachan et al. 2002) to accommodate the oblique collision of Baltica with Laurasia, with >500 km of sinistral movement also taking place along the HBF at this time (e.g. Dewey & Strachan 2003). It is clear that this latter scenario is not supported by the sedimentological evidence from the Cowie Sandstone Formation and that from the late Mid-Silurian to the Mid-Devonian the HBF had little or no influence on LORS deposition with the GT forming a contiguous basal surface with that of the MVB. Tanner (2008) presents evidence for very limited post LORS strike-slip movement on the HBF such that any strike-slip movement must have been pre-Mid Silurian.

The preservation of Silurian LORS deposits on both the MVT and GHT indicate that sedimentation occurred across the HBF. If the GHT was not the direct source for LORS detritus a mechanism for generation of significant relief immediately east and north of the MVB is required to supply substantial volumes of coarse clastic sediment to the basin. It has long been recognised that some sediment was supplied by fluvial systems draining the Scandian Orogen to the east of the MVB (e.g. Bluck 2000), however in most reconstructions this sediment source supplements material derived from the GHT. We suggest that the Scandian Orogen is the sole source of clastic material for LORS fluvial systems (Fig. 3). The correspondence between Scandian deformation and the onset of LORS sedimentation in the Wenlock further suggests that the LORS basin-fill developed as part of the Scandian foreland. The suture zone between Baltica and the edge of the MVT and GHT currently lies 100 to 150 km directly east of the Midland Valley (Coward et al. 2003) and would have been closer prior to Mesozoic extension in the North Sea.

Conclusions

A study of the Mid to Late Silurian succession located adjacent to the Highland Boundary Fault, allows the timing of fault movement on this major Caledonian structure to be constrained. A lack of evidence for syn-sedimentary fault moment such as fault-scarp derived scree deposits, growth strata or palaeocurrent deflection together with evidence for stratal thickening across the fault indicate that there has been no significant post-Ordovician strike-slip movement on the HBF. The observations indicate that LORS sedimentation was continuous across the HBF and that the HBF did not form the northern margin of the MVB and did not migrate southwards during LORS deposition. The HBF did not therefore accommodate any Scandian shortening or strike-slip movement and should not be included in late Palaeozoic palaeogeographic reconstructions of NW Europe and contiguous areas. Implications of these observations when placed within the Caledonian tectonic framework for the Silurian are that the LORS basin-fill succession which covered the low-lying and contiguous Midland Valley and Grampian Highland Terranes was derived primarily through erosion of the developing Scandian Orogen to the east.

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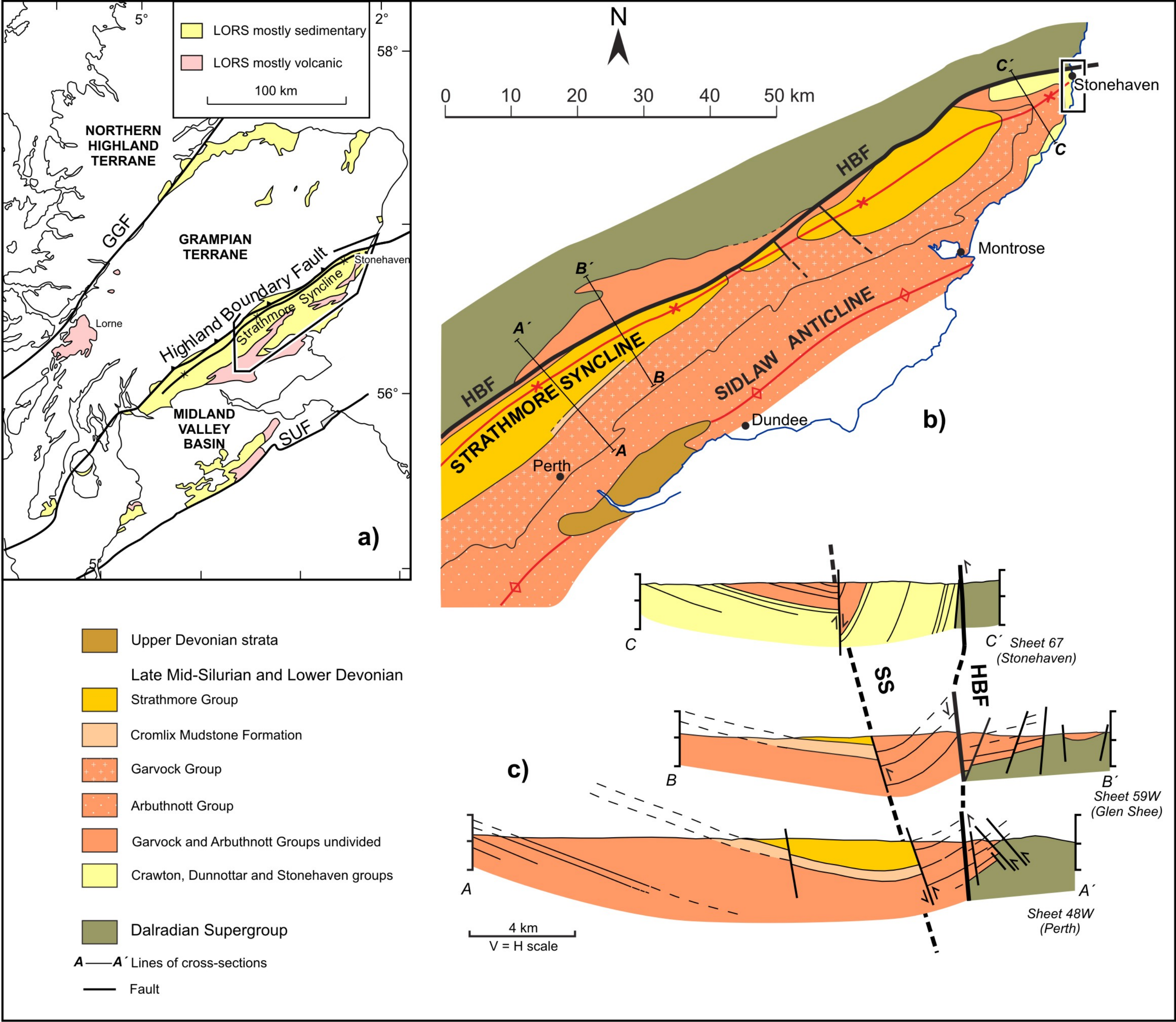
List of Figures

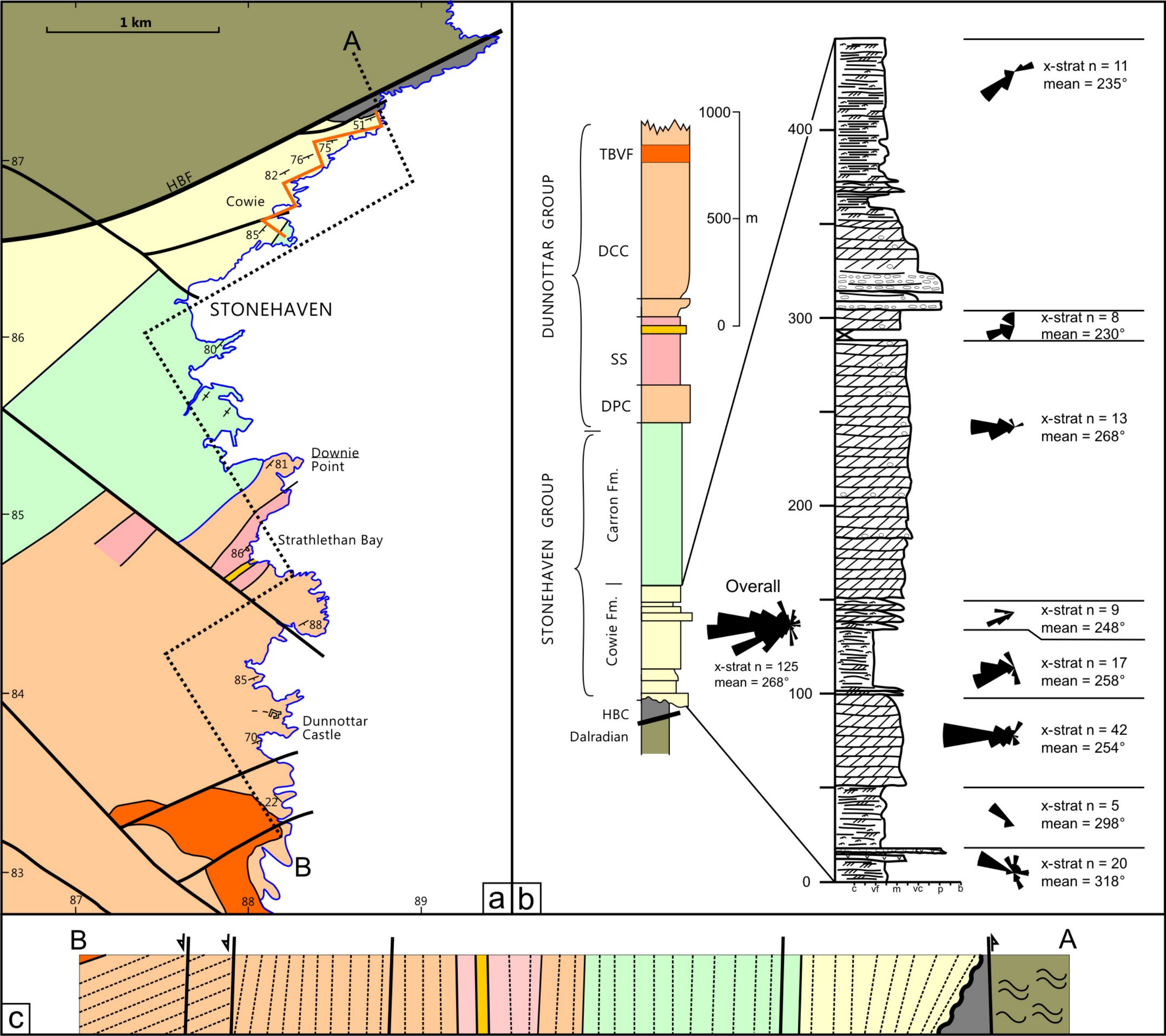
Fig. 1 a) Map of northern and central Scotland showing the distribution of LORS outcrop and the main terranes, basins and faults. Box highlights area of map in b). Fig. 1b) Geological map of northeastern part of the MVB showing the relationship between the main structures and stratigraphy, modified after Tanner (2008). Fig. 1c) Three cross-sections illustrating the relationship between the HBF and the basin-fill. Note the presence of thick LORS packages immediately north of the fault (modified after Tanner 2008).

Fig. 2a) Geological map of the Cowie area (modified from Trewin and Gillan 1987 and British Geological Survey 1999). Red line shows location of logged section shown in (b), line of cross-section shown in (c) is labelled A-B and marked as a black dashed line. 2b) Stratigraphic column of the lower part of the LORS basin-fill succession and sedimentary log of the Cowie Sandstone Formation with palaeocurrent data (corrected for bed dip). 2c) Cross-section taken orthogonal to the strike of the HBF showing changes in dip southwards away from the fault, .

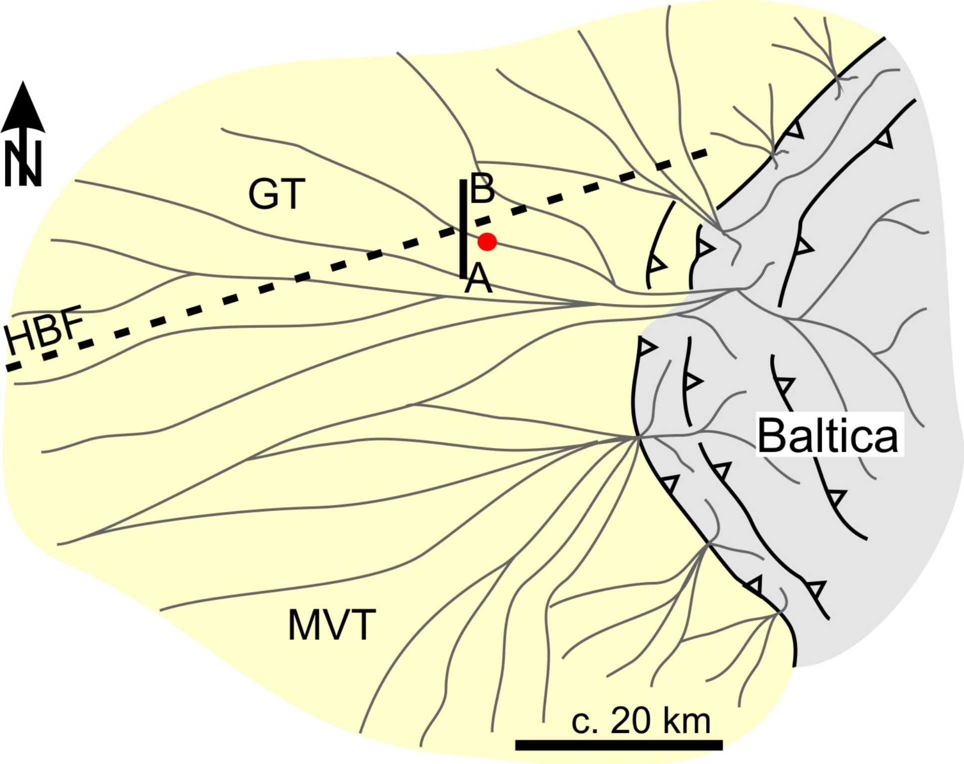
Fig.3 Reconstruction of LORS depositional setting and basin geometry, top diagram shows a palaeogeographic reconstruction of fluvial systems draining the developing orogen associated with collision of Baltica and Laurentia to the east of the Midland Valley, note the location of where the HBF will develop after LORS deposition. Bottom diagram shows simple cross-section restored across the present day location of the HBF with location of LORS stratigraphic section shown in Fig. 2 (red dot), note thickening northwards.

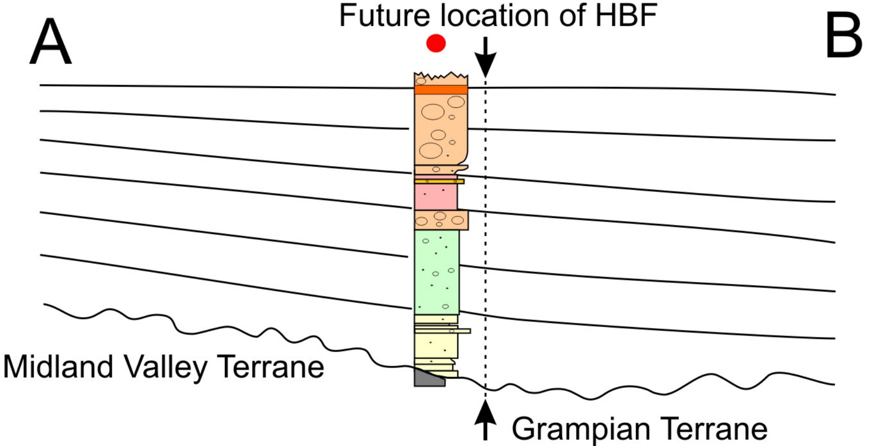


5°
2°
58°
56°
LORS mostly sedimentary
LORS mostly volcanic
100 km
NORTHERN HIGHLAND TERRANE
GGF
GRAMPIAN TERRANE
Highland Boundary Fault
Stonehaven
Strathmore Syncline
Lorne
MIDLAND VALLEY BASIN
SUF
a)
N
0 10 20 30 40 50 km
C´
C
Stonehaven
HBF
Montrose
B´
A´
B
A
SIDLAW ANTICLINE
STRATHMORE SYNCLINE
Dundee
Perth
b)
C
C´ Sheet 67 (Stonehaven)
SS
HBF
c)
B
B´ Sheet 59W (Glen Shee)
A
A´
Sheet 48W (Perth)
4 km
V = H scale
Upper Devonian strata
Late Mid-Silurian and Lower Devonian
Strathmore Group
Cromlix Mudstone Formation
Garvock Group
Arbuthnott Group
Garvock and Arbuthnott Groups undivided
Crawton, Dunnottar and Stonehaven groups
Dalradian Supergroup
A——A´ Lines of cross-sections
Fault



1 km
A
B
HBF
Cowie
STONEHAVEN
Downie Point
Strathlethan Bay
Dunnottar Castle
87
86
85
84
83
88
89
51
75
76
82
85
80
81
86
88
85
70
22
a
b
c
DUNNOTTAR GROUP
STONEHAVEN GROUP
TBVF
DCC
SS
DPC
Carron Fm.
Cowie Fm.
HBC
Dalradian
1000
500 m
0
Overall
x-strat n = 125
mean = 268°
x-strat n = 11
mean = 235°
x-strat n = 8
mean = 230°
x-strat n = 13
mean = 268°
x-strat n = 9
mean = 248°
x-strat n = 17
mean = 258°
x-strat n = 42
mean = 254°
x-strat n = 5
mean = 298°
x-strat n = 20
mean = 318°
400
300
200
100
0
c vf m vc p b


N
GT
B
A
HBF
Baltica
MVT
c. 20 km


Future location of HBF
A
B
Midland Valley Terrane
Grampian Terrane