Facies analysis of the Greywacke Conglomerate Formation, Glenbuck, Scotland.

Mitten, A.J.[1] 0000-0002-0526-0368 ; Gough, A.[2] 0000-0001-5146-3476; Leslie, A.G.[3] 0000-0003-1932-8420; Clarke, S.M.[1]; Browne, M.A.E.[3]

[1] Basin Dynamics Research Group, School of Geography, Geology and the Environment, Keele University, Keele, Staffordshire, ST5 5BG, UK. *a.j.mitten@keele.ac.uk

[2] SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK.

[3] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP, UK.

For submission to the Scottish Journal of Geology.

Abstract

The early Devonian Greywacke Conglomerate Formation of the Lanark Basin, south-western Midland Valley of Scotland, has been exposed by a new road cut in the Glenbuck area, East Ayrshire, enabling, a high-resolution sedimentological analysis of this unusually high-quality section. This study provides a facies analysis of the sedimentary rocks exposed in the Glenbuck area, and comparison with contemporaneous bedrock sections from across the Lanark Basin and adjacent Southern Upland High. Eleven lithofacies are identified, grouped into five associations: aggradational talus cone, progradational talus cone, debris flow lobe, fan surface alluvial deposits, and gravel barform deposits. These comprise medial and proximal alluvial fan deposits, controlled by autogenic scour and avulsion along with general fan progradation. Contemporaneous sediments are present around Silurian inliers in the Lanark Basin and adjacent regions of the Southern Upland High. Whilst

deposits in the Lanark Basin are genetically similar, contemporaneous deposits of the Southern Upland High preserve a distinctly more angular clast assemblage indicating textural immaturity relative to those in the Lanark Basin.

Abbreviated title: *Facies analysis of the GRWC.*

The Greywacke Conglomerate Formation (GRWC) is the oldest formation of the Silurian – Early Devonian Lanark Group (Old Red Sandstone Supergroup) deposited in the Lanark Basin of the south-western Midland Valley, Scotland (MVS) (**Fig. 1** (**a**) (**b**)) (Syba 1989; Paterson *et al.* 1998; Phillips *et al.* 1998; Smith *et al.* 2006). The basal conglomerates of the GRWC are widespread across the southern MVS and may locally be over 500 m thick (**Fig. 1** (**c**)). The GRWC rests unconformably on tightly folded Wenlock and Llandovery age strata of the North Esk inlier in the eastern Lanark Basin, and Ordovician to Llandovery age strata in the Hagshaw Hills Inlier in the south-west of the Basin (Phillips *et al.* 1998; Phillips 2007). The formation thins and becomes more sandstone-rich towards the north-west. Sediments of the lowest Old Red Sandstone Supergroup are typically deposits of arid to semi-arid (Domeier and Torsvik 2014) alluvial fans sourced from the Southern Uplands region (Trewin and Thirlwall 2002). Contemporaneous with these Lanark Basin alluvial fans, the Great Conglomerate Formation was shed from local highs on the Southern Upland High terrane. Previously published interpretations of gross depositional environment were based on the broad lithology and large-scale geometry of the formation (Phillips *et al.* 1998), but no detailed process-based facies analysis has yet been attempted .

This study presents new data from a fresh-cut road section on the north-east side of the A70, at Glenbuck, East Ayrshire (**Fig. 1** (**d**)). The section exposes strata from the Silurian Quarry Arenite Formation overlain, unconformably, by strata of the Silurian-Early Devonian GRWC (**Fig. 1** (**e**)). Outstanding preservation and exposure of the GRWC within an almost 30 m thick continuous exposure makes the outcrop ideal for detailed logging and analysis. This quality of outcrop is unusual for the stratigraphical interval in the south-western Midland Valley, and provides a unique insight into earliest Devonian depositional processes and palaeogeography. The study provides a facies analysis for the section logged, and interprets the depositional environment and processes by which the GRWC formed, including temporal changes. It considers the wide distribution of these deposits and their differing characteristics across the Lanark Basin and adjacent Southern Uplands.

Geological Setting

The Midland Valley of Scotland is a *c*. 90 km wide, complex graben striking ENE–WSW, bounded to the NW by the Highland Boundary Fault Zone and to the SE by the Southern Uplands Fault and related structures, like the Pentland Fault (**Fig. 1 a**) (Browne and Monro 1989; Floyd 1994; Read et al. 2002). These regional-scale faults formed as significant discontinuities during the Caledonian Orogeny associated with closure of the Iapetus Ocean (Oliver et al. 2008). Sinistral strike-slip displacements of tens to hundreds of kilometres were associated with major fault zones (Oliver et al. 2008). Deformation along these structures was reduced during the early Devonian, leading to more local transpressional and transtensional structures that influenced contemporary depositional systems (Thirlwall 1989, Bluck 1995; Trewin and Thirlwall 2002). During this Period, sediment accumulated in two Midland Valley basins: the Strathmore Basin, formed contemporaneously with the Strathmore Syncline adjacent to the Highland Boundary Fault Zone to the north, and the Lanark Basin formed in the south and south-west (Smith 1995; Phillips et al. 1997).

The Devonian succession rests unconformably on Silurian strata that are exposed in inliers across the Lanark Basin (Smith 1995; Phillips et al. 1997; Phillips 2007). However, the degree to which the dip of the Devonian strata is significantly different from that of the underlying Silurian rocks varies, depending on their location relative to the Southern Upland Fault and related structures. In the central Lanark Basin (Phillips 2007) the unconformity is predominately disconformable and is typically marked by greater angularity towards the north-east of the Lanark Basin, and south of the Pentland Fault (Smith 1995; Phillips et al. 1997). These contrasting relationships demonstrate the impact that strike-slip deformation had upon structural frameworks in the Basin during the late Silurian to Early Devonian (Smith 1995; Phillips et al. 1997).

The Siluro-Devonian Old Red Sandstone deposits in the Midland Valley represent the initial fill of the basin, where the supply of detritus was controlled by post-Caledonian orogenic uplift, cooling and erosion. Old Red Sandstone sediment derived from the Grampian High to the north (McKellar et al. 2020a) was deposited in the Strathmore Basin (Trewin and Rollin 2002; McKellar et al. 2020a) whereas the source of deposits in the Lanark Basin is conjectural. Both the Southern Uplands (Trewin and Thirlwall 2002), and Silurian inliers within the Midland Valley (Phillips 2007), have been thought to have been the source for these deposits.

Palaeocurrent indicators in the Siluro-Devonian strata suggest a south-westerly drainage in the Strathmore Basin, reflecting a large river system that flowed from uplands created by Scandian (c.430 Ma) uplift of the Caledonian Orogen, and also entrained polycyclic detritus from the Scottish Highlands (Bluck 2000, McKellar et al. 2020b). Palaeocurrent data in the Lanark Basin, generally support this sediment source and a south-westerly flowing fluvial model. However, the distribution, routing and sources of sediments preserved present a more complex pattern than that in the Strathmore Basin (that was derived from the Dalradian Supergroup (Haughton 1989, McKellar 2020a), with sediment recycled both from the erosion of actively deforming Silurian inlier strata (Smith 1995; Phillips et al. 1997; Phillips 2007) and from the Southern Uplands (Browne *et al.* 2002; Smith et al. 2006). After an extensive petrographic analysis of clast material and sandstones within the basal Greywacke Conglomerate Formation (GRWC) of the Lanark Basin succession, Philips (2007) concluded that lithic sandstone and conglomerate clast compositions reflect detritus derived from Silurian inliers within the MVS and not from the Southern Uplands.

Sedimentology of the Greywacke Conglomerate Formation

The Glenbuck section (**Fig. 1 d**) exposes a 27 m thick section that includes strata from both the Silurian Quarry Arenite Formation and the Greywacke Conglomerate Formation, separated by an irregular unconformity ~80 cm from the base of the exposure (**Fig. 2**). The section was logged at centimetre-scale resolution, and a standard lithofacies analysis was carried out for the strata of the GRWC. Lithofacies proportions were determined from the vertical intervals of the logged section formed by them.

Lithofacies of the Greywacke Conglomerate Formation

Eleven lithofacies (**Table 1**) are identified in the GRWC section at Glenbuck. These are all typically polymictic, with clast assemblages comprising dominantly granodiorite, poly- and mono-crystalline quartz, with subordinate andesitic fragments and chert. These assemblages concur with those recorded by Philips (2007). Their relative proportions do not change significantly throughout the logged section.

Four paraconglomerate (conglomerates that are dominantly matrix-supported) lithofacies, form approximately 60% of the GRWC: reversely graded (Cmr), imbricated normally graded (Cmn), rafted (Cmb), and disorganised paraconglomrerates (Cmd) (**Table 1**). Matrix-support and long-axis imbrication of normally graded deposits suggests that they are products of non-Newtonian flow and pseudo-plastic flow respectively (Leeder 1999). Reverse grading and rafting within the paraconglomerates (Cmr and Cmd, respectively) is a consequence of frictional drag on the basal surface of the flow during transport (Blair *et al.* 1999).

Twenty percent of the Greywacke Conglomerate section comprises units of structureless (Ccm) or cross-bedded (Ccc) orthoconglomerate (conglomerates that are dominantly clast-supported) (**Table 1**). Cross-bedded orthoconglomerates are interpreted as products of gravel-grade bedforms migrating in a high-energy Newtonian flow (Miall 1977, 1996). However, structureless orthoconglomerates are interpreted to result from winnowing of the finer matrix component of paraconglomerates originally deposited by non-Newtonian processes (Collinson *et al.* 2006).

The remaining 20 % of the GRWC section consists of sandstones: poorly developed planar horizontal laminated (Sh), trough crossbedded (St), and lenticular bodies (where observable). These range in grainsize from medium- to very coarse-grained (**Fig. 2**). Structureless (Sm) and pebble-bearing, normally graded sandstones (Sc) occur locally. Overall, the sandstones in this section are interpreted to have been deposited under high-energy Newtonian flow that waned quickly, preventing wide-spread development of ripple bedforms and low-energy structures (Miall 1996; Leeder 1999). The poor preservation of sedimentary structures within the sandstones reflects high sediment-load conditions (Bridge and Best 1988; Todd 1996), supressing bedform development.

Lithofacies associations of the Greywacke Conglomerate Formation

The lithofacies of the GRWC (**Table 1**) can be grouped into five associations based upon the processes of deposition, relative juxtaposition, thickness and general grainsize, and supposed flow regime trends across bedding surface contacts. The associations identified (**Table 2**) reflect deposition in: aggradational talus cones (AT), progradational talus cones (PT), debris flows (DF), fan surface aqueous-alluvial deposits (AF), and gravel barforms (GB).

Aggradational Talus Cone Deposits (AT)

Description: This association is *c*. 2 metres thick and consists of reversely graded, matrix-supported, paraconglomerate (Cmr, 60 %) with subrounded, moderately spherical pebble- to cobble-grade clasts encased in a poorly sorted medium- to very coarse-grained matrix. It is overlain gradationally by paraconglomerate held on the surface of the flow (Cmb, 40 %) (**Fig. 2**), a reversely graded, matrix-supported paraconglomerate with a poorly sorted medium- to very coarse-grained matrix, and rafted boulder-grade clasts (up to 25 cm diameter) alongside sub-rounded, moderately spherical, pebble- to cobble-grade clasts. Such rafting, is not observed in other lithofacies. Together, these lithologies represent the coarsest deposits in the outcrop with an overall coarsening-upwards. Like all described here, this association extends laterally across the road cut.

Interpretation: The association is interpreted as reflecting deposition within a talus cone during aggradational lobe building. The matrix-supported conglomerates with reverse grading are a result of frictional drag on the substrate of the flow causing in-transport organisation of the clasts, and suggest transport by debris flows (Nemec and Steel 1984; Coussot and Meunier 1996), The boulder-grade clasts suggest rockslide deposition, entraining bedrock blocks that were rafted on top of the flow (Nemec and Steel 1984; Blair et al. 1999), potentially evidencing avalanche type deposits (Nemec and Steel 1984; Coussot and Meunier 1996).

Progradational Talus Cone Deposits (PT)

Description: This association is *c*. 1–2 metres thick and comprises reversely graded paraconglomerates (Cmr, 70 %) that are locally scoured by lenses of horizontally laminated sandstone (Sh, 28 %). Rarely, there are sharp contacts with structureless orthoconglomerate (Ccm, 2 %) and surrounding reversely graded paraconglomerate (Cmr) (**Fig. 2**). Lithofacies Cmr, as described above (AT), is reversely graded and matrix supported. Lithofacies Ccm is structureless, ungraded, clast-supported cobble to boulder grade orthoconglomerate with poor sorting of rounded clasts and a poorly preserved matrix. The final lithofacies (Sh) is a planar horizontally laminated coarse- to very coarse-grained moderately sorted sandstone with sub-angular moderately spherical grains. The association shows a crude reverse grading of the conglomerates, the tops of which are typically down cut by minor sandstone lenses a minimum of 30 cm in width and *c.* 20 cm thick.

Interpretation: This association is interpreted as reflecting deposition within a talus cone during a period of progradational lobe building (PT). Reversely graded paraconglomerates (Cmr) represent transport by avalanche gravity flows, with reverse grading a result of frictional drag, causing in-transport clast organisation (Nemec and Steel 1984; Coussot and Meunier 1996). The massive orthoconglomerate facies (Ccm) was deposited in a non-Newtonian, high sediment load, debris flow in which the matrix was removed by subsequent winnowing, suggesting a period of quiescence following deposition. Horizontally laminated sandstones (Sh) were formed by backfilling of incisions into the underlying deposits by minor alluvial surface flows (Miall 1996). Such flows have an incredibly narrow geometry with a width to thickness ratio of approximately 1.5:1 (from the minimum observed width). This is far lower than typical fluvial deposits which, at minimum, have a 15:1 width to thickness ratio for narrow fixed channels (Gibling 2006). The poor preservation of sedimentary structures and the low width to thickness ratio together, suggest rapid incision and backfilling of channels with deposition from a pseudo-laminar flow (Todd 1996).

Debris Flow Deposits (DF)

Description: This association is *c.* 1–1.6 metres thick. The base comprises normally graded paraconglomerate (Cmn, 70 %), scoured by horizontally laminated sandstones (Sh, 28 %), overlain by trough cross-bedded sandstones (St, 2 %). The principle lithology is a crudely normally-graded, pebble- to cobble-grade paraconglomerate with sub-rounded to rounded, clasts that are orientated along the long axis, and matrix-supported by poorly sorted medium- to very coarse-grained sandstone. The basal clasts show no discernible alignment, but some crude alignment and clast contacts become apparent up-section. Lithofacies Sh, is a coarse- to very coarse-grained, horizontally laminated sandstone. Lithofacies St is a coarse- to very coarse-grained, moderately sorted, trough cross-bedded sandstone with sub-angular grains. As a whole, the association is normally graded, fining sharply from the basal conglomerate facies (Cmn) to the sandstones (Sh and St). The boundary between these sharply grading lithologies commonly shows evidence of minor erosion and scour.

Interpretation: This association is interpreted as reflecting deposition within hyperconcentrated debris flows during a period of lobe building (progradation) of the alluvial fans. The normally graded nature of the basal paraconglomerate (Cmn) suggests an absence of frictional drag at the base of the flow, indicating that the flow itself had sufficient water content to freely pass over its substrate (Nemec and Steel 1984; Coussot and Meunier 1996; Haughton et al. 2009). The water content was low enough to enable pseudo-plastic flow at the base of the association but as the flow rapidly waned and as the coarsest sediment was deposited, the water content (relative to the sediment-load) became sufficient to support high sediment-load, turbulent Newtonian flow conditions (Coussot and Meunier 1996). This argument is supported by the presence of horizontally laminated (Sh) and trough cross-bedded (St) sandstones occupying channels cut into the surface of the basal normally-graded paraconglomerate (Cmn) (**Fig. 2**). The deposit is therefore interpreted as the product of rapidly waning hyperconcentrated composite debris flows that evolved from initial rapid sediment deposition (Cmn) to progressively more Newtonian conditions (Sh and St).

Fan Surface Aqueous-Alluvial Deposition (AF)

Description: This association is *c.* 1.8 metres thick and comprises an erosive base overlain by intercalated units of normally graded paraconglomerates (Cmn) and disorganised paraconglomerate (Cmd, accounting for 40 %). These basal deposits were eroded and overlain by cross-bedded orthoconglomerates (Ccc, 10 %), and clast-bearing (Sc, 30 %), trough cross-bedded (St, 10 %), and horizontally laminated (Sh, 10 %) sandstones. Lithofacies Cmn, described above (DF), is a matrix-supported, crudely normally graded, pebble- to cobble-grade paraconglomerate. Lithofacies Cmd is a matrix-supported, poorly sorted granule- to cobble-grade paraconglomerate, with sub-rounded clasts of moderate to low sphericity. The matrix is extremely poorly sorted, comprising fine- to very coarse-grained sandstone with sub-rounded grains. Lithofacies Ccc is a clast-supported, crudely reversely graded, granule- to pebble-grade, cross-bedded orthoconglomerate with sub-rounded to rounded clasts of moderate to low sphericity. Matrix present locally is of moderately sorted, fine- to very coarse-grained sandstone. Litofacies Sc is a medium- to coarse-grained, poorly sorted, normally graded sandstone with floating cobble- to granular-grade clasts. As described above, lithofacies St, (DF), is a trough cross-bedded sandstone, and lithofacies Sh, (DF), is horizontally laminated sandstone. The association is normally graded from basal conglomerate into the sandstone. There is no discernible clast alignment in the basal conglomerates, but some organisation is present towards the top of the normally graded paraconglomerate (Cmn).

Interpretation: This association (AF) is interpreted as representing the deposits of proximal fluvial flows that incise the surfaces of underlying deposits during the channel-building stage of fan development. The lack of basal erosion, coupled with the presence of normally graded paraconglomerate (Cmn), suggests that the initial high-energy, high sediment-load backfilling phase of the alluvial flows were relatively laminar (Miall 1996). As in the debris flow deposits (DF) there was a switch from a laminar pseudo-plastic flow to a more turbulent Newtonian flow, demonstrated by normal grading of alluvial flow deposits, scouring of horizontally laminated sandstones (Sh), and normally graded clast-bearing sandstones (Sc). The clast-bearing deposits (Sc) suggest a continued waning flow but in sustained sub-aqueous conditions, where coarse bedload material was deposited as the flow waned (Miall 1996; Collinson et al. 2006). The structureless to poorly laminated nature of the rocks suggests that deposition occurred under high sediment-load (Bridge and Best 1988; Todd 1996).

Gravel barform deposits (GB)

Description: This association is *c.* 1–2 metres thick comprising cross-bedded orthoconglomerates (Ccc, 88 %) with eroded surfaces commonly pitted and occupied by lenses of horizontally laminated (Sh, 12 %) sandstones. Lithofacies Ccc, described above (AF), is a clast-supported, crudely reversely graded granule- to pebble-grade, cross-bedded orthoconglomerate. Here, it shows an alignment of clasts along the surfaces of planar cross-bed foresets. Lithofacies Sh, described above (PT), is a horizontally laminated sandstone. Overall, the association is reversely graded and the upper bounding surface of lithofacies Ccc is commonly cut by minor horizontally laminated lenses of Sh.

Interpretation: This association is interpreted as reflecting deposition in a gravel bar (GB) formed during the channel building stage of fan development. The pits on the otherwise conformable basal surface imply that small eddies were generated and these may have been the catalyst for bedform development (Gershenzon et al. 2015).Cross-bedded orthoconglomerates (Ccc) were deposited in sediment-laden Newtonian flows (Allen 1983; Miall 1996). Clast alignment along foreset surfaces suggests bedload was the dominant transport process, with clasts avalanching as grainflows down the lee slopes of the bedforms. Sustained flow resulted in migrating bars, with stacking indicating bedform trains, like those seen in the headwater regions of fluvial systems, proximal to the gravel-sand transition (Miall 1977, 1996).

Facies model for the Greywacke Conglomerate Formation

The analysis presented here describes the sub-aerial processes responsible for the deposition of the Greywacke Conglomerate exposed at Glenbuck. The sedimentary log (**Fig. 2**) indicates the presence of extremely coarse clasts and matrix throughout the entire succession. The nature of both non-Newtonian and Newtonian flows together with such coarse grain-sizes suggest alluvial fan deposition (**Fig. 4**) (Nemec and Steel 1984; Blair *et al.* 1999). The processes that formed the GRWC are similar to those of piedmont-zone deposition. Lithofacies associations such as those of the aggradational talus cone (AT) and progradational talus cone (PT) are typical of non-Newtonian dominated, sub-aerial, alluvial deposits developed around the margins of topographic highs (independent of whether these are of palaeotopographical or syn-tectonic in origin). These associations comprise 8.5 and 48.5 %, respectively, of the logged section (**Table 2**). At Glenbuck their widespread distribution reflects their proximal position , relative to any sediment source area and palaeotopographic high. These non-Newtonian, sub-aerial deposits are accompanied by debris flow deposits (DF) that had a higher water content relative to the sediment concentration (**Fig. 4**). Such deposits comprise 22 % of the logged section and represent conditions at the boundary between Newtonian and non-Newtonian deposition.

Deposits indicating Newtonian flow conditions are also present in the GRWC, reflecting deposition under high sediment-load. These deposits (AF) and gravel bars (GB) represent most of

Newtonian flow deposition within the succession, comprising 13.5 % and 7.5 %, respectively, of the logged succession (**Table 2**). Both associations indicate significant flow, in some cases sustained, within the GRWC at Glenbuck. The intermittent nature of alluvial flow and gravel bar deposition, throughout the succession, suggests that debris flow deposition commonly punctuated deposition and may indicate flash-floods. However, whilst the outcrop provides no direct evidence of confinement, the presence of gravel bars suggests that alluvial flow must, at some time, have been sustained and confined (Miall 1977; 1996). (**Fig. 4**).

The GRWC succession at Glenbuck shows a general coarsening upwards trend (**Fig. 5a**), despite individual lithofacies associations showing normal grading (**Fig. 2**). The base of the succession is characterised by a series of progressively thickening and coarsening debris flow deposits (DF) that grade normally up into alluvial flow deposits (AF). These are overlain in turn by a progradational talus cone deposit (PT), that is relatively fine-grained compared to progradational talus cone deposits (PT) further up the sequence (**Fig. 2 and 5a**). The succession demonstrates a transition to a period of what must have been more sustained flow, reflected in the 1.5 metre thick gravel bar deposit (GB). Above this the sequence becomes less ordered (**Fig. 2** and **5**) with alternations of coarsening progradational talus cone (PT) and alluvial flow (AF) deposits overlain by a debris flow deposit (DF, *c*. 0.6 m). The remainder of the outcrop is characterised by alternations of progradational talus cone deposits and aggradational talus cone deposits, progressively coarsening-upwards.

The basal series of debris flow deposits (DF) of the GRWC exhibit a thickening and coarsening-upwards, indicating progradation of sheet-like high sediment-load deposits (0.8–3.2 m, **Fig. 5**). The alluvial flow (AF) dominance (3.2–5.0 m, **Fig. 5**) in the succession that follows suggests that the environment of deposition had a higher water discharge rate, until a sustained (possibly channelised) alluvial flow (AF) could promote the deposition of a gravel barform (GB) (5.8–9.2 m). This sustained flow was punctuated by a single progradational talus cone deposit (5.0–5.8 m, **Fig. 5**) that is presumed to have travelled further than other examples of such flows, given its relatively lower grainsize. Cyclic deposition of progradational talus cone (PT) and alluvial flow (AF) (9.2–16.2 m, **Fig. 5**) suggest intermittent fluctuations in water discharge within the system, or the increased dominance of more non-Newtonian processes spatially across the alluvial fan. The final portion of the succession was dominated by sub-aerial mass flow (PT and AT), indicating that low water content mass flow became the dominant depositional process. Given that such deposits (PT and AT) typically dominate the proximal regions of alluvial fans, and alluvial flow deposits dominate the distal portions of alluvial fans, it is suggested that the system prograded through time. Progradation can be quantified by the maximum clast size, with general clast size increasing throughout the succession. The medial fan dominated by 15-18 cm clasts, and proximal fan showing 20-29 cm clasts.

From the sub-division of the section and the progradational nature of the succession, two distinct depositional intervals may be proposed. The lower portion of the section (0.8–17.4 m) is dominated by debris-flow (DF) and alluvial-flow (AF) deposits, comprising 28 % and 42 %, respectively (**Fig. 5**). The remaining 30 % of the lower section reflects minor incursions of the more distal progradational talus cone (PT, 20 %) and gravel bar (GB, 10%) deposits. The upper portion of the section (17.4–27 m, **Fig. 5**) is dominated by aggradational and progradational talus cone deposits (AT and PT), representing the most proximal region of piedmont-zone sedimentation. The nature of the different units can be interpreted as reflecting spatial zones within an alluvial fan. The lower alluvial unit (0.8–-17.4 m, **Fig. 5**) indicates pseudo-plastic debris flows and alluvial run-off, suggesting a more medial zone deposition. The upper section (17.4–27 m, **Fig. 5**), dominated by talus cone deposits, represents the proximal alluvial fan and talus cone region. A medial, rather than distal, setting interpretation is preferred in the lower half of the section due to the general abundance of distal progradational talus cone and debris flow deposits, along with the thickness and sustained nature of alluvial flows.

The extent of alluvial fan deposition across the northern Southern Upland Margin

The deposits of the GRWC described here are not confined to the Glenbuck area. There are multiple exposures of the formation throughout southern parts of the Lanark Basin. Many have been reported previously, but the processes-based approach in this study has not been applied. Given the biostratigraphical age (Llandovery) of the Silurian rocks from inliers in the south-western MVS (Cocks and Toghill 1973), Phillips (2007) suggested the GRWC represents recycling of Silurian conglomerates from inlier highs within the Lanark Basin such deposits are still exposed surrounding several inliers (Phillips *et al*. 1998; Phillips 2007). Here we compare examples of piedmont-zone alluvial fan deposits from the eastern portion of the Lanark Basin with others in the Southern Uplands, south-east of the Southern Upland Fault (**Fig. 1** (**a**)).

The sediments of the GRWC at Glenbuck are moderately- to well-rounded and contain a polymictic clast assemblage of chert, granodiorite, monocrystalline quartz and andesitic volcanic fragments. Rounding of these clasts is attributed to sediment recycling from previously mobilised Silurian deposits, adding textural maturity to clasts in a relatively immature environment. This assumption is confirmed by the provenance analysis of Phillips *et al*. (1998) and Phillips (2007) that suggests that the GRWC at Glenbuck was probably sourced from the Silurian Parishholm Conglomerate of the Hagshaw Hills inlier (Phillips 2007). Parallels with this interpretation may be drawn from the relative abundance of similar clasts comprising the GRWC at Glenbuck.

In the Carlops region, on the south-eastern flanks of the Pentland Hills (**Fig. 6** (**b**)), the GRWC preserves lithofacies similar to those at Glenbuck, comprising dominantly reverse-graded paraconglomerates (Cmr) with minor scour surfaces overlain by trough cross-bedded sandstones (St) (**Table 1**). These also represent progradational talus cone deposits (**Table 2**), with minor fan-top modification channels eroded and filled by trough cross-bedded sandstones (**Fig. 6** (**e**)). The Carlops succession also preserves normally graded orthoconglomerate deposits (Ccn) (**Table** 1) similar to those in the debris flow deposits (DF) of Glenbuck (**Table 2**). The clasts are again well-rounded, suggesting that they are recycled. However, while the clasts are as texturally mature as those at Glenbuck, they include no granite, little chert, and far more metamorphic rock. Thus, while Silurian lithologies remain the suggested source of the sediment, this is likely to have been derived from the North Esk inlier, and not the Hagshaw Hills (Phillips *et al*. 1998; Philips 2007). The Llandovery sandstone- and conglomerate-dominated Cock Rig Formation (Cocks and Toghill 1973; Philips 2007) is thought to be the principal source of this detritus, providing further evidence of alluvial fans shed from highs within the Lanark Basin.

South-east of the Southern Upland Fault, on the Southern Uplands High, exposures of the Lower Devonian Great Conglomerate Formation at Chapel-on-Leader and Lammermuir Deans show a similar range of lithofacies to those at Glenbuck (**Fig. 7**). However, in the Great Conglomerate Formation, progradational talus cone (PT) and debris flow (DF) deposits are dominant and both the Chapel-on-Leader (**Fig. 7** (**b**) and (**c**)) and Lammermuir Deans sections contain significantly greater proportions of angular and texturally immature clasts than are seen in either the GRWC at Glenbuck or Carlops, north of the Southern Upland Fault.

Discussion

The Glenbuck road-cut section in the GRCW includes eleven lithofacies grouped in five associations. The process-based interpretations support the general interpretation of Trewin and Thirlwall (2002) and indicate that the Glenbuck sequence was deposited in alluvial fans. Two depositional intervals are recognised within the section, the lower 17.40 m (**Fig. 2** and **5**) representing alluvially dominated medial fan deposition and the upper 17.40 to 27 m representing sub-aerial mass flow sediments deposited in proximal fan environments. This change of sub-environment suggests a progradational alluvial fan environment.

The abrupt change from medial to proximal fan deposits is highlighted by the erosive contact of reversely graded paraconglomerate and trough cross-bedded and planar laminated sandstones (17.40 m, **Fig. 2** and **5**). The nature of this change in depositional style is explained *either* as reflecting avulsion of fan-surface channels *or* by lobe switching within the fan (Field 2001; Reitz and Jerolmack 2012). Both autogenic changes can produce a relative progradation (Salcher et al. 2010; Hajek et al. 2012; Miall 2014). However, the somewhat chaotic interbedding of deposits of debris flows and and those of alluvial processes, leading to the sub-environment boundary at 17.40 m of the sequence (**Fig.2** and **5**), also indicated by the gradually increasing regularity and thickness of decimetre to metre scale distal talus cone incursions (10.5-17.4 m, **Fig. 2** and **5**), may reflect progradation of the alluvial fan. This raises the argument that the upper part of the medial fan depositional interval is transitional between medial and proximal fan environments, with an upper bounding surface that is erosional., This suggests in turn that the change from medial to proximal fan deposition is complex. Given the predominately debris flow nature of overlying deposits (Nemec and Steel 1984; Coussot and Meunier 1996; Todd 1996; Goa et al. 2019), a major scour should not have occurred, but it is evident nevertheless. Therefore, two fan-scale processes must be in operation contemporaneously. The first is a general transitional progradation from alluvial Newtonian and pseudo-plastic deposition into more proximal talus cone dominated deposition across the medial to proximal fan boundary. The second is turbulent scour and abandonment of local environments driven by turbulent erosional flow (de Hass et al. 2014). It is therefore proposed that there are two scales of autogenic processes represented within the GRWC strata. The first, fan progradation was induced by the progressive denudation of Silurian inliers. The second, autogenic scour and abandonment by turbulent Newtonian flows, created topographic lows on medial fan deposits. These small-scale lows were filled by non-Newtonian processes on the proximal fan, producing the complex medial to proximal fan transition surface. This study assumes an autogenic control upon progradation of the alluvial fan system due to hinterland wasting, primarily as a result of the scale of observation. Climate change cannot be proven or disproven as a control on progradation. However, decreased rainfall altered the sediment water ratio and thereby the resulting depositional products.

This study used one-dimensional logs in a complex system, and interpretations are therefore based upon the temporal translation of the facies into space and it is not possible to comment on the radial nature of the alluvial fan environment. The sediments documented are typical of proximal piedmont-zone facies, specifically of alluvial fan deposits. A fan morphology and accompanying radial nature is implied for these GRWC deposits, simply due to their common occurrence across deep time (Allen 1981; DeCelles et al. 1991; Chen et al. 2017) and in the modern environment (Blair 1999; Field 2001; Harvey 2011; Arzani and Jones 2016; Goa et al. 2019) as shown in **Figure 8**.

It is common for piedmont-zone alluvial fan facies to dominate the hanging walls or relatively downthrown sides of major faults within basins (Suresh et al. 2007). This study suggests that alluvial fan deposition within the Lanark Basin was more widespread, incorporating sediment shed from intrabasinal highs (Phillips et al. 1998; Phillips 2007). This view is supported by the clast compositions at Glenbuck and Carlops, reported here and by Philips (2007). Such varied topography produced an extremely complex early Devonian stratigraphy and palaeogeography of proximal terrestrial sediments, that may be expressed in the morphology of a single fan or across an entire basin. While progradational environments may be inferred from such successions, they do not indicate that inliers were active during deposition, especially given that there is no change in clast assemblages moving up section. Progradational environmental signatures (as observed at Glenbuck) indicate that the rate of sediment supply outpaced the creation of accommodation space (Catuneanu 2020). Based upon these new data and interpretations, it is suggested that detailed palaeocurrent and process mapping of deposits should be undertaken for the remaining GRWC surrounding Silurian inliers. Such a study may have significant implications for antecedent topography and its controls on initial basin fill.

Conclusion

The Greywacke Conglomerate Formation comprises alluvial facies assemblages represented by aggradational talus cone, progradational talus cone, debris flow, alluvial flow and gravel bar deposits. These formed in an alluvial fan environment and, in the Glenbuck area, show a general progradation from medial to proximal fan deposition. The transition is marked by erosional scour from turbulent flow with proximal fan deposits in filling the depressions formed. Such observations indicate that, despite an overall progradational regime, autogenic processes such as turbulent scour and avulsion continued to play a role in alluvial fan stratigraphy. They were common around Silurian inliers within the Lanark Basin, in the Midland Valley of Scotland and in the Early Devonian complex topography was a key control on terrestrial sedimentation.

Acknowledgements

Thanks are given to Amy Regis and Charlotte Priddy for help in the proofing of this manuscript. Tom Dodd is thanked for his thoughts with regards to the interpretations made herein. Thanks are given to reviewers Stuart Archer and Peter Haughton for their comments and insight, they have greatly improved the manuscript. Editor Colin Braithwaite is also thanked for the extensive comments he has made in the improvement of this manuscript and help during the review process. Graham Leslie and Michael Browne publish with the permission of the Director, British Geological Survey.

References

Allen, J.R.L. 1983. Studies in fluviatile sedimentation: bars, bar complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders. *Sedimentary Geology*, **33**, 237–293, https://doi.org/10.1016/0037-0738(83)90076-3

Allen, P.A., 1981. Sediments and processes on a small streamflow dominated, Devonian alluvial fan, Shetland Islands. *Sedimentary Geology*, **29**(1), 31-66, https://doi.org/10.1016/0037-0738(81)90056-7

Arzani, N. and Jones, S.J., 2018. Upstream controls on evolution of dryland alluvial megafans: Quaternary examples from the Kohrud Mountain Range, central Iran. *Geological Society, London, Special Publications*, **440(**1), 245-264, https://doi.org/10.1144/SP440.2

Blair, T.C., 1999. Cause of dominance by sheetflood vs. debris-flow processes on two adjoining alluvial fans, Death Valley, California. Sedimentology, 46(6), 1015-1028, https://doi.org/10.1046/j.1365-3091.1999.00261.x

Bluck, B.J. 1995. W.Q. Kennedy, the Great Glen Fault and strike-slip motion. *Geological Society, London, Memoirs*, **16**, 57–65, https://doi.org/10.1144/GSL.MEM.1995.016.01.08

Bluck, B.J. 2000. Old Red Sandstone basins and alluvial systems of Midland Scotland. Geological Society, London, Special Publications, **180**, 417–437, https://doi.org/10.1144/GSL.SP.2000.180.01.22

Bridge, J.S. & Best, J.L. 1988. Flow, sediment transport and bedform dynamics over the transition from dunes to upper stage plane beds – implications for the formation of planar laminae. *Sedimentology*, **35**, 753–763, https://doi.org/10.1111/j.1365-3091.1988.tb01249.x

British Geological Survey, 1995. Hamilton. Scotland Sheet 23W. Solid. 1:50 000. (Keyworth, Nottingham: British Geological Survey).

British Geological Survey, 1999. New Cumnock. Scotland Sheet 15W. Solid. 1:50 000. (Keyworth, Nottingham: British Geological Survey).

Browne, M.A.E. and Monro, S.K., 1989. Evolution of the coal basins of Central Scotland. *Congrès international de stratigraphie et de géologie du Carbonifère*, 1-19.

Browne, M.A.E., Smith, R.A., & Aitken, A.M. 2002. Stratigraphical framework for the Devonian (ORS) rocks of Scotland south of a line from Fort William to Aberdeen. *British Geological Survey Research Report*, RR/01/04.

Catuneanu, O., 2019. Model-independent sequence stratigraphy. *Earth-science reviews*, **188**, 312-388, https://doi.org/10.1016/j.earscirev.2018.09.017

Chen, L., Steel, R.J., Guo, F., Olariu, C. and Gong, C., 2017. Alluvial fan facies of the Yongchong Basin: Implications for tectonic and paleoclimatic changes during Late Cretaceous in SE China. *Journal of Asian Earth Sciences*, **134**, 37-54, https://doi.org/10.1016/j.jseaes.2016.10.010

Collinson, J.D., Mountney, N. P. and Thompson, D. B. 2006. *Sedimentary Structures*. Third edition, Terra Publishing, Hertfordshire.

Coussot, P. and Meunier, M., 1996. Recognition, classification and mechanical description of debris flows. *Earth-Science Reviews*, **40**(3-4), 209-227, https://doi.org/10.1016/0012-8252(95)00065-8

de Haas, T., Ventra, D., Carbonneau, P.E. and Kleinhans, M.G., 2014. Debris-flow dominance of alluvial fans masked by runoff reworking and weathering. *Geomorphology*, **217**, 165-181, https://doi.org/10.1016/j.geomorph.2014.04.028

Decelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Pivnik, D.A., Pequera, N. and Srivastava, P., 1991. Controls on synorogenic alluvial-fan architecture, Beartooth Conglomerate (Palaeocene), Wyoming and Montana. *Sedimentology*, **38**(4), 567-590, https://doi.org/10.1111/j.1365-3091.1991.tb01009.x

Dempster, T.J. 1985. Uplift patterns and orogenic evolution in the Scottish Dalradian. *Journal of the Geological Society, London*, **142**, 111–128, https://doi.org/10.1144/gsjgs.142.1.0111

Domeier, M. and Torsvik, T.H. 2014. Plate tectonics in the late Palaeozoic. *Geoscience Frontiers*, **5**, 303–350, https://doi.org/10.1016/j.gsf.2014.01.002

Ellen, R., Browne, M.A.E., Mitten, A.J., Clarke, S.M., Leslie, A.G. and Callaghan, E., 2019. Sedimentology, architecture and depositional setting of the fluvial Spireslack Sandstone of the Midland Valley, Scotland: insights from the Spireslack surface coal mine. *Geological Society, London, Special Publications*, *488*(1), pp.181-204.

Field, J., 2001. Channel avulsion on alluvial fans in southern Arizona. *Geomorphology*, **37**(1-2), 93-104, https://doi.org/10.1016/S0169-555X(00)00064-7

Floyd, J.D., 1994. The derivation and definition of the 'Southern Upland Fault': a review of the Midland Valley–Southern Uplands terrane boundary. *Scottish Journal of Geology*, **30***,* (1), 51-62, https://doi.org/10.1144/sjg30010051

Gao, C., Ji, Y., Wu, C., Jin, J., Ren, Y., Yang, Z., Liu, D., Huan, Z., Duan, X. and Zhou, Y., 2020. Facies and depositional model of alluvial fan dominated by episodic flood events in arid conditions: An example from the Quaternary Poplar Fan, north-western China. *Sedimentology*, **67**(4), 1750-1796, https://doi.org/10.1111/sed.12684

Gershenzon, N.I., Soltanian, M., Ritzi, R.W. and Dominic, D.F., 2015. Understanding the impact of open-framework conglomerates on water–oil displacements: the Victor interval of the Ivishak Reservoir, Prudhoe Bay Field, Alaska. *Petroleum Geoscience*, **21**(1), 43-54, https://doi.org/10.1144/petgeo2014-017

Gibling, M.R. 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *Journal of Sedimentary Research*, **76**, 731–770, https://doi.org/10.2110/jsr.2006.060

Hajek, E.A., Heller, P.L. and Schur, E.L., 2012. Field test of autogenic control on alluvial stratigraphy (Ferris Formation, Upper Cretaceous–Paleogene, Wyoming). *GSA Bulletin*, **124**(11-12), 1898-1912, https://doi.org/10.1130/B30526.1

Harvey, A., 2011. Dryland alluvial fans. *Arid zone geomorphology: Process, form and change in drylands*, 333-371.

Haughton, P., Davis, C., McCaffrey, W. and Barker, S., 2009. Hybrid sediment gravity flow deposits–classification, origin and significance. Marine and Petroleum Geology, 26(10), 1900-1918, https://doi.org/10.1016/j.marpetgeo.2009.02.012

Haughton, P.D.W., 1989. Structure of some Lower Old Red Sandstone conglomerates, Kincardineshire, Scotland: deposition from late-orogenic antecedent streams? *Journal of the Geological Society, London*, **146**, 509–525, https://doi.org/10.1144/gsjgs.146.3.0509

Leeder, M.R. 1999, *Sedimentology and Sedimentary Basins: from Turbulence to Tectonics*. Blackwell Science, Oxford.

McKellar Z, Hartley AJ. 2020. Caledonian foreland basin sedimentation: A new depositional model for the Upper Silurian-Lower Devonian Lower Old Red Sandstone of the Midland Valley Basin, Scotland. *Basin Research,* 1–25, https://doi.org/10.1111/bre.12494

McKellar, Z., Hartley, A. J., Morton, A. C., & Frei, D. (2020). A multidisciplinary approach to sediment provenance analysis of the late Silurian-Devonian Lower Old Red Sandstone succession, northern Midland Valley Basin, Scotland. *Journal of the Geological Society, London*, **177**, 297–314, https://doi.org/10.1144/jgs20 19-063

Miall, A.D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1–62, https://doi.org/10.1016/0012-8252(77)90055-1

Miall, A.D. 1996. *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology*. Springer, Berlin.

Mykura, W. 1991. Old Red Sandstone. *In*: Craig, G.Y. (ed.), Geology of Scotland (3rd edition). *The Geological Society, London*, 297–346.

Nemec, W., Steel, R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravity mass-flow deposits. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, **10**, 1–31.

Oliver, G. J. H., Wilde, S. A., & Wan, Y. (2008). Geochronology and geodynamics of Scottish granitoids from the late Neoproterozoic break-up of Rodinia to Palaeozoic collision. *Journal of the Geological Society*, **165**, 661–674. https://doi.org/10.1144/0016-76492 007-105

Paterson, I B, McAdam, A D, and MacPherson, K A T. 1998. Geology of the Hamilton district. *Memoir of the British Geological Survey*, Sheet 23W (Scotland).

Phillips, E. R. (2007). Petrology and provenance of the Siluro-Devonian (Old Red Sandstone facies) sedimentary rocks of the Midland Valley, Scotland. British Geological Survey Internal Report, IR/07/040.

Phillips, E.R., Barron, H.F., Smith, R.A. AND Arkley, S. 2004. Composition and provenance of the Silurian to Devonian sandstone sequences of the southern Midland Valley. *Scottish Journal of Geology*, **40**, 23–42, https://doi.org/10.1144/sjg40010023

Phillips, E.R., Smith, R.A. & Carroll, S. 1998. Strike-slip, terrane accretion and the pre-Carboniferous evolution of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **89**, 209–224, https://doi.org/10.1017/S0263593300006957

Read, W.A., Browne, M.A.E., Stephenson, D. & Upton, B.J.G. 2002. Carboniferous. *In:* Trewin, N.H. (ed.) The Geology of Scotland. 4th Edition, Geological Society, London, 251-300.

Reitz, M.D. and Jerolmack, D.J., 2012. Experimental alluvial fan evolution: Channel dynamics, slope controls, and shoreline growth. *Journal of Geophysical Research: Earth Surface*, **117**(F2), https://doi.org/10.1029/2011JF002261

Salcher, B.C., Faber, R. and Wagreich, M., 2010. Climate as main factor controlling the sequence development of two Pleistocene alluvial fans in the Vienna Basin (eastern Austria)—A numerical modelling approach. *Geomorphology*, **115**(3-4), 215-227, https://doi.org/10.1016/j.geomorph.2009.06.030

Smith, R.A., Jones, N.S., Monaghan, A.A. and Arkley, S. 2006. Fluvial and aeolian deposition in the Siluro-Devonian Swanshaw Sandstone Formation, SW Scotland. *Scottish Journal of Geology*, **42**, 161–177, https://doi.org/10.1144/sjg42020161

Suresh, N., Bagati, T.N., Kumar, R. and Thakur, V.C., 2007. Evolution of Quaternary alluvial fans and terraces in the intramontane Pinjaur Dun, Sub-Himalaya, NW India: interaction between tectonics and climate change. *Sedimentology*, **54**(4), 809-833, https://doi.org/10.1111/j.1365-3091.2007.00861.x

Syba, E. 1989. The sedimentation and provenance of the Lower Old Red Sandstone Greywacke Conglomerate, southern Midland Valley, Scotland (Doctoral dissertation, University of Glasgow).

Thirlwall, M.F. 1981. Implications for Caledonian plate tectonic models of chemical data from volcanic rocks of the British Old Red Sandstone. *Journal of the Geological Society*, *London*, **138**, 123–138, https://doi.org/10.1144/gsjgs.138.2.0123

Thirlwall, M.F. 1989. Short Paper: Movement on proposed terrane boundaries in northern Britain: constraints from Ordovician–Devonian igneous rocks. *Journal of the Geological Society, London*, **146**, 373–376, https://doi.org/10.1144/gsjgs.146.3.0373

Todd, S.P. 1996. Process deduction from fluvial sedimentary structures. In: Carling, P.A. & Dawson, M.R. (eds) advances in Fluvial Dynamics and Stratigraphy. Wiley, Chichester, 299–350.

Trewin, N.H. AND Thirlwall, M.F. 2002. Old Red Sandstone. *In*: Trewin, N.H. (ed.), *The Geology of Scotland,* 4th Edition. The Geological Society, London, 213–249.

Table Captions

Table 1. Facies table for the sediments that comprise the Greywacke Conglomerate Formation.

Table 2. Facies associations of the Greywacke Conglomerate Formation with an idealised log for each association. Note, see **Fig. 2** for idealised log key and that colour bars indicate facies associations, as shown in **Fig. 4**.

Figure Captions

Fig. 1. (**a**) Map of the Midland Valley of Scotland (MVS), showing the major town and cities, study location and major fault structures within the basin (Modified from Ellen *et al.* 2019). D.F. – Dechmont Fault, P.F. – Pentland Fault, W.O.F. – West Ochil Fault, E.O.F. – East Ochil Fault. (**b**) Google Earth Image of the western MVS, highlighting the location of Glenbuck and the study map in **Fig. 1.** (**d**). (**c**) Simplified regional generalised vertical section from New Cumnock area (modified from Phillips et al. 2004). Note, unconformities are shown in red and labelled 'UC'. (**d**) Geological map showing the position of the new road cut section and the log path along it. The position of the photo in (e) is shown. The map is modified from the published geological 1:50 000 scale maps for Hamilton (Sheet 23W, BGS, 1995) and New Cumnock (Sheet 15W, BGS 1999). Contains British Geological Survey materials © UKRI [1995, 1999] and Ordnance Survey data © Crown copyright and database rights 1995, 1999. Ordnance Survey Licence No. 100021290. (**e**) Photograph of the Quarry Arenite Formation and the Greywacke Conglomerate Formation irregular unconformity, at the base of the logged section.

Fig. 2. Sedimentary log through the Glenbuck road-cut section of the Greywacke Conglomerate Formation and relative palaeocurrent direction of cross-bedding and imbricated

clasts. Note, the first 80 cm of the log comprise deposits of the Quarry Arenite Formation and are not discussed herein. Note, the colour bar representing facies associations is coloured according to **Table 2**.

Fig. 3. Photoplate of the Greywacke Conglomerate Formation. (**a**) Long-axis imbrication of cobble clasts in normally graded paraconglomerate. (**b**) Erosive bedding contact (marked with white arrows) between disorganised paraconglomerate and orthoconglomerate. (**c**) Massive coarse-grained litharenite lens within a disorganised paraconglomerate. (**d**) Gravel lenses in poorly planar horizontally laminated coarse-grained to very coarse-grained litharenite. (**e**) Normally graded pebble clast litharenite. (**f**) Poorly preserved bedding contact (marked with white arrows) between two poorly cross-bedded orthoconglomerates. The cross-bedding foresets are slightly oblique to the outcrop section. The beds have a difference of approximately 50° in palaeocurrent direction. (**g**) Trough cross-bedded litharenite grading-upwards into a planar laminated litharenite. (**h**) Bedding contact (marked with white arrows) between trough cross-bedded litharenite and well developed planar horizontally laminated litharenite. Note, pencil for scale shown in images is 15 cm long.

Fig. 4. A schematic representation of the GRWC environment of deposition. The image shows an alluvial fan deposit inset map, with a red square indicating the position of the larger image. The main image consists of the five facies associations, flowing over the fan surface, identified in the GRWC, along with their representative sedimentary logs(**Table 2**).

Fig. 5. Evidence for the change in depositional environment from medial to proximal alluvial fan deposition at 17.40 m of the logged section. (**a**) Simplified sedimentary log through the GRWC succession at Glenbuck. (**b**) The process character throughout the logged section. Note, N – Newtonian; PP – Pseudo-plastic; NN – Non-Newtonian. (**c**) Facies association log, showing the position and vertical juxtaposition of one facies association relative to another. Note, abbreviations of facies associations (x-axis) are the same as those in **Table 2**; A – Avalanche, GD – Granular debris flow; HD – Hyperconcentrated debris flow; AF – Alluvial flow; GB – Gravel barform. (**d**) **.** A schematic

representation of the upper part of the GRWC logged section’s sub-environment of deposition, a proximal alluvial fan. (**e**) A schematic representation of the lower part of the GRWC logged section’s sub-environment of deposition, a medial alluvial fan. Note, for a key, see **Fig. 3** and **4**.

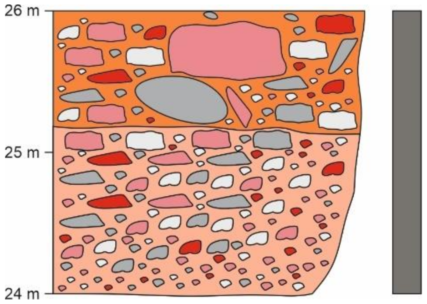
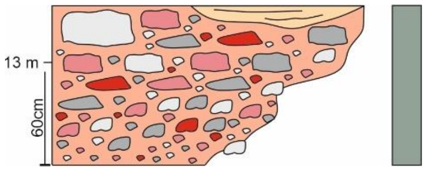
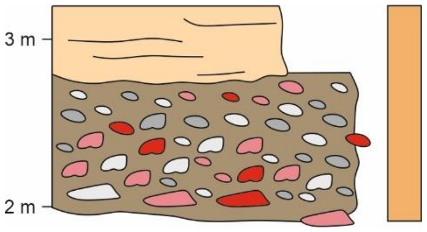
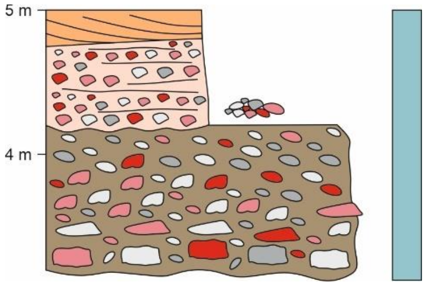
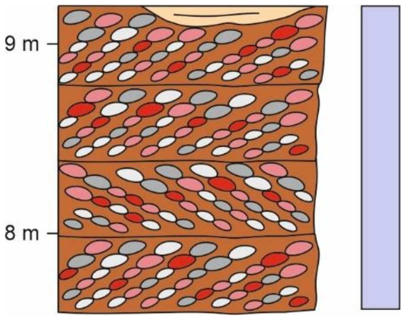
Fig. 6. The spatial extent of alluvial fan depositional processes beyond the Glenbuck area. (**a**) Map showing the southern Lanark Basin of the MVS and the northern margin of the Southern Uplands, highlighting study sites (blue) and their relationship to Silurian inliers (Grey) and faults (red). (**b**) Outcrop of the Carlops Quarry GRWC, with the log position of (**e**) highlighted and inset image of (**c**) (MAEB Photo). (**c**) Facies scale image of quarry face shown in (**b**), the position of the image is indicated in (**e**) (MAEB Photo). (**d**) Facies-scale interpretation of (**c**). (**e**) Schematic log through the log path displayed in (**b**), coloured by facies. A facies association log is also present to the right of the facies-scale schematic log. (**f**) Key for the figure.

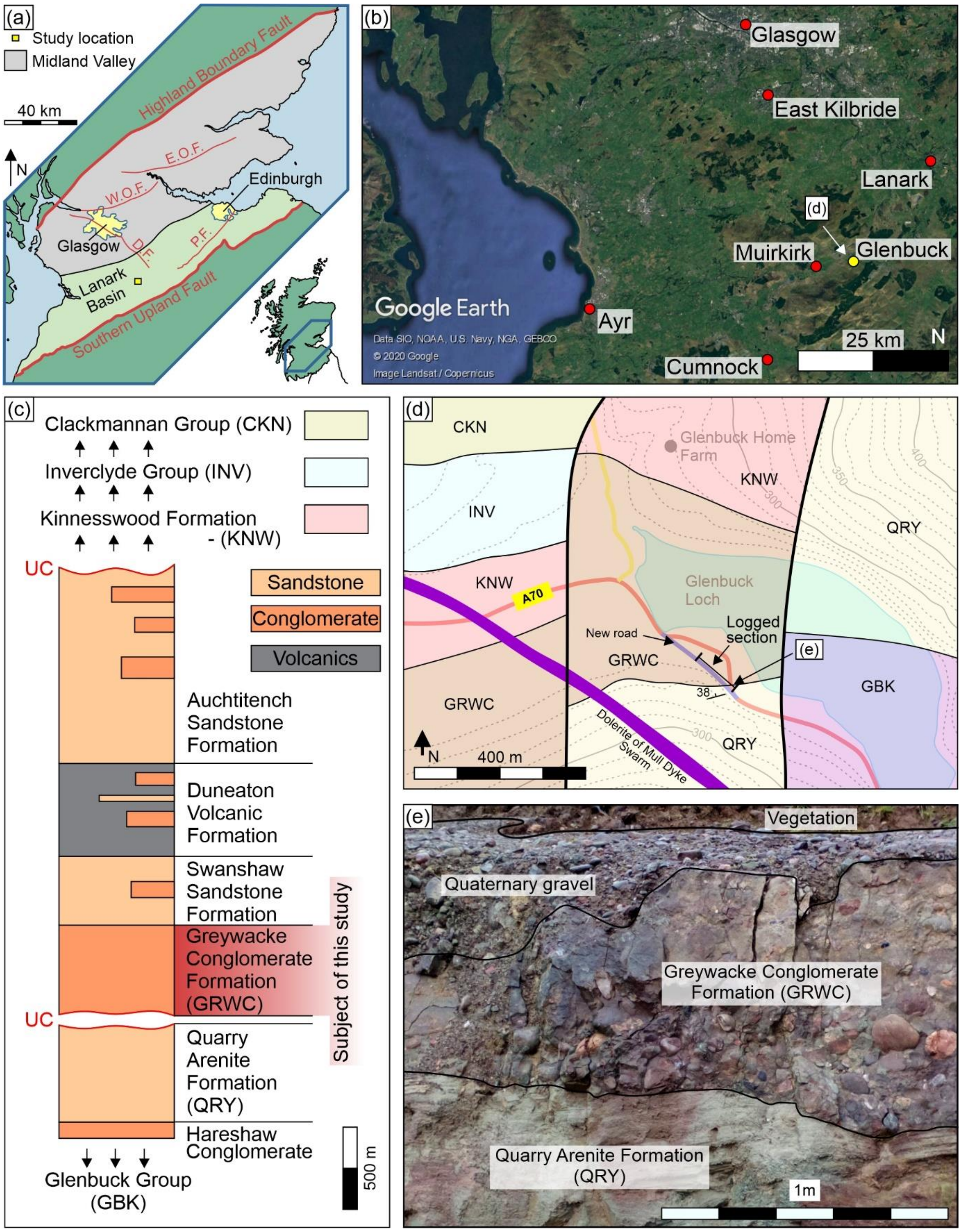
Fig. 7 Alluvial fan processes preserved on the Southern Uplands High. (**a**) Great Conglomerate Formation at Lammermuir Deans. Photograph P616220, British Geological Survey © UKRI 2006. (**b**) Outcrop of the Chapel on Leader Great Conglomerate Formation, with the log position of (**f**) (MAEB Photo). (**c**) Facies association scale interpretation of (**b**), the position of the image is indicated in (**f**) (MAEB Photo). (**d**) Facies-scale image from the Chapel on Leader outcrop. (**e**) Facies association scale interpretation of (**d**). (**f**) Schematic log through the log path displayed in (**b**) and (**c**), coloured by facies. A facies association log is also present to the right of the facies-scale schematic log. (**g**) Key for the figure.

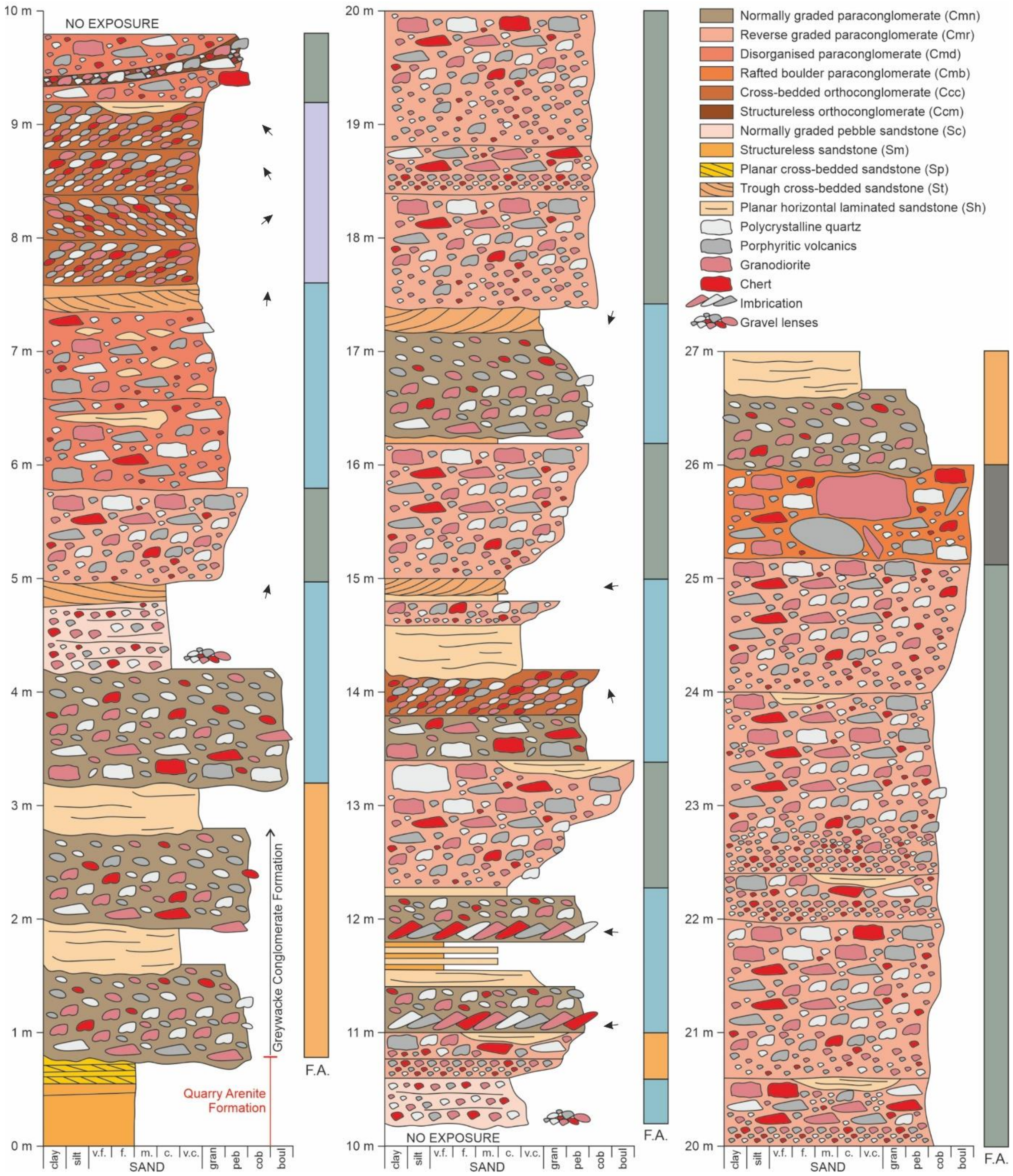
Fig 8 Modern day alluvial fans deposited in arid depositional settings. Whilst these may not be a one-to-one comparison to those of the GRWC, the modern fans show similar architecture. (**a**) Basin and Range Province, Nevada, USA showing position of (**b**). (**b**) Basin bounding high shown in (**a**) and outwash alluvial fans draining to the SW. (**c**) Alluvial fan shown in the top right of (**b**). (**d**) Interpretation of (**a**), note, key at the bottom of the image. (**e**) Interpretation of (**b**), note, key at the bottom of the image. (**f**) Interpretation of (**c**), note, key at the bottom of the image. (**g**) Death Valley, California, USA showing position of (**h**). (**h**) Basin bounding high shown in (**g**) and outwash alluvial fans draining to the SW. (**i**) Alluvial fan shown in the centre of (**h**). (**j**) Interpretation of (**g**), note, key at the bottom of the image. (**k**) Interpretation of (**h**), note, key at the bottom of the image. (**l**) Interpretation of (**i**), note, key at the bottom of the image.

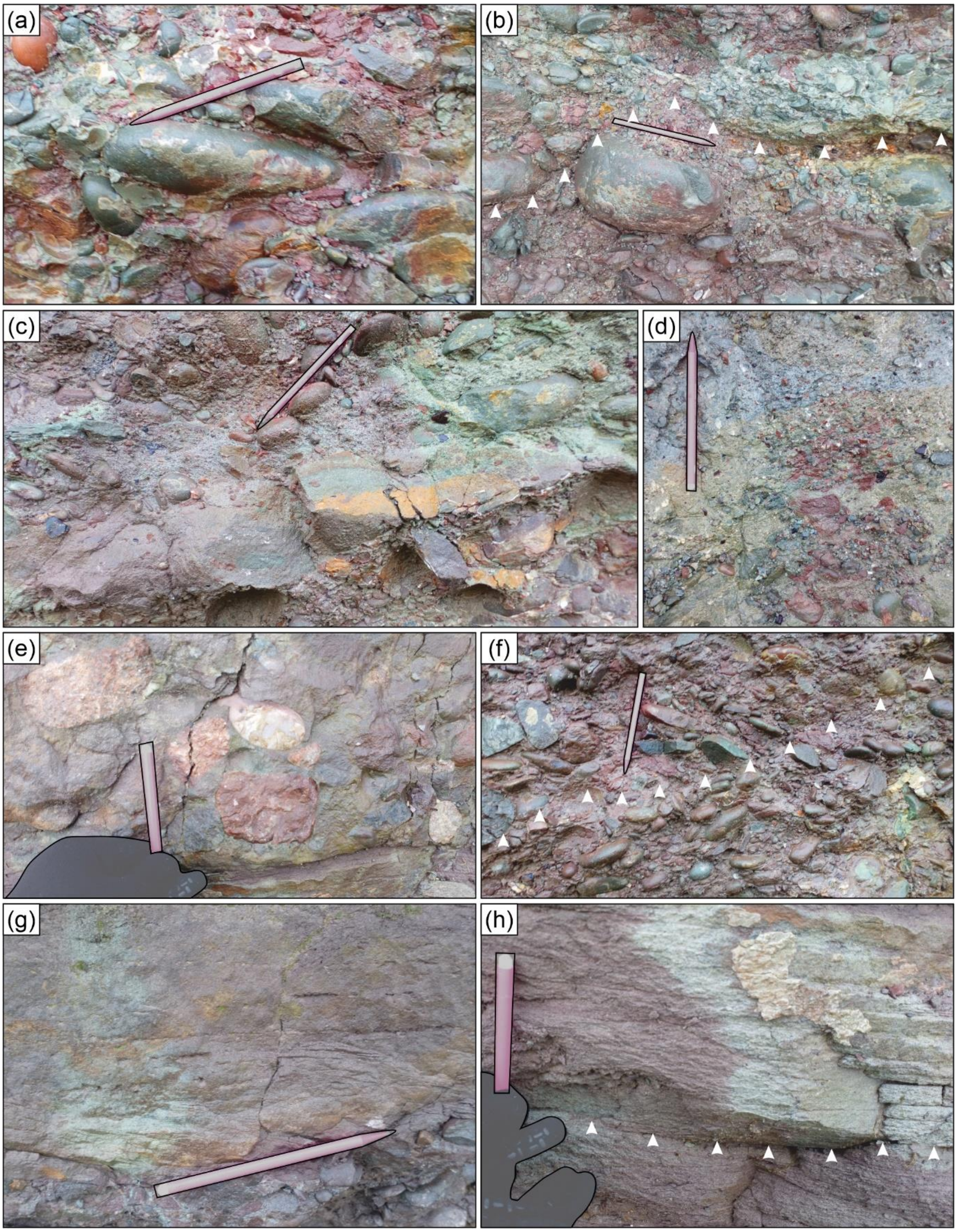
Facies	**Description**	**Interpretation**
Normally graded paraconglomerate (Cmn)	Matrix-supported conglomerate, crudely normally graded, occasionally rapid towards the top of the bed. Matrix is poorly sorted, medium- to very coarse-sandstone. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, sub-rounded to rounded, moderately spherical, typically pebble- to cobble-grade. Imbrication along clast long axis is typical.	Non-Newtonian, high sediment-load debris flow deposit. Crude and rapid normal grading suggests minor fluid content and rapid waning of flow (Nemec and Steel 1984; Blair *et al.* 1999) (**Fig. 3.** (**e**)).
Reverse-graded paraconglomerate (Cmr)	Matrix-supported conglomerate, reversely graded. Matrix is poorly sorted, medium- to very coarse-grained sandstone. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, sub-rounded to rounded, moderately spherical, typically pebble to cobble-grade.	Non-Newtonian, high sediment-load debris flow deposit. Reverse grading suggests in-flow sorting of sediment produced by frictional drag on the basal surface of a dry flow (Nemec and Steel 1984; Blair *et al.* 1999).
Rafted boulder paraconglomerate (Cmb)	Matrix-supported conglomerate, reversely graded. Matrix is poorly sorted, medium- to very coarse-grained sandstone. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, sub-rounded to rounded, moderately spherical, typically pebble- to boulder-grade, out-sized clasts >25 cm.	Non-Newtonian, high-energy, high sediment-load debris flow deposit. Reverse grading and rafting of out-sized clasts suggests in-flow sorting of sediment produced by frictional drag on the basal surface of a dry flow (Nemec and Steel 1984; Blair *et al.* 1999).
Disorganised paraconglomerate (Cmd)	Matrix-supported conglomerate with no organisation to clast and matrix. Matrix is extremely poorly sorted, fine- to very coarse-grained sandstone. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, sub-rounded, moderate to low sphericity, granule- to cobble-grade.	Rock avalanche deposit, short transport distance and rapid cessation of flow leading to a lack of grading (Nemec and Steel 1984; Blair *et al.* 1999) (**Fig. 3.** (**b**)).
Cross-bedded orthoconglomerate (Ccc)	Clast-supported conglomerate, with very crude reverse grading of forests. Matrix is moderately sorted, fine- to very coarse-grained sandstone. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, sub-rounded to rounded, moderately spherical, typically granule- to pebble-grade.	High sediment-load pseudo-plastic flow deposits. Cross-bedding is produced by moderate turbulence within the flow and avalanche deposits on the lee-slope of gravel bedforms, crude reverse grading in caused by frictional drag on the lee slope of bedforms (Nemec and Steel 1984; Miall 1977, 1996) (**Fig. 3.** (**f**)).
Structureless orthoconglomerate (Ccm)	Clast-supported conglomerate with no organisation to clast and matrix. Matrix is poorly preserved. Clasts of porphyritic volcanic material, granodiorite with poly- and mono-crystalline quartzite, rounded, moderate to low sphericity, granule- to pebble-grade.	Non-Newtonian high sediment-load debris flow deposit. Poor preservation of matrix is interpreted to be due to secondary erosion and winnowing of the matrix (Collinson *et al.* 2006) (**Fig. 3.** (**b**)).
Normally graded pebble clast sandstone (Sc)	Medium- to coarse-grained litharenite, poorly sorted, sub-angular, moderately spherical, comprised mainly of lithic fragments and quartz, normally graded. Cobbles to granular clasts of porphyritic volcanic material, granodiorite with poly- and	Bedload dominated flow deposits. Pebble to granule-grade bedload shows normal grading formed through waning flow deposition (Miall 1996; Collinson *et al.* 2006) (**Fig. 3.** (**d**)).

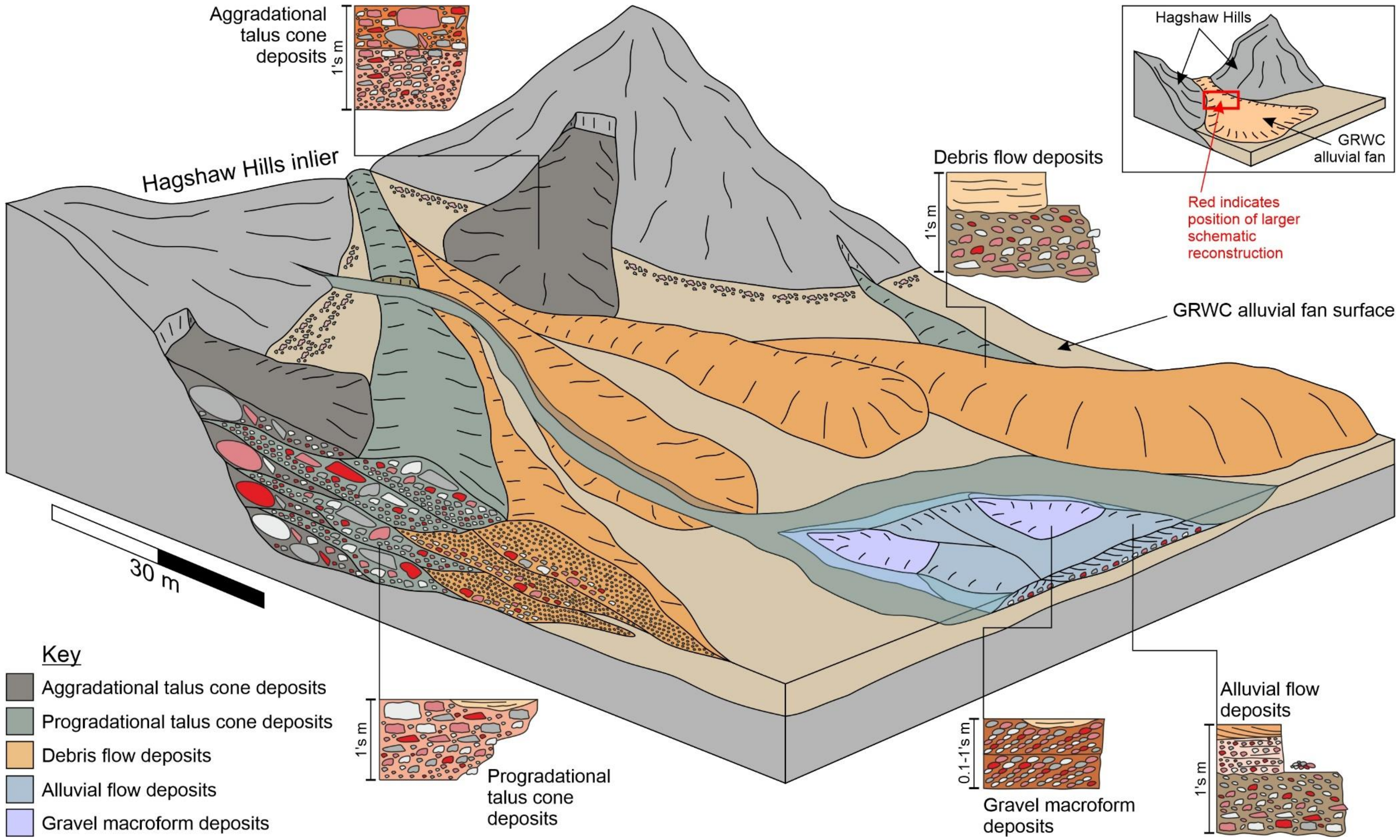
	mono-crystalline quartz also grade normally. Gravel lenses are common.	
Structureless sandstone (Sm)	Very fine- to fine-grained litharenite, moderately sorted, sub-angular, moderately spherical, comprised mainly of lithic fragments and quartz, no discernible grading.	Rapid deposition of high sediment bedload in a Newtonian flow (Miall 1996; Leeder 1999; Collinson *et al*. 2006) (**Fig. 3.** (**c**)).
Trough cross-bedded sandstone (St)	Coarse- to very coarse-grained trough cross-bedded litharenite, moderately sorted, sub-angular, moderately spherical, comprised mainly of lithic fragments and quartz, no discernible grading.	Deposition from lower-flow regime sinuous crested dune-scale bedforms migrating in a turbulent Newtonian flow (Miall 1996; Collinson *et al*. 2006) (**Fig. 3.** (**g**)).
Planar horizontally laminated sandstone (Sh)	Coarse- to very coarse-grained poorly planar horizontally laminated litharenite, moderately sorted, sub-angular, moderately spherical, comprised mainly of lithic fragments and quartz, no discernible grading.	Lower-flow regime plane bed deposition in a high sediment-load Newtonian flow. Poor preservation of structure indicates a pseudo-laminar flow (Miall 1996; Collinson *et al.* 2006) (**Fig. 3.** (**h**)).

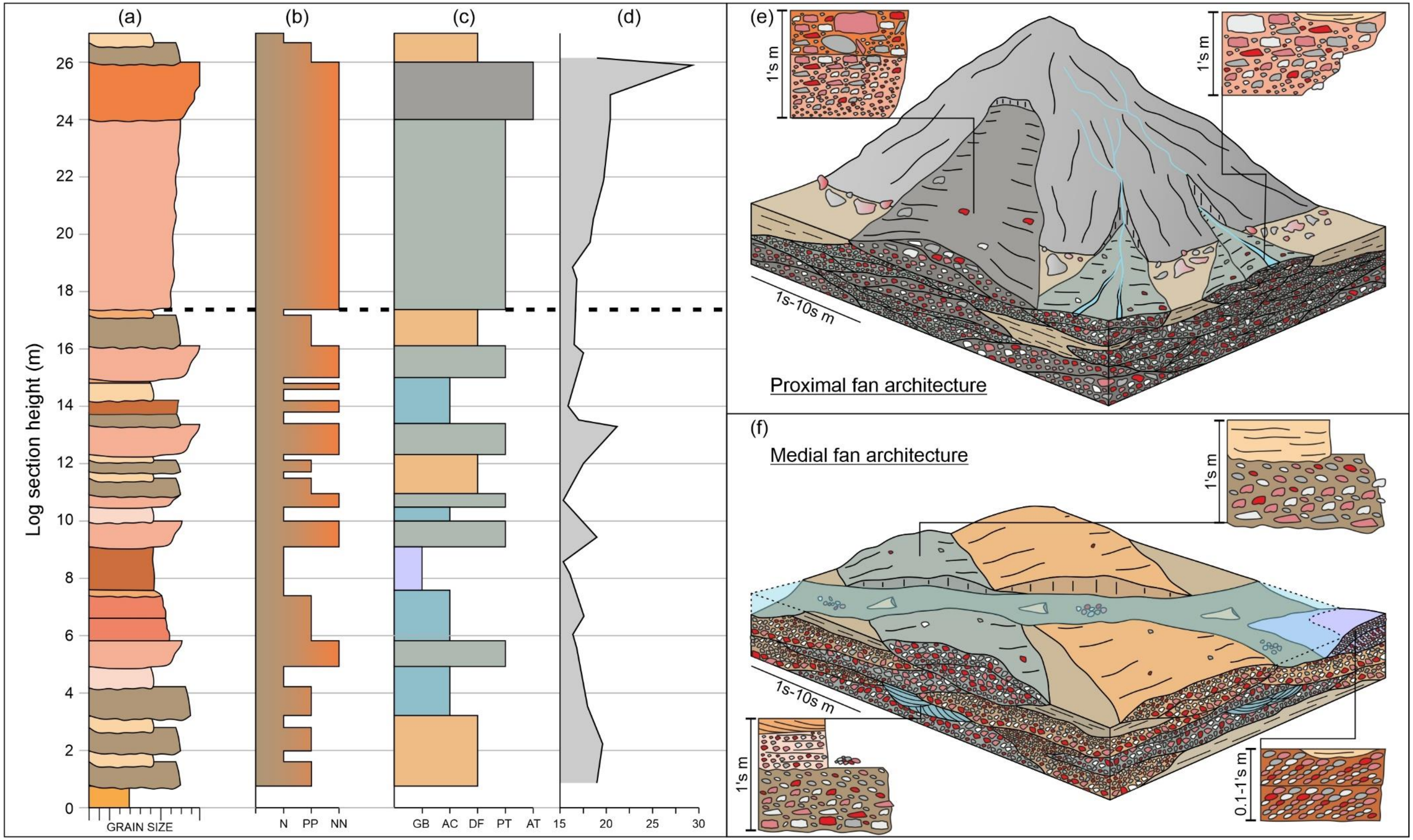
Association	Description	Interpretation	Idealised log
Aggradational talus cone deposits (AT)	Comprises 8.5% of the logged formation. Composed of Cmr (60%) and Cmb (40%) facies. Comprises crude reverse grading across bedding surfaces within the association. Rafting of large boulder sized clasts at the top of the association.	Gravity flow deposits derived from proximal mass flows (Nemec and Steel 1994; Blair *et al.* 1999).	
Progradational talus cone (PT)	Comprises 48.5% of the logged formation. Composed of Cmr (70%), Ccm (2%) and Sh (26%) facies. Association is crudely reversely graded and shows minor Sh lenses at its top (typically between 50 cm wide and 20 cm thick).	Low-water content debris flow. Reverse grading produced by basal traction (Coussot and Meunier 1996; Blair *et al.* 1999).	
Debris flow deposits (DF)	Comprises 22% of the logged formation. Composed of Cmn (65%), Cmd (12%), Sh (20%) and St (3%) facies. The association grades normally from plastic flow to high-energy upper flow regime plane bed deposition.	Mixed water and sediment debris flow. Pseudo-plastic flow at its base grades rapidly and normally as the flow rapidly wanes (Coussot and Meunier 1996).	
Alluvial flow deposits (AF)	Comprises 13.5% of the logged formation. Composed of Cmn (40%), Sc (30%), Ccc (10%), St (10 %), Sh (10%) facies. The association grades from pseudo-plastic debris flows to Newtonian flow deposits and bedform development.	High sediment-load aqueous flow, rapid initial waning of the deposit causes basal conglomerate facies deposition, more gradual grading leads to massive sandstone and eventually lower flow regime bedload Newtonian deposition (Miall 1996).	
Gravel barform deposits (GB)	Comprises 7.5% of the logged formation. Composed of Ccc (88%) and Sh (12%) facies. Deposits show reverse grading of cross-bedded strata from lee slope avalanche deposits. The top of the association shows a minor Sh lens at its top (approximately 40 cm wide and 20 cm thick).	Barform development with avalanche deposits on the lee slopes of amalgamating bedforms (Miall 1977; Miall 1996).	

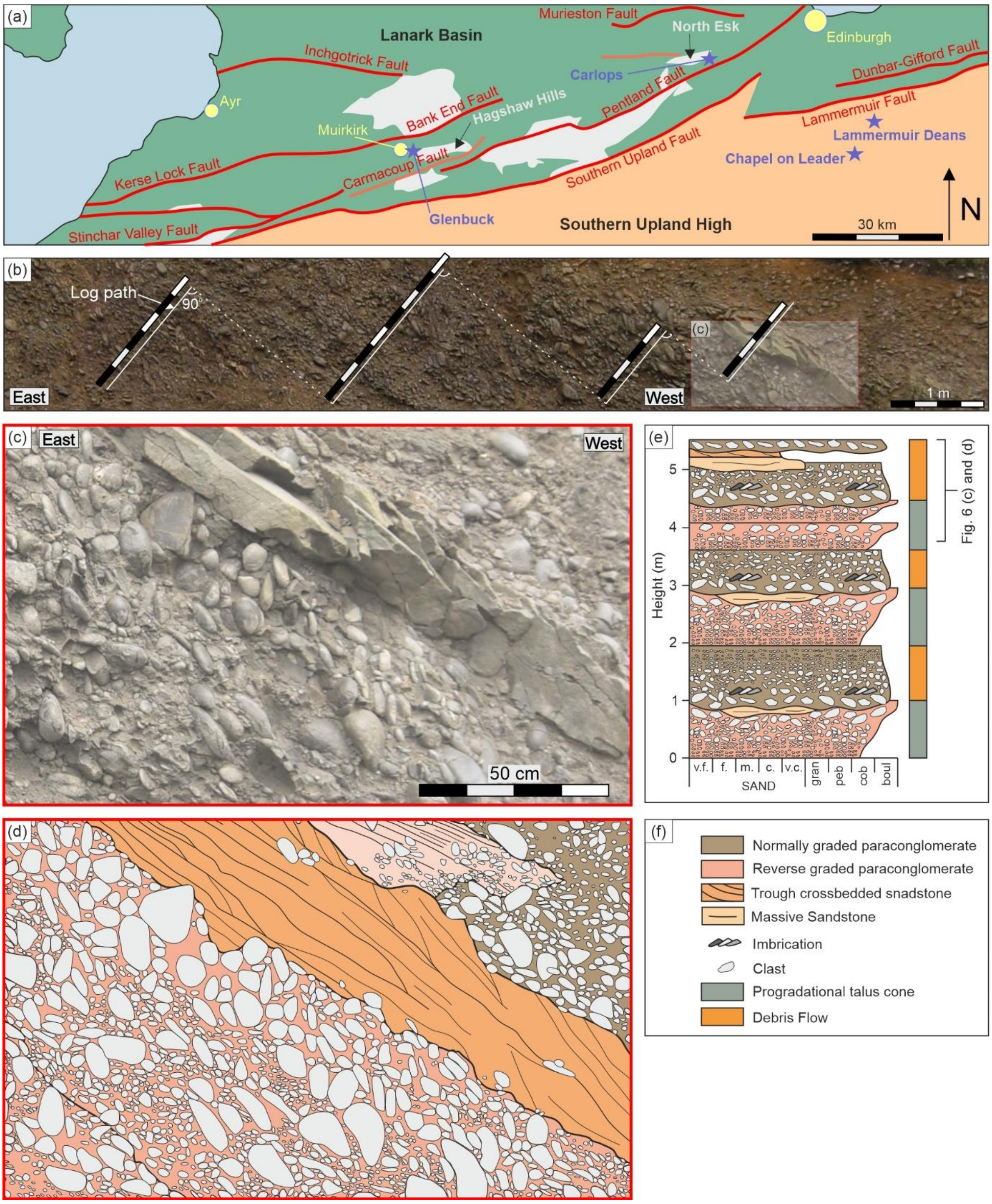

(a)
Study location
Midland Valley
40 km
N
Highland Boundary Fault
E.O.F.
W.O.F.
Edinburgh
Glasgow
D.F.
P.F.
Lanark Basin
Southern Upland Fault
(b)
Glasgow
East Kilbride
Lanark
(d)
Muirkirk
Glenbuck
Ayr
Cumnock
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2020 Google
Image Landsat / Copernicus
25 km
N
(c)
Clackmannan Group (CKN)
Inverclyde Group (INV)
Kinnesswood Formation - (KNW)
UC
Sandstone
Conglomerate
Volcanics
Auchtitench Sandstone Formation
Duneaton Volcanic Formation
Swanshaw Sandstone Formation
Greywacke Conglomerate Formation (GRWC)
Subject of this study
UC
Quarry Arenite Formation (QRY)
Hareshaw Conglomerate
Glenbuck Group (GBK)
500 m
(d)
CKN
Glenbuck Home Farm
KNW
INV
QRY
400
350
300
KNW
A70
Glenbuck Loch
New road
Logged section
(e)
GRWC
GBK
38
GRWC
Dolerite of Mull Dyke Swarm
300
QRY
N
400 m
(e)
Vegetation
Quaternary gravel
Greywacke Conglomerate Formation (GRWC)
Quarry Arenite Formation (QRY)
1m

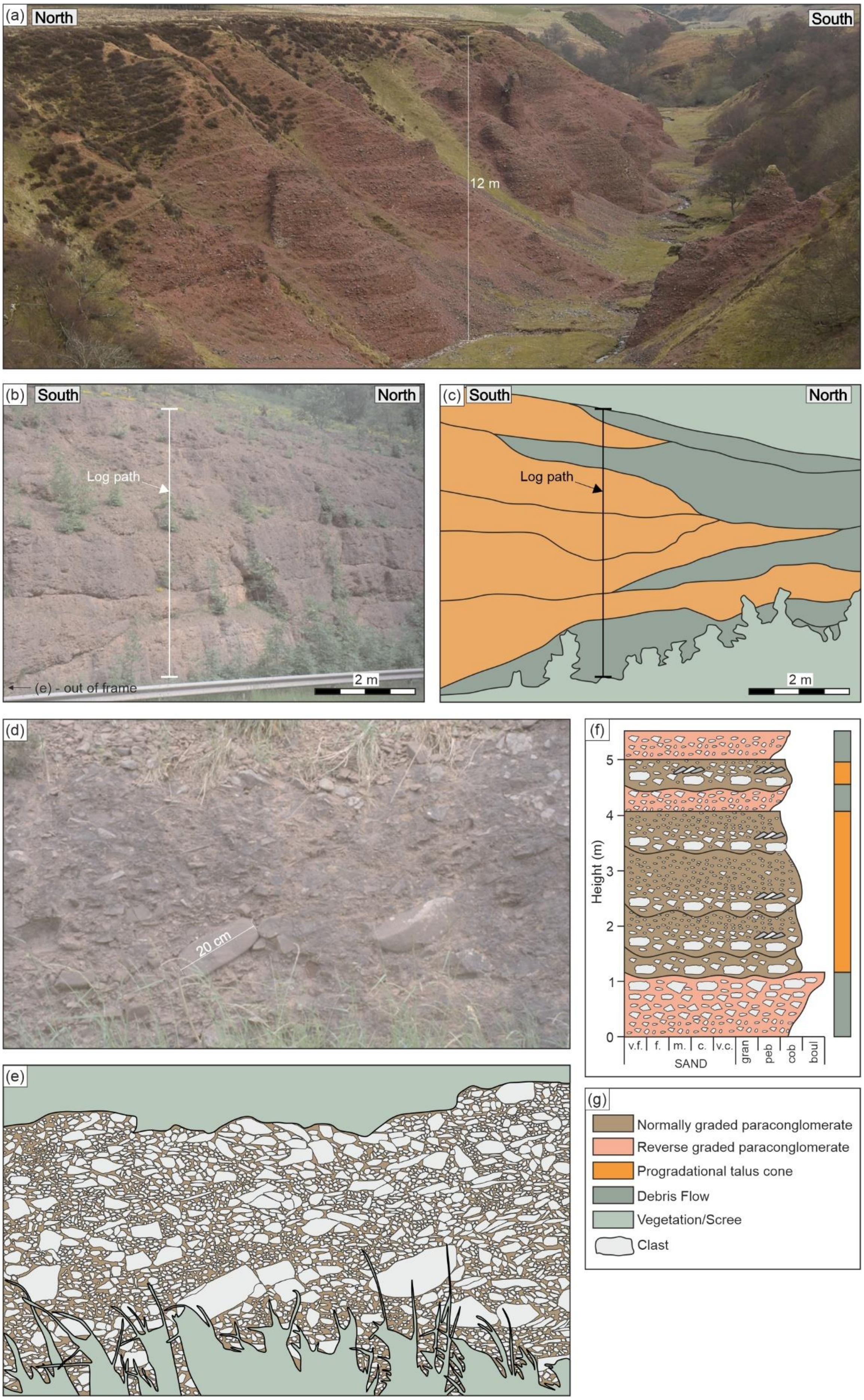

10 m
NO EXPOSURE
9 m
8 m
7 m
6 m
5 m
4 m
3 m
2 m
1 m
0 m
Greywacke Conglomerate Formation
Quarry Arenite Formation
F.A.
clay
silt
v.f.
f.
m.
c.
v.c.
SAND
gran
peb
cob
boul
20 m
19 m
18 m
17 m
16 m
15 m
14 m
13 m
12 m
11 m
10 m
NO EXPOSURE
27 m
26 m
25 m
24 m
23 m
22 m
21 m
Normally graded paraconglomerate (Cmn)
Reverse graded paraconglomerate (Cmr)
Disorganised paraconglomerate (Cmd)
Rafted boulder paraconglomerate (Cmb)
Cross-bedded orthoconglomerate (Ccc)
Structureless orthoconglomerate (Ccm)
Normally graded pebble sandstone (Sc)
Structureless sandstone (Sm)
Planar cross-bedded sandstone (Sp)
Trough cross-bedded sandstone (St)
Planar horizontal laminated sandstone (Sh)
Polycrystalline quartz
Porphyritic volcanics
Granodiorite
Chert
Imbrication
Gravel lenses

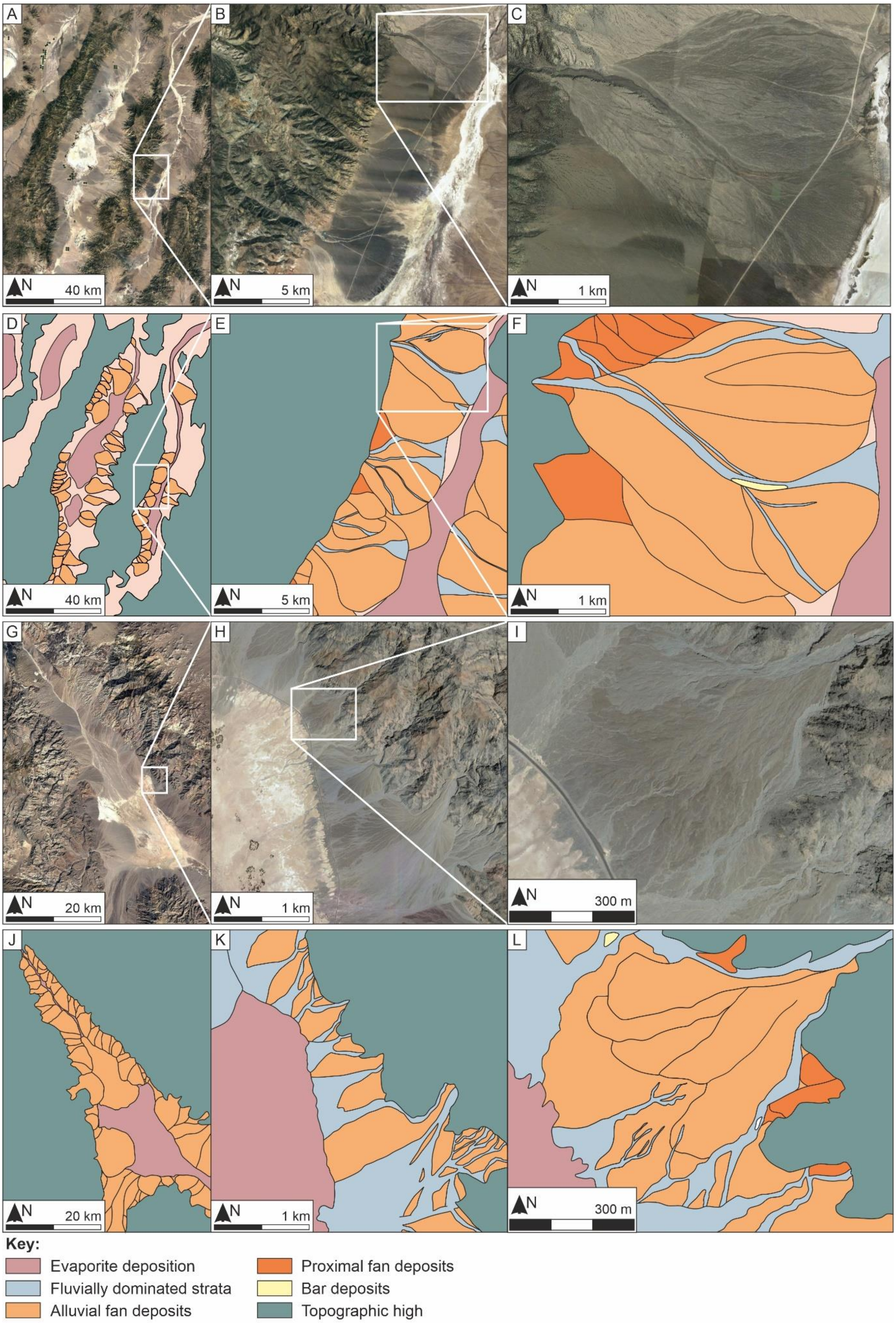

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)


Aggradational
talus cone
deposits
1's m
Hagshaw Hills inlier
Debris flow deposits
1's m
GRWC alluvial fan surface
Hagshaw Hills
GRWC
alluvial fan
Red indicates
position of larger
schematic
reconstruction
30 m
Key
Aggradational talus cone deposits
Progradational talus cone deposits
Debris flow deposits
Alluvial flow deposits
Gravel macroform deposits
1's m
Progradational
talus cone
deposits
0.1-1's m
Gravel macroform
deposits
Alluvial flow
deposits
1's m


(a)
(b)
(c)
(d)
Log section height (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
GRAIN SIZE
N
PP
NN
GB
AC
DF
PT
AT
15
20
25
30
(e)
1's m
1's m
1s-10s m
Proximal fan architecture
(f)
Medial fan architecture
1's m
1s-10s m
1's m
0.1-1's m


(a)
Lanark Basin
Murieston Fault
North Esk
Edinburgh
Inchgotrick Fault
Carlops
Dunbar-Gifford Fault
Pentland Fault
Ayr
Hagshaw Hills
Bank End Fault
Lammermuir Fault
Lammermuir Deans
Muirkirk
Southern Upland Fault
Chapel on Leader
Kerse Lock Fault
Carmacoup Fault
Glenbuck
Southern Upland High
30 km
N
Stinchar Valley Fault
(b)
Log path
90°
(c)
East
West
1 m
(c)
East
West
50 cm
(d)
(e)
Height (m)
0
1
2
3
4
5
v.f.
f.
m.
c.
v.c.
SAND
gran
peb
cob
boul
Fig. 6 (c) and (d)
(f)
Normally graded paraconglomerate
Reverse graded paraconglomerate
Trough crossbedded snadstone
Massive Sandstone
Imbrication
Clast
Progradational talus cone
Debris Flow


(a)
North
South
12 m
(b)
South
North
Log path
2 m
(e) - out of frame
(c)
South
North
Log path
2 m
(d)
20 cm
(f)
Height (m)
0
1
2
3
4
5
v.f.
f.
m.
c.
v.c.
SAND
gran
peb
cob
boul
(e)
(g)
Normally graded paraconglomerate
Reverse graded paraconglomerate
Progradational talus cone
Debris Flow
Vegetation/Scree
Clast


A
N
40 km
B
N
5 km
C
N
1 km
D
N
40 km
E
N
5 km
F
N
1 km
G
N
20 km
H
N
1 km
I
N
300 m
J
N
20 km
K
N
1 km
L
N
300 m
Key:
Evaporite deposition
Fluvially dominated strata
Alluvial fan deposits
Proximal fan deposits
Bar deposits
Topographic high