

Ice dynamics and sediment movement: last glacial cycle, Clyde basin, Scotland

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ABSTRACT. The nature and behaviour of sediment beneath glaciers influences how they flow and respond to changing environmental conditions. The difficulty of accessing the bed of current glaciers is a key constraint to studying the processes involved. This paper explores an alternative approach in which accessible sediments under the beds of former mid-latitude ice sheets are examined and related to changing ice behaviour during a glacial cycle. The paper focuses on the partly marine-based Pleistocene British Ice Sheet in the Clyde basin. A three-dimensional computation of subsurface glacial sediment distribution is derived from 1260 borehole logs. Sediment distribution is linked to an empirically-based reconstruction of ice sheet evolution, permitting identification of distinctive phases of sedimentation. Maximum sediment mobilisation and till deposition ($<0.04 \text{ m a}^{-1}$) occurred during ice advance into the basin from adjacent uplands. Subglacial processes were influenced locally by the relative stiffness of pre-existing sediments, the permeability of the sub-till lithology, and topography; the resulting mean till thickness is 7.7 m with a high standard deviation of 7.0 m. In places, focused till deposition sealed pre-existing permeable substrates, promoting lower effective pressures. Sediment remobilisation by meltwater was a key process as ice margins retreated back through the basin, upon deglaciation.

INTRODUCTION

Patterns of sediment movement beneath soft-bedded glaciers are poorly understood, despite proposed links to glacier dynamics (e.g. Alley, 1991; Boulton, 1996; Alley and others, 1997; Clarke, 2005). The original distribution and subsequent redistribution of sediment, not only has implications for glacier motion, but also affects the landscape that glaciers override (Nolan and others, 1995; Motyka and others, 2006), producing feedbacks that can influence glacier flow. Despite the success of some recent investigations on present glaciers (e.g. Smith and others, 2007), quantifying the volume and style of subglacial sediment mobilisation remains a challenge, largely due to inaccessibility of the bed.

The geological record in formerly glaciated landscapes offers an alternative approach. Here landforms and sediments contain a cumulative signature of recent ice sheet cycles, which enable reconstructions of palaeo-ice sheet evolution to be made (e.g. Boulton and Clark, 1990; Kleman and others, 1997; Stokes and others, 2009). Where formerly glaciated areas have densely-spaced borehole datasets, these can be used to compute a three-dimensional geological model of glacial deposits, allowing their distribution and volumes to be calculated. Combining these geological models with time-transgressive ice sheet reconstructions make it possible to reconstruct patterns of sediment mobilisation during a glacial cycle - a key aid in understanding glacial sediment transport

and deposition mechanisms (Alley, 1991; Boulton, 1996; Alley and others, 1997; Piotrowski and others, 2001; Thomason and Iverson, 2009).

In the Clyde basin, western Scotland (Fig. 1), a well-preserved landform and sediment record documents the build up and decay of the last, Main Late Devensian, British Ice Sheet (BIS) (Geikie, 1863; Price, 1975; Rose and Smith, 2008). An extensive database of borehole logs exists for the area (e.g. Menzies, 1976, 1981). Consequently, the basin provides an ideal case study to examine both former ice sheet evolution and sediment mobilisation. Finlayson and others (2010) presented a synthesis of geomorphological and stratigraphical evidence from west central Scotland (including the western part of the Clyde basin) (Fig. 1), to derive a conceptual model of ice sheet advance and decay during the last glacial cycle. The aim of the work reported here is to elucidate the pattern and volume of sediment that was mobilised during the glacial cycle, and examine the implications for the style of sediment transport during different phases of glaciation.

PHYSIOGRAPHIC AND PALAEO-GLACIOLOGICAL SETTING

The Clyde basin (3173 km²) is a predominantly lowland, formerly glaciated landscape (Fig. 1). It is drained by the River Clyde, which flows in a north-westerly direction for ~120 km, from its source in the Lowther Hills, through the Glasgow conurbation, to reach the coast at the Inner Firth of Clyde. Much of the eastern and central basin is underlain by cyclically deposited sedimentary rocks (Scottish Coal Measures Group and Clackmannan Group). These are bounded to the north and west by lavas forming the Kilpatrick Hills, Campsie Fells, and Renfrew Hills, and to the south by turbidite sequences and lavas, which underlie the fringes of the southern Uplands. Most of the ground surface is less than 250 m above sea level (a.s.l.), with the surrounding hills rising to <700 m a.s.l.

The Clyde basin is first known to have been glaciated ~0.45 Ma BP; however, earlier episodes of glacier ice advance into the basin may also have occurred (Lee and others, in press). Since then, a further four continental-scale ice sheet glaciations are thought to have affected the British Isles. The most recent ice sheet overrode the Clyde basin sometime after 35 ka BP (Brown and others, 2007; Jacobi and others, 2009). Initial glacier advance was from the northwest, sourced from an ice cap over the Scottish Highlands; ice flow was then diverted eastwards following the coalescence of Highland and Southern Upland ice masses (Price, 1975; Sutherland and Gordon, 1993). During or soon after maximum glaciation, an ice divide migrated eastward over the Clyde basin, at a time of enhanced drawdown towards western marine outlets of the BIS (Eyles and McCabe, 1989; Finlayson and others, 2010). Final deglaciation of west central Scotland was characterised, once more, by south-eastward and eastward ice flow (a configuration similar to initial ice sheet advance), prior to complete glacier stagnation. The Clyde basin is thought to have become ice free by ~15 ka BP, at which time relative sea level locally approached 40 m a.s.l. (Peacock, 1971, 2003; Rose, 2003).

The regional glacial stratigraphy for the Clyde basin has been well documented (Rose, 1981; Menzies, 1981; Browne and McMillan, 1989; Finlayson and others, 2010). For context, key units relevant to this study are summarised in Table 1. A buried till (older than 35 ka), the Ballieston Till Formation, has been recorded in parts of northern Glasgow. It is overlain by glaciofluvial gravelly sands derived from a glacier margin positioned near the entrance to the basin (the Cadder Sand

Formation), which have yielded woolly rhinoceros bones dated to 35 ka cal BP (Jacobi and others, 2009). Isolated pockets of glaciolacustrine sediments (the Broomhill Clay Formation) also locally overlie the Ballieston Till Formation. All these deposits predate glacier advance into the basin and are predominantly found filling a concealed bedrock valley that trends west-southwest to east-northeast under the floodplain of the River Kelvin (Fig.1), or in bedrock hollows beneath the River Clyde. Above rests the regional till of the area, the Wilderness Till Formation. In places, the Wilderness Till Formation is overlain by the Broomhouse Sand and Gravel, Bellshill Clay, and Ross Sand formations; these being glaciofluvial, glaciolacustrine and glaciodeltaic deposits, respectively. Raised glaciomarine deposits of the Clyde Clay Formation are found at, or close to, the ground surface across western parts of the basin that lie below 40 m a.s.l.

METHODS

To determine the pattern of sediment mobilisation through the last glacial cycle in the Clyde basin, two sets of information were required: (i) an event stratigraphy, based on geomorphological investigation; and (ii) a 3D geological model that reveals the volume and distribution of glacial sediments laid down during particular events or stages.

Geomorphological investigation

As noted, Finlayson and others (2010) have synthesised evidence from west central Scotland, including the western half of the Clyde basin. In this study, the remainder of the Clyde basin was observed to produce a basin-wide geomorphological dataset to complement the 3D geological modelling (described below). The glacial geomorphology was investigated using digital surface models (DSMs) and georectified 1:10 000 monoscopic aerial photographs, interrogated within ESRI Arcmap 9.3. The DSMs, built from NEXTMap Britain™ topographic data (1.5 m vertical and 5 m horizontal resolution) were illuminated from the north-west and north-east in order to limit bias that can be introduced by relief shading (Smith and Clark, 2005) and enable the capture of landforms with different alignments. The DSMs were viewed at several scales, ranging from 1:10,000 to 1:200,000, and sub-sampled at progressively lower horizontal resolutions, from 5 m to 50 m, in order to capture both small- and large-scale features. Mapped distributions of glaciomarine, glaciodeltaic, glaciolacustrine, and glaciofluvial sediments were based upon a digital 1:50,000-scale geological map of the whole area (DiGMapGB 50).

3D Geological modelling

The dimensions and distribution of subsurface glacial sediments in the Clyde basin were established using the geological modelling software: GSI3D (©Insight GmbH) and GOCAD™. In this study, GSI3D (Kessler and others, 2009) was used primarily for development of the model, while GOCAD was used for model interrogation. Input datasets required for the geological modelling process are summarised in Figure 2. Using GSI3D, 85 digital cross-sections (total length = 1860 km) were created at regular (2 to 4 km) intervals. These cross-sections were constrained by 1260 borehole logs, the 1:50,000-scale digital superficial geology map, a digital surface model, and a bedrock elevation model. In the Clyde basin, the bedrock elevation model is based on an extensive borehole dataset with 44753 proven bedrock elevation records; it is also 'influenced' by a further 7028 total depth (bedrock not reached) records (Lawley and Garcia-Bajo, 2009). Collectively, the 85

cross-sections formed a 'fence diagram', which was combined with the digital geological map of the basin to create envelopes, representing the lateral (surface and buried) extent of model units (Table 1). Triangulated Irregular Networks (TINs) were then computed for the surface and base of each unit in GSI3D, by interpolating between regularly-spaced x,y,z nodes on the cross sections and envelopes using an incremental Delaunay triangulation algorithm (Green and Sibson, 1978).

The borehole log and location files, used in the cross-sections, were imported from a nation-wide database, which includes geotechnical site investigation logs, water well records, sand and gravel assessment reports and coalfield investigations. Because the original focus of each data subset was different, the detail concerning the glacial deposits is variable. Consequently, during selection of the 1260 boreholes used for the geological modelling, preference was given to those that described the glacial deposits in most detail and those that penetrated the full thickness of the glacial deposits. Data handling limitations and variable borehole record quality precluded use of the full 50,000+ borehole dataset for the geological modelling. Care was taken to ensure that selected boreholes were from sites evenly distributed throughout the model area. The only 'holes' in the borehole data are where bedrock is present at the land surface. However, since these sites lie outside the envelopes created for model units, they did not affect the calculation.

A requirement of the GSI3D program is that the geological model adheres to an assigned stratigraphy. The stratigraphy used here (Table 1) is a simplification of the stratigraphy developed by Browne and McMillan (1989), and is consistent with that given by Menzies (1981). Due to the scale of the study area, 'till' was treated as a homogeneous unit. The Wilderness Till Formation has been described as a deformation till (Rose and others, 1988), and predominantly comprises a massive matrix supported diamict. However, lenses of sand and gravel, tectonised sorted sediments and till stratification have also been observed (Menzies, 1981; Browne and McMillan, 1989). These till heterogeneities were too small-scale to be included in the present basin-wide study, although they are a focus of ongoing work within the Glasgow conurbation using densely-spaced geotechnical data and geostatistical analyses (Kearsey and others, 2011).

RESULTS AND DISCUSSION

The geomorphology of the Clyde basin

A prerequisite for interpretation of the 3D geological modelling results is an event stratigraphy, based here on geomorphological data. Results of the geomorphological investigation (Fig. 3) and the interpreted event stratigraphy are given below. Note that data for the western part of the basin has been published previously (Finlayson and others, 2010)(Fig. 1), and that new mapping encompasses the remainder of the basin. However, for clarity the basin as a whole is summarised.

Description

The north-western part of the basin is dominated by a landscape of drumlins and ribbed moraine over the low ground (underlain by sedimentary rocks). There is little sediment cover over the volcanic rocks forming the higher ground, where numerous striations have been recorded (Paterson and others, 1998). The drumlinised landscape is overlain by glaciodeltaic sequences in parts of the Kelvin Valley, and by raised glaciomarine sediments in the Glasgow area. The south-eastern part of

the Clyde basin is characterised by glaciofluvial deposits (including eskers) and by meltwater channels.

Drumlins in the Clyde basin possess differing alignments (Fig. 3), as previously noted by Rose and Letzer (1977) and Rose and Smith (2008). Individual flow sets (e.g. Boulton and Clark, 1990; Kleman and others, 2006; Stokes and others 2009), inferred from drumlin alignment are shown for the Clyde basin in Figure 4A. The relative age of each flow set is based on landform overprinting (e.g. Fig. 4B) (Hughes and others, 2010), and stratigraphical evidence synthesised from sites across west central Scotland (Finlayson and others, 2010). As expected, drumlin morphological characteristics are consistent with those observed for British drumlins by Clark and others (2010). The range of drumlin lengths, widths and elongation, and their relationships, are shown as a plot of co-variation in Figure 5, following the approach of Clark and others (2010).

In the Clyde basin (and Ayrshire basin to the south) ribbed moraine, where present, always appear to be overprinted by drumlins - a pattern also apparent in the subglacial bedform map of Hughes and others (2010). Finlayson and others (2010) suggested that some of these ribbed moraine may have initiated as ice marginal sediment ridges, generated by folding and thrusting of thick sequences of proglacial sediments, during ice sheet advance into the basin from the north-west. There is sedimentological evidence that supports this, where till overlies a low ridge of glaciotectionally thrust silts, sands and gravels (McMillan and Browne, 1983). These landforms tend to be present only in the lower Clyde basin, where a number of the factors considered important for genesis of glaciotectionic phenomena (Aber and others, 1989) were likely to have operated (e.g. ice advance against topography, damming of proglacial lakes).

The ice marginal landforms, including meltwater channels, glaciodeltaic deposits, glaciolacustrine deposits and moraines, reveal stages of ice margin retreat (e.g. Clark and others, in press), shown in Figure 6. A zone of ice cap separation is inferred across the Southern part of the basin in the vicinity of the Carstairs esker (Fig. 3). This supports the suggestion of Thomas and Montague (1997) that the esker system developed in an interlobate sediment sink, during uncoupling of northern- and southern-sourced ice caps. Similar persistent subglacial conduits have been observed in modern glacial environments, separating the behaviour of confluent ice masses (Benn and others, 2009). Aside from minor differences in ice margin detail, the overall pattern of glacier retreat inferred here supports that presented by Clark and others (in press).

Interpretation: An event stratigraphy

Combining the geomorphological evidence with recently published reconstructions for adjacent parts of the last BIS, allows an event stratigraphy to be proposed for the Clyde basin (Fig. 7). Initial ice sheet advance into the Clyde basin was from the northwest (Fig. 7A) sometime after 35 ka BP (Jacobi and others 2009). The configuration (Fig. 7A) would have permitted the build up of an ice-dammed lake by blocking the River Clyde (Price, 1975). The buried glaciolacustrine (Broomhill Clay Formation) sediments (Table 1) may be remnant deposits from this lake. In the Kelvin Valley, outwash sediments of the Cadder Sand and Gravel Formation were overridden during glacier advance.

An ice dome developed over the Southern Uplands, and coalesced with Highland-sourced ice to form an ice divide to the west of the Clyde basin, forcing flow towards the northeast (Fig. 7B). The drumlins of flow set 1 probably initiated at that time. This configuration may have broadly persisted until the BIS approached its maximum extent, around 27 ka BP (Clark and others 2011). Enhanced drawdown towards western marine outlets (Eyles and McCabe, 1989; Scourse and others, 2009; Dunlop and others 2010) then forced the ice divide to migrate over the Clyde basin (Fig. 7C). Flow set 2 may have begun to develop during, or following, this phase; it is not possible to establish if flow set 3 also began to form at that time, or later. In general the geomorphological signature of this stage (Fig. 7C) is limited in the Clyde basin. However, westerly and south-westerly flow left a strong imprint in the Ayrshire basin to the south-west (Finlayson and others, 2010). The presence of an ice divide over the Clyde basin, with associated low or zero velocities, favoured preservation of subglacial bedforms left during the earlier part of the glacial cycle (Clark, 1993).

During ice sheet decay (Fig. 7D), ice flow in the lower Clyde basin was from the north-west, documented by flow set 4. A zone of separation developed between the northern-sourced ice and ice caps centred over the Southern Uplands (Fig. 6) (Thomas and Montague, 1997). Glaciofluvial sand and gravel deposits, and glaciolacustrine deposits, were focused along this corridor (Fig. 3). The latter stages of deglaciation in the Clyde basin (Fig. 7E) were accompanied by the deposition of lacustrine and deltaic sediment into 'Lake Clydesdale', which was dammed by an ice margin positioned at the Blantyreferme moraine (Bell, 1874) (Fig. 3). Drumlins of flow set 4 probably continued to form at this stage, as well as those belonging to flow set 5. Final retreat of Highland-sourced ice in the Clyde basin was accompanied by invasion of the contemporary sea, in which glaciomarine sediments were deposited up to altitudes 40 m a.s.l. (Browne and McMillan, 1989).

3D geological modelling results

The computed model of glacial deposits (total volume = 9.75 km³) in the Clyde basin is shown in Figure 8. Volumes of individual units are given in Table 2 and modelled thicknesses of example units are shown in Figure 9. The buried till and buried glaciofluvial deposits are generally restricted to the concealed bedrock valley under the floodplain of modern River Kelvin. Here, they exceed 40 m in thickness (Fig. 9), representing an important aquifer. Buried glaciofluvial deposits are also present in concealed channels in the upper Clyde basin. Buried glaciolacustrine deposits are restricted in extent, only occurring as isolated pockets in deepenings under the River Clyde.

There is only one bulk till unit across much of the basin; it accounts for ~70% of the total sediment in the basin. Variations in till thickness are apparent, ranging from 0.01 m to more than 40 m (Fig. 9). Median and mean modelled till thickness is 5.8 and 7.7 m respectively (standard deviation = 7.0). These values are consistent with the 6 m mean thickness calculated by Menzies (1981) for till in central Glasgow. Till is generally thin (or absent) around the margin of the basin (Fig. 9). The thickest till sequences are developed over the buried glaciofluvial deposits (Fig. 10), which are more permeable than the surrounding sedimentary rocks. The presence of thick till over these glaciofluvial gravelly sands supports suggestions elsewhere that efficient sub-till drainage can cause dewatering and stiffening of subglacially mobilised sediments, thereby promoting deposition (Boulton and others, 2001; Meranio and Eyles, 2009). However, the distribution of thick till probably also partially

reflects infilling of the pre-existing topography (e.g. Boyce and Eyles, 2000), since the buried glaciofluvial deposits tend to be preserved in bedrock depressions. Assuming the buried glaciofluvial deposits are correlative with the Cadder Sands and Gravel Formation (Table 1), the overlying till package *in those areas* can be considered wholly a product of the last glacial cycle. Figure 11 shows an example of one such till package, which overlies the largest deposit of buried glaciofluvial sediments in the Kelvin valley. Here a net volume of 0.62 km^3 was deposited over 32 km^2 . Thick till is also present in an area immediately down ice from zones likely to have been occupied, initially, by soft deformable sediment during ice sheet advance (see below).

Glaciofluvial, glaciodeltaic and glaciolacustrine deposits are widespread alongside drainage pathways in the Clyde basin where they reach up to 20 m thickness, in places (Fig. 9). Collectively, these deposits represent 11% of the total sediment volume in the basin. The raised marine deposits in the lower Clyde basin provide the second largest contribution (13%) to the total basin sediment volume; these sediments exceed 20 m thickness along pre-existing topographic lows.

Reconstructing sediment mobilisation during the last glacial cycle

Using the event stratigraphy (Fig. 7) and the geological modelling results, progress can be made towards a basin-scale reconstruction of sediment mobilisation during the last glacial cycle.

Ice sheet advance (Fig 7A)

It has been theorised that ice sheet advance is a key phase of till deposition (Boulton, 1996). The preservation of sediments and bedforms interpreted to have begun formation during, or following, this initial stage of the glacial cycle (ribbed moraine and flow set 1 drumlins), does indeed suggest that a significant volume of till had been deposited during the ice sheet advance phase. Sediment within drumlins is often found to pre-date the drumlin forming event (Knight and McCabe 1997; Stokes and others, 2011). If this were also true for the Clyde basin drumlins, it also supports a case for an early phase of till deposition. The till package that rests on the buried fluvial deposits (Fig. 11) in the Kelvin valley is considered to have been deposited during the last glacial cycle (see above). Here 0.62 km^3 of till has been deposited over 31 km^2 , which equates to a uniform net deposition rate through the glacial cycle ($\sim 35 \text{ ka BP}$ to $\sim 15 \text{ ka BP}$) of 0.001 m a^{-1} (or $\text{m}^3 \text{ m}^{-2} \text{ a}^{-1}$). However, if much of that till package was deposited during advance through the basin (this could have occurred over as little as $\sim 0.5 \text{ ka}$, according to the recent BIS simulation of Hubbard and others 2009), which is a prerequisite for drumlins to have formed in those sediments, reconstructed net deposition increases to $\sim 0.04 \text{ m a}^{-1}$. These till deposition rates are only slightly higher than those proposed for ice marginal zones by Boulton (1996) and are of a similar order of magnitude to rates of subglacial till deposition considered by Sugden and John (1976), but they assume no latter erosion. This assumption can be partially justified here on two accounts: the Clyde basin was subsequently positioned close to, or under, an ice divide during maximum glaciation (Figs. 7B, 7C; Finlayson and others, 2010), where minimal erosion would have been expected (Boulton, 1996); and bedforms interpreted to have formed during early ice flow stages are preserved. It should be noted that these till accumulation rates cannot be used to estimate bedrock erosion, since a significant fraction was likely to have derived from remobilised sediment (discussed below).

It is clear, however, that till deposition during advance was not uniform across the basin; the ~20 m thickness of till described above, in the Kelvin Valley, is not reproduced everywhere (Fig. 9). Pre-conditioning factors may therefore have influenced till accumulation. It is notable that no marine deposits and little glaciolacustrine deposits are revealed below till in the model. However, conditions prior to ice sheet build up indicate that such deposits were likely to have been locally extensive: global sea level was at least 6.6 m higher during the last interglacial (MIS 5e; Kopp and others 2009) and relative sea level was probably higher during the prior continental-scale ice sheet deglaciation (MIS 6); ice-dammed lakes are also likely to have accompanied ice sheet build up by blocking the River Clyde (Price, 1975). Reworking of these deposits probably formed the bulk of till that accumulated during ice sheet advance (e.g. Ó Cofaigh and others 2011); indeed lenses of folded laminated sediments, have been observed in till in the Glasgow area (e.g. Menzies, 1981). The presence of the thickest till packages in the vicinity, or immediately down ice, from modern marine and glaciolacustrine sediments (Figs. 3, 9) lends support to the idea that similar sediments were previously a key source for till deposited during advance. Where ice sheet advance was into relatively soft, water-saturated sediments (e.g. glaciomarine, glaciolacustrine, or deltaic deposits), deformation probably ensued as plug flow (Leysinger Vieli and Gudmundsson, 2010). Sediment removal up glacier, may have been in excess of 20 m, based on the thickness of raised marine deposits presently occupying the Clyde basin. Subsequent deposition of thick till then occurred when glaciotectonic stress (lateral stress + shear stress, Aber and others, 1989) fell below sediment strength, possibly through sediment dewatering as it moved over more permeable (buried glaciofluvial deposits) material, or as the ice margin passed over leading to a reduction in glaciotectonic stress. The result is that overall transport distances were relatively short, consistent with the limited down ice distribution of thick till sequences and the preservation of some sedimentary structures locally within the till. Where ice advanced over stiffer, pre-existing till, overriding or mixed flow (Leysinger Vieli and Gudmundsson, 2010) was more likely, with reduced basal sediment mobilisation and reduced accumulation of 'new' till. A switch to these conditions would also have taken place in zones previously characterised by plug flow, once the supply of relatively soft sediments became exhausted, otherwise the thick till wedge would have migrated down glacier with the advancing ice front. Thus, spatial variations in sediment mobilisation by deformation were probably governed by the relative stiffness of pre-existing substrate, with implications for the glacier flow mechanism.

A result of geological modelling, and previous stratigraphical work in the Glasgow area (e.g. Menzies, 1981; Browne and McMillan, 1989), is that, with the exception of those restricted locations where buried till packages are identified (Fig. 9), only one main till layer (median thickness = 5.6 m) is present in the basin. It is extremely unlikely that the ~7 km³ of till forming that layer is wholly a deposit from the last glacial cycle. To generate that volume of till again would require ~3 times the volume of all other sediments presently available in the basin for reworking. Given the topographically confined (by Clyde Plateau Volcanic Formation) north-western entrance to the basin, which has little or no till cover (Fig. 9), transport of the remaining volume of till into the basin via a continuous deforming bed is not probable. It is more likely that till from previous glaciations remained in the basin and was, to an extent, reused by the next.

Ice sheet established; ice divide migration (Figs. 7B, 7C)

Coalescence of Highland and Southern Upland ice masses allowed an ice divide to develop in the vicinity of the Clyde basin. The transition of the Clyde basin, from being positioned down ice from the equilibrium line, to being positioned close to the ice divide (Figs. 7A, 7B) meant that overall sediment erosion was limited, since maximum erosion is thought occur just up ice of the equilibrium line (Boulton, 1996). The initial position of the ice divide ~30 km to the west facilitated eastward flow associated with drumlins of flow set 1; these probably formed by erosion and deposition by a mobile till layer (Boyce and Eyles, 1991; Johnson and others, 2010). It is not possible to quantify the volumes involved; however, the presence of much thinner, and in places absence of, till at the eastern boundary of the basin (Fig. 9), suggest that overall sediment loss through continuous bed deformation would have been restricted. Furthermore, preservation of both sediments and landforms from early parts of the glacial cycle (Browne and McMillan, 1989; Finlayson and others, 2010) indicates that basal motion was probably concentrated at or near the ice-sediment interface, limiting large-scale sediment transport by deformation. Subsequent migration of the ice divide to a position over the Clyde basin (Fig. 7C) would have further limited any sediment mobilisation.

Eastward ice flow (Fig. 7C) became more established towards the end of this phase, as deglaciation commenced. It is interesting to note that there is no difference in characteristics of the eastward oriented drumlins between zones of buried glaciofluvial deposits and adjacent areas (Fig. 12). Lengths (L) and elongation ratios (ER) for drumlins overlying buried glaciofluvial deposits ($n = 46$, median $L = 645$ m, median $ER = 2.6$) and drumlins within a 2 km zone beyond the margin of the buried glaciofluvial deposits ($n=81$, median $L = 660$, median $ER = 2.9$) were statistically indistinguishable (Mann Whitney: $z = 0.9$, $p = 0.37$ for L ; $z = 0.91$, $p = 0.36$ for ER). Drumlin elongation has been suggested to be a proxy for relative basal ice flow velocity (Stokes and Clark, 2001), while basal motion is linked to subglacial water pressure (Paterson, 1994). It is therefore likely that enhanced drainage through the buried glaciofluvial gravelly sands (which were at the land surface prior to advance), was precluded by the thick till preferentially deposited on top of these deposits (Fig. 10). This would have equalised effective pressures between zones underlain by buried fluvial deposits and adjacent areas. Thus, by focusing thick till sequences over more permeable substrates during advance, the ice sheet may have essentially regulated its basal conditions, facilitating smoother overall basal motion.

Ice cap uncoupling and deglaciation (Figs. 7D, 7E)

During and following ice cap uncoupling, glacier flow in the lower Clyde basin was generally towards the southeast, documented by flow set 4. The drumlins formed during this stage are some of the best preserved in the basin and indicate that till erosion and down-ice deposition was locally occurring at this time. However, for reasons outlined above, it is unlikely that significant volumes of till were lost from the basin by continuous deformation.

The combined volume of the glaciofluvial, glaciolacustrine, glaciodeltaic deposits is 1.08 km^3 , giving an approximation for the minimum volume of sediment remobilised (predominantly by sub-/pro-glacial fluvial processes) during ice sheet withdrawal. The approximation is a minimum since drainage was diverted eastward (via successive overflow cols towards the Firth of Forth) for a period following ice cap decoupling, which would have resulted in some unaccounted sediment loss, and sediment loss to the Firth of Clyde is not included. These sediments make up 11% of the total

sediment volume in the basin. The duration over which they were deposited only represents the final 2.5% of the last glacial cycle in the area (~0.5 ka maximum, based on a synthesis of dates and ice margin retreat isochrones published in Clark and others (in press)), indicating that transport and deposition by glacial meltwater formed a disproportionately high contribution to the basin sediment budget as the ice margin retreated back through the basin. This supports the suggestion by Alley and others (1997) that high sediment transport capacities are achieved by subglacial streams in ice marginal areas, where surface water accessing the bed, promotes high water discharges forced by steep head gradients.

WIDER IMPLICATIONS

The work presented here has attempted to characterise the volume and style of sediment mobilisation through the last glacial cycle in the Clyde basin. During that time the basin was occupied by an advancing outlet glacier; it was then positioned under a migrating ice divide, and then once more by an outlet glacier during ice sheet uncoupling and deglaciation. The data presented here may therefore provide insight into sediment mobilisation in such environments. Although the Clyde basin may have temporarily been located close to the onset zone of fast glacier flow, it was not occupied by an ice stream and is thus not representative of ice streaming conditions.

Ice margin advance is shown to have been associated with highly variable spatial and temporal pattern of sediment mobilisation. Where ice advanced into relatively soft glaciomarine and glaciolacustrine deposits, sediment fluxes in the marginal area were high. Only rare opportunities exist to study modern glaciers advancing into soft sediments, but where observed, high fluxes are apparent. For example, advance of the Taku Glacier, Alaska, which is a good modern analogue for the Clyde glacier in its advance stage, has displaced >100 m of marine sediment from its bed since 1890 (Nolan and others, 1995). In the case of the Clyde glacier, this high rate of sediment mobilisation and re-deposition was spatially, and probably temporally, restricted. Reduced basal sediment mobilisation took place where relatively soft sediments were absent, or following the exhaustion of soft sediments.

The preferential deposition of thick till over glaciofluvial sediment appears to have acted as a seal, negating the increased drainage capacity of the latter. This suggests that glacier advance and till deposition can alter basal conditions by promoting lower effective pressures. As a result, motion is focused at the ice-till interface, and ice infiltration into the bed by regelation inhibited (Iverson, 2010). In the case of the Clyde basin, this would have favoured preservation of both sediments (Browne and McMillan, 1989) and bedforms (Finlayson and others, 2010) that were produced early in the glacial cycle. However, localised erosion and deposition by a relatively shallow layer of flowing sediment (Boyce and Eyles, 1991; Clark, 2010) must also have occurred in order to carve bedforms during subsequent phases of the glacial cycle.

The Clyde basin is a relatively small area at the ice sheet scale. Thus, it highlights the spatially variable nature of some bed properties over small areas. The highly variable modelled till thickness (Fig. 9) (mean = 7.7 m, standard deviation = 7.0 m) demonstrates that uniform till sheets (e.g. Alley, 1991) do not necessarily occur in all lowland areas.

A considerable volume of sediment in the Clyde basin was remobilised by glacial meltwater during ice sheet withdrawal, highlighting its role as a geomorphological agent. While the subglacial imprint (e.g. drumlins) often produces the most striking landscape features, ice margin advance and deglaciation are suggested, in the case of the Clyde basin, to have been key (possibly more important) factors influencing overall sediment mobilisation during the glacial cycle.

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LIST OF FIGURE CAPTIONS

Figure 1. The boundary of the Clyde basin is shown by the red outline. Dashed white rectangle shows area studied by Finlayson and others (2010). Abbreviations: LH – Lowther Hills; RH – Renfrew Hills; KH – Kilpatrick Hills; CF – Campsie Fells; RK – River Kelvin. Locations of subsequent figures are shown. Hill-shaded digital surface model built from Intermap Technologies NEXTMap Britain topographic data (NW illumination). Offshore bathymetry from BGS DigBath contours. Inset: Location of Clyde basin within a UK context. White line gives approximate extent of last British and Irish Ice Sheet, based on Bradwell and others (2008) (solid line) and Clark and others (2011) (dashed line).

Figure 2. Upper box: input datasets required for the 3D geological modelling. Lower box: summary of workflow.

Figure 3. Geomorphology and glacial geology of the Clyde basin. Glacial striations taken from Paterson and others (1998).

Figure 4. A: Flow sets inferred from drumlin alignment in the Clyde basin. B: Interference pattern developed immediately to the east of the Clyde basin. Here, north-easterly oriented drumlins of Flow set 1 are overprinted by easterly oriented drumlins of Flow set 3.

Figure 5. Co-variation plot of Clyde basin drumlin characteristics. The scale dependent elongation limit, first recognised for drumlins by Clark and others (2010), can be seen.

Figure 6. Suggested pattern of ice cap separation and subsequent retreat, interpreted from ice marginal landforms (e.g. meltwater channels, ice-dammed lake deposits, moraines). Black arrows denote ice flow direction. Dashed line shows retreat direction.

Figure 7. Reconstructed stages showing the evolution of the last BIIS in the Clyde basin. See text for discussion. Hill-shaded digital surface model built from Intermap Technologies NEXTMap Britain topographic data (NW illumination).

Figure 8. Computed geological model showing glacial deposits in the Clyde basin. Inset: geological model is vertically separated to show individual sediment packages.

Figure 9. Thicknesses of selected units. Upper panel shows till thickness draped over bedrock elevation model. Cumulative plots are shown for till thickness revealed from borehole observations, and for till thickness represented in the geological model. The overall thickness distribution in the geological model is consistent with the population of till thickness records from boreholes, demonstrating that the model remains faithful to the observed data.

Figure 10. Histograms of modelled till thickness, in areas where: till rests on Carboniferous sedimentary rocks (upper plot); and till rests on glaciofluvial sands and gravels (lower plot).

Figure 11. Till package overlying buried glaciofluvial deposits. This till package it likely to be wholly a product of the Late Devensian glacial cycle.

Figure 12. Drumlinised terrain in north Glasgow. The zone of buried glaciofluvial deposits revealed by the geomodel is delimited by the white dashed line. The extent of streamlining is statistically indistinguishable inside and outside this zone of buried glaciofluvial deposits.

LIST OF TABLE CAPTIONS

Table 1. Stratigraphy of glacial sediments in the Clyde basin.

Table 2. Computed volumes of glacial sediments in the Clyde basin.

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