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BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet

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BOREAS

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M. & Sheehy, M.: BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. *Boreas*. https://doi.org/10.1111/bor.12273. ISSN 0300-9483.

During the last glaciation, most of the British Isles and the surrounding continental shelf were covered by the British–Irish Ice Sheet (BIIS). An earlier compilation from the existing literature (BRITICE version 1) assembled the relevant glacial geomorphological evidence into a freely available GIS geodatabase and map (Clark *et al.* 2004: *Boreas* 33, 359). New high-resolution digital elevation models, of the land and seabed, have become available casting the glacial landform record of the British Isles in a new light and highlighting the shortcomings of the V.1 BRITICE compilation. Here we present a wholesale revision of the evidence, onshore and offshore, to produce BRITICE version 2, which now also includes Ireland. All published geomorphological evidence pertinent to the behaviour of the ice sheet is included, up to the census date of December 2015. The revised GIS database contains over 170 000 geospatially referenced and attributed elements – an eightfold increase in information from the previous version. The compiled data include: drumlins, ribbed moraine, crag-and-tails, mega-scale glacial lineations, glacially streamlined bedrock (grooves, roches moutonnées, whalebacks), glacial erratics, eskers, meltwater channels (subglacial, lateral, proglacial and tunnel valleys), moraines, trimlines, cirques, trough-mouth fans and evidence defining ice-dammed lakes. The increased volume of features necessitates different map/database products with varying levels of data generalization, namely: (i) an unfiltered GIS database containing all mapping; (ii) a filtered GIS database, resolving data conflicts and with edits to improve geo-locational accuracy (available as GIS data and PDF maps); and (iii) a cartographically generalized map to provide an overview of the distribution and types of features at the ice-sheet scale that can be printed at A0 paper size at a 1:1 250 000 scale. All GIS data, the maps (as PDFs) and a bibliography of all published sources are available for download from: https://www.sheffield.ac.uk/geography/staff/clark_chris/britice.

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Palaeo-ice sheets provide the opportunity to study ice-sheet behaviour over a longer time period (10 000s of years) than can be achieved by studying current ice sheets (10s of years) thereby permitting exploration of the long-term role of ice sheets in the climate system. The extent, geometry and dynamics of palaeo-ice sheets can be reconstructed from the geomorphological and geological evidence they leave behind, with the mapping, logging and description of such evidence being the vital ingredients. For many palaeo-ice sheets, such as the British–Irish Ice Sheet (BIIS), the accumulation of evidence at individual field-sites has been ongoing for well over 100 years (e.g. Geikie 1894) yielding thousands of publications. Using such work to build local to regional reconstructions of ice dynamics is feasible, but at the ice-sheet scale the volume of information becomes unmanageable. Often the information is spread across so many publications and across many decades of work, whereby interpretative modes often change; this is the *Compilation Issue*. Solving this problem assists in both illuminating the 'big picture' and in documenting and pointing to key local-scale work that might otherwise be lost. If we now consider an ice-sheet modeller interested in knowing how well their model simulations match with empirical evidence, of say ice-sheet extent and flow, compilations certainly help, but the issue of data availability, ownership and format then arises; this is the *Open Data Issue* (cf. The Royal Society Science Policy Centre Report 2012). Ideally then, evidence of ice-sheet activity could be compiled and made freely available in easily accessible data formats and maps, and also in a manner that promotes (and cites) the value of the individual building blocks of evidence.

During the last glaciation, most of the British Isles and the surrounding continental shelf were covered by the BIIS (for overviews see Chiverrell & Thomas 2010; Clark *et al.* 2012). To assist investigation of the extent and geometry of the former ice sheet covering Britain, the BRITICE project tackled the compilation and open data issues by reading relevant publications and assessing, collating and digitizing the described evidence-base of glacial landforms to create a publication reporting the

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methods (Clark *et al.* 2004), including a printed Glacial Map of Britain (at a scale of 1:625 000) and an accompanying freely available GIS geodatabase with >20 000 features (available from https://www.sheffield.ac.uk/geography/staff/clark_chris/britice). The compiled evidence was reviewed in Evans *et al.* (2005). The BRITICE V.1 map and these publications have been widely accessed and used by the scientific community, the education sector and the general public, with over 25 000 downloads from the website up to December 2016. The GIS files have been used to compare with results from numerical ice-sheet modelling (Hubbard *et al.* 2009; Patton *et al.* 2013).

A number of important developments, since the production of the original version, have highlighted its shortcomings and motivated us to fully revise the database to produce BRITICE version 2. Specifically, (i) much research has been published subsequent to the V.1 census date of 2002, along with various omissions and corrections; (ii) inclusion of data for Ireland (missing from BRITICE V.1) were required to better understand the entire ice-sheet footprint; (iii) the availability of high-resolution digital elevation models (DEMs) has permitted high-integrity mapping of the whole of the Irish and British landscapes (Greenwood & Clark 2008; Hughes *et al.* 2010) replicating patches of earlier field-mapping but considerably extending the coverage and improving the consistency; and (iv) mapping from newly available bathymetric data sets has revolutionized our information on submerged (offshore) glacial geomorphology (e.g. Graham *et al.* 2007; Bradwell *et al.* 2008; Benetti *et al.* 2010; Dunlop *et al.* 2010; Clark *et al.* 2012). Furthermore, the area covered by the last BIIS is now thought to have been considerably greater than previously envisioned, with glacial landforms and sediments recorded at many localities near the continental shelf break and across the North Sea Basin (Bradwell *et al.* 2008; Clark *et al.* 2012; Praeg *et al.* 2015; Thébaudeau *et al.* 2015; Sejrup *et al.* 2016). The purpose of this paper is to present an updated glacial map and geodatabase of glacial landforms relating to the BIIS, and to highlight the evidence gathered in the 15 years since the Clark *et al.* (2004) and Evans *et al.* (2005) syntheses. The aim of this compilation is the same as that of the original version: to present the geomorphological evidence pertinent to the behaviour of the whole ice sheet, and with emphasis on the primary observations rather than wider interpretations based upon them. The increased volume of features in V.2 (Fig. 1) necessitates different map and database products with varying levels of generalization and abstraction (see later).

Method of database creation

During the last glacial the British–Irish Ice Sheet is considered to have reached its maximum areal coverage around 27 ka BP in the Dimlington Stadial of the Late Devensian Substage (British chronostratigraphical unit) and its Irish equivalent the Late Midlandian Substage (Gibbard & Clark 2011). These are equivalent to the Late Weichselian and Late Wisconsinan elsewhere in the world (Europe and North America) and to Marine Isotope Stage 2 (MIS 2). We restrict inclusion of features in the database to those that are reasonably known to have formed in this last glaciation. Most glacial landforms in the British Isles, especially those that are depositional rather than erosional, undoubtedly relate to the last ice sheet that covered the area, but it is worth noting that this is a presumption on the basis of them being at the surface and that ice sheets are usually considered to be effective at destroying landforms from previous glaciations. We note that most landforms have not actually been geochronometrically dated as belonging to the last glacial; the task would be huge. Some of the landforms may belong to earlier glaciations, but we suspect this to be rare (e.g. Kleman 1994).

Figures and maps of glacial landforms published since 2002 were sought from journal articles, Ph.D. theses, British Geological Survey archives and Geological Survey of Ireland databases, including omissions that we were alerted to from prior to this date. Figure 2 outlines the procedure employed to compile these mapped features into the GIS database. The census date for the version we report here was 31/12/2015. The most recent data for Ireland can be accessed through the map viewers on http://www.gsi.ie. In Britain, studies relating solely to the Loch Lomond Stadial (LLS; equivalent to Greenland Stadial 1 and Younger Dryas) were not included, and we note that these are the focus of a similar map and GIS compilation produced by Bickerdike *et al.* (2016) and the main LLS ice limit is recorded on V.1 of the Glacial Map (Clark *et al.* 2004). However, some features within the LLS limit are included, as they are reported within regional studies, remain undated, and may actually relate to deglaciation of the main Dimlington Stadial (MIS 2) ice sheet. In cases where authors kindly provided us with their mapping in digital form (e.g. shapefiles) no further georeferencing was required and data entry was straightforward (Fig. 2). For the majority of cases however, data gathered from the literature were georeferenced using the annotated grid or tick marks in their figures and maps. Where such positional marks were absent or insufficient for georeferencing, the geomorphological data were visually transferred to a (Ordnance Survey) topographical map of the area using features such as coastlines, rivers or mountain summits, as a guide. Although probably rare, positional errors of 100s of metres could occur due to insufficient or inaccurate geographical referencing of maps in the source publications and due to our attempt to position features using the above method. When using the database we recommend the original sources are consulted whereupon such geo-locational issues can be readily appreciated. For consistency across the GIS

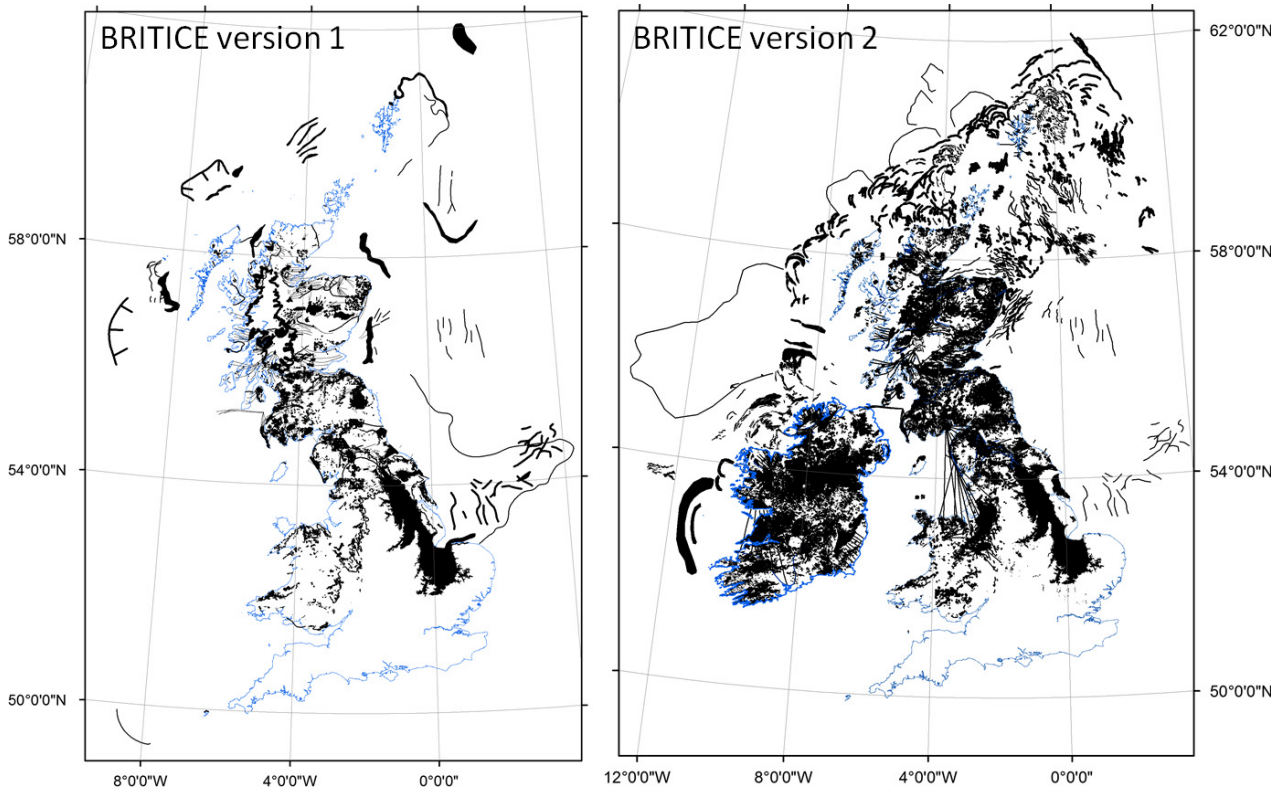

Fig. 1. Comparison of the density and distribution of mapped features (in black) in the previous version (V.1 >20 000 features) with the new version (V.2 >170 000 features). The main additions are coverage of Ireland, offshore ice-marginal features, subglacial bedforms are individually mapped rather than their pattern generalized, and the inclusion of many more meltwater channels.

database all shapefiles are stored in a common projection (British National Grid).

Once the figures and maps had been georeferenced, the features were manually digitized into thematic layers and a citation to the published source and any additional comments were recorded in the GIS attribute table. The manner in which individual features are linked to their source citation varies, but always a source is noted, sometimes more than one. Many published figures and maps are inadequately drafted with respect to geographical coordinates, which can lead to them appearing in the wrong place once entered in the GIS. To improve the spatial accuracy of each feature, a further process of correction was undertaken by comparison to a high-resolution DEM (of 5 m grid-size; ©NEXTMAP GB, Intermap Techologies) whereby the true geographical location of a meltwater channel for example could be ascertained. Features were thus moved short distances (100s of metres) where deemed necessary (Fig. 3). This procedure was also applied to the V.1 data, thereby improving the positional accuracy of individual features. If landform features appeared to be absent from the DEM they were considered to be below the DEM resolution and so were not moved. Offshore, such adjustments were not possible, but the majority of offshore mapping appears to have low georeferencing errors (<5 m), due to the availability of grid references.

The Geological Survey of Ireland (GSI) conducted a similar procedure to that of the BRITICE V.1 above for Ireland with an objective to produce a spatially accurate geomorphology database. Features were mapped directly from Ordnance Survey Ireland (OSI) aerial imagery and DEMs and GSI LiDAR data. Reports in the literature (e.g. Flint 1930; Knight *et al.* 1999; McCabe *et al.* 1999; Greenwood 2008), where available, were consulted and considered. These features were amalgamated with that of BRITICE V.1 data and the updated features were digitized from the recent literature into an 'Unfiltered GIS Database' (Fig. 2). This unfiltered database is available for download, and retains all the features that were considered for the Glacial Map including conflicts and repetition where features have been mapped more than once, as well as citations to the original sources.

To avoid unnecessary confusion, duplications of mapped features were manually removed to build the filtered database. References and comments pertaining to the removed features were added to the attribute table of the remaining feature in order to retain traceability to the original workers and provide historically appropriate citations. In this reconciliation process the choice of feature to retain was based upon geo-locational accuracy, regional consistency with other features and the level of detail. Figure 4 illustrates an example of this reconciliation process (for an unusually popular area!)

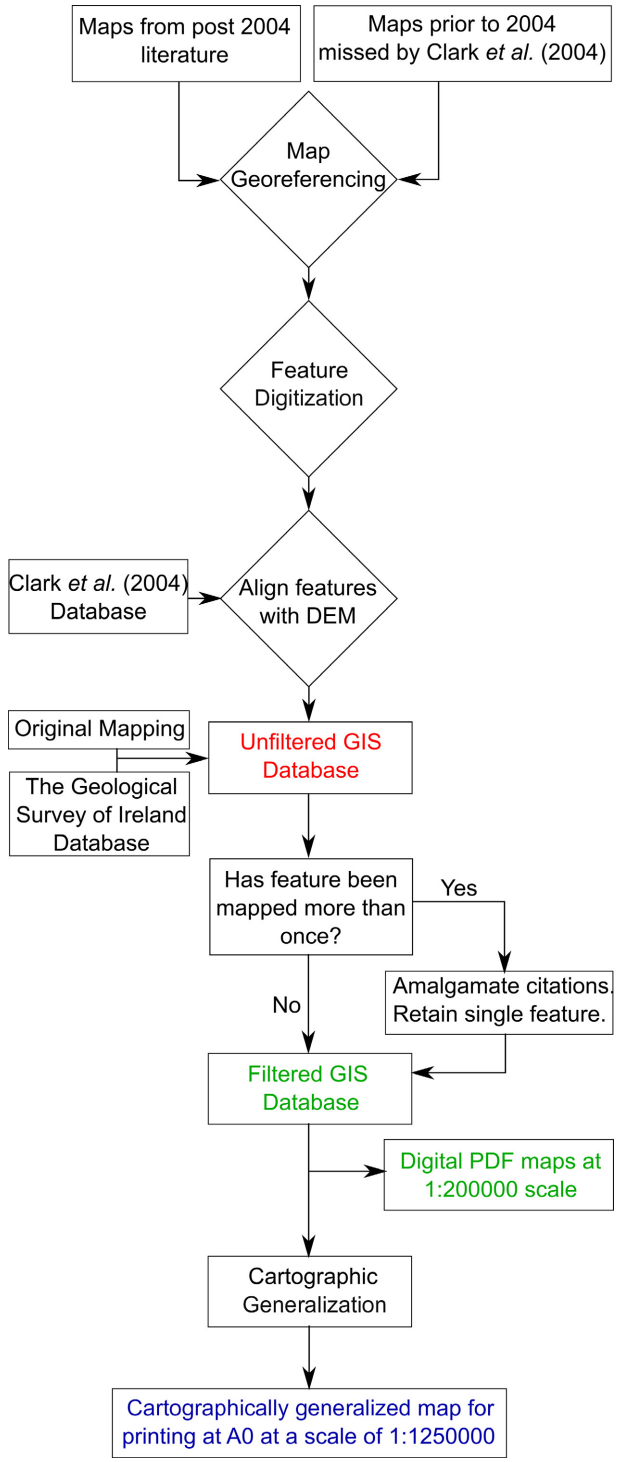

Fig. 2. Methodological overview of work-flow for database creation, and the three main products made available (highlighted in colour). See text for more details.

and also shows a rare example of conflict resolution where the same geomorphological features have been interpreted as different glacial landforms. In such cases, for historical correctness, both interpretations are retained in the attribute table of such features in the unfiltered data set.

Although conflicts of interpretation between feature types were rare, other examples of conflicts between the V.1 database and subsequent mapping (e.g. Hughes 2009; Hughes *et al.* 2010) were also resolved for the filtered database. This was mostly where the categorization of meltwater channels had been improved or changed (i.e. subglacial, lateral or proglacial types). In such cases the alternative interpretations are listed in the attribute table of those features.

Two landform types not recorded in BRITICE V.1 are included in this revised synthesis, namely glacially moulded bedrock and cirques (corries, coombes or cwms). For the inclusion of glacially moulded bedrock an extensive literature review was undertaken and the procedure outlined in Fig. 2 adopted. For the inclusion of cirques, we found that publications and maps did not sufficiently distinguish between arêtes, glacially moulded scarps and true cirques, and most mapping focussed on their distribution rather than their individual shape and size (e.g. Evans 2006). For these reasons, cirques were manually digitized from available high-resolution DEMs (NEXTMAP 5 m for Britain, SRTM 30 m for Ireland), using published distribution maps as a guide to their locations. Each cirque was given a confidence rating following Evans & Cox (1995), ranging from classic (1) to speculative (5). Publications covering cirques for each of the areas are referenced in the attribute table of the cirque shapefile. These two new landform types were added to the existing types from V.1 (subglacial lineations, crag-and-tails, eskers, subglacial ribs, meltwater channels, moraines, trimlines, trough-mouth fans, proglacial lakes and information regarding erratics) to yield our revised glacial geomorphological map of the BIIS.

Due to the high density and detail of the assembled features in the V.2 filtered database, two map products of differing scale, detail and purpose are presented. Three large maps, which contain all features in the filtered database (Fig. 5A) are made available as PDF files (Ireland, projected to Irish National Grid; North Scotland and offshore, British National Grid; and mainland Britain, British National Grid). These are designed to be viewed digitally at scales of around 1:200 000. Users can 'pan' across them or zoom and perhaps print off selected local regions of interest. However, the level of detail and scale prevent any sensible printing of the whole map (paper size would need to be around 5 by 5 metres). Therefore, we also present a cartographically generalized map of the whole ice-sheet domain (excerpt shown in Fig. 5C; and whole map in Fig. 10). Lengthy endeavours were required to produce this map with the density of features reduced via a process of cartographic generalization. Taking inspiration from the Glacial Map of Canada (Prest *et al.* 1968), multiple landforms were

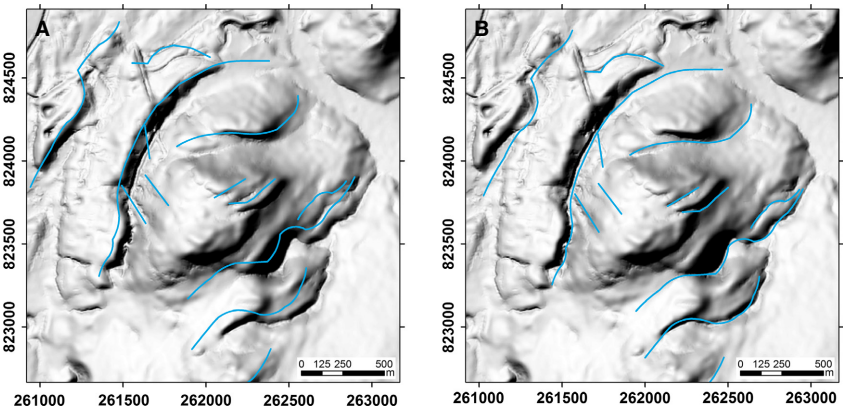

Fig. 3. Example of editing the position of mapped features to better fit the correct locations. A. Meltwater channels mapped by Turner *et al.* (2014), near the Great Glen region of Scotland, appear misaligned with their DEM representation due to georeferencing errors. B. These features were therefore moved to correspond to the DEM (which has a robust geocoding) in order to improve their positional accuracy.

often grouped under the same symbol. Figure 5 shows an example of feature rationalization in this manner. The generalized map is projected to the British National Grid.

Mapped features

Over 170 000 features exist in the filtered database as a series of thematic GIS shapefiles. Each feature class is

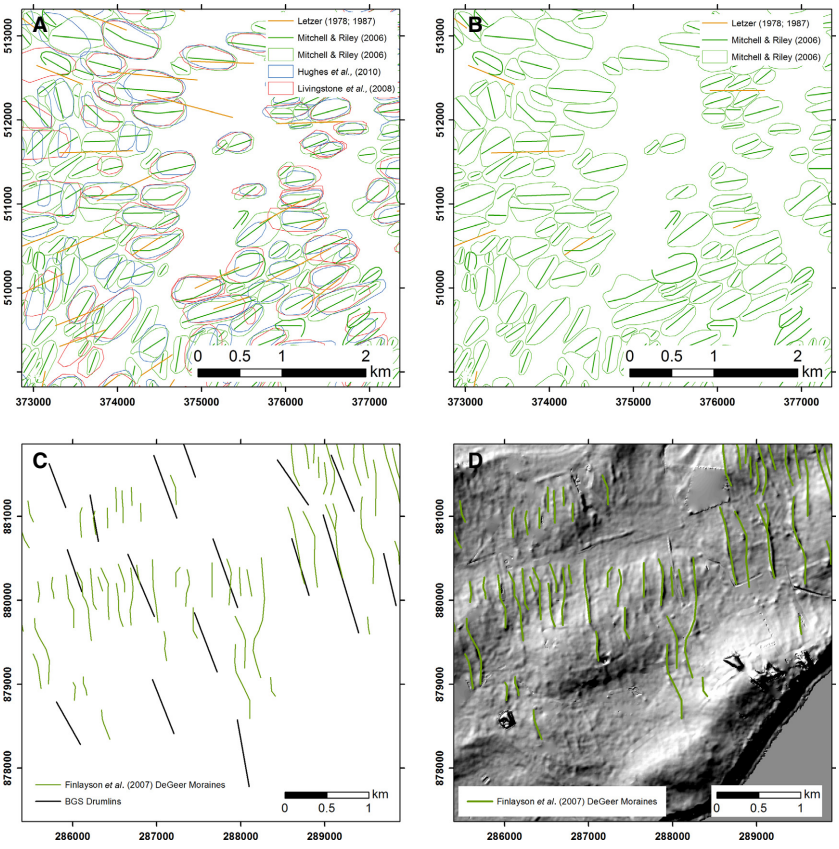

Fig. 4. Examples of landform reconciliation arising from conflict detection, duplication and resolution. A. Drumlins in the unfiltered database located in the Vale of Eden, England, illustrating up to fivefold duplication in their mapping. B. The filtered database used for map production. Note that in this case the majority of remaining features are from Mitchell & Riley (2006), due to the higher level of detail presented in that study. C. A rare example of a conflict in feature interpretation. In this location near between the Cromarty and Dornoch Firths, northeast Scotland, the same landforms have been mapped and interpreted as drumlins (British Geological Survey 1972) and as DeGeer moraines (Finlayson *et al.* 2007). D. Through consulting with the conflicting sources, the interpretation of DeGeer moraines is retained, based upon their scale, morphological appearance and supporting evidence in Finlayson *et al.* (2007).

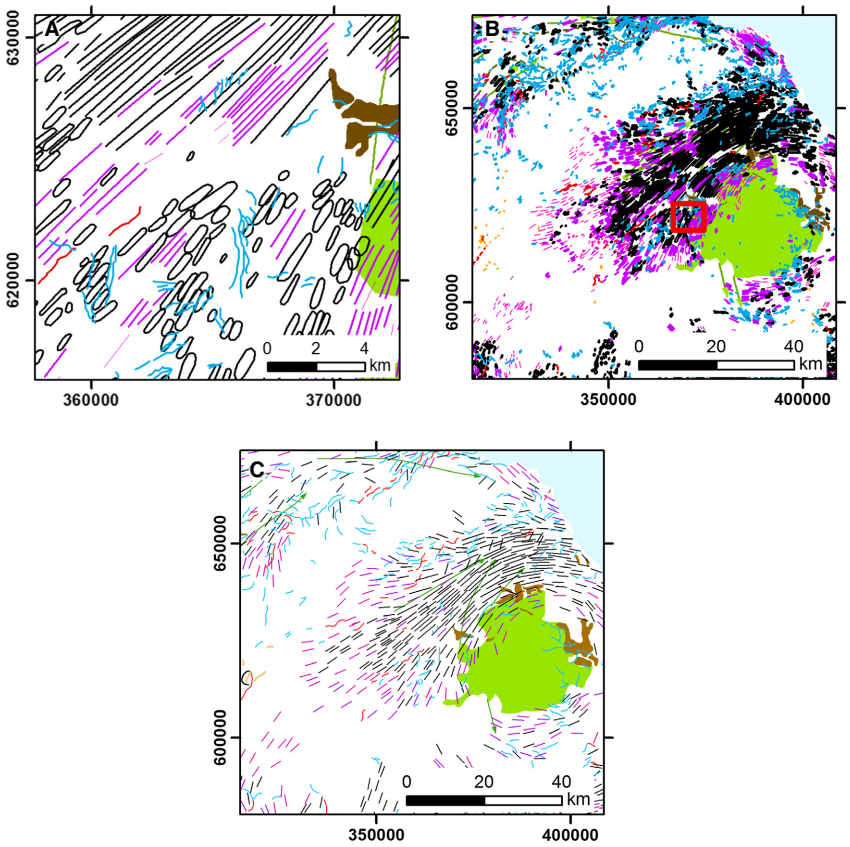

Fig. 5. An example of the generalization process, centred on the Tweed Palaeo-ice stream area, NE England. A. Small excerpt of the filtered database, showing the level of detail. B. Database over a broader area demonstrating that the density of features at this scale renders the map incomprehensible. Red box marks the position of excerpt in (A). C. Example of how data density were reduced, by cartographic generalization, to produce a map that is comprehensible at the scale of the whole ice sheet (AO at 1:1 125 000).

recorded as either polygons or lines appropriate to the size and nature of the landform. As illustrated in Fig. 6 each feature can be queried (via the attribute tables) to reveal the source publication from where the feature was taken, as well as further comments including sources within which the same feature was reported or mapped. Below we report on further details per theme.

Subglacial bedforms and crag-and-tails

Subglacial bedforms are the most common features in the database, totalling 106 367 polygons or lines (13 236 subglacial ribs; 85 824 subglacial lineations; and 7307 crag-and-tails). No subglacial ribs (i.e. Rogen or ribbed moraine) were included in the BRITICE V.1. Here we compile mapping of vast swathes of subglacial ribs in the 'Drumlin Belt' of Ireland (Knight & McCabe 1997; Clark & Meehan 2001; Greenwood & Clark 2008), which often display transitions into drumlins or are superimposed by drumlins (Fig. 7). Subglacial ribs occur less often in Britain, but noteworthy examples occur in northern Scotland (Finlayson & Bradwell 2008), west of Glasgow (Finlayson *et al.* 2010), in the Solway lowlands (Livingstone *et al.* 2008; Hughes *et al.* 2010) and offshore of Anglesey (Van Landeghem *et al.* 2009).

Subglacial lineations are stored in polygon or line shapefiles according to how they were originally mapped by the authors. Whilst grouped here as 'subglacial lineations', reference to their reported landform 'type' (drumlin or mega-scale glacial lineation) is recorded in the attribute table. The majority of subglacial lineations are of a size and shape that would class them as drumlins (Clark *et al.* 2009). These drumlin fields form radial, often cross-cutting, patterns (Livingstone *et al.* 2008; Hughes *et al.* 2010, 2014). Irregular shaped drumlins occur south of Dumfries (Salt & Evans 2004; Hughes *et al.* 2010). These features are distinguished in the attribute table of the lineation shapefile as 'tadpole drumlins' after Hughes *et al.* (2010). The lineation record has also been extended offshore, with drumlin fields being found on the seabed in several studies (e.g. Van Landeghem *et al.* 2009; Benetti *et al.* 2010; Dunlop *et al.* 2010; Howe *et al.* 2012; Bradwell & Stoker 2015; Fig. 7B). Mega-scale glacial lineations (Clark 1993; Spagnolo *et al.* 2014; Ely *et al.* 2016) also occur near Berwick-upon-Tweed (Everest *et al.* 2005;

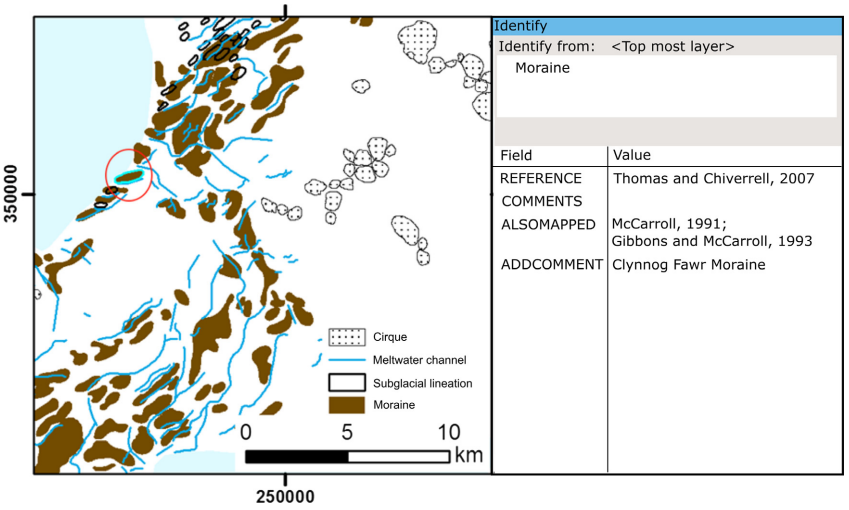

Fig. 6. All features within the GIS can be queried to reveal the source publication from which the feature was taken, and further comments including alternative sources that may have also reported or mapped it. In this example from the Lleyn Peninsula in North Wales, clicking and highlighting (cyan) the moraine ridge near the top-left (see red circle), opens up data from the attribute table (on the right), which reports the reference from which the work was taken and citations to earlier work that also reported on the feature.

Hughes *et al.* 2010), near Drogheda and Charlestown in Ireland (Greenwood & Clark 2008; Meehan 2013), and have been imaged beneath the seabed in the North Sea Basin (Graham *et al.* 2007).

Numerous studies subsequent to the V.1 database differentiate between subglacial lineations and crag-and-tails. Their identification and differentiation are aided by the use of high-resolution imagery, which better resolves the crag, or by additional detail being provided on the surface materials and sediment thickness (e.g. Greenwood & Clark 2008; Hughes *et al.* 2010). Hence, crag-and-tails are now distinguished as a separate layer in the database, and we suggest they are displayed in GIS as arrows, because their flow direction is evident. There may of course be landforms in the subglacial lineation category that are in fact crag-and-tails but we had insufficient detail with which to observe the crag.

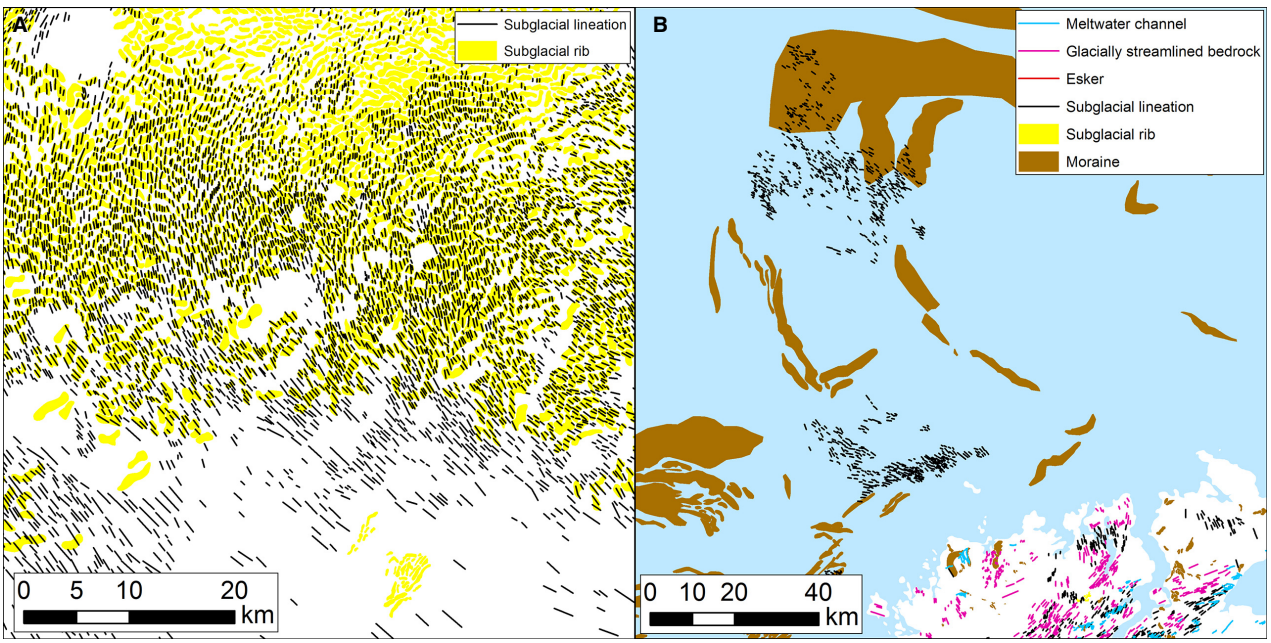

Fig. 7. Examples of subglacial bedforms and other landforms as portrayed on the Glacial Map. A. Subglacial ribs and drumlins across the 'Drumlin Belt', central Ireland. B. Drumlins and moraines mapped on the Malin shelf sea floor, northwest Ireland (see Benetti *et al.* 2010 and Dunlop *et al.* 2010), merged with onshore data.

Due to high-resolution geospatial data and continued extensive field mapping since 2002, we now have a comprehensive picture of the occurrence and distribution of subglacial bedforms onshore in Britain and Ireland. This could be improved by further field studies and the interpretation of improved resolution DEM and imagery. Our knowledge of offshore subglacial lineations has also improved since the V.1 database but higher resolution bathymetric data is required to complete the coverage and improve the detail. Especially useful may be 2D and 3D sub-bottom geophysical data, to reveal bedforms that have been buried by postglacial sediments (e.g. Stoker & Bradwell 2005; Graham *et al.* 2007).

Glacially streamlined bedrock

It is often possible to discern streamlining and former ice-flow direction from exposed bedrock surfaces (e.g. Bradwell 2005) expressed as lineated or grooved surfaces or as streamlining in the form of roches moutonées or whalebacks. Such information drawn from publications yielded 14 529 features that we have recorded mostly as simple lines showing the sense of flow orientation and sometimes as polygons revealing the areal extent, for example, of roches moutonées. Where authors have distinguished between the various forms of glacial streamlining comments to this effect are made in the attribute tables. These layers are best used to provide information on former ice-flow direction, and zones of glacial erosion on hard beds. The map should be regarded as a reconnaissance-level database in that it is far from complete or systematic in its categorizations between various landform types. We suggest that there is much further work that could be conducted on the distribution and form of these erosional subglacial landforms so that they can be more effectively used in palaeoglaciological reconstructions.

Erratic transport

For Britain not much new information has been uncovered for erratics since V.1 but we have now included such information for Ireland. The sources of erratics are depicted as either a polygon defining the source bedrock area or as a line defining a lithological boundary. The erratics are located at the downstream end of the shapefile lines (erratic paths; best displayed with an arrowhead) and the precise route of the path is merely inferred from other ice-flow directional indicators such as subglacial bedforms. We accept that the actual transport path could have been very different and the erratic may have moved in a number of discrete stages. Where authors noted the limits defining a line beyond which erratics were not found, these lines have been added (erratic limits). For Ireland, further information on how ice flow transported subglacial materials can be seen in the work of Greenwood & Clark (2009) where they relate and map till lithologies to their upstream bedrock outcrops. For more information on the erratic layer refer to the V.1 paper (Clark *et al.* 2004).

Eskers

Our map now includes the extensive esker systems of Ireland, with a total of 4662 esker segments (i.e. individual mapped ridges that comprise an esker system) portrayed as polygons and lines in ESRI shapefile format. As the underlying data from which the esker systems were compiled came from surficial geological maps, academic publications (e.g. Warren & Ashley 1994) and close scrutiny of the entire terrestrial areas using DEMs, we consider that the database on esker distribution is nearly complete and is a comprehensive systematic record. Use of improved resolution DEMs and imagery coupled with analysis of field exposures and geophysical surveying should permit improved extraction of information in the future.

Meltwater channels

Meltwater channels (n = 27 916) are recorded for terrestrial and offshore areas and where authors have interpreted their various types this information is recorded in the attribute tables. Types include: subglacial meltwater channel; lateral meltwater channel; proglacial channel; tunnel valley; or as unspecified meltwater channel. Many of the channels have been systematically categorized into these types according to the criteria of Greenwood *et al.* (2007), and with levels of confidence in the interpretation annotated in the attribute tables. For the terrestrial part of Britain this layer is probably nearly complete because it was conducted by systematic mapping from a high-resolution (5 m) DEM, although it is likely that more channels could be found with analysis of higher resolution DEMs (e.g. from Lidar). Field checking could help because true meltwater channels can sometimes be difficult to distinguish from postglacial subaerial channels and because the latter sometimes occupy the former, further confusing the origins. Meltwater channels in Ireland were mapped from OSI elevation data and aerial imagery at a resolution of 10 m and further mapping at higher resolution would probably find many more examples than are shown here. Many meltwater channels remain to be discovered and mapped for the offshore areas, and most of the data reported here relate to the larger features (i.e. tunnel valleys) and hence this layer is far from complete. A difficulty is that multiple sets of tunnel valleys are often visible in sea-floor and sub-bottom geophysical data, only some of which will have been cut or occupied during the last glaciation. Using stratigraphical superposition and observations of sediment infilling to distinguish between valleys of different age is a large task that we have not undertaken and we merely report those already

deemed to be of last glacial in age. We suppose that in reality there will be many more such features, and consider that identifying them is an important future task (e.g. Jørgensen & Sandersen 2006; Kristensen *et al.* 2007).

Moraines

The moraine layer has been significantly extended and fully revised in comparison to the V.1 edition. This is mostly due to improved offshore data coverage where extensive moraine systems have surprisingly been found since BRITICE V.1 (e.g. Bradwell *et al.* 2008; Dunlop *et al.* 2010; Clark *et al.* 2012) and by systematic survey of the whole terrestrial area using DEMs and satellite images (Greenwood 2008; Hughes 2009; Clark *et al.* 2012; Meehan 2013). The layer now contains 15 109 moraines, recorded as lines for the smaller features and polygons for larger features. It is probably the most useful layer in the database, because for the first time we now have an impressive continental-shelf-wide spatial spread of information that records the retreat pattern of the whole ice sheet. A cumbersome and internally conflicted nomenclature exists for categorizing moraines, one which we largely ignore in our database (although see comments in the attribute tables). For our purposes we take a broad view of the definition of a moraine as including any accumulation of sediment with a positive topographical expression forming a distinct landform and that has been interpreted to have accumulated ice-marginally. Moraines usually comprise glacial diamict but our broad definition includes ice-contact fans that may contain fluvially deposited sands and gravels. No distinction is made between terrestrial and offshore setting (e.g. moraines vs. morainal banks) and some of the latter features probably include grounding-zone wedges.

Trimlines

Weathering limits, separating mountain summits with frost-weathered detritus from lower elevation ice-scoured slopes are frequently recognised in the uplands of Ireland and Britain; many have been called trimlines. We have now updated this layer to include trimlines in Ireland and with more examples from Britain from papers published since the census date for V.1. A total of 187 summits are now identified. Previously, in Clark *et al.* (2004) we noted that authors of papers usually interpreted trimlines as marking the maximum upper limit of the ice sheet – thereby defining nunataks – but that an alternative interpretation also existed; that trimlines marked subglacial boundaries between erosive warm-based ice and non-erosive cold-based ice. More recently, cosmogenic-nuclide dating of glacially deposited boulders on some Scottish and Irish summits above mapped trimlines has yielded exposure ages that falsify the interpretation of the trimline representing the maximum upper ice-sheet surface elevation (Fabel *et al.* 2012; Ballantyne & Stone 2015). These authors suggest that these cosmogenic-nuclide data support the interpretation that British and Irish trimlines mark boundaries or zones between warm-based and cold-based ice. It remains an open question as to whether all trimlines in the database were produced at ice-sheet thermal boundaries or whether both types exist. Trimlines are retained in the database as important markers of ice-sheet activity and erosional evidence, and it will prove interesting to compare their location with ice-sheet modelling experiments that track such subglacial thermal boundaries and their evolution over time.

Cirques

New to this version of the Glacial Map we include glacially produced part-open hollows cut into mountain flanks and variously called corries (Scottish), cwms (Welsh) or cirques (French and internationally used). Whilst much has been published on British and Irish cirques (e.g. Harker 1901; Sale 1970; Evans 2006) a complete map of their occurrence and distribution has until now been missing. The database contains 2208 examples. The cirques range in size from 47 to 965 m in depth (relief) and with mean elevations above sea level from 64 to 1188 m and they exist in all the main upland regions including some islands. The method of cirque mapping and analysis of their size and shape are to be reported elsewhere. In the attribute table we include data on cirque metrics including: length, width, a measure of circularity, minimum, maximum and mean elevations, directional aspect, mean slope, a measure of plan closure, distance to modern day coastline, information on their host rock lithology, and the cirque name (e.g. Cwm Idwal), and a grade indicative of its certainty and definition (Evans & Cox 1995). We suggest that within the limits of cirque definition that this is a complete record across the landscape.

Trough-mouth fans

Major accumulations (or fans) of sediment deposited at the continental shelf edge interpreted to have been mostly fed by focussed ice-sheet flow, such as in ice streams, are included. Six large examples are portrayed, namely: the Foula Wedge; Sandoy Fan; Suduroy Fan; Rona Wedge; Sula Sgeir Fan; and the huge (300×200 km in size) Barra and Donegal Fan.

Ice-dammed lakes

In common with the V.1 database we break with the restriction of only including glacial landforms by providing layers relating to ice-dammed lakes. We do so because they provide important information on the position of ice margins. Glacial lakes have mostly been reported in the literature from lake deposits found in positions that require an ice margin to dam the water body. A polygon layer defines the extent of ice-dammed lakes interpreted by authors of the cited publications. Caution is required in

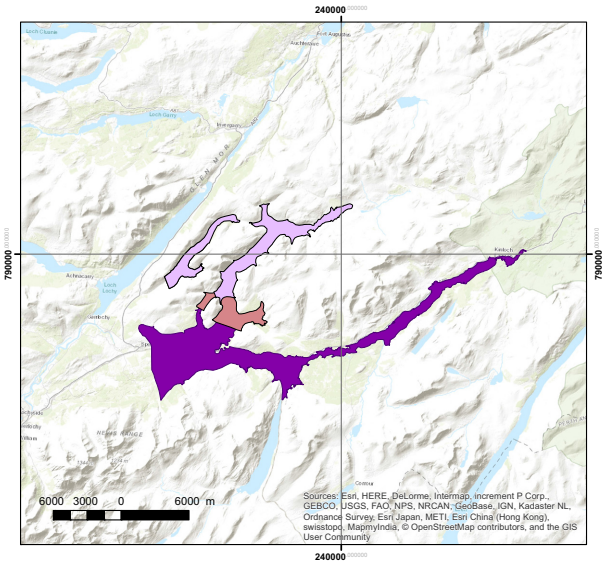

Fig. 8. Map representation of a series of ice-dammed lakes (in purple hues) in Glen Spean, Glen Roy and Glen Gloy, Scotland. Note that the ice-dam positions are to the south and west and that multiple water levels (355, 350, 325, 260 m a.s.l.) and lake extents are defined, from which the positions of impounding ice margins can be inferred. These lake extents are from Turner *et al.* (2014) and this paper and the wider literature of the area should be consulted for information on the relative and absolute timing of the lakes; the colouring and superposition shown here are merely to illustrate their extents.

that the evidence is rarely complete enough to robustly define full lake extents. Furthermore, potential glacio-isostatic adjustments are at present unknown and hence we assume horizontal shorelines, an assumption that is almost certainly incorrect. Typically it is necessary to extrapolate far beyond patches of evidence with the aid of manual 'contour-following' or using GIS operations on DEMs. The evidence for ice-dammed lakes mostly comes from the elevation of sediments interpreted as being lacustrine found in sedimentary sections or from boreholes, or in some cases by shorelines or spillways. One layer defines former lake extents, and in V.2 we have also included multiple water levels and concomitant lake extents where these have been defined in the literature (Fig. 8). The most notable examples of multiple lake levels are seen in the Scottish Glens of Spean, Roy, Gloy and Doe (from Turner *et al.* 2014) and the various levels of Lake Lapwoth and its nearby lakes in the Cheshire-Shropshire lowlands (Murton & Murton 2012). A thematic layer (Lake-dams) is used to define the approximate position and orientation of the inferred ice position required to hold back the lake body, and thereby provides an indication of the direction of ice retreat. Given that the existence of ice-dammed lakes is primarily defined by observations of lake sediments, a polygon layer is provided to show their distribution where authors have inferred they arise from ice-dammed rather than normal (non-ice-dammed) subaerial lakes. Over 50 British glacial lakes are defined in the database, but no information is provided for Irish cases even though examples are reported in the literature. The information on ice-dammed lakes should be seen as a work-in-progress as there is much more that needs to be achieved with Irish and additional British lakes being defined and their extents and lake levels more robustly established. Murton & Murton (2012) do an excellent job reviewing the work on ice-dammed lakes and defining lake extents, levels and ages. We drew heavily from this work and readers are referred to it for lakes in our database and especially so for analysis of the weakly constrained, and not uncontroversial, large lake in eastern England (Glacial Lake Fenland and its possible connection to Lake Humber). Our database does not include the large ice-dammed (Dogger) lake that is thought to have existed in the southern North Sea Basin (e.g. Belt 1874; Valentin 1958; Woldstedt 1958), because substantive evidence for the lake has yet to be found and published even though it must surely have existed given the terrestrial emergence of this area, with a topographical depression and a complete ice dam across the North Sea preventing northwards escape of water (Sejrup *et al.* 2016).

Conclusions

We have undertaken a survey of the glacial geomorphological evidence of onshore and offshore Britain and Ireland to produce a new BRITICE map and GIS database (version 2). To our knowledge, all published geomorphological evidence in the themes that we targeted and relating to the extent and behaviour of the last ice sheet that covered much of the British Isles is now included (up to the census date of 31st December 2015). The fully revised GIS database contains over 170 000 geospatially referenced and attributed elements – an eightfold increase in information from the previous version (V.1; Clark *et al.* 2004). The spatial coverage has been increased (Ireland and continental shelf) and some new thematic layers added (cirques, crag-and-tails and glacially streamlined bedrock). The geolocation of many features has been improved. Data are stored in thematic layers including: drumlins, ribbed moraine, crag-and-tails, mega-scale glacial lineations, glacially streamlined bedrock (grooves, roches moutonées and whalebacks); glacial erratics; eskers; meltwater channels (subglacial, lateral, proglacial and tunnel valleys); moraines; trimlines; cirques; trough-mouth fans and evidence defining ice-dammed lakes. Not included are themes such as raised shorelines, glacial striae, hummocky moraine, kame terraces, periglacial and aeolian landforms, alluvial and delta-fans, which if compiled in a future version, could help constrain aspects of ice cover, retreat and dynamics. Features thought to relate to previous glaciations (e.g. Anglian Stage) are also not included and could form the basis of future work. Features relating to the later and smaller Loch Lomond Stadial ice masses are excluded, but have already been compiled in Bickerdike *et al.* (2016). Comments or help to correct mistakes or add

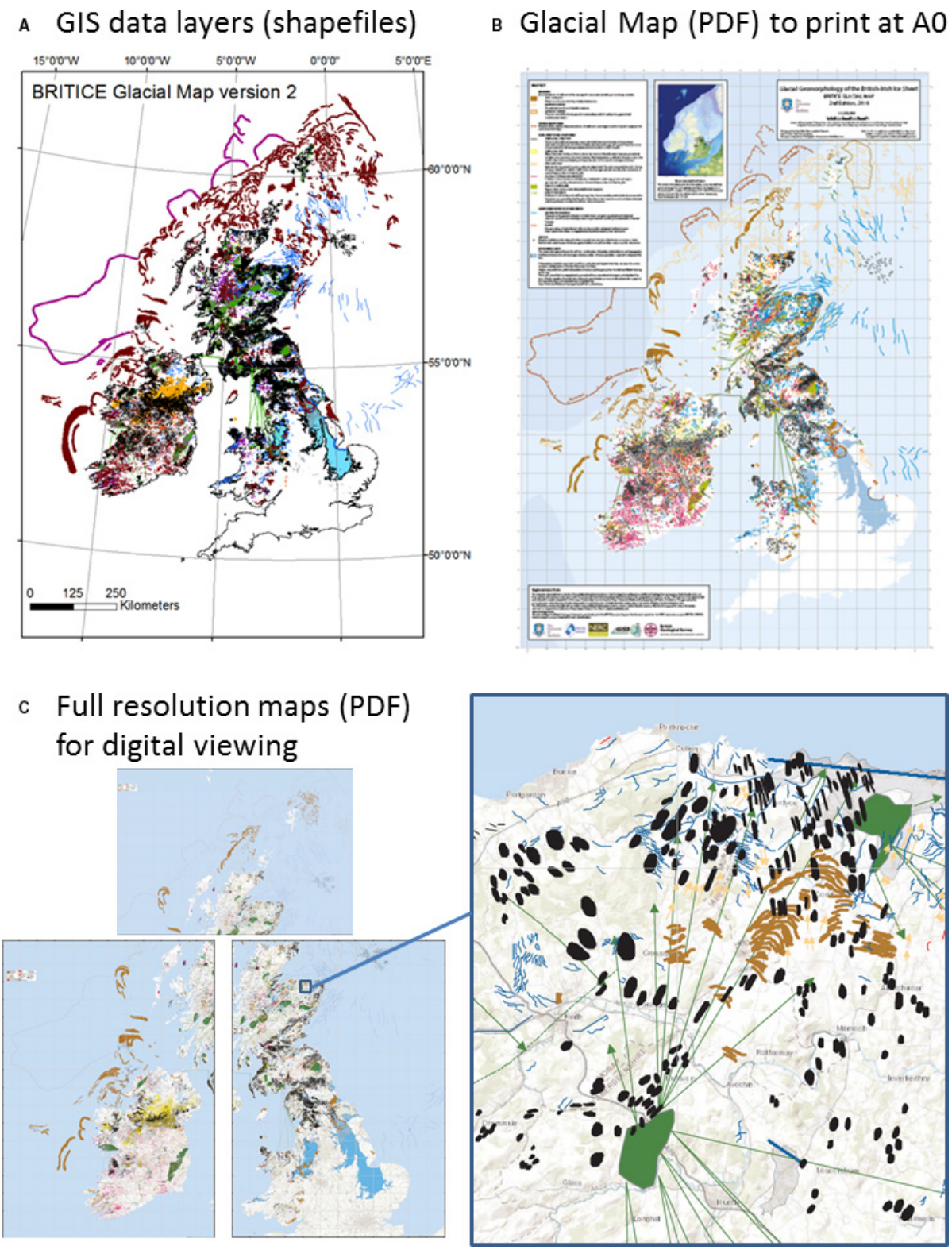

Fig. 9. BRITICE V.2 is available in varying scales and formats, with different levels of generalization and abstraction, which vary according to their anticipated use. A. Full-resolution GIS database (filtered or unfiltered), best used for maximum levels of information and for local to regional scale investigations. Data are provided as ESRI ArcMap shapefiles (Data S3). B. Cartographically generalized map (PDF) to provide an overview of the distribution and types of features at the ice-sheet scale (see Fig. 10, Data S2). C. Example of viewing the full-resolution database without using GIS. A series of three maps is available which are designed to be viewed as digital PDFs at scales of around 1:20 000 across which one can 'pan and scroll' to view areas of interest, or to print out selected areas (Data S2).

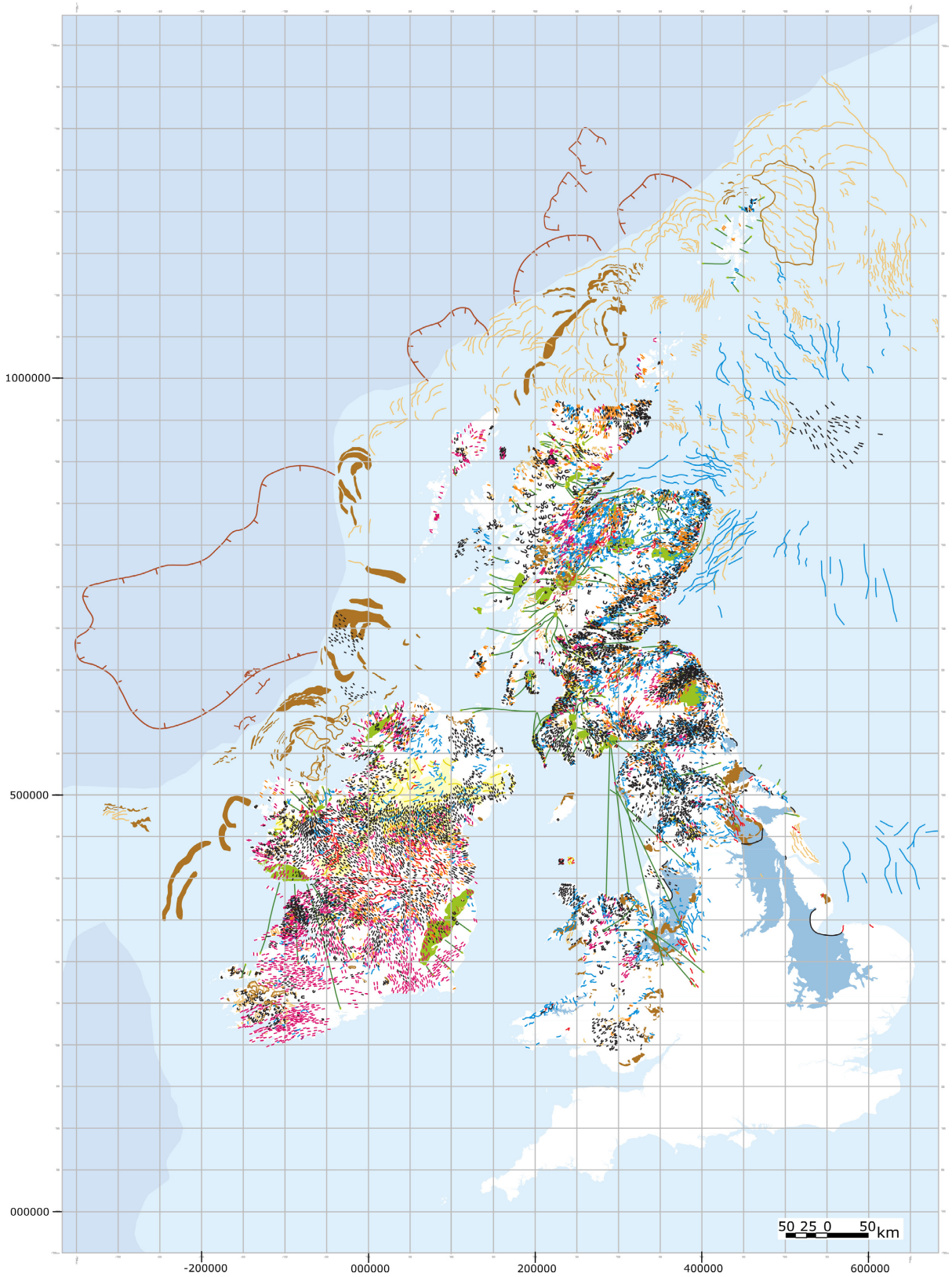

Fig. 10. Overview of the cartographically generalized Glacial Map designed for viewing or printing at a paper size of A0 (84×119 cm) and scale of 1:1 250 000. The features are not properly visible at the scale reproduced here: refer to the PDF that can be downloaded (see note at end of the paper and Supporting Information).

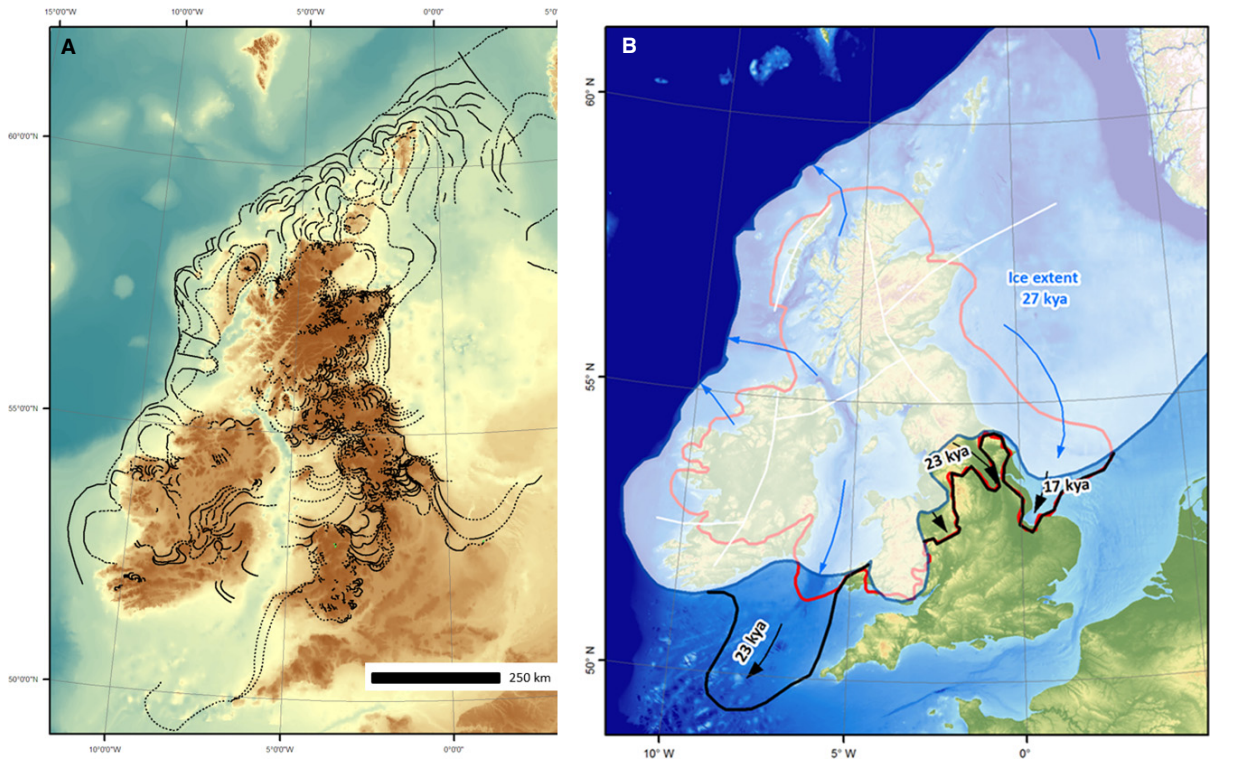

Fig. 11. A. Reconstruction of the pattern of retreat for the British–Irish Ice Sheet inferred from data in the BRITICE V.2 database, including moraines, meltwater channels, eskers and subglacial bedforms (adapted from Clark *et al.* 2012). B. Overview of the maximum ice-sheet extent, noting that it reached this at different times in various sectors. The red line depicts the earlier long-standing view of an ice sheet of more restricted extent as summarized in Bowen *et al.* (1986), and the white-shaded area shows ice extent at 27 ka BP with black lines depicting subsequent advances of the southern margin (from Clark *et al.* 2012).

new layers for a future version are welcome and should be directed to the lead author.

We encourage users of this BRITICE V.2 database to fully read this article and the V.1 publication so that they can appreciate and pay due regard to the caveats that we clearly set out regarding data quality and geographical spread. The revised database has some inconsistencies, most notably that some layers are nearly complete (e.g. subglacial bedforms) whilst some exist at a more reconnaissance-level (e.g. ice-dammed lakes). Consequently, the absence of features on the map in a specific place might merely reflect the failure of the research community to find them (or us to compile them) rather than a real absence. The V.1 map included 'drift limits', but this layer has been retired in this version. Meltwater features have been especially difficult to categorize into their subtypes (e.g. lateral meltwater channels; subglacial meltwater channels; tunnel valleys/channels) and we note that unlike most other layers that these have yet to be scientifically exploited, along with the eskers, to gain insight regarding subglacial hydrology. Given the high topographical variability across the British Isles, along with a mostly temperate former ice-sheet cover, we regard it likely that subglacial lakes existed. Some of the lake sediments reported in the database might actually relate to subglacial lakes (e.g. McCabe & Ó Cofaigh 1994) and perhaps further examples will be discovered (e.g. in deep Scottish Lochs and fjords), but it remains difficult to robustly demonstrate a subglacial origin for lake sediments (Livingstone *et al.* 2012).

BRITICE V.2 is available in four map scales and formats, each with different levels of generalization and abstraction, which vary according to their anticipated use (Fig. 9). In the Supporting Information to this paper and on the BRITICE website (https://www.sheffield.ac.uk/geography/staff/clark_chris/britice) the following are available:

- An unfiltered GIS database containing all mapping, including overlaps and conflicts between mapping derived from different publications. This is highly detailed and best used in GIS for local to regional areas and where the maximum level of information is desired. Data are provided as ESRI ArcGIS shapefiles with notes and citations in the attribute tables (Data S3).
- A filtered GIS database, resolving data conflicts and with improved geo-locational accuracy to provide a consistent synthesis of highly detailed information. This is also best used in GIS for local to regional areas. Data are provided as shapefiles with notes and citations in the attribute tables (Data S3).

- To view the filtered database without using GIS, a series of three full-resolution PDF maps (Fig. 9C; Ireland; England, Scotland &Wales; Northern Scotland and offshore) are available that are designed to be viewed as digital PDFs at scales of around 1:200 000, across which one can 'pan and scroll' to view areas of interest, or to print out selected areas (Data S2). It would be impractical to attempt to print these as maps because at a scale sufficient to see the detail the paper would need to be 5 by 5 metres in size.
- A cartographically generalized map (Fig. 10) to provide an overview of the distribution and types of features of the whole ice sheet and which can be printed at a paper size of A0 (84×119 cm) and scale of 1:1 250 000 (Data S2). Although much detail is lost because of the generalization (e.g. extent of drumlin fields and flow orientations are shown rather than individual landforms) this map provides a holistic overview and could make an appropriate sized poster map to go on a wall.
- A bibliographic list of all sources used in this compilation is too long to include in this paper but the full citations are reported in the GIS shapefiles and a reference list is available for download (Data S1).

It should be clear from the above that there has been a large increase in the volume of glacial geomorphological evidence pertaining to the last ice sheet that covered much of the British Isles. The glacial maps and GIS database we present here help to celebrate this. They should assist those who wish to make sense of this rich information-base and hopefully will promote further work to discover more. Ongoing and new national mapping programmes and academic research can continue to make important contributions to these data sets. Most of the features have already been used to make a first-order map of the pattern of retreat of the ice sheet (Fig. 11A) and, together with published geochronometric dates, to build a reconstruction of the timing and pattern of retreat of the whole ice sheet (Clark *et al.* 2012). A major highlight of the new information base, especially offshore, is that the ice sheet was much more extensive than previously thought (e.g. Bowen *et al.* 1986), as shown in Fig. 11B. The ice-sheet retreat map is being used by the BRITICE-CHRONO project (2012–2018) to act as a spatial framework for collecting samples of organics, sand and boulders in a large dating programme (~800 new dates using OSL, ^{14}C and cosmogenic-nuclide techniques) to better constrain the timing of ice retreat, explore the controls on retreat, and to improve ice-sheet modelling (http://www.britice-chrono.group.shef.ac.uk/). The project has undertaken a quality control exercise of all existing geochronometric dates (Small *et al.* 2017) and it is anticipated that these might be incorporated in future versions of the BRITICE map and database.

In addition to other thematic features noted earlier (e.g. glacial striae, raised shorelines) future versions of the BRITICE map may include the addition of layers reporting chronology of ice retreat (from the BRITICE CHRONO project), including sample locations and metadata for radiocarbon, cosmogenic and luminescence ages, and reconstructed margin positions at say 1000 year timesteps. Maps of ice-sheet thickness and elevation per timestep is another possibility for inclusion, derived from ice-sheet modelling experiments fitted to the landform and stratigraphically constrained chronological data.

The BRITICE V.2 GIS data (shapefiles), maps (as PDFs) and the full bibliography (PDF) can be downloaded from https://www.sheffield.ac.uk/geography/staff/clark_chris/britice, and are also available as Data S1–S3. The V.1 data and maps are also available at the same website. Additionally, in collaboration with Esri UK, a BRITICE V.2 web application exists that allows users free access to view the landforms overlaid on a zoomable geographical base map with places names, and also to turn layers on and off and query individual features. It can be found by web searching for BRITICE Esri or using the link: http://maps.arcgis.com/apps/webappviewer/index.html?id=70dd45e769534ff08cb41c9571ec5258.

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Note that this list only includes references cited in the main text – references for the database are listed separately at the end of the online version of this article and in the Supporting Information (Data S1).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Data S1. Reference list for sources used to compile the database.

Data S2. Glacial Maps as PDFs: A. Cartographically generalized Glacial Map (poster) for viewing or printing at A0 paper size and scale of 1:1 250 000. B. Three full-resolution PDF maps: Ireland; England, Scotland &Wales; Northern Scotland and offshore.

Data S3. Esri GIS shapefiles of features stored as separate layers per theme (e.g. eskers).

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