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Veness, R.L. orcid.org/0000-0002-2884-3267, Clark, C.D. orcid.org/0000-0002-1021-6679, Ely, J.C. orcid.org/0000-0003-4007-1500 et al. (3 more authors) (2025) Modelling erratic dispersal accounting for shifting ice flow geometries: A new method and explanations of erratic dispersal of the British–Irish Ice Sheet. Journal of Quaternary Science. ISSN 0267-8179

https://doi.org/10.1002/jqs.3720

JOURNAL OF QUATERNARY SCIENCE (2025) 1–14 ISSN 0267-8179. DOI: 10.1002/jqs.3720

JQS Journal of Quaternary Science QRA Quaternary Research Association

Modelling erratic dispersal accounting for shifting ice flow geometries: A new method and explanations of erratic dispersal of the British–Irish Ice Sheet

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Received 23 October 2024; Revised 3 March 2025; Accepted 15 April 2025

ABSTRACT: Glacial erratics are geologically distinctive rocks transported away from their source area by ice sheets and deposited in lithologically different bedrock areas. They have attracted much scientific curiosity with >24 000 observations across the British Isles. A common misinterpretation is that they took a nearly direct line of transport from source to resting position, neglecting to change ice flow directions during ice sheet growth and decay. To rectify this, we sequentially modelled erratic time-space trajectories at 1000-year timesteps using ice flowlines in an empirically constrained ice sheet model simulation to predict erratic deposition areas. We addressed the processes of entrainment and deposition by combining all potential trajectories into a single footprint of possible locations. Erratic dispersal is predicted for three geologically distinctive lithologies; Shap Granite of Northern England, Galway Granite of Ireland and the Glen Fyne igneous complex from Scotland. The footprint of predicted trajectories compared against 1883 observations of erratic locations was found to successfully explain 77% of the observed erratics. Most erratics were explained by flow directions during ice retreat; however, some required earlier ice divide shifts to produce potentially long-duration, multiphase pathways. Our analysis demonstrates the possibility of explaining many erratics without explicitly modelling the complex processes of entrainment and deposition.

KEYWORDS: British–Irish ice sheet; glacial erratic; modelling; shifting flow directions

Introduction

Glacial erratics are geologically distinctive rocks transported away from their source area by ice sheets and deposited in lithologically different bedrock areas. They often stand out as visually and geologically anomalous and have attracted much curiosity and scientific interest for over a 100 years, with many thousands of observations, for example, across the British Isles. A simple first assumption is that an erratic took a nearly direct, predictable, line of transport from its source to its resting position. However, this neglects the complexities of changing ice flow directions during ice sheet build-up and decay (Parent et al., 1996; Astakhov et al., 2016; Jouvet et al., 2017; Carling et al., 2023; Clarke et al., 2024). This makes interpreting the dispersal of erratics left behind by paleo ice sheets challenging, especially when considered in isolation without other indicators of flow direction. In this paper, we make a simple and first methodological step by modelling the time-space trajectory that erratics could have travelled along, using shifting flowlines in a previously published and empirically constrained ice sheet model simulation to predict erratic deposition areas (footprints) (Clark et al., 2022) (see Ice sheet model description section). We addressed the processes of entrainment and deposition by combining all potential trajectories into a single footprint of possible locations. The methods and findings are relevant for explaining erratic distributions and former ice flow directions. With further work, it is suggested that erratic distributions could be used as formal tests of ice sheet model simulations or integrated with them in data-calibration investigations. The potential for integrating erratics into numerical model testing is timely, as increasing demands are being placed on our understanding of paleo ice sheets for help with forecasting future changes to the Greenland and Antarctic ice sheets (Church et al., 2001; Nicholls and Cazenave 2010). One area where our understanding of paleo ice sheets still falls short is in how ice sheet catchments and flow geometries vary over time (Stokes et al., 2022). In addition to erratics having the potential to provide such information on basic flow directions and changes therein, they may also reveal important information on ice catchment changes and the location of ice divides and how these vary over time.

In Britain, erratic boulders have been studied and recorded for longer than the possibility of glaciation of the island has been considered. To account for the unusual locations of erratics, early scientists proposed a wide variety of hypotheses varying from transport in the great biblical flood (Greenough, 1819; Buckland, 1823), to debris carried in icebergs (Darwin, 1848), to toys of Trolls (Krüger, 2013) and finally to transport by glacial ice in large ice sheets (Buckland, 1842; Lyell, 1841; Agassiz, 1842; Howarth, 1908; Harmer 1928; Boylan, 1998). These intriguing boulders eventually became known as (glacial) erratics. The term ‘erratic’ is commonly applied only to large boulders (weighing many tonnes), which in early work added to the mystique of how they travelled so far from their geological source. In this work, the

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term 'erratic' is used more broadly to describe surface boulders, cobbles (lodged in till) and indicator grains (constituting till), which have been found outside of their geological source area. This work assumes that erratics are glacially transported unless otherwise stated.

It was not until the 1840s when Agassiz visited the British Isles and proposed the notion of past glaciations that the possibility of glacial transport began to arise as an explanation for erratic boulders in Britain and Ireland. Over the 2 years following Agassiz's visits to Britain and Ireland in 1840, a large body of evidence was laid down for widespread glaciation, including 22 sites where erratic boulders were interpreted to have been glacially transported (Buckland, 1842; Lyell, 1841; Agassiz, 1842; Geikee, 1894; Boylan, 1998). This marked the beginning of a conceptual transition from Diluvialism (attributing erratics to the large biblical flood in the Bible) to glacial transport, although it took decades for widescale acceptance. As part of this transition, the Royal Society of Edinburgh's Boulder Committee collated the location of thousands of erratic boulders over the course of 10 reports and 13 years (Christison et al., 1871, 1884). In 1871, the first call went out from the Boulder Committee to catalogue all erratic boulders of Scotland (Christison et al.,1871). This call mobilised academic geologists and reverends of each local parish to help resolve the issue of iceberg rafting of erratics versus glacial transport. Subsequently, the British Association for the Advancement of Science (BAAS) set up their own Boulder Committee covering England, Wales, Isle of Man and Ireland, which reported annually from 1873 to 1914. By the late 19th century, the academic consensus was that erratic boulders across Britain and Ireland were glacially transported. The work presented here builds on the long history of investigating erratic boulders in the British Isles, with a reanalysis and survey of much of the earlier-recorded boulder locations from the 19th century.

The 20th century saw a gradual decline in academic interest in glacial erratics in Britain and Ireland. Notable developments included using lodgement erratics as a central tool to understand the origins of till (Jamieson 1906; Bremner, 1928, 1934, 1939) and in the identification of surface erratic boulders in Scotland (Mackie, 1901; Raistrick, 1931; Cumming and Bate 1933). Work by Mackie (1901) stands out for its early use of a microscope to identify subtle differences in Highland granite erratics and how these pertain to shifts in ice flow orientation. Similarly, Charlesworth (1953) used erratic dispersal of Galway Granites and numerous regions of striations to reconstruct the build-up of the last Irish Ice Cap. This was eventually used in his influential reconstruction of the British–Irish Ice Sheet (Charlesworth, 1953) including the complex geometry of ice flow directions that arose from the confluence of the Scottish and Irish ice sheets.

Interest in the erratic boulders of the British Isles has continued into the 21st century (Clark et al., 2004; Greenwood and Clark, 2009b; Jouvet et al., 2017, Carling et al., 2023), mostly with the aim of improving ice sheet reconstructions. As part of this renewed interest in erratics, we used a new database of glacial erratic locations compiled by one of the authors (Knight) and presented in this work. It was compiled by a combination of literature searching (of the early Boulder Committee works) and field resurveying.

Internationally, erratic and indicator grain dispersal investigations have received significantly more interest, notably in Canada where geological exploration and drift prospecting are major academic and industrial pursuits, including a recent database of North American dispersal trains (Cummings and Russell, 2018). Relevant to catchments of the Antarctic Ice Sheet, Marschalek et al. (2023) built a modelling approach for predicting the lithological provenance of indicator sediments beyond the ice margins, which was used to test ice sheet model simulations. Recent interest in a mountain glacier scale has used entrained markers, including erratics, airplane wreckages, the corpses of deceased mountaineers and radio nuclear isotopes from bomb testing as proxies of englacial flow routing and duration (Jouvet and Funk 2014; Jouvet et al., 2017; 2020; Compagno et al., 2019; Ugelvig et al., 2016; Scherler and Egholm, 2020; Margirier et al., 2025). The focus of these works has been on the duration of transport and vertical position of the clast as the flow direction is largely a function of topographic confinement. Erratic transport pathways on large and topographically unconfined ice sheets have mostly been ignored by the numerical ice sheet modelling community, although see Hooke et al. (2013), Melanson et al., 2013, Jouvet et al. (2017) and Marschalek et al. (2023).

Aims and Methods

Our focus in this work is on the X–Y plane of erratic transport. We explore how changes in ice flow geometry affect erratic pathways over time when largely unconstrained by topography. We focus on X–Y displacement by avoiding directly calculating entrainment and deposition to estimate the vertical positioning (Z) of debris in the ice column. By doing so, we can investigate the following questions: (i) to what extent do X–Y plane flow geometrical variations over time matter for explaining known erratic distributions? And (ii) How well do simple rules applied to output from an ice sheet model simulation explain known erratic distributions?

To account for the full range of entrainment and deposition uncertainty, we make the simplifying assumption that erratic transport velocity varies anywhere between 0% (boulder is subglacially lodged) and 100% of ice surface velocity (sat on the ice surface). This will necessarily lead to an over-prediction in the footprint of final erratic resting places. This simple approach allows us to isolate shifting flow geometry changes from processes of entrainment and deposition. Although one might expect transported materials to progressively get smaller, until almost undetectable, the recent work of Carling (2024) shows that large boulders, which lack fractures, are remarkably unmodified by glacial transport. This supports our simplistic assumption. By isolating flow geometry in this way, we can test the flow geometry of a numerical ice sheet model, independently of erosion and deposition processes, which are generally poorly known or constrained at ice sheet spatial resolutions.

To predict the likely footprint of erratic dispersal, one could devise a scheme of seeding individual boulders from the outcrop source area into an ice sheet model simulation and then sequentially estimate each boulder's direction of flow and transport distance at each timestep to plot the trajectory. However, over the large time and spatial scales of a paleo-ice sheet, such an approach is currently computationally unfeasible. Here, we take a simpler approach and extract ice flowlines from a pre-existing ice sheet model simulation and use these as part of a GIS workflow to create sequentially built up-trajectories along which erratics could move. By varying the transport distance between 0% and 100% of flow velocity, this workflow simulates all possible trajectories an erratic could take, irrespective of the exact transport distances actually undertaken. The output from our transport model must therefore be considered a maximal footprint according to the model output used. Of course, this is not expected to be a true representation of reality, given the uncertainties in ice sheet modelling and our simplified transport approach. In other words, an observed lack of erratics across the entirety of the footprint we predict is expected. Our line of enquiry (questions above) is more general than trying to exactly recreate reality.

Ice sheet model description

No new ice sheet modelling was performed in this work; we instead used an existing model simulation to extract ice flow directions for tracking erratic transport. We used the BRITICE–CHRONO model simulation of the last British–Irish Ice Sheet, between 31 and 15 ka BP (Clark et al., 2022), the set-up of which is described here in brief. This simulation (henceforth referred to as the B–C model) combines the physics of ice sheet modelling with an extensive record of empirical constraints on ice margin position and timing, including many hundreds of geochronometric dates (Benetti et al., 2021; Bradwell et al., 2021a, 2021b; Chiverrell et al., 2021; Clark et al., 2021; Evans et al., 2021; Ó Cofaigh et al., 2021; Scourse et al., 2021). The B–C model reconstruction is a PISM (Winkelmann et al., 2011) model simulation with a grid-size resolution of 2.5 km and whose input parameters were based on the culmination of a series of (600) model ensemble runs. These ensemble runs identified input parameters, which performed well in model-data comparison tests (Ely et al., 2019b; 2024; Clark et al., 2022). The approach for combining modelling and empirical data in a single simulation was iterative (more details in Clark et al., 2022) aiming to align ice extent, timing and thickness closely with observed data, while also accounting for global glacial isostatic adjustment (GIA), sea level changes, and ice streams and shelves. First, a computationally cheap, steady-state, plastic-ice flow, numerical model (ICESHEET 1.0; Gowan et al., 2016) was used to build a static ice sheet that exactly fitted the optimum ice extent defined by the BRITICE–CHRONO empirical reconstruction (Clark et al., 2022). Variations in basal shear stress were explored and varied until the modelled ice thickness distribution reasonably recreated the necessary loading to explain the sea level and GIA constraints (Bradley et al., 2023). This can be thought of as a nudge to get the ice thickness approximately correct. These ice sheet elevations were then extracted at each 1 ka timestep and used as an initialisation surface for the more physically realistic PISM ice sheet model, which was driven by a climate field. These more free-running simulations mostly yielded ice sheet extents that matched with the empirical record but in places they overran the known ice limits. For such cases, a numerical nudge using additional melting was applied locally to encourage the margin back within the empirical extent for that time period. Similarly, the ice shelf melt rate and calving rate were varied over time to encourage the ice to extend to known dated marine margins at key times. Despite these efforts to constrain the model to observations, no numerical model is a perfect representation of reality, and there is some data-model disagreement in the model output (Clark et al., 2022; Ely et al., 2024).

Implementation of erratic transport

From the ice sheet model output at each 1 ka year time-step, ice flowlines (Fig. 1) are produced using a bespoke MATLAB script, which plots iteratively from seedpoints defined at grid nodes within the ice sheet area. Each iteration produces a flowline, the vertices of which are examined to identify grid cells intersected by the flowline. Grid nodes (i.e., seedpoints) corresponding to these cells are eliminated from the next iteration. The iteration is continued until each of the grid cells within the ice sheet is crossed by at least one flowline. The grid resolution, which controls the minimum spacing of the flowlines, and the flowline resolution, that is, segment length of the polyline, which controls the sensitivity of grid node elimination, can be varied freely by the user. The flowlines used in this work were published in Clark et al. (2022).

To create composite pathways (trajectories) along which erratics may travel, we assume that at any point in time, an erratic can travel between 0% and 100% of the modelled ice velocity at that location and in the ice flow direction. Therefore, at any subsequent point in time, an erratic could be deflected in a different direction from any location along the original flowline (Figs. 1 and 2), depending upon how far it had travelled at the velocity and elapse of time. The maximum potential erratic dispersal was derived using an ArcGIS workflow, which combines flowlines to create a composite flow path for a specific geological source area. When conducted at coarse temporal resolutions (1000-year increments), it is feasible to conduct this work in ArcGIS rather than writing a bespoke code. The workflow is summarised in Fig. 2, the steps in Fig. 2B to 2C are repeated until the end of the glaciation. Note, whenever an intersection is referenced, this refers to an intersect in flowlines, from one timestep to another, within 5 km (one model grid cell) of the referenced feature. In some instances, this 5 km tolerance therefore allows lateral drift, expanding the dispersal footprint downflow over time. When truncating line segments, no up-ice flow or drift of erratics is permitted even at a subpixel scale.

The workflow selects and extracts all modelled flowlines, which intersect the erratic source (Fig. 2A). Extracted lines are truncated to remove the flowline upstream of the erratic source (Fig. 2A). For the following time step, all flowlines that intersect either the erratic source or the active flowlines (black lines) are selected and extracted (Fig. 2B). This is repeated until the maximum dispersal footprint is established. At this point, the peripheral flowlines and endpoints are used to generate a maximum dispersal footprint, and a 5 km buffer is applied. We present an indicative selection of the flowlines and present the full flowpaths in the Table S1.

When working on coarse temporal resolutions (1000 years) for a small ice sheet, it is reasonable not to truncate the downflow line segments as these are likely to be shorter than the maximum transport distance possible over the given timescale. Assuming a mean ice velocity along a flowline of 200 ma^{-1}, erratics could be expected to travel 200 km during a 1000-year time period. Under such assumptions, it is reasonable to expect that an erratic travelling at the velocity of the ice could have reached the ice sheet margin. However, as the temporal resolution of the analysis increases (e.g., to 100 years), or in the case of larger ice sheets, the likelihood increases that flowlines will exceed the maximum transport distance possible at the assumed ice velocity. It is therefore preferable to truncate the downstream ends of the flowlines, limiting their length to the maximum transport distance for the given timestep. While such modifications can be made in a GIS environment, performing them manually becomes impractical, making automation a realistic necessity.

Erratic source selection

We selected three erratic source areas to test our method, one each from England, Scotland and Ireland, primarily motivated

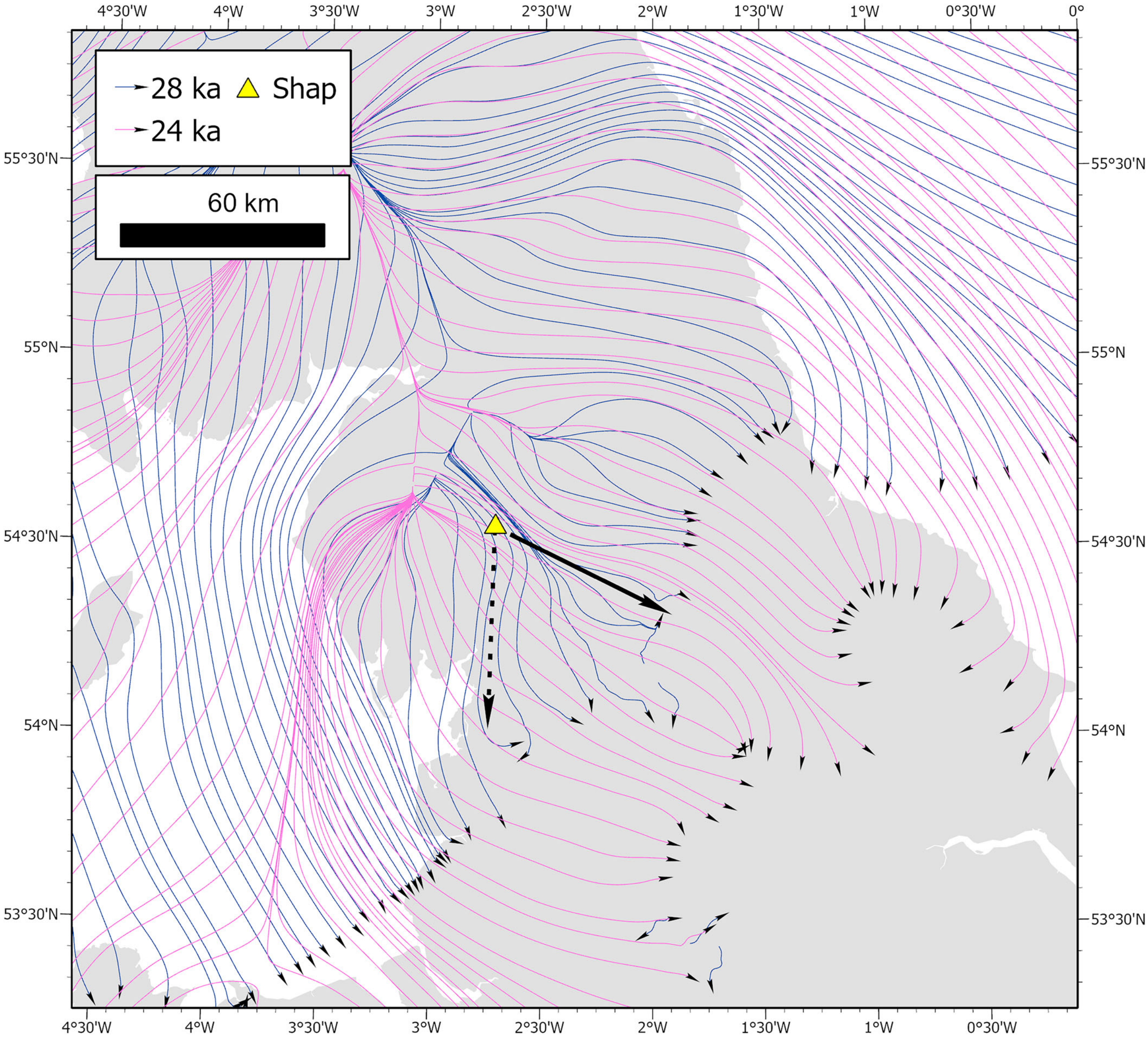

Figure 1. Flowlines (pink and blue) plotted for two timeslices (24 and 28 ka) from the B–C model reconstruction. The source outcrop of Shap granite erratics (yellow triangle) exists in an area that experienced a large variation in flow directions between 28 ka with flow to the south (dashed line) and to the SE (solid line). The challenge is to use such flowlines to successively trace trajectories that erratics could take, noting that they start being transported south, travelling a long or short distance (0% to 100% transport distance) before then being deflected to the SE, such that erratics are likely to experience composite journeys (trajectories) that often will not match a specific flowline. [Color figure can be viewed at wileyonlinelibrary.com]

by three characteristics: geographic distribution, data availability, and anticipated complexity of ice flow. Erratic boulders were found and entered into GIS using a range of methods including historic records from the literature (e.g., Boulder Committee). Most observations of erratic boulders in this investigation have previously been published, mostly in the Boulder Committee proceedings (c.f. Christison et al., 1871 and 1884), and subsequently in Clark et al. (2004), Greenwood and Clark (2009) and Carling et al. (2023). The database used in this study records the locations of many of these erratics, based on an extensive field survey conducted by one of the authors (Knight). This work involved re-surveying the original Boulder Committee erratics to create a new database that integrates published records with new observations and field verification of numerous existing entries. The majority of erratic locations used in this paper are taken directly from this database, some of which were recently published in Carling et al. (20232). Additional observations were drawn from Greenwood (2008) and published erratic compilations including Greenwood and Clark (2009) for the Galway Granites in Ireland (Charlesworth, 1953; Warren, 1992) and Clark et al. (2004) for the Glen Fyne erratics (Sutherland, 1984). Although Glen Fyne erratics were predominantly drawn from Clark et al. (2004), these are supplemented by six boulders from the Knight Database. All erratics used in this work are of cobble size or larger to aid with identification.

Shap Granite is the most famous and popular glacial erratic of the early boulder collective and has long since drawn the intrigue of glaciologists and geologists (Dakyns, 1878; Raistrick, 1931; Clark, et al., 2004; Carling et al., 2023). Shap Granite originates from a small (<5 km) magmatic pluton in the east of the Lake District in Cumbria. It is readily distinguished from other granites by its large K-Feldspar mega crystals and is easily identifiable by its pink tint (Nicolson, 1868; Cox et al., 1996). Shap is located east of the mountains of the Lake District and west of the Pennines at the crest of the col between the Pennines and the Lake District and is therefore likely to be influenced by both the Cumbrian and the Pennine

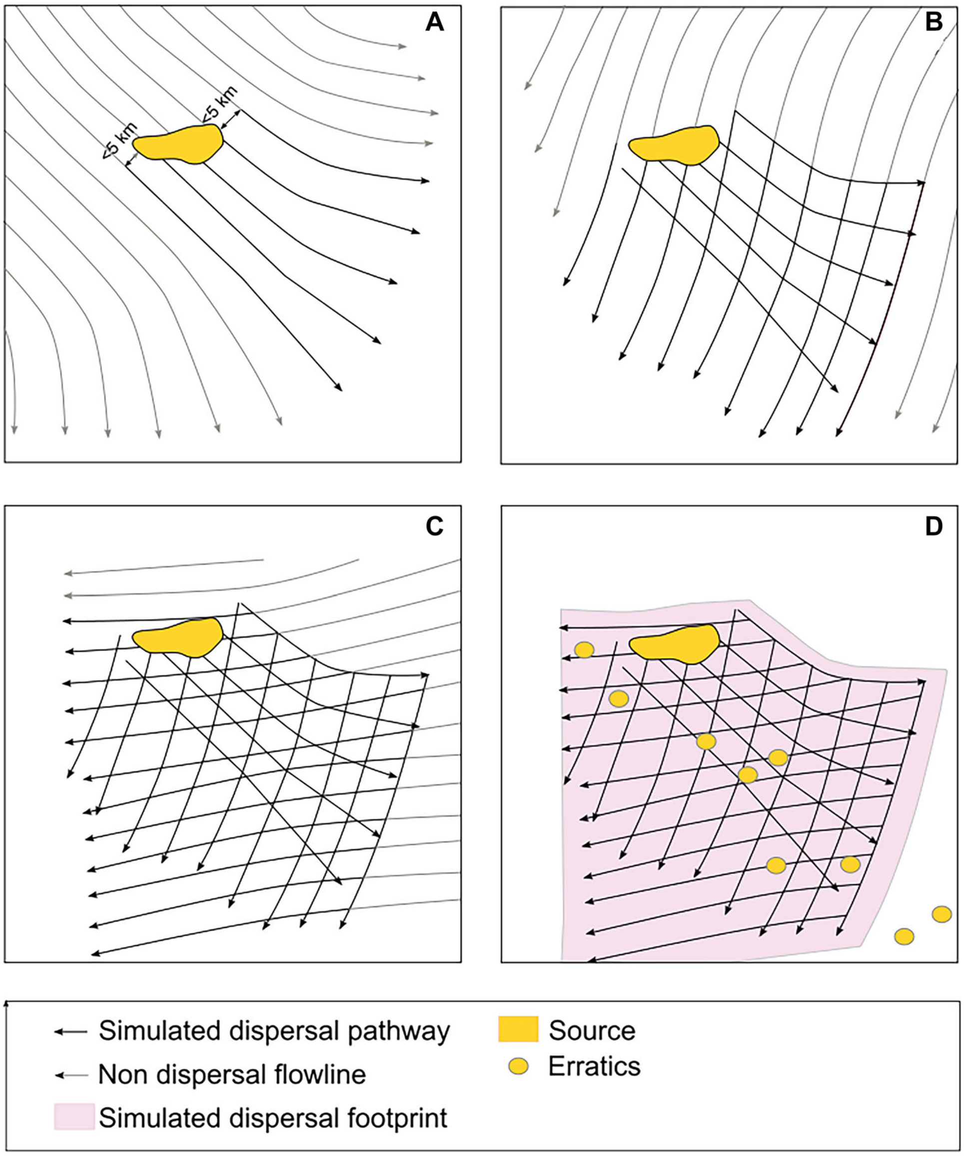

Figure 2. Simple transport model used to predict the footprint of possible erratic deposition under a shifting flow regime. An outcrop rock source (yellow) experienced ice flow towards the SE at (A). In our GIS-workflow, flowlines are selected that intersect the source (including a 5 km buffer zone) and are truncated to remove upflow line segments; the black lines being possible erratic pathways at this time step. Flow towards the SW at stage (B) can entrain new erratics from the source outcrop and deflect those already moving from their original flow direction to the new flow direction. The black lines are possible erratic pathways combining both time steps, which can be thought of as direct dispersal from the outcrop and deflected or palimpsest dispersal from those that had already migrated. A further flow shift occurs in (C) to a flow towards the west, and in (D), the simulated dispersal footprint is plotted in which erratics could have been deposited. When observed erratics (yellow circles) are found within this footprint, the model has accounted for them; however, this is not the case when they are found outside the footprint. In our workflow, grey lines are those flowlines that are excluded from analysis. [Color figure can be viewed at wileyonlinelibrary.com]

Icefields, in addition to experiencing ice flowing south from Scotland (McDougall 2001; Evans et al., 2018).

The Glen Fyne igneous complex is in a small (20 km^2) valley situated on the west coast of Scotland (Nockolds, 1940). The site is of particular interest to the dispersal of erratics as it is located in a region of fluctuating ice divides and has a relatively large number of erratic boulders attributed to it. The majority of the erratics used for the Fyne valley (26) are discussed in Sutherland (1984) and further reproduced in Clark et al. (2004). In addition, we present six new erratic boulders, which were surveyed from descriptions in the Boulder Committee (c.f. Christison et al., 1871 and 1884). In recent-years, interest in Glen Fyne has increased with Scotgold Resources, proposing the site may have geochemical potential for a commercial gold mine (Webb et al., 2024).

The Galway Granites have intrigued glaciologists for decades, with numerous attempts to explain their history and origin (Charlesworth, 1953; Warren, 1992). The Galway Hills are located on the west coast of Ireland, and erratic location data are taken from the work of Greenwood (2008), which were reproduced from Charlesworth (1953) and Warren (1992). The Galway Granites are found in a roughly south to east arc radiating up to 150 km away from the source. One hundred and twenty-eight erratics from this source were included.

Results

Maximum simulated erratic dispersal areas (footprints) of the three chosen source areas (Shap, Fyne and Galway) are compared against a sample of 1883 terrestrial erratics, deemed to have come from those sources according to observations drawn from the scientific literature (Charlesworth, 1953; Sutherland,1984; Warren, 1992; Clark et al.; 2004; Knight pers. comm., 2021). We use the erratic transport model to

Table 1. Summary of erratic transport modelling results. Quantification of success of the erratic transport model in explaining erratic dispersal. The number and percentage of erratics matched is normalised by the number of erratic sources used.

Erratic source	Total erratics	Erratics matched	Percent matched
Shap	1727	1414	82%
Fyne	28	28	100%
Galway	128	0	0%
Total	1883	1442	Mean match 61% Percentage 77%

recreate the maximum dispersal area for each erratic source region. In the simplest possible comparison, erratics are considered to be accounted for if they sit within 5 km (one model grid cell) of the maximum simulated footprint. Using this metric, 77% of glacial erratics (Table 1) in the sample are explained by the predictions but with some wide variations. All Glen Fyne erratics were accounted for (100%), despite their complex transport trajectories. In comparison, 82% of the Shap erratics were explained, while none of the erratics from the Galway Granite source were matched (0%).

Shap Granites

The largest body of erratic data in Britain relates to Shap Granite, with over an order of magnitude more observations than Glen Fyne and Galway combined. The flowline transport model successfully reproduces the majority of Shap boulders, accounting for 1442 clasts, or 82% of the recorded erratics (Table 1 and Fig. 3). The central location within the ice sheet and distribution of erratics to all four quadrants of the compass makes it an excellent and challenging site to investigate with regards to modelled erratic dispersal. Erratics south of Shap can broadly be split into three groupings (Fig. 3), a western trunk spanning the length of the Lune Valley as far as the river Mersey (henceforth referred to as the 'Lune Valley'), a central trunk along the Vale of York and an eastern trunk along the east coast of the UK from the Tyne to the Humber (referred to as the 'East Coast' erratics). Fifteen erratics are recorded beyond the Devensian ice limit, extending north into the Vale of Eden and east into Northumberland. Additionally, three erratics have been recorded on the Isle of Man (see later).

The erratic trajectory modelling recreates two of the main dispersal trains of erratics (along the Vale of Lune and the Vale of York). According to the predictions, the Lune Valley train could have been emplaced during the advance or retreat phases of the ice sheet, whereas the Vale of York train can only be explained by ice flow during the growing phase to the maximum extent when ice flow crossed over the topographic barrier of the Pennine hills.

Several outlying regions of erratics are not recreated by the dispersal model, including those north of Shap, such as to the east of the Vale of Eden and to the northeast in Northumberland (Fig. 3). The dispersal modelling insufficiently predicts northwards flow from Shap, with the only chance for dispersal in this direction being during ice sheet retreat at 18 ka where flow along the Vale of Eden is predicted, emanating from a large Pennine Icefield. No erratics are predicted to flow west and onto the Isle of Man. The largest body of erratics not explained is situated along the east coast of England, between Northumberland and Humber Rivers (Fig. 3). In this region, 243 erratic observations exist, largely lodged in till, and generally sitting within 15 km of modern shorelines. In the south, 38 observed erratics are situated beyond the Devensian ice extent and have little chance of being explained in the dispersal modelling because the B–C ice sheet model was specifically nudged to try and reproduce this limit.

Glen Fyne

The erratic dispersal modelling successfully explained all 28 erratics (100%) attributed to the Glen Fyne Igneous complex (Fig. 3). The observed erratics are all dispersed south of the source, with a notable dispersal train flowing to the west and to the east. To the west, most erratics are observed on islands or peninsulas, which allow observations offshore from mainland Britain. To the east, most erratics sit within the topographic low of the Firth of Forth. These dispersal trains are explained by the migration of the ice divide in the B–C model. This was mostly positioned over the Glen Fyne source outcrops during the build-up of the Scottish Ice Sheet, with dispersal initially south, before flowing east into the Firth of Forth Ice Stream (following the advanced dispersal paths in Fig. 4). Eastward migration of the ice divide reversed flow directions to the south and west, effectively cutting off any further erratic supply to the Firth of Forth Ice Stream. This eastward dispersal train was delivered by a relatively short-lived (<1000 years) and narrow flow trajectory, emphasising how sensitive erratic travel may be to modelled flow dynamics.

Although close agreement between predicted and observed dispersal exists in the north, this is not the case in the south, where widespread predictions are made with no observations (that we know of) of erratics. It is interesting to note predictions of erratic travel to South Wales, Anglesey, the Cheshire Basin and to the east coast of England and would be useful to know if any observations exist in these locations.

Galway Granite

Erratic dispersal modelling completely failed (0%) to explain observations of Galway Granites in our database because predicted dispersal was to the west and the observations exist to the south and east (Fig. 5). However, we note that Roberts et al. (2020) reported the presence of granites from mainland Galway perched on Carboniferous limestone pavements on Inis Meain, an island approximately 16 km offshore in Galway Bay. This fits with the westward-predicted dispersal pathways, as well as evidence of ice flow towards and onto the continental shelf, grounding on the Porcupine Bank to the west (Peters et al., 2016; Callard et al., 2020; Wilton et al., 2021; Clark et al., 2022). Other Galway Granites may have been transported westwards and deposited on islands or offshore, in line with the model predictions, though we are either unaware of these or they have yet to be discovered. Nevertheless, the Galway Granite prediction model remains inadequate, as it fails to explain the observed extensive inland dispersal to the south and east. This is because, in the B–C model simulation, no flow paths in these directions occurred.

Discussion

Evaluating the performance of the erratic transport model

The simple, transport trajectory prioritising approach used in this work to simulate the dispersal of erratics highlights how little process information is needed to successfully explain a large number (77% or 61% depending on the measure used; Table 1) of erratic observations. We suggest that given an ice sheet model that has been driven towards the empirical reconstruction, flow direction shifts and how they affect the

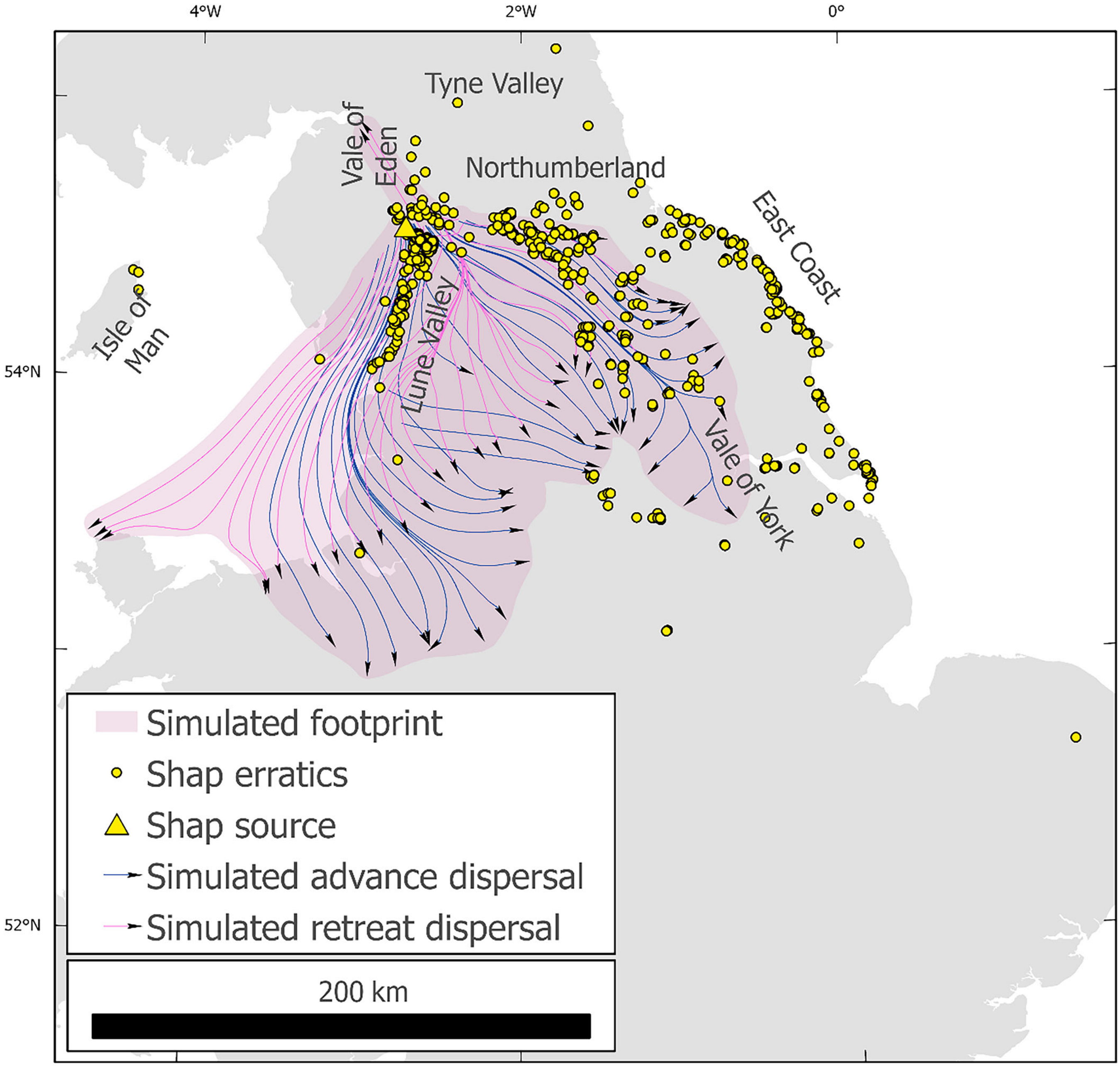

Figure 3. Predicted erratic transport trajectories from the Shap Granite outcrop compared with erratic observations. The erratic predictions arise from shifts in flow directions from the BRITICE–CHRONO model simulation from 29 ka to 17 ka, split into advance (blue lines) and retreat (pink lines) phases. The predicted maximum area of possible dispersion is shown by the pink footprint. Erratics are predicted to have been deposited at any location along the pink and blue lines, not just at the arrow heads. Observations of erratic boulders of Shap Granite are shown in yellow ($n = 1727$), with 1414 (82%) explained by the predictions. It is notable that the model successfully explains the occurrence of erratics on both sides of the Pennine Hills, with dispersal across all four quadrants of the compass. This suggests the migration of the ice divide over time. Not all the erratics are explained by the predictions (18%), mainly down the east coast. The model (and transport pathways) predominantly sits within the empirical margin from Clark et al. (2022) and therefore does not explain a number of erratics beyond the supposed Devensian ice limit. [Color figure can be viewed at wileyonlinelibrary.com]

trajectories outweigh issues of sediment entrainment and deposition, at least in this ice sheet.

Discrepancies between predicted and observed erratics may stem from deficiencies in the erratic dispersal algorithm, limitations in the robustness of the numerical ice sheet model simulation (B–C model) in capturing true ice dynamics or issues with the sample of erratic observations used, including their representativeness of the true population. A challenge is how to disentangle these, in order to guide future investigations.

We highlight two features of the model, which may reduce its performance and are worth investigating to seek improvements. Erratic trajectories were computed at 1 ka time steps, and this might be too low a temporal resolution to adequately capture changes in flow directions and speeds. This could be especially important if a final trajectory is highly sensitive to short-lived early flow line shifts. In this pilot investigation, the choice of 1 ka was made to accommodate variations in maximum transport velocities (and distances) in a GIS workflow-based approach. Coded automation is likely required to decrease the temporal resolution, for example, to 100-year time steps. In future work, we aim to fully automate the model, building on this proof of concept. The 5 km lateral dispersal tolerance was used to minimise discrepancies between the data sets in terms of their spatial resolution and geometric fidelity. Exploring the sensitivity of results to this threshold value could be valuable, with the aim of reducing it and any lateral drift, thereby tightening the prediction areas.

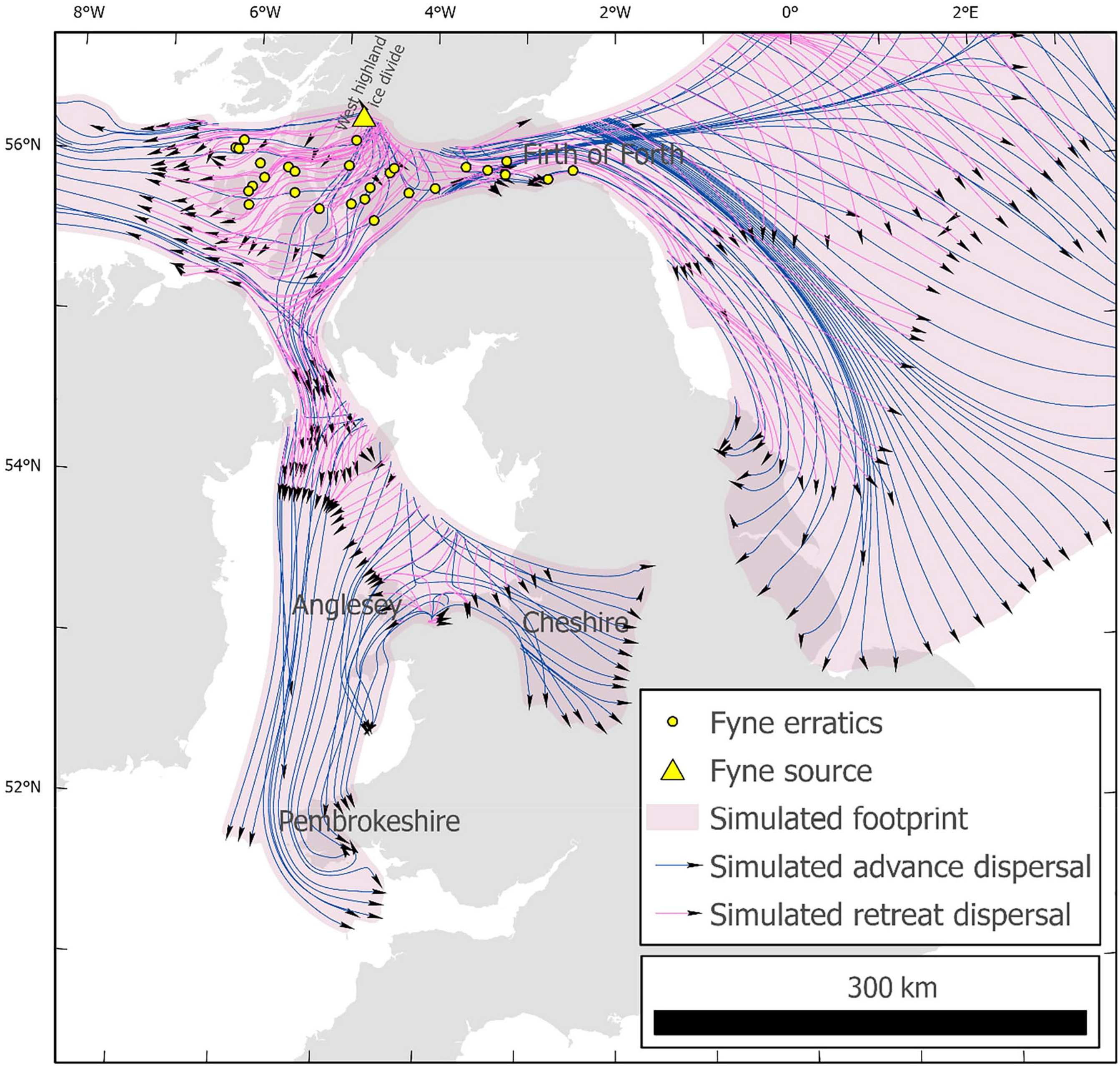

Figure 4. Predicted erratic transport trajectories from the Glen Fyne source, compared with erratic observations. The erratic predictions arise from shifts in ice flow directions from the B–C model run from 31 ka to 15 ka, split into advance (blue lines) and retreat (pink lines) phases. The predicted maximum area of possible dispersion is shown by the pink footprint. Erratics are predicted to have been deposited at any location along the pink and blue lines, not just at the arrow heads. Observations of erratic boulders from the Glen Fyne igneous complex are shown in yellow ($n = 28$), with all of these (100%) explained by the predictions. Both the observed westward and eastward dispersal trains are explained as a result of migration of the ice divide in the B–C model. It is interesting to note predictions of erratic travel to South Wales, Anglesey, the Cheshire Basin and the east coast of England and would be useful to know if any observations exist in these locations. [Color figure can be viewed at wileyonlinelibrary.com]

While sensitivity testing prior to full automation is challenging, it represents a logical next step in future efforts to automate the workflow.

Sensitivity of erratic travel to ice flow geometry

A surprise with this work is the significance of small km-scale changes in divide and flow geometry on the erratic dispersal record. Some erratic sources are highly sensitive to small changes in ice sheet geometry, especially near divides. The most notable example of this is with the Glen Fyne erratics where a small shift (5–10 km) in the West Highland ice divide was sufficient to cut off the dispersal of erratics eastwards, through the Firth of Forth Ice Stream. Small shifts in ice divide position and flow geometry also affected the alternating east and westward dispersal of erratics from Shap. This underlines the importance of starting with an empirically constrained, but by no means perfect, ice sheet model simulation, and we suggest that these should ideally be optimised or tested against other flow-directional observations such as from drumlins (e.g., Gandy et al., 2019, 2021; Ely et al., 2019b, 2024) or striae. This would be a good approach if wanting to predict erratic travel or use these methods in mineral dispersal exploration. Alternatively, if wanting to use erratic observations as formal tests of a model simulation, then this finding suggests that careful choice should be made of which erratic sources are used. Erratics near ice divides or those crossing major topographic barriers are likely to be more diagnostic than simple dispersal trains in the outer reaches of the ice sheet or those running down a single large valley, for example.

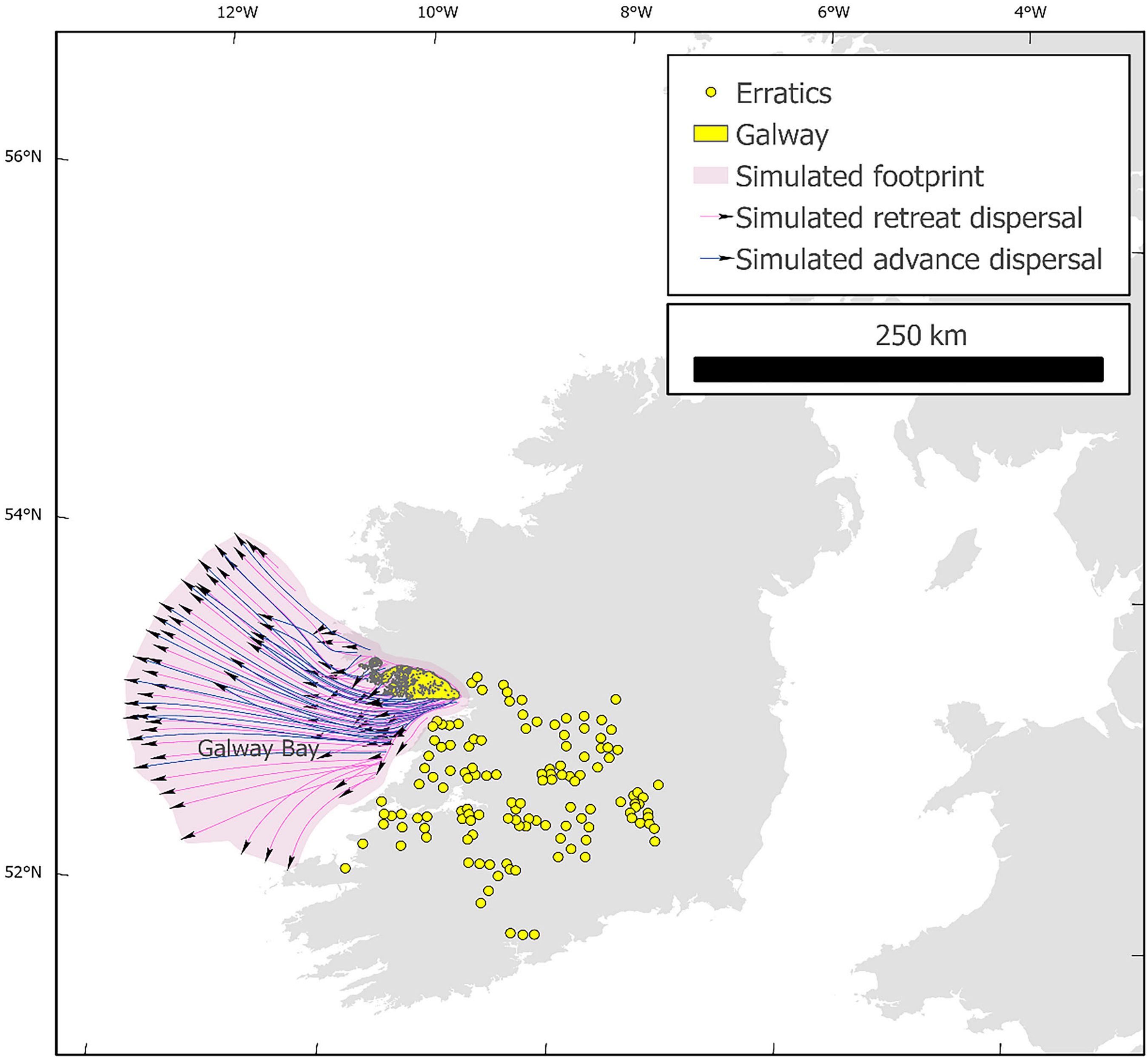

Figure 5. Predicted erratic transport trajectories from the Galway Granite source, compared with erratic observations. The erratic predictions arise from shifts in ice flow directions from the B–C model run from 28 ka to 17 ka, split into advance (blue lines) and retreat (pink lines) phases. The predicted maximum area of possible dispersion is shown by the pink footprint. Erratics are predicted to have been deposited at any location along the pink and blue lines, not just at the arrow heads. Observations of erratic boulders from the Galway Granite source, in our database, are shown in yellow ($n = 128$), with none of these (0%) explained by the predictions. Note, however, that ice flow to the west has been hypothesised in the literature based on a range of empirical sources, and granite erratics from the mainland have been found (though not included in our database) in Roberts et al. (2020). [Color figure can be viewed at wileyonlinelibrary.com]

Additionally, it seems important for models to accurately capture ice flow during ice sheet growth phases, as demonstrated in the case of Shap Granites, where dispersal trains in an early phase were later reworked and redirected during ice sheet retreat. This is an example of the palimpsest dispersal train concept, as described by Parent et al. (1996) and Greenwood and Clark (2009).

Erratics not explained by modelling

The most striking discrepancies occurred in the case of Galway Granites where no erratics in the initial survey were explained (Fig. 4). The B–C model predicted trajectories to the west and failed to explain the observed inland dispersal to the south and east (Fig. 5). The problem must arise from the flow geometry in the B–C model simulations, and we explore this issue below.

Given that the B–C model does not produce any eastward iceflow, we consider a number of possible solutions to account for the dispersal of the observed erratics. One solution for explaining the dispersal of Galway Granites is the long-standing hypothesis of initiation and growth of the Irish Ice Sheet from ice caps including those which formed from the Connemara Mountains (Charlesworth, 1953; Hull, 1878; Warren, 1992). This suggests that glaciation in Ireland originated from the mountain regions around the western rim of the island, flowing and expanding eastwards across Ireland, prior to significant glacial invasion from the Scottish Ice Sheet. Together, these phases formed the primary ice divides of the Irish Ice Sheet. The latter phase is more constrained, resulting in westward to south-westward flow onto the continental shelf and into Galway Bay (e.g., Smith and Knight 2011; McCarron et al., 2018; Clark et al., 2022; Roberts et al. 2020). It seems plausible then that the inland dispersal of Galway Granites might have been transported in the growth phase from a mountain-centred ice cap or perhaps by flow in a final retreat phase if deglaciation shrank back to Connemara (e.g., Warren, 1992; Smith and Knight 2011). To explain the erratic dispersal, the Connemara ice caps would be required to expand over 150 km eastwards and so be of substantial ice thickness. The B–C model simulation that we used does not simulate such a large Connemaran Ice Cap either during growth or retreat and this might be a correct result. Alternatively, it might be an inadequacy in the modelling because of the limited spatial resolution of the model (2.5 km), which reduces both the glacierisation potential of these mountains. Perhaps, the evolution of the Irish Ice Sheet is highly sensitive to these early stages, which may have been inadequately captured in the modelling. Ice sheet modelling investigations elsewhere have found orographic feedback on precipitation and growth from mountain-centred glaciations to be highly sensitive to model resolution (Marshall and Clarke, 1999; Ziemen et al., 2016; Margason et al., 2023). The B–C simulation used in this work did not include a coupled climate model, which could respond locally to orogenic factors. If a Connemaran Ice Cap could be used to explain the eastwards dispersal of the erratics, then they could easily be reworked south during subsequent ice sheet glaciation. It is interesting that a late-stage Connemaran Ice Cap has been reconstructed in Foreman et al. (2022) where the ice margin is suggested to have withdrawn westwards from the Irish interior back to the mountains. To be able to explain the Galway erratics, such an ice cap would have needed to have been much more extensive than simulated by the B–C model and to have persisted for at least 0.5 ka, assuming high mean velocities of 200 ma^{-1}. A useful future test of the potential for more complex cross-cutting dispersals would be to incorporate other erratic source/sink combinations, which may intersect the Galway Granites (e.g., from Northern Ireland or Scotland).

Another scenario for producing the required eastward flow of ice (and erratics) from the Galway source is that the main or subsidiary ice divide of the Irish Ice Sheet may have been positioned further west, likely requiring considerable ice thickness on the continental shelf. Such a position for the ice divide as far west as this seems radical but not as implausible as it would have appeared before multiple lines of evidence were used to hypothesise that the last glacial ice limit reached as far as the continental shelf break (Peters et al., 2015; Callard et al., 2020; Roberts et al., 2020; Ó Cofaigh et al., 2021; Clark et al., 2022). This might make it possible if the catchment size of the Irish Sea Ice Stream was larger than typically reconstructed (Chiverrell et al., 2013). This would help by drawing down the ice and driving the ice divide westward. Perhaps the activity of this ice stream has been underestimated in models and empirical reconstructions. For example, the Evans Ice Stream in Antarctica extends to within 100 km of the West Antarctic coast, yet it feeds an ice stream that terminates 500 km to the north (Rignot et al., 2011).

While Shap Granite dispersal was mostly well explained by the B–C model in conjunction with the dispersal model, a significant proportion on the east coast of England was left unexplained (Fig. 3). This is interesting because the Tyne Valley Ice Stream was a prominent flow feature, likely capable of transporting erratics from the Pennine Hills eastward to the coast, and we suggest it played a key role in transporting Shap erratics (Davies et al., 2019). The main problem in our modelling was insufficient northward flow early in the glacial period, preventing erratics from being transported down the Tyne Ice Stream to the coast. We suggest this is because the ice sheet build-up in the B-C model did not produce large enough ice fields over the Lake District or Pennines. If these had been larger, they could have distributed Shap erratics across the Pennines for dispersal down the Tweed Ice Stream and down the east coast due to the interaction with North Sea ice (Davies et al., 2011; 2012; Evans et al., 2021). Future work to further constrain the timing and extent of ice build-up geometries may help clarify these issues. Westward dispersal from Shap to the Isle of Man is implied in the database, but these three erratics all lie close to sea level, and it is plausible to suggest they may have been transported as ship ballast and left at the shoreline.

Twenty-five erratics were unexplained by our modelling because they lay beyond the ice extent reached in the B-C model simulation, which was adjusted to fit the empirically defined ice limits during the Devensian glaciation (Fig. 6). These were all Shap erratics, distributed across the English Midlands and East Anglia, and were almost certainly dispersed during an earlier glaciation. This raises the question of whether all erratics within the Devensian ice limit were solely moved during that glaciation, or whether some were dispersed in earlier glaciations and later remobilised during the most recent one. This is difficult to answer, but given the extreme scarcity of pre-Devensian glacial deposits found within the Devensian ice limit, a reasonable starting assumption is that these erratics were transported during the last glaciation.

Predicted erratic locations with no observations

We briefly discuss regions where erratic deposition is predicted, but no erratics have been recorded. These areas could be of interest for field investigation to determine whether they are truly absent, or if there are useful process explanations for why none are found in these locations. Many of the predicted erratic sites are now offshore, greatly hindering the investigation of erratics. We have not systematically searched publications reporting the lithology of clasts reported from seabed cores but suggest this could be useful to compare against the predictions.

Simulations suggest erratics from Glen Fyne, for example, should be found on the Isle of Man, Anglesey, along the North Welsh Coast and in Pembrokeshire (Fig. 3). These regions have a low number of erratics recorded in the literature and none from Glen Fyne. This may, in part, be due to the long potential transport distances, which could have abraded the boulders down to smaller sizes, or the difficulty in distinguishing small pieces of (Glen Fyne) igneous rocks from one another.

Although we have not considered clast reduction in size during transport, it is well known that such an effect occurs and transport distances for particular source rocks can be estimated (Boulton, 1978). In many cases, erratic clast size has been recorded and is available in erratic databases, leaving open the potential to use our dispersal trajectories to conduct the investigation of distance decay in clast size. If achieved, this might explain some predicted locations with no observed erratics; they simply never made it there at a large enough size to be spotted.

Future uses of erratics in model-data comparison

A potentially significant avenue for further research is using the dispersal of erratics to evaluate the performance of a numerical ice sheet model. As both ice sheet modelling and empirical databases have grown in number and sophistication, data-modelling interactions are becoming increasingly common (Stokes and Tarasov, 2010; Jamieson et al., 2014; Jouvet et al., 2017; Ely et al., 2019a, 2019b, 2024; Clark et al., 2022). Modelled ice flow directions have been compared to observed

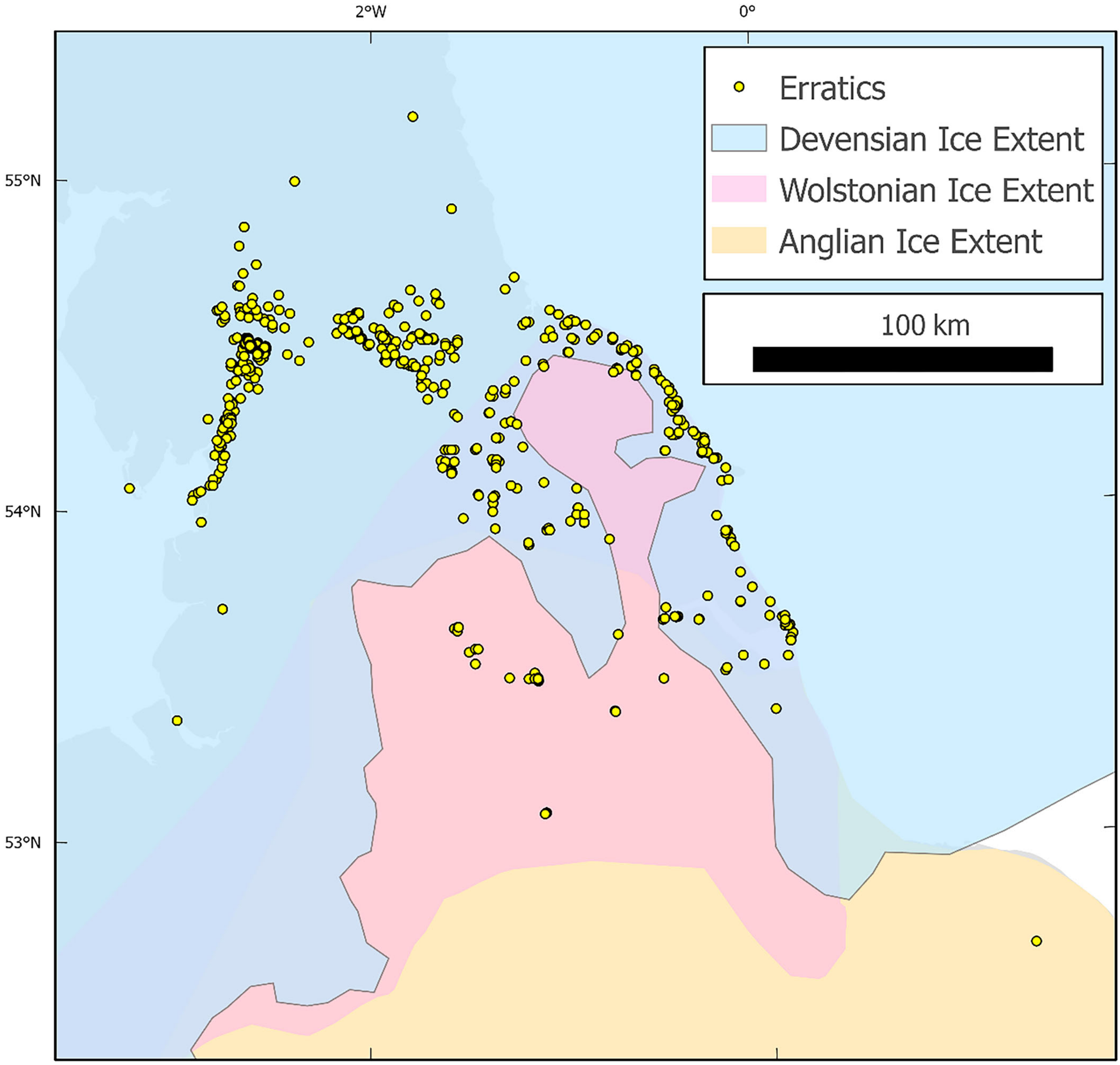

Figure 6. Some erratics were unexplained by the dispersal modelling because they lay beyond the limits of glaciation in the B–C model simulation. Thirty-two Shap erratics exist in the database beyond the empirically defined limit of the last glaciation (blue) and were likely transported in earlier glaciations such as the Wolstonian (pink) or Anglian (orange) glaciations. Ice extents are from Gibbard and Clark (2011). [Color figure can be viewed at wileyonlinelibrary.com]

flow directions using drumlins and flow sets (Jamieson et al., 2014; Gandy et al., 2019; 2021, Ely et al., 2019b, 2024, Archer et al., 2023), and these provide useful constraints or tests. A difficulty with these, however, is determining when during the history of the ice sheet the observed flow indicators were formed, because drumlin fields almost certainly record brief snapshots in time (tens to hundreds of years), compared with the 1000-year flow evolution of an ice sheet. A possible advantage of erratic travel, as shown in this paper, is that their trajectory provides a time-integrated representation of shifting flow geometries. Their use might therefore help circumvent the problem of determining when flow occurred and provide more rigorous tests of models. Complex changes in the flow geometry of an ice sheet may in fact be stored in erratics and indicator grains. When using erratic data to score and choose between ensemble members of model runs, greater care may need to be taken in devising and using appropriate metrics to score them. For example, it is likely more appropriate to use precision and recall methods rather than simple percentage matches because a model with too many false positives (i.e., overprediction) would need penalising using the precision metric. For the Shap Granite, the recall was calculated as 0.529 and precision as 0.226. In other words, only 22.6% of predicted erratic dispersal pixels had observed erratics in them, showing a high number (77.4%) of false positive pixels. Our recall of 0.529 highlights that over half of the observed erratics were explained by the model. We could conceivably use this information to identify an ice sheet model simulation that meets the optimum amount of erratic dispersal, without producing too high a percentage of false positives.

In the opposite direction of thinking, we suggest that an ice sheet model simulation, especially nudged or chosen to align with flow direction indicators such as drumlins and flow sets, could be used to predict the dispersal of economically important minerals. Such flow-optimised ice sheet modelling could become valuable in mineral dispersal tracing, allowing indicator grains found in bulk till samples to be used to trace back to upstream potential source locations.

Conclusions

In summary, a new method of modelling erratic transport was presented, which focuses on how time-transgressive shifts in ice flow geometry affect the pathways and final resting places of erratics. We sequentially modelled erratic time-space trajectories at 1000-year timesteps using an empirically constrained ice sheet model simulation to predict the footprint of erratic deposition areas. The trickier aspects regarding processes of entrainment and deposition and how these affect transport distances were deliberately neglected with the tool using a simple set of assumptions as to how a clast may travel through the glacial system as a percentage of the ice velocity.

Erratic dispersal was predicted for three geologically distinctive lithologies: Shap Granite of Northern England, Galway Granite of Ireland and the Glen Fyne igneous complex from Scotland. The footprint of predicted trajectories compared against observations of erratic locations ($n = 1883$) was found to successfully explain 77% of the observed erratics. The majority were explained by flow directions during ice retreat but highlighted that some required earlier ice divide shifts to produce multiphase pathways. The comparison has proven useful in testing how accurately an ice sheet model simulation captures the positions of ice divides and the sequence of flow through time. Our analysis is surprising in being able to explain so many erratics without modelling the complex processes of entrainment and deposition.

We find that the flow geometries from the B–C are not capable of recreating the dispersal of Galway Granites. In exploring erratics that could not be explained by our erratic trajectory workflow and the underlying BRITICE–CHRONO model simulation it used, we conclude that most of the mismatches arose because the B–C model simulation insufficiently grew large enough topographically centred ice caps during ice sheet build-up.

It is anticipated that this work could be used as a methodological foundation and motivation for future testing of ice sheet model simulations here and elsewhere. We also suggest that an ice sheet model simulation specially chosen to best fit with flow direction indicators such as from drumlin flow sets could be used to predict the dispersal of economically important minerals. Such flow-optimised ice sheet modelling could become valuable in predicting the upstream source ore locations from indicator erratics found in bulk till samples. Finally, we suggest some predicted areas of erratic deposition without any current observations that warrant further field investigation.

Acknowledgements. A PhD studentship from the University of Sheffield to RLV is gratefully acknowledged, under the Hossein Farmey studentship scheme. This work benefited from the PalGlac team of researchers with funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme to CDC (Grant Agreement No. 787263). J.C.E received support from a NERC independent fellowship award (grant no. NE/R014574/1).

Data availability statement

Erratic boulders locations are available with OS Easting and Northings and a text table Table S1. The B–C model simulation is available from Clark et al. (2022).

Supporting information

Additional supporting information can be found in the online version of this article.

Table S1: Location of erratics used in this work in Easting and Northings. Erratic source areas and references are also included. All erratics are available from the corresponding author as a shapefile upon request.

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