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From Highlands to Henge: Refining the Provenance and Transport Pathways of Stonehenge's Altar Stone

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ABSTRACT: The Altar Stone, the 6000 kg central sandstone megalith at Stonehenge in southern England, is suggested to have originated from the Orcadian Basin in northeast Scotland, some 700 km away. However, its source location within this large basin remains unresolved and its mode of transport uncertain. Proposed mechanisms include Neolithic human transport via marine or overland routes or southward movement as a glacial erratic. Here, we combine sandstone provenance analysis with ice flow modelling to constrain potential sources and transport pathways. Ice sheet reconstructions show that southward transport vectors from northeast Scotland were highly localised, making precise source determination critical to evaluating glacial erratic transport plausibility. Candidate source areas farther south within the Orcadian Basin are more compatible with southward glacial dispersal, but show weaker correspondence with the detrital zircon age spectra that characterise the Altar Stone. By contrast, sandstones from Caithness on the mainland of northeast Scotland provide the closest match in zircon age structure; yet, modelled glacial transport from this region is predominantly towards the north-east, with a localised south-eastward pathway directed towards Dogger Bank. Glacial dispersal to Dogger Bank would reduce the anthropogenic transport distance required to Stonehenge from 700 km to 400 km. However, such a model raises an additional temporal problem, as Dogger Bank was inundated by post-glacial sea-level rise before the Altar Stone likely arrived at Stonehenge. Glacial transport may have provided an intermediate stage in the stone's journey, but alone cannot account for the final emplacement on Salisbury Plain. Even under a glacially assisted scenario, substantial anthropogenic transport would have remained necessary.

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KEYWORDS: Altar Stone; British–Irish ice sheet; detrital zircon; glacial transport; Stonehenge

Introduction

An intriguing aspect of Stonehenge, the Neolithic stone circle on Salisbury Plain, is the non-local origin of its multi-tonne megaliths. The building blocks of Stonehenge fall into three main categories (Fig. 1). The sarsen stones, composed of silicified sandstone or silcrete, form the iconic lintelled stones, including massive uprights and the inner trilithon horseshoe weighing an average of 25 tonnes each (Pitts, 2022). The bluestones are a broad group of lithologies widely interpreted to derive from the Mynydd Preseli, including volcanic tuff, rhyolite, dolerite and sandstones, typically weighing between 2 and 5 tonnes (Ixer and Bevins, 2017; Pitts, 2022). The Altar Stone, a single six-tonne megalith, is the third lithology present, comprising Devonian Old Red Sandstone (ORS) (Fig. 1; Bevins et al., 2020; Clarke et al., 2024).

The sarsen stones have a proposed provenance from West Woods, 25 km from Stonehenge (Nash et al., 2020). In

contrast, the bluestones are interpreted to derive from the Mynydd Preseli in Wales some 230 km to the west (Ixer and Bevins, 2017). Recent work proposed a provenance for the Altar Stone, the central recumbent megalith of Stonehenge, from the Orcadian Basin of northeast Scotland, 700 km north of Salisbury Plain (Clarke et al., 2024).

How the non-local building blocks of Stonehenge arrived at Salisbury Plain is widely debated. Some propose that the bluestones from Mynydd Preseli were transported by Neolithic people from quarrying sites via an overland or sea route (Parker Pearson et al., 2015; Pearson et al., 2019). Others suggest that anthropogenic transport may have included an intermediate period as a part of a stone circle that was subsequently dismantled (Parker Pearson et al., 2021), though this interpretation of the Waun Mawn site has been criticised (Darvill, 2022). Others favour glacial transport of these bluestones from Mynydd Preseli towards Stonehenge during a prior glaciation (Thorpe et al., 1991; John, 2018, 2024), though recent detrital zircon–apatite fingerprinting of Salisbury Plain river sediment found no evidence that glacial processes delivered the bluestones to southern England (Clarke and Kirkland, 2026).

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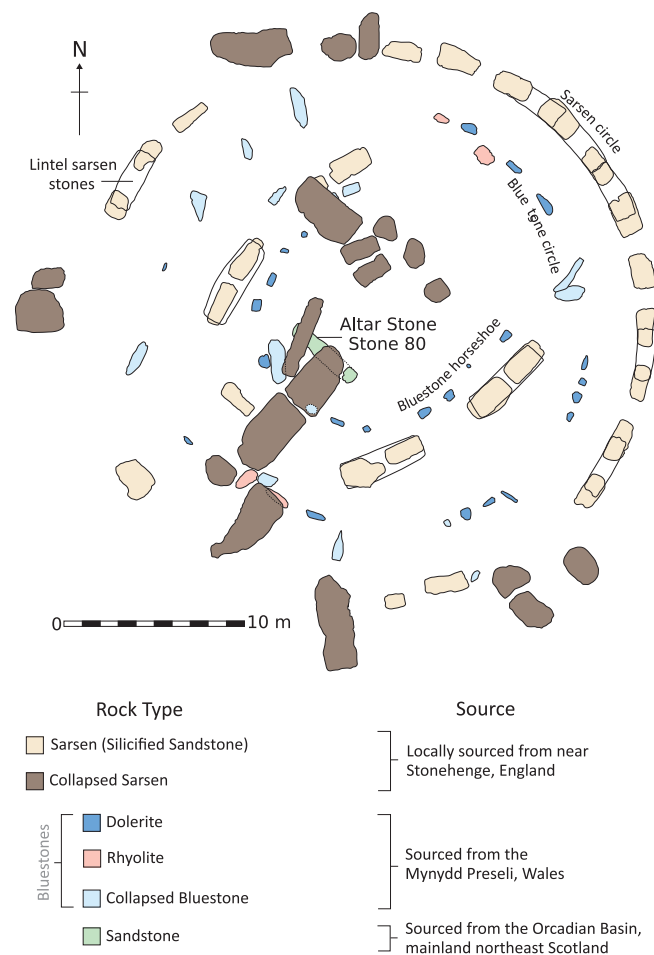


Figure 1. A plan view of exposed megaliths at Stonehenge. The provenance for each type of building block is indicated. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

The suggestion of an Orcadian Basin provenance for the Altar Stone (Clarke et al., 2024) further stimulates megalith transport investigations; how did a six-tonne sandstone megalith measuring $4.9 \times 1.0 \times 0.5$ m travel 700 km southward from northeast Scotland? Human transport via maritime (Clarke et al., 2024) and overland routes (Parker Pearson et al., 2024) has been hypothesised. Here, we explore a third mechanism: glacial transport southwards. This idea was initially regarded as unlikely due to the general north and eastward directions of ice flow across much of the Orcadian Basin during the last glaciation (Late Devensian; ca. 29 to 12 ky BP), as depicted by flow vectors in the time slices of the BRITICE-CHRONO ice sheet reconstruction (Clark et al., 2022). Nonetheless, this interpretation does not consider that a glacial erratic takes thousands of years to be transported within the ice, during which ice flow vectors can shift in direction.

This motivated us to model trajectories of glacial erratics, accounting for such shifting flow vectors over time to yield predictions of transport routes and distance. A complicating factor is that the Orcadian Basin sat near the ice sheet's north–south ice drainage divide (>1 km thick at times). Small movements (tens of kilometres) of this ice divide, as the ice sheet fluctuated, could have transported boulders in a multitude of directions. An investigation of the possible time-integrated flow routes is thus warranted to explore the plausibility of southward transport as an erratic. The key here is that rather than considering a single ice transport vector, we now examine if the Altar Stone could have first been transported in one direction and later in another as ice

flow directions shifted. Could such multistage ice transport have carried the Altar Stone closer to Salisbury Plain? Given the complexity of ice flow directions in the region, refining likely locations of the source area is crucial to exploring this time-integrated ice flow analysis of possible erratic pathways.

Further refinement to the provenance of the Altar Stone is a formidable task, as the Orcadian Basin crops out over 5000–10 000 km² and is up to 4 km thick in Caithness (Fig. 2; Barclay et al., 2005). Furthermore, Altar Stone-like siliciclastic lithologies of the Orcadian Basin are heterogeneous, widely distributed and vary from aeolian arenites to lacustrine flagstones (Reading, 1996; Barclay et al., 2005). Indeed, the Orcadian Basin represents the remains of *Lake Orcadie*, which exceeded 50 000 km² at its mid-Devonian maximum extent (Reading, 1996). Isotopic analyses (e.g., U–Pb) of geological material provide a powerful tool for archaeological provenance investigations that can aid in understanding trade and cultural connections (Kelloway et al., 2014; Shewan et al., 2021). Accordingly, Clarke et al. (2024) implemented a basin-level detrital mineral comparison to match Altar Stone accessory mineral ages and geochemical signatures to the ORS of the Orcadian Basin (Strachan et al., 2021).

To further constrain the Altar Stone's provenance, we present an intra-basin analysis of detrital zircon dates between the Altar Stone and ORS outcrops in Scotland. We then use a new tool for exploring time-integrated erratic transport pathways in ice sheet model simulations (Veness et al., 2025) to examine the potential for southwards ice-mediated megalith transport from the Orcadian Basin.

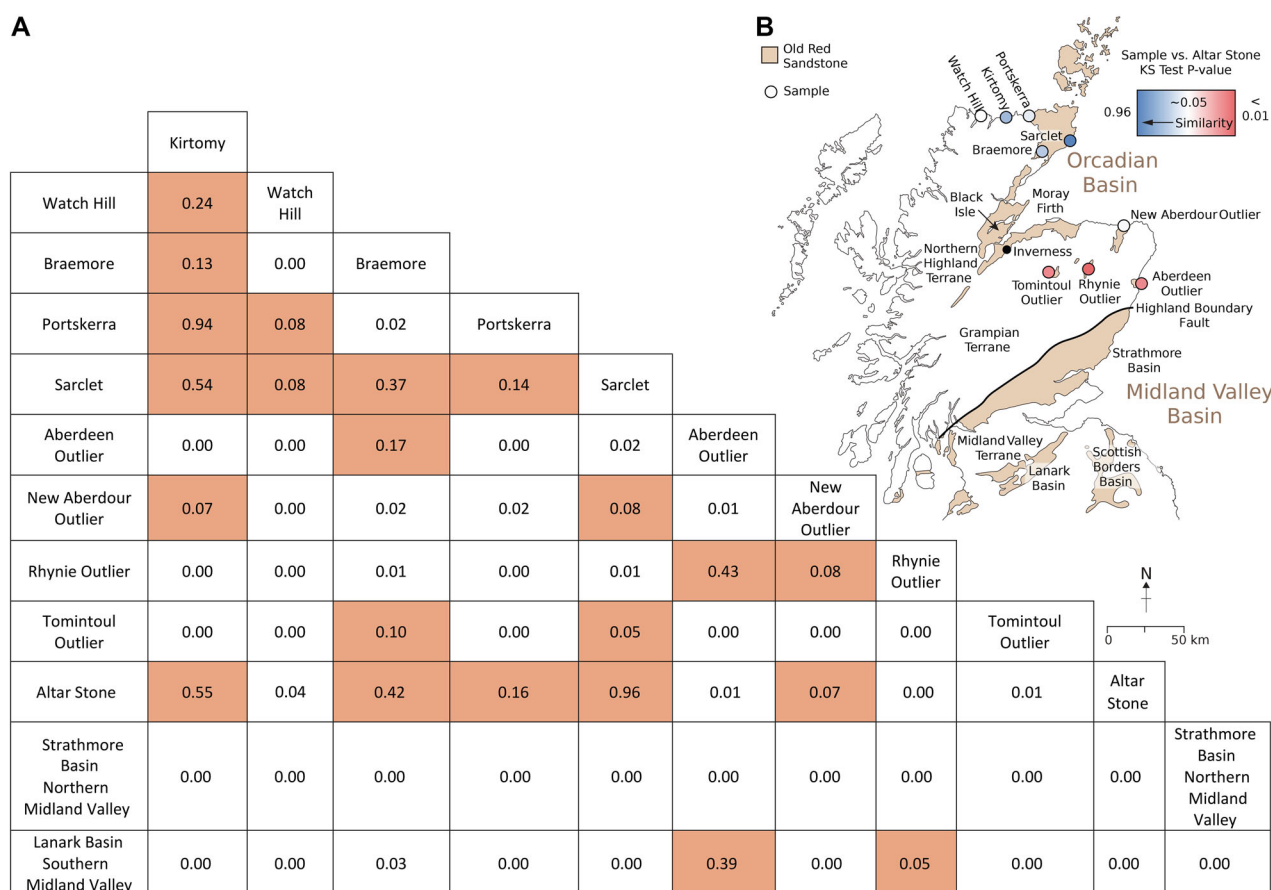


Figure 2. Overview of Scottish Old Red Sandstone. (A) Kolmogorov–Smirnov test result table, showing P values for the test on zircon data sets from the Altar Stone and potential source areas. Highlighted values in orange are test results where $p > 0.05$, pointing towards a shared provenance. (B) Old Red Sandstone outcrops of Scotland. Sample locations are coloured by detrital zircon similarity between the potential source and the Altar Stone, as determined by a Kolmogorov–Smirnov test. [Color figure can be viewed at wileyonlinelibrary.com]

Materials and methods

Detrital zircon analysis

We use the reported Altar Stone zircon U–Pb concordia dates from Clarke et al. (2024), which are compiled from three thin sections: MS3, 2010k.240 and FN593 (Bevins et al., 2020; Clarke et al., 2024). Comparative detrital zircon age data sets include Orcadian Basin ORS (Strachan et al., 2021), Grampian outlier ORS (McKellar et al., 2021), Northern Midland Valley ORS (Strathmore Basin) (McKellar et al., 2020) and Southern Midland Valley Basin ORS (Lanark Basin) (Phillips et al., 2009) (Fig. 2). These data sets encompass all currently published detrital zircon U–Pb ages from Scottish Old Red Sandstone successions. Zircon dates from individual Midland Valley ORS outcrops were compiled into basin-level data sets (for Strathmore and Lanark) to assess the input of any southern detrital zircon components into ORS north of the Highland Boundary Fault (Fig. 3).

We implemented a two-sample Kolmogorov–Smirnov (KS) test to compare the compiled zircon ages with those from the Altar Stone (Fig. 2). The KS test compares the maximum probability difference between two cumulative density age plots. The test evaluates the null hypothesis that both zircon age data sets are drawn from the same distribution based on a critical value dependent on the number of analyses and a chosen confidence level. Multidimensional scaling plots (MDS) for zircon data sets were created using the MATLAB script of Nordsvan et al. (2020). Here, we used a bootstrap resampling (>1000 times) procedure with Procrustes rotation of KS test values to estimate comparison uncertainty ellipses at a 95% confidence level (Vermeesch and Garzanti, 2015).

Glacial erratic modelling

Potential ORS source areas for the Altar Stone were used to seed a glacial transport model that accounts for shifting ice flow variations during the Late Devensian using the approach of Veness et al. (2025). Ice flow directions were taken from the BRITICE-CHRONO ice sheet model simulation of Clark et al. (2022) at 1000-year time steps between 30 000 and 15 000 years BP. This simulation used the Parallel Ice Sheet Model (Winkelmann et al., 2011), calibrated against geological indicators of the extent and timing of ice margins and using glacio-isostatic constraints (Bradley et al., 2023). The modelled erratic dispersal footprints predict zones where erratic rocks could have come to rest, given the source area and time-variant ice flow geometries (Fig. 3). Although ice extended further south during the Anglian glaciation c. 450 000 BP (Fig. 4), no modelled ice flow simulations of sufficient resolution exist for this ice sheet, making it impossible to meaningfully calculate or test glacial erratic trajectories at this time. Given this present constraint, we focus our modelling on higher fidelity flow geometries of the last (Late Devensian) ice sheet.

Discussion

Orcadian Basin sources

Published detrital zircon data sets for the Orcadian Basin are currently limited to mainland exposures (Strachan et al., 2021), precluding zircon-based comparison with ORS exposed on Orkney. Nonetheless, based on handheld XRF geochemical

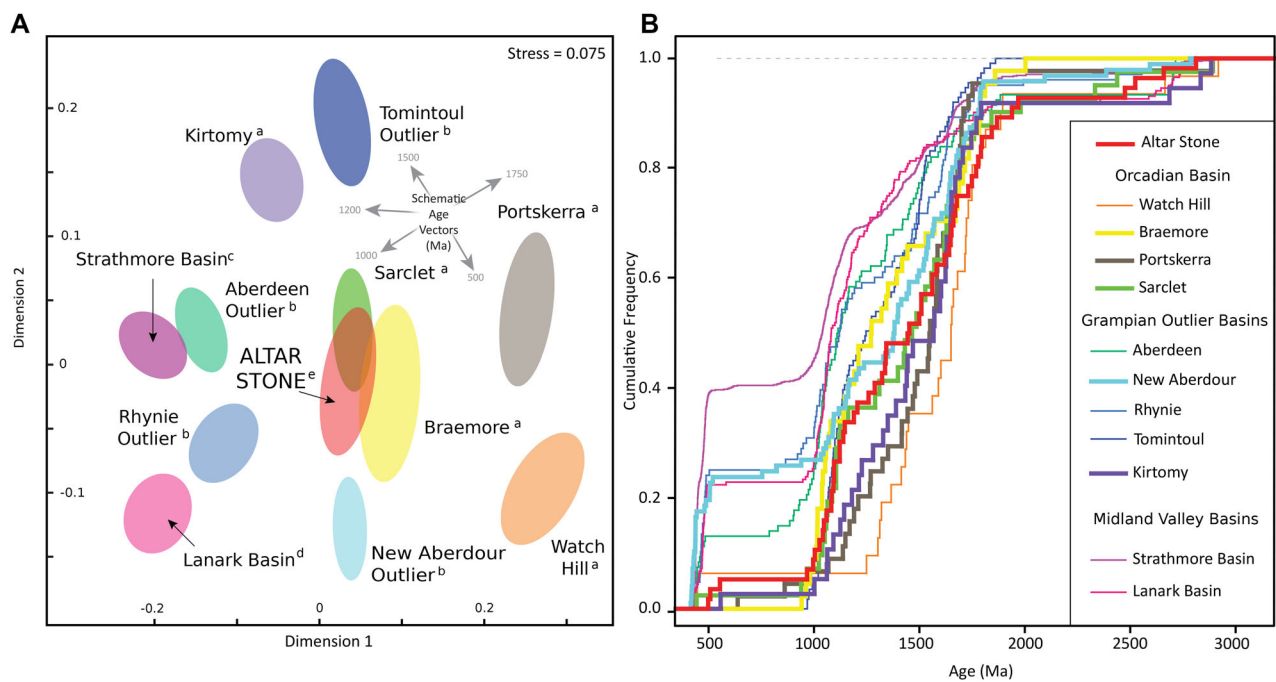


Figure 3. Orcadian Basin detrital analysis. (A) Multidimensional scaling plot of concordant zircon U–Pb ages from the Altar Stone and comparative data sets, with ellipses at the 95% confidence level (Nordsvan *et al.*, 2020). Zircon populations that are statistically similar plot close to each other. Detrital zircon U–Pb data sets include (a) Strachan *et al.* (2021), (b) McKellar *et al.* (2021), (c) McKellar *et al.* (2020), (d) Phillips *et al.* (2009) and (e) Clarke *et al.* (2024). (B) Cumulative probability plot of zircon U–Pb ages from comparative outcrops, basins and the Altar Stone. Thick cumulative probability plot lines are for those comparative data sets with KS test $p > 0.05$. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.com)]

analysis, Bevins *et al.* (2024) excluded Orkney ORS as a potential source for the Altar Stone (Fig. 2). Therefore, in this study, we consider the remaining Orcadian Basin ORS source areas, including northeast mainland Scotland (Fig. 2). Five outcrop-level detrital zircon sample data sets from the Orcadian Basin are available for comparison (Fig. 3; Strachan *et al.*, 2021).

KS and MDS analyses demonstrate that the sample most similar to the Altar Stone zircon population is the ORS at Sarclet (p -value = 0.96) (Fig. 2). The Altar Stone detrital zircon cargo is also indistinguishable from ORS at Braemore, Kirtomy and Ports Kerrera (Fig. 3)—all northern mainland expressions of the Orcadian Basin from mid to upper ORS (Strachan *et al.*, 2021). Moreover, detrital zircon dates from the New Aberdour (Turrieff) outlier are also indistinguishable from the Altar Stone; however, the detrital zircon similarity is lower (p -value = 0.08) than the more northerly samples (Fig. 2). Although KS tests indicate that Kirtomy, Ports Kerrera and New Aberdour zircon populations are statistically indistinguishable from the Altar Stone ($p > 0.05$), their multidimensional scaling uncertainty ellipses do not overlap in ordination space (Fig. 3B). Such differences arise because the KS test compares age distributions pairwise, whereas multidimensional scaling represents the relative (dis)similarity of all data sets simultaneously. In any case, importantly, both approaches identify Sarclet as the closest match to the Altar Stone zircon population.

Detrital zircon spectra do not support a provenance for the Altar Stone from the Grampian Outlier ORS at Rhynie, Aberdeen or Tomintoul (Fig. 3). Although separated by the Highland Boundary Fault, the zircon age spectra of Grampian Outlier basins are more similar to successions to the south in the Midland Valley Basin than the Orcadian Basin. Key features that differentiate Grampian Outlier Basins from the Altar Stone are pronounced mid-Palaeozoic and Neoproterozoic zircon shed from the Midland Valley Terrane (McKellar *et al.*, 2021). Therefore, a comparison of detrital zircon dates from the Altar Stone and the Orcadian Basin suggests a source

from mainland northeast Scotland for the Altar Stone and not ORS from the Grampian Terrane (Fig. 3). In summary, due to their detrital zircon signature, our new analysis excludes three potential southern source areas (Tomintoul, Rhynie and Aberdeen Outliers) (Fig. 2).

Erratic dispersal modelling

Based on suitable geology, we identify three source areas that we seed into the glacial erratic modelling: (i) Sarclet & Braemore, combined and henceforth named as Caithness; (ii) Inverness and the Black Isle; and (iii) the New Aberdour Outlier (Fig. 2). In the ice flow modelling, source regions represent ORS outcrops rather than individual detrital zircon sampling sites. The Inverness–Black Isle region was included because it represents a major Old Red Sandstone outcrop positioned between the Caithness exposures and the New Aberdour Outlier, and has potential for erratic dispersal.

Inverness–Black Isle and New Aberdour ORS erratics are simulated to be dispersed towards the north and east, with southeast possible as far as Dogger Bank in the North Sea (ca. 470 and 450 km southwards, respectively) (Fig. 4A). Dogger Bank is a topographic high, comprising a Devensian end moraine complex (Cotterill *et al.*, 2017) that was exposed as dry land during Late Pleistocene sea-level low stand (Bradley *et al.*, 2023). Rocks dispersed from the New Aberdour Outlier to Dogger Bank could have remained above sea level until ca. 9–8 ka BP (Bradley *et al.*, 2023; Emery *et al.*, 2020) and possibly as late as c. 7 ka (Wessex Archaeology, 2014). The Inverness and the Black Isle areas were modelled, as they represent a major outcropping region of ORS between two plausible sources. The most sustained dispersal from the Inverness and the Black Isle is to the northeast, but modelling shows a southeast stream extending towards Dogger Bank, 50 km short of the New Aberdour Outlier dispersal footprint (Fig. 4B).

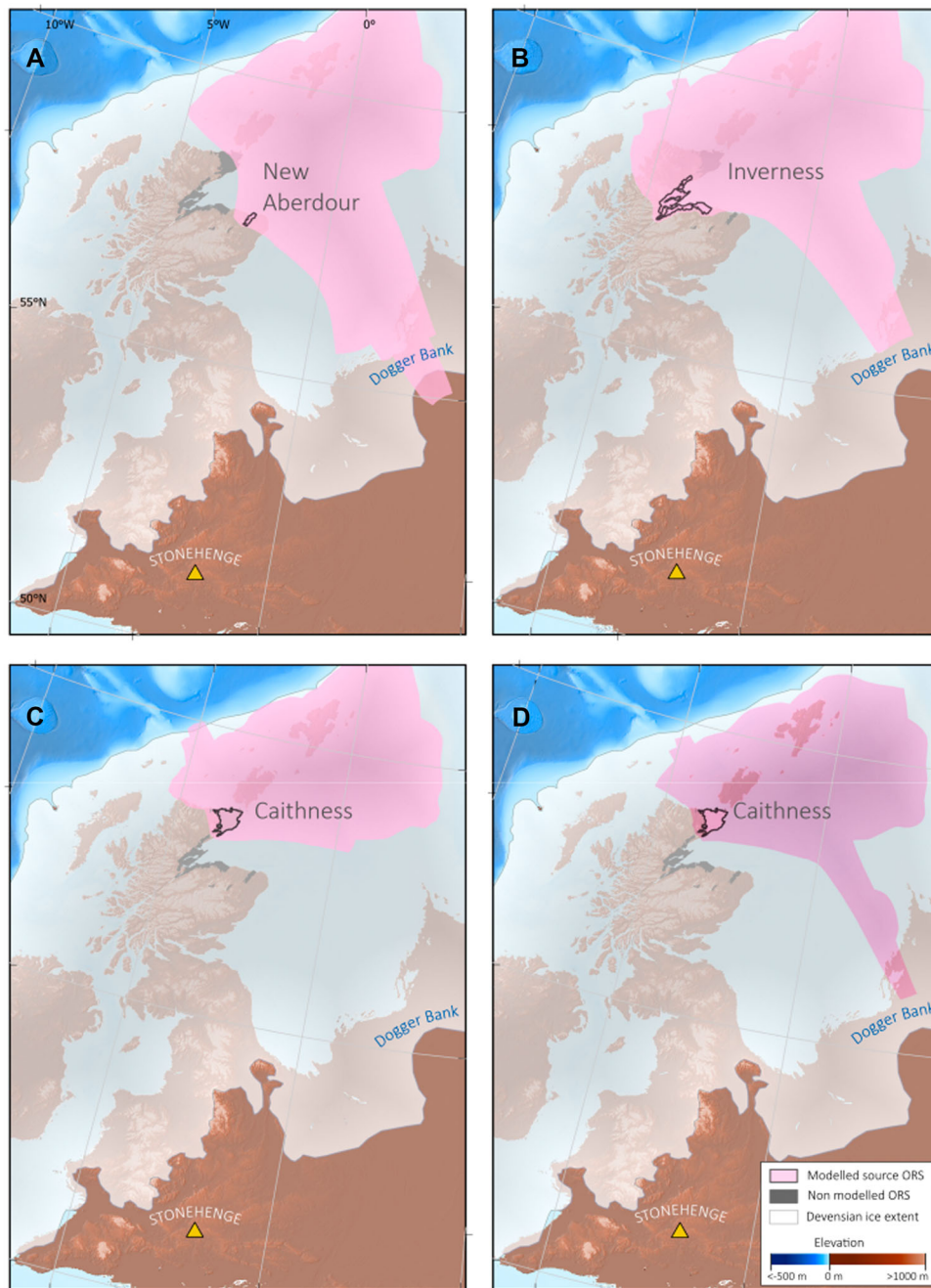


Figure 4. Modelled maximum dispersal footprints of Old Red Sandstone by the Late Devensian British–Irish Ice Sheet. The footprint demarcates all possible areas of deposition, not a specific site or probability assessment. The marine limit (highest shoreline) is derived from the glacial isostatic adjustment-corrected topography of Bradley *et al.* (2023) for 14 ka BP. (A) Modelled dispersal from the New Aberdour Outliers; (B) from Inverness and the Black Isles; (C) from the Caithness region; and (D) from Caithness using modified initial conditions with source rocks placed in the Moray Firth, simulating earlier southward transport. This scenario yields a wider dispersal footprint extending south-eastward to the Dogger Bank. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Dispersal from Caithness produces a comparatively restricted footprint to the north and east (Fig. 4C), with limited transport southwards. However, we note that this area (in the BRITICE-CHRONO model simulation) sometimes feeds ice ~10 km southwards into the adjacent Moray Firth, whereupon ice flow at other times carries rocks much further south. Given this high sensitivity to location, and limitations in the spatial (2.5 km) and temporal resolution (1000-year timesteps) of the BRITICE-CHRONO model simulation, we conducted a second experiment (Fig. 4D), which initiated the erratic dispersal from Caithness with source rocks already transported into the Moray Firth. We used retreat flow geometries from 17 ka BP, as these had the potential to result in the largest natural southwards dispersal into the Firth. The 17 ka BP geometries could

represent more extensive buildup geometries or Mid Devensian retreat subsequently re-entrained by Late Devensian ice flow. This scenario produced a dispersal footprint from Caithness that extended southeast to Dogger Bank (Fig. 4D). Overall, our modelling of rock dispersal by the last (Late Devensian) ice sheet highlights the possibility that rock of suitable lithology could have been glacially delivered north-east to the Shetland Isles or as far southeast as Dogger Bank.

Ice streams with southward flow and the potential to deliver erratics to Dogger Bank have been previously modelled (Gandy *et al.*, 2019) and inferred from buried geomorphological and sedimentological evidence (Cotterill *et al.*, 2017; Emery *et al.*, 2019; Phillips *et al.*, 2022). Extensive moraines (Cotterill *et al.*, 2017) at Dogger Bank of Late Devensian age

imply large volumes of mixed-grade sediment, and include observations of sandstone cobbles. Larger boulders are widely reported in the geotechnical literature from windfarm development, but the location and lithology are poorly documented. This absence of lithological data for the larger clasts likely reflects a combination of sampling bias and the industrial interest in the site. Bed samples from the region are largely derived from vibrocores, which are poorly suited to recovering large clasts (Finkl and Khalil, 2002). 3D ultra-high resolution seismic geophysical surveys can image boulders in the shallow subsurface, but the resolution of publicly available 2D surveys is insufficient to resolve boulder-sized features. Furthermore, much of the available subsurface imaging, site investigation and seabed obstacle data from Dogger Bank derive from offshore windfarm development, where the focus is engineering hazard management rather than geological characterisation. Consequently, large boulders may be identified or cleared without detailed provenance recording (Finkl and Khalil, 2002).

Human and ice transport?

Our models do not predict any Late Devensian glacial transport directly to Stonehenge and therefore infer that long anthropogenic transport must have been required to move the Altar Stone. This interpretation is consistent with detrital mineral fingerprint evidence from Salisbury Plain, indicating that the Stonehenge landscape lacks a detrital signature expected from direct glacial delivery of megalith-derived material from northeast Scotland (Clarke and Kirkland, 2026). However, within this context, we outline one scenario under which glacial transport may have reduced the anthropogenic

transit of the Altar Stone. Glacial transport modelling reveals the possibility that the Late Devensian ice sheet transported erratics from the southern Orcadian Basin to Dogger Bank, located approximately 400 km northeast of Stonehenge (Fig. 4). The moraine landscape left after the retreat of ice from Dogger Bank was subaerially exposed between ca. 23 ka BP and 8 ka BP (Emery et al., 2020), forming a topographic high point in the surrounding landscape, which could have held some cultural significance to prehistoric humans occupying the area (Walker et al., 2022). Furthermore, the Dogger Bank region would have been devoid of bedrock outcrops, meaning that large boulders would have needed to have been sourced from moraine deposits.

Glacial transport to Dogger Bank, bypassing uplands in Scotland and Northern England, could conceivably decrease some of the challenges of transporting the Altar Stone. Nevertheless, human agency would still have been required, which may have included primarily maritime pathways via the southeast coast or overland passage along the Berkshire Ridgeway, a prehistoric high-ground route used from at least the Neolithic, linking the Thames corridor with the Avebury/Wessex chalklands (Steane, 1983; Fig. 4). Geographically, a route from Dogger Bank would have involved more sheltered waterways and shorter distances than those from northeast Scotland.

Any human transport of rocks from Dogger Bank must have occurred prior to inundation by rising relative sea level between 8 and 7 ka BP (Bradley, 2023). This constraint places any such transfer roughly three millennia before the Altar Stone was erected at Stonehenge. A Dogger Bank origin therefore requires not a single episode of transport, but a more complicated history: the Stone would first have had to be removed from a landscape undergoing marine transgression, taken to at least one location

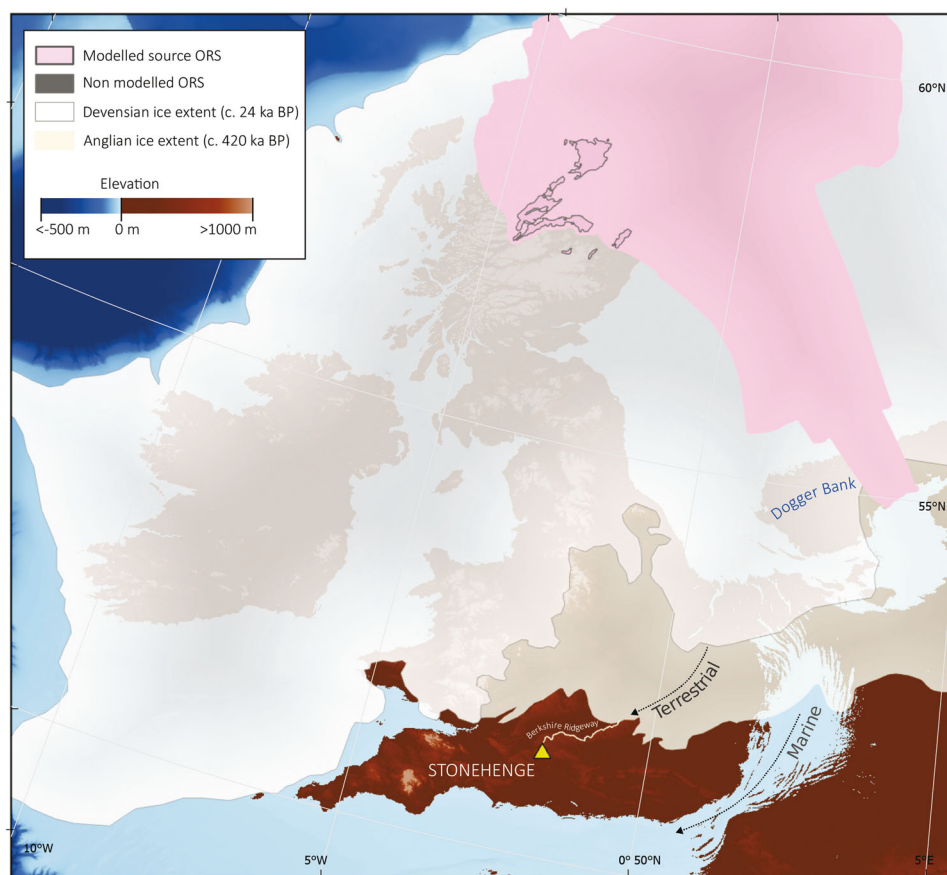


Figure 5. Modelled dispersal of Old Red Sandstone erratics from the Orcadian Basin by Late Devensian ice flow of the British–Irish Ice Sheet. Terrestrial extent is indicated by a 9 ka BP shoreline. Potential minimum anthropogenic transport routes are indicated by arrows and the Berkshire Ridgeway is indicated by a white line. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

that remained above sea level for thousands of years, before finally being transported to Stonehenge. Such a scenario requires prolonged cultural significance or multiple-phase activity, across an exceptionally large temporal gap. The need to invoke such a long, multi-stage chain of events challenges the plausibility of Dogger Bank as an intermediate source and correspondingly, therefore, of a Late Devensian glacially derived pathway for the Altar Stone.

However, Late Devensian transport may not have produced the most extensive southern glacial transport distance. The Anglian glaciation c. 450,000 BP provides an empirically well-documented southern extent well beyond the Devensian Limit. Given multiple glaciations, it is plausible that erratic transport could extend beyond our modelled extent for the Devensian reconstruction shown in Fig. 5. As no high spatial or temporal resolution numerical ice flow simulations exist for the Anglian to date, it is, as yet, impossible to meaningfully calculate or test ice flow geometries for such scenarios.

Under a Late Devensian glacial transport scenario, transfer of the Altar Stone from a Dogger Bank depositional site to Stonehenge would still have required movement over some 400 km, implying considerable Late Neolithic capacity for organisation, labour mobilisation and overland and marine transport. Direct transport from northeast Scotland would have represented a formidable undertaking, requiring sophisticated logistical planning, technological solutions and durable long-distance social networks. Either scenario therefore implies a society capable not merely of moving stone but also coordinating complex, large-scale acts of monument construction across extensive geographic ranges. Such long-distance movement fits within a broader framework of prehistoric connectivity across Britain (Parker Pearson et al., 2024), supported by isotopic signatures (Evans et al., 2022), shared rock art motifs (Bradley, 2023), and the presence of a Scottish Lewisian gneiss mace head at Stonehenge (Parker Pearson, 2023).

Conclusions

Based on a statistical comparison of available detrital zircon U–Pb data sets, we propose that the Altar Stone derives from mainland northeast Scotland's Lower to Middle Old Red Sandstone. The Caithness region, or the Inverness–Black Isle area, is the most likely source of rocks for the Altar Stone. We started by posing the following question: given a Scottish provenance for the Altar Stone, could glacial transport have contributed to its southward transport? It is not possible to prove that the Altar Stone was transported southwards by an ice sheet; our approach was to assess in which directions and by how far it could have been transported by ice flow on the basis of known ice extents and flow directions. Results from erratic transport modelling show that glacial dispersal from these regions could have moved boulders north, east and southeast.

We show that transport of the Altar Stone from the Orcadian Basin of Scotland to Dogger Bank is plausible under multi-phase southeast ice flow during the Late Devensian glaciation. Emplacement of a large boulder on Dogger Bank is compatible with geomorphic interpretations of the depositional landscape and would locate the stone within a region inferred to have been inhabited during the Mesolithic. Yet, such a scenario still demands a prolonged residence time before further movement, because inundation of Dogger Bank preceded erection of the Altar Stone at Stonehenge by several millennia. Late Devensian glacial transport provides only an intermediate stage in the stone's history, reducing the overall anthropogenic transport distance but not removing the need for substantial later human agency.

Due to the complex ice flow in the region, we show that determining the precise provenance within the Orcadian Basin is critical to evaluating this potential glacial transport pathway. A more southerly source would facilitate glaciological dispersal but shows weaker geological affinity with the Altar Stone. Our combined provenance and ice flow results weaken the case for a wholly glacial explanation of Altar Stone transport to Salisbury Plain. Glacial transport of the Altar Stone towards Dogger Bank cannot yet be ruled out; however, such a scenario would require a narrow coincidence between source location and ice dispersal pathway to be combined with a monument-scale block being moved by people over a further ~400 km. Glaciation may therefore have provided, at most, partial transport rather than a complete delivery mechanism.

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Conflicts of Interest—The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article, as no data sets were generated or analysed during the current study.

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