

Detrital zircon–apatite fingerprinting challenges glacial transport of Stonehenge’s megaliths

Corresponding Author: Dr Anthony Clarke

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This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Dr Clarke,

Your manuscript titled "Detrital zircon–apatite fingerprinting challenges glacial transport of Stonehenge’s megaliths" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. Specifically, we ask you to:

1. Enhance the robustness of conclusions by considering the geomorphology history of Salisbury Plain, including former Paleogene lithology.
2. Fully justify the glacial transport hypothesis and provide a clearer explanation of zircon-apatite signature, ensuring that the zircon age data is appropriately supported.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This is a relatively brief review, since the authors appear to have overlooked a major factor in the geology of Salisbury Plain – that the area was once covered by a significant thickness of Paleogene floodplain, deltaic, estuarine, marginal-marine, and marine sediments, which overlay the Chalk. These sediments – including the Thanet Sand noted by the authors – have mostly been removed by erosion, but remain preserved as outcrops to the southeast of Salisbury and southeast of Marlborough (and, more extensively, to the east within the London Basin). They also form the host sands within which the sarsen stones of Stonehenge and the Marlborough Downs developed, and exist in remnant form as the widespread Clay-with Flints. There is an extensive literature on the likely former distribution of Paleogene sediments within the Hampshire Basin and London Basin, including across Salisbury Plain (see Harding et al. [2025] for a recent synthesis; <https://www.doi.org/10.1017/ppr.2024.13>).

The source provenance of the Paleogene sediments of southern Britain has been widely discussed, with various studies linking them to the Scottish Highlands (see Morton et al. [1982] as an early example; [https://doi.org/10.1016/S0016-7878\(82\)80003-5](https://doi.org/10.1016/S0016-7878(82)80003-5)). As such, the identification of a Laurentide crystalline basement signature, potentially deriving from northern Britain, in zircon U-Pb ages from stream sediments on Salisbury Plain is completely unsurprising, as apatite ages post-dating the Chalk in this area.

The authors are correct in saying that U-bearing detrital grains in stream sediments on Salisbury Plain are most plausibly sourced from zircon and apatite-rich crystalline lithologies beyond the Plain. However, the reported zircon-apatite signatures are likely to simply reflect the former Paleogene cover. In this context, the framing of the paper as a counter to the Stonehenge glacial transport hypothesis is flawed. If the paper was entitled “Detrital zircon–apatite fingerprinting shows that Paleogene sediments, likely derived from northern crystalline terrain, once covered Salisbury Plain”, then I would be happy to recommend publication.

The most interesting finding within the study – and which really should form the focus of the paper – is the overall lack of zircon U-Pb ages of 464–462 Ma within the four stream sediment samples. I agree fully with the authors that, if the bluestones were glacial erratics as argued by Brian John, there should be many more sediment grains with a c.464 Ma age. Clearly, the discovery of one zircon U-Pb age of 464 Ma amongst 550 analyses does not totally preclude the presence of bluestone erratics but, as the authors suggest, it is a small nail in the coffin. Checking the supplementary data, the one 464 Ma age comes from sample SH1, which was collected to the east of Stonehenge. If it were from west of Stonehenge and lying on a path between the Preseli Hills and the monument, it could plausibly support the glacial transport theory, but from a drainage system near Andover, I very much doubt it.

I cannot recommend publication of the manuscript in this form. However, I do think there are some important data here that deserve to be published somewhere. What the authors have without realising it is really detailed evidence of the zircon-apatite signatures of the former Paleogene cover on Salisbury Plain. If they were to reshape the manuscript and focus it onto the bluestone question, it has the potential to be a powerful intervention. Even with four sampling points, the presence of only a single zircon grain with a U-Pb age of 464 Ma amongst 550 analyses is significant counter-argument to the bluestone glacial transport hypothesis.

Given the flaws in the framing of the manuscript, I have only a handful of detailed comments:

Lines 36, 49, 65 – no need for the additional “The” – plain “Salisbury Plain” is fine.

Line 37 – I’m assuming you mean Avebury here?

Line 41 – plain “West Woods” is fine.

Line 43 – “2-5 tonnes” would be better.

Lines 50–54 – the way this paragraph is phrased gives a false sense of balance between the two sets of theories. By far the majority of studies favour human intervention, whereas the glacial transport theory is essentially a niche view. I would suggest rephrasing to reflect this. Presumably Clarke et al. (2024) needs to be added to the list of citations for the sea/overland viewpoint?

Lines 59–64 – doesn’t this assume that glacial outwash was deposited on or around Salisbury Plain? Is there documented evidence of outwash in this area, either from the Anglian or Devensian? How could the presence of outwash be explained geomorphologically, given that Salisbury Plain is an elevated area? How could outwash flow reach rivers like the Avon and Wylfe? What are the drainage connections?

Line 65–68 – what this lacks is a description of the structural geology and particularly the topography and drainage configuration of the area.

Line 216-219 – could these bioapatite sources simply be inherited from the Paleogene sediments that once covered Salisbury Plain? Why do they need to be derived from the Chalk?

Lines 220-226 – could these older apatite sources simply be inherited from the Paleogene sediments that once covered Salisbury Plain?

Line 275 – I'm interested to know whether the authors think that four stream samples is of sufficient size to underpin the kinds of claims made in the paper. A smaller journal, perhaps, but – in my view – a Nature-family journal, no.

Reviewer #2 (Remarks to the Author):

The central claim in this paper is that modern river sediment on the Salisbury Plain is derived from the locality, or the catchments of the local streams. I find this claim to be novel and true on the basis of the supplied zircon data, which demonstrate that detritus in southern England at the end of the Cretaceous can be dominated by Laurentian sources very similar to those present in modern river sediment.

The implications for Stonehenge are significant – despite the local streams preserving zircon populations that appear very Laurentian (i.e. Ireland/Scotland-like), these populations are found by the authors to be typical of sandstone units that were deposited in southern Britain 10s of millions of years before glaciation. This would apparently bolster arguments that the stones at Stonehenge were moved large distances by humans and not just what was lying around post-glaciation. Taken at face value I would assume that would suggest that the site was culturally important across a wide area for prehistoric people of Britain. This provides an interdisciplinary aspect to the paper and it will be read by a broad audience.

The paper is well-written and appropriately structured. There is not any major missing information. Though I have some suggestions below.

I have no "major" comments, just some moderate points that might affect the emphasis of some sections – and then small edits that are included in an annotated pdf (click the highlights to see my comments).

Best wishes,
Gary O'Sullivan
Trinity College Dublin

Moderate points:

Lines 12–16 (abstract): This section is awkwardly written for a broad audience, and also sort of misses the main point. The main finding is that modern river sediment on the Salisbury plain resembles sediments found elsewhere in southern Britain WRT its zircon populations, and thus a glacial origin does not need to be invoked. The Alpine orogeny is not really very relevant to that finding and renders the abstract less impactful and less easily understood by a general scientific audience.

Line 22–26: Something that is never addressed properly in this paper is the different sensitivity of zircon and apatite to weathering processes. It makes no sense that zircon are mostly Laurentian and derived from multi-cyclic sediments and there are no similar old apatite, unless the reader understands that apatite is far less likely to survive sedimentary recycling than zircon. The fact that there are zero Laurentian apatite despite apatite being very common in the Laurentian basement speaks to repeated, profound and extreme weathering of the source rocks of these zircon in the Salisbury modern river sediments.

Lines 68–70: This section is factually incorrect. The chalk local to Stonehenge is well-known to be strongly phosphatic. I have about a kilo of rock from drill cores under stonehenge sitting on my desk – which I have U–Pb dated (don't try it the 'age' is nonsense due to fluid interaction). So I would challenge the finding of low P in the local chalk – some of the chalk horizons are effectively phosphorite. These samples are from the A303 boreholes and were given to me by Rory Mortimore. See Mortimore et al., 2017 below which details the phosphate rich nature of the stonehenge chalks.
<https://doi.org/10.1016/j.pgeola.2017.02.003>

Lines 73–74: There is important missing context here about the recovery rate of the minerals from these sediments. It is easier to generate an exotic heavy mineral population where the proportion of the mineral is very very low. Can you comment on this?

Apatite U–Pb section. The ultimate lithology of the apatite is presented as a mystery, but it needn't be one. It is actually still possible to tell if the grains are from an authigenic source. This can be done by looking at the 206/208 ratios. U in marine phosphate is derived from bacterial scavenging from seawater, which has extremely low Th/U, meaning that the Th/U ratio of marine phosphate is ludicrously low. The 206/208 ratios of your apatite should be abnormally high if the apatite are still very low Th/U. Check this – it'll take 2 minutes.

Lines 124–125: These apatite are from modern river sediments, so is it possible that this rounding is recent?

Lines 163–164: I don't find this a particularly convincing argument, the local rock is purportedly zircon-free chalk, so any

extraneous source of zircon would dominate the local zircon budget by definition. Doesn't change the fact I believe your interpretation, but I think this is a weak line.

Lines 168–171: the best part

Lines 175–179: What mechanism can be invoked to explain zircon storage on the Salisbury plain from removed overburden after millions or tens of millions of years? You need to address this. What about the drainage patterns of the rivers, is there anything that they traverse that could deliver zircon?

Lines 181–183: Would the ORS not contain a lot more Grampian than present in the Thanet?

Lines 216–219: Again, add the Mortimore 2017 reference from earlier. The whole region is infested with phosphatic chalk. <https://doi.org/10.1016/j.pgeola.2017.02.003>. Part of the issue is that marine phosphate is too porous to hang on to daughter products. The apatite you've analysed could represent the recrystallisation of primary phosphate into more coherent crystalline apatite grains millions of years after deposition.

Line 228: having such high U is indicative of sedimentary phosphate origin of apatite.

Lines 236–242: While this is plausible and I broadly think a sensible guess (i.e. linking apatite age to Alpine) - is it also plausible that the apatite are incompletely and inconsistently overprinted, meaning that the 'age' of the overprint is difficult to determine with any certainty. Unless you can prove it more concretely or convincingly, I would emphasise that this is a section that is your interpretation of something that fits the data plausibly, but I'm not convinced its 100% proven.

Lines 255–257: Is it possible that zircon is present in low volume in the chalk, and that the chalk and Thanet formation derived zircon from a similar drainage pattern. As in – is the Thanet formation a middleman that is required in this story, or just a formation with a similar provenance for its detrital components? More simply – is Thanet the dad or is it the brother? Is it not plausible that the prolonged weathering of the chalk at source causes the carbonate component to dissolve into the river load, leaving a gradually more concentrated residue of whatever scraps of detritus were originally in the carbonates? Whether from the odd tiny bed of detritus or from windblown grains etc.? Maybe my option is less likely for some reason, but address this possibility somewhere.

Figure 1: A stratigraphic column should be added, and also the inset should have the British palaeoshoreline in the late Cretaceous and show the major terranes.

Reviewer #3 (Remarks to the Author):

The authors address indirectly the intriguing and enduring question as to whether megaliths were transported to Stonehenge as glacial erratics by one or more Pleistocene ice sheets. Their approach is novel - to use detrital zircon-apatite finger printing of modern stream sediments to test if the sediments record glacial transport and reworking of these mineral grains in the surroundings of Stonehenge. The analytical methods and results are convincing and point to an alternative origin from recycling of minerals from London Basin cover rocks during Cenozoic denudation.

The current ms has several weaknesses that need to be addressed before publication.

1. The glacial transport hypothesis is not adequately explained to the reader. What are the arguments/evidence for this proposal? All comments are negative. There is no map of Anglian ice sheet limits, generally regarded as representing the maximum extent of the British-Irish ice sheet in England during the Pleistocene. Nor of ice flow lines for this ice sheet. It is plausible that an earlier ice sheet reached Salisbury Plain - the maximum limits of ice sheets in N Europe and S of the Great Lakes locally lie outside the MIS 12 limits. This possibility is not mentioned.
2. There is no thorough statement of how the glacial hypothesis is tested by the Zr data. What would be expected in the Zr age data if ice flow from the NW had reached Salisbury Plain? Yes, there is one sentence on the lack of Cadomian Zr ages but no more detail. Are former ORS cover rocks in Wales a potential source? If so, could glacial erosion and transport of those rocks supplied the Laurentian Zr?
3. If there is no clear glacial signature in the Zr data then the authors miss an important implication of their results - that the BIIS did not advance onto Salisbury Plain and so the Anglian ice sheet limit is the maximum Pleistocene ice limit in southern England.
4. The text in the Abstract and Introduction needs careful revision. See detailed comments on the attachment.

If these weaknesses can be eliminated then the paper will be a valuable contribution to the questions of the origins of the Stonehenge stones, the maximum extent of Pleistocene glaciation in the British Isles and the long-term history of exhumation and sediment cycling in Britain.

benefits**

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Dear Dr Clarke,

Your revised manuscript titled "Detrital zircon–apatite fingerprinting challenges glacial transport of Stonehenge's megaliths" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I thank the authors for responding to my comments and for making substantive changes to the manuscript. The paper is now much improved. However, in attempting to address all of the reviewer comments, the authors have lost some of the sharpness of argument of the original manuscript. This is particularly evident in the introduction, which could be much more succinct. It is not my job to re-write the manuscript. I have suggested some areas where the text could be improved, but in reality, the introduction needs a careful review and edit to make the arguments about glacial vs. anthropogenic transport more forceful.

My big concern remains that the authors still have not adequately explained how even one zircon grain of 464 Ma age could have got into the sediment around Stonehenge without some sediment input from Wales. This needs addressing otherwise it will provide low hanging fruit for anyone wanting to dismiss the findings.

Specific comments:

Abstract – This is a classic case where addressing reviewer comments has weakened the flow of the argument. Surely, if there is even a single 464 Ma zircon age consistent with the Preselis (line 13-14) then – unless you can provide a plausible argument for how else this one zircon grain got into fluvial sediments around Stonehenge – you cannot “rule out” (line 19) glacial transport of the bluestones. As I pointed out in my initial review, you can weaken the glacial hypothesis considerably, but you can’t rule it out. The text here needs reviewing and editing.

Lines 46-55 – for completeness, you need a sentence here about the former and remnant Paleogene cover.

Line 60 – “...transported to the Stonehenge area...” or “...transported to Salisbury Plain...” would be fairer.

Beyond Line 56, the introduction needs a bit of a rethink. In responding to reviewers, the authors have lost much of the thrust of their initial argument. For example...

Line 58-73 – this paragraph is muddled in its rewritten form. On the one hand you are saying there is no evidence for glaciation of Salisbury Plain while on the other you suggest it may have lain within the ice margin. “Absence of evidence not indicating evidence of absence” is one thing but on this reasoning, Southampton could have been within the Anglian limit. I think you could make your argument much more succinctly and more forcefully here. I suggest that you start with something like “Based on current evidence, it is difficult to prove or disprove if ice ever covered all or part of Salisbury Plain during the Anglian” and build from there.

Line 74 – Again, you could be more forceful here. Start with “Geochemical data for detrital minerals offer a novel test of the competing “anthropogenic vs. glacial” transport hypotheses. If ice ever covered Salisbury Plain it would be expected to leave persistent and detectable provenance signatures, preserved in the landscape as indicators of sediment routing and crystalline source regions following ice retreat. Erratics and other glacially-transported sediments should have contributed a measurable...”

Line 88-93 – in the response to reviewers, the authors point out that this is one of the biggest zircon dating studies of this type for southern Britain – it might be worth stating that here.

Line 153 – “northern” would be better.

Line 156 – for clarity, perhaps say “Instead, East Avalonian and Megumian age modes...”

Line 165 – for clarity, perhaps say “...the dearth of East Avalonian and Megumian ages...”

Lines 170-173 – The firmness of the statements in this paragraph about the Anglian and Salisbury Plain is now out of line with what you say in the introduction – you need to cross-check and rephrase if necessary.

Line 174 – you would strengthen your argument if you said “Even if glacial erratics and meltwater outwash had contributed...”

Line 203 and throughout – Chalk is a proper name and should be capitalised.

Line 234-235 – for clarity state “...in our study...”

Line 234-236 – as stated above, you still need to give a plausible reason for why this one grain might be present.

Line 238 – perhaps “...much more common...”

Line 281 – is there a word missing before Th/U?

Line 303 – I assume you mean “liable”?

Line 320-322 – the signature is rare but as critics will argue, it is there. You need another sentence to strengthen your conclusion. Surely, if ice of sufficient thickness to transport 80+ multi-tonne bluestone erratics from the direction of west Wales had covered Salisbury Plain, you would expect to see a much stronger 464 Ma signature?

Line 345-347 – again, if there is even one zircon grain that could be from the Preselis, I don’t think you can be this forceful.

Line 350 – critics are going to say, “How can you base your conclusions on 4 samples?” You need to incorporate some of your response to my original review here to counter this.

Reviewer #2 (Remarks to the Author):

I am satisfied with the authors alterations to the manuscript and answers to reviews. The data collection and interpretation are all very clear and are likely close to the truth in my opinion. Figures are more useful. I have no major comments.

The only area I would emphasise more in this work is the fact that the absence of any old apatite in the detrital samples is extremely strong evidence against glacial transport, e.g. at the end of lines 300–306 I would add “...during multiple sedimentary cycles, and is inconsistent with first-cycle glacial detritus” or something more elegant to the same effect. It would not be possible to deliver old zircon recently without also delivering old apatite. It is obvious that the source is old and recycled/altered.

Reviewer #3 (Remarks to the Author):

The authors have dealt with the points raised in my earlier review.
With one exception.

I maintain that addition of the Anglian glacial maximum limit and general ice flow lines to the inset location map would help the reader to understand the glacial transport hypothesis and its difficulties.

AMH

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Detrital zircon–apatite fingerprinting challenges glacial transport of Stonehenge’s megaliths

Anthony Clarke and Christopher Kirkland

Detailed comments

Line 6. While glacial processes can impart macroscale signatures onto a landscape (e.g., moraines, eskers), evidence for such features on the Salisbury Plain is sparse or ambiguous.

Here you virtually dismiss the alternative hypothesis before you present any findings. Sharpen this point and make it later in the Abstract. You are testing whether or not Salisbury Plain was glaciated in the Pleistocene. The logic is that if there is no firm evidence for the British-Irish ice sheet reaching Salisbury Plain then the blocks at Stonehenge cannot have been glacially transported to the site.

Abstract

Line 8 *modern* stream sediments..... to test the competing hypotheses

Line 10. Now in one sentence say why the results are incompatible with glacial transport. This is consistent with the lack of firm evidence for glaciation from tills etc. Note that *sparse* evidence for glaciation is still evidence for glaciation.

Line 11. Instead, the detrital record captures the imprint of tectonism linked to the nascent Alpine Orogeny. During basin inversion, reworking of the London Basin released recycled Laurentian zircon, while fluid–rock interaction reset bioapatite U–Pb systematics. Both mechanical and chemical signals reflect Alpine-induced remobilisation, offering a *tectonically driven alternative to glacial transport* and supporting human agency in moving the megaliths.

This section is unclear.

The phrase in italics reads like it applies to the Stonehenge blocks, not the detrital minerals.

The detrital ZR record indicates recycling after erosion of Palaeozoic cover (in Wales?) and transport by rivers or longshore drift to the London Basin. During basin inversion at the onset of the Alpine orogeny, bioapatite U–Pb systematics were reset by fluid–rock interaction, providing ~60 Ma ages. Consistent with previous results. Suggesting also that Salisbury Plain remained unglaciated in the Pleistocene. Ruling out glacial transport of blocks to Stonehenge.

Introduction

Line 18 Put *such as zircon and apatite* in here.

Line 21 As this paper is about flux and provenance, the nascent regolith comment is not needed. “Nascent regolith” is anyway puzzling – is this the effect of weathering on Zr?

Line 22 Resistant detrital grains in modern stream sediments can be linked to direct source-sink transport or to more complex and cryptic, multi-cycle transport histories.

Line 25 Cut the final phrase?

Line 27 Direct versus recycled sources for refractory Zr and apatite now found in Quaternary sediments or older sedimentary rocks have been identified across Britain ...

Line 34 Move this to line 49.

Line 37. Is this Avebury?

Line 37. An outstanding question is how megaliths were transported to Stonehenge. Glacial or man?

Line 37 Simplify. Megaliths at Stonehenge form three groups.

Line 51 Routes

Line 53 State the glacial hypothesis more clearly. It is about the Welsh material only. The case rests on what evidence? Line 55 does not inform the reader, and it is too dismissive. Then state that Stonehenge is thought to lie outside Pleistocene glacial limits, although those limits are poorly constrained in central Southern England. Hence, there is doubt about whether Salisbury Plain was ever glaciated in the Pleistocene.

Now bring in Line 73-74. This is a test for the glaciation hypothesis – Zr should be from S Wales and should include ages x to y. State the expected provenance signature. Alternatively, if no ice cover, then Zr and apatite sourced during denudation of sedimentary cover. State the expected provenance signature Bring in Line 25 and following.

Line 74. New paragraph. Limited/no support for ice cover on Salisbury Plain. No glacial erratic transport. Hence, anthropogenic transport likely.

Results

Clear. No comments.

Discussion

Line 132 Laurentian zircon on Salisbury Plain

Line 143 Focus on Wales and the English Midlands

Line 149. This is where you need to nail down the idea that the Zr population in the stream sediments is not of glacial origin. Ice flow likely SW from S Wales or S from Midlands. Either should be dominated by Zr ages <650 Ma. And it is not.

Line 154 Move to Line 166 or thereabouts.

Line 156. Result consistent with known ice limits. Salisbury Plain lacks till, erratics and glaciectonic structures, tunnel valleys (the latter typical in chalk near Elsterian glacial limits in Harz, Germany). Even if the first glaciation of Salisbury Plain was Early Pleistocene traces of these features would survive in valleys. Your results support the Anglian glacial limit as the maximum Pleistocene glacial limit in south central England.

Line 163. The answer is possibly. There are tens of metres of glacial sediment in places at the southern ice sheet limits in East Anglia and Germany. Cut this IMO.

Line 165 Now switch to the alternative hypothesis. To investigate other potential sediment sources and pathways...

Line 185 Clarify. Is this 500 km long longshore drift during basin inversion? The Palaeogene drainage of Britain had the main rivers running W to E.

Line 195. Ubiquitous? Or common?

Line 199 This argument is weak IMO and the paragraph can be deleted. A thin cover of till with those lithologies deposited at ~400 Ma would be strongly weathered at surface and only the most resistant clasts would survive. Weathering would be even more effective if the glaciation was older.

Line 272 Finish with no evidence for ice cover. Hence, megaliths were not glacially transported.

Figure 1. Add Anglian ice limit and ice flow lines. Is Amesbury correct?

Figure 5. Label axes

Detrital zircon–apatite fingerprinting challenges glacial transport of Stonehenge's megaliths

Abstract

How the building blocks of Stonehenge arrived on the Salisbury Plain remains enigmatic, with glacial and anthropogenic transport proposed. While glacial processes can impart macroscale signatures onto a landscape (e.g., moraines, eskers), evidence for such features on the Salisbury Plain is sparse or ambiguous. Here, we present grain-level U–Pb fingerprinting for detrital zircon and apatite grains from stream sediments surrounding Stonehenge. Zircon ages span 3396–285 Ma with age peaks at 1089, 1694, and 1744 Ma, pointing towards ultimate crystalline sources in the Laurentian crystalline basement of northern Britain. However, Pleistocene glacial reconstructions suggest direct glacial delivery is improbable. Instead, the detrital record captures the imprint of ~60 Ma tectonism linked to the nascent Alpine Orogeny. During basin inversion, reworking of the London Basin released recycled Laurentian zircon, while fluid–rock interaction reset bioapatite U–Pb systematics. Both mechanical and chemical signals reflect Alpine-induced remobilisation, offering a tectonically driven alternative to glacial transport and supporting human agency in moving the megaliths.

17 Introduction

18 The isotopic and chemical analysis (e.g. U–Pb and trace elements) of detrital grains
19 represents a versatile toolkit to trace sediment flux (Cawood et al., 2012; Dröllner et al., 2023;
20 Morón et al., 2019), sediment provenance (Andersen, 2012; Gehrels and Pecha, 2014;
21 Moecher and Samson, 2006) and nascent regolith formation (Bonich et al., 2017; Clarke et
22 al., 2024b; Salama et al., 2022). Detrital grains such as zircon and apatite within basins and
23 unconsolidated regolith can reflect direct source-to-sink pathways or more complex and
24 cryptic, multi-cycle transport histories, given the refractory nature of these heavy minerals
25 under certain physical and chemical conditions (Dröllner et al., 2025; Morton and Hallsworth,
26 1994; Zametzer et al., 2024).

27 The relative contributions of direct versus recycled detrital sources into regolith and
28 sedimentary rocks throughout Britain have been highlighted, though regional, inter-basin
29 variability remains unresolved (Clarke et al., 2025; Morton et al., 2016; Morton et al., 2015;
30 Stevens and Baykal, 2021). Clarifying sediment transport pathways can help inform
31 paleogeographic reconstructions and basin evolution (Barham et al., 2018; Cawood et al.,
32 2012; Morton et al., 2024). Moreover, resolving source-to-sink relationships can contribute to
33 provenance debates in archaeological science (Kelloway et al., 2014; Tochilin et al., 2012),
34 including whether megaliths on Salisbury Plain, England, were transported by glacial
35 processes or human agency (Figure 1).

36 The Salisbury Plain represents a rich Neolithic archaeological landscape, including
37 monumental architecture at Stonehenge and Amesbury (Pitts, 2022). Stonehenge is
38 renowned for the non-local origin of its constituent megaliths, which can be grouped into three
39 distinct types. The largest are the ca. 25-tonne sarsen stones, composed of silcrete, which
40 form the lintelled outer circle and inner trilithon horseshoe. The sarsen stones are
41 comparatively local; most were sourced from the West Woods, ca. 25 km from Stonehenge
42 (Ciborowski et al., 2024; Nash et al., 2020). The Bluestones, sourced from ca. 230 km away

in the Mynydd Preseli in Wales, weigh between 5–2 tonnes and include an assemblage of volcanic and sedimentary rocks such as tuff, rhyolite, dolerite, and sandstone (Ixer and Bevins, 2017). The third type is the Altar Stone, a single six-tonne slab of Palaeozoic Old Red Sandstone (ORS) (Clarke et al., 2024a; Ixer et al., 2020). Recent research suggests the Altar Stone originated in the Orcadian Basin of northeast Scotland, over 700 km from Stonehenge (Clarke et al., 2024a).

How the non-Sarsen building blocks of Stonehenge arrived on the Salisbury Plain is debated. Some posit that Neolithic people transported the bluestones from the Mynydd Preseli and Orcadian Basin to the Salisbury Plain via an overland or sea route (Parker Pearson et al., 2024; Parker Pearson et al., 2015). Others favour a glacial transport mechanism whereby the non-Sarsen rocks were delivered to Stonehenge as erratics during Pleistocene glaciations (John, 2024; Thorpe et al., 1991).

The absence, ambiguity or inaccessibility of purported glacial features on the Salisbury Plain hampers efforts to reconstruct potential ice flow and erratic transport pathways (John, 2024; Scourse, 1997). Indeed, the extent of the Anglian glacial episode (ca. 478–424 ka), where ice sheets potentially reached central southern Britain, is poorly constrained (Gibbard and Clark, 2011). Nonetheless, glacial outwash can transport fine detrital grains (typically <200 µm) well beyond the terminal margins of ice sheets, whereas larger erratics, often ranging from tens of centimetres to several metres, are typically deposited closer to the ice front (Veness et al., 2025). Both transport mechanisms are expected to leave persistent provenance signatures, preserved in the landscape as indicators of sediment routing and crystalline source regions following ice retreat (Eyles, 2006; Hagg, 2022).

The Salisbury Plain is a chalk plateau covering ca. 775 km² in southern England. River valleys (e.g., the Avon, Wylfe, and Bourne) define the plain's margins and dissect stratigraphy to expose older Mesozoic rocks (Allen and Crane, 2019; Blackwood and Tubbs, 1970) (Figure 1). Given the chalk's low zirconium and phosphorus content, detrital zircon and apatite are

69 unlikely to be locally derived, unless apatite is present as a secondary biogenic precipitate,
70 such as from phosphatic microfossils. Instead, U-bearing detrital grains in stream sediment
71 are more plausibly sourced from zircon and apatite-rich crystalline lithologies beyond the plain,
72 with glacial processes representing a potential transport mechanism (Hagg, 2022).

73 Here, we report U–Pb isotopic data for detrital zircon and apatite collected from streams
74 draining the Salisbury Plain, England (Figures 2,3) (Table 1). Our results demonstrate the
75 widespread dispersal of multi-cycle Laurentian detritus across Britain. We use the contrasting
76 detrital fingerprint of unconsolidated river sands to constrain potential glacial-sediment
77 pathways, which have implications for the anthropogenic versus ice transportation debate for
78 the building blocks of Stonehenge.

Results

Zircon U–Pb

U–Pb isotopic data were obtained from 550 individual zircon grains. Four hundred and one analyses are defined as concordant ($< \pm 10\%$ discordant). Concordant zircon dates span 3396 ± 30 to 285 ± 5 Ma (Figure 2), with coherent age peaks defined by ≥ 10 grains (Gehrels, 2011) ranging from the Silurian to Paleoproterozoic, including components at ca. 432 (n=16), 447 (n=15), 460 (n=11), 1015 (n=21), 1054 (n=22), 1089 (n=30), 1167 (n=13), 1184 (n=15), 1213 (n=11), 1251 (n=10), 1375 (n=10), 1403 (n=10), 1502 (n=13), 1526 (n=15), 1542 (n=11), 1575 (n=11), 1672 (n=18), 1694 (n=23), 1744 (n=24), 1798 (n=13), 1848 (n=23), and 1870 Ma (n=22).

Zircon Morphology

Zircon grains exhibit elongate to sub-rounded shapes with aspect ratios ranging from $\sim 2:1$ to $5:1$. Grains have a length up to $\sim 250\mu\text{m}$, with most $50\mu\text{m}$ long (Figure 4). Cathodoluminescence imaging reveals a variety of internal zoning patterns consistent with a diverse dominantly igneous sources, including oscillatory zoning (e.g. SH1.12, SH2.59), sector zoning (e.g. SH3.26), and rare examples of core-rim relationships suggestive of metamorphic overgrowths (e.g. SH1.19) (Figure 4). Most grains show signs of rounding and abrasion, implying sedimentary transport and recycling. Complex internal structures, such as inherited cores (e.g. SH2.91), support derivation from polyphase crustal sources.

Apatite U–Pb

On a Tera-Wasserburg plot, apatite U–Pb data frequently define one or more mixing lines, typically between a time-significant radiogenic lead component and an initial common lead (Pb_c) component(s). The position of analyses along such arrays reflects the relative proportion of initial to radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratios ($=F^{207\%}$), while lower intercepts indicate the timing of radiogenic Pb accumulation. Two hundred and fifty apatite U–Pb analyses were obtained across four samples.

105 Unanchored regressions through apatite analyses from each sample yield discordia lower
106 intercepts equivalent to late Cretaceous to Paleogene ages and ordinate $^{207}\text{Pb}/^{206}\text{Pb}_i$
107 intercepts of ca. 0.8462, consistent with the Stacey and Kramers (1975) model of terrestrial
108 Pb_c evolution for late Cretaceous (ca. 65 Ma) crust. A free fitted discordia line (Vermeesch,
109 2018) through all analyses yields a lower intercept on concordia of 60 ± 3 Ma and an upper
110 intercept $^{207}\text{Pb}/^{206}\text{Pb}_i$ of 0.8462 ± 0.0023 (Figure 3), interpreted to indicate the average time of
111 radiogenic-Pb accumulation and the dominant common Pb signature, respectively.

112 Additionally, individual ^{207}Pb corrected ages for each analysis were calculated using Stacey
113 and Kramers (1975) terrestrial Pb isotopic evolution model, with iteration until convergence. A
114 kernel density estimate of these ^{207}Pb corrected single-spot apatite ages with $F^{207\%} < 98\%$
115 ($n=122$) yields a peak age of 65 Ma, overlapping within uncertainty to the regression lower
116 intercept age (Figure 3).

117 Despite being dominated by a c. 65 Ma age component, the single spot $^{207}\text{Pb}/^{206}\text{Pb}_i$ values,
118 for detrital apatite, imply the presence of older (>65 Ma) Pb relative to the Stacey and Kramers
119 (1975) model. Based on the Stacey and Kramers (1975) Pb evolution model, a kernel density
120 estimate of apparent model ages hints at older apatite components (175, 215, 300 and 625
121 Ma), but no radiogenic age can be calculated for these given they are dominated by common
122 Pb (Figure 3).

123 **Apatite Morphology**

124 Apatite grains are anhedral to subhedral, with rounded shapes suggesting mechanical
125 abrasion during sediment transport (Figure 4). Imaging reveals homogeneous internal textures
126 with low-intensity CL response. The absence of clear zoning or relic magmatic textures
127 suggests limited thermal overprinting, typical of sedimentary or low-temperature diagenetic
128 apatite. The consistent CL response and morphology across multiple grains (e.g. SH4.3,
129 SH3.41) implies a detrital population sourced from mature potentially chemically weathered
130 sedimentary source material (Figure 4).

Discussion

Laurentian Salisbury Plain Zircon

Kolmogorov–Smirnov tests of zircon age spectra from each river sand sample indicate no statistically significant differences ($P > 0.05$), indicating the zircon age cargo of all samples is indistinguishable and remarkably uniform. This inter-sample consistency supports the aggregation of all concordant U–Pb zircon dates ($n = 401$) into a composite dataset for provenance interpretation (Figure 2).

The compiled age spectrum spans 3396–285 Ma (Figure 2) but is dominated by Meso to Paleoproterozoic peaks at ca. 1089, 1694, and 1744 Ma, consistent with an ultimate provenance from specific tectonostratigraphic domains of Laurentian basement from north Britain, including the Grenville, Penokean, and Trans-Hudson orogens (Cawood et al., 2007; Hoffman, 1991; Strachan et al., 2021) (Figure 5). Such age modes are conspicuously absent in the crystalline basement of southern Britain, which is instead composed of rocks from the Cadomian orogeny (ca. 650–600 Ma) (Accotto et al., 2022; Murphy et al., 2013), Neoproterozoic arc-related magmatism (590–540 Ma) (Pharaoh and Carney, 2000), Silurian–Devonian intrusions (ca. 430–390 Ma) (Henderson et al., 2016), Carboniferous (370–360 Ma) (Stephenson et al., 2003) and Variscan metamorphic overprinting and granite emplacement (~300 Ma) (Neace et al., 2016).

Such non-Laurentian ages would be diagnostic markers for distinguishing local, first-cycle basement contributions to the detrital budget of the Salisbury Plain. However, the dearth of such ages (only 8% of zircon are Phanerozoic) (Figure 2) and the uniformity of age spectra across multiple catchments, coupled with the scarcity of local bedrock sources, demonstrates that the detrital zircon assemblage is not first-cycle material derived from the underlying East Avalonian crystalline basement (Figure 5). Rather, the detrital zircon cargo of the Salisbury Plain necessitates a north-to-south sediment transport and recycling mechanism.

Direct glacial delivery of northern detritus to the Salisbury Plain is inconsistent with the maximum southern extent of known ice-flow vectors (Clark et al., 2022; Ely et al., 2024). During the Anglian Stage, the most intense recent glaciation, glaciers did not reach as far south as the Salisbury Plain (Gibbard and Clark, 2011). Furthermore, the Salisbury Plain lacks tills, erratics, or other diagnostic indicators of glacial activity (Bowen and Smith, 1977; Green, 1973; McOmish et al., 2002) that could evidence long-distance erratic transport or outwash of material from northern Britain. Even if glacial erratics and meltwater outwash had reached the Salisbury Plain, would both mechanisms' comparatively minor sedimentary contributions have delivered sufficient material to dominate the detrital zircon budget of river sands?

To investigate potential sediment sources, we compare the age spectra of the Salisbury Plain zircon population with detrital datasets from Paleogene, Carboniferous, and Devonian sedimentary units across Britain and Ireland (Figure 5). Of relevance here is the Thanet Formation a ca. 30 m thick early Palaeocene (59.2–56 Ma) fine-grained glauconitic sand unit deposited in shallow marine conditions within the London Basin (Ellison et al., 1994) which contains a detrital zircon age cargo statistically indistinguishable from the Salisbury Plain dataset (KS test, $P > 0.05$; Figure 5) (Stevens and Baykal, 2021). The Thanet Formation sits unconformably atop the Chalk Groups of the Salisbury Plain (Bristow et al., 1997) (Figure 1), suggesting that these rocks or related London Basin strata served as an intermediary source of Laurentian zircon now incorporated into modern Salisbury Plain river sands (Figure 1). We posit that during Alpine Orogen uplift and subsequent geological inversion and denudation of the London Basin (Angrand and Mouthereau, 2021; Hawkes et al., 1998), the overlying Thanet Formation released its detrital cargo of refractory minerals onto the zircon-poor Chalk Groups of southern Britain. Indeed, several kilometres of London Basin strata may have been removed during the Paleogene (Lewis et al., 1992).

How fine-grained Laurentian detritus became incorporated into the Thanet Formation remains uncertain (Stevens and Baykal, 2021). One plausible mechanism involves reworking older zircon, from eroding ORS and the Pennine Basin into the London Basin during the Paleogene

uplift of the Wales-Brabant Massif (Stevens and Baykal, 2021). Alternatively, longshore drift along the Palaeocene proto-North Sea margin delivered northern detritus to the Thanet Formation, which subsequently became mixed via the proto-Thames River (Gibbard et al., 2017). In any case, the Laurentian zircon fingerprint (Figure 2) observed in Salisbury Plain sediments reflects polycyclic sediment routing pathways in Britain dominated by the reworking of earlier strata and does not support direct delivery via glacial transport.

The detrital fingerprint of the Salisbury Plain also helps inform hypotheses regarding Mynydd Preseli bluestone ice transport from west Wales. Rhyolite bluestones from the Stonehenge area and the Mynydd Preseli have been dated to the Darriwilian (464–462 Ma), consistent with a source from the Fishguard Volcanic Group, southwest Wales (Bevins et al., 2016). From 550 U–Pb analyses, a single concordant analysis at 464 ± 16 Ma represents the only potential Bluestone-derived zircon (Figure 2; Appendix 1). If the bluestones are glacial erratics, then the ca. 464 Ma detrital age would be expected to be ubiquitous throughout the drainage systems on the Salisbury Plain. It is not; hence, this observation is consistent with previous studies, which do not report bluestone clasts in the Salisbury Plain stream sediments (Green, 1973; Scourse, 1997).

Moreover, the river sands contain no fresh, coarse-grained cobbles or boulders of lithic fragments such as granites, gneiss, or mafic lithologies that would be expected if the zircon or apatite population had arrived as first-cycle erratic detritus transported from exposed Laurentian basement. Instead, the well-rounded, compositionally mature (Figure 4) nature of the zircon-bearing sands implies a history of sedimentary recycling rather than direct transport via ice.

Salisbury Plain Apatite

The Salisbury Plain is dominated by the White Chalk Subgroup, deposited in a stable epicontinental shelf setting throughout the mid to late Cretaceous (Hopson, 2005). Specifically, the river sand samples are underlain by the Seaford (SH1, SH2), West Melbury (SH3) and Newhaven (SH4) chalk formations, which span the Cenomanian to Santonian stages of the mid-Cretaceous (Figure 1) (Bristow et al., 1997; Hopson, 2005).

Detrital apatite U–Pb analyses from Salisbury Plain River sands yield a dominant array on a Tera-Wasserburg plot, implying most radiogenic-Pb retention from 60 ± 3 Ma ($n=250$) (Figure 3). This Palaeogene U–Pb apatite age postdates the youngest Chalk formations in Britain, including the Portsdown and Tarrant Chalks [ca. 77–70 Ma; Hopson (2005)]. Therefore, we interpret the ca. 60 Ma date to reflect post-depositional U–Pb disturbance of a mixed Mesozoic population, dominated by bioapatite. The chalk formations underlying the study area were deposited in shallow marine environments conducive to biogenic phosphate accumulation (Muscente et al., 2015; Pacey, 1985), providing a plausible local source of bioapatite (fish teeth and bone fragments) later reworked into the chalk.

The scattering of $^{207}\text{Pb}/^{206}\text{Pb}_i$ ratios up to 0.8793 points towards the presence of older apatite. These elevated values exceed crustal Pb compositions modelled for ca. 60 Ma continental crust (Stacey and Kramers, 1975), indicating prolonged U–Pb evolution before ca. 60 Ma and minor inheritance from other older sources. The preservation of variable initial $^{207}\text{Pb}/^{206}\text{Pb}$ values coupled to a coherent lower intercept age reflects the contrasting chemical mobility of U and Pb in apatite (Chew and Spikings, 2021; Kirkland et al., 2018) during fluid flux at ca. 60 Ma.

Apatite grains from the Salisbury Plain typically occur as 400–100µm euhedral to anhedral, angular fragments exhibiting faint sector zonation, with up to 500ppm of U (Figure 4). The porous, poorly crystalline structure of bioapatite facilitates U gain (due to the solubility of U^{6+}) from oxidised seawater and pore fluids (Cumberland et al., 2016; Wang et al., 2024). In

231 contrast, Pb^{2+} is relatively immobile and structurally bound or sequestered within lattice defects
232 (Cumberland et al., 2016). As a result, recrystallisation during post-depositional alteration of
233 U-enriched apatite yields the dominant lower intercept age, while initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratios in
234 low U grains (or domains) were better preserved, retaining evidence of older, heterogeneous
235 detrital components (Figure 3).

236 At ca. 60 Ma, the nascent Alpine Orogeny (Angrand and Mouthereau, 2021; Rosenbaum and
237 Lister, 2005) initiated far-field compressional stresses across western Europe, driving
238 prolonged basin inversion in southern Britain. This tectonism produced folding of the Chalk at
239 Lulworth Cove and reactivation of structures associated with the broader Purbeck–Isle of
240 Wight Disturbance (Underhill and Stoneley, 1998). It is feasible that fluid-rock interaction at
241 this time, facilitated by inversion-related deformation and faulting, enabled U mobilisation and
242 recrystallisation in detrital (bio)apatite (Cumberland et al., 2016; Wang et al., 2024).

Conclusions

New U–Pb dates for detrital zircon and apatite collected from streams draining the Salisbury Plain, England, reveal Cenozoic sediment transport and reworking, which help inform hypotheses surrounding the transport of the megaliths at Stonehenge.

Zircon dates span 3396–285 Ma, with prominent age peaks at 1089, 1694, and 1744 Ma, consistent with derivation from Laurentian crystalline basement to the north. However, Quaternary glacial reconstructions indicate that ice sheets did not extend as far south as the Salisbury Plain, making direct transport of zircon-bearing erratics or glacial outwash unlikely. Moreover, the multi-cycle nature of detrital zircon, combined with the absence of proximal crystalline sources, argues against a primary glacial origin. Instead, the Palaeocene Thanet Formation of the London Basin, which unconformably overlies the Chalk of the Salisbury Plain and possesses a zircon age spectrum statistically indistinguishable from modern river sands, represents a more plausible source. This suggests that Laurentian zircon was recycled through Paleogene sedimentary rocks and remobilised during ongoing denudation in southern Britain, providing a sustained and local reservoir of reworked material.

Detrital apatite is dominated by a ca. 60 Ma age population, consistent with recrystallised bioapatite derived from the underlying Late Cretaceous Chalk Group of the Salisbury Plain. Variably radiogenic initial $^{207}\text{Pb}/^{206}\text{Pb}$ compositions suggest the presence of a minor, heterogeneous Mesozoic component. We interpret this assemblage as a mixture of bioapatite sources, partially reset during early Paleogene fluid flow associated with basin inversion and far-field compressional stresses linked to the nascent Alpine Orogeny.

Ultimately, the detrital zircon and apatite records from the Salisbury Plain capture the imprint of early Paleogene tectonism linked to the nascent Alpine Orogeny. Reworking of the Thanet Formation during basin inversion released recycled Laurentian zircon onto the chalk-dominated landscape, while coeval fluid–rock interaction reset U–Pb systematics in locally derived bioapatite. These minerals archive complementary mechanical and chemical

269 responses to Paleogene crustal deformation, revealing a unified signal of Alpine-induced
270 sedimentary remobilisation in southern Britain. This tectonically driven reworking provides a
271 parsimonious alternative to glacial transport, explaining the presence of far-travelled fine
272 detritus, removing the need to invoke ice sheet transport to the Salisbury Plain.

Methods

Mineral Separation

Four river sand samples (SH1–SH4) weighing ca. 1kg were collected from the Salisbury Plain (Figure 1) (Table 1). Collected material was processed at the John deLaeter Centre, Curtin University. Unprocessed sand was first sieved at $\leq 250 \mu\text{m}$ to yield ca. 100 g fractions, which subsequently underwent heavy mineral separation using a Jasper Canyon Research shaking platform (Dumitru, 2016). Coarse magnetic minerals were removed using a handheld neodymium magnet. To further fractionate the fine fraction, heteropolytungstate heavy liquid (2.85 g cm^{-3}) was used to remove light minerals (e.g. quartz, feldspars). A round of Frantz isodynamic magnetic separation (using a side-slope angle of 10° and an Amperage of 1.7) allowed for the retrieval of a final non-magnetic, heavy concentrate. Lastly, the non-magnetic fraction ($\leq 0.2 \text{ g}$) was bulk mounted into 25 mm-diameter epoxy discs.

Sample	Latitude	Longitude	UTM	River	Underlying Geology
SH1	51.19809	-1.55350	30U 601065E, 5672848N	Pillhill Brook	Seaford Chalk Formation
SH2	51.17070	-1.78518	30U 584928E, 5669510N	Avon	Seaford Chalk Formation
SH3	51.15671	-2.06805	30U 565173E, 5667665N	Wylfe	West Melbury Marly Chalk Formation
SH4	51.05465	-1.77801	30U 585644E, 5656613N	Avon	Newhaven Chalk Formation

Mounts were polished to a one μm finish, and embedded minerals were imaged using a TESCAN Integrated Mineral Analyser in the John De Laeter Centre, Curtin University, with a $1 \mu\text{m}$ resolution for back-scattered electron imaging, and $9 \mu\text{m}$ resolution for energy dispersive X-ray spectroscopy dot mapping. Additional imaging was undertaken using a Clara FE-SEM to identify internal textures and crystal morphologies, aiding laser ablation site selection.

Isotopic Analysis

Zircon U–Pb analysis

Analyses were performed using the LA-ICP-MS instrumentation at the GeoHistory Facility, JdLC (Appendix 1). Zircon U–Pb data were collected using an Agilent 8900 ICP-MS. Ablations from zircon grains were created using a RESOlution LR193 nm ArF equipped with a Laurin Technic S-155 cell. The carrier gas was high-purity Ar with a flow rate of 0.98 L min⁻¹. A spot size of 28 µm was combined with an on-sample fluence of ~ 2.8 J/cm⁻² and a repetition rate of 5 Hz. Two cleaning pulses preceded each analysis, and signals from zircon and the background were analysed for 30 s. The sample cell was cleansed using ultrahigh-purity He (350 ml min⁻¹) and N₂ (3.8 ml min⁻¹), dwell times for U–Pb measurements included 0.1 s for ²³⁸U and ²³²Th, 0.2 s for ²⁰⁸Pb, 0.7 s for ²⁰⁷Pb, 0.4 s for ²⁰⁶Pb and 0.3 s for ²⁰⁴Pb and ²⁰²Hg.

GJ1 zircon 601.95 ± 0.40 Ma (Horstwood et al., 2016; Jackson et al., 2004) was the primary reference material for all zircon U–Pb analyses. Secondary reference zircons were analysed after every ~15 unknowns and included Plešovice = 337.13 ± 0.37 Ma, Sláma et al. (2008); OG1 = 3465.4 ± 0.6 Ma, (Stern et al., 2009) and Maniitsoq = 3008.70 ± 0.72 Ma, (Marsh et al., 2019). The calculated weighted mean U–Pb and Pb–Pb dates for secondary reference zircon were within 2σ uncertainty of published values.

We measure U–Pb discordance using concordia log distance (%) and apply a ±10% threshold to define discordance. Over 95% of analyses within our discordance filter are within analytical uncertainty of concordia at the 2SE confidence level. We use single-spot concordia ages for further statistical analysis, which offers several advantages over single ratio U–Pb or Pb–Pb ages as previously discussed (Clarke et al., 2024a).

Apatite U–Pb analysis

In-situ apatite U–Pb analyses were conducted using a Nu Plasma II multi-collector mass spectrometer coupled to a Resonetics S-155-LR 193 nm excimer laser ablation system at the

GeoHistory Facility, John De Laeter Centre, Curtin University. Apatite grains were ablated with the same laser system as zircon but used a beam diameter of 38 μm (Appendix 2).

The following masses were measured: ^{202}Hg , $^{204}(\text{Pb} + \text{Hg})$, ^{206}Pb , ^{207}Pb , ^{208}Pb , and ^{238}U . All masses were measured on ion counters for 210 cycles with a 0.3 s integration time. The laser fluence measured at the sample surface was ca. 3.5 J cm^{-2} , and a pulse frequency of 5 Hz was used. Data acquisition consisted of two cleaning pulses, a 40–20 s blank flush out, a 15–30 s ablation time, and a total of 45 s of baseline acquisition. The sample cell was flushed with ultrahigh-purity He (320 ml/min) and N_2 (1.2 ml/min), and ultra-high-purity Ar was employed as the plasma carrier gas.

Comparative Datasets

Zircon U–Pb data for the crystalline basement rocks of Britain, Ireland and continental Europe were sourced from Stevens and Baykal (2021) and Fairey et al. (2018). Detrital zircon datasets from Britain used for comparison include Orcadian Basin Old Red Sandstone (ORS) (Strachan et al., 2021), Grampian Outlier ORS (McKellar et al., 2021), Strathmore Basin (northern Midland Valley) (McKellar et al., 2020), Lanark Basin (southern Midland Valley) (Phillips et al., 2009), Pennine Basin (Hallsworth et al., 2000; Morton et al., 2015; Morton et al., 2021; Morton et al., 2024), Anglo-Welsh Basin ORS (Morton et al., 2015), Wessex Basin (Morton et al., 2016), and the Thanet Formation, London Basin (Stevens and Baykal, 2021). For Ireland, detrital datasets include the Dingle Peninsula Basin ORS (Fairey et al., 2018) and Munster Basin ORS (Fairey et al., 2024). Age data for the Altar Stone was sourced from Clarke et al. (2024a) and Bevins et al. (2020). All zircon U–Pb data for sedimentary and crystalline rocks within Britain and Ireland were filtered for discordance.

Acknowledgements

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Figure Captions

Figure 1. A simplified Salisbury Plain, England, geological map was modified after (Hopson, 2005). A black star indicates the location of the river sand sample locations. Coordinates are in decimal degrees (WGS84). Stream sediment sampling sites (SH1–SH4) are located within the Avon–Test drainage system catchments, as illustrated by the regional hydrology shown by blue lines. The geodetic system used is WGS 84.

Figure 2. U–Pb data for detrital zircon from the Salisbury Plain.

Top: A kernel density plot of detrital zircon U–Pb ages from all stream sediment samples (SH1–SH4, total n of concordant grains = 401/650), plotted with 20 Ma bandwidths and overlaid with histogram bins. Peak age components occur at ca. 1089 Ma, 1694 Ma, and 1744 Ma (Vermeesch, 2018). The inset pie chart shows the proportion of concordant zircon analyses by age.

Bottom: Cumulative probability plots for each sample location, colour-coded by stream and catchment: SH1 (Pillhill Brook), SH2 (River Avon), SH3 (River Wylye), and SH4 (River Avon). Curves show similar age distributions across sites, consistent with common provenance dominated by Mesoproterozoic and Palaeoproterozoic sources.

Figure 3. U–Pb isotopic data and Pb composition for detrital apatite grains from the Salisbury Plain.

Top: Tera-Wasserburg diagram for apatite analyses, coloured by U concentration (ppm). Error ellipses and intercept uncertainties are shown at 2σ . The regression is a least-squares best fit through the measured ratios alone and reflects more than one age component; nonetheless, radiogenic-Pb is dominated by a 60 Ma signal. [model-2 from IsoplotR (Vermeesch, 2018)] with the grey band representing the uncertainty envelope of the regression. The inset shows a kernel density estimate of ^{207}Pb -corrected ages for grains with relatively low common Pb content ($n=122$) [$F^{207}\text{Pb} < 98\%$ (Kirkland et al., 2018)], showing a peak at 65 Ma.

Bottom: A kernel density estimation of initial common Pb compositions (Stacey and Kramers, 1975) for the detrital apatite population. A spread towards more radiogenic compositions (e.g. >0.85) indicates incorporating older common Pb components.

Figure 4. Cathodoluminescence images of zircon and apatite grains with laser ablation spots. The top three rows show zircon grain images with sample identifiers, the calculated concordia age, and their respective 2σ uncertainties. Images of apatite are shown in the bottom two rows with ^{207}Pb -corrected ages annotated.

Figure 5. A multidimensional scaling plot of concordant zircon ages from stream sediment samples (SH1–SH4) and comparative age datasets, including crystalline source terranes and sedimentary basins. Schematic age mode vectors illustrate how specific ages influence the positioning of individual datasets. Sources are provided in the methods section. Ellipses represent 95% confidence intervals (Nordsvan et al., 2020). Stress values quantify how well the plot distances represent the original dataset's dissimilarities. Values below 0.15 indicate an “excellent” fit (Nordsvan et al., 2020).

385 **Table Captions**

386 Table 1. A summary table of sample localities and underlying geology from the British
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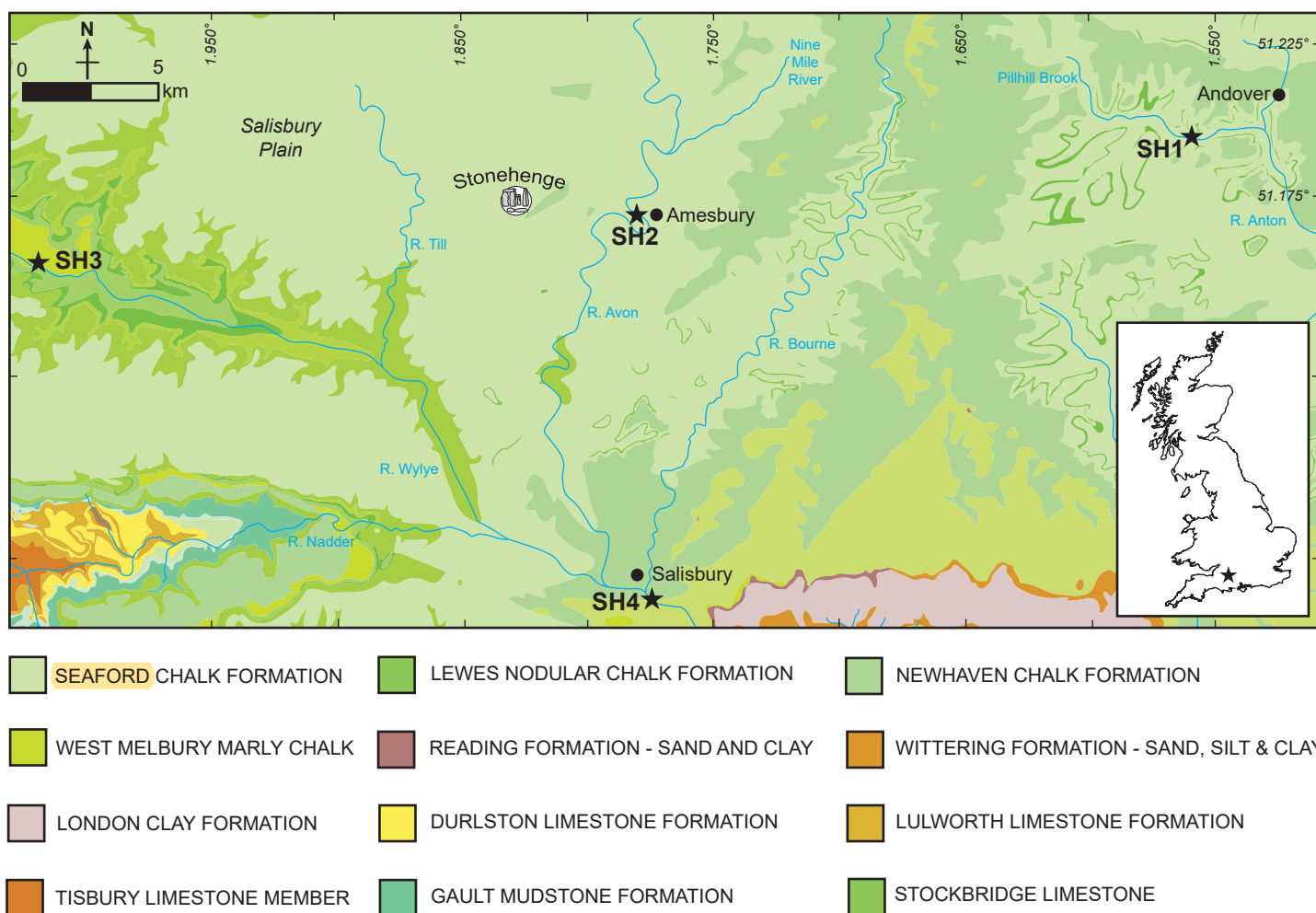


FIGURE 1

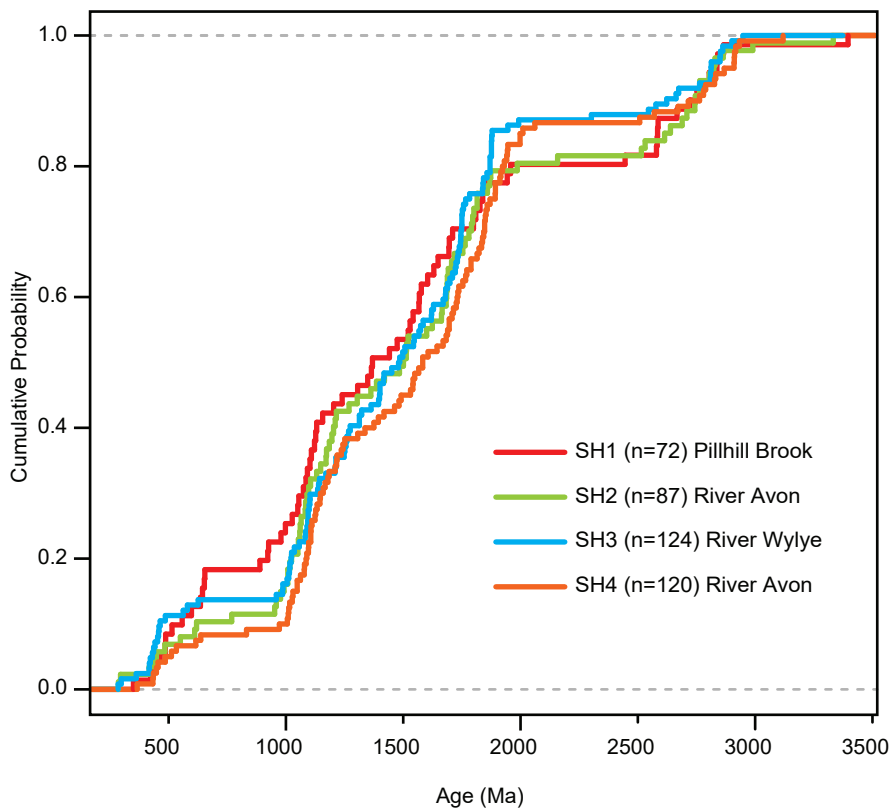
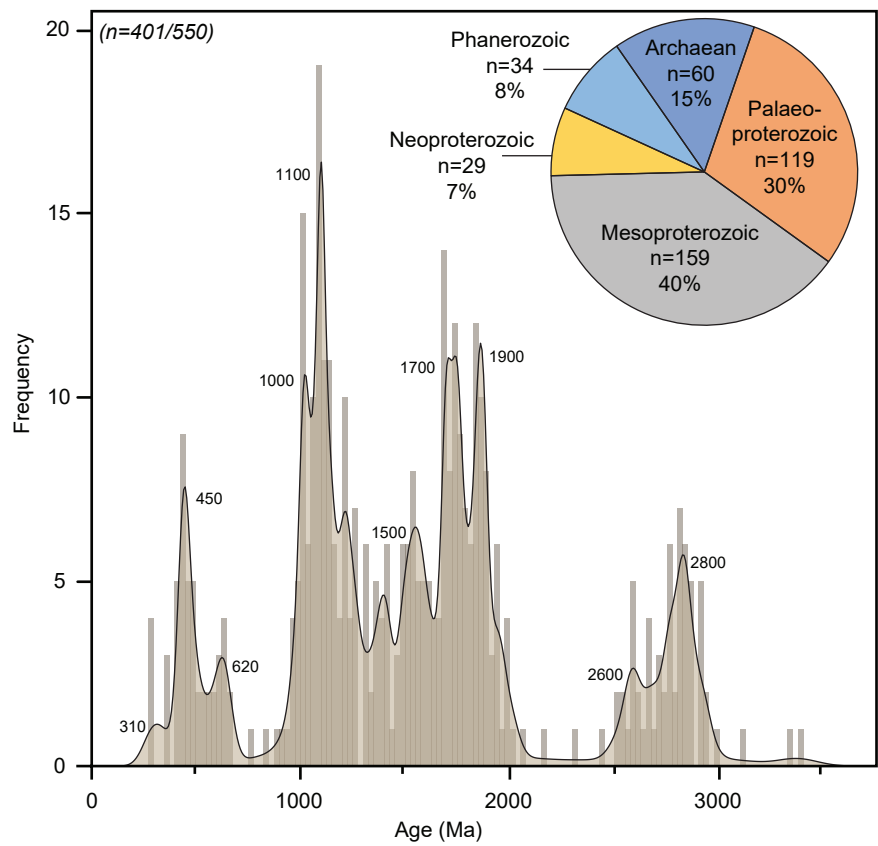


FIGURE 2

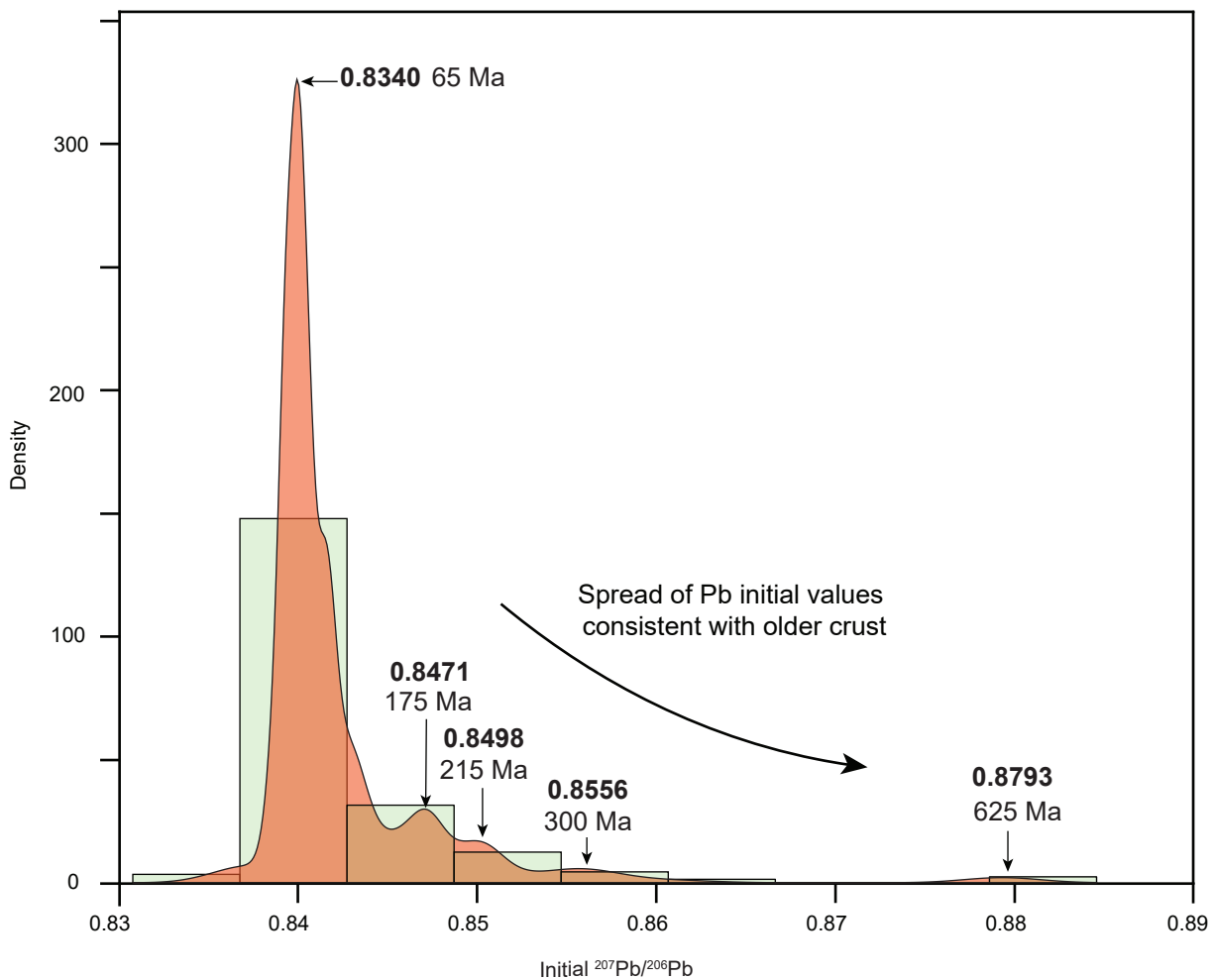
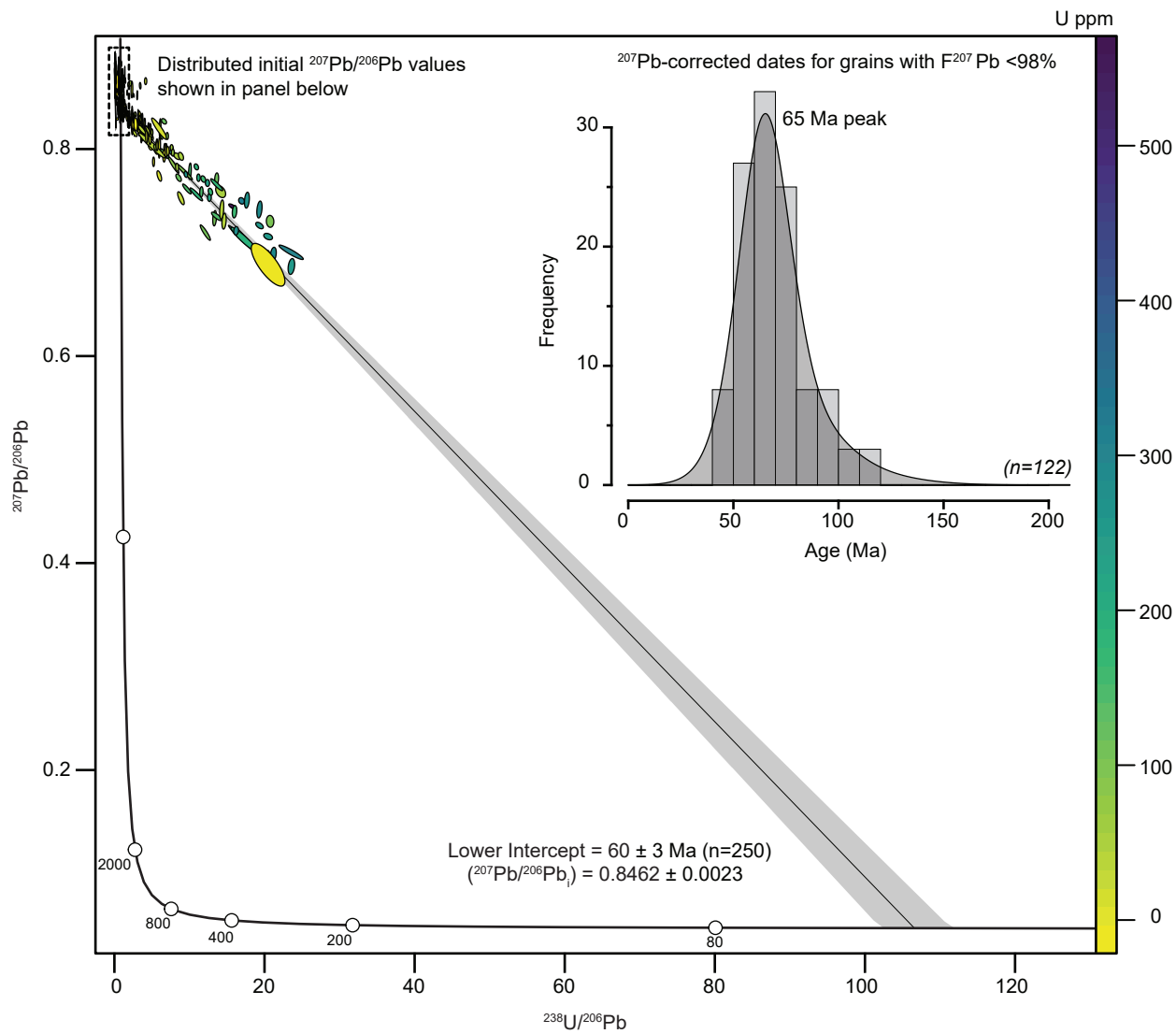


FIGURE 3



FIGURE 4

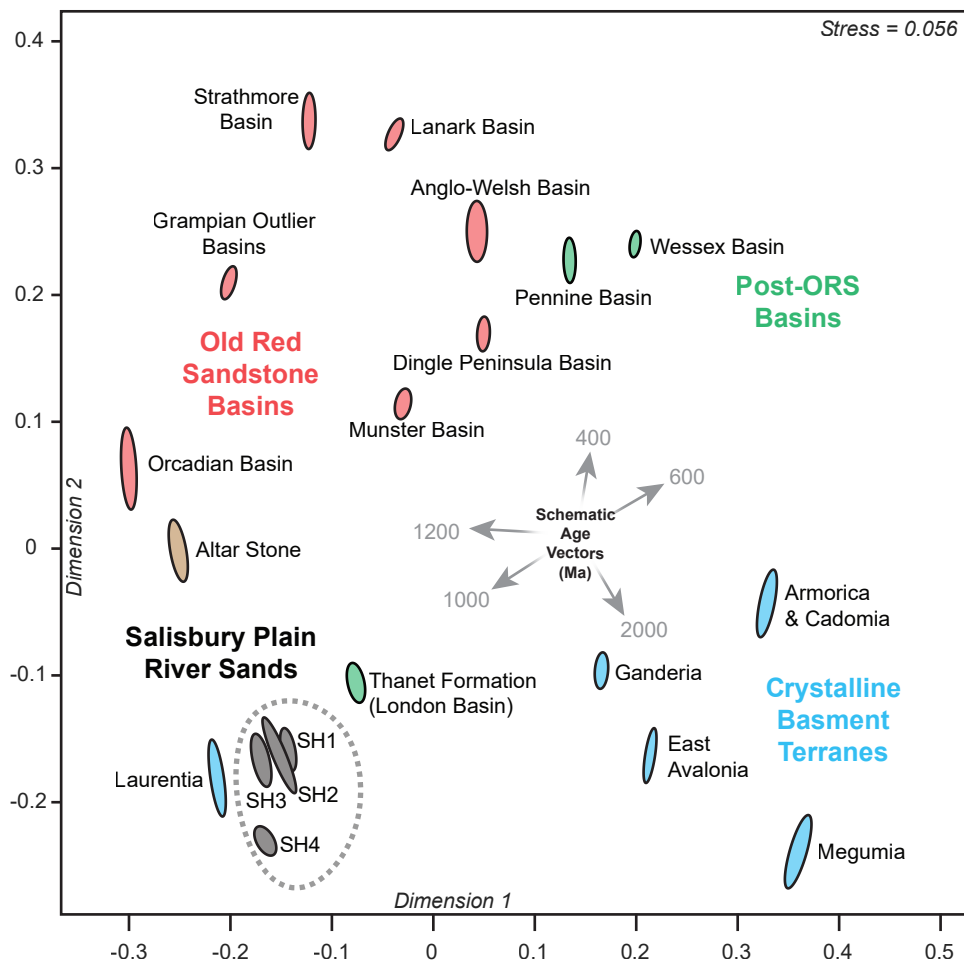


FIGURE 5

Review 1 Comment	Response
This is a relatively brief review, since the authors appear to have overlooked a major factor in the geology of Salisbury Plain – that the area was once covered by a significant thickness of Paleogene floodplain, deltaic, estuarine, marginal-marine, and marine sediments, which overlay the Chalk. These sediments – including the Thanet Sand noted by the authors – have mostly been removed by erosion, but remain preserved as outcrops to the southeast of Salisbury and southeast of Marlborough (and, more extensively, to the east within the London Basin). They also form the host sands within which the sarsen stones of Stonehenge and the Marlborough Downs developed, and exist in remnant form as the widespread Clay-with Flints. There is an extensive literature on the likely former distribution of Paleogene sediments within the Hampshire Basin and London Basin, including across Salisbury Plain (see Harding et al. [2025] for a recent synthesis; https://www.doi.org/10.1017/ppr.2024.13).	We thank Reviewer 1 for drawing attention to the importance of the former Paleogene cover across the Salisbury Plain. We agree that such cover is important and, indeed, concluded in the reviewed manuscript that Paleogene cover was integral to explaining the detrital fingerprint obtained. We specifically mentioned the Thanet Fm. as this has published age data (Stevens & Baykal, 2021). We therefore respectfully disagree that we “overlooked” this factor. In any case, we agree that Paleogene strata, including other related deposits, are a potentially significant factor in regional provenance that should be considered when explaining the Salisbury stream’s detrital load. To address this comment, we further discuss the role of Paleogene cover in the manuscript, see: “More broadly, the Thanet Formation should be considered within the context of the wider Paleogene succession that formerly covered much of Salisbury Plain (Figure 1). This cover includes floodplain, estuarine, marginal-marine, and marine deposits preserved today in the Hampshire and London Basins, as well as in remnant form as the Clay-with-Flints deposits (Harding et al., 2024; Hopson, 2005). These deposits would have mantled Salisbury Plain chalk (Figure 1) prior to their removal during subsequent erosion, and served as the host for the sarsen silcretes of the Marlborough Downs and Stonehenge landscape (Nash et al., 2021). Their erosion and recycling during Paleogene basin inversion provides a plausible pathway for the release of refractory heavy minerals into the zircon-poor Chalk landscape, consistent with the detrital signature we observe (Figure 2). In this context, the Thanet Formation represents a well-studied component of a larger Paleogene cover sequence that collectively acted as a local reservoir for recycled Laurentian zircon.”
The source provenance of the Paleogene sediments of southern Britain has been widely discussed, with various studies linking them to the Scottish Highlands (see Morton et al. [1982] as an early example; https://doi.org/10.1016/S0016-7878(82)80003-5). As such, the identification of a Laurentide crystalline basement signature, potentially deriving from northern Britain, in zircon U-Pb ages from stream sediments on Salisbury Plain is completely unsurprising, are apatite ages post-dating the Chalk in this area.	The provenance of the Paleogene sediments in southern Britain has been widely discussed, but has not been extensively demonstrated using detrital mineral ages. The paper referred to (Morton, 1982) provides an important characterisation of resistive minerals (e.g., heavy mineral proportions determined by grain counts in defined sieve fractions); however, it does not provide age or isotopic signatures that could be more diagnostic of a Laurentian source. Whilst it is reasonable to infer such a source based on heavy mineral concentrations alone, more robust interpretations of source-to-sink pathways are

	possible via a multi-proxy isotopic approach, as demonstrated in our research.
The authors are correct in saying that U-bearing detrital grains in stream sediments on Salisbury Plain are most plausibly sourced from zircon and apatite-rich crystalline lithologies beyond the Plain. However, the reported zircon-apatite signatures are likely to simply reflect the former Paleogene cover. In this context, the framing of the paper as a counter to the Stonehenge glacial transport hypothesis is flawed. If the paper was entitled “Detrital zircon–apatite fingerprinting shows that Paleogene sediments, likely derived from northern crystalline terrain, once covered Salisbury Plain”, then I would be happy to recommend publication.	We agree that the zircon–apatite signatures most plausibly reflect the former Paleogene cover across Salisbury Plain, which was derived in part from northern crystalline terranes, i.e., sources beyond Salisbury Plain. However, we consider the framing of the Stonehenge glacial transport debate to be justified, as our data show that in all four sampled catchments surrounding Stonehenge, there is no detrital signal consistent with distinct glacial input of Laurentian or East Avalonian material on scales greater than the micron. While the Paleogene provenance story is central, we see these observations as directly relevant to the ongoing archaeological debate, since they imply that glacial transport did not deliver a significant detrital component to Salisbury Plain. We have therefore retained the dual framing. Although the Paleogene cover interpretation is the primary geological conclusion, the implications of our data extend to the Stonehenge question.
The most interesting finding within the study – and which really should form the focus of the paper – is the overall lack of zircon U-Pb ages of 464-462 Ma within the four stream sediment samples. I agree fully with the authors that, if the bluestones were glacial erratics as argued by Brian John, there should be many more sediment grains with a c.464 Ma age. Clearly, the discovery of one zircon U-Pb age of 464 Ma amongst 550 analyses does not totally preclude the presence of bluestone erratics but, as the authors suggest, it is a small nail in the coffin. Checking the supplementary data, the one 464 Ma age comes from sample SH1, which was collected to the east of Stonehenge. If it were from west of Stonehenge and lying on a path between the Preseli Hills and the monument, it could plausibly support the glacial transport theory, but from a drainage system near Andover, I very much doubt it	Agreed, the near absence of “bluestone” zircon on Salisbury Plain is a counter to arguments of glacial transport. The ca. 464 Ma grain is from SH3, the river Wylfe (the most western sample collected). In their comment, the reviewer is referring to spot #1 from SH1, which is 20% discordant (Appendix 1), has lost radiogenic Pb, and we, conservatively, do not place age interpretation on this grain. In any case, a single zircon with an age consistent with a source from the Mynydd Preseli does not provide compelling evidence for large erratic transport from southwest Wales. Moreover, similar Ordovician ages are found throughout many igneous and sedimentary rocks throughout the UK, including the Thanet Formation (albeit as a rare component).
I cannot recommend publication of the manuscript in this form. However, I do think there are some important data here that deserve to be published somewhere. What the authors have without realising it is really detailed evidence of the zircon-apatite signatures of the former Paleogene cover on Salisbury Plain. If they were to reshape the manuscript and focus it onto the bluestone question, it has the potential to be a powerful intervention. Even with four sampling points, the presence of only a single zircon grain with a U-Pb age of 464 Ma amongst 550 analyses is significant counter-argument to the bluestone glacial transport hypothesis.	We thank the reviewer for these constructive comments and agree that our dataset provides robust evidence for the zircon–apatite signatures of the former Paleogene cover on Salisbury Plain. We also agree that the near-absence of ca. 464 Ma zircon ages, despite >550 analyses, is itself an important observation that directly bears on the Stonehenge bluestone glacial transport debate. We have reframed the manuscript to better focus on the west Wales bluestone debate, e.g. “If glacial erratics had reached Salisbury Plain, they should have contributed a measurable ca. 464 Ma zircon signature from Mynydd Preseli

	source rocks (Bevins et al., 2017) from southwest Wales or from northern Britain (Ganderian-Laurentian signatures) to the local sediment budget (Figure 1)."
Lines 36, 49, 65 – no need for the additional "The" – plain "Salisbury Plain" is fine.	Definite articles removed.
Line 37 – I'm assuming you mean Avebury here?	"Amesbury: replaced with "Avebury".
Line 41 – plain "West Woods" is fine	Definite article dropped.
Line 43 – "2-5 tonnes" would be better.	Done, weight range reversed.
Lines 50-54 – the way this paragraph is phrased gives a false sense of balance between the two sets of theories. By far the majority of studies favour human intervention, whereas the glacial transport theory is essentially a niche view. I would suggest rephrasing to reflect this.	You are right, the majority of archaeological studies favour human transport of Stonehenge's megaliths (Pearson et al., 2015, 2024). Nevertheless, debate over glacial limits and megalith provenance persists (John, 2024; Thorpe et al., 1991, cf. Bevins et al., 2024). See our edits below: "An alternative view, the glacial transport hypothesis, posits that non-Sarsen rocks, specifically the Mynydd Preseli bluestones or the Altar Stone, were transported to Stonehenge (Figure 1) as erratics during Pleistocene glaciations (John, 2024; Thorpe et al., 1991).
Presumably Clarke et al. (2024) needs to be added to the list of citations for the sea/overland viewpoint?	Good point; Clarke et al. (2024) have been added to the discussion on sea/overland viewpoints.
Lines 59-64 – doesn't this assume that glacial outwash was deposited on or around Salisbury Plain? Is there documented evidence of outwash in this area, either from the Anglian or Devensian? How could the presence of outwash be explained geomorphologically, given that Salisbury Plain is an elevated area? How could outwash flow reach rivers like the Avon and Wylfe? What are the drainage connections?	Our intention was not to imply that extensive glacial outwash is documented on Salisbury Plain, but rather to highlight the contrasting scales at which fine detritus versus large erratics are typically dispersed by ice and meltwater. See the revised text: 'While there is no geomorphic evidence for outwash deposits on Salisbury Plain itself, glacial outwash can transport fine detrital grains (typically <200 µm) well beyond the terminal margins of ice sheets, whereas larger erratics, often ranging from tens of centimetres to several metres, are typically deposited closer to the ice front (Veness et al., 2025)."
Line 65-68 – what this lacks is a description of the structural geology and particularly the topography and drainage configuration of the area.	We have revised the manuscript to include a brief description of the structural geology, topography, and drainage configuration of Salisbury Plain. "Salisbury Plain exhibits low-amplitude relief, with elevations generally between 100 and 250 metres above sea level, and is dissected by a dendritic network of rivers, including the Avon, Wylfe, and Bourne, which drain towards the south and southeast (Figure 1)."

Line 216-219 – could these bioapatite sources simply be inherited from the Paleogene sediments that once covered Salisbury Plain? Why do they need to be derived from the Chalk? Lines 220-226 – could these older apatite sources simply be inherited from the Paleogene sediments that once covered Salisbury Plain?	Apatite from stream sands is endemic to the Salisbury Plain. Reviewer 2 has highlighted the phosphorus-rich nature of the bedrock surrounding Stonehenge. Indeed, some samples from the nearby A303 boreholes (Mortimore et al., 2017) indicate that discrete chalk horizons are effectively phosphorite. Therefore, we interpret apatite from stream sands (which is highly enriched in uranium, with distinct Pb-ratios & anhedral to subeuhedral) to be derived from phosphorite horizons (rather than predominantly bioapatite) within Salisbury Plain chalk. We agree that the older apatite sources we tentatively attribute (based on initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratios) could be derived from older source rocks that were reset during a ca. 60 Ma period of fluid flux (see Figure 3).
Line 275 – I'm interested to know whether the authors think that four stream samples is of sufficient size to underpin the kinds of claims made in the paper. A smaller journal, perhaps, but – in my view – a Nature-family journal, no.	The selected samples were chosen to represent the main drainage areas of Salisbury Plain. Moreover, the zircon signatures are internally consistent between samples, providing a robust signal from a large geographic area, such as Salisbury Plain. We complemented the zircon dataset with apatite U–Pb analyses. Therefore, ~700 individual grains were analysed here, which makes our study one of the largest detrital zircon studies in southern Britain. As demonstrated in Vermeesch (2004), approximately 120 grains are considered sufficient to generate statistically meaningful provenance information. Thus, our zircon-apatite approach provides confidence that the observed provenance patterns reflect the regional sediment source rather than sample-specific anomalies. Hence, the sampling scale is entirely appropriate to the scientific questions being asked.

Review 2 Comment	Response
The central claim in this paper is that modern river sediment on the Salisbury Plain is derived from the locality, or the catchments of the local streams. I find this claim to be novel and true on the basis of the supplied zircon data, which demonstrate that detritus in southern England at the end of the Cretaceous can be dominated by Laurentian sources very similar to those present in modern river sediment.	We thank the reviewer for their supportive comment on our central claim.

The implications for Stonehenge are significant – despite the local streams preserving zircon populations that appear very Laurentian (i.e. Ireland/Scotland-like), these populations are found by the authors to be typical of sandstone units that were deposited in southern Britain 10s of millions of years before glaciation. This would apparently bolster arguments that the stones at Stonehenge were moved large distances by humans and not just what was lying around post-glaciation. Taken at face value I would assume that would suggest that the site was culturally important across a wide area for prehistoric people of Britain. This provides an interdisciplinary aspect to the paper and it will be read by a broad audience.	We agree that the zircon-apatite geochronology supports the hypothesis that the Stonehenge megaliths were transported by humans, rather than deposited by glacial action.
The paper is well-written and appropriately structured. There is not any major missing information. Though I have some suggestions below. I have no "major" comments, just some moderate points that might affect the emphasis of some sections – and then small edits that are included in an annotated pdf (click the highlights to see my comments).	Thank you for your positive assessment of the manuscript. Here, we have included comments from your annotated PDF. Please find our changes to your suggestions detailed below.
Lines 12–16 (Abstract): This section is awkwardly written for a broad audience, and also sort of misses the main point. The main finding is that modern river sediment on the Salisbury plain resembles sediments found elsewhere in southern Britain WRT its zircon populations, and thus a glacial origin does not need to be invoked. The Alpine orogeny is not really very relevant to that finding and renders the abstract less impactful and less easily understood by a general scientific audience.	Thanks for the suggestion. We have redrafted the abstract to emphasise the main finding of our research, namely, that the detrital zircon populations in Salisbury Plain sediments closely resemble those elsewhere in southern Britain, and that a glacial transport mechanism is therefore unnecessary. References to the Alpine orogeny (although interesting!) have been removed to improve accessibility for a broad readership.
Line 22–26: Something that is never addressed properly in this paper is the different sensitivity of zircon and apatite to weathering processes. It makes no sense that zircon are mostly Laurentian and derived from multi-cyclic sediments and there are no similar old apatite, unless the reader understands that apatite is far less likely to survive sedimentary recycling than zircon. The fact that there are zero Laurentian apatite despite apatite being very common in the Laurentian basement speaks to repeated, profound and extreme weathering of the source rocks of these zircon in the Salisbury modern river sediments.	Absolutely, this observation deserves consideration. We have added the following discussion text: “The apparent absence of Laurentian apatite in the modern river sediments of Salisbury Plain, despite the presence of Laurentian-derived zircon, likely reflects the differential susceptibility of these minerals to destruction during sedimentary processes. Apatite is more labile to chemical dissolution and alteration during sedimentary reworking, whereas zircon is highly durable (Clarke et al., 2023; Glorie et al., 2022; O’Sullivan et al., 2020). Consequently, the survival of multi-cyclic Laurentian zircon without corresponding apatite is consistent with the

	selective removal of apatite during chemical weathering and sedimentary recycling.”
Lines 68–70: This section is factually incorrect. The chalk local to Stonehenge is well-known to be strongly phosphatic. I have about a kilo of rock from drill cores under stonehenge sitting on my desk – which I have U–Pb dated (don't try it the 'age' is nonsense due to fluid interaction). So I would challenge the finding of low P in the local chalk – some of the chalk horizons are effectively phosphorite. These samples are from the A303 boreholes and were given to me by Rory Mortimore. See Mortimore et al., 2017 below which details the phosphate rich nature of the stonehenge chalks. https://doi.org/10.1016/j.pgeola.2017.02.003	Thank you for bringing Mortimore et al. (2017) to our attention. The presence of abundant U-rich apatite in stream sands (see Appendices 2 and 3) was initially enigmatic; however, a locally derived phosphatic origin provides an excellent explanation for the provenance, rather than a purely bioapatite source. We have updated the introduction as follows: “Conversely, phosphorite horizons are known to occur within the chalk surrounding Stonehenge; thus, apatite in stream sediments could be comparatively local (Mortimore et al., 2017; Pacey, 1985). Thus, incorporating a multi-mineral approach provides a more comprehensive picture of sediment provenance and post-depositional processes.”
Lines 73–74: There is important missing context here about the recovery rate of the minerals from these sediments. It is easier to generate an exotic heavy mineral population where the proportion of the mineral is very very low. Can you comment on this?	Agreed, this is an important point. We consider the following: 1. In our samples, zircon and apatite are relatively abundant (zircon: 1.5–56 wt%, apatite: 3.5–13 wt% across SH1–SH4), which reduces the likelihood that rare exotic grains disproportionately influence the detrital population (Appendix 3). 2. The consistent patterns observed across multiple stream samples indicate that these DZ signatures reliably reflect sediment provenance across a large geographic area (i.e. the entire Salisbury Plain). 3. Grains were randomly picked from bulk mounts, and the separation and mounting procedures were consistent across all samples. We also include automated mineralogy maps in Appendix 3 to illustrate the abundance and morphology of apatite and zircon in the river sand samples.

Apatite U–Pb section. The ultimate lithology of the apatite is presented as a mystery, but it needn't be one. It is actually still possible to tell if the grains are from an authigenic source. This can be done by looking at the $^{206}\text{Pb}/^{208}\text{Pb}$ ratios. U in marine phosphate is derived from bacterial scavenging from seawater, which has extremely low Th/U, meaning that the Th/U ratio of marine phosphate is ludicrously low. The $^{206}\text{Pb}/^{208}\text{Pb}$ ratios of your apatite should be abnormally high if the apatite are still very low Th/U. Check this – it'll take 2 minutes.	Thank you for your valuable suggestion regarding the Th/U ratios in apatite. We have examined the $^{206}\text{Pb}/^{208}\text{Pb}$ ratios in Salisbury Plain apatite, finding a median value of 0.59 with no abnormally high ratios (e.g., > 10–100) that would indicate a primary marine authigenic (phosphogenic) source. Nonetheless, we consider that the high uranium concentrations and previous studies (Pacey, 1985; Mortimore et al., 2017) support the interpretation of a locally derived (bio)apatite component from phosphorite horizons on Salisbury Plain.
Lines 124–125: These apatite are from modern river sediments, so is it possible that this rounding is recent?	Interesting point. Some modern rounding could occur. However, we point towards the consistency in apatite morphology across samples. For example, Sample SH1 comes from Pillhill Brook, a small, low-energy stream, where only minor rounding could have occurred during recent transport. Nevertheless, SH1 contains abundant rounded to equant apatite (Appendix 3). Given the limited transport distance of SH1 and the consistent rounded–subrounded shapes across all grains, it is unlikely that the observed morphology is solely the result of modern fluvial abrasion. We consider that textures more plausibly reflect inherited rounding from prior sedimentary reworking, such as from the overlaying of Pliocene sediment formation.
Lines 163–164: I don't find this a particularly convincing argument, the local rock is purportedly zircon-free chalk, so any extraneous source of zircon would dominate the local zircon budget by definition. Doesn't change the fact I believe your interpretation, but I think this is a weak line.	Thanks for this point. The redrafted text now reads: “Although glacial erratics and meltwater outwash may have contributed only minor volumes of sediment, the local chalk is nearly devoid of zircon; therefore, any extraneous zircon input would strongly influence the river sand detrital zircon signature.”
Lines 168–171: the best part	Thank you.

Lines 175–179: What mechanism can be invoked to explain zircon storage on the Salisbury plain from removed overburden after millions or tens of millions of years? You need to address this. What about the drainage patterns of the rivers, is there anything that they traverse that could deliver zircon?

Good point, much of the Cenozoic overburden (e.g., Thanet Formation) has been removed from Salisbury Plain. Nonetheless, some Laurentian-zircon-bearing sediments remain stored on the Salisbury Plain. We consider the following:

1. As Reviewer 1 noted, Palaeogene lithologies remain preserved as outcrops to the southeast of Salisbury Plain and southeast of Marlborough (and, more extensively, to the east within the London Basin). They also form the host sands within which the sarsen stones of Stonehenge (Nash et al., 2020) and the Marlborough Downs developed, and exist in remnant form as the widespread Clay-with-Flints.
2. We posit that local topographic lows across Salisbury Plain, such as shallow valleys and depressions, would have acted as sediment traps. Zircon-rich sands from these Palaeogene units could accumulate in these lows and be shielded from complete erosion during later Cenozoic denudation.
3. Palaeodrainage systems, including the ancestral courses of the Avon and Wylfe rivers, would have transported zircon-bearing sediments from upstream Palaeozoic or Mesozoic lithologies into the Salisbury Plain region. Sediments deposited along these low-energy channels and valley floors could preserve zircon grains even after much of the overlying Thanet Formation and other Cenozoic cover was removed.

Please see the modified text in the discussion below:

“Much of the Cenozoic overburden on the Salisbury Plain has been removed; Laurentian zircons could have persisted in remnant Palaeogene sands and Clay-with-Flints strata, accumulating in local topographic lows and along palaeodrainage channels, such as the ancestral courses of the Avon and Wylfe rivers (Figure 1). This combination of preserved sediments and ancient fluvial pathways provides a plausible mechanism for zircon survival on the Salisbury Plain despite extensive erosion.”

Lines 181-183: Would the ORS not contain a lot more Grampian than present in the Thanet?	We agree that if ORS had been the dominant contributor, a stronger Grampian and Laurentian zircon component would be expected in the Thanet Formation. See Figure 5. Please see the redrafted text below: “How fine-grained Laurentian detritus became incorporated into the Thanet Formation remains uncertain (Stevens and Baykal, 2021). While the reworking of ORS is one possible pathway, the relative paucity of Grampian and Laurentian-aged zircon in the Thanet Formations suggests that this mechanism cannot have been the sole contributor. Instead, a mixture of recycled sources, including Pennine Basin rocks and ORS, likely fed the London Basin during the Paleogene uplift of the Wales–Brabant Massif (Stevens and Baykal, 2021).”
Lines 216–219: Again, add the Mortimore 2017 reference from earlier. The whole region is infested with phosphatic chalk. https://doi.org/10.1016/j.pgeola.2017.02.003. Part of the issue is that marine phosphate is too porous to hang on to daughter products. The apatite you've analysed could represent the recrystallisation of primary phosphate into more coherent crystalline apatite grains millions of years after deposition.	Mortimore et al. (2017) reference added throughout. We agree that Salisbury Plain apatite represents the partial recrystallisation of primary bioapatite from local phosphorite horizons..
Line 228: having such high U is indicative of sedimentary phosphate origin of apatite.	The median U concentration of Salisbury Plain stream apatite is 34 ppm, and some grains exceed 500 ppm. However, the low $^{206}\text{Pb}/^{208}\text{Pb}$ ratios measured (~ 0.59) indicate that these grains have undergone recrystallisation, incorporating common Pb (consistent with their porosity) while preserving their overall sedimentary phosphate bioapatite provenance.
Lines 236–242: While this is plausible and I broadly think a sensible guess (i.e. linking apatite age to Alpine) - is it also plausible that the apatite are incompletely and inconsistently overprinted, meaning that the 'age' of the overprint is difficult to determine with any certainty. Unless you can prove it more concretely or convincingly, I would emphasise that this is a section that is your interpretation of something that fits the data plausibly, but I'm not convinced its 100% proven.	This section is an interpretation based on the most plausible geological context for the observed apatite U–Pb systematics. While we agree that incomplete or heterogeneous resetting cannot be excluded, the Alpine-related fluid overprint provides the most consistent explanation for the partial Pb isotope patterns and best accounts for the apatite age distribution (Figure 3). Nonetheless, following your guidance, we have removed our Alpine interpretation from the abstract.

Lines 255-257: Is it possible that zircon is present in low volume in the chalk, and that the chalk and thanet formation derived zircon from a similar drainage pattern. As in – is the Thanet formation a middleman that is required in this story, or just a formation with a similar provenance for its detrital components? More simply – is Thanet the dad or is it the brother? Is it not plausible that the prolonged weathering of the chalk at source causes the carbonate component to dissolve into the river load, leaving a gradually more concentrated residue of whatever scraps of detritus were originally in the carbonates? Whether from the odd tiny bed of detritus or from windblown grains etc.? Maybe my option is less likely for some reason, but address this possibility somewhere.

Good point. Some detrital zircon would be present in Salisbury Plain chalk. See our additions to the discussion:

“Alternatively, it remains possible that zircon is present in trace quantities within Salisbury Plain chalk (Figure 1), and that both the Chalk and Thanet Formation record sediment derivation from a broadly similar drainage network. In this case, the Thanet Formation would represent a related, rather than uniquely required, intermediary. However, the correspondence between the Thanet and Salisbury Plain zircon age spectra (Figure 5) supports the interpretation that Paleogene strata acted as the principal recycled source.”

Good suggestion. We have added an inset showing the crystalline terranes of Britain, after Waldron et al. 2014:

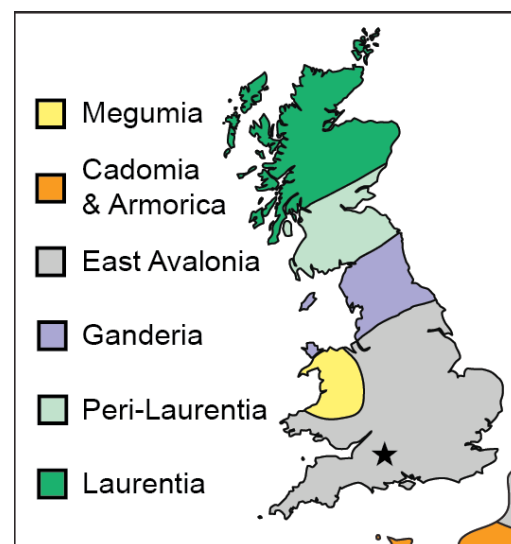
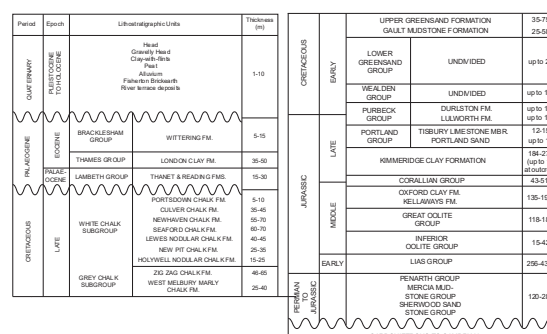


Figure 1: A stratigraphic column should be added, and also the inset should have the British palaeoshoreline in the late Cretaceous and show the major terranes.

We have also added a stratigraphic log, adapted after Hopson et al. 2005:



We note that during the Late Cretaceous, the entire Salisbury Plain region, located along southern Britain, was submerged beneath the Chalk Sea, with palaeoshorelines situated far to the northwest (e.g., northern Scotland). As such, there is no meaningful local shoreline to illustrate across the study area.

I'm aware I'm having a moan here – but I'm very frustrated by the lack of trace element data for apatite. The ultimate lithology of the apatite is presented as a mystery, but it needn't be one – I (O'Sullivan et al., 2020, Earth Science Reviews) and many others (e.g. Belousova et al., 2002, Journal of Geochemical Exploration) have produced models to use apatite trace element composition for sediment provenance. These models are well known and well disseminated. There is extensive data available on authigenic apatite compositions also (some collated in my 2020 paper), those compositions are clearly separable from apatite from crystalline bedrocks (using Ce anomaly, Y/Ho ratio etc.). I understand the dating employed a multiple collector ICPMS. But a 10-15 micron spot on the edge of a grain would provide acceptable precision for REE analysis, as there are effectively no backgrounds on REEs using ICPMS.	Although our current study focused on U–Pb isotopic systematics using MC-ICPMS, the suggestion to undertake in situ trace element analyses, potentially on 10–15 µm spots fringes of grains, is welcome. There is more data, e.g., trace elements and Lu–Hf, Sm–Nd to be gleaned from Salisbury Plain apatite (and indeed from detrital apatite from other locations in Britain and Ireland!). Appendix 3's mounts provide an excellent resource, and we would be keen to collaborate on trace element analysis in the future.
I largely agree, but this is not an appropriate figure to call out here, as it is just the apatite and zircon – perhaps a supplemental figure image of the bulk sand?	Good point; for the interested reader, we have added Appendix 3, which includes automated mineralogy maps and mass % abundance for minerals within each sand sample.
Quote an age range from single grain lower intercepts rather than the regression lower intercept – it isn't a population so not a great way to present the ages.	Can do. See the following text: “Detrital apatite U–Pb analyses from Salisbury Plain River sands yield a dominant array on a Tera-Wasserburg plot, implying most radiogenic-Pb retention at 60 ± 3 Ma (n=250) (Figure 3). Alternatively, ^{207}Pb corrected ages for apatite, with an $F^{207} < 98\%$ span of 32–115 Ma, and also show a dominant age peak at approximately 65 Ma (Figure 3). “

Review 3 Comment	Response
The authors address indirectly the intriguing and enduring question as to whether megaliths were transported to Stonehenge as glacial erratics by one or more Pleistocene ice sheets. Their approach is novel - to use detrital zircon-apatite finger printing of modern stream sediments to test if the sediments record glacial transport and reworking of these mineral grains in the surroundings of Stonehenge. The analytical methods and results are convincing and point to an alternative origin from recycling of minerals from London Basin cover rocks during Cenozoic denudation. The current ms has several weaknesses that need to be addressed before publication.	Thank you for reviewing our work. We agree that our zircon–apatite results provide strong evidence for an alternative, local origin of these minerals, resulting from the recycling of the London Basin rather than through glacial transport. Please see our edits to your suggestions below.
1. The glacial transport hypothesis is not adequately explained to the reader. What are the arguments/evidence for this proposal? All comments are negative. There is no map of Anglian ice sheet limits, generally regarded as representing the maximum extent of the British_Irish ice sheet in England during the Pleistocene. Nor of ice flow lines for this ice sheet. It is plausible that an earlier ice sheet reached Salisbury Plain	We appreciate this comment and, following your suggestions below, have expanded and clarified our discussion of glacial transport to make the rationale and testing framework more explicit. Please see the specific edits below. We have not included a map of the Anglian ice sheet limits or ice flow lines because

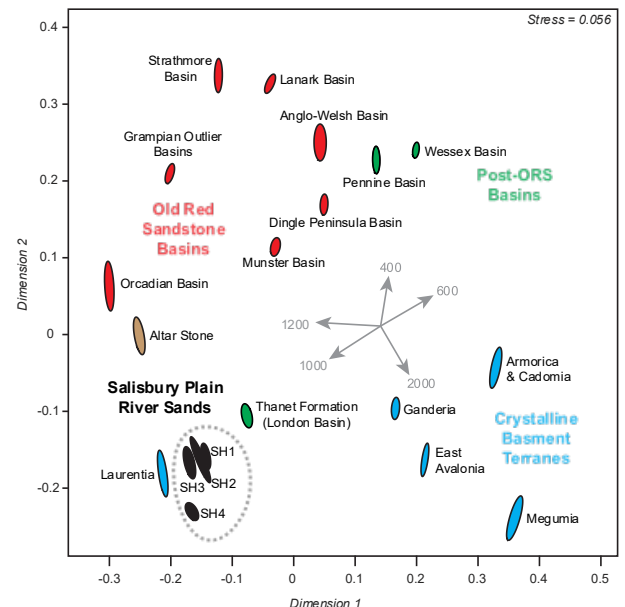
- the maximum limits of ice sheets in N Europe and S of the Great Lakes locally lie outside the MIS 12 limits. This possibility is not mentioned.

existing published reconstructions consistently show that ice did not reach Salisbury Plain. Additionally, these reconstructions vary considerably in detail and extent, reflecting inherent uncertainties in the precise ice margins during the Pleistocene. Including any single map risks implying a false precision or consensus. Instead, we reference multiple studies that collectively demonstrate the relevant glacial context and support our interpretation.

2. There is no thorough statement of how the glacial hypothesis is tested by the Zr data. What would be expected in the Zr age data if ice flow from the NW had reached Salisbury Plain? Yes, there is one sentence on the lack of Cadomian Zr ages but no more detail. Are former ORS cover rocks in Wales a potential source? If so, could glacial erosion and transport of those rocks supplied the Laurentian Zr?

Thank you for your insightful comment. The revised manuscript now thoroughly addresses how the glacial hypothesis is tested using zircon U–Pb data. Specifically, we outline the expected zircon age signatures if ice flow from northwest Britain or west Wales had reached Salisbury Plain, including the presence of ca. 464 Ma ages from the Mynydd Preseli and Cadomian-aged zircons indicative of local basement sources. Our data show only a single 464 Ma zircon grain and a sparse representation of non-Laurentian ages, inconsistent with significant glacial transport.

Welsh ORS does not contain a pronounced Laurentian zircon component and are therefore unlikely to have supplied significant Laurentian zircon through glacial erosion and transport. This is supported by our multivariate scaling plot (Figure 5):



3. If there is no clear glacial signature in the Zr data then the authors miss an important implication of their results - that the BIIS did not advance onto Salisbury Plain and so the Anglian ice sheet limit is the maximum Pleistocene ice limit in southern England.

While our zircon data show no clear glacial signature indicative of ice advance onto Salisbury Plain, we acknowledge that definitively constraining the maximum extent of the British-Irish Ice Sheet (BIIS) requires the integration of multiple geological proxies beyond detrital zircon provenance alone. Our results are consistent with the Anglian ice sheet

	limit representing the southernmost Pleistocene ice advance in this region, but we recognise that this interpretation should be considered alongside other geomorphological and stratigraphic evidence.
4. The text in the Abstract and Introduction needs careful revision. See detailed comments on the attachment.	Thank you for your suggestions. Please see our edits below.
Line 6. While glacial processes can impart macroscale signatures onto a landscape (e.g., moraines, eskers), evidence for such features on the Salisbury Plain is sparse or ambiguous. Here you virtually dismiss the alternative hypothesis before you present any findings. Sharpen this point and make it later in the Abstract. You are testing whether or not Salisbury Plain was glaciated in the Pleistocene. The logic is that if there is no firm evidence for the British-Irish ice sheet reaching Salisbury Plain then the blocks at Stonehenge cannot have been glacially transported to the site.	We have revised the abstract in response to the guidance from Reviewers 2 and 3. Our redrafted abstract reads: “How the building blocks of Stonehenge arrived on Salisbury Plain, England, remains enigmatic, with glacial and anthropogenic transport proposed. Here, we test the possibility of Pleistocene glacial sediment input using grain-scale U–Pb fingerprinting of detrital zircon and apatite from modern stream sediments near Stonehenge. Zircon ages span 3396–285 Ma, with age peaks at ~1090, 1690, and 1740 Ma, indicating ultimate derivation from the Laurentian basement of northern Britain. A single zircon dated at 464 Ma matches the Mynydd Preseli bluestone source, yet its rarity is inconsistent with any significant glacial input from west Wales. Salisbury Plain detrital zircon ages match those of southern British rocks from the London Basin and lack any signal of glacial provenance. Apatite ages of ~60 Ma record regional post-depositional U–Pb resetting during basin inversion. Collectively, our results indicate that Salisbury Plain remained unglaciated during the Pleistocene, ruling out glacial transport of the Stonehenge blocks and supporting human agency in their movement.”
Line 8 <i>modern</i> stream sediments..... to test the competing hypotheses	
Line 10. Now in one sentence say why the results are incompatible with glacial transport. This is consistent with the lack of firm evidence for glaciation from tills etc. Note that <i>sparse</i> evidence for glaciation is still evidence for glaciation.	
Line 11. Instead, the detrital record captures the imprint of tectonism linked to the nascent Alpine Orogeny. During basin inversion, reworking of the London Basin released recycled Laurentian zircon, while fluid–rock interaction reset bioapatite U–Pb systematics. Both mechanical and chemical signals reflect Alpine-induced remobilisation, offering a <i>tectonically driven alternative to glacial transport</i> and supporting human agency in moving the megaliths. This section is unclear. The phrase in italics reads like it applies to the Stonehenge blocks, not the detrital minerals. The detrital ZR record indicates recycling after erosion of Palaeozoic cover (in Wales?) and transport by rivers or longshore drift to the London Basin. During basin inversion at the onset of the Alpine orogeny, bioapatite U–Pb systematics were reset by fluid–rock interaction, providing ~60 Ma ages. Consistent with previous results. Suggesting also that Salisbury Plain remained unglaciated in the Pleistocene. Ruling out glacial transport of blocks to Stonehenge.	
Line 18 Put <i>such as zircon and apatite</i> in here.	Ok, “such as zircon and apatite” added.
Line 21 As this paper is about flux and provenance, the nascent regolith comment is not needed. “Nascent regolith” is anyway puzzling – is this the effect of weathering on Zr?	We have removed “nascent”. The streams of the Salisbury Plain are actively forming regolith (river terrace sands), and thus apatite-zircon U–Pb analyses from the Salisbury Plain can help us understand regolith formation.
	Thanks for your suggestion. The redrafted text now reads:

Line 22 Resistant detrital grains in modern stream sediments can be linked to direct source-sink transport or to more complex and cryptic, multicycle transport histories	“Resistant detrital grains in modern stream sediments can be linked to direct source-sink transport or to more complex and cryptic, multicycle transport histories, given the refractory nature of these heavy minerals under certain physical and chemical conditions (Dröllner et al., 2025; Morton and Hallsworth, 1994; Zametzer et al., 2024).”
Line 25 Cut the final phrase?	We prefer to retain “given the refractory nature of these heavy minerals under certain physical and chemical conditions” as it provides background on our zircon-apatite approach and the complementary insight provided by both minerals.
Line 27 Direct versus recycled sources for refractory Zr and apatite now found in Quaternary sediments or older sedimentary rocks have been identified across Britain ...	We agree that the distinction between direct and recycled sources of detrital zircon and apatite in British Quaternary (The Thanet Formation is Paleocene) and older sedimentary rocks has been identified in previous studies. However, we have chosen to retain our original wording to reflect the current state of the literature. Although zircon-based studies (e.g., Morton et al., 2015, 2016; Stevens and Baykal, 2021) provide strong evidence for both direct and recycled sources, there are only a handful of comparable apatite U–Pb studies available for Britain (e.g., Greig et al., 2022; Metcalfe et al., 2024). As such, regional and inter-basin variability remains unresolved, and we feel our phrasing more accurately conveys this ongoing uncertainty.
Line 34 Move this to line 49.	We appreciate the suggestion to relocate this sentence. We have chosen to retain it in the broader discussion of detrital provenance approaches because it frames the Stonehenge debate within the context of sedimentary transport and archaeological science. We aim to demonstrate how source-to-sink methods address questions at multiple scales, ranging from regional paleogeography to archaeological case studies.
Line 37. Is this Avebury?	Good spot. “Avebury”, added.
Line 37. An outstanding question is how megaliths were transported to Stonehenge. Glacial or man?	Good suggestion, please see the redrafted text below: “The origin of the non-Sarsen building blocks of Stonehenge is debated. Most suggest that Neolithic people transported the bluestones from the Mynydd Preseli and Orcadian Basin to the Salisbury Plain via overland or sea routes (Clarke et al., 2024a; Parker Pearson et al., 2024; Parker Pearson et al., 2015). An alternative view, the glacial transport hypothesis, posits that non-Sarsen rocks, specifically the Mynydd Preseli bluestones or the Altar Stone, were transported to Stonehenge (Figure 1) as erratics during Pleistocene glaciations (John, 2024; Thorpe et al., 1991). The case for glacial transport of megaliths rests on

	geomorphological arguments that pre-Devensian ice streams (e.g., Anglian or Wolstonian) may have extended farther south toward Salisbury Plain, and on reports of isolated boulders in southern England inferred to be of Welsh origin (John, 2018; John, 2024; Thorpe et al., 1991).”
Line 37 Simplify. Megaliths at Stonehenge form three groups.	Done, text edited to “Megaliths at Stonehenge form three groups”.
Line 51 Routes	“routes” added.
Line 53 State the glacial hypothesis more clearly. It is about the Welsh material only. The case rests on what evidence?	Good point, the glacial transport hypothesis should be made explicit. See our redrafted text: “The origin of the non-Sarsen building blocks of Stonehenge is debated. Most suggest that Neolithic people transported the bluestones from the Mynydd Preseli and Orcadian Basin to the Salisbury Plain via overland or sea routes (Clarke et al., 2024a; Parker Pearson et al., 2024; Parker Pearson et al., 2015). An alternative view, the glacial transport hypothesis, posits that non-Sarsen rocks, specifically the Mynydd Preseli bluestones or the Altar Stone, were transported to Stonehenge (Figure 1) as erratics during Pleistocene glaciations (John, 2024; Thorpe et al., 1991). The case for glacial transport of megaliths rests on geomorphological arguments that pre-Devensian ice streams (e.g., Anglian or Wolstonian) may have extended farther south toward Salisbury Plain, and on reports of isolated boulders in southern England inferred to be of Welsh origin (John, 2018; John, 2024; Thorpe et al., 1991).”
Line 55 does not inform the reader, and it is too dismissive. Then state that Stonehenge is thought to lie outside Pleistocene glacial limits, although those limits are poorly constrained in central Southern England. Hence, there is doubt about whether Salisbury Plain was ever glaciated in the Pleistocene.	Agreed, the redrafted text below provides better context: “The absence, ambiguity or inaccessibility of purported glacial features on the Salisbury Plain hampers efforts to reconstruct potential ice flow and erratic transport pathways (John, 2024; Scourse, 1997). Nonetheless, the extent of the Anglian glacial episode (ca. 478–424 ka), where ice sheets potentially reached central southern Britain, is poorly constrained (Gibbard and Clark, 2011) and Salisbury Plain may have lain within the ice margin, allowing for the possibility of glacial erratic transport onto Salisbury Plain (John, 2018; Thorpe et al., 1991). While there is no geomorphic evidence for extensive glaciation on Salisbury Plain itself, glacial outwash can transport fine detrital grains (typically <200 µm) well beyond the terminal margins of ice sheets, whereas larger erratics, often ranging from tens of centimetres to

	several metres, are typically deposited closer to the ice front (Veness et al., 2025).”
Now bring in Line 73-74. This is a test for the glaciation hypothesis – Zr should be from S Wales and should include ages x to y. State the expected provenance signature. Alternatively, if no ice cover, then Zr and apatite sourced during denudation of sedimentary cover. State the expected provenance signature Bring in Line 25 and following. Line 74. New paragraph. Limited/no support for ice cover on Salisbury Plain. No glacial erratic transport. Hence, anthropogenic transport likely.	The test offered by detrital mineral fingerprinting should be made clear. Please see our edits below: “Glacial sediment transport mechanisms are expected to leave persistent and detectable provenance signatures, preserved in the landscape as indicators of sediment routing and crystalline source regions following ice retreat (Eyles, 2006; Hagg, 2022). Indeed, geochemical data for detrital minerals offer a novel test of these competing hypotheses. If glacial erratics had reached Salisbury Plain, they should have contributed a measurable ca. 464 Ma zircon signature from Mynydd Preseli source rocks (Bevins et al., 2017) from southwest Wales or from northern Britain (Ganderian-Laurentian signatures) to the local sediment budget (Figure 1).”
Results Clear. No comments.	Thank you.
Line 132 Laurentian zircon on Salisbury Plain	Subtitle edited to “Laurentian Zircon on Salisbury Plain”.
Line 143 Focus on Wales and the English Midlands. Line 149. This is where you need to nail down the idea that the Zr population in the stream sediments is not of glacial origin. Ice flow likely SW from S Wales or S from Midlands. Either should be dominated by Zr ages <650 Ma. And it is not.	Agreed, focusing on what would be expected for glacially transported sediments versus what we actually measured is important. See the redrafted section below: “Such Mesoproterozoic age modes are conspicuously absent in the Gondwanan-derived crystalline basement of southern Britain (Henderson et al., 2016). East Avalonian and Megumian dominate the bedrock of southern Britain, including Wales and southern England (Figure 1) and include rocks from the Cadomian orogeny (ca. 650–600 Ma) (Accotto et al., 2022; Murphy et al., 2013), Neoproterozoic arc-related magmatism (590–540 Ma) (Pharaoh and Carney, 2000), Silurian–Devonian intrusions (ca. 430–390 Ma) (Henderson et al., 2016), Carboniferous (370–360 Ma) (Stephenson et al., 2003) and Variscan metamorphic overprinting and granite emplacement (~300 Ma) (Neace et al., 2016). Such non-Laurentian ages would be diagnostic markers for distinguishing local, first-cycle basement contributions to the detrital budget of the Salisbury Plain. If Salisbury Plain detritus had been introduced by glacial transport, the ice-flow directions most relevant to detrital

	zircon fingerprint would have been southward from the English Midlands or southwestward from south Wales (Clark et al., 2022; Gibbard and Clark, 2011). However, the dearth of such ages (only 8% of zircon are Phanerozoic) (Figure 2) and the uniformity of age spectra across multiple catchments, coupled with the scarcity of local bedrock sources, demonstrates that the detrital zircon assemblage is not first-cycle material locally derived or transported from the underlying East Avalonian and Megumian basement terranes (Figure 5).”
Line 154 Move to Line 166 or thereabouts.	Done, redrafted text now reads: “Ultimately, the detrital zircon cargo of the Salisbury Plain necessitates a north-to-south sediment transport and recycling mechanism from northern Britain. To investigate potential sediment sources, we compare the age spectra of the Salisbury Plain zircon population with detrital datasets from Paleogene, Carboniferous, and Devonian sedimentary units across Britain and Ireland (Figure 5).”
Line 156. Result consistent with known ice limits. Salisbury Plain lacks till, erratics and glaciectonic structures, tunnel valleys (the latter typical in chalk near Elsterian glacial limits in Harz, Germany). Even if the first glaciation of Salisbury Plain was Early Pleistocene traces of these features would survive in valleys. Your results support the Anglian glacial limit as the maximum Pleistocene glacial limit in south central England.	Agreed, if the Anglian glaciation was as severe as necessitated for Stonehenge megalith transport, a detrital remnant of this would persist in the stream sediments of Salisbury Plain.
Line 163. The answer is possibly. There are tens of metres of glacial sediment in places at the southern ice sheet limits in East Anglia and Germany. Cut this IMO	Done, this speculative section is removed.
Line 165 Now switch to the alternative hypothesis. To investigate other potential sediment sources and pathways...	Your earlier suggestion to move 154 assisted in explaining the hypotheses. See the edits above.
Line 185 Clarify. Is this 500 km long longshore drift during basin inversion? The Palaeogene drainage of Britain had the main rivers running W to E.	We have revised the text to describe the Palaeogene sediment routing better and to avoid implying an extensive (>500 km) longshore transport system. The revised version now notes that longshore drift along the southeastern margin of the Palaeocene proto-North Sea was likely limited in scale and acted in conjunction with local fluvial reworking within the London Basin, consistent with predominantly west-east Paleogene drainage. Please see our edits: “Alternatively, shorter-scale longshore drift and coastal reworking along the Palaeocene proto-North Sea margin transported northern detritus to the Thanet Formation and Chalk Groups (Gibbard et al., 2017).”
Line 195. Ubiquitous? Or common?	Common is a better word choice. Edit made.
Line 199 This argument is weak IMO and the paragraph can be deleted. A thin cover of till with those lithologies deposited at ~400 Ma would be strongly weathered at surface and only the most resistant clasts would survive. Weathering would be even more effective if the glaciation was older	We thank the reviewer for this suggestion. We have revised the sentence to emphasise the well-rounded, compositionally mature nature of the zircon-bearing sands, which provides a robust indicator of multicycle sedimentary recycling rather

	than direct glacial transport. The redrafted text now reads: “Moreover, the river sands contain no coarse-grained first-cycle lithic clasts (e.g., granite, gneiss, or mafic fragments) that would be expected if Laurentian zircon had arrived as primary erratic detritus. Combined with the well-rounded, compositionally mature nature of the zircon-bearing sands (Figure 4, Appendix 3), this indicates a history of multicycle sedimentary recycling rather than direct glacial transport.”
Line 272 Finish with no evidence for ice cover. Hence, megaliths were not glacially transported	Agreed, that is what our data shows. We have redrafted the conclusion: “This tectonically driven reworking provides a parsimonious alternative to glacial transport, explaining the presence of far-travelled fine detritus. There is no evidence for direct glacial cover or ice-sheet transport in this region, and consequently, we contend that Stonehenge’s megaliths were not emplaced by glacial processes.”
Figure 1. Add Anglian ice limit and ice flow lines. Is Amesbury correct?	Amesbury is correct. To our knowledge, there are no Anglian ice-flow models at the required scale, so we cannot use them to place ice flow lines and extent on Figure 1. Nor would ice-flow lines appear in the area covered by Figure 1.
Figure 5. Label axes	Labels have been placed on the outside of the axes for clarity.

Review 1 Comment	Response
I thank the authors for responding to my comments and for making substantive changes to the manuscript. The paper is now much improved. However, in attempting to address all of the reviewer comments, the authors have lost some of the sharpness of argument of the original manuscript. This is particularly evident in the introduction, which could be much more succinct. It is not my job to re-write the manuscript. I have suggested some areas where the text could be improved, but in reality, the introduction needs a careful review and edit to make the arguments about glacial vs. anthropogenic transport more forceful.	We thank the reviewer for their constructive assessment and for noting the improvements made to our manuscript. We have undertaken a careful review of the introduction and revised it to frame the contrasting hypotheses of glacial versus anthropogenic transport clearly.
My big concern remains that the authors still have not adequately explained how even one zircon grain of 464 Ma age could have got into the sediment around Stonehenge without some sediment input from Wales. This needs addressing otherwise it will provide low hanging fruit for anyone wanting to dismiss the findings.	Fair point, this warrants explanation. We have addressed this by adding the following to the discussion: “Isolated, outlier zircon are a feature of large n detrital datasets, reflecting the extreme durability and long multi-cycle residence times of zircon. Moreover, Darriwilian zircon is not unique to the Mynydd Preseli. Comparable ages occur sporadically in recycled Cenozoic sedimentary units across southern Britain, including the Thanet Formation. Thus, the most parsimonious explanation for this lone 464 Ma grain is its incorporation through multi-cycle sedimentary recycling from Cenozoic units, rather than the arrival of any sediment derived from the Mynydd Preseli”
Abstract – This is a classic case where addressing reviewer comments has weakened the flow of the argument. Surely, if there is even a single 464 Ma zircon age consistent with the Preselis (line 13-14) then – unless you can provide a plausible argument for how else this one zircon grain got into fluvial sediments around Stonehenge – you cannot “rule out” (line 19) glacial transport of the bluestones. As I pointed out in my initial review, you can weaken the glacial hypothesis considerably, but you can’t rule it out. The text here needs reviewing and editing.	We are limited by <i>Communications Earth and Environment</i> abstract constraints (<150 words). Nonetheless, please see our revised abstract: “How Stonehenge’s building blocks arrived on Salisbury Plain remains debated, with glacial and human transport mechanisms proposed. Here we test the possibility of Pleistocene glacial sediment input using grain-scale U–Pb fingerprinting of detrital zircon and apatite from modern stream sediments surrounding Stonehenge. Zircon ages span 3396–285 Ma, with age peaks at ~1090, 1690, and 1740 Ma, matching the Laurentian basement of northern Britain. Salisbury Plain detrital zircon ages match those of southern British rocks sourced from the London Basin, implying local sediment recycling rather than glaciogenic transport. Apatite ages of ~60 Ma reflect post-depositional U–Pb resetting, consistent with the distal effects of the Alpine orogeny. Collectively, our data show Salisbury Plain remained unglaciated during the Pleistocene, making direct glacial transport of Stonehenge’s megaliths unlikely.”
Lines 46-55 – for completeness, you need a sentence here about the former and remnant Paleogene cover.	We have added the following to the introduction: “Prior to Neogene erosion, Paleogene sediments once covered much of the Salisbury Plain plateau, with remnants persisting locally as relict deposits, including the Clay-with-Flints deposits²⁸⁻³⁰.”

Line 60 – “...transported to the Stonehenge area...” or “...transported to Salisbury Plain...” would be fairer.	“Stonehenge” replaced with “Salisbury Plain”.
Beyond Line 56, the introduction needs a bit of a rethink. In responding to reviewers, the authors have lost much of the thrust of their initial argument. For example...	Thank you for your suggestions. Please see our edits below.
Line 58-73 – this paragraph is muddled in its rewritten form. On the one hand you are saying there is no evidence for glaciation of Salisbury Plain while on the other you suggest it may have lain within the ice margin. “Absence of evidence not indicating evidence of absence” is one thing but on this reasoning, Southampton could have been within the Anglian limit. I think you could make your argument much more succinctly and more forcefully here. I suggest that you start with something like “Based on current evidence, it is difficult to prove or disprove if ice ever covered all or part of Salisbury Plain during the Anglian” and build from there.	We thank the reviewer for highlighting the potential ambiguity in this paragraph. We have revised the text, see below: “The absence, ambiguity, or inaccessibility of purported glacial features on Salisbury Plain hampers efforts to reconstruct potential ice flow and erratic transport pathways ^{35,37}. Thus, based on current evidence, it is difficult to prove or disprove whether ice ever covered all or part of Salisbury Plain during pre-Devensian glaciations. Nonetheless, the maximum extent of the Anglian Stage glaciation (ca. 478–424 ka) in central southern Britain remains poorly constrained ³⁸, although no diagnostic evidence demonstrates direct glacial incursion onto the Plain itself ^{34,36}.”
Line 74 – Again, you could be more forceful here. Start with “Geochemical data for detrital minerals offer a novel test of the competing “anthropogenic vs. glacial” transport hypotheses. If ice ever covered Salisbury Plain it would be expected to leave persistent and detectable provenance signatures, preserved in the landscape as indicators of sediment routing and crystalline source regions following ice retreat. Erratics and other glacially-transported sediments should have contributed a measurable...”	We have redrafted the paragraph to adopt the reviewer’s recommended opening and to present the argument more directly. “Geochemical data for detrital minerals offer a novel test of the competing hypotheses of anthropogenic versus glacial transport. If glacial erratics had reached Salisbury Plain, they would be expected to contribute a substantial ca. 464 Ma zircon population from Mynydd Preseli source rocks ⁴² in southwest Wales or Ganderian-Laurentian signatures from northern Britain to the local sediment budget (Figure 1). Given the Chalk’s low zirconium content, detrital zircon is unlikely to be locally derived. Instead, detrital zircon grains in stream sediment are more plausibly sourced from zircon-rich crystalline lithologies beyond the plain, with glacial processes representing one potential transport mechanism ⁴⁰. In contrast, apatite could plausibly derive from phosphorite horizons within the surrounding Chalk ^{43,44}. In any case, a combined zircon-apatite approach provides a more comprehensive means of distinguishing first-cycle from multi-cycle detritus and post-depositional processes ⁴⁵⁻⁴⁷.”
Line 88-93 – in the response to reviewers, the authors point out that this is one of the biggest zircon dating studies of this type for southern Britain – it might be worth stating that here.	Following journal recommendations, we wish to avoid superlatives.
Line 153 – “northern” would be better.	“North” replaced with “Northern”.
Line 156 – for clarity, perhaps say “Instead, East Avalonian and Megumian age modes...”	Done, “Instead, East Avalonian and Megumian age modes...” added.

Line 165 – for clarity, perhaps say “...the dearth of East Avalonian and Megumian	Done, “However, the dearth of East Avalonian and Megumian ages...” added.
Lines 170-173 – The firmness of the statements in this paragraph about the Anglian and Salisbury Plain is now out of line with what you say in the introduction – you need to cross-check and rephrase if necessary.	Good spot, we have redrafted the text in the conclusion, see: “Our results are consistent with the maximum southern extent of known ice-flow vectors for Pleistocene glaciations ^{38,60,61}. During the Anglian Stage, the most intense recent glaciation, ice margins are generally interpreted to the north of Salisbury Plain ³⁸. Furthermore, there is no unequivocal evidence that ice penetrated onto the plateau as the Salisbury Plain lacks undisputed tills, erratics, or other diagnostic indicators of glacial activity ⁶²⁻⁶⁴ that could evidence long-distance erratic transport or outwash of material from northern Britain. Even if glacial erratics and meltwater outwash had contributed minor volumes of sediment, the local Chalk is nearly devoid of zircon; therefore, any extraneous zircon input would strongly influence the river sand detrital zircon signature.”
Line 174 – you would strengthen your argument if you said “Even if glacial erratics and meltwater outwash had contributed...”	Done, “even if glacial erratics and meltwater outwash had contributed minor volumes of sediment” added.
Line 203 and throughout – Chalk is a proper name and should be capitalised.	“Chalk” capitalised.
Line 234-235 – for clarity state “...in our study...”	“From 550 U–Pb analyses in our study, a single concordant analysis...” added.
Line 234-236 – as stated above, you still need to give a plausible reason for why this one grain might be present.	Agreed. We have added the following to the discussion: “Isolated, outlier zircon are a feature of large n detrital datasets, reflecting the extreme durability and long multi-cycle residence times of zircon. Moreover, Darriwilian zircon is not unique to the Mynydd Preseli. Comparable ages occur sporadically in recycled Cenozoic sedimentary units across southern Britain, including the Thanet Formation. Thus, a single 464 Ma grain does not uniquely fingerprint a Preseli source”.
Line 238 – perhaps “...much more common...”	Ok, “much more common” added.
Line 281 – is there a word missing before Th/U?	Ok, “extremely low” added.
Line 303 – I assume you mean “liable”?	“liable” added.
Line 320-322 – the signature is rare but as critics will argue, it is there. You need another sentence to strengthen your conclusion. Surely, if ice of sufficient thickness to transport 80+ multi-tonne bluestone erratics from the direction of west	Ok. We have added the following to the conclusion: “If ice of sufficient thickness and extent had transported tens of large, multi-tonne bluestone erratics from west Wales to Salisbury Plain, it would

Wales had covered Salisbury Plain, you would expect to see a much stronger 464 Ma signature?	be expected to leave a pronounced Darriwilian zircon signature in the fine detrital fraction; its near absence instead indicates that such large-scale glacial transport did not occur".
Line 345-347 – again, if there is even one zircon grain that could be from the Preselis, I don't think you can be this forceful.	Fair point, the edited text below now reads: "This tectonically driven reworking provides a parsimonious alternative to sediment transport via glaciation, explaining the presence of far-travelled fine detritus that constitutes Salisbury Plain's detrital mineral spectrum; consequently, we consider glacial emplacement of Stonehenge's megaliths unlikely."
Line 350 – critics are going to say, "How can you base your conclusions on 4 samples?" You need to incorporate some of your response to my original review here to counter this.	Good suggestion. We have added the following to the discussion section: "The consistency of detrital zircon signatures between samples provides a robust regional detrital fingerprint signal, rather than sample-specific anomalies, across Salisbury Plain."

Review 2 Comment	Response
I am satisfied with the authors alterations to the manuscript and answers to reviews. The data collection and interpretation are all very clear and are likely close to the truth in my opinion. Figures are more useful. I have no major comments.	We appreciate your constructive review, which helped improve this contribution.
The only area I would emphasise more in this work is the fact that the absence of any old apatite in the detrital samples is extremely strong evidence against glacial transport, e.g. at the end of lines 300–306 I would add "...during multiple sedimentary cycles, and is inconsistent with first-cycle glacial detritus" or something more elegant to the same effect. It would not be possible to deliver old zircon recently without also delivering old apatite. It is obvious that the source is old and recycled/altered.	Good suggestion, we have added the following: "Such a decoupled zircon-apatite fingerprint for Salisbury Plain is inconsistent with first-cycle glacially-derived detritus, which would necessarily deliver zircon and apatite from crystalline sources."

Review 3 Comment	Response
The authors have dealt with the points raised in my earlier review. With one exception. I maintain that addition of the Anglian glacial maximum limit and general ice flow lines to the inset location map would help the reader to understand the glacial transport hypothesis and its difficulties.	We thank the reviewer for their positive assessment of our work. We have chosen not to add the Anglian limit (of which there is variability in ice extent and flow lines) to avoid cluttering the small inset map.