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Peer Review File

Estimating Earth's past field strength from individual sources in archaeological ceramics using Quantum Diamond Microscopy

Corresponding Author: Dr Ualisson Bellon

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

Version 0:

Decision Letter:

Dear Dr Bellon,

Thank you for submitting your manuscript titled "Microscale Pseudo-Thellier palaeointensity using a Quantum Diamond Microscope". Regretfully, we cannot publish it in Communications Earth & Environment.

It is our policy to decline a substantial proportion of manuscripts without sending them to referees, so that they may be sent elsewhere without further delay. Such decisions are made by the editorial staff when papers do not meet the criteria for publication in Communications Earth & Environment.

At this stage we consider, for example, whether a manuscript is likely to be of considerable interest to those working in the same area of the Earth, planetary and environmental sciences and to stimulate new thinking in the field. In this case, we are not persuaded that your findings represent a sufficiently striking advance to justify publication in Communications Earth & Environment. Please note, however, that we do not question the validity of your work.

As a service to our authors, we have also assessed potential suitability for consideration in Communications Sustainability, a new journal from the Nature Portfolio, but we have not found your article suitable.

Although we cannot offer to publish your manuscript, we believe the Editorial Board at Scientific Reports will find it interesting and recommend you transfer there. To transfer your manuscript there, please use our manuscript transfer portal. You will not have to re-supply manuscript metadata and files, unless you wish to make modifications. For more information, please see our manuscript transfer FAQ page.

We are sorry that we cannot be more positive on this occasion and thank you for the opportunity to consider your work.

Best regards,

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment
Communications Sustainability

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Bellon,

Your manuscript titled "Microscale Pseudo-Thellier palaeointensity using a Quantum Diamond Microscope" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns. Specifically, a revised manuscript must:

1. Fully clarify the bias field’s justification and provide robust evidence that it does not perturb ultra-soft or superparamagnetic grains during imaging.

2. Expand the discussion on anisotropy and grain interaction, ensuring these factors are addressed in the context of QDM’s model-dependence and inversion limitations.

3. Provide stronger support for the single-dipole assumption and include contextual data linking magnetic map features to specific minerals to enhance the technique’s reliability.

We hope you will find the reviewers' comments useful as you decide how to proceed. If additional work allows you to either incorporate or refute these criticisms, we will be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers’ comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors’ comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers’ comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Alireza Bahadori, PhD
Senior Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

EDITORIAL POLICIES AND FORMAT

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Summary: The authors report a full palaeointensity workflow using Quantum Diamond Microscopy (QDM) to analyze individual magnetic anomalies in an archaeological ceramic thin section, combining stepwise AF demagnetization, ARM acquisition, and IRM-based coercivity filtering with dipole-based inversions of QDM field maps. They propose that selectively inverted, well-behaved (dipolar) sources can yield palaeomagnetic directions that match bulk ChRM and intensities consistent with classical Thellier-Thellier results on sister samples (~44 μT when stringent statistical thresholds are used). In short, it establishes a non-heating, microscale Pseudo-Thellier pathway to potentially exclude problematic carriers that can often dominate bulk signals.

Measurements of AF demagnetization and ARM acquisition of the thin section were measured with a superconducting rock magnetometer. QDM maps were made at every AF/ARM step in two regions of the thin section. Filters were applied so that only well-behaved dipole signals were used to assess the magnetization of the sample.

The authors note that the benefits of this workflow include the avoidance of multidomain grains that might bias directional (and paleointensity) data. A comparison of the thin-section paleointensity using a Pseudo-Thellier technique using both SRM data and QDM data retrieves similar results when a goodness of fit of 0.8 is used. Increasing the goodness of fit threshold to 0.9 for the QDM data retrieves results similar to classical Thellier-Thellier values on sister samples. This is indeed very promising!

This manuscript shows that QDM-enabled, grain-selective Pseudo-Thellier can reproduce accepted palaeointensity values while avoiding common pitfalls of bulk/heating methods by excluding poorly behaved carriers. The work is methodologically careful and complementary to traditional approaches. Addressing three points—(i) the bias-field effect, (ii) anisotropy handling, and (iii) generality beyond ceramics—would substantially enhance its impact and robustness.

ARM-TRM equivalency: The elephant in the room is the equivalency of ARM techniques, and if they adequately replicate TRM acquisition in natural samples. The workflow is intended to use QDM to track remanence changes at a particle level during the Pseudo-Thellier methods, a less destructive means of acquiring paleofield information by isolating ideal magnetic recorders.

However, the Pseudo-Thellier approach presumes a proportionality between ARM coercivity spectra and TRM blocking-temperature spectra. As written, the manuscript acknowledges that the current calibration factors are calculations are empirical with sizable uncertainty and that no analytical framework exists for vortex-state TRM. The authors mitigate the imperfect ARM–TRM equivalence by (i) selecting only well-behaved sources and (ii) focusing on directional statistics. Still, the equivalence is an approximation, not a law.

The workflow is intended to use QDM to track remanence changes at a particle level during the Pseudo-Thellier methods, a less destructive means of acquiring paleofield information by isolating ideal magnetic recorders. Much of the work presented is reliant on non-thermal methodologies. Thermally driven paleointensity techniques (Thellier-Thellier being the classic example) often have high failure rates, complicated by domain states within the samples. The authors advocate for microscale Pseudo-Thellier experiments via QDM tracking, coercivity via IRM sign tests, and behavioral screening during AF/ARM, statistics and micromagnetic modeling.

However, to convince those that are Thellier-faithful that this is a better way to measure paleointensity will require more effort. I will outline potential issues with the technique that I believe need to be further addressed as caveats of the technique.

QDM vs Discrete samples: I cannot comment on the inversion method used for the magnetic anomalies within the thin section and the windows surveyed, or the statistics used for the goodness of fit. However, QDM analyses are model-dependent, and inversion techniques are not the same as the use of discrete samples for analysis. Potential advantages of the workflow of a QDM-based micropaleomagnetism technique include the isolation of individual magnetic carriers, allowing for filtering of problematic grains – ones that are multidomain, have a high coercivity, or demonstrate non-dipole behavior. The authors note that there is the potential to reduce the failure rates common to heating-based methods.

QDM imaging is performed under a non-zero bias field (reported as 0.9 mT, periodically reversed to an effective ~400 nT) to read out NV centers and define the quantization axis. The manuscript describes field reversal and processing to isolate the sample's stray field in projected magnetic microscopy mode. However, it does not analyze whether this bias field could perturb ultra-soft, low-coercivity, or superparamagnetic grains during imaging. While practical safeguards (R^2 filtering, IRM-based coercivity screening, invisibility of SP grains to static stray-field mapping) likely limit bias-induced artifacts in the retained dataset, an explicit justification or control is absent and would strengthen the methodology section.

Utility for natural samples: The study uses a single archaeological ceramic thin section (17th-century kiln-fired tile fragment). Ceramics, because they are (mostly) uncomplicated, are good for a proof of concept. I am not convinced - at this stage - that the approach is transferable to natural materials (basalts, samples with complicated geologic histories). The manuscript could benefit from a more explicit analysis of how source density, grain interactions, and anisotropy fabrics influence the fidelity of QDM-based palaeointensity beyond ceramics.

Anisotropy: Where this method is inadequate - for now - is in addressing anisotropy of TRM acquisition. The inversion does not model anisotropy explicitly; it assumes dipoles. Anisotropy manifests indirectly (e.g., ARM directions failing to fully align with the applied field even at 100 mT; outliers at specific AF steps) and is addressed by filtering or interpretive caution, not by tensor-level corrections. The authors do note that remanence anisotropy likely remains significant, and that future applications would benefit from explicit anisotropy corrections and/or micromagnetic constraints.

Strengths of the manuscript:
- Demonstrates end-to-end, microscale Pseudo-Thellier using QDM with robust filtering and MC uncertainty propagation.
- Achieves directional and intensity agreement with bulk and Thellier–Thellier results on sister samples—bridge-building rather than adversarial.
- Provides a transparent workflow and figures illustrating the effect of R^2 thresholds and filtering on outcomes.

Limitations:
- Model dependence (dipole assumption; depth/standoff sensitivity; no direct domain-state/geometry).
- No explicit anisotropy correction; anisotropy is mitigated by selection/statistics rather than modeled.
- Bias-field safety vis-à-vis ultra-soft or SP grains is not discussed, leaving a methodological gap that could be closed with analysis or controls.
- Generality beyond ceramics is asserted but not systematically evaluated across diverse lithologies.

Recommendations for Revisions/Extensions.
- Add a compact bias-field justification (order-of-magnitude argument and/or a control demonstrating anomaly stability across bias reversals or magnitudes).
- Include an explicit anisotropy discussion (when ARM fails to align; what corrections or pre-screening are advisable).
- Clarify the limits of the dipole model and provide guidance on when to employ QDM + tomography.
- Outline a roadmap for micromagnetic calibration (Tb–Bcr relationships; size/shape distributions; potential use of FORC-informed priors).
- If feasible, add a second material case (e.g., a basalt thin section) to gauge generality.

Reviewer #2 (Remarks to the Author):

This is a well-timed and relevant manuscript that aims to develop a quantum diamond microscopy (QDM) data inversion technique to enable reliable high-resolution paleomagnetic studies. Other papers by some of the authors (some already published, a few under review) present adaptations of Euler deconvolution and single-dipole fitting, which form the basis of the technique, but focusing mostly on recovering robust paleomagnetic directions from QDM data. Here, the authors attempt to extract quantitative information about the strength of the paleomagnetic field by summing the recovered net magnetic moments of a large number of individual dipole-like sources. The strength of this technique stems from its presumed ability to identify and isolate the magnetic signal of high-fidelity magnetic recorders, using only those in the retrieval of paleomagnetic records. This would improve such records compared to estimates obtained from bulk measurements of rock samples, which integrate the contributions of every magnetic grain present in the sample irrespective of their magnetic recording capabilities.
Although the reasoning provided for some of the assumptions made is sound, other suppositions are not well justified and require further elaboration and discussion. For instance, it is stated that one of the key advantages is that the technique relies solely on magnetic data and does not require additional time-consuming measurements such as micromagnetic tomography data. However, the lack of any contextual data (e.g., petrographic images, compositional maps, tomography data) that relate features visible in a magnetic map to specific magnetic minerals/grains is a major weakness of the technique in its current form. This makes it unlikely that grains with superior magnetic fidelity are being properly identified, and those with poor magnetic fidelity are being effectively filtered out by the processing. In turn, this would bring into question the significant additional effort associated with collecting and processing magnetic microscopy data only to arrive at a result that is, at best, comparable to those obtained from bulk measurements.
The reliance on whether a source is well-represented by a single dipole as an indication of its quality as a magnetic recorder is highly debatable, and a thorough justification for this assumption should be provided. The goodness-of-fit criterion used

essentially measures how well their simple single-dipole model reproduces an isolated feature in the magnetic map and, in principle, bears no direct relation to whether the underlying grains are effectively good paleomagnetic recorders (e.g., dipolar sources that exhibit large directional swings at every AF demagnetization step, even at low levels, are frequently observed in QDM maps and indicate poor magnetic recording properties despite being dipolar). In particular, the exclusion of clusters of small grains due to their multipolar nature may very well remove from the analysis the very sources that could be most reliable (e.g., a concentration of single-domain grains with its expected directional dispersion -- even if one were to assume that poor recorders have a multipolar magnetic signature, which has not been established, it would not mean that every multipolar source is a poor recorder).
Moreover, the argument that the confidence interval (CI) for the paleointensity produced by the technique is better because it is closer to that obtained from bulk thermal experiments seems to rely on contradictory arguments: (i) How would those same poor magnetic recorders that were supposedly eliminated from the new paleointensity estimate not produce the same pernicious effects on the CI obtained from the Thellier experiment using bulk measurements? (ii) Given that the ARM-TRM calibration factor was also obtained from bulk measurements, which included the poor magnetic recorders, how is it possible that the paleointensity estimation from QDM data has better accuracy when it uses the same calibration? (iii) By discarding the magnitude of the individual particle moments, would not this bias the analysis toward weakly magnetic minerals while minimizing the contributions of strongly magnetic minerals such as magnetite, in effect favoring a category of poor recorders?
In closing, this technique is quite promising and may enable robust quantitative paleomagnetic studies at very fine spatial scales. With the increasing number of quantum diamond microscopes in paleomagnetism and rock magnetism laboratories, reliable quantitative analytical techniques are in great demand to take full advantage of high-resolution magnetic microscopy and tackle novel science questions. Nevertheless, further clarification and/or refinement of some aspects of the technique are needed to effectively establish its accuracy and scope of applicability.

Version 2:

Decision Letter:

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Dear Dr Bellon,

Your revised manuscript titled "Microscale Pseudo-Thellier palaeointensity using a Quantum Diamond Microscope" 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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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alireza Bahadori, PhD
Senior Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I appreciate the authors' substantial efforts in revising the manuscript and providing extensive new analyses, including focused ion beam (FIB) nanotomography, particle-orientation statistics, and micromagnetic modeling. These additions significantly strengthen the paper, particularly in clarifying the nature of non-dipolar anomalies and the role of anisotropy in the studied ceramic sample. The manuscript is now clearer, more rigorous, and more transparent about its methodological limitations.

Nearly all of my concerns were addressed by the authors, and I appreciate the effort. This is a proof-of-concept paper, after all, and not everything can be adepquately addressed.

My original comment requested an explicit justification or control demonstrating that the QDM bias field (0.9 mT, reversed to 400 nT) does not perturb ultra-soft, low-coercivity, or superparamagnetic grains during imaging.

In the revised manuscript and supplementary material, the only statement remains:

"A bias magnetic field of 0.9 mT was applied during acquisition, periodically reversed to yield an effective net bias field of 400 nT."

The rebuttal letter states a good argument/response to my query. I think a statement summarizing that initial response either in the main text or in the supplement would be an asset and my only suggested change to the manuscript as it stands.

Reviewer #2 (Remarks to the Author):

This revised manuscript adequately addresses several issues previously raised by the reviewers. It includes new SEM-EDS data using FIB tomography to investigate a region in the thin section with complex magnetization patterns that was excluded by their quality criteria, which helps elucidate some questions. Therefore, my recommendation is for the publication of the manuscript in its present form.

Dear Editorial Board

We are grateful for the opportunity to have our paper considered for peer review. In the responses below, we have numbered each of the points raised by the reviewers (in red), followed by our replies. Some of the revisions made to the manuscript are quoted here (in blue) after each response, while most additional changes are also highlighted in the tracked changes version of the main text. We believe that we have addressed the reviewers' concerns adequately and that our main conclusions remain unchanged. The revised manuscript does, however, include substantial new material, notably focused ion beam (FIB) tomography to further investigate the nature of the magnetic particles we observe, followed by micromagnetic modelling to support our interpretations. As a result of these additions, we have included an additional co-author who contributed to the acquisition and processing of the FIB data.

Our sincere best wishes,

Reviewer 1

Dear reviewer 1,

We are pleased to read your positive comments about our paper and, more importantly, to allow us to address your concerns. Please note that we have separated your comments into topics so it is easier to reply to them. We hope to have satisfied all of your queries.

Best wishes,

The authors.

1. QDM vs Discrete samples: QDM imaging is performed under a non-zero bias field (reported as 0.9 mT, periodically reversed to an effective 400 nT) to read out NV centers and define the quantization axis. The manuscript describes field reversal and processing to isolate the sample's stray field in projected magnetic microscopy mode. However, it does not analyze whether this bias field could perturb ultra-soft, low-coercivity, or superparamagnetic grains during imaging. While practical safeguards (R^2 filtering, IRM-based coercivity screening, invisibility of SP grains to static stray-field mapping) likely limit bias-induced artifacts in the retained dataset, an explicit justification or control is absent and would strengthen the methodology section.

Response: Indeed, we do not explore the effect of ultrasoft magnetic particles. However, several important points should be noted. First, superparamagnetic (SP) particles have such small volumes and magnetic moments that even sensitive QDM measurements would struggle, if not fail, to detect them with the current setup. Magnetic field intensity decays rapidly with distance; for dipolar anomalies, it decreases with the cube of the distance between the particle and the observation point. In our measurements, the sensor is positioned at the sample surface, typically about 5 µm away from the magnetic sources. In a recent paper, we demonstrated that even single-domain (SD) particles are extremely challenging to detect at this distance because of both signal attenuation and noise [1]. This difficulty is even greater for clusters of SD particles, and more so for SP particles, whose effect we therefore consider negligible. In addition, both classical Néel single-domain theory [2] and more recent micromagnetic studies [3–5] have shown the relationship between increasing grain size and coercivity. For multidomain magnetite particles, where such an ultrasoft regime may be expected, there is no guarantee that the paleomagnetic information is reliable. Finally, because SP particles do not contribute to remanence – and their signal would in any case have low coercivity – they are screened out by our analysis protocols.

2. Utility for natural samples: The study uses a single archaeological ceramic thin section (17th-century kiln-fired tile fragment). Ceramics, because they are (mostly) uncomplicated, are good for a proof of concept. I am not convinced - at this stage - that the approach is transferable to natural materials (basalts, samples with complicated geologic histories). The manuscript could benefit from a more explicit analysis of how source density, grain interactions, and anisotropy fabrics influence the fidelity of QDM-based palaeointensity beyond ceramics.

   Response: We understand the reviewer's concerns. Ceramics are indeed an excellent target for archaeomagnetic protocols using QDM because, in the limited examples reported so far in the literature, they can display spatially well-resolved magnetic anomalies. The reviewer suggests that we test the approach on a rock sample, or on more complex lithologies. The scope of the present study is to provide a proof of concept for a complete pseudo-Thellier protocol using QDM. Extending the manuscript to include a different sample type would therefore be both beyond the intended scope and unfeasible at this stage. That said, in another recently published paper [6], although we did not perform a full palaeointensity protocol, we showed that for a basalt thin section with densely distributed anomalies, our dipole-only inversion with filtering criteria was able to recover the same NRM measured in a classical rock magnetometer. This already addresses, at least in part, the question of applicability to other geological materials. In addition, another study is currently in preparation presenting the recovery of a full Thellier–Thellier protocol using both ceramic and basalt samples, which further explains why this aspect is outside the scope of the present pseudo-Thellier paper. More generally, issues related to source density, grain interactions, and clustering have already been explored in another recent publication [1]. Our objective here is not to focus on the theoretical framework, but rather to provide an empirical demonstration of the method in a proof-of-concept paper for a communications journal.

3. Anisotropy: Where this method is inadequate - for now - is in addressing anisotropy of TRM acquisition. The inversion does not model anisotropy explicitly; it assumes dipoles. Anisotropy manifests indirectly (e.g., ARM directions failing to fully align with the applied field even at 100 mT; outliers at specific AF steps) and is addressed by filtering or interpretive caution, not by tensor-level corrections. The authors do note that remanence anisotropy likely remains significant, and that future applications would benefit from explicit anisotropy corrections and/or micromagnetic constraints.

   Response: We appreciate the reviewer's point and agree that remanence anisotropy is an important consideration, as noted several times in the manuscript. However, we would like to clarify that the degree of multipolarity is not necessarily tied to whether a particle or assemblage exhibits anisotropic behaviour. Stray fields produced by highly non-uniformly magnetised particles may still appear predominantly dipolar at the measurement height because higher-order field components decay more rapidly with distance. This is a general physical principle, and the use of a dipolar fit does not inherently imply that anisotropic behaviour is being neglected. In fact, the dipolar component carries most of the field strength at the measurement plane, even for sources that are internally highly non-dipolar [1, 7].

   That said, we have explored this issue further by performing focused ion beam (FIB) tomography (new figure 5) in a region associated with a highly non-dipolar anomaly that was not inverted by our model. Our new particle analysis confirms that, as suggested in the manuscript, the magnetic fabric is indeed anisotropic and that anisotropy corrections would be valuable in future work. **The reviewer can find this discussion in the new section added to the paper**.

   At the same time, we would like to stress that this is not the main objective of the present study. The central result of this paper is that, empirically, we demonstrate the first full pseudo-Thellier protocol using a QDM, showing that it can reproduce classical SRM measurements while also offering much greater spatial selectivity. In particular, individual anomalies can be chosen, signals can be analysed separately, and inconsistent behaviour can be identified directly. **There is, in principle, nothing preventing the application of a full anisotropy tensor correction in future work.** However, this was not part of the original experimental design of the present study, which is already methodologically broad, and it is no longer possible with this sample because, after application of a 2.7 T IRM, AF demagnetisation can no longer be performed.

"The area selected for FIB tomography lies within a strongly non-dipolar region that is not resolved by our dipolar fitting. Any anomaly detected there would therefore have been excluded by our filtering process. Our aim was to understand what kind of information is being omitted and to use this opportunity to better visualise the remanence carriers in our samples. SEM-EDS of the scanned region (Supplementary Figure S8a) reveals a texturally complex sample, dominated by a silicate matrix with more well-defined anhedral silicate crystals ranging from 2 to 50 µm. Iron oxides, here interpreted as magnetite, also occur at the surface as anhedral particles, with the most prominent grains reaching around 5 µm, although some are as small as 1 µm (Supplementary Figure 8b). Titanium oxides (Supplementary Figure 8c) are also distributed across the imaged region and in some cases coexist with iron, suggesting the presence of titanomagnetite-series minerals within the sample. From 948 serial slice images, segmentation of the processed dataset allowed us to isolate n = 1880 highly dense particulates, which we interpret as the magnetic particles (Figure 5a).

We performed PCA on the external coordinate cloud of each particle to determine its maximum, intermediate, and minimum dimensions. We detected particles ranging in size from the resolution limit (approximately 0.015 µm) up to 3 µm. Most particles, however, form a left-skewed distribution with a mean of approximately 0.170 µm (Figure 5b), with most of the distribution falling between 0.10 and 1 µm. To better quantify particle morphology, we use the aspect ratio (AR). For prolate particles, AR is defined as the maximum elongation divided by the minimum elongation, yielding values greater than 1. For oblate particles, AR is defined as the minimum elongation divided by the maximum elongation, yielding values smaller than 1. A spherical or equidimensional particle would therefore have an aspect ratio close to 1. The imaged region shows a fairly even distribution of oblate and prolate particles (Figure 5c). Most oblate particles are only moderately flattened, and similarly most prolate particles are only moderately elongated. Nevertheless, strongly oblate and strongly prolate particles are also present. By converting these directions into azimuth and plunge, we can evaluate the general orientation of the imaged particles (Figure 5d). The stereograms show a broad dispersion in the directions of the particles' major axes. However, the maximum elongation axes also display a marked vertical clustering (Figure 5d), indicating that a strong fabric control may also be present. This observation reinforces our interpretation that anisotropy corrections, for example through calculation of the full anisotropy of remanence tensor, are likely necessary for archaeomagnetic materials such as ceramics, as also suggested by Poletti *et al.* [8]."

4. Model dependence: dipole assumption; depth/standoff sensitivity; no direct domain-state geometry.

Response: The use of dipolar fits in magnetic microscopy is well established [6, 9–11]. There is nothing in the underlying physics that precludes applying this approach to QDM data. The key requirement is instead to identify which anomalies are adequately described by a dipolar field. This is precisely the point we emphasise throughout the paper: only anomalies that are well explained by a dipolar model are retained for interpretation. In this context, the coefficient of determination provides a direct measure of how well the observed anomaly is described by the calculated dipolar field. If an anomaly cannot be explained satisfactorily as a dipole, we do not use it.

For most stable, isolated magnetite particles, a dipolar anomaly is the expected signature at typical measurement heights. As shown by Bellon *et al.* [1], introducing higher-order multipolar terms for anomalies that are already strongly dipolar provides only limited improvement when fitting noisy experimental data. Likewise, the effects of depth and stand-off distance are not ignored here; they are explicitly treated in the numerical framework underlying this study and have been explored in detail in our previous work [1, 6, 11]. The main limitation is therefore not the use of a dipolar model itself, but rather that non-dipolar anomalies are not incorporated into the present inversion. Such anomalies may arise for several reasons, including: (i) non-uniform magnetisation states observed at very short distances from small particles, (ii) superposition of stray fields from nearby but unresolved sources, and (iii) contributions from multidomain grains at variable depths. Inversion of such signals would require much stronger prior constraints, including accurate source positions, sufficient spatial resolution and sensitivity to resolve all relevant contributors, and noise levels low enough to preserve the higher-order field terms. In practice, this is a demanding problem and the solutions can easily become non-unique. For this reason, we focus here on the subset of anomalies that can be robustly treated within a dipolar framework. As noted in the Discussion, methods such as MMT could in future be combined with our workflow to target selected non-dipolar anomalies in specific cases.

The new micromagnetic simulations (new figure 6) based on the FIB data further highlight why this distinction matters. They show that highly non-dipolar anomalies may still contain contributions from stable particles, but that these signals can be dominated by larger multidomain grains. In such cases, even if some stable carriers are present, the inverted signal would be strongly biased toward the contribution of the less stable multidomain particles. More generally, direct inversion of domain-state geometry from QDM data is still not fully achievable at present. QDM data can provide constraints on possible source configurations, but recovering the full internal domain structure remains an open research problem.

5. No explicit anisotropy correction; anisotropy is mitigated by selection/statistics rather than modeled.

   Response: As noted above, we do not apply an explicit anisotropy correction in the present study because the purpose of this paper is to provide an empirical proof of concept. The existence of remanence anisotropy, and its potential importance for interpretation, was already acknowledged in the first version of the manuscript. In the revised version, we further emphasise this point using the new FIB data and the associated particle-orientation analysis, which confirm that anisotropy is likely significant in this sample. At present, there is no single mandatory correction strategy for this type of problem, and several approaches could in principle be considered [8, 12]. Indeed, one could even envisage a protocol in which anisotropy corrections are applied on an anomaly-by-anomaly basis, rather than uniformly at the whole-sample scale. However, developing and validating such a framework lies beyond the scope of the present contribution.

   We therefore agree that anisotropy is not explicitly modelled here, but we do not consider this a flaw that undermines the main result of the paper. The central objective of this study is to demonstrate that a full pseudo-Thellier workflow can be implemented empirically using QDM data, and that this approach allows much more selective interrogation of magnetic signals than conventional bulk measurements. Explicit anisotropy correction is an important next step, but not a prerequisite for establishing the proof of concept presented here.

6. Bias-field safety vis-à-vis ultra-soft or SP grains is not discussed, leaving a methodological gap that could be closed with analysis or controls.

   Response: We reply to this in the first topic of our responses.

7. Generality beyond ceramics is asserted but not systematically evaluated across diverse lithologies.

   Response: We reply to this in the second topic of our responses.

Reviewer 2

Dear Reviewer 2,

We would like to sincerely thank you for your comments. We have organized our responses into different topics below in order to address your concerns more clearly and thoroughly. We hope that we have satisfactorily addressed all of your concerns.

Best wishes,

The authors

1. Although the reasoning provided for some of the assumptions made is sound, other suppositions are not well justified and require further elaboration and discussion. For instance, it is stated that one of the key advantages is that the technique relies solely on magnetic data and does not require additional time-consuming measurements such as micromagnetic tomography data. However, the lack of any contextual data (e.g., petrographic images, compositional maps, tomography data) that relate features visible in a magnetic map to specific magnetic minerals/grains is a major weakness of the technique in its current form. This makes it unlikely that grains with superior magnetic fidelity are being properly identified, and those with poor magnetic fidelity are being effectively filtered out by the processing. In turn, this would bring into question the significant additional effort associated with collecting and processing magnetic microscopy data only to arrive at a result that is, at best, comparable to those obtained from bulk measurements.

Response: We thank the reviewer for this important comment and agree that, in its present form, our method does not robustly link each magnetic anomaly to a specific magnetic recorder in the same way that MMT potentially can. We acknowledge this limitation in the manuscript and discuss it alongside the advantages of the method. In particular, we agree that, for selected cases, the most robust approach would be to combine our inversion method with MMT.

That said, our method does not preclude a more classical magnetic mineralogy workflow, including further inspection through petrography and electron microscopy. To address some of these concerns, we performed focused ion beam tomography and SEM–EDS analyses on particles located within a region characterized by highly non-dipolar anomalies (see Supplementary Figure 8 for the experimental setup). These observations show that most particles in that region fall within the 1–1000 nm size range (Figure 5b), which is generally consistent with high magnetic stability. At the same time, larger multidomain grains are also present in the sample, and our estimates indicate that, in this highly non-dipolar region, their magnetic contribution can dominate over that of the smaller grains (Figure 6c).

Therefore, we agree with the reviewer that removing non-dipolar anomalies may also remove part of the stable magnetic signal. However, this must be weighed against several practical limitations: the dominance of stronger signals, the spatial resolution limits of the QDM, the decay of magnetic field strength with particle volume and distance, and the presence of noise. Together, these factors can make the inversion of magnetic domain structure and magnetic moments highly non-unique. For this reason, filtering strongly non-dipolar anomalies remains a practical step in the current implementation of the method.

2. The reliance on whether a source is well-represented by a single dipole as an indication of its quality as a magnetic recorder is highly debatable, and a thorough justification for this assumption should be provided. The goodness-of-fit criterion used essentially measures how well their simple single-dipole model reproduces an isolated feature in the magnetic map and, in principle, bears no direct relation to whether the underlying grains are effectively good paleomagnetic recorders (e.g., dipolar sources that exhibit large directional swings at every AF demagnetization step, even at low levels, are frequently observed in QDM maps and indicate poor magnetic recording properties despite being dipolar). In particular, the exclusion of clusters of small grains due to their multipolar nature may very well remove from the analysis the very sources that could be most reliable (e.g., a concentra-

tion of single-domain grains with its expected directional dispersion – even if one were to assume that poor recorders have a multipolar magnetic signature, which has not been established, it would not mean that every multipolar source is a poor recorder).

Response: We agree with the reviewer and have now highlighted in the revised results that good magnetic recorders may be excluded when non-dipolar anomalies are removed. Our reliance on dipolar sources derives solely from the ability of our models to predict their magnetic moments, which has been demonstrated both numerically [6, 11] and now empirically, as we recover results comparable to those obtained using classical rock magnetometers. By contrast, highly non-dipolar anomalies are inherently more complex and may arise from a variety of different circumstances. We have nonetheless also added a note clarifying that a dipolar signal does not necessarily guarantee a good magnetic recorder:

"It is important to note, however, that a dipolar anomaly, although more readily resolved numerically, does not necessarily imply magnetic stability. Owing to the decay of the stray field with distance, even MD grains may generate apparently dipolar anomalies, meaning that the inclusion of such signals could introduce poor magnetic recorders into the dataset. Nevertheless, the relatively low coercivity of MD grains suggests that these signals are likely to be removed rapidly during AF demagnetisation and to be readily magnetised in low AF fields during ARM acquisition. Because our method enables the same anomalies to be tracked across successive steps, such behaviour can, in principle, be recognised and flagged. In this respect, our inversion approach offers a level of control and signal analysis at the thin-section scale that cannot be achieved using bulk rock measurements."

3. Moreover, the argument that the confidence interval (CI) for the paleointensity produced by the technique is better because it is closer to that obtained from bulk thermal experiments seems to rely on contradictory arguments: (i) How would those same poor magnetic recorders that were supposedly eliminated from the new paleointensity estimate not produce the same pernicious effects on the CI obtained from the Thellier experiment using bulk measurements?

Response: We recognise that we need to clarify that our inverted estimate is not better than the bulk result merely because it is closely aligned with the bulk thermal experiments, and we have therefore included the following statement:

"It should also be noted that showing that our R^2 values for well-resolved anomalies (> 0.9) are in close agreement with those observed in bulk heating Thellier–Thellier experiments does not necessarily guarantee that we are isolating only the best magnetic recorders, since, ultimately, nanoscale tomography would be required to establish that directly. In principle, the same poorly behaving magnetic minerals may therefore be present in both our microscopy-based method and the corresponding bulk measurements. However, we deliberately selected this sample because results from its sister sample [13] have already shown it to exhibit exceptionally good thermal behaviour; poor recorders would instead be expected to produce heating tails [14, 15] or strongly non-linear behaviour in the Arai plot. Furthermore, unlike bulk measurements, our approach offers the potential to track individual anomalies and thereby identify instabilities during demagnetisation/magnetisation directly."

4. (ii) Given that the ARM-TRM calibration factor was also obtained from bulk measurements, which included the poor magnetic recorders, how is it possible that the paleointensity estimation from QDM data has better accuracy when it uses the same calibration?

   Response: We agree that this represents an important limitation. We do state that the ARM–TRM correction factor could, in principle, be better constrained, although this falls beyond the scope of the present study. Under the current framework, the relatively large uncertainty associated with this correction factor causes the paleointensity estimates obtained for the $R^2 > 0.8$ and $R^2 > 0.9$ subsets to overlap. Nevertheless, the results indicate that restricting the analysis to anomalies that are especially well resolved numerically may provide a route towards improved precision, as the estimated values tend to shift towards higher values. At present, however, we are limited by the number of sources that are sufficiently well resolved. As we discuss in the manuscript, including additional maps would provide more high-quality data and a broader basis on which to test this possibility.

   In principle, one could also perform an AARM measurement on the thin section afterwards in order to derive a correction parameter for each anomaly. More generally, even when the correction factor is obtained from bulk measurements, there may be better prospects for improving it by considering the expected behaviour of the particles that dominate the stable results, particularly the smaller grains, for example through FORCINN + micromagnetic models or tomography + micromagnetic models, than with the current approach.

5. (iii) By discarding the magnitude of the individual particle moments, would not this bias the analysis toward weakly magnetic minerals while minimizing the contributions of strongly magnetic minerals such as magnetite, in effect favouring a category of poor recorders?

   Response: First, we would like to clarify that, based on well-established estimates of the magnetic moment of magnetite [16] and the corresponding stray fields they produce [1], the magnetic signal from magnetite particles is, in principle, sufficiently strong that even a single-domain magnetite grain may be resolved by QDM [9]. In practice, however, detectability is also limited by source-to-sensor distance, spatial resolution, and measurement noise, which make the smallest particles difficult to observe unless they are located very near, or at, the surface. Nonetheless, single-vortex and multivortex states may still be detected provided that they are not too deep and may be particularly detectable when particles occur in clusters [1]. By contrast, more weakly magnetic minerals must generally be substantially larger than magnetite in order to be detected, since their magnetic moments are typically orders of magnitude smaller and they therefore produce much weaker stray fields. For this reason, discarding the magnitudes of the individual particle moments does not necessarily bias the analysis towards weakly magnetic minerals. In addition, the coercivity of individual magnetic anomalies can be tracked and used as a more direct indicator of magnetic stability. As we show in this study, coercivity-based filters can therefore also be used to identify and exclude poor recorders, for example by removing anomalies below or above a given coercivity threshold, depending on the objective of the analysis.

   Finally, we do consider that the inverted moment magnitudes themselves could be used in future analyses. We chose not to do so here because the present study includes only two maps, which limits the robustness of such filtering. With a larger dataset, one could analyse the distribution of inverted moment directions and magnitudes more thoroughly and test the effects of different filtering strategies, for example by retaining only anomalies within one or two standard deviations of the median, while explicitly evaluating any bias introduced by preferentially excluding stronger signals.

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Dear Editorial Board

Once again, we are grateful for the opportunity to provide the final revisions to our manuscript.

We have revised the title and abstract to better reflect the journal's broad scientific readership, and we have included the statement on superparamagnetic particles requested by Reviewer 1.

We have also addressed the remaining technical editorial recommendations. In the responses below, we have numbered the point raised by Reviewer 1 (in red), followed by our reply. Revisions made to the manuscript are quoted here (in blue), while the additional changes are also highlighted in the tracked changes version of the main text.

We believe that the manuscript is now ready for publication in its present form, but we would be happy to make any further adjustments if required.

Our sincere best wishes,

Dear Reviewer 1,

Thank you once more for you assessment. As requested, we have included a statement on our perspective over the contribution of superparamagnetic particles in our data.

Best wishes,

The authors.

1. My original comment requested an explicit justification or control demonstrating that the QDM bias field (0.9 mT, reversed to 400 nT) does not perturb ultra-soft, low-coercivity, or superparamagnetic grains during imaging. In the revised manuscript and supplementary material, the only statement remains: "A bias magnetic field of 0.9 mT was applied during acquisition, periodically reversed to yield an effective net bias field of 400 nT." The rebuttal letter states a good argument/response to my query. I think a statement summarizing that initial response either in the main text or in the supplement would be an asset and my only suggested change to the manuscript as it stands.

Response: We have now explicitly state our perspective over the influence of SP particles in our QDM data.

"Ultra-soft superparamagnetic particles are unlikely to contribute significantly to our quantum diamond microscope measurements. Their small volumes and magnetic moments make them difficult to detect at the sensor–sample distances used here, typically around 5μm from the magnetic sources. Because dipolar fields decay with the cube of distance, these signals are strongly attenuated before reaching the sensor. We have previously shown that even single-domain particles are extremely challenging to detect under similar conditions [1]; superparamagnetic particles should therefore have a negligible effect on the measured anomalies."

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