

## Proposed identification criteria of the Martian lower crust and mantle excavated by the Isidis impact.

Corresponding Author: Dr Alexander Trowbridge

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

Version 0:

Decision Letter:

Hi Joao,

I forgot to BCC you into this decision letter when I sent it "Excavation of lower crust and mantle by Isidis impact, Mars: deposition in circum-Jezero".

FYI I agree with your Revise decision and have just adapted the Editorial thresholds slightly.

Cheers,  
Joe

**\*\* 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 Trowbridge,

Please allow us to apologise for the delay in sending a decision on your manuscript titled "Excavation of lower crust and mantle by Isidis impact, Mars: deposition in circum-Jezero". It has now been seen by 2 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 points and assess a revised manuscript before we make a final decision on publication.

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. In the revise version please make sure to:

- i) Present a robust comparison between the model and the natural example, including strong justification for the choice of impact angle and its implications, discussion of the model's uncertainties and other comparable examples.
- ii) Adapt your interpretations by taking into account the discrepancies between observations and your model, such as the lack of mantle material observed at Jezero.
- iii) Incorporate the limitations associated with sampling constraints and how your results can inform decision-making about future sampling locations.

Please submit your point-by-point 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.

We are committed to providing a fair and constructive peer-review process. Please don't 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 referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

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,

Joao Duarte, PhD  
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Communications Earth & Environment  
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Joe Aslin  
Deputy Editor  
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## REVIEWER COMMENTS:

### Reviewer #1 (Remarks to the Author):

This study aims to provide guidance for the Perseverance rover in sampling ejecta deposits from the Isidis impact crater near the Jezero crater, thereby offering an opportunity to investigate the interior mineralogy and composition of Mars. It proposes a methodology for determining whether the shock metamorphic features of the extracted materials originate from excavated deep crustal and mantle materials, while effectively excluding potentially confounding impact products from the Jezero crater. The research addresses a significant topic and demonstrates notable innovation. However, improvements in model validation, key assumptions, and scholarly context are necessary to robustly support its core conclusions. The following specific recommendations are offered:

1 Insufficient Model Validation: Figure 1 and the main text lack clear, direct comparisons between the simulation results (e.g., basin morphology, geological maps, gravity anomalies) and actual Martian observational data (e.g., MOLA topography, satellite imagery). It is recommended to supplement the study with direct visual and quantitative comparisons to demonstrate that the current model accurately reproduces the key characteristics of the Isidis Basin. This is fundamental to the credibility of all subsequent analyses.

2 Inadequate Justification for Excluding Jezero Crater Materials: The impact products of the Jezero crater represent a key potential source of contamination. The study suggests that sampling locations should be at least 5 km from the Jezero crater center. To validate this critical conclusion, the formation conditions of the Jezero crater (e.g., impactor size, velocity, angle) must be explicitly stated. The manuscript currently only cites a reference (lines 341-342) without providing specific descriptions. Supplementing this information is essential to enhance the credibility of the exclusion criterion.

3 Incomplete Discussion of Impact Angle Effects: The text (lines 334-339) indicates gravitational anomalies consistent with an oblique impact for the Isidis crater. Consequently, the authors supplement their model with a 45° oblique impact simulation, suggesting a 240 km impactor could generate a 1500 km diameter crater with ejecta reaching the Jezero vicinity.

- (1) The rationale for selecting a 45° angle is not explained. Clarification is needed on whether this is based on specific geological evidence from the Isidis Basin or represents a general assumption.
- (2) Crucially, preceding conclusions are based on vertical impact models (e.g., the shock pressure distribution in Figure 5 defines diagnostic features as products of 45-60 GPa shock metamorphism). Extensive research (e.g., Pierazzo & Melosh, 1999; Ma et al., 2025) establishes that impact angle significantly influences the maximum shock pressure and its distribution. This alters the shock pressure distribution within the ejecta and, consequently, the final deposition characteristics. Therefore, a specific discussion on the effects of impact angle on shock products and their distribution is required. The discriminative shock pressure criteria derived from vertical impacts may not be directly applicable to the oblique impact scenario central to this study.

4 Insufficient Contextualization within Existing Literature: The manuscript does not adequately situate itself within existing research. Utilizing shock metamorphism to study impact craters and deep material provenance is not a novel concept, with prior discussions for other planetary bodies (e.g., Yue et al., 2013; Black & Marchi, 2024; Charalambous et al., 2025). It is recommended to:

- (1) Briefly review previous applications of similar methodologies on Earth, the Moon, or other Martian meteorites in the Introduction or Discussion.
- (2) Emphasize the new challenges and opportunities presented by the specific geological context of the Jezero-Isidis region on Mars, thereby highlighting the unique contribution of this study.

### Reviewer #2 (Remarks to the Author):

This is an interesting and ambitious manuscript. The work addresses an important question—whether the Isidis-forming impact delivered lower crustal and mantle material to the Jezero region, where the Perseverance rover could detect or sample it. This topic is relevant to Mars Sample Return, studies of early Martian differentiation, and our broader understanding of basin-forming impacts.

The manuscript has many strengths, including a comprehensive set of 2D and 3D iSALE simulations, generally clear figures, and a thoughtful attempt to tie modeling results to rover operations. However, a number of substantive issues need to be addressed before the manuscript is suitable for publication. My comments below are aimed at strengthening the clarity, accuracy, and realism of the interpretations.

## Major Comments

1. The choice of a 180-km impactor, much larger than most previous estimates, is treated as the single optimal solution. However, crustal thickness, geothermal gradient, impactor size, and melt viscosity jointly influence the outcome. The authors need to clarify that the “best-fit” model is one plausible solution within a multi-parameter space. They should consider providing misfit statistics, sensitivity tests, or additional justification for this choice.

2. The manuscript suggests that materials shocked to 45–60 GPa are predominantly mantle-derived. While this is true statistically, crustal materials also occupy this range in the simulations. Moreover, real megabreccia deposits often mix materials from many depths and shock states. The authors need to temper claims that shock state can uniquely identify mantle material and clarify that additional mineralogical, textural, or isotopic indicators are also required.

3. To date, Perseverance has not identified definitive mantle-derived lithologies or ultramafic megabreccias in the Jezero region, despite extensive imaging, compositional analyses, and textural characterization. Given the modeling results presented in the manuscript, this discrepancy merits discussion:

--Is mantle material present but not exposed?

--Are predicted abundances lower than expected?

--Are exposures too deeply buried or eroded?

--Could shear viscosity or impact angle assumptions shift ejecta out of rover-accessible regions?

--Has the rover team missed something? Is it possible that extended traverses or traverses in other directions might improve the chances of finding mantle material?

4. The manuscript implies that the upper ~15 km of ejecta is preserved, but surface exposures at Jezero are limited to a few tens of meters at most due to erosion, sediment deposition, and regolith development. Moreover, Perseverance has only ~10 sample opportunities remaining. This follows on the previous comment, but the authors need to clarify where high-priority mantle signals are most likely to occur, given realistic exposure depths, and discuss the sampling implications for the remaining mission timeline. I feel that this is probably the most valuable contribution this paper could make.

5. The Apollo 14 mission attempted to sample deep Imbrium ejecta at the Fra Mauro Formation, and despite careful planning, astronauts found ejecta heterogeneity and limited accessibility. This is an excellent analog to the situation at Jezero, where large-basin ejecta may be difficult to identify or reach. The authors should include a brief comparison (2–3 sentences) that would strengthen the context for Perseverance’s sampling strategy.

6. Figure 3f doesn’t seem to match what is shown in Figure 4d. My look at Figure 3f seems to indicate that the deeper mantle materials are buried where Figure 4d shows an inverted stratigraphy. Figure 4d is what would be expected. Figure 3 doesn’t make much sense and doesn’t seem to support the idea of finding mantle material very easily around Jezero.

## Minor Comments

Tone down overly strong conclusions (“thus we conclude,” “critical,” “unique”).

The CRISM massif survey is interesting but not fully integrated; consider tying this more directly to expected mantle signatures.

Figures are generally good, but some captions repeat too much text from the main body.

## Summary

This is a valuable and potentially impactful study, but several interpretations require moderation, and the manuscript would benefit from stronger integration with rover observations and sampling constraints. With revisions, the paper could make a significant contribution to the geology of Isidis, Jezero, and early Mars.

I hope these comments are helpful and constructive.

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Version 1:

Decision Letter:

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Dear Dr Trowbridge,

Your manuscript titled "Excavation of lower crust and mantle by Isidis impact, Mars: deposition in circum-Jezero." 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,

Joao Duarte, PhD  
Editorial Board Member  
Communications Earth & Environment  
[orcid.org/0000-0001-7505-3690](https://orcid.org/0000-0001-7505-3690)

Joe Aslin  
Deputy Editor,  
Communications Earth & Environment  
Consulting Editor,

## REVIEWERS' COMMENTS:

### Reviewer #1 (Remarks to the Author):

The authors have provided a thorough and responsive revision that addresses all comments in detail. Model validation, justification of Jezero ejecta contamination, impact angle effects, shock pressure discriminant robustness, and contextualization with Apollo/Imbrium analogs are all substantially improved. The manuscript is now scientifically rigorous and well-supported. Only minor issues with figure clarity and slight textual redundancy remain, which do not impede publication. I recommend acceptance for publication.

### Reviewer #2 (Remarks to the Author):

#### Major Comments

The authors took both reviews seriously and made substantial efforts to address all comments and concerns.

--Their model validation has been significantly improved as a result. They have added comparison to topography and gravity, quantified the mismatch (~6%), and included crustal collar validation.

--Contamination from Jezero has been much better constrained. They have explicitly described the Jezero impact model, including size, velocity, etc. They have clarified the spatial limits of contamination and acknowledged a thin veneer of highly shocked ejecta. Now, it's clear that sampling beyond certain distances reduces contamination.

--I feel they also addressed the concerns with the impact angle used in their model. This was a more subtle concern I had (and a major concern of the other reviewer). However, they have clarified that Isidis is not strongly oblique and justified a 45° impact as statistically most likely and consistent with a non-elliptical geometry. They also tested the 45-60 GPa peak shock range for diagnosing mantle-derived ejecta.

--I appreciate the discussion of Apollo 14 and Cone Crater, which now places their effort in a historical and scientific context.

#### Minor Comments

The authors obviously believe their model—and they should. However, some of the language in the manuscript sounds overly optimistic. For example, “best fit model” is stated repeatedly, but it remains a non-unique solution. The authors need to explicitly state that their key conclusions are insensitive to parameter trade-offs or to show that mantle delivery occurs across the parameter space. The 45-60 GPa diagnostic window may also be oversold. It's really probabilistic. The authors should consider adding a sentence combining shock pressure with mineralogy and sample context to improve the identification of mantle material. Finally, contamination from Jezero assumes that shock effects from Jezero are a thin veneer (~50 m) and that erosion would expose underlying ejecta. But who knows how much erosion has taken place, which was likely spatially variable. The authors should explicitly acknowledge the uncertainty in the exposure of pristine Isidis ejecta, because Perseverance may never see it, even if their model is completely accurate. I feel that all these comments could be addressed in a couple of words by modifying a few sentences.

#### Overall Evaluation

The authors have substantially improved the manuscript in response to reviewer comments. In particular, the addition of model–data comparisons, clarification of Jezero-related contamination, and expanded treatment of impact angle effects significantly strengthen the robustness and clarity of the study. The integration of hydrocode modeling with rover-scale sampling strategy remains a compelling and novel contribution.

I believe the manuscript is now close to publication quality. However, I recommend a small number of minor, targeted revisions to improve clarity and ensure that key conclusions are appropriately framed given model uncertainties.

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href="http://www.nature.com/authors">www.nature.com/authors</a> for information about policies, services and author benefits\*\*

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## REVIEWER COMMENTS:

### Reviewer #1 (Remarks to the Author):

This study aims to provide guidance for the Perseverance rover in sampling ejecta deposits from the Isidis impact crater near the Jezero crater, thereby offering an opportunity to investigate the interior mineralogy and composition of Mars. It proposes a methodology for determining whether the shock metamorphic features of the extracted materials originate from excavated deep crustal and mantle materials, while effectively excluding potentially confounding impact products from the Jezero crater. The research addresses a significant topic and demonstrates notable innovation. However, improvements in model validation, key assumptions, and scholarly context are necessary to robustly support its core conclusions. The following specific recommendations are offered:

1 Insufficient Model Validation: Figure 1 and the main text lack clear, direct comparisons between the simulation results (e.g., basin morphology, geological maps, gravity anomalies) and actual Martian observational data (e.g., MOLA topography, satellite imagery). It is recommended to supplement the study with direct visual and quantitative comparisons to demonstrate that the current model accurately reproduces the key characteristics of the Isidis Basin. This is fundamental to the credibility of all subsequent analyses.

**We have updated Figure 1 to show a direct comparison between our best fit 3D iSALE simulation and observations (topography and free-air gravity anomaly). We fit an ellipse to the simulation crater rims as well as the crustal collar and compared that to the proposed ~750 km crater rim (Andrews-Hanna and Zuber, 2010) and the free-air gravity anomaly (NASA GMM-3 gravity; Genova et al., 2016). The reason the crustal collar bulge was compared to the region of lowest free-air gravity is that previous modeling of the full evolution of mascon basins (from initial impact through thermal cooling and viscoelastic relaxation) show that the crustal collar corresponds to the similar radial distance as the most negative free-air gravity (Melosh et al., 2013; Freed et al., 2014; Trowbridge et al., 2020). The Isidis crustal collar is hard to see from an azimuthal average of the crustal thickness map produced from all the spherical harmonics; therefore, under the advice of Mark Wieczorek (who made those maps), we have also added a supplementary figure showing the existence of Isidis' crustal collar that has an azimuthal fit to the crustal thickness map where the global, longer wavelength features (i.e. the lowest spherical harmonics;  $l < 12$ ) were removed. The residual clearly shows the existence of a crustal collar.**

**Our mean radius is 703 km for the topographic rim and 517 km for the crustal collar. With the observations being ~1500 km for the rim and ~1100 km for the free-air gravity negative, our best fit 3D simulation slightly under predicts topography and the free-air gravity anomaly by ~6%.**

**We have added the following text to the manuscript to make this comparison clear:**

In Main text:

“To constrain our 3D models, we compared a fitted ellipse of the simulation’s rim and crustal collar to the proposed rim diameter of ~1500 km<sup>37</sup> and the diameter of the lowest free-air gravity negative, ~1100 km (see magenta line in Figure 1). The region of lowest free-air gravity was chosen to constrain the crustal collar because previous modeling of lunar mascon basins show that the crustal collar corresponds to the similar radial distance as the most negative free-air gravity<sup>38,39</sup>. Our best fit 3D simulation used a 240 km impactor and produced a diameter of 1,406 km for the rim and 1,034 km for the crustal collar, thereby slightly under predicting observations by ~6% (see Methods for details). “

In Methods:

“Comparing 3D Outputs with Observations

To compare with observations, we outputted multiple cross sections at various distances along the semimajor axis. We collected the (x,y) coordinates of the lowest portion of the crustal bulge and the highest topographic part of the crater rim. We then conducted an elliptical fit to the collected data points and compared with proposed rim dimensions<sup>37</sup> and the observed Free-air gravity<sup>75</sup> (see magenta lines in Figure 1).

The Isidis crustal collar is hard to see from an azimuthal average of the crustal thickness map produced from all the spherical harmonics. Therefore, to verify its existence, we produced an azimuthal fit to the crustal thickness map where the global, longer wavelength features (i.e., the spherical harmonics degrees <12) were removed. The resulting residual crustal figure shows a distinct thickening of crust at ~600 km radial distance indicating the presences of a crustal collar (see Figure S6).”

In addition, we have added another supplementary figure showing a comparison of all our 2D simulations to the observed crustal thickness.

2 Inadequate Justification for Excluding Jezero Crater Materials: The impact products of the Jezero crater represent a key potential source of contamination. The study suggests that sampling locations should be at least 5 km from the Jezero crater center. To validate this critical conclusion, the formation conditions of the Jezero crater (e.g., impactor size, velocity, angle) must be explicitly stated. The manuscript currently only cites a reference (lines 341-342) without providing specific descriptions. Supplementing this information is essential to enhance the credibility of the exclusion criterion.

This is a very good point. We did not put in significant information about this simulation as the manuscript with the published Jezero simulations was still in review. It has since been published. Therefore, we have added the following description of those simulations:

“We used the same impact modeling setup as recently published 2D iSALE modeling of Jezero crater that matched the observed diameter as well as the depth of a less infilled, similarly sized, nearby crater<sup>77</sup>. This model contained a 4 km diameter dunite projectile impacting a basalt target at 9 km/s and a thermal gradient of 11°C/km. This is a close match to other recent iSALE modeling of Jezero crater whose best-fit was a 3.8 km diameter basalt projectile at 9.4 km/s<sup>78</sup>. We utilized a basalt ANEOS equation of state for the Martian crust and a dunite ANEOS equation of state for the Martian mantle and impactor. To simulate the rheology of basalt and dunite, we incorporated a rock-like strength model, a damage model with an exponential dependence on plastic strain, a dilatancy model, a thermal weakening model corresponding to the temperature- and pressure-dependence of the material, an acoustic fluidization model, and an exponentially decaying porosity model. For references for each model (see above) and for all input values used for each model (see ref. 77).

The mesh geometry included a high-resolution zone containing cells 50 m in size and extended 700 cells from the crater center and to a depth of 700 cells. The best-fit run utilized a resolution of 40 cells-per-projectile-radius (CPPR).

Previous hydrocode modeling of Jezero concluded that the crater rim is shocked to <2 GPa<sup>78</sup>. While this is true for the majority of material that constitutes the crater rim of Jezero, in our simulations, a thin veneer of highly shocked ejecta was identified within the Lagrangian tracer particles (see Figure S5b).”

3 Incomplete Discussion of Impact Angle Effects: The text (lines 334-339) indicates gravitational anomalies consistent with an oblique impact for the Isidis crater. Consequently, the authors supplement their model with a 45° oblique impact simulation, suggesting a 240 km impactor could generate a 1500 km diameter crater with ejecta reaching the Jezero vicinity.

Lines 334-339 were not intended to indicate an oblique impact angle (<45° angle) and should not be interpreted as such. The same offset is observed at Chicxulub, whose impact angle was likely steep (~45-60° angle; Collins et al., 2020); therefore, an offset between the Bouguer gravity high and crater center does not indicate an oblique impact. In fact, the low eccentricity of Isidis (<1.2; Andrews-Hanna and Zuber, 2010) is indicative of an impact angle greater than 34°, which is the transitional angle from circular to elliptical craters predicted by pi-scaling relationships (Andrews-Hanna and Zuber, 2010). To make this clearer to readers, we have added the following text to the main text:

“It should be noted that the offset between the Bouguer gravity high, and the center of Isidis does not necessarily indicate an oblique impact. The recent 3D modeling of the Chicxulub impact event that this analysis is based on indicated a steeply inclined angle (45-60° from horizontal)<sup>76</sup>. Moreover, as stated above, the low eccentricity of Isidis (aspect ratio <1.2) indicates similarly inclined impact angle<sup>37</sup>.”

(1) The rationale for selecting a 45° angle is not explained. Clarification is needed on whether this is based on specific geological evidence from the Isidis Basin or represents a general assumption.

A 45° angle was chosen to test dependence on impact angle as it is the most statically likely angle (Melosh, 1989). As stated above, impact angles less than 34° would produce an elliptical crater, which is not observed for Isidis. We have changed the following paragraph to strengthen the rationale for selecting a 45° angle and excluding more oblique impacts:

“For constant impact energy, a shallower angle of impact generates a smaller transient crater volume, decreases the depth of excavation, forms a more elliptical basin, decreases and partitions more peak shock pressure at shallower depths downrange, and produces a more asymmetric distribution of ejecta<sup>33–35</sup>. To test the effect of impact angle, we conducted additional simulations utilizing iSALE 3D for a projectile coming in at 45 degrees from the horizontal. An impact angle of 45 degrees was chosen as it is the statically most probable angle for an impact<sup>36</sup>. Additionally, the transitional impact angle that marks the onset of an elliptical basin (aspect ratio >1.2) for Isidis is around 34 degrees from the horizontal<sup>37</sup>. Isidis is not an elliptical basin (aspect ratio <1.2)<sup>37</sup>; therefore, we did not consider more oblique impact angles.”

(2) Crucially, preceding conclusions are based on vertical impact models (e.g., the shock pressure distribution in Figure 5 defines diagnostic features as products of 45-60 GPa shock metamorphism). Extensive research (e.g., Pierazzo & Melosh, 1999; Ma et al., 2025) establishes that impact angle significantly influences the maximum shock pressure and its distribution. This alters the shock pressure distribution within the ejecta and, consequently, the final deposition characteristics. Therefore, a specific discussion on the effects of impact angle on shock products and their distribution is required. The discriminative shock pressure criteria derived from vertical impacts may not be directly applicable to the oblique impact scenario central to this study.

This is a very good point and was considered deeply when writing up the manuscript. We agree that impact angle can redistribute peak shock pressures and introduce downrange asymmetry, including for moderately oblique impacts. Our key discriminator, however, is not that peak pressures are unchanged, but that in the Jezero-relevant annulus the high-shock ejecta class used for diagnosis remains predominantly mantle-derived. We therefore explicitly tested this using a 45° iSALE 3D simulation and found that the mantle fraction within the diagnostic shock-pressure class in the circum-Jezero region remains dominant (Fig. S3). Given Isidis' low ellipticity, extremely shallow impact angles are unlikely; thus our vertical-incidence criteria are used as a first-order framework and their robustness is demonstrated by the 45° case.

We have followed the reviewer's advice and improved the discussion within the manuscript as follows:

**“This correlation between mantle material and the 50-60 GPa peak shock pressure range was also observed in our 3D simulations (see Figure 5b). As stated above, impact angle is expected to modify both the magnitude and spatial distribution of peak shock pressures relative to vertical (axisymmetric) impacts. Recent 3D simulations<sup>40</sup> of the contact-compression stage demonstrate that mean peak shock pressure scales approximately as  $P(\varphi) = P(90^\circ) \cdot \sin \varphi$  (with  $\varphi$  defined as the impact angle from horizontal), with a corresponding temperature reduction that is even steeper ( $T(\varphi) = T(90^\circ) \cdot \sin^{3/2} \varphi$ ); these simulations also show pronounced thermodynamic stratification of downrange ejecta at lower angles. Earlier 3D hydrocode work<sup>34,35</sup> similarly found that decreasing impact angle weakens peak shock pressures in the isobaric core and produces a stronger downrange shock, yielding asymmetric isobaric-core and melt regions. Accordingly, shock-pressure discriminants inferred from vertical models should not be assumed to be transferable to oblique impacts without verification. Our iSALE-3D simulations at 45° show this expected decrease in peak shock pressure in the circum-Jezero sector; however, the 45–60 GPa peak-shock range remains predominantly associated with mantle-derived ejecta in our best-fit oblique Isidis simulation (see Figure 5b and Figure 6), supporting the applicability of our diagnostic window for the moderate obliquity implied by Isidis’ non-elliptical geometry.”**

4 Insufficient Contextualization within Existing Literature: The manuscript does not adequately situate itself within existing research. Utilizing shock metamorphism to study impact craters and deep material provenance is not a novel concept, with prior discussions for other planetary bodies (e.g., Yue et al., 2013; Black & Marchi, 2024; Charalambous et al., 2025). It is recommended to:

- (1) Briefly review previous applications of similar methodologies on Earth, the Moon, or other Martian meteorites in the Introduction or Discussion.
- (2) Emphasize the new challenges and opportunities presented by the specific geological context of the Jezero-Isidis region on Mars, thereby highlighting the unique contribution of this study.

**We agree and have added a contextualization introduction section that summarizes how shock metamorphism and crater modeling have been used to constrain impact processes. Additionally, we also explicitly state our unique contribution of this work: linking basin- scale provenance predictions to Jezero sampling strategy.**

Reviewer #2 (Remarks to the Author):

#### Major Comments

1. The choice of a 180-km impactor, much larger than most previous estimates, is treated as the single optimal solution. However, crustal thickness, geothermal gradient, impactor size, and melt viscosity jointly influence the outcome. The authors need to clarify that the “best-fit” model is one plausible solution within a multi-parameter space. They should consider providing misfit statistics, sensitivity tests, or additional justification for this choice.

We have added a line to illustrate our “best-fit” is one plausible solution within a multi-parameter space. Additionally, we have added a supplementary figure showing a fit of all our simulations to the crustal thickness. Additionally, we evaluated each model’s performance using a  $1\sigma$  convergence (fraction of points within observational uncertainty) and ranked each model accordingly. Lastly, to constrain our 3D models, we compared a fitted ellipse of the simulations rim and crustal collar to the proposed rim diameter of ~1500 km and the diameter of the lowest free-air gravity negative, ~1100 km (see magenta line in Figure 1). The region of lowest free-air gravity was chosen to constrain the crustal collar because previous modeling of lunar mascon basins show that the crustal collar corresponds to the similar radial distance as the most negative free-air gravity. Our best fit 3D simulation used a 240 km impactor and produced a mean rim diameter of 1406 km and 1034 km for the crustal collar: thereby, slightly under predicting observations by ~6%

Lastly, we have added the following text to the manuscript:

“Figure 2 shows a comparison between our best-fitting 2D model (red line) and the observed azimuthally averaged crustal profile of Isidis Planitia (black line). With a 180 km diameter dunite projectile impacting at 12 km/s into a 40 km thick average basalt crust with a geothermal gradient of 30 K/km, the model reproduces 64% of the observed radial bins within their  $1\sigma$  measurement uncertainties. While this represents one of the closest matches within the explored parameter space (see Figure S1), the solution is nonunique. Some input parameters (e.g., melt viscosity and thermal gradient) exert partially compensating effects on the final crustal thickness distribution. Accordingly, this best-fit model represents one region of parameter space consistent with available observations rather than a uniquely determined solution. A comparison of all simulations with observed crustal thickness is provided in Figure S1.”

2. The manuscript suggests that materials shocked to 45–60 GPa are predominantly mantle-derived. While this is true statistically, crustal materials also occupy this range in the simulations. Moreover, real megabreccia deposits often mix materials from many depths and shock states. The authors need to temper claims that shock state can uniquely identify mantle material and clarify that additional mineralogical, textural, or isotopic indicators are also required.

We agree. We have temper claims that shock state can uniquely identify mantle material and added the following text to the manuscript:

“Importantly, shock pressure alone cannot uniquely identify mantle material. Instead, the 45–60 GPa shock window should be interpreted as a statistical enrichment criterion that must be used in combination with mineralogical, textural, and geochemical indicators of ultramafic composition.”

As well as:

“Real megabreccia deposits often mix materials from many depths and shock states. For instance, the Apollo 14 samples provide a useful operational analog, even though Cone Crater is not a basin-rim exposure: the Fra Mauro traverse targeted materials interpreted as Imbrium ejecta via a superposed crater excavation<sup>41</sup>, yet the sampled deposits were heterogeneous<sup>42</sup>, cross contaminated by nearby craters<sup>42</sup>, and access to the most diagnostic exposures was limited<sup>43</sup>. Similarly, our Jezero/Isidis modeling predicts that impact mixing (including central peak collapse and later overprinting) can obscure provenance near Jezero, making ejected materials difficult to identify unambiguously at rover scale. The 3D simulations show that the stratigraphy of deposited ejecta 600-700 km radially from the center of the basin (encompassing Jezero’s location) is more heterogeneous than deposits located farther from the basin center (see Figure 6). Mantle material is predominantly concentrated toward the top but is also dispersed throughout the ejecta column due to mixing during central uplift collapse, rather than forming a laterally continuous layer (see top row of Figure 6). This implies that mantle-derived clasts may occur throughout the megabreccia deposit even where the original uppermost ejecta surface is no longer preserved. Such heterogeneous ejecta stratigraphy likely results from the outward flow of the collapsing central uplift, which mixes previously deposited ejecta during emplacement.

Recent rover observations show that olivine- and carbonate-bearing units occur along the Jezero margin and rim<sup>44</sup>; however, such ultramafic lithologies are interpreted to represent cumulates<sup>45</sup>, altered crustal units<sup>44</sup>, or diverse volcanics<sup>46</sup>. *Perseverance* has also identified a suite of two compositions of boulders on the Jezero western fan inferred to be transported from the watershed. The first are ultramafic, olivine-dominated boulders may represent primitive melts, lower crust, or even mantle peridotites; however, these samples contained no observed shock features that would be expected for ejected mantle materials, and their provenance remains unresolved<sup>47</sup> (discussed more below). The second are extremely resistant low-Ca pyroxene-bearing boulders, such as the Mount Meeker target, that contain unusually high  $\text{Al}_2\text{O}_3$  and may represent impact melt derived from altered basaltic protoliths or other unusual igneous processes<sup>48</sup>. These latter boulders are among the most pristine rocks encountered along the rover traverse and are compositionally distinct from many other units in Jezero<sup>49</sup>. Such lithologies may therefore represent strongly shocked or impact-derived crustal materials and provide an additional candidate target for identifying basin ejecta within the heterogeneous megabreccia deposits predicted by our simulations.

As for the crater rim and immediately exterior, the identification of mantle material could contain cross contamination from Jezero or nearby craters, similar to the Imbrium ejecta discussed above. Our simulations indicate that Isidis ejecta and central peak collapse deposits constitute at least the upper ~5 km of material originally deposited at Jezero. While the Jezero impact locally shocked material to >50 GPa, most of this material is a thin veneer (~50 m) and deposited within a few kilometers of Jezero’s rim (Figure S5b).

Beyond the crater rim of Jezero might provide the best chance to sample shocked mantle material. Our models predict that ejecta deposited 700–800 km from the basin center (>20 km from Jezero’s rim) exhibit reduced heterogeneity and a stratigraphy more consistent with an inverted ejecta sequence, in which mantle-derived material overlies shallower crustal material (see bottom row of Figure 6). Although heterogeneity is still expected, given the Imbrium analog, these results provide a framework for prioritizing candidate sampling locations most likely to contain mantle-derived ejecta from Isidis.”

3. To date, Perseverance has not identified definitive mantle-derived lithologies or ultramafic megabreccias in the Jezero region, despite extensive imaging, compositional analyses, and textural characterization. Given the modeling results presented in the manuscript, this discrepancy merits discussion:

--Is mantle material present but not exposed?

--Are predicted abundances lower than expected?

--Are exposures too deeply buried or eroded?

--Could shear viscosity or impact angle assumptions shift ejecta out of rover-accessible regions?

--Has the rover team missed something? Is it possible that extended traverses or traverses in other directions might improve the chances of finding mantle material?

We have added a discussion to this in the following text as well as an additional figure (see Figure 6):

“Real megabreccia deposits often mix materials from many depths and shock states. For instance, the Apollo 14 samples provide a useful operational analog, even though Cone Crater is not a basin-rim exposure: the Fra Mauro traverse targeted materials interpreted as Imbrium ejecta via a superposed crater excavation<sup>41</sup>, yet the sampled deposits were heterogeneous<sup>42</sup>, cross contaminated by nearby craters<sup>42</sup>, and access to the most diagnostic exposures was limited<sup>43</sup>. Similarly, our Jezero/Isidis modeling predicts that impact mixing (including central peak collapse and later overprinting) can obscure provenance near Jezero, making ejected materials difficult to identify unambiguously at rover scale. The 3D simulations show that the stratigraphy of deposited ejecta 600-700 km radially from the center of the basin (encompassing Jezero’s location) is more heterogeneous than deposits located farther from the basin center (see Figure 6). Mantle material is predominantly concentrated toward the top but is also dispersed throughout the ejecta column due to mixing during central uplift collapse, rather than forming a laterally continuous layer (see top row of Figure 6). This implies that mantle-derived clasts may occur throughout the megabreccia deposit even where the original uppermost ejecta surface is no longer preserved. Such heterogeneous ejecta stratigraphy likely results from the outward flow of the collapsing central uplift, which mixes previously deposited ejecta during emplacement.

Recent rover observations show that olivine- and carbonate-bearing units occur along the Jezero margin and rim<sup>44</sup>; however, such ultramafic lithologies are interpreted to represent cumulates<sup>45</sup>, altered crustal units<sup>44</sup>, or diverse volcanics<sup>46</sup>.

*Perseverance* has also identified a suite of two compositions of boulders on the Jezero western fan inferred to be transported from the watershed. The first are ultramafic, olivine-dominated boulders may represent primitive melts, lower crust, or even mantle peridotites; however, these samples contained no observed shock features that would be expected for ejected mantle materials, and their provenance remains unresolved<sup>47</sup> (discussed more below). The second are extremely resistant low-Ca pyroxene-bearing boulders, such as the Mount Meeker target, that contain unusually high  $\text{Al}_2\text{O}_3$  and may represent impact melt derived from altered basaltic protoliths or other unusual igneous processes<sup>48</sup>. These latter boulders are among the most pristine rocks encountered along the rover traverse and are compositionally distinct from many other units in Jezero<sup>49</sup>. Such lithologies may therefore represent strongly shocked or impact-derived crustal materials and provide an additional candidate target for identifying basin ejecta within the heterogeneous megabreccia deposits predicted by our simulations.

As for the crater rim and immediately exterior, the identification of mantle material could contain cross contamination from Jezero or nearby craters, similar to the Imbrium ejecta discussed above. Our simulations indicate that Isidis ejecta and central peak collapse deposits constitute at least the upper ~5 km of material originally deposited at Jezero. While the Jezero impact locally shocked material to >50 GPa, most of this material is a thin veneer (~50 m) and deposited within a few kilometers of Jezero's rim (Figure S5b).

Beyond the crater rim of Jezero might provide the best chance to sample shocked mantle material. Our models predict that ejecta deposited 700–800 km from the basin center (>20 km from Jezero's rim) exhibit reduced heterogeneity and a stratigraphy more consistent with an inverted ejecta sequence, in which mantle-derived material overlies shallower crustal material (see bottom row of Figure 6). Although heterogeneity is still expected, given the Imbrium analog, these results provide a framework for prioritizing candidate sampling locations most likely to contain mantle-derived ejecta from Isidis.”

We have also added the following comparison to the recently discovered ultramafic float rocks at Jezero:

“As noted above, the ultramafic float rocks identified by *Perseverance* at Jezero that may represent Isidis-derived mantle material do not exhibit shock features expected for  $\geq 15\text{--}30$  GPa (e.g., no reported brittle deformation) and are therefore most consistent with very low shock pressures ( $< \sim 15\text{--}20$  GPa), although subtle micro-scale shock effects cannot be excluded<sup>47</sup>. This observation is not inconsistent with our modeling results. Our 3D simulations show that excavated mantle material deposited in the Jezero region spans a broad range of peak shock pressures, extending down to ~10 GPa and a mean of 29.2 GPa (Figure 5b). However, the simulations also indicate that material shocked to these lower pressures is more commonly derived from the lower crust than from the mantle with a mean of 7.13 GPa. Consequently, if the float rocks were emplaced by the Isidis impact and experienced only low shock pressures, a lower-crustal provenance is statistically more likely. Future high-resolution laboratory analyses

of returned samples (e.g., TEM) may reveal micro-scale shock features (such as PDFs in olivine) that would imply peak pressures >15 GPa and increase the likelihood of a mantle origin.

In addition, if Mount Meeker is correctly interpreted as impact melt, it is more likely to represent locally shocked and subsequently reworked Jezero-impact material than a distal Isidis ejecta clast. This interpretation is supported by our Jezero simulation, which indicates that material shocked to >50 GPa forms a thin, near-surface ejecta veneer concentrated within ~5 km of the rim (see Figure S5b), and by the interpretation that the pyroxene-bearing fan boulders were later redistributed by high-energy fluvial transport<sup>52</sup>. In this scenario, Mount Meeker would have formed as part of a thin veneer of highly shocked material emplaced during the Jezero-forming impact and later eroded and redeposited within the western fan, potentially leaving less strongly shocked material exposed beneath.

Taken together, the mineralogical and shock characteristics observed in rocks analyzed by *Perseverance* to date are not fully consistent with expectations for mantle material excavated by the Isidis impact according to our modeling. This result suggests that identifying unequivocal mantle ejecta may require investigation of materials located farther from the currently explored Jezero outcrops or within regions where models predict a greater abundance of deeply excavated Isidis ejecta.”

We have also added the following text to the conclusion:

“As of the writing of this manuscript, *Perseverance* has limited sample opportunities remaining and is limited to sampling only a few tens of meters of the surface<sup>52</sup>. Based on our results here, we suggest that the most likely place to locate excavated mantle material is within megabreccia samples exposed by valleys that have shock characteristics consistent with the 45-60 GPa peak shock pressure range, >20 km away from Jezero’s rim in the direction opposite of Isidis’ center (to maximize the chance for mantle dominated upper stratigraphy), and >5 km radially from the rims of craters the size of Jezero or smaller (to minimize cross contamination from smaller craters in the region). Given the distance needed to travel likely requires an extended traverse; however, according to these simulations, it would increase the percentage of the near surface being dominated by Isidis mantle ejecta from 25% to 73.9%.”

4. The manuscript implies that the upper ~15 km of ejecta is preserved, but surface exposures at Jezero are limited to a few tens of meters at most due to erosion, sediment deposition, and regolith development. Moreover, *Perseverance* has only ~10 sample opportunities remaining. This follows on the previous comment, but the authors need to clarify where high-priority mantle signals are most likely to occur, given realistic exposure depths, and discuss the sampling implications for the remaining mission timeline. I feel that this is probably the most valuable contribution this paper could make.

We have added the following text:

“As of the writing of this manuscript, Perseverance has limited sample opportunities remaining and is limited to sampling only a few tens of meters of the surface<sup>52</sup>. Based on our results here, we suggest that the most likely place to locate excavated mantle material is within megabreccia samples exposed by valleys that have shock characteristics consistent with the 45-60 GPa peak shock pressure range, >20 km away from Jezero’s rim in the direction opposite of Isidis’ center (to maximize the chance for mantle dominated upper stratigraphy), and >5 km radially from the rims of craters the size of Jezero or smaller (to minimize cross contamination from smaller craters in the region). Given the distance needed to travel likely requires an extended traverse; however, according to these simulations, it would increase the percentage of the near surface being dominated by Isidis mantle ejecta from 25% to 73.9%.”

5. The Apollo 14 mission attempted to sample deep Imbrium ejecta at the Fra Mauro Formation, and despite careful planning, astronauts found ejecta heterogeneity and limited accessibility. This is an excellent analog to the situation at Jezero, where large-basin ejecta may be difficult to identify or reach. The authors should include a brief comparison (2–3 sentences) that would strengthen the context for Perseverance’s sampling strategy.

We have added the following text:

“Real megabreccia deposits often mix materials from many depths and shock states. For instance, the Apollo 14 samples provide a useful operational analog, even though Cone Crater is not a basin-rim exposure: the Fra Mauro traverse targeted materials interpreted as Imbrium ejecta via a superposed crater excavation<sup>41</sup>, yet the sampled deposits were heterogeneous<sup>42</sup>, cross contaminated by nearby craters<sup>42</sup>, and access to the most diagnostic exposures was limited<sup>43</sup>. Similarly, our Jezero/Isidis modeling predicts that impact mixing (including central peak collapse and later overprinting) can obscure provenance near Jezero, making ejected materials difficult to identify unambiguously at rover scale. The 3D simulations show that the stratigraphy of deposited ejecta 600-700 km radially from the center of the basin (encompassing Jezero’s location) is more heterogeneous than deposits located farther from the basin center (see Figure 6). Mantle material is predominantly concentrated toward the top but is also dispersed throughout the ejecta column due to mixing during central uplift collapse, rather than forming a laterally continuous layer (see top row of Figure 6). This implies that mantle-derived clasts may occur throughout the megabreccia deposit even where the original uppermost ejecta surface is no longer preserved. Such heterogeneous ejecta stratigraphy likely results from the outward flow of the collapsing central uplift, which mixes previously deposited ejecta during emplacement.

Recent rover observations show that olivine- and carbonate-bearing units occur along the Jezero margin and rim<sup>44</sup>; however, such ultramafic lithologies are interpreted to represent cumulates<sup>45</sup>, altered crustal units<sup>44</sup>, or diverse volcanics<sup>46</sup>. *Perseverance* has also identified a suite of two compositions of boulders on the Jezero western fan inferred to be transported from the watershed. The first are

ultramafic, olivine-dominated boulders may represent primitive melts, lower crust, or even mantle peridotites; however, these samples contained no observed shock features that would be expected for ejected mantle materials, and their provenance remains unresolved<sup>47</sup> (discussed more below). The second are extremely resistant low-Ca pyroxene-bearing boulders, such as the Mount Meeker target, that contain unusually high  $\text{Al}_2\text{O}_3$  and may represent impact melt derived from altered basaltic protoliths or other unusual igneous processes<sup>48</sup>. These latter boulders are among the most pristine rocks encountered along the rover traverse and are compositionally distinct from many other units in Jezero<sup>49</sup>. Such lithologies may therefore represent strongly shocked or impact-derived crustal materials and provide an additional candidate target for identifying basin ejecta within the heterogeneous megabreccia deposits predicted by our simulations.

As for the crater rim and immediately exterior, the identification of mantle material could contain cross contamination from Jezero or nearby craters, similar to the Imbrium ejecta discussed above. Our simulations indicate that Isidis ejecta and central peak collapse deposits constitute at least the upper ~5 km of material originally deposited at Jezero. While the Jezero impact locally shocked material to >50 GPa, most of this material is a thin veneer (~50 m) and deposited within a few kilometers of Jezero's rim (Figure S5b).

Beyond the crater rim of Jezero might provide the best chance to sample shocked mantle material. Our models predict that ejecta deposited 700–800 km from the basin center (>20 km from Jezero's rim) exhibit reduced heterogeneity and a stratigraphy more consistent with an inverted ejecta sequence, in which mantle-derived material overlies shallower crustal material (see bottom row of Figure 6). Although heterogeneity is still expected, given the Imbrium analog, these results provide a framework for prioritizing candidate sampling locations most likely to contain mantle-derived ejecta from Isidis.”

6. Figure 3f doesn't seem to match what is shown in Figure 4d. My look at Figure 3f seems to indicate that the deeper mantle materials are buried where Figure 4d shows an inverted stratigraphy. Figure 4d is what would be expected. Figure 3 doesn't make much sense and doesn't seem to support the idea of finding mantle material very easily around Jezero.

The stack plot in Figure 4 does not represent distinct uniform layers or stratigraphy but rather are cumulative tracers within the circum-Jezero region. We tried to make that apparent by having “Note: the stack plot does not represent distinct uniform layers or stratigraphy.” We have further highlighted this by italicizing that sentence.

Additionally, as shown within our 3D simulations (see Figure 6), the deposition of mantle material is heterogenous (although mantle material does make up the predominately percentage of the upper layers) due to mixing caused by the collapse of the central peak. However, slightly further out (>20 km from Jezero's rim in the NW direction), the stratigraphy resembles the more expected inverted stratigraphy with mantle material sitting on top (see Figure 6).

#### Minor Comments

Tone down overly strong conclusions (“thus we conclude,” “critical,” “unique”).

**We have toned down overly strong conclusions.**

The CRISM massif survey is interesting but not fully integrated; consider tying this more directly to expected mantle signatures.

**We decided to remove this from the manuscript as we feel there are not enough massifs around Isidis to make a definitive comparison.**

Figures are generally good, but some captions repeat too much text from the main body.

**We have reduced redundancy of figure captions and the text from the main body.**

## REVIEWERS' COMMENTS:

### Reviewer #1 (Remarks to the Author):

The authors have provided a thorough and responsive revision that addresses all comments in detail. Model validation, justification of Jezero ejecta contamination, impact angle effects, shock pressure discriminant robustness, and contextualization with Apollo/Imbrium analogs are all substantially improved. The manuscript is now scientifically rigorous and well-supported. Only minor issues with figure clarity and slight textual redundancy remain, which do not impede publication. I recommend acceptance for publication.

We appreciate the reviewers time and comments. They greatly improved the manuscript. The reviewer should know that we had to change the title and abstract to be compliant with Communication: Earth and Environments' format.

### Reviewer #2 (Remarks to the Author):

#### Major Comments

The authors took both reviews seriously and made substantial efforts to address all comments and concerns.

--Their model validation has been significantly improved as a result. They have added comparison to topography and gravity, quantified the mismatch (~6%), and included crustal collar validation.

--Contamination from Jezero has been much better constrained. They have explicitly described the Jezero impact model, including size, velocity, etc. They have clarified the spatial limits of contamination and acknowledged a thin veneer of highly shocked ejecta. Now, it's clear that sampling beyond certain distances reduces contamination.

--I feel they also addressed the concerns with the impact angle used in their model. This was a more subtle concern I had (and a major concern of the other reviewer). However, they have clarified that Isidis is not strongly oblique and justified a 45° impact as statistically most likely and consistent with a non-elliptical geometry. They also tested the 45-60 GPa peak shock range for diagnosing mantle-derived ejecta.

--I appreciate the discussion of Apollo 14 and Cone Crater, which now places their effort in a historical and scientific context.

We appreciate the reviewers time and comments. They greatly improved the manuscript. The reviewer should know that in addition to the changes below we also had to change the title and abstract to be compliant with Communication: Earth and Environments' format.

## Minor Comments

The authors obviously believe their model—and they should. However, some of the language in the manuscript sounds overly optimistic. For example, “best fit model” is stated repeatedly, but it remains a non-unique solution.

We have modified the manuscript to contain the following:

“Accordingly, the use of the term best-fitting model here and throughout the manuscript refers to a simulation that best reproduces the observed azimuthally averaged crustal profile of Isidis Planitia as well as the crustal bulge at ~600 km radial distance for the parameter combinations explored (see Figure S1 for that comparison). It should be noted that given the partially compensating effects of similar parameters as described above there might exist another parameter combination unexplored which produces an even better fit to observation.”

The authors need to explicitly state that their key conclusions are insensitive to parameter trade-offs or to show that mantle delivery occurs across the parameter space.

We have modified a sentence to say the following:

“In conclusion, the excavation of mantle material and its deposition in the Jezero region occurred in all simulations, insensitive to investigated numerical parameters; therefore, in the next section, we discuss how the *Perseverance* rover could distinguish this excavated mantle from crustal material.”

The 45-60 GPa diagnostic window may also be oversold. It’s really probabilistic. The authors should consider adding a sentence combining shock pressure with mineralogy and sample context to improve the identification of mantle material.

We have modified a sentence to the following:

“Importantly, shock pressure alone cannot uniquely identify mantle material. Instead, the 45–60 GPa shock window should be interpreted as a statistical enrichment criterion that must be used in combination with geochemical indicators of ultramafic composition as well as sample context that indicates ejecta, such as mega breccia.”

Finally, contamination from Jezero assumes that shock effects from Jezero are a thin veneer (~50 m) and that erosion would expose underlying ejecta. But who knows how much erosion has taken place, which was likely spatially variable. The authors should explicitly acknowledge the uncertainty in the exposure of pristine Isidis ejecta, because *Perseverance* may never see it, even if their model is completely accurate.

We have added the following paragraph:

“In this section, we discussed the possibility of identifying excavated mantle material from other ejecta cross contamination; however, there remains the uncertainty in subsequent geologic activity

after the Isidis impact (as described in the introduction), which might limit exposure of pristine Isidis ejecta despite the accuracy of our models. To account for such a probability, we suggest that in addition to looking further out (700-800 km from Isidis center) for mantle material to focus the search to the walls of the interior of valleys.”

I feel that all these comments could be addressed in a couple of words by modifying a few sentences.

#### Overall Evaluation

The authors have substantially improved the manuscript in response to reviewer comments. In particular, the addition of model–data comparisons, clarification of Jezero-related contamination, and expanded treatment of impact angle effects significantly strengthen the robustness and clarity of the study. The integration of hydrocode modeling with rover-scale sampling strategy remains a compelling and novel contribution.

I believe the manuscript is now close to publication quality. However, I recommend a small number of minor, targeted revisions to improve clarity and ensure that key conclusions are appropriately framed given model uncertainties.