PEER REVIEW REPORT

PLANETARY RESEARCH

This peer review report contains the editor decisions, reviews, and author rebuttals for each round of peer review. The peer review rounds are ordered chronologically, and the final acceptance decision is not included.

The published manuscript can be found on the journal website: https://planetary-research.org.

TITLE

Geology of Atlas crater, the prime landing site of the Emirates Lunar Mission Rashid-1 rover

AUTHORS

J. Flahaut et al.

DOI

https://doi.org/10.53480/4e7a4y94

EDITOR DECISION
round 1

Dear Dr. Jessica Flahaut,

I would like to thank you for submitting your manuscript "Geology of Atlas crater, the prime landing site of the Emirates Lunar Mission Rashid-1 rover" (#274) to Planetary Research. I have now received the reviews and associate editor assessment of your submission, which are included at the bottom of this email. Based on my evaluation of your submission, your manuscript should in principle be suitable for publication after revision focusing specifically on the realism of the petrological implications of the model.

Please provide us with a point-by-point response to all comments and identify what changes you have made to the revised manuscript. In addition to the rebuttal, we ask that you also provide a document that tracks all changes that have been made to your manuscript since its initial submission.

When you have completed your revisions, you can upload the revised manuscript, your response and a tracked changes document from your submission dashboard.

If you have any questions about the recommendations in your review, or if you are unsure how to respond or proceed, please do not hesitate to contact me from your submission dashboard.

Sincerely,

Justin Filiberto
Editor, Planetary Research

Associate editor recommendation

I believe the reviewers make a compelling case to revise regarding their central hypothesis, specifically on the compositional aspects brought up by Reviewer 1.

The following comments were received from the reviewers.

Reviewer 1:
Recommendation: Revisions Required With Review

All pre-existing data used in the manuscript are publicly available and sufficient information is provided so that they can be found and accessed.

Yes

All significant data products generated as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI).

Yes

All significant numerical codes developed as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI or SWHID).

Yes

All pre-existing software used as part of the study are acknowledged, and sufficient information is provided to find, access, and understand the software. If the software is restricted, the conditions under which it can be accessed are publicly available.

Yes

If you answered no to any of the above questions, please provide supporting information.

I am uploading an annotated version of the manuscript.

No

Comments for the authors

This study presents a detailed investigation of the lunar Atlas crater, which was the prime target of the Emirates lunar mission. The authors base their work on multi-spectral datasets and use a multi-method approach for the characterization including geological mapping, crater counting, spectral analysis, rheological modelling, and Earth based telescopic observations. The choice of datasets is broad and covers compositional, mineralogical and topographical properties of the studied area very well.
A central hypothesis is the genetic link of a shallow laccolith intrusion suggested to be evolved in compositions, and the pyroclastic deposits in the two dark mantle deposits (DMDs). This is unusual and requires some petrological considerations in the discussion. All returned lunar pyroclastic beads are mafic to ultramafic in composition. Furthermore, petrological constraints suggest very deeps sources of more than 300km, with low viscosity melts rising at speeds of 20 to 30 m/s (Wilson & Head 2018 GRL). Therefore, DMD-forming low viscosity melts are unlikely to form shallow laccoliths capable of causing the observed uplift. This would require slowly moving low-viscosity melts instead. The authors need to reconcile this problem.
Figure 4 suggests a genetic link between the intrusion creating the dome and the two DMDs on the northern and southern edges of the dome. Can you make any predictions on the nature of the intrusion given the spectral properties and compositional information on the DMDs? Most DMDs are interpreted to consist of materials similar to the orange, black, and green pyroclastic glass beads returned by the Apollo missions. These melts had very low viscosities and are interpreted to originate from deep mantle sources. Here, a link to a dome-forming intrusion of these melts would be a new observation. Please expand on this question. For example, would picritic melts with low viscosities fit the observed dome formation?
Can you constrain the DMD composition more by using compositional and spectral observations? The DIVINER map in Figure 5d suggests slightly elevated CF for the DMDs,

relative to the remaining crater floor. Can you expand a bit on the difference to the rest of the crater floor? This might provide additional constraints on the nature of the pyroclastic deposits.
Figure 8 e, f, and g need to be revised. It is very hard to read these figures and I suggest to enlarge them substantially.
L71/L78: Unpublished reference. I am not sure what the policy is at Planetary Research when it comes to citing unpublished papers.
L498: I am skeptical of the description of pyroclastic materials as rough and angular. The pyroclastic beads sampled by Apollo, Luna, and Chang'e missions are spherical, and only rarely angular when the beads are fractured. Can you reconcile this with your spectral observations?
L552: This is unclear. Are you suggesting that the pyroclastic deposits have evolved compositions as well?
L579: Please add an appropriate reference for the subsurface thermal gradient effect on the CF

Reviewer 2:
Recommendation: Revisions Required Without Review

All pre-existing data used in the manuscript are publicly available and sufficient information is provided so that they can be found and accessed.

Yes

All significant data products generated as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI).

Yes

All significant numerical codes developed as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI or SWHID).

Not applicable

All pre-existing software used as part of the study are acknowledged, and sufficient information is provided to find, access, and understand the software. If the software is restricted, the conditions under which it can be accessed are publicly available.

Not applicable

If you answered no to any of the above questions, please provide supporting information.

I am uploading an annotated version of the manuscript.

No

Comments for the authors

This is a clearly written and reasoned manuscript about a fascinating patch of the Moon. I have one minor suggestion for manuscript flow:
Section 2 needs a paragraph that outlines or introduces the section. There are lots of different data sets, observation methods or models that could have been used, the reader would like to know why these particular ones were chosen and if/how they complement or each other. I found the figures illustrative and well described, and the conclusions based on the findings in the paper. I will enjoy seeing this manuscript in print.

AUTHOR REBUTTAL
round 1

Response to the editor & reviewers

Dear Dr. Jessica Flahaut,

I would like to thank you for submitting your manuscript "Geology of Atlas crater, the prime landing site of the Emirates Lunar Mission Rashid-1 rover" (#274) to Planetary Research. I have now received the reviews and associate editor assessment of your submission, which are included at the bottom of this email. Based on my evaluation of your submission, your manuscript should in principle be suitable for publication after revision focusing specifically on the realism of the petrological implications of the model.

Please provide us with a point-by-point response to all comments and identify what changes you have made to the revised manuscript. In addition to the rebuttal, we ask that you also provide a document that tracks all changes that have been made to your manuscript since its initial submission.

When you have completed your revisions, you can upload the revised manuscript, your response and a tracked changes document from your submission dashboard.

If you have any questions about the recommendations in your review, or if you are unsure how to respond or proceed, please do not hesitate to contact me from your submission dashboard.

Sincerely,

Justin Filiberto
Editor, Planetary Research

Dear Sir,

We are grateful to the reviewers for their very positive evaluation of our manuscript. Please find below a detailed response to their comments.

We hope our modifications match your expectations.

Thank you for your consideration.

Jessica Flahaut, on behalf of the authors

Associate editor recommendation

I believe the reviewers make a compelling case to revise regarding their central hypothesis, specifically on the compositional aspects brought up by Reviewer 1.

The following comments were received from the reviewers.

Reviewer 1:

Recommendation: Revisions Required With Review

All pre-existing data used in the manuscript are publicly available and sufficient information is provided so that they can be found and accessed.

Yes

All significant data products generated as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI).

Yes

All significant numerical codes developed as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI or SWHID).

Yes

All pre-existing software used as part of the study are acknowledged, and sufficient information is provided to find, access, and understand the software. If the software is restricted, the conditions under which it can be accessed are publicly available.

Yes

If you answered no to any of the above questions, please provide supporting information.

I am uploading an annotated version of the manuscript.

No

Comments for the authors

This study presents a detailed investigation of the lunar Atlas crater, which was the prime target of the Emirates lunar mission. The authors base their work on multi-spectral datasets and use a multi-method approach for the characterization including geological mapping, crater counting, spectral analysis, rheological modelling, and Earth based

telescopic observations. The choice of datasets is broad and covers compositional, mineralogical and topographical properties of the studied area very well.
A central hypothesis is the genetic link of a shallow laccolith intrusion suggested to be evolved in compositions, and the pyroclastic deposits in the two dark mantle deposits (DMDs). This is unusual and requires some petrological considerations in the discussion. All returned lunar pyroclastic beads are mafic to ultramafic in composition. Furthermore, petrological constraints suggest very deeps sources of more than 300km, with low viscosity melts rising at speeds of 20 to 30 m/s (Wilson & Head 2018 GRL). Therefore, DMD-forming low viscosity melts are unlikely to form shallow laccoliths capable of causing the observed uplift. This would require slowly moving low-viscosity melts instead. The authors need to reconcile this problem.

Thank you for this comment. This observation is actually not uncommon on the Moon, especially in floor-fractured craters, where shallow intrusions co-occur with pyroclastic deposits (e.g., in Atlas, but also Alphonsus crater, Humboldt crater, Petavius crater, etc...). Because the DMDs are distributed along the fractures created by the intrusion and subsequent uplift, it is reasonable to assume they postdate the emplacement of the laccolith. We will hence argue that both can be same magmatic system evolving through time, with first, magma rising but stalling beneath the crater floor, and spreading laterally as a sill or lens-shaped intrusion, causing uplift and radial/concentric fractures. Those fractures could have later acted as pathway for the rapid ascend and decompression of gas-rich magmas, resulting in fire-fountain–style eruptions. Previous authors have already discussed the consequences of magmatic intrusion evolution such as magma degassing/volatile production, and the possibility of associated venting / vulcanian eruptions vs mare eruption (e.g., Jozwiak et al., 2015; Head and Wilson, 2017).

This hypothesis is now further explained in the text, l. 473 :

“ Another important implication of FFC formation by magmatic intrusion and sill formation is the subsequent cooling, evolution, and degassing of the laccolithic magma which can be associated with venting and pyroclastic eruptions (e.g., Head and Wilson, 1979; Jozwiak et al., 2015). Volatile accumulations exceeded the tensile strength of the overlying crater floor would result in localized explosive, vulcanian eruptions emplacing both fine-grained juvenile and non-juvenile material. Previous studies predict that associated pyroclastic deposits will be localized along fractures, specifically near the periphery of the crater floor, where subsidiary diking from the intrusion is most likely to occur (Jozwiak et al., 2015).“

In addition, we added the following references that describe other FFC with pyroclastics deposits:

- Head and Wilson, 1979
- Head and Wilson, 2017
- Wilson and Head, 2017
- Keske et al., 2020

Figure 4 suggests a genetic link between the intrusion creating the dome and the two DMDs on the northern and southern edges of the dome. Can you make any predictions on the nature of the intrusion given the spectral properties and compositional information on the DMDs? Most DMDs are interpreted to consist of materials similar to the orange, black, and green pyroclastic glass beads returned by the Apollo missions. These melts had very low viscosities and are interpreted to originate from deep mantle sources. Here, a link to a dome-forming intrusion of these melts would be a new observation. Please expand on this question. For example, would picritic melts with low viscosities fit the observed dome formation

Can you constrain the DMD composition more by using compositional and spectral observations? The DIVINER map in Figure 5d suggests slightly elevated CF for the DMDs, relative to the remaining crater floor. Can you expand a bit on the difference to the rest of the crater floor? This might provide additional constraints on the nature of the pyroclastic deposits.

The dome is not within the area mapped in figure 4. It seems that the reviewer is referring to mounds from the Altas crater central peak complex ? In this case, as explained lines 357-360 and 458-472 , the mineralogy of the central peaks is characterized by the presence of mixed pyroxene, plagioclase and spinel signatures and interpreted as evidence for a pluton at depth. The link between intrusive activity and DMDs was addressed in the previous comment.

The DMDs have mafic mineral signatures with both M3 and Diviner and are indeed likely the result of the rapid ascent of low viscosities melts (as they preserved their gas). The CF of the DMD, which are likely dominated by glass and pyroxene, is indeed higher than the crater floor, initially of feldspathic nature, which is consistent with their enrichment in mafic minerals. We added the following sentence to clarify, as suggested :

l. 355 *"Diviner CF values of 8.2 within the DMDs suggest the presence of mafic components"*.

We also further expanded the discussion session to discuss the spectral signatures of pyroclastic deposits :

l. 489-504: *"Spectral analyses of DMD at a global scale have uncovered a wide compositional diversity among deposits (e.g., Gaddis et al., 2000, 2003; Besse et al., 2014)* *that evidence varying modes of emplacements (e.g., Head and Wilson, 2017). Whereas regional DMD have been argued to form as the result of strombolian or hawaiian eruptions, localized DMD such as the ones in Alphonsus crater have been interpreted as evidence for vulcanian eruptions (Head and Wilson, 1979, 2017). In the latter, the explosion of a solid, near-surface plug of wall-rock material at the top of a dike would result in proximal accumulation of coarse clasts with limited dispersion of fine ash material (Head and Wilson, 2017; Keske et al., 2020).*

Atlas crater deposits were previously described as small-scale pyroclastic deposits, with a highland component mixed with fragmental basalt and a low glass content (Gaddis et al., 2003, 2012). Our spectral analysis of both deposits is consistent with VNIR signatures of LCP and/or green glass, although they show different albedos and TiO2 contents. Diviner CF values are slightly more elevated than those of the crater floor, and could be consistent with mixed wall-rock and juvenile (glass or crystalline basalt) material. Hence Atlas pyroclastic deposits could be, as in Alphonsus crater, products of a vulcanian eruption. Analyses of both photometric and spectropolarimetric data confirm that the pyroclastic deposits differ from mare basalts, with a distinct porosity, grain size or roughness, and/or glass content (see next section)."

In addition, we added the following references that describe spectral analyses of pyroclastic deposits :

- Gaddis et al., 2000
- Besse et al., 2014

Figure 8 e, f, and g need to be revised. It is very hard to read these figures and I suggest to enlarge them substantially.

Agreed, figure 8 was reformatted and enlarged.

L71/L78: Unpublished reference. I am not sure what the policy is at Planetary Research when it comes to citing unpublished papers.

The reference to Dapremont et al. was removed as the manuscript in still under revisions/ pending acceptance.

The reference to Els et al. was removed as the paper is still not submitted and was replaced by an EGU abstract (2021) from the same author.

L498: I am skeptical of the description of pyroclastic materials as rough and angular. The pyroclastic beads sampled by Apollo, Luna, and Chang'e missions are spherical, and only rarely angular when the beads are fractured. Can you reconcile this with your spectral observations?

Except for Apollo 17, none of the previous landed missions really analyzed large DMDs as those identified from orbit. Gaddis et al., (2003) show a great diversity of signatures and compositions within DMDs, with some of them like being emplaced by vulcanian or Hawaiian eruptions, while others most likely correspond to strombolian eruptions. Head and Wilson (2017) specify that orange and black beads such as the ones from Apollo 17 / Taurus-Littrow are diagnostic of fast cooling in Hawaiian-style eruptions, which is not the model favored for FFC craters such as Alphonsus or Atlas. On the contrary, the authors suggest that Alphonsus crater is the result of a Vulcanian eruption, with less juvenile components (i.e., more wall rock contribution) being observed in the DMDs. Spectral analyses by Allen et al. (2013) in Alphonsus also concluded "that the eruption products should be dominated by crystalline basalt fragments similar in elemental composition and mineralogy to mare lavas". We believe the same conclusions apply to Atlas crater.

Hence, the signatures of LCP within Atlas crater could correlate with the presence of rougher blocks from the wall rocks or from scoria and would argue against a large proportion of smaller, glassy beads.

We clarified this point in the discussion

L497 : " *Atlas crater deposits were previously described as small-scale pyroclastic deposits, with a highland component mixed with fragmental basalt and a low glass content (Gaddis et al., 2003, 2012). Our spectral analysis of both deposits is consistent with VNIR signatures of LCP and/or green glass, although they show different albedos and TiO2 contents. Diviner CF values are slightly more elevated than those of the crater floor, and could be consistent with mixed wall-rock and juvenile (glass or crystalline basalt) material. Hence Atlas pyroclastic deposits could be, as in Alphonsus crater, products of a vulcanian eruption. Analyses of both photometric and spectropolarimetric data confirm that the pyroclastic deposits differ from mare basalts, with a distinct porosity, grain size or roughness, and/or glass content (see next section).*"

L552: This is unclear. Are you suggesting that the pyroclastic deposits have evolved compositions as well?

No, this sentence was referring to the viscous dome. We added *", for instance in viscous domes"* for clarification (this is now line 585).

L579: Please add an appropriate reference for the subsurface thermal gradient effect on the CF

A reference to Lucey et al. (2021) was added.

Reviewer 2:

Recommendation: Revisions Required Without Review

All pre-existing data used in the manuscript are publicly available and sufficient information is provided so that they can be found and accessed.

Yes

All significant data products generated as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI).

Yes

All significant numerical codes developed as part of the study have been uploaded to a public repository (or will be at the time of acceptance) and are cited using a persistent identifier (such as a DOI or SWHID).

Not applicable

All pre-existing software used as part of the study are acknowledged, and sufficient information is provided to find, access, and understand the software. If the software is restricted, the conditions under which it can be accessed are publicly available.

Not applicable

If you answered no to any of the above questions, please provide supporting information.

I am uploading an annotated version of the manuscript.

No

Comments for the authors

This is a clearly written and reasoned manuscript about a fascinating patch of the Moon. I have one minor suggestion for manuscript flow:

Section 2 needs a paragraph that outlines or introduces the section. There are lots of different data sets, observation methods or models that could have been used, the reader would like to know why these particular ones were chosen and if/how they complement or each other. I found the figures illustrative and well described, and the conclusions based on the findings in the paper. I will enjoy seeing this manuscript in print.

We are very grateful to the second reviewer for his very positive and encouraging words. As suggested, we have added the following section to briefly introduce section 2:

" A range of techniques, including remote sensing analyses of lunar orbiters data (sections 2.1 to 2.3) and telescopic, spectropolarimetric observations (section 2.5) were combined with rheologic modeling (section 2.4) to infer the geologic and magmatic history of the area".