

**Integrated Mineralogy and High Resolution Geologic Context of Lunar
Impact Melt Deposits: Implications for Crustal Diversity and the
Impact Cratering Process**

By

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of the degree of Doctor of Philosophy

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RESEARCH INTERESTS

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RESEARCH EXPERIENCE

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▪ Remote mineralogical characterization of impact-melt deposits on the Moon. ▪ Carried out non-linear spectral mixture analysis for quantitative mineral abundance estimation. ▪ Analyzed spectral character of high titanium basalts at Mare Tranquillitatis on the Moon. ▪ Actively participated in the image data calibration of NASA Moon Mineralogy Mapper (M³) instrument onboard India's Chandrayaan-1 mission. Contributed towards mineral spectral signature validation among variety of calibration versions for numerous lunar targets.	
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PUBLICATIONS IN PEER REVIEWED JOURNALS

1. Pieters C.M. K.D. Hanna, L. Cheek, **D. Dhingra**, T. Prissel, C. Jackson, D. Moriarty, S. Parman and L.A. Taylor (2014) The distribution of Mg-Spinel across the Moon and constraints on crustal origin, *American Mineralogist*, *in press*
2. Prissel T.C., S.W. Parman, C.R.M. Jackson, M.J. Rutherford, P.C. Hess, J.W. Head, L. Cheek, **D. Dhingra**, and C.M. Pieters (2014) Pink Moon: The Petrogenesis of Pink Spinel Anorthosites and Implications Concerning Mg-suite Magmatism, *Earth and Planetary Science Letters*, *Accepted*
3. **Dhingra D.**, C.M. Pieters, J.W. Head, P.J. Isaacson (2013) Large Mineralogically-distinct Impact melt feature at Crater Copernicus: Evidence for Retention of Compositional Heterogeneity, *Geophys. Res. Lett.*, **40**, 1-6, doi: 10.1002/grl.50255
4. **Dhingra D.**, C.M. Pieters, J.W. Boardman, J.W. Head, P.J. Isaacson and L.A. Taylor (2011) Compositional Diversity at Theophilus Crater: Understanding the Geological Context of Mg-Spinel bearing Central Peaks, *Geophys. Res. Lett.*, **38**, L11201, doi: 10.1029/2011GL047314
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8. Staid, M. I., C. M. Pieters, S. Besse, J. Boardman, **D. Dhingra**, R. O. Green, J. W. Head, P. Isaacson, R. Klima, G. Y. Kramer, J. F. Mustard, C. Runyon, J. M. Sunshine, and L. A. Taylor (2011) The mineralogy of late stage lunar volcanism as observed by the Moon Mineralogy Mapper on Chandrayaan-1, *J. Geophys. Res.*, **116**, E00G10, doi:10.1029/2010JE003735
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10. **Dhingra D.** (2008) Exploring Links Between Crater Floor Mineralogy and Layered Lunar Crust, *Adv. in Space Res.*, **42**, 275 – 280

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12. Bhandari N., V. Adimurthy, D. Banerjee, N. Srivastava and **D. Dhingra** (2004) Chandrayaan-1 Lunar Polar orbiter: Science Goals and Payloads, *Proc. International Lunar Conference 2003 / ILEWG 5*, Hawaii, 33-42
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OTHER PUBLICATIONS

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7. **Dhingra D.**, J.F. Mustard, S. Wiseman, M. Pariente, C.M. Pieters and P.J. Isaccson (2011) Non-linear spectral unmixing using Hapke modeling: Application to remotely acquired M³ spectra of spinel bearing lithologies on the Moon, *42nd Lunar and Planet. Sci. Conf.*, Abst#2431. *Poster Presentation*
8. **Dhingra D.**, C.M. Pieters and 7 Others (2010) Spectroscopic signature of the high Titanium basalts at Mare Tranquillitatis from Moon Mineralogy Mapper (M³), *41st Lunar and Planet. Sci. Conf.*, Abst# 2494. *Oral Presentation.*
9. **Dhingra D.** (2009) Lithological mapping of lunar terranes using hybrid classification approach, *40th Lunar and Planet. Sci. Conf.*, Abstract#1456. *Poster Presentation.*
10. **Dhingra D.** (2008) Compositional mapping of Tsiolkovsky central peak: Feasibility study of probable lunar landing site, *National Symposium on Advances in Remote*

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11. **Dhingra D.**, N. Srivastava and N. Bhandari (2004) Global high resolution studies of olivine rich areas on the Moon by Hyper Spectral Imager onboard Chandrayaan-1 mission: Possible Implications, *National Symposium on Planetary Sciences Research in India*, PRL, Ahmedabad.

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 - Icarus, Elsevier
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 - Core Team Member – Indian Imaging Payloads onboard Chandrayaan – 1
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TEACHING PROFICIENCY AND DEVELOPMENT

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- Science Teaching Volunteer, Vartan Gregorian Elementary School, Providence, RI (2012-2013). Developed and taught science lessons to 2nd graders.
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 - Teaching Consultant Program. Developed teaching strategies through peer observation as well as skills to provide effective feedback.
 - Professional Development Seminar. Developed teaching portfolio including teaching philosophy statement, course syllabus and broad research impact statement.

SCIENCE COMMUNICATION

Articles/Reports

- **Dhingra D.** (2014) Fireworks in the Earth's Sky Sent from the Moon: Reflections from LPSC 2014 (<http://www.planetary.org/blogs/guest-blogs/2014/0401-fireworks-in-the-earths-sky.html>)

- **Dhingra D.** and R.D. Dhingra (2009) Lunar and Planetary Science Conference, Meeting Report, *Current Science*, 97(10), 1403-04
- **Dhingra D.** (2008) Planetary Impacts in Focus, Research News, *Current Science*, 95(10), 1394-95
- **Dhingra D.** (2007) Lunar and Planetary Science, Meeting Report, *Current Science*, 93(3), 283-85

Popular Science Talks

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- Indian Moon Mission, National Science Day celebrations, Shivaji University, Kolhapur (*Feb., 2004*)
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- Interesting Science Targets on Lunar Far Side for Chandrayaan-2, Discussion Meeting on probable Science Experiments & Instrumentation on Chandrayaan-2 Mission, Physical Research Laboratory, Ahmedabad (*October, 2007*)
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- Departmental Webmaster, IIT Roorkee Website (2001-02).
- Chief Editor, Departmental Wall Magazine, IIT Roorkee (2000-01).

Acknowledgments

I wish to dedicate this thesis to my family: my parents, wife Rajani and little angel, Oas. I will remain indebted to my parents who, despite their age constraints, supported me in coming to US for Ph.D., leaving them alone in India; my wife who put her career at stake by leaving her job and joining me; and my daughter Oas, who could not get as much love and attention from her father as she deserved ☹. I hope it improves.

My journey into lunar science started 12 years ago with an opportunity to work for India's maiden venture Chandrayaan-1 and a *shloka* (writing) in Sanskrit written several thousand years ago. The Moon was always there in the sky but it suddenly attained a special significance for me ever since I joined the Moon mission team and started learning about it. As the mission documents were being prepared, the *shloka* cited there became a motivation for me. I wish to share it here and by way of it, wish to thank the Moon for enlightening my life:

त्वं सोम प्रचिकितो मनीषा ।
त्वं रजिष्ठ मनु नेषि पन्थाम ॥

(Sanskrit)

(Hindi)

हे सोम ! बुद्धि से हम तुमको जान सकें ।
तुम हमारे लिए उत्तम मार्ग प्रशस्त करो ॥

O Moon!
We should be able to know you
Through our intellect
You enlighten us through the right path

Āgveda part – I / 91 / 1

In my endeavor to learn about the Moon, I feel proud and privileged to have worked with my advisor, Prof. Carle Pieters. I wish to acknowledge all the support that I got from her including her positive responses and excitement for even small results that I used to bring for discussion, her patient listening (especially when I was agitated), her support for attending international conferences and her forgiving nature. It helped me a lot to keep my channels open with her and communicate my needs and concerns. Thank you Carle!

There are a couple more reasons for thanking Carle which I would like to mention here. First and foremost, when I started learning planetary science in India on my own, most of my reading list in lunar spectroscopy was dominated by papers from Carle and her colleagues. Somehow, I was glued to those papers and developed a close affinity with Brown and Carle, so much so, that when I met Carle at the International Lunar Conference in Udaipur (India), I asked for her autograph! There was certainly a lot conveyed through those research papers that created interest in me for lunar science and reflectance spectroscopy. And I wish to thank Carle for this initiation through her work.

There is one more reason to acknowledge my advisor and which has been critical for my presence at Brown. Not many people know that I was admitted to Brown in the year 2004 but decided to withdraw due to personal circumstances. Despite this decision of mine, Carle supported me for a short-term visit in 2007 and later, whole-heartedly supported me when I expressed my intent to come to Brown for Ph.D. Such a positive attitude is rarely seen and I was fortunate to have a person who stood by my side and gave me another opportunity to work with her. Thanks Carle for this generosity and

understanding. There are times in life when things cannot be explained and it was great to see that you still tried to understand the situation.

Before coming to Brown, there have been many strong influences on me which propelled me to take up planetary science as a career. My previous institution, Physical Research Laboratory (PRL), the birth place of the Indian Space Program deserves mention here along with the PLANEX (Planetary Sciences and Exploration) program, where I started my career in planetary science. Prof. Narendra Bhandari and Prof. J.N. Goswami had been my mentors and guides who gave me the opportunity to work on India's Chandrayaan-1 mission. I wish to acknowledge their support in getting me started with lunar and planetary science, their efforts in providing adequate scientific exposure as well as for their trust.

It is also important to acknowledge the people who helped me in applying to Brown by giving recommendation letters. I wish to thank Prof. S.K. Tandon at IIT Kanpur, Prof. G.J. Chakrapani and Prof. B. Parkash at IIT Roorkee for supporting me in my endeavor. Besides, I learnt some of my first lessons in Geology from them. Life is a long journey and there are very few people whom we can always trust. My friend Prabhat is one of those people who has always been there to lend an ear to my concerns, to share my joys and sorrows as well as to give opinion and advice whenever I asked for it. I wish to acknowledge his support in all these years while I was working on my Ph.D.

Coming back to Brown and Providence, there are so many people to thank for their help, initiative and motivation. I wish to give my special thanks to Barbara, Charles, Nancy and Dewey Christy for their personal interest in ensuring the well-being of my

family in all these years. I always consider them as my parents in US. Anne Cote is another person who has helped me right from the time I got into Providence. Thanks Anne for all the help.

Coming to Brown always felt like an honor with the opportunity to work with people like Jim Head, Pete Schultz and Jack Mustard. These were the names I had read in research papers so much that I already had a relationship with the people. I got especially mesmerized by Pete's ability to recall features on the Moon in split second and oozing passion for his observations. It was electrifying. Thanks Pete for the charging.

After coming to Brown in 2009, I also met so many other great minds, Alberto, Liang, Reid and Steve. I am glad to have some of them on my thesis committee. Thank you Steve, Liang, Jack and Jim for being there and providing your inputs in all the five years. I truly appreciate your support and encouragement. I would like to especially thank Jim for his great insights on several topics, in grooming me to write crisply and effectively, to Steve for his teaching and always positive attitude, to Liang for his carefree, accommodating and supportive approach. I did not get an 'A' in your mineralogy class but really enjoyed your teaching. I wish if all the classes were taught that way. Thank you Jack for your inputs on non-linear mixing, for offering help whenever I asked and for your calm attitude. I cannot forget Lynn Carlson for her immensely helpful course on GIS, her commitment to making us understand and for being always available to help whenever needed.

Special thanks to Stefanie Tompkins for agreeing to be my external reader for the thesis. Being alumni of the department and one of the key people who worked on

laboratory spectral characterization of impact melt samples, I also know you for your objectivity and helpfulness. I am glad to have somebody like you for academic discussions and inputs.

Acknowledgement cannot end without friends. Rebecca Greenberger and Chris Havlin are two names that deserve special thanks for all that they did for me. Sandra Wiseman has helped me on so many occasions including programming in IDL, help with ISIS and radiative transfer modeling. Thank you Sandra for the initiative and interest. Jenny, Tim and Jay have always been positive people, willing to help. Thanks Guys. Dan, Leah, Kerri, Shuai and Peter have been there for me on several occasions, helping out and so thanks to you.

Thanks are due to all the awesome admin staff that have promptly helped me all through these years. Bill Collins is one of his kind and so will always be remembered. Thank you Nancy Fjeldheim, Patricia Davey, Margaret, Melissa, Peter Neivert, Lisa Nobel, Gloria and others. It has been a fruitful 5 years and I hope I can emulate the commitment, calmness and smile that all of you carry.

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INTRODUCTION

Planetary surfaces bear imprints of the various geological processes that have taken place and therefore have been extensively used in understanding the evolution of planetary bodies. The global anorthositic layer on the Moon is reminiscent of the magma ocean phase in its evolutionary history [e.g. *Ohtake et al.*, 2009]. Several generations of large scale fractures on some of the icy satellites are an indicator of the changing stress fields on these bodies over geological time-scales [e.g. *Patthoff et al.*, 2011]. The process of impact cratering on planetary bodies make the surface studies all the more productive because it excavates and distributes rocks occurring at several kilometers depth thereby making the subsurface composition available on the surface. Remote sensing of planetary surfaces therefore does not merely skim surface properties but is capable of profiling the sub-surface to a great extent. Geophysical remote sensing such as determination of gravity signatures takes us even deeper.

Compositional information is one of the most important input in understanding the origin and evolution of a planetary body. Although many techniques are used to decipher composition, spectral reflectance studies are one of the foremost analytical methods used in determining composition of planetary surfaces. We use them extensively in this research to understand one of the products of impact cratering, namely impact melt. A brief background of the relevant topics is presented below.

1. Background

1.1. Reflectance Spectroscopy

The technique of reflectance spectroscopy is one of the most powerful remote sensing methods utilized in deciphering the mineralogy of far off surfaces and is based on

the character of reflected light in the UV-VIS-NIR spectral range (400-3000 nm). Sunlight falling on a planetary surface is collected by spectrometer which splits the light into different wavelengths (Figure 1). The intensity of light at different wavelengths is affected by the mineralogy of the surface (along with a host of other factors) and therefore can be used in identifying the dominant composition.

The underlying principle of this technique is linked to the crystal structure of the mineral which is a unique property of each mineral species. Transition elements occupying the various cation sites within the mineral structure (viz. M1, M2) are affected by a crystal field produced by the mineral [*e.g. Burns et al.*, 1993]. In this context, the energies of the d-orbitals of the transition elements are split uniquely by the respective mineral such that the electronic transitions in the cations lead to absorptions around specific wavelengths. There are other modes of absorptions too such as charge transfer and vibrational absorptions which occur in specific parts of the energy spectrum. Thus, minerals have diagnostic absorption bands at specific wavelengths (Figure 2). There are finer scale absorption band position differences within the each mineral group. This information forms the basis of identification of dominant mineralogy on planetary surfaces. There are associated complexities such as the effect of grain size, the optical character of other component minerals as well as the effect of weathering processes. Although these parameters put constraints on the extent of information that can be uniquely derived, even weak absorption bands hold clues to the mineralogical character. At this stage, it depends on the quality of observations in terms of spatial and spectral resolution.

Moon being the closest object in space to our Earth, telescopic studies of the lunar surface have extensively used reflectance spectroscopy for mineralogical identifications [e.g. *McCord and Jhonson*, 1969; *McCord et al.*, 1972; *Pieters and McCord*, 1976]. Further, with the availability of lunar samples, measurements were also made in the laboratory [e.g. *Adams and Jones*, 1970] which continue to provide the crucial ground truth for remote measurements [e.g. *Pieters et al.*, 2000; *Taylor et al.*, 2001]. Reflectance spectroscopy is one of the most commonly used methods for remote compositional analysis. This has been the primary tool in this presented research along with high resolution imaging data.

1.2. Impact Cratering

The process of impact cratering is a fundamental process that has taken place on all the solar system bodies (including the Earth) all through the early history, although with variable intensity. It is an extremely energetic process that occurs over a very short time interval and is unique in this context compared to any other known geological process. The intensity of pressure and temperature reached in a common impact cratering process is several orders of magnitude higher than other geological processes, leading to diagnostic signatures preserved in the cratering products. Although the spatial extent of impact cratering process spans from a zap pit at micron scale to several hundred kilometer sized basins, there are some common aspects of the process that have been identified (Figure 3) [e.g. *Gault*, 1968; *Melosh*, 1989].

The cratering process is commonly divided into 3 stages: i) contact and compression ii) excavation and iii) modification. The exact nature and extent of these

stages varies with crater size. The first stage involves contact of the projectile with the target surface and transfer of energy to the target body. A shock wave is propagated both through the target and the projectile leading to vaporization of most of the projectile material and intense compression of the target to a large spatial extent from the point of impact.

The second stage is dominated by decompression and active displacement and removal of the highly shocked, fractured and partially melted material forming a cavity (transient cavity) at the impact point which grows rapidly. The third stage involves modification of the transient cavity by collapse and slumping of material from the crater walls and large scale movement of the material on the crater floor, which may be melted to different extents. Large scale terraces and rings form during this modification. On large scales, there is significant rebound of the material at depth forming raised structures on the crater floor which are called central uplifts (peaks). These materials have been suggested to represent some of the deepest materials exposed on the surface and are believed to be coming from below the melted zone.

Impact melt is one of the common products of the cratering process that occurs in a variety of forms and spatial scales (Figure 4). It can occur as small melt blobs scattered around the crater, large glass bombs, flows, thick pervasive veneer over the crater units, dikes in the subsurface, host of melt-rock mixtures (with different names) and also as an extensive melt sheet. The vast diversity of morphological forms coupled with their extensive spatial distribution makes impact melt deposits a very interesting geological target. These deposits host wealth of information about the geological character of the target and in some cases, even the projectile. On the Moon, dating of impact melt

deposits has been carried out to obtain geological ages of various large basins which is crucial to understand the cratering rate in the geological past [e.g. *Tera et al.*, 1974]. On Earth, some of them are related to economic mineral deposits. Altogether, impact melt deposits are compelling geological targets. They have been extensively studied on Earth and the Moon in terms of their petrology, structure, morphology, chemistry and several other aspects. However, an integrated remote mineralogical-morphological perspective of impact melt deposits has been largely missing from the research efforts. As a consequence, we do not know the detailed mineralogical character of impact melt deposits, their variability and any association with their morphological form.

While Earth is affected by processes of erosion and weathering making the study of intact exposures difficult, Moon hosts a wealth of information on impact melt deposits largely in their pristine form. We wish to tap into this source of information for understanding the properties of impact melt and their implications for the compositional record of the Moon.

2. Terminology and Usage of Certain Concepts

We wish to discuss a few concepts and terms used in this research and hope that it would clarify any ambiguities that may otherwise creep in owing to certain similarities with terrestrial literature and laboratory/field analysis terminology. The focus of this research on remote sensing observations merits expanding the scope of some of the terminology.

2.1. Impact Melt in the Context of This Study

The term *impact melt* has been used in our research as an umbrella term for various melt-bearing impact products that can be identified by remote sensing observations. These include melt ponds, flows, textured melt, melt deposits with rock fragments and rock fragments coated with impact melt. Unlike terrestrial studies where the impact melt sample can be observed in the field and analyzed in the laboratory, in our case, at the best resolution of 1-10 meters per pixel, it is usually not possible to decipher the melt to un-melted fragment (clast) proportion which is used to sub-classify impact products such as breccias, suevite, melt etc.

We define *impact melt* as partially or completely molten material generated during the impact cratering process which occurs in and around the impact crater. The melted material exhibits diversity of morphological forms and degree of crystallinity as a function of its cooling history.

2.2. Megaclasts

The term *megaclast* has been extensively used in the forthcoming chapters and refers to meter to kilometer-sized rock boulders commonly observed on the melt-rich crater floor. The boulders are either partially or completely covered with impact melt and sometimes, their existence can only be deciphered by small-scale locally elevated features. The relationship of these boulders with impact melt is similar to the occurrence of millimeter to centimeter sized un-melted rock fragments or clasts that are observable in a hand sample of impact melt as well as under a microscope. In both cases, there may or may not be any genetic relationship of the melt with the accompanying clasts. It is

possible that the two entities were formed in different places but were fused together due to the chaotic nature of the cratering process.

We wish to clarify the big size difference between the *megaclasts* and the general term *clast* (Figure 5), the latter being common in impact literature as well as general petrological investigations. The geological entities represented by these two terms may have entirely different way of formation and therefore should not be confused with each other.

In our studies, we have defined 3 varieties of *megaclasts* defined mainly by their respective average size but also by their mode of occurrence to a certain extent. The largest megclasts are referred to as *megablocks*. These are several km in size and many a times have elevations comparable to the central peaks. The second largest megaclasts are known as *isolated mounds*. These are smaller in size than megablocks, a km or so and usually occur as scattered boulders without significant relief around them. The third category of megaclasts is the smallest in size, usually a few 10s to 100s of meters. These are referred to as *hummocky unit* and commonly occur in clusters where subtle relief is observable and distinguishable from the smooth melt devoid of boulders.

2.3. Mineralogical color composites

We make extensive use of color composites derived from spectral reflectance data in order to identify dominant mineralogical differences that are observable on large spatial scales. However, it should be noted that color composites are used as ‘*mineralogical indicator maps*’ and represent only the first step in our mineralogical studies. It is always followed by detailed spectral extraction and analysis. The difference

in mineralogy can only be confirmed by the actual spectra and *not* by color composites alone. Therefore, regions with similar color in color composites may *not* have similar mineralogy. Color composites are generated by mathematical operations on various spectral parameters and therefore they are essentially a representation of mathematical differences to the minutest details. Trained human eye is perhaps better at identifying real differences compared to such mathematical representations. Therefore, the interpretation of color composites should be trusted within the constraints described above.

3. Outline of Chapters

The presented research has been carried out at a variety of spatial scales with each of them offering information of different kind. Accordingly, the chapters in the thesis zoom in and zoom out providing glimpses of the important scientific observations at different spatial scales.

Chapter 1 presents the observations of mineralogy and morphology of impact melt deposits at number of complex craters in survey mode. The idea here is to gather a general feel of the properties of impact melt deposits in terms of what is more common, what is unique and to document the diversity of impact melt at various craters. Since no coordinated mineralogical and morphological studies have been carried out earlier, this forms an essential first step. This information is later used to identify trends and select craters or a particular aspect for further studies. The chapter documents mineralogical heterogeneity as well as homogeneity in impact melt deposits. We then discuss the likely interpretation of the same in terms of geologic setting and the cratering process. The

study also provides a contrast between melt properties at geologically young Copernican craters (<1 billion years) and slightly older Eratosthenian craters (1 – 3.2 billion years).

Chapter 2 focuses on a unique melt feature at Copernicus crater that has a distinct mineralogy compared to surrounding melt deposits. In contrast to its spectral distinctiveness, the feature is not easily detectable on albedo images, neither it has an identifiable topographical signature. The chapter describes the feature using multiple datasets from recent missions. We subsequently use this information in understanding the impact cratering process in terms of mixing of melt at crater scale and the role of target lithologies in influencing the nature of the melt mineralogy.

Chapter 3 presents another focused investigation at Copernicus crater. Here, we provide spectral and morphological evidence for multiple origins of olivine lithology at Copernicus crater. At least one exposure is associated with impact melt indicating its secondary origin. The observations include an in-depth analysis of previously proposed northern wall olivine deposit [*e.g. Lucey et al., 1991*] and its comparison to the well-known olivine-bearing central peaks of Copernicus crater [*Pieters, 1982*]. We also present evidence for occurrence of olivine exposures on the crater floor, highlighting a previously unknown geologic setting for this lithology at Copernicus. We discuss in detail as to what these three occurrences of olivine lithology (in the peaks, wall and crater floor) mean in terms of sources of olivine lithology and highlight the critical implications of this finding on the olivine occurrences elsewhere on the Moon, namely that it is unlikely for all olivine detections to be directly linked to be mantle. We emphasize that some of the olivine exposures (and similarly other mineralogies) could be associated with impact melt making them to be of secondary origin.

Chapter 4 presents a comprehensive analysis of the entire Copernicus crater (still Copernicus, it is so interesting!) excluding the two observations discussed in *Chapter 2 and 3*. The main aspects covered in the chapter include geological mapping of the crater floor and walls, identifying different melt units, mineralogical characterization of impact melt deposits inside and outside of the crater and finally a reconstruction of the pre-impact target geology at the crater location. The melt mineralogy is evaluated at different spatial scales and the obtained results are interpreted in terms of local melt generation and crater-scale melt dynamics. We identify radial differences in the mineralogy of impact melt ponds, potential olivine occurrences in the crater wall and an asymmetry in the mineralogy of the crater floor which aligns with the generally understood geological setting of the area. We also document a large impact melt feature on the southern rim that seems to cut through the thick ejecta pile.

Chapter 5 discusses the impact melt characteristics from the perspective of impact conditions. We compare two craters Jackson and Tycho which are of similar size and formed in broadly similar lithology targets (highlands). Both the craters are geologically young making them good candidates for comparisons in terms of melt morphology and mineralogical character. The basic premise of this study was to evaluate the nature of impact melt deposits formed under similar conditions but at two geographically different locations.

Besides the comparison, the investigation provides an in-depth analysis of the impact melt morphology and mineralogy at each of the craters. It also includes geological mapping of the crater floor region which represents the single largest repository of impact melt. Elevation information was included as an additional parameter in the mapping

effort at both Jackson and Tycho apart from morphology and albedo information. Impact melt deposits on the crater walls and rim, although not specifically mapped, were studied spectrally and morphologically. Several interesting morphological observations related impact melt mobility, mineralogical observations of heterogeneity and some textural association with mineralogy have been discussed here.

Chapter 6 discusses the highlights of the research presented in previous chapters and identifies unresolved issues which could be critical for interpretations. We discuss some new directions that we would like to pursue in future and also suggest improvements in the capabilities for spectrometers on future planetary missions.

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Figure Captions

Figure 1 A schematic showing the determination of surface mineralogy using the technique of reflectance spectroscopy.

Figure 2 Spectral reflectance characteristics of various minerals measured in the laboratory. Note that each of them have absorption bands at slightly different wavelength positions enabling their remote detection. Image taken from Pieters et al., [2014].

Figure 3 A schematic diagram showing the various processes taking place during the cratering event. Subsequent to the contact and compression stage, material is either transported out of the crater (excavated) or moved around (displaced) forming the transient cavity. During the process various regions in the target zones undergo different level of shock. The same is indicated in blue coloration with the numbers representing shock pressures in GPa. Accordingly, the material is vaporized, melted and/or disintegrated. The designation SIV to S0 represents the degree of shock metamorphism undergone by rocks with increasing distance from the impact point. Image source: Kenkmann et al., [2014]

Figure 4 Wide diversity in the spatial scale and nature of impact melt deposits. (a) Exposed massive impact melt sheet displaying columnar jointing at Mistastin Lake, Canada. (b) Dark colored impact melt surrounded by rounded gneiss fragments of different sizes. Southwest sector of the Vredefort structure, South Africa. (c) Impact melt

glass (dark elongated mass) scattered in a matrix of crushed rock fragments. Ries crater, Germany. Images modified from French, [1989].

Figure 5 Difference between clast and megaclast. (a) Light-colored mineral clasts in fine-scale impact melt matrix from Mistastin Lake, Canada. Image Source: French [1998] (b) Megaclasts of various sizes observed on the floor of crater Jackson on the far side of the Moon as observed in Kaguya Terrain Camera image. Note the difference in scale in the two images.

Figures

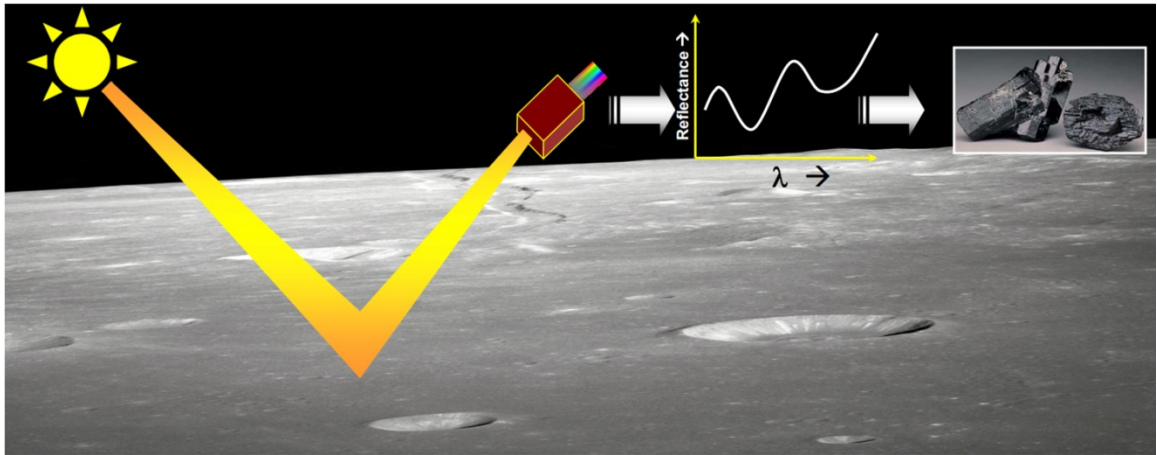


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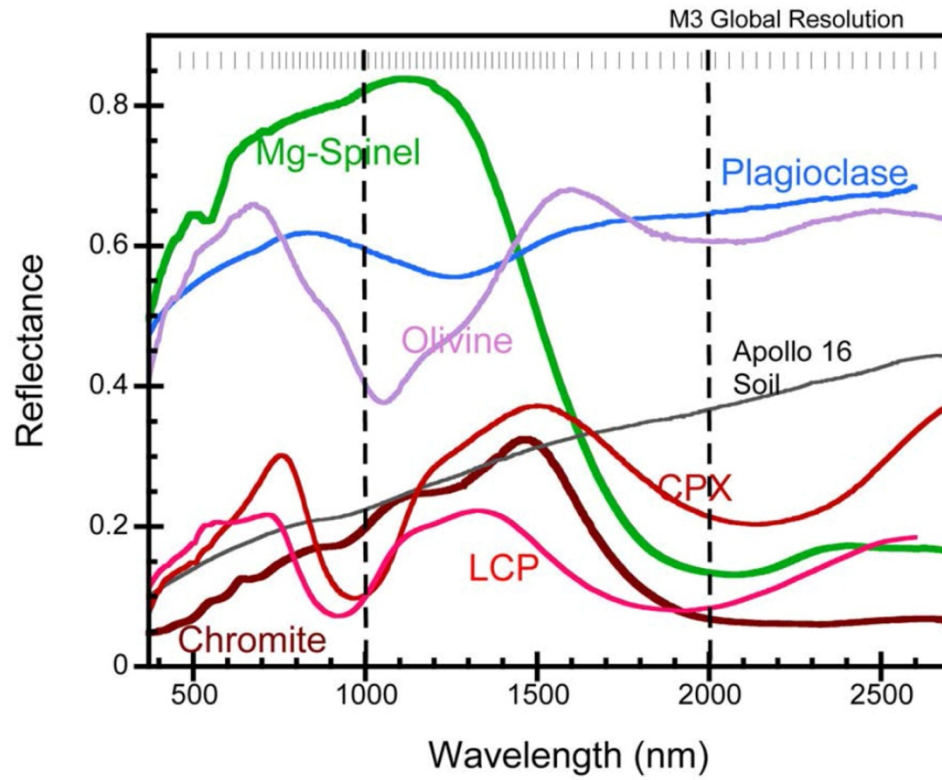


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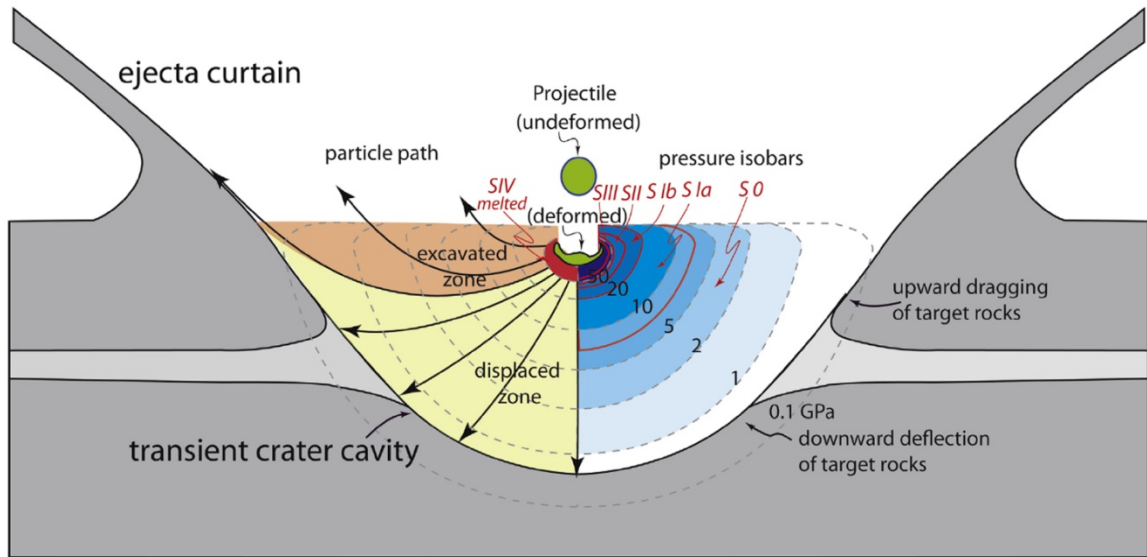


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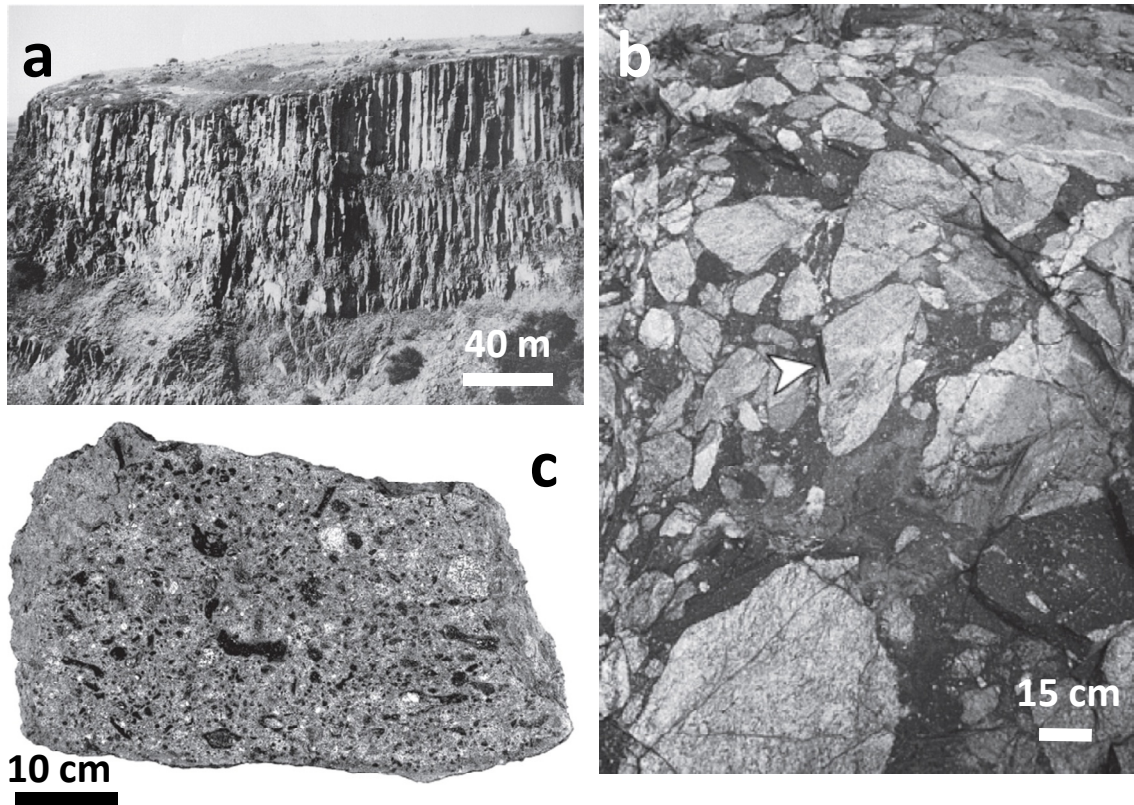


Figure 4 Wide diversity in the spatial scale and nature of impact melt deposits. (a) Exposed massive impact melt sheet displaying columnar jointing at Mistastin Lake, Canada. (b) Dark colored impact melt surrounded by rounded gneiss fragments of different sizes. Southwest sector of the Vredefort structure, South Africa. (c) Impact melt glass (dark elongated mass) scattered in a matrix of crushed rock fragments. Ries crater, Germany. Images modified from French, [1989].

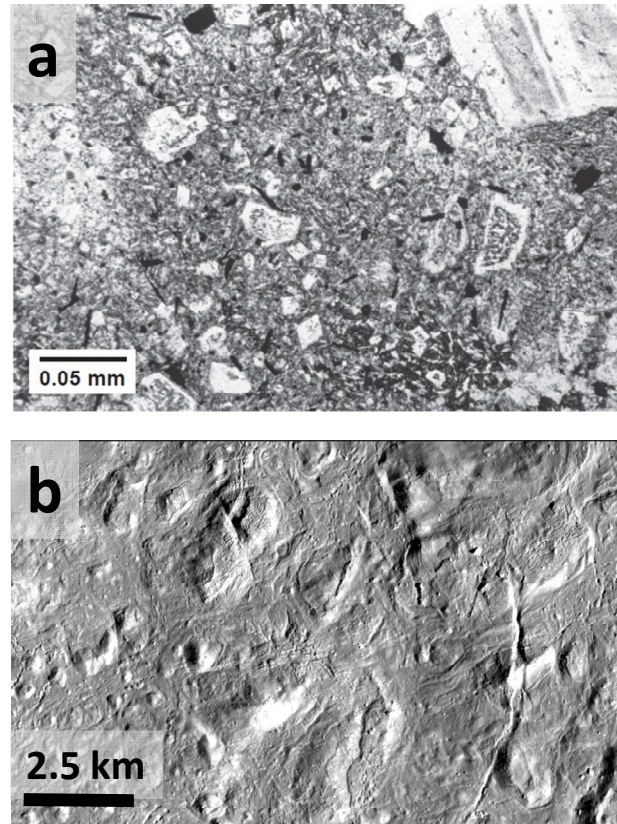


Figure 5 Difference between clast and megaclast. (a) Light-colored mineral clasts in fine-scale impact melt matrix from Mistastin Lake, Canada. Image Source: French [1998] (b) Megaclasts of various sizes observed on the floor of crater Jackson on the far side of the Moon as observed in Kaguya Terrain Camera image. Note the difference in scale in the two images.

CHAPTER 1: Survey of Impact Melt Properties at Lunar Complex
Craters: An Integrated Mineralogical and Morphological Study

Deepak Dhingra

Abstract

Remote mineralogical characterization of impact melt deposits at several lunar complex craters was carried out along with their high resolution geologic context. Impact melt deposits exhibit compositional diversity with well-defined mineral spectral signatures, occasionally similar to igneous rocks. Quench glass is rarely (if ever) observed, and there are no unique spectral signatures observed to be associated with impact melt deposits. In fact, melt mineralogy is closely tied with the nature of the target lithology. We report melt mineralogy that is homogeneous on crater scale as well as heterogeneous impact melt among the studied craters. Mineralogical heterogeneity of impact melt is documented at crater scale (several tens of kilometers) and at small melt ponds (few kilometers) indicating that melt mixing is not always efficient during the cratering process at least at the scale of complex craters. Impact melt mineralogy is shown to be an important contributor to the remotely observed mineralogical diversity of the crust emphasizing the fact that not all of it is primary in origin. Morphological diversity of impact melt deposits is documented along with their geographic extent with several new observations including the documentation of melt fronts (similar to wavefronts) spanning several kilometers. These features could have important implications for impact melt emplacement during the cratering process.

1. Introduction

Impact cratering is one of the most fundamental and widespread process in the solar system that has occurred (and is still occurring with much reduced intensity) on all planetary bodies and at all spatial scales ranging from micron size (e.g. zap pit by micro-meteorite) to thousands of kilometers (forming basins). The geological data record has indicated that the intensity of impact cratering (or the cratering flux) has been variable through geological time [e.g. *Tera et al.*, 1974] although the exact nature of this variation is still debated [e.g. *Morbidelli et al.*, 2012]. The impact process is primarily comprised of three stages: (1) contact and compression, (2) excavation, and (3) modification [e.g., *Gault et al.*, 1968]. Impact melt is a common product of the cratering process and is formed and emplaced primarily during the excavation and modification stages [e.g., *Grieve et al.*, 1977].

Once generated, impact melt is emplaced both within and outside of the crater with greater melt volume residing within as the crater size increases [*Cintala and Grieve*, 1998]. Studies of impact melt deposits at several terrestrial impact craters have provided wealth of information about their character, distribution and the process of formation [e.g. *Grieve et al.*, 1977; *Osinski et al.*, 2008] in different geologic settings. However, as a consequence of weathering and erosional processes on the Earth, it is usually hard to find terrestrial impact craters in an unmodified and unaltered geologic setting. As a consequence, it may become complicated to fully understand the original geologic context including the pre-impact target lithology.

The (largely) pristine surface of the Earth's Moon provides an excellent opportunity to study the products of impact cratering in their unmodified form (except in

the case of modification due to a later impact or volcanic event). The lack of erosion and wide scale tectonic activity coupled with the absence of atmosphere on the Moon has helped preserve the geologic landscape ever since the cratering flux dropped to a minimum, several hundred million years ago. Impact melt on the Moon has been well studied by remote sensing in terms of its morphological diversity and physical properties [e.g. *Howard and Wilshire, 1975; Hawke and Head, 1977*]. It still forms an active field of research [e.g. *Bray et al., 2010; Denevi et al., 2012; Ashley et al., 2012; Stopar et al., 2013*] in view of the availability of high resolution datasets from recent remote sensing missions. Impact melt samples from lunar missions and meteorites is another treasure trove that has been extensively explored [e.g. *Tompkins and Pieters, 2010*] and has provided numerous insights including the occurrence of completely crystalline impact melt rocks which appear almost identical to primary igneous rocks.

In contrast, there has been a dearth of information on the large-scale mineralogical character of lunar impact melt (remote sensing perspective) which forms the crucial end-member other than sample-based studies, since the latter represents only a very small subset with limited geological context. It is critical to understand the larger geologic context and the nature of spectral diversity of impact melt deposits at crater scale and beyond. Impact melt encompasses a wide diversity of melt-rock mixtures ranging from smooth melt to melt-rich clasts to clast-rich melt (Figure 1) giving rise to a diversity of morphological forms including smooth ponds, melt veneers, melt/debris flows and also as a large hummocky landscape with un-melted rock boulders (megaclasts) surrounded by pools of melted rock. It therefore represents a continuum which also encompasses varying degrees of crystallinity (as a function of cooling history)

from glassy to completely crystalline [e.g. *Tompkins and Pieters*, 2010]. This observed diversity in the morphology and crystallinity begs an obvious question about the spectral (compositional) character of impact melt and whether these secondary compositions have any role in contributing to the crustal compositional diversity. This is the prime motivation of the study presented here.

Very few studies in the past [e.g. *Smrekar and Pieters*, 1985; *Dunkin and Heather*, 2003] have dealt with the mineralogical character of impact melt from orbit (or telescopes in the past) leaving a large gap in our understanding of these deposits. This study forms part of an extensive effort [e.g. *Dhingra and Pieters*, 2011; *Dhingra and Pieters*, 2012; *Dhingra et al.*, 2013a, *Dhingra et al.*, 2014a, 2014b] in characterizing the impact melt mineralogy on the lunar surface along with their corresponding geologic context.

2. Scope of Research and Major Objectives

The high density of craters [e.g. *Head et al.*, 2010] observable on the lunar surface is reminiscent of the huge volume of impact melt produced during their formation over geological time scale. The relatively pristine lunar surface has preserved these impact melt deposits and therefore significant quantity of impact melt likely resides in the lunar crust (concentrated in the upper few kilometers). Impact melt, by virtue of its formation by recycling of primary and/or secondary crusts on the planetary surfaces could be regarded as the Moon's tertiary crust. While this nomenclature is different than the conventional description of tertiary crust [e.g. *Taylor*, 1989] where it has been suggested to form only at convergent plate margins on the Earth, the formation of impact melt by

crustal recycling and its global extent technically qualifies it as a tertiary crust. It is especially relevant in case of the Moon since much of the impact melt is still preserved there. One of the objectives of this research is to evaluate the impact melt deposits from the perspective of a pervasive (although discontinuous) crustal unit.

Recent high resolution imaging (from multiple instruments onboard different missions) has highlighted the pervasive nature of impact melt deposits, especially noticeable at some of the geologically young craters (<1 billion years, Copernican age) such as Tycho, Jackson and Giordano Bruno. Apart from being present on the crater floor and walls, impact melt has also been observed to be covering the central peaks in some cases [*e.g. Ohtake et al.*, 2009; *Kuriyama et al.*, 2013; *Dhingra et al.*, 2014a, 2014b]. Their occurrence as ponds and flows on both inside and outside of crater floor, known from previous remote sensing observations [*e.g. Howard and Wilshire*, 1975], has witnessed a dramatic rise in terms of the spatial extent and diversity, with the availability of new datasets.

It is therefore important to document the mineralogical character of these pervasive deposits to answer questions such as: Do the impact melt deposits have any distinctive spectral signature? What is the dominant mineralogical form of impact melt deposits: glassy/amorphous or crystalline? Can impact melt deposits be mineralogically distinguishable from the primary, un-melted lithologies exposed at crater walls, central peaks and in the crater ejecta deposits? What is the role of impact melt mineralogy in the observed mineralogical diversity of the crust?

We have carried out a systematic survey of impact melt deposits at selected complex craters on the Moon in order to answer some of these questions. This study

documents the mineralogical character of impact melt along with its corresponding geologic context in order to identify the major impact melt properties across craters. Subsequently, we aim at understanding the physical basis of these observations and their implications for the mineralogy of the lunar crust as well as the cratering process.

3. Data and Methods

We have used high spatial and spectral resolution data from various missions sent to the Moon in recent times. In order to determine mineralogy of the melt deposits, data from Moon Mineralogy Mapper (M³) instrument [Pieters *et al.*, 2009; Green *et al.*, 2011] onboard Chandrayaan-1 mission [Goswami and Annadurai, 2009] was used. High resolution imaging data from Terrain Camera [*e.g.* Haruyama *et al.*, 2008] onboard Kaguya mission and Narrow Angle Camera (NAC) [*e.g.* Robinson *et al.*, 2010] onboard Lunar Reconnaissance Orbiter mission [*e.g.* Chen *et al.*, 2010] were used to determine the geologic context for the spectral observations. The instrument details are provided in Table 1. These datasets were acquired for 13 complex craters (Table 2) located in different parts of the Moon (Figure 2) and range in diameter from 22 – 114 km. Most of the selected craters are geologically young (~1 billion years old or younger) and therefore offer the best chance for studying impact melt deposits in their least altered form. The selected craters sample a diversity of geological terranes with varied lithologies and crustal thicknesses allowing assessment of impact melt properties in different geologic settings. Additionally, we have also focused on craters located in heterogeneous targets (*e.g.* Mare-Highland boundary) to understand the process of melting including degree of mixing and retention of original target heterogeneity.

The datasets were used independently to extract useful information and also together (by overlaying and cross-comparison) to carry out complimentary science. The spectral data from M³ was initially explored by generating spectral parameters for identifying major compositional differences. In this regard, each crater was observed independently in several parameters and also in the form of a color composite by combining parameters. We have used two types of color composites in this study. The most common composite is called M³ standard color composite where the strength of 1000 nm band (IBD 1000) is coded in red color, the strength of 2000 nm absorption band (IBD 2000) is coded in green color and blue color represents reflectance at 1489 nm. In this rendition, olivine and/or quenched glass dominated regions would appear red, pyroxene dominated regions would appear green and orange while feldspathic terrains and fresh craters would appear blue. The three parameters are graphically shown in Figure 3a and described in Table 2.

A complementary color composite was used to sub-divide the pyroxene-rich regions into low-calcium pyroxenes (common in lunar highlands) and high-calcium pyroxenes (common in mare regions). In this color composite, the green and blue colors are assigned to band strength at 1900 nm (BD1900) and 2300 nm (BD2300). The red color is still assigned to IBD1000. The derivation of the BD1900 and BD 2300 parameters along with band assignments used for the two color composites is also provided in Table 3. It should be noted here that the parameter images are only indicative of the relative dominance of a particular mineralogy but do not uniquely confirm their presence. Accordingly, the color of a region does not mean anything unless confirmed by the spectral character. Therefore, the initial compositional analysis using parameter

images and color composites was followed by an evaluation through actual spectral sampling and analysis of the spectra with and without continuum removal, as necessary. The continuum removal process removes the spectral slope and helps to identify the fine scale spectral differences such as shape and wavelength position of the absorption bands.

The high resolution imaging data was used to identify different melt morphologies which could then be compared in terms of their mineralogical character. This integrated analysis was very useful in cases where strong spectral signature was observed but the relatively low spatial resolution of the spectral data (140-280 m/pixel) was insufficient to determine the specific feature associated with the signature. In such cases, high spatial resolution imaging data (1-10 m/pixel) helps a lot to understand the geologic context.

In the presented work, we have made a general schematic of the likely crustal composition at each of the studied craters. In this context, we have utilized the detailed mineralogical analysis of the crater and the broad geologic context of the region. The purpose of this schematic is to develop an expectation for the likely impact melt mineralogy at the crater. Although representative spectra from the crater may be useful for interpreting melt mineralogy, the schematic helps in further understanding the relative proportions of different mineral components as well as their likely physical form.

An example schematic is shown in Figure 3b. Here, the dominant mineralogy is represented by the background color. In cases, where there are two dominant mineralogies such as anorthosite and noritic anorthosite, we display the background as combination of two colors with changing gradient. Other major lithologies are displayed as large and small boxes within the dominant mineralogy and at different relative depths

guided by the observations of various crater units (wall lithology would be near-surface while peak lithology would be from greater depth). In certain cases, the same mineralogy may be observed in different physical form. An example is clinopyroxenes occurring in basalts on the surface and as intrusions/breccia units at depth and observable either in the central peaks.

It should be noted that the intent of the schematic is mainly to provide a broad scale understanding of the target geologic setting. The presented schematic is not a geologic cross-section.

4. Results

There is a wide spectral diversity in the character of impact melt deposits in addition to their morphological diversity, some of which is known from earlier studies. We describe below the properties of impact melt at each of the craters in terms of the observed melt morphology, spatial distribution and dominant mineralogical trends. We also broadly describe the geologic setting of the region to provide an understanding of the pre-impact target geology and then compare it with the observed mineralogical signatures at the crater. Subsequently, we contrast the observed properties between the studied craters in order to identify any common properties and unique signatures.

4.1 Copernicus

4.1.1 Regional Geology

Copernicus (9.62° 339.92°; 96 Km) is a young impact crater (~880 million years) with an extensive ray system, located on the nearside of the Moon (Figure 4a, b). It

defines the youngest stratigraphic unit of the lunar time scale (Copernican age; <1.1 billion years). Copernicus is located in the Oceanus Procellarum region, very close to the southern end of Imbrium basin. There are extensive basalts surrounding Copernicus along with large pyroclastic deposits in the east (e.g. Rima Bode, Sinus Aestuum). Stratigraphically, Copernicus crater formed on top of all these geological units and likely had the opportunity to excavate through this diverse geologic setting (Figure 4e). The mineralogical character of lithologies in and around Copernicus, amply capture this diversity (Figure 4f, g). The crater has been extensively studied using telescopic and spacecraft datasets [e.g. *Lucey et al.*, 1991; *Pinet et al.*, 1993]. The region is dominated by norites-anorthositic norites in the north (characterized by low-calcium pyroxenes) and basalts in the south (characterized by high calcium pyroxenes). The well-known olivine-bearing central peaks at Copernicus [*Pieters*, 1982] indicate an additional level of heterogeneity in the target at depth. A large olivine-bearing exposure on the northern wall was suggested later [e.g. *Lucey et al.*, 1991] and confirmed more recently [*Song et al.*, 2013]. Based on the recent datasets, chrome-rich spinels have been reported in Sinus Aestuum [e.g. *Sunshine et al.*, 2010; *Yamamoto et al.*, 2013] and found to occur close to the eastern rim of Copernicus [*Sunshine et al.*, 2014]. Lastly, heterogeneities have been observed in the impact melt at large scale [e.g. *Dhingra et al.*, 2013a] and small scale [*Dhingra et al.*, 2013b; *Dhingra et al.*, 2014a, 2014b] highlighting the complex nature of the pre-impact target material.

4.1.2 Impact Melt Distribution and Morphology

Impact melt deposits are observed all over Copernicus crater including crater exterior, walls and the floor. There seems to be some melt cover on the peaks, in particular, the south face of the western peak unit and the northern part of the eastern peak unit. However, the exposures are indistinct and could also be debris flow. The impact melt displays diverse morphologies including large ponds on the terraces and close to the crater rim. Melt veneers are observed all over the crater, especially observable on the walls. Some spectacular flow features occur at Copernicus. A well-known flow occurs on the northern wall. Two additional features are reported in this study. One of them is located outside the southern rim and extends for several tens of kilometers. The second feature is morphologically not detectable and was discerned through mineralogical analysis [Dhingra *et al.*, 2013a] wherein the sinuous nature of the feature is nicely captured (see Figure 4d, green feature on the crater floor). *Chapter 4* focuses exclusively on Copernicus crater and carries an in-depth description of the impact melt analysis including its mapping and spectral character. A summarized version is however, provided here for highlighting major impact melt observations and to allow comparison with impact melt properties of other craters discussed in this study.

4.1.3 Impact Melt Mineralogy

The mineralogy of impact melt at Copernicus crater is perhaps the most diverse among the various craters analyzed in this study and is observed at different spatial scales, each one recording a different part of the cratering process that led to the formation of Copernicus. The mineralogy of the melt is spatially variable and cannot be generalized. The soil on the melt-rich crater floor displays a very weak to non-existent

absorption band in the north-western quadrant except within the sinuous melt feature (described under special mention). The soils in the remaining part of the crater are either featureless or relatively more mafic.

Interestingly, the mineralogy of the impact melt ponds follows similar trend as the floor melt and is also shared by the mineralogy of ejecta material. Morphologically identifiable melt ponds located in different parts of the crater systematically document feldspathic (featureless) mineralogy in the north and more mafic mineralogy in the south. The observed mineralogical differences in impact melt ponds are detectable even in the soils and therefore indicate that very distinct lithological components were melted in different parts of the craters and they did not have much mixing with each other. The detailed description of this analysis is provided in *Chapter 4*.

The local melt mineralogy is much more heterogeneous. Fresh craters in the western part of the melt-rich floor display high-calcium pyroxene signatures [*Dhingra et al.*, 2013]. Pyroxenes are also more prevalent species on the southern crater floor. The exposures are usually small craters but are sometimes represented by fresh exposures of large blocks on the floor. We also observe olivine or quenched glass-bearing isolated outcrops on the crater floor. The spectral signatures of some of the outcrops are as strong as the olivine signatures in the peaks or the northern wall exposure while other exposures have weak and noisy spectra due to their small size. Most of the exposures are associated with high standing mounds which are located in the northern part of the crater, usually far from the olivine-bearing peaks. We have interpreted these to be likely un-melted target rocks incorporated into the impact melt [*Dhingra et al.*, 2014a; *Dhingra et al.*, 2014b].

Detailed analysis, interpretations and implications of this finding is presented in *Chapter 3*.

Scattered exposures bearing strong 1000 nm absorption band are observed in different parts of the crater and associated with either impact melt (Figure 5) or in-situ wall exposures. The southern rim and beyond show much more spectral diversity as compared to the remaining crater. In some cases, impact melt ponds and flows can be morphologically identified and spectrally discernable, contributing to the observed spectral diversity. In other cases, it is hard to distinguish melt splashes and veneer from lithified ejecta. Irrespective, there is ample evidence for impact melt displaying distinct mineralogy and heterogeneity at Copernicus.

4.1.4 Special Mention

Two observations at Copernicus merit special mention for their unique properties and implications for our understanding of impact melt systematics:

- i) On a regional scale, a 30 Km long sinuous feature is observable on the crater floor with low-calcium pyroxene mineralogy in contrast to high-calcium pyroxene mineralogy of the nearby impact melt excavated through two fresh craters (See color composite in Figure 4d). It is the only documented melt feature of this nature on the Moon so far [Dhingra *et al.*, 2013] and clearly illustrates the preservation of target heterogeneity in impact melt and lack of sufficient mixing of the melt column after it was produced. The nature of this sinuous impact melt feature is discussed in detail in *Chapter 2*.

ii) On a more local scale, a previously documented olivine-bearing unit on the northern wall [e.g. *Lucey et al., 1991; Song et al., 2013*] of the crater has been interpreted to be associated with impact melt based on our observations of the area using high resolution data from Kaguya Terrain Camera and LRO NAC coupled with M³ observations [*Dhingra et al., 2014a; Dhingra et al., 2014b*]. The northern wall olivine-bearing unit has a very distinctive albedo and morphology that is entirely different from olivine-bearing central peaks. Copernicus crater is therefore hosting olivine-bearing lithologies with different origins which is a unique observation so far on the Moon (Figure 5). It is the focus of *Chapter 3*.

4.2 Tycho

4.2.1 Regional Geology

Tycho (-43.29° 348.78°, 86 Km) is a Copernican age (108 million years) crater located in the southern highlands region on the lunar near side (Figure 6). It has an extensive ray system that is observable with a naked eye, a majestic central peak and spectacular impact melt deposits (e.g. Figure 1) that occur almost everywhere on the crater including the rim, walls, floor and even the central peak [e.g. *Dhingra et al., 2011*]. Mineralogically, Tycho has high-calcium pyroxene bearing central peaks [e.g. *Tompkins and Pieters, 1999*] which has been an enigma owing to the highland setting of the crater. The high-calcium pyroxene signatures have been suggested to be representing an exposure of a buried pluton [e.g. *Tompkins et al., 1999*]. More recently, Mg-spinel has been reported] from various locations in the crater [e.g. *Kaur et al., 2012; Pieters et al.,*

2014. Tycho is also known for its dark halo observable under high solar illumination and has been suggested to be representing quenched glass [e.g. *Smrekar and Pieters, 1985*].

4.2.2 *Impact Melt Distribution and Morphology*

Tycho has been at the focus of impact melt observations owing to its very young age. Earlier workers used crater counting to compare ages of the ejecta and impact melt deposits around Tycho and found a discrepancy between the two landforms although the expectation was that they will have the same age owing to formation in the same impact event. Based on the observed age differences, the melt deposits were interpreted to represent young volcanism [e.g. *Strom et al., 1968*]. Although the ejecta-melt age differences still remain [e.g. *Van der Bogart et al., 2010; Kruger et al., 2013*] along with suggestions of young volcanism at Tycho [e.g. *Chauhan et al., 2012*], there is ample evidence for those deposits to be interpreted as impact melt. It includes similar nature of deposits at numerous other craters (and therefore not all can be correlated with volcanism), no correlation between the spatial distribution of the melt deposits with any volcanic centers, extensive literature on impact melt properties from the study of terrestrial impact craters and lastly the knowledge about the thermal history of the Moon. In the present context, we therefore consider the deposits around Tycho (and elsewhere) with identifiable morphological features in relevant geologic settings as impact melt.

The spatial distribution of impact melt at Tycho is pervasive in the crater interior and covers majority of the area except, some steep wall surfaces. The young age of the crater seems to have preserved the morphology of these deposits very well. There is an immense diversity in morphological form of the melt deposits. On the crater floor, the

north eastern part has a smoother surface structure as compared to the rubbly nature of the remaining floor material (Figure 6b). The melt-rich floor of craters Copernicus (96 Km) and to a lesser extent, Jackson (71 Km) and Giordano Bruno (22 Km) share this character. There are also extensive cooling cracks at various spatial scales throughout the crater floor. Some of them are large enough to be recognized on mineralogical color composites (at 140-280 m/pixel) owing to the fresh exposed surfaces along the fractures (Figure 9). Melt flows of various forms (narrow, smooth flows; braided flows, large waveforms) can be observed all over with random orientations indicating the highly chaotic nature of melt movement (Figure 7).

There are excellent examples of melt mobility in different parts of the crater with multiple layers of melt accumulation at the distal end of channels, evidence of channel carving (needs continuous flow) as well as rippled flow fronts in certain cases indicating continuous feeding of melt material (Figure 8). On the crater exterior, the eastern and southern parts have some large melt ponds and flows. Recent mapping studies around Tycho have suggested a non-uniform melt pond distribution with a higher density of ponds in the northwest region [*e.g. Kruger et al.*, 2013]. Although the surface around Tycho has been significantly modified to large distances, it is sometimes difficult to distinguish between an impact melt, fluidized ejecta and debris flow. We have therefore restricted ourselves to features which can be confidently identified as impact melt related.

4.2.3 *Impact Melt Mineralogy*

Tycho was imaged by M³ in optical periods Op1b, Op2a and OP2c1. The character of impact melt is different than what would be expected from a typical highland

assemblage with spectral signatures indicating a pre-dominance of high calcium pyroxene signatures (Figure 6) although with variable band strengths depending upon the nature of the exposure (fresh impacts on impact melt vs mature surface). Certain areas of the crater also show featureless spectra despite bearing morphological signatures of impact melt. It could be due to the presence of feldspathic material or the mature nature of the surface. Crystalline plagioclase has been reported from the central peaks and we also report it from the crater rim (Figure 6, Spectrum #5) suggesting that it could be an important contributor to the impact melt mineralogy on a local scale. Although spectral differences in pyroxene mineralogy have been noted, no distinct low-calcium pyroxene mineralogy could be observed at Tycho which is quite surprising when compared to the predominantly highland setting of the crater. As described above, large polygonal cooling cracks can be observed distinctly on the crater floor. Interestingly, they also have a discernable spectral signature and can be identified in color composites created from lower resolution spectral data (Figure 9).

4.2.4 Special Mention

The eastern wall of crater Tycho stands out as a distinctive unit on color composites displaying a strongly mafic character, dominated by high-calcium pyroxene as compared to the remaining crater walls which appear more heterogeneous (Figure 6c, d). This distinctive character of the eastern wall is also well captured in the spectra with eastern wall spectrum (#1, Figure 6g) having absorption bands, especially the one around 2000 nm, distinctively at longer wavelengths than other pyroxene exposures at the crater (#2, Figure 6g). This may be linked to the excavation and melting of a distinct target

lithology during the cratering process. An in-depth study of Tycho is presented in *Chapter 5*.

4.3 Jackson

4.3.1 *Regional Geology*

Jackson (22.4°N 163.1°W; 71 km) is a young crater (Copernican age) located on the lunar far side, east of Mare Moscoviense and north of SPA basin (Figure 10). The crater perhaps has one of the most spectacular ray system on the far side, has well-formed terraces as well as a cluster of central peaks with varying degrees of morphological freshness. The crater is located in deep far side highlands and therefore the geologic setting is principally feldspathic (Figure 10e). The southernmost central peak of Jackson has been reported to host a mafic lithology surrounded by a notable occurrence of crystalline plagioclase [*e.g. Ohtake et al., 2009*]. The mafic lithology has been proposed to be likely of impact melt origin [*e.g. Ohtake et al., 2009*]. The mineralogy of the region is dominated by crystalline and shocked plagioclase and likely mixture of low and high- calcium pyroxene.

4.3.2 *Impact Melt Distribution and Morphology*

Jackson displays morphologically identifiable impact melt deposits scattered around the crater. Melt ponds occur throughout the crater wall filling the lows created by terraces and are usually elongated in shape ranging in size from 2-7 km. They also occur on the crater exterior, notably on the southern rim (1-2 km long) and the western rim (3-7 km long) but no major flows are observed on the crater exterior. The melt-rich crater

floor provides a rich diversity of impact melt morphology (Figure 11) including textured, blocky melt deposits in the northern part and smooth impact melt in the southern crater floor. There is also an albedo difference (Figure 11b) between the two units which is linked to the dominant mineralogy and is discussed in the next section. The impact melt is observed to be draping parts of the central peaks in the form of continuous sheets or melt-fronts, similar to the reported occurrences at Tycho. A detailed study of Jackson crater is presented in *Chapter 5*.

4.3.3 *Impact Melt Mineralogy*

Jackson was observed by M³ in optical periods Op2c1 and Op2c2. The M³ standard color composite (Figure 12a) highlights a very distinct and widespread mineralogical difference on the melt-rich crater floor indicating the occurrence of at least two floor units with the northern part appearing as strongly feldspathic and the southern crater floor appearing slightly mafic. These two distinct units are also observable in albedo images with bright northern part and relatively darker southern part. Several spectra extracted from the two regions highlight the subtle but identifiable mineralogical differences. The northern crater floor soils have no observable absorption bands while the southern crater floor displays a weak but consistent absorption feature around 1000 nm indicative of its mafic affiliation (Figure 12b).

4.3.4 *Special Mention*

The north-south mineralogical heterogeneity observable on the crater floor is quite distinct and is likely replicated with a stronger contrast in the peak mineralogy.

The mafic peak unit surrounded by crystalline plagioclase is analogous to the mineralogy observed on the crater floor.

4.4 Giordano Bruno

4.4.1 Regional Geology

Giordano Bruno (35.96°, 102.89°; 22 Km) is one of the youngest craters on the Moon (1-10 Ma) [*e.g. Morota et al., 2009; Basilvesky & Head, 2012*] located on edge of a Harkhebi basin (98.74°, 40.87° 337 Km) on the eastern lunar far side (Figure 13). The crater lacks a central peak and does not have extensive terraces. In this sense, it appears like a simple crater which may affect the distribution of excavated materials including the impact melt. The crater has extensive bright rays and has been interpreted to be largely dominated by feldspathic material [*e.g. Pieters et al., 1994*]. However, recent high resolution data has indicated that it is locally quite diverse with widely scattered exposures of high-calcium pyroxene in the area [*e.g. Ogawa et al., 2011*]. Some large mare filled craters (Lomonosov, Maxwell and Richardson) are also observed SW of Giordano Bruno hinting at the presence of shallow subsurface magmatic bodies. M³ observations indicate the occurrence of feldspathic material along with low and high-calcium pyroxene in different parts of the crater leading to diversity in the crater ejecta as observed in color composites shown in Figures 13 (c) and (d). The pre-impact target was therefore sufficiently heterogeneous.

4.4.2 *Impact Melt Distribution and Morphology*

Giordano Bruno displays an extraordinary diversity of impact melt morphologies [e.g. *Bray et al.*, 2010] in different parts of the crater (Figure 14). The impact melt deposits are quite widespread and can be observed to large distances (a few crater radii). Ropy, intertwined melt deposits (Figure 14 d) occur NE, E, SE and NW of the crater. The occurrence of these deposits was likely guided by the pre-existing topography as melt appears to have accumulated in local lows there. Apart from the well-documented whirlpool melt pond on the west floor (Figure 14 f), there are other interesting flows and extensive melt deposits. It includes a prominent flow in the northern part of crater exterior (Figure 14c) which appears to be morphologically subdued compared to the well-documented flow feature on the southern rim of the crater (Figure 14e). It is surprising to note that the two features which formed during the same cratering event have such a different morphological nature.

We also note localized occurrence of dark albedo material on the western rim of the crater (Figure 14b). High resolution images of the area indicate it to be pulverized and distinct from impact melt occurring in the close vicinity. We interpret it to be ejecta derived from some locally occurring target having limited geographic extent. The melt distribution on the floor is quite uneven with the western and southern parts hosting melt-rich deposits while the north-eastern and south-eastern sections are dominated by boulder units with melt occurring in miniscule quantities. The central part of the crater floor (Figure 14 g) bears morphological similarity with a river channel with melt lobes bi-furcating around a central island and then joining again down slope. There

are some extensive impact melt deposits on the south-eastern rim, closer to the southern melt flow but having the morphology of a thick-melt veneer.

4.4.3 *Impact Melt Mineralogy*

M³ observed Giordano Bruno in optical period Op2c1 and nicely captures the mineralogical diversity of the crater. Many of the morphologically distinctive impact melt deposits are also identifiable as distinct spectral units. The most noteworthy among these are ponded melt deposits and flow features (Figure 15a) that tend to appear green in the M³ standard color composite. The spectral character of these units indicate stronger absorption bands as compared to melt poor deposits (Figure 15c). The mineralogy of the impact melt is dominated by high-calcium pyroxene although there is an indication that crystalline plagioclase might also be a contributor. The inflection around 1250 nm in the pyroxene spectra could be due to crystalline plagioclase. However, it can also be caused by the 1200 nm pyroxene absorption due to different cooling history [*e.g. Klima et al., 2008*].

4.4.4 *Special Mention*

The astounding diversity of impact melt deposits at Giordano Bruno is unique considering its small size. The young age of the crater has enabled the preservation of this diversity and it could hold important clues about the impact melt formation process.

4.5 Glushko

4.5.1 *Regional Geology*

Glushko (8.11°, 282.33°; 40 Km) is a Copernican age crater located on the western near side, NE of Orientale basin and close to the mare - highland boundary (Figure 16). It has an extensive ray system, no well-developed terraces, a small central peak and a scalloped rim in the N-NW which coincides with a compositionally-distinct unit. Glushko is surrounded by floor-fractured craters, Olbers on the SE and Vasco De Gama R on the NW indicating that the shallow subsurface had been intruded by magma. The location of the crater is also quite close to the Orientale basin and therefore the target material was likely significantly modified before the impact took place. We expect some signatures of this complexity in the impact melt deposits. M³ analysis suggests presence of predominantly high-calcium pyroxene material with some localized low-calcium pyroxene lithology.

4.5.2 *Impact Melt Distribution and Morphology*

Glushko has morphologically identifiable impact melt deposits on the crater floor, northern wall, rim and beyond as well as small melt ponds on some of the terraces (Figure 17). The melt-rich crater floor is mostly rough textured, interrupted by boulders of various sizes. Although there are several large blocks on the crater floor, it is not clear if all of them define the central peaks. In this study, we are considering a slightly off-centered pyramidal structure as the central peak (Figure 17b) and remaining large blocks as material from shallower depths. The latter is extensively covered by the impact melt

while the pyramidal peak, although modified, does not bear any distinctive signatures of impact melt cover.

The northern wall and rim host small melt ponds of various sizes (typically 2-3 km across) which sometimes occur in well-defined lows (Figure 17c and 18c). A large melt deposit further north of the crater rim (Figure 17e) has been previously identified based on radar studies [e.g. *Carter et al.*, 2012]. We can also observe it in high resolution albedo images but it is not very distinctive. The whole northern sector near the crater rim and beyond have a darker albedo compared to nearby regions (Figure 17d). Melt deposits all across the crater show extensive cooling cracks, probably hinting at their morphologically fresh nature.

4.5.3 *Impact Melt Mineralogy*

Glushko has been observed by M³ in optical periods Op2a and Op2c1. It has a largely homogeneous melt floor mineralogy dominated by high calcium pyroxene (Figure 18). High sun Op2c1 data shows low albedo in NW-NE sector, some of which contains impact melt deposits. The low-albedo region correlates with a mafic mineralogy and is identifiable as a distinct spectral unit in the color composites (Figure 16c, d, 18a). Mineralogical differences are observed in the small impact melt ponds located on the northern wall and rim with wall hosted melt pond indicating a strongly high-calcium pyroxene composition and rim hosted melt pond showing likely pyroxene mixture owing to small differences in the band positions, especially around 2000 nm (Figure 18d,e). It is noteworthy that the ponds are located on the same side of the crater and still preserve these differences indicating that impact melt was derived from local lithology and did not

have a uniform mineralogy, similar to our observation of impact melt ponds around Copernicus crater. In contrast, the impact melt mineralogy on the crater floor does not display any observable difference in its spectral character.

4.5.4 *Special Mention*

i) *Distinctly mafic NW sector:* The NW scalloped wall and rim with its different mineralogy compared to the rest of the crater wall indicates tapping of different lithology which also is preserved in the impact melt that is produced in this area. It is however not clear whether this exposed unit is also contributing to the high-calcium pyroxene signatures observed in the impact melt on the crater floor or there is a more extensive magmatic intrusion in the subsurface that was tapped during the cratering event and is contributing to the mafic signatures. The presence of floor-fractured craters in the immediate vicinity indicates that the latter possibility is very likely. The northern mafic unit might just be a surface manifestation of that mafic unit.

ii) *Variable melt pond mineralogy at Kilometer scale:* Within the broader mafic unit in the northern wall (as described above), smaller scale variations hinting at different mineralogy exist. It is generally difficult to acknowledge that in such a chaotic and high energy event, where there is a large scale transport of material (including melt), such differences remain preserved and can be detected by sampling the topmost layer on the surface.

4.6 Ohm

4.6.1 *Regional Geology*

Ohm (18.32°, 246.22°; 62 Km) is a Copernican age crater located on the lunar far side highlands, east of Jackson crater and N-NW of Orientale basin (Figure 19). It has an extensive ray system, similar to Jackson and Tycho. One of the ray units on the eastern side of the crater is observed to be clearly enveloping the central peaks of another crater Robertson (21.84°, 254.63°; 89 km) located about 360 km away. The predominant geologic setting is largely feldspathic with prominent Mare occurrences about 900 km away. However, there are indications of mafic material in some nearby craters hinting at likely shallow subsurface emplacement of magma. The crater has some well-defined terraces and a cluster of low lying central peaks. The peaks have a mafic mineralogy dominated by high-calcium pyroxene. The crater walls are largely feldspathic along with scattered high-calcium dominated exposures although at times, there are minor differences within the latter mineralogy. In contrast to the largely feldspathic setting, the wall and peak mineralogy highlight the heterogeneous nature of the pre-impact target (Figure 19e).

4.6.2 *Impact Melt Distribution and Morphology*

Ohm has several morphologically identifiable melt deposits located in different parts of the crater (Figure 20). The crater floor has ponded deposits of impact melt, laden with boulders and displaying cooling cracks in almost all parts of the floor. We also observe evidence for impact melt cover on some of the central peaks, may be due to their lower elevation (Figure 20d). The southern peak is the only unit where

impact melt cover is not observed (Figure 20c). Sheets of impact melt are observed at the interface of the crater floor and wall with the melt-front (similar to wave front) pointing in up-wall direction (Figure 20b). These sheets are observed in the northern and south-western floor region (extending upto 6 km in length) and indicate the dynamic nature of melt movement. We also note similar occurrences in other geologically young craters (e.g. Tycho, Jackson; See *Chapter 5*).

The northern wall also hosts some other melt morphologies. A small region in the north-western crater wall displays intertwined melt flows cascading down slope. In the north-eastern part, small melt ponds (2 km across) are also observed in the middle and lower sections. The crater exterior has thin melt ponds on the south-eastern rim but no other significant melt occurrences could be observed.

4.6.3 *Impact Melt Mineralogy*

M³ observed Ohm in optical periods Op1b, Op2a and Op2c1. Ohm has a relatively homogenous melt composition on the crater floor. Soil spectra from different parts of the melt-rich floor indicate very similar mineralogy dominated by high-calcium pyroxene. The peaks also indicate a high-calcium pyroxene dominated mineralogy (Figure 19g, #2) which may be due to an extensive impact melt presence as described above. There are no extensive melt deposits that could be mineralogically evaluated.

4.6.4 *Special Mention*

Ohm has a peculiar compositional pattern inside the crater, concentrated around the wall-floor interface but radiating out on the walls with limited exposure

outside the crater rim. It is distinctly observed in the color composites forming a prominent ring or halo (Figure 21b, c) at the crater bottom. While rayed ejecta is mostly observed out of the crater, at Ohm the outward radiating material with distinct spectral signatures is mostly limited to crater walls and is likely not dominated by ejecta. The proximity to the crater floor suggests a possible role of impact melt. However, further detailed studies would be required to resolve the cause of this observation.

4.7 King

4.7.1 Regional Geology

King (4.96°, 120.49°; 76 km) is a Late Eratosthenian to Copernican age crater [e.g. *Ashley et al.*, 2012] located on the lunar far side highland region in a distinctively high albedo terrain (Figure 22). The crater is surrounded by mare-bearing units including Mare Smythii on the west, mare-flooded crater Tsiolkovsky on the south and Mare Moscoviense in the north-east. This regional geologic setting hints at a lithologically heterogeneous target which is amply demonstrated by the mineralogy of various parts of the crater. Based on the analysis of Clementine multi-spectral data, it was suggested that the crater floor units had diverse mineralogies with the western floor being more feldspathic than the eastern floor [e.g. *Dunkin and Heather*, 2003]. The central peaks of King are unusual in their morphology with a distinctive ‘V-shape’ that appears to be connected to the southern wall through a neck. Mineralogically, the crater appears to be composed of multiple lithologies. King has also been well studied with high resolution imaging data from lunar orbiter era [e.g. *El-Baz*, 1972, *Hawke and Head*, 1977] to the more recent LRO WAC and NAC datasets [e.g. *Ashley et al.*, 2012] owing largely to its

impact melt deposits which display some of the most spectacular views capturing various aspects of the impact melt formation and emplacement process. Our observations using M³ data highlight a mafic dominated geologic setting at King with extensive high calcium pyroxene exposures and more limited low-calcium pyroxene occurrences (Figure 22f, g).

4.7.2 *Impact Melt Distribution and Morphology*

King crater has extensive impact melt deposits distributed in various parts of the crater and in nearby regions (Figure 23). There are three principal melt-bearing units that can be readily identified:

i) *North-Western Al-Tusi Melt Pond*: A large melt pond (~19 x ~15 km) exists right outside the northern rim of King crater and has been known from the lunar orbiter images. The pond is hosted by a pre-existing crater and formed by preferential emplacement of impact melt (produced during the King crater formation) along the low-lying rim section. This aspect has been noted in several other craters and indicates the dominant role of pre-impact topography on the emplacement of the impact melt [e.g. Hawke and Head, 1977]. The Al-Tusi pond has been recently analyzed in further detail [e.g. Ashley *et al.*, 2012] using high resolution datasets to understand its evolution. Several negative topography features have been identified in the pond which likely indicates sub-surface drainage of the melt.

ii) *Crater Floor*: The crater floor of King is morphologically quite diverse with a smooth SW part and in general, more rugged remaining floor (Figure 22b). The western crater floor appears to host a mega-block (11 km x 5 km) which is draped in melt

and could represent a wall block or may bear some relation to the central peaks. Similar mega-blocks have also been observed on crater floors of Jackson and Tycho (See *Chapter 5*). The northern and eastern crater floor represents a variable mix of melt and boulders (of different sizes) with observable small melt flows and lobes. The melt is also fractured in some places but not extensively as has been observed at Tycho, Jackson and Giordano Bruno. Small dome like features have been reported from the floor [*e.g. Dunkin and Heather, 2003*] and interpreted to be non-volcanic in origin.

iii) *North-western Rim and Beyond*: This region is defined on the east by the periphery of the NW melt pond and the west by craters Viviani, Katchalsky and Bingham H. The northern extent is less certain, although the locations of small craters Guyot K and Guyot J could be used as a conservative estimate to define the extent. Although this region is also located in the same topographic low as the Al-Tusi pond, the melt emplacement pattern has been different in this region as compared to the simple melt ponding on the northern rim. This region is largely characterized by melt sheets, mostly observable near the periphery of the topographic low (Figure 23c). Several melt-fronts (similar to wave-fronts) can be identified indicating the highly dynamic environment of melt emplacement during the King cratering event. There is evidence suggesting that coherent melt-fronts travelled much further and beyond the topographic low. A specific occurrence in this regard is observed at an unnamed crater (9.31°, 117.54°; 15 km) located 41 km further north, almost 4 crater radii away (Figure 23d).

4.7.3 *Impact Melt Mineralogy*

King crater has been observed by M³ in optical periods Op2c1 and Op2c2. Owing to partial coverage in both optical periods, we have combined color composites generated from the two optical periods to provide a more complete view of the crater mineralogy (Figure 22c, d). The impact melt on the crater floor and the northern rim appear as a distinct compositional unit with a mafic character. There is a pre-dominance of high-calcium pyroxene in the impact melt with the northern wall exposure (Figure 22g, #1) having a absorption bands center around 1000 nm and 2200 nm respectively. The large melt pond on the northern rim has weak mafic absorptions. The melt mineralogy is in contrast to the highland setting of the crater but consistent with the expectation of magmatic intrusions at depth (Figure 22e).

4.7.4 *Special Mention*

The preferential distribution of impact melt north of King crater highlights the dominant role of pre-impact topography. Apart from the large melt pond, our observations of the melt-fronts on the eastern limits of the topographic low as well as further out in the north extends the morphological diversity of impact melt at King.

4.8 Kovalevskaya

4.8.1 *Regional Geology*

Crater Kovalevskaya (30.86°, 230.56°; 114 km) is upper Imbrian in age and represents the largest crater in this study (Figure 24). The crater overlaps with the older crater, Kovalevskaya Q, in the southwest sector, has well-developed terraces and

prominent central peaks. It is located on the lunar farside, deep in the feldspathic highlands, away from any known major mare occurrence suggesting a simple geologic setting with a predominance of feldspathic lithology. However, previous studies [e.g. *Tompkins and Pieters, 1999*] have reported multiple lithologies in the central peaks at this crater. We support the observations based on our analysis of M^3 data for the region. The dominant peak lithologies comprise of crystalline plagioclase and high-calcium pyroxene. Additionally, there are outcrops showing plagioclase-pyroxene mixtures. We also report the presence of a distinctly identifiable mafic nature of the eastern part as compared to the feldspathic nature of the western part. We could not correlate this mafic/feldspathic material with any obvious ray component from nearby craters. At the same time, the compositional units do not have a radial pattern as would be expected if they were part of the excavated sequence (as observed at Jackson; Figure 12a). They have a rather limited spatial extent and span from the rim to inside of the crater, covering the walls and almost half of the crater floor. We do not have a straightforward explanation for the origin of this unit. In view of the non-radial nature in the crater ejecta, we are tentatively considering one of them to be later emplaced ejecta from another crater. The relationship of these units with impact melt may provide some additional constraints.

4.8.2 *Impact Melt Distribution and Morphology*

An identifiable large melt pond (9 x 16 km) occurs on the south-western rim of the crater (Figure 25, white arrow) where it overlaps with the older crater, Kovalveskaya Q. An elongated melt pond (30 x 4 km) also occurs on the southern wall of the crater, hosted on one of the terraces. The crater floor is assumed to be likely

comprised dominantly of impact melt although any obvious morphological indicators like cooling cracks, distinct flows or veneer covered boulders are missing. The lack of such features is likely a function of crater age. The crater floor is largely smooth except the NW-SE sector which is relative rougher. Incidentally, this location also coincides with the mafic unit reported earlier. It is unclear if the two observations bear any relationship to each other.

There are other smooth areas on the crater rim which could potentially be impact melt deposits. Another potential impact melt occurrence that deserves mention here is located in the western part, beyond crater Kovalveskaya Q. The area appears to be resurfaced, either by ejecta material or perhaps impact melt from Kovalveskaya. We are considering the latter possibility because due to crater overlap, impact melt would have preferentially been emplaced in the western sector. Also, for such a large crater, we do expect a huge amount of melt production.

4.8.3 Impact Melt Mineralogy

The crater has been covered by M³ in optical period Op2a, although the eastern walls and rim are missing from the coverage. The melt-rich crater floor is partially covered with a mafic unit with 2000 nm absorption bands centered at longer wavelengths indicating high-calcium pyroxene mineralogy (#4, Figure 24). There are albedo differences with the eastern mafic section having a slightly lower albedo than western sector. A closer examination of the western sector through some fresh craters indicates high-calcium pyroxene mineralogy (Figure 26) similar to what is observed in the eastern part of the crater floor (Figure 24g, #4). This analysis suggests that there is

some material on the crater floor that postdates the crater formation. The impact melt is largely homogeneous in mineralogy and is dominated by high-calcium pyroxene component.

4.9 Eratosthenes

4.9.1 *Regional Geology*

Eratosthenes crater (14.47°, 348.68°; 59 Km) defines the second youngest stratigraphic unit of the lunar time scale (Eratosthenian, 3.2 – 1 billion years). It is located on the southern edge of Imbrium basin and overlies the basaltic cover in the region, postdating the same. This geologic setting clearly illustrates the presence of multiple lithologies in the pre-impact target providing a diverse suite (Figure 27e). The crater (Figure 27) has a prominent central peak with ‘V-shape’ similar to King crater along with well-developed terraces. The central peak captures the diverse geologic setting in terms of exposure of multiple lithologies [e.g. *Tompkins and Pieters*, 1999]. Based on M³ analysis, we observe a pre-dominance of high-calcium pyroxene, shocked plagioclase and an olivine dominated lithology (Figure 27g).

4.9.2 *Impact Melt Distribution and Morphology*

No morphologically distinctive impact melt deposits could be identified at Eratosthenes, likely affected by its older age. The crater floor however, is still assumed to be representing largely impact melt deposits and has been explored morphologically and mineralogically. The floor is relatively smooth in the western and north-eastern sectors and rougher in the remaining part, comprising of boulder of various sizes. There are no

observable cooling cracks. The crater terraces, although numerous and well developed do not seem to host any distinctly identifiable impact melt deposits except a potential candidate pair on the south-eastern terrace of the crater wall.

4.9.3 *Impact Melt Mineralogy*

Eratosthenes was observed in M³ optical periods Op1b and Op2a. Our main focus for evaluating the impact melt mineralogy has been on the crater floor owing to the lack of any other identifiable melt-related features. In contrast to the heterogeneous central peaks, impact melt-rich crater floor either displays very weak features at 1000 and 2000 nm (#1, Figure 28) or is featureless (#2, #4). The strength of the features are too subtle for detailed analysis of their mineralogy. The weak signatures could either be due to the presence of a largely feldspathic composition or could simply be the effect of space weathering [e.g. Hapke, 1970; Pieters *et al.*, 1993]. In view of the diverse lithologic target, we prefer the space weathering explanation for muting of spectral features at this crater. It is also supported by relatively stronger absorption feature of a crater on the eastern floor (#3, Figure 28) which displays bands centered around 1000 nm and beyond 2000 nm, indicative of high-calcium pyroxene component.

4.9.4 *Special Mention*

The heterogeneous nature of the target is not reflected in the mineralogy of analyzed impact melt on the crater floor. The aging of the crater likely plays an important role in muting the expected mineralogical heterogeneities of the target in the impact melt. At the same time, it is possible that the sampling depth of the impact melt may not be

sufficiently heterogeneous to be reflected in the impact melt mineralogy. The latter is less likely though in view of the location of Eratosthenes on the ejecta of a large basin.

4.10 Aristillus

4.10.1 Regional Geology

Crater Aristillus (33.88°, 1.20°, 54 km) is a young rayed, Copernican age crater, located on the near side of the Moon (Figure 29). Aristillus impacted close to the eastern margin of the basalt flooded Imbrium basin. The target lithology likely comprised of a pile of basalts (of unknown thickness), highland material and impact melt breccias produced during Imbrium impact. The ejecta surrounding the crater rim has albedo differences with the northern sector having higher albedo than the southern rim region (Figure 29b). Wall terraces are poorly formed although present. A distinctive morphological feature of the crater is a low-albedo bi-furcating (fork-shaped) linear unit that originates on the crater floor, continues on the crater walls and goes well beyond the crater rim to almost 1 crater radii. It may represent a mineralogically distinct unit in the target which was excavated. The crater has well-formed central peaks which have been suggested to host multiple lithologies [*e.g. Tompkins and Pieters, 1999*]. Earlier studies of the region have also suggested the occurrence of quenched glass originating from impact melt [*e.g. Smrekar and Pieters, 1985*]. M³ observations of the region (Figure 29) suggests presence of pervasive low-calcium pyroxene component in the walls and central peaks (#1, #3 in Figure 29g.). The low-albedo streak described above however has absorption band characteristics consistent with a high-calcium pyroxene.

4.10.2 Impact Melt Distribution and Morphology

Aristillus has morphologically identifiable impact melt deposits on the crater floor, walls and likely on the central peaks (Figure 30). The crater floor largely displays a smooth texture with clearly identifiable cooling cracks in number of places indicating an impact melt origin which cooled with time. The cooling cracks display various geometries. Sometimes they radiate from a point, on other occasions, they occur as closely spaced parallel set of cracks (Figure 30d). The cracks although present, are not as pervasive as observed at some of the very young craters (e.g. Giordano Bruno) and are likely filled or deteriorated with age.

The northern wall hosts an identifiable impact melt (2x1 Km) deposit on one of its terraces, characterized by smooth deposit bearing cooling cracks. Immediately below the melt deposit, a large section of the wall (~10 km) has a very smooth texture (Figure 30b). We interpret it to be representing melt veneer that has plastered the wall. The central peaks might also have an impact melt cover although it is a tentative identification at present. In one case on the northern part of the peak, there is a low-albedo veneer with several identifiable layers that likely represent impact melt (Figure 30c). What makes the observations tentative and challenging to interpret is the large scale albedo variation on the peaks due to their rugged topography. In addition, some of the regions are not fully illuminated making the observations difficult. Nevertheless, these observations provide a sound background for undertaking detailed studies in conjunction with other datasets. These observations are also consistent with some recent studies reporting detection of impact melt on lunar central peaks [e.g. *Kuriyama et al.*, 2013; *Dhingra et al.*, 2014a, 2014b]

4.10.3 Impact Melt Mineralogy

Aristillus was observed by M³ in optical period Op1b and Op2c1. The mineralogy of impact melt at Aristillus is largely homogeneous with the melt-rich crater floor indicating an assemblage dominated by high-calcium pyroxene (Figure 31). This mineralogy is in contrast with the low-calcium pyroxene dominated central peaks and likely indicates two different source regions. We also found small regions on the NW wall and on the central peaks which share the same spectral character (high-calcium pyroxene signature) as the low-albedo streak on the NE wall. Although, it is difficult to ascertain the origin of the feature, it is possible that it represents melted material which was splashed out.

4.10.4 Special Mention

The distinct contrast in the mineralogy of the impact melt and the central peaks highlights the fact that they were derived from different source regions. This relationship could potentially be used to interpret the compositional nature of the crustal column sampled by the cratering event and is discussed in details in section 5.3.

4.11 Burg

4.11.1 Regional Geology

Burg (45.07°, 28.20°; 41 km) is a Copernican age complex crater with well-defined central peaks, located within Lacus Mortis (45.13°, 27.31°; 159 km) on the lunar near side, north of Serenitatis basin (Figure 32). It is in an area of thin mare basalts

which likely erupted through the ejecta deposits of Imbrium and Serenitatis (Figure 32e). Burg, later impacted through the thin basaltic cover and the local highland lithologies (including basin ejecta pile and may be the megaregolith).

The relatively high albedo ejecta around Burg, as compared to the surrounding basalts, support the fact that it penetrated through the basalts. The walls of Burg display diverse mineralogies with some parts showing a distinct high calcium pyroxene component (#1 in Figure 32f, g) while other parts are featureless. The central peaks although varied in mineralogy hint at either a mixture of low and high calcium pyroxenes or just a high calcium pyroxene component. While the former scenario is more likely in view of basalt-highland stratigraphy of the region, the latter may be true for certain parts of the peak. The complex target at Burg suggests the possibility of similar complexity in the impact melt mineralogy.

4.11.2 Impact Melt Distribution and Morphology

Burg does not display any morphologically distinct impact melt deposits. However, based on the observations at geological very young craters like Tycho, Jackson and Giordano Bruno which display extensive melt deposits all over the crater, the crater floor is interpreted as mostly representing impact melted material. Elsewhere, there are hints of likely impact melt ponds such as on the northern wall terrace and small pockets on the western wall (Figure 33). The flat surface morphology of these locations in comparison to the relatively rugged appearance of nearby wall material has been used to interpret a likely impact melt origin for these deposits. There is no other evidence of any significant ponding of material, either inside or outside of the crater, nor are there any

major flow units that can be identified with the available high resolution imaging datasets. On the crater floor, there are no observable large scale fractures. Most of the crater floor is relatively smooth with no identifiable morphological sub-units. These characteristics are in contrast with the Copernican age of the crater. We propose that Burg is likely slightly older in age which may have subdued the occurrence of impact melt deposits. This interpretation is consistent with our observations of impact melt deposits in this study where all other Copernican craters have distinctly identifiable impact melt deposits.

4.11.3 Impact Melt Mineralogy

Burg was observed by M³ in optical periods Op1b and Op2c3. We focused our analysis mostly on the crater floor since there are no other large impact melt deposits that could be morphologically identified. In contrast to the heterogeneous target lithology described above, the impact melt deposits lack any major observable difference in their mineralogy (Figure 34) although they do display identifiable absorption bands. The floor impact melt soils indicate a uniform mafic composition. Weak, broad bands around 2000 nm in the soils make it difficult to identify the specific pyroxene affiliation. In addition, most of the floor material appears quite mature making it difficult to identify any mineralogical differences that may be present. However, a few fresh craters on the melt-rich floor (#5, #6, Figure 34) have absorption band positions consistent with low-calcium pyroxene mineralogy in contrast to the high-calcium pyroxene affiliation of the central peaks. This contrast in the mineralogy of central peak and floor melt is similar to the observations at Aristillus crater.

4.12 Theophilus

4.12.1 Regional Geology

Theophilus (-11.45°, 26.28°; 99 km) is an Eratosthenian age crater (3.2 – 1.1 billion years) on the lunar nearside located on the inner ring of Nectaris basin (Figure 35). There are extensive mare basalts to the north and south of Theophilus (Sinus Asperitatis in the north and Mare Nectaris in the south). Additionally, Theophilus impacted on the edge of an older crater Cyrillus (-13.29°, 24.06°; 98 Km) and likely flooded it. The geologic setting is quite complex and should ideally be reflected in the impact melt mineralogy. Theophilus has some well-formed terraces but the remaining walls have steep sides with slumped material at the bottom. The prominent central peaks of the crater have been recently documented [*e.g. Dhingra et al., 2011*] to contain excellent exposures of the new rock type Mg-Spinel Anorthosite [*e.g. Pieters et al., 2011*]. Theophilus has accordingly been suggested to be the type locality for this lithology [*e.g. Pieters et al., 2014*]. Other than Mg-spinel, the peaks also bear extensive exposures of shocked and crystalline plagioclase and small amounts of olivine and pyroxene representing the complexity of the target (Figure 35f, g). The walls are less spectacular although some diversity in mineralogy is still observable. The northern walls are dominated by high calcium pyroxene lithology while the southern walls are usually featureless.

4.12.2 Impact Melt Distribution and Morphology

Theophilus hosts some morphologically identifiable impact melt deposits. The crater floor displays a rough texture in the western and south-eastern part while the

northern and south-western floor is relatively smooth with no large boulders (Figure 36a). We do not observe any cooling cracks on the floor or elsewhere where impact melt deposits are interpreted to be present. The second major occurrence of impact melt deposits is on the northern and north-eastern rim region. Extensive flat-ponded material occurs in local lows and interpreted to be impact melt. Some terraces also likely host impact melt deposits (as would be expected) but they are few (e.g. NW Wall) and do not display distinctly identifiable morphologies.

Surprisingly, there are no observable impact melt deposits on SW rim where Theophilus impacted into Cyrillus. As has been reported for some of the craters in this study (e.g. King, Kovalveskaya), impact melt usually tends to accumulate preferentially along intersecting or collapsed rim segments. In case of Theophilus, the SW rim somehow could still survive although it intersected with the older crater Cyrillus. Topography data shows that Cyrillus is at a slightly higher elevation than Theophilus at present. Although, it is not clear whether the same relationship existed at the time of impact but if that was the case, it may explain the lack of any observable large melt ponds in the vicinity of the south-western rim.

4.12.3 Impact Melt Mineralogy

Theophilus was observed by M³ in optical periods Op1b and Op2c3. The mineralogy of impact melt at Theophilus is largely uniform across the crater floor (Figure 36d). The soils are usually featureless or have very weak absorption around 1000 nm. Sampling of the fresh craters display strong absorption around 1000 nm but weak or non-existent 2000 nm absorptions (Figure 36e). The interpretation of these spectral signatures

as quenched glass is possible but not preferred here in view of the very broad absorption centered on 1000 nm which bears similarity to high-calcium pyroxene. The spectra also are relatively brighter. Boulder fragments sampled in this study provide a good contrast with some showing crystalline plagioclase (anorthosite) affiliation while others showing more mafic, pyroxene-like spectra. There are several small Mg-Spinel exposures on the crater floor reported in an earlier study [Dhingra *et al.*, 2011; also see Figure 36f]. We look at them a little closely here with respect to their specific geologic context in view of similar Mg-Spinel occurrence on the melt-rich floor of Copernicus crater [Dhingra *et al.*, 2013a]. There also appears to be some albedo variation in the impact melt on the crater floor with the north-eastern sector being darker than the remaining crater floor. However, we could not identify any distinctive compositional differences in these regions.

4.12.4 Special Mention

Mg-spinel exposures on the crater floor are mostly scattered in the western part which is also blocky in nature. All of the Mg-spinel occurrences on the floor are associated with isolated boulders, craters formed in large blocks (Figure 36c) or occur on the edges of the rocky fragments. Since central peaks contain pervasive occurrence of Mg-spinel, it is likely that the large rock fragments and boulders on the crater floor which are hosting Mg-Spinel exposures are sourced from the central peaks.

4.13 Lowell and associated Unnamed Crater

4.13.1 Regional Geology

Lowell (-12.96°, 256.58°; 63 km) is a Copernican age crater, located on the western edge of Outer Rook Ring of Orientale basin (Figure 37). A smaller, unnamed crater (-13.3°,-102.45°;10 km) impacted later on the eastern rim of Lowell producing some spectacular flows which also have a distinctive high-calcium pyroxene dominated mineralogy [e.g. *Srivastava et al.*, 2014; *Wöhler et al.*, 2014]. We would discuss the nature of impact melt from both these craters together since they are spatially co-located. Lowell crater has poorly developed terraces but has a prominent central peak which is mafic in character although the crater appears to be in a predominantly feldspathic terrain. However, owing to its location on the basin ring, there is a possibility of basaltic emplacement at different depths (Figure 37e). There are documented occurrences of basalts in close vicinity as well as along other basin rings [e.g. *Head*, 1977; *Whitten et al.*, 2011]. The closest occurrence is at Lacus Veris about 150 km NE of Lowell.

The smaller unnamed crater on the eastern rim of Lowell is a simple bowl shaped crater with collapsed western section. As a result, material from the floor directly flowed down slope on to the floor of larger Lowell crater. There are different opinions on the origin of the flows. *Srivastava et al.*, [2014] contend that the distinctive high-calcium pyroxene mineralogy of the flows could indicate that the flows represent very young basaltic volcanism aided by the formation of the small, unnamed crater. Alternatively, they suggest it could also be an impact melt deposit which has been the interpretation by *Wöhler et al.*, [2014]. We prefer the impact melt interpretation as it is directly linked with the collapsed crater rim and there is ample evidence for basaltic emplacement in the

geological past (not recent as suggested by *Srivastava et al.*, 2014) along the rings. Accordingly, the high-calcium pyroxene mineralogy of the young flows could simply be derived from a pre-existing basaltic target. This interpretation is also consistent with the thermal history of the Moon.

4.13.2 Impact Melt Distribution and Morphology

The impact melt at Lowell occurs on the crater floor as boulder-free, textured ponds in the northern and western part while rougher impact melt, laden with boulders, is present in eastern and southern part of the floor (Figure 38a). The eastern rim of Lowell hosts a small, elongated melt pond (9x3 km). The impact melt associated with the smaller, unnamed crater on the eastern rim of Lowell occurs as elongated flows, about 4 km in length although length varies between flows (Figure 38e, f). At the distal end of the flows, the melt occurs as flat-lying melt ponds on the floor of Lowell spread across a distance of about 7 km from edge of the flows. These floor impact melt deposits are relatively boulder free, although occasionally, small boulder fields can be observed. Extensive cooling cracks, mostly interconnected, are present on the surface of this young impact melt unit. In contrast, the relatively older melt sheet on Lowell's floor has isolated occurrences where cooling cracks are visible.

4.13.3 Impact Melt Mineralogy

Lowell was observed by M³ in optical periods Op1b, Op2a and Op2c1. The melt mineralogy at Lowell is largely homogeneous and dominated by high-calcium pyroxene (Figure 38d). It is also consistent with the mineralogical signatures extracted

from the clasts and is in contrast to the broadly feldspathic geologic setting of the region. It seems that extensive basaltic emplacement occurred at depth which contributed to the mafic central peaks and floor (Figure 37e). The feldspathic component might either have been limited in extent at this specific site or may have been muted due to its shocked nature whereby crystalline absorption bands are lost. Evidence for extensive shocked anorthosite in the region is known from previous studies [e.g. *Spudis et al., 1984; Cheek et al., 2013*]. It should also be noted that although topographically still fresh, the Orientale basin also has an extensively pulverized and melted material scattered within and outside. If Lowell tapped some of this highly modified material, the detection of any specific mineralogy might be difficult. That may have aided in the distinct detection of later emplaced, fresher basaltic material which also is optically more detectable.

The impact melt from the small, unnamed crater is also dominant in high-calcium pyroxene. It is interesting to note that mineralogy of impact melt derived from both the craters (Lowell and Unnamed crater on the eastern rim) has pre-dominance of high-calcium pyroxene indicating that the target lithologies of Lowell and the unnamed crater were similar and any magmatic activity that emplaced high-calcium pyroxene material at depth, predates the formation of Lowell crater. Therefore, the high-calcium pyroxene bearing flows at younger crater are not likely related with a younger episode of basaltic volcanism. It is only the young age of the unnamed crater that makes these flows more distinctive than the surrounding impact melt deposits.

4.13.4 *Special Mention*

The morphologically fresh impact melt flows from the small unnamed crater on Lowell east rim contrast with impact melt on the large crater Lowell. The well-preserved flows are perhaps one of the best known examples of impact melt on the Moon, along with impact melt occurrences at Tycho, Jackson and Giordano Bruno. An additional point to note here is the contrast between emplacement morphology of these flows and the nature of cratering event. It is a little surprising that despite the collapse of the entire western sector of the small, unnamed crater and steep wall of Lowell (where the impact took place), several overlapping occurrences of very-well formed flows can still be observed. Ideally, it is expected that the whole melt body would just splash down slope as one large flow and no significant melt supply remains. This aspect has been very well documented in case of partially collapsed rims of craters such as. Donner and King [e.g. *Hawke and Head, 1977; Wöhler et al., 2014*].

The emplacement of impact melt as several distinct flows could be in an environment similar to a partially open cavity wherein the impact melt moved down slope as soon as it was produced leading to a continuous trickle of melted material rather than a scenario where melt had a chance to accumulate before the western wall section collapsed. In such a scenario, one would also expect radial (or may be asymmetric) splashes of impact melt around the crater. However, in this case, only well-formed melt flows are observed.

5. Discussion

The character of impact melt at various craters analyzed in this study illustrates their rich diversity within craters and across craters. Clearly, there are no unique spectral signatures associated with impact melt deposits; rather their character is closely tied to the local geologic setting (including target lithology) as well as their mode of emplacement (e.g. large pond, flow or veneer). In our attempt to understand the mineralogy of impact melt deposits, the dominant processes involved and the implications of melt mineralogy for the Moon (and in general other planetary bodies) there are certain trends that are observed in our analysis. Tabulated summaries of mineralogical and morphological observations at various craters are presented in table 4a and 4b respectively.

5.1 Melt Mineralogical Heterogeneity

Distinctly different mineralogy of impact melt deposits located within a crater is one of the key observations documented in this study. Craters such as Copernicus and Jackson display mineralogically heterogeneous impact melt bodies at crater scale. The 30 km long sinuous melt feature on the floor of Copernicus is perhaps the best example to illustrate this aspect [Dhingra *et al.*, 2013]. Its low-calcium pyroxene mineralogy in contrast to the high-calcium pyroxene composition of the nearby impact melt highlights the large scale compositional heterogeneity that could be present in impact melt deposits. On a smaller spatial scale, the melt ponds on the northern wall and rim of crater Glushko display spectral differences indicating compositional differences. These observations contrast with some of the early studies on impact melt sheets at terrestrial impact craters

[*e.g. Phinney and Simonds, 1977*] where impact melt deposits were suggested to be very well mixed and therefore uniform in composition. Some of the recent studies at terrestrial impact craters have documented heterogeneous impact melt mineralogy at kilometer scale [*e.g. Lambert, 2010*], consistent with our observations. Our detailed investigations in this study highlight and document the heterogeneous mineralogical character of impact melt deposits on the Moon where the record is much more complete and continuous.

The observations described above have some very important implications for our understanding of the target geology, the impact cratering process as well as the observed mineralogical diversity of the crust [*e.g. Pieters, 1986*]. The heterogeneous melt mineralogy indicates that the mineralogical character of the pre-impact target rocks may be preserved in the impact melt and not necessarily gets homogenized during the cratering process. While it could be argued that the observed melt mineralogy could be the result of differentiation processes, there are several lines of evidence which do not support such a possibility at least at the scale of impact crater sizes studied here. The small scale of occurrence of these impact melt deposits, the morphological nature of at least some of the melt features (*e.g. sinuous flow could not potential differentiate*) as well as close correspondence between observed melt mineralogy and target rocks strongly favor a scenario where un-melted clasts of target rocks are the source of observed mineralogical heterogeneity. We would like to contend that this is still an interpretation and needs more detailed investigations. At the same time, we also acknowledge the fact that impact melt differentiation could be playing a larger role in case of large cratering events such as basin formation [*e.g. Vaughan et al., 2012*].

The implication for the cratering process is that our understanding of the impact melt formation and emplacement as a highly chaotic process may not be entirely true. The small spatial scale of preservation of the melt mineralogical heterogeneity such as in small ponds on the northern wall of Glushko suggests that melt is derived from local horizons and emplaced or this is at least one of the formation mechanisms. It is possible that there are multiple processes happening at the same time at different spatial scales. It is interesting to note that if melt is derived from local lithologies, it is similar to crater ejecta which involves minimal lateral mixing (if any) with the nearby lithologies. Under this scenario, impact melt cannot be considered as a single entity at a given crater with a common set of characteristics. Instead, each mineralogically distinct melt unit would be representing a different geological unit and could potentially contribute to the observed mineralogical diversity. An essential element of this scenario is that the documented mineralogical heterogeneity would no longer be of primary origin. This aspect has direct implications for the interpretation of the observed heterogeneous mineralogy in some of the central peaks [*e.g. Tompkins and Pieters, 1999*] and is discussed in section 5.3.

5.2 Uniform Melt Composition

In contrast to the heterogeneous melt mineralogy observed at some of the craters, several other craters (*e.g. Aristillus, Lowell, Ohm, and Eratosthenes*) display a largely homogeneous melt composition. The physics of the cratering process and more specifically impact melt formation is not expected to change and therefore cannot be invoked to form homogeneous impact melt at one crater and heterogeneous impact melt at another crater, especially at similar crater sizes. A more direct cause is the mineralogy

of the target rocks which is likely mimicked in the impact melt, at least at crater sizes observed in this study. There are however cases, when such a direct comparison is not useful and additional factors need to be taken into account (e.g. Eratosthenes).

5.2.1 *Uniform target lithology (Mono-mineralogic or Uniformly Heterogeneous)*

If the target rocks are largely dominated by a single rock type, then, the impact melt generated from such a source is expected to be largely uniform. On the Moon, except at very small spatial scales (few kilometers), occurrence of a uniform target lithology is seldom the case and mineralogical heterogeneity is the norm. Even in deep highlands, far away from known mare occurrences, there are instances of high calcium pyroxene signatures, likely from subsurface magmatic intrusions [e.g. *Andrews-Hanna et al.*, 2013]. It was likely the case at crater Aristillus where the dominant mineralogy is noritic (rich in low-calcium pyroxene). Basaltic cover of unknown extent, but likely thin, was also there. Impact melt deposits at multiple locations on the floor of Aristillus crater (Figure 31) have a remarkably similar spectral signature indicative of uniform melt mineralogy. It is unclear if it is high-calcium pyroxene mineralogy or a mixture of low and high-calcium pyroxene (which would be more consistent with geologic setting) since the band centers are aligned around 2000 nm. A longer wavelength shift (beyond 2000 nm) would have strongly indicated high calcium pyroxene origin but it likely seems to be a mixture.

Irrespective of the actual mineralogy, an important interpretation is that the distribution of lithologies prior to the impact was largely uniform and no significant lateral differences existed. During the impact process, the vertical mixing of melted crustal column led to the formation of melt with uniform mineralogy.

5.2.2 *Non-uniform target lithology*

There are geological scenarios in which a non-uniform target lithology might also lead to largely uniform melt mineralogy. Craters such as Eratosthenes and Lowell would likely fall into this category, although for two entirely different reasons. Spectral reflectance observations have always been affected by the relative maturity of the target material. As a consequence of the interaction of rocks with solar wind and micro-meteorites on an airless Moon, the diagnostic spectral bands are gradually muted, the spectrum gets darker and attains a redder slope [e.g *Adams and Jones, 1970; Hapke et al., 1970; Pieters et al., 1993*]. The impact melt deposits, like other rocks on the Moon, would also be subjected to this process and with the passage of time, might have weak to non-existent spectral signatures. This aspect is discussed further in section 5.4. The geologic setting of Eratosthenes in terms of its location on the ejecta deposits of Imbrium basin clearly indicates a laterally heterogeneous target and yet we do not see mineralogical variations in the impact melt there (Figure 28). In contrast to the multiple lithologies observed in the central peaks, soil spectra from crater floor either is featureless or have very weak features making it difficult to identify any mineralogical differences. We interpret space weathering as the likely cause of homogeneous impact melt at Eratosthenes despite having a non-uniform target lithology. This argument is strengthened by the fact that probing one of the fresh craters on the floor (Figure 28, #3) indicates high- calcium pyroxene rich mineralogy in comparison to the featureless/weak spectra of the soils.

Lowell (Figure 38) also shows largely uniform melt mineralogy dominated by high-calcium pyroxene. In fact, the mineralogical signature of impact melt from a

subsequent crater that impacted on the eastern rim of Lowell also displays high-calcium pyroxene signatures (#3, #4 in Figure 38). Lowell is a Copernican age crater therefore maturity effects will not be playing a major role in affecting the spectral signatures. It is also evident by the relatively strong spectral bands of the sampled lithologic exposures. The geologic setting of Lowell clearly indicates a non-uniform target consisting of a largely feldspathic target that was locally intruded (and extruded) by magma. Exposure of high-calcium pyroxene at Lowell as well as in the melt flows of the younger crater on its rim indicate excavation and melting of such an intrusion. The question is that why we only see the signatures of the intrusion and not the extensive feldspathic material in the form of crystalline absorption band of plagioclase and may be low-calcium pyroxene (in case of noritic mineralogy).

Extensive portions of the feldspathic Orientale basin are shocked [e.g. *Pieters et al.*, 2009; *Cheek et al.*, 2013] leading to loss of the crystalline absorption band in plagioclase. As a consequence, even if the impact melt deposits contain different proportions of shocked plagioclase and high-calcium pyroxene at different locations, it will likely not be possible to detect this mineralogical heterogeneity in the melt by spectral reflectance observations. We suggest it as one of the possible causes.

5.3 Melt Mineralogy Vs Peak Mineralogy

In this study, it was observed that the mineralogy of impact melt deposits on the floor and the mineralogy of the central peaks were similar in certain cases and different in other craters. Considering the physics of cratering process [e.g. *Melosh*, 1982; *Cintala and Grieve*, 1998], the central peak material originates below the depth of melting thus

sampling an entirely different section of the crust as compared to the impact melt. In the simplistic case, similarity in the mineralogy of impact melt on the floor and the mineralogy of central peaks would indicate that the crustal section represented by the combined sampling depth of impact melt (shallow subsurface) and the peaks (deeper subsurface) is largely uniform. Under this consideration, similar mineralogical character of the central peaks and the impact melt at a given crater would indicate uniform mineralogy of the pre-impact target upto the excavation depth of the crater. Conversely, different mineralogical character of the central peaks and the impact melt at a given crater could be an indication of vertically heterogeneous target.

Observations based on data from high resolution sensors onboard recent missions have reported presence of impact melt cover (to different spatial extents) on the central peaks of number of impact craters [e.g. *Kuriyama et al.*, 2013; *Dhingra et al.*, 2014]. As a consequence of these observations, direct interpretation of central peak mineralogies [e.g. *Tompkins and Pieters*, 1999; *Cahill et al.*, 2009] and their comparison with impact melt mineralogy could be problematic and may mislead about the subsurface mineralogy. However, spectral reflectance observations in conjunction with high resolution imaging data for central peaks could be a useful tool in ruling out the presence of impact melt on the peaks and allow a more direct and relevant comparison with the impact melt mineralogy on the crater floor.

5.4 Melt Mineralogy and Geological Age Relationships

The effects of space weathering were briefly discussed in section 5.2. Although majority of the selected craters in this study are geologically very young (Copernican

age), we intentionally selected some slightly older craters (Eratosthenian and older) to contrast our observations of impact melt detection and its mineralogical evaluation. The best contrast in the morphological signatures of impact melt is provided by comparing the craters Tycho and Giordano Bruno (Copernican age) with Kovalevskaya (Upper Imbrian) and Theophilus (Eratosthenian). While Tycho and Giordano Bruno display extraordinary diversity of impact melt deposits (see Figures 1, 7, 8 and 14) there are no large identifiable impact melt deposits at either Kovalevskaya or Theophilus despite the fact that both the craters are quite large. Impact melt could only be located with confidence on the SW rim of Kovalevskaya and North and East rim of Theophilus, these being the only identifiable significant impact melt deposits.

Considering the fact that the process of impact cratering operated in the same way at all the craters (although there could be differences in the total impact melt volumes generated in each cratering event), the only factor that makes it difficult to identify and characterize impact melt deposits at older craters (Eratosthenian and older) is the effect of age. Otherwise, we would expect the older craters to show comparable diversity of impact melt and geographic extent as observed at the younger craters. We have been trying to identify potential impact melt deposits at such craters in order to substantiate the suggestion that age effects modify the morphologic signatures of impact melt deposits to such an extent that they merge with the general background. Even at crater Burg, which is classified as Copernican in age, it is difficult to identify the impact melt deposits and we would argue that it is likely older than Copernican age, may be Eratosthenian. We have identified two potential impact melt deposits at Burg (Figure 33), which are not obvious but could be identified as likely of impact melt origin based on their local

geologic setting (e.g. flat deposits on small terraces as shown in 33b). The morphological characteristics of these potential impact melt deposits are perhaps at the verge of being destroyed and document the transition from morphologically distinct melt deposits to apparently non-existent features. High resolution imaging radar data has been recently used in identifying some of the previously unknown impact melt deposits [e.g. *Carter et al., 2012, Neish et al., 2014*] around impact craters and has helped to extend the mapping of these deposits. The mineralogical characterization of these deposits would still be a problem though.

6. Summary / Conclusions

This study presents a detailed characterization of impact melt deposits on the Moon by integrating mineralogical and morphological information from recently available remote sensing datasets. Several new insights have been presented about impact melt properties, the impact melt generation during cratering process and implications of impact melt mineralogy for understanding the crustal diversity. This study highlights the fact that impact melt does not necessarily have a distinctive spectral signature; rather the mineralogical character is closely tied to the nature of the target lithologies. It has been demonstrated at 3 craters (Copernicus, Jackson and Glushko) that heterogeneity in impact melt mineralogy exists and may occur at different spatial scales, ranging from small km size melt ponds to crater size melt features.

The study also documents impact melt with uniform mineralogy and presents the possible determining factors. Impact melt covering central peaks could be a major factor that has not been taken into account while determining peak mineralogy and interpreting

it in terms of subsurface lithological diversity. High resolution datasets could now enable such an initiative and could help refine previous estimates. We also discuss that there are as extensive impact melt deposits occurring at older craters (> 1.1 billion years) as have been documented at the younger craters. However, at older crater, impact melt deposits have been morphologically deteriorated, sometimes beyond recognition. Radar studies could shed some light on the distribution of impact melt at such craters although it would still make it difficult to determine the mineralogy of these deposits due to space weathering effects. Nevertheless, such an effort would still enable a better evaluation of the spatial extent of impact melt on the lunar surface and its implications for understanding the surface evolution of planetary bodies.

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Table 1 Details of various datasets used in this study

No.	Sensor	Mission	Spatial Resolution	Spectral resolution	Wavelength Range
1.	Moon Mineralogy Mapper (M ³)	Chandrayaan-1	140-280 m	10-20 nm	460-3000 nm
2.	Terrain Camera (TC)	Kaguya/ SELENE	10 m	N/A	
3.	LRO Narrow Angle Camera (NAC)	Lunar Reconnaissance Orbiter (LRO)	0.5-1 m	N/A	
4.	LRO Wide Angle Camera (WAC)	LRO	~ 100 m		

Table 2 List of craters analyzed in this study

No.	Crater Name	Location	Diameter (Km)
1	Copernicus	9.62°, 339.92°	96
2	Tycho	-43.29°, 348.78°	86
3	Jackson	22.04°, 196.68°	71
4	Giordano Bruno	35.96°, 102.89°	22
5	King	4.96°, 120.49°	76
6	Aristillus	33.88°, 1.20°	54
7	Eratosthenes	14.47°, 348.68°	59
8	Glushko	8.11°, 282.33°	40
9	Ohm	18.32°, 246.22°	62
10	Kovalevskaya	30.86°, 230.56°	114
11	Burg	45.07°, 28.20°	41
12	Theophilus	-11.45°, 26.28°	99
13	Lowell	-12.96°, 256.58°	63

Table 3 Spectral parameters used in the analysis and their assignments in various color composites.

Spectral parameter	Algorithm
IBD 1000	$\sum_{n=0}^{26} 1 - \frac{R(789 + 20n)}{R_c(789 + 20n)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm
IBD 2000	$\sum_{n=0}^{21} 1 - \frac{R(1658 + 40n)}{R_c(1658 + 40n)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm
BD 1900	$1 - \frac{R_{1898}}{\left(\frac{R_{2498} - R_{1408}}{2498 - 1408}\right) * (1898 - 1408) + R_{1408}}$
BD 2300	$1 - \frac{R_{2298}}{\left(\frac{R_{2578} - R_{1578}}{2578 - 1578}\right) * (2298 - 1578) + R_{1578}}$
M³ Standard Color Composite	Red – IBD 1000 ; Green – IBD 2000 ; Blue – Albedo at 1489 nm
Complementary Color Composite	Red – IBD 1000; Green – BD 1900; Blue – BD 2300

Table 4a Summary of Observed Mineralogical Characteristics

	Crater Name	Dia. (Km)	Major Min.	Minor Min.	Min. in Melt	Melt Nature	Peak Min.
1	Copernicus	96	Shkd Plag, Opx, Cpx, Olv,	Xl Plag, MgS	Opx, Cpx, Olv	Het, LS, SS	Olv, Shkd Plag
2	Tycho	86	Shkd Plag, Cpx	Xl Plag, Opx?	Cpx	Het, LS, SS	Cpx, MgS?
3	Jackson	71	Shkd Plag, Cpx	Opx?	Shkd Plag?, Cpx	Het, LS, SS	Xl Plag, Cpx
4	Giordano Bruno	22	Shkd Plag, Cpx	Opx	Cpx	Het, SS	N/A
5	Glushko	40	Shkd Plag?, Cpx	Opx	Cpx	Het, SS	Cpx
6	Ohm	62	Shkd Plag?, Cpx	-	Shkd Plag, Cpx	Homo	Cpx
7	King	76	Shkd Plag?, Cpx	Opx	Cpx	Homo	Cpx
8	Kovalevskaya	114	Shkd Plag?, Cpx	Xl Plag, Shkd Plag	Cpx	Homo	Cpx, Xl Plag, Shkd Plag
9	Eratosthenes	59	Shkd Plag?, Cpx	Olv	Cpx?, LAF	?	Shkd Plag, Olv, Cpx
10	Aristillus	54	Shkd Plag?, Cpx, Opx	-	Cpx	Homo	Opx, Cpx
11	Burg	41	Shkd Plag?, Cpx, Opx	-	Opx	Homo	Cpx, Opx
12	Theophilus	99	Shkd Plag,	Xl Plag, Cpx, Olv	Cpx	Homo?	MgS, Xl Plag, Shkd Plag, Olv, Cpx,
13	Lowell	63	Shkd Plag, Cpx	Opx	Cpx	Homo	Cpx

Interpretation Keys:

Mineralogy - **Olv** = Olivine; **Opx** = Orthopyroxene; **Cpx** = Clinopyroxene; **Xl Plag** = Crystalline Plagioclase; **Shkd Plag** = Shocked Plag; **MgS** = Mg-Spinel, **LAF** = Low Albedo & Featureless

Melt Nature - **Homo**= Homogeneous; **Het** = Heterogeneous; **LS** = Large Scale (Several 10s of kilometers); **SS** = Small Scale (100s of meters to few kilometers)

Table 4b Summary of Morphological Characteristics

No.	Crater Name	Diameter (Km)	Flows	Ponds	Melt Fronts	Peak Melt	Smooth Floor	Rough Floor
1	Copernicus	96	Y	Y	?	Y?	Y(NW)	Y
2	Tycho	86	Y	Y	Y	Y	Y (NE)	Y
3	Jackson	71	N	Y	Y	Y	Y (S)	Y
4	Giordano Bruno	22	Y	Y	N	N/A	N	Y
5	Glushko	40	Y?	Y	?	?	N	Y
6	Ohm	62	?	Y	Y	Y?	Y	N
7	King	76	N	Y	?	?	Y(SW)	Y
8	Kovalevskaya	114	N	Y	N	?	Y (S)	Y
9	Eratosthenes	59	?	?	N	?	N	Y
10	Aristillus	54	?	Y	?	Y?	Y	Y
11	Burg	41	?	Y	N	?	Y	N
12	Theophilus	99	?	Y	N	N	Y	N
13	Lowell	63	Y	Y	?	Y	Y (W)	Y

Interpretation Keys:

Y = Yes; **N** = No; **N/A** = Not Applicable; **N** = North; **S** = South; **W** = West; **NE** = North

East; **NW** = North West; **SW** = South West

Figure Captions

Figure 1 Morphological diversity of impact melt, over a very small spatial scale is illustrated in this image of the north-eastern wall of crater Tycho. *Image source: Kaguya Terrain Camera.*

Figure 2 Location of craters analyzed in this study shown on albedo map derived from Wide Angle Camera (WAC) onboard Lunar Reconnaissance Orbiter (LRO). The yellow circles mark the locations of the crater and their sizes represent the relative crater diameters.

Figure 3 (a) Graphical representation of the spectral parameters used in generating standard color composite. Red colored region represents the IBD 1000 parameter and is the strength of absorption band around 1000 nm, Green colored region represents the IBD 2000 parameter and is the strength of absorption band around 2000 nm, Blue arrow indicates the wavelength 1498 nm. These parameters and the corresponding colorations have been used to generate M^3 standard color composite. (b) Schematic illustrating the likely nature of target geology at a given crater location.

Figure 4 Copernicus crater (a) Location on the lunar side (b) Kaguya TMC image showing the crater with its well-formed terraces and cluster of central peaks on the crater floor. (c) M^3 standard color composite highlighting the crater scale mineralogical diversity. North-south mineralogical heterogeneity (feldspathic-mafic) is clearly observed

in this composite. (d) Complementary color composite highlighting the sinuous melt feature on the crater floor (in green) which was not distinct in the standard color composite. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. The reflectance scale is offset for Spectrum 3 by 0.1. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 5 Diversity in geologic setting of olivine lithology at Copernicus crater (a) Kaguya TC image showing the northern wall with location of olivine exposure marked by yellow box. (b) M^3 color composite overlain on Kaguya TC data showing the olivine-bearing exposure in deep red (within yellow box). (c) Kaguya TC image of impact melt on the terrace of southern crater wall with olivine-bearing exposure marked by yellow dotted box. (d) M^3 color composite overlain on Kaguya TC data showing that olivine-bearing material occurs in the ejecta of a fresh crater in impact melt deposit. (e) M^3 color composite overlain on Kaguya TC data showing olivine-bearing central peaks with the box indicating peaks that have more extensive olivine signatures. (f) Spectra of olivine lithology from the three locations described above showing similarity in spectral signatures, consistent with the presence of olivine. (g) Continuum removed spectra showing the same spectra as in f, highlighting the absorption band characteristics. The numbers correspond to the locations in the crater as marked in c.

Figure 6 Tycho crater (a) Location on the lunar side (b) M^3 image showing the crater with its well-formed terraces and central peaks. (c) M^3 standard color composite

highlighting the crater scale mineralogical diversity. Note the distinct character of eastern wall (1) unit in yellow-orange as compared to the crater walls in the vicinity. (d) Complementary color composite of the region. Eastern wall is again observed as distinctive unit. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Tycho. The reflectance scale is offset for spectrum 3 by 0.1 and spectrum 4 by 0.08. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands for the various lithologies.

Figure 7 Morphological diversity of impact melt on the crater floor of Tycho (a) Melt fronts (marked by yellow arrows) draped on to the nearby crater wall indicating upslope flow towards the wall. (b) Similar melt fronts on the NW wall. (c) Another example of well-defined melt-fronts draping the high standing wall topography and oriented in up slope direction. (d) Large impact melt deposit on the NE wall of the crater showing several flow fronts moving down slope in a braided fashion. *Image source: LRO Narrow Angle Camera.*

Figure 8 Morphological forms of impact melt at Tycho. (a) Multiple flow fronts, perhaps formed by draining through channels up slope on the NE wall. (b) Well-marked channels and pervasive melt cover on the northern wall. (c) The eastern rim of Tycho shows this spectacular flow with a rippled surface, likely defined by break in slope. *Image source: LRO Narrow Angle Camera.*

Figure 9 Large scale fractures in impact melt at Tycho. (a) M³ standard color composite showing the strong mafic character of polygonal floor fractures (as marked in white box). (b) LRO NAC image of a polygonal fracture (same as shown in white box in a). (c) Spectra comparison of melt within the fracture (1) and from the fresh fracture surface (2). The fresh fracture has much stronger spectral bands indicating high-calcium pyroxene mineralogy.

Figure 10 Jackson crater (a) Location on the lunar far side (b) M³ image showing the crater with its well-formed terraces and central peaks. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. North-south mineralogical heterogeneity (feldspathic-mafic) on the crater floor is indicated in this composite. (d) Complementary color composite highlighting mafic central peak and the southern crater floor (in pink and red). (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 11 Character of floor impact melt deposits at Jackson crater. (a) M³ context image showing floor of Jackson crater with some albedo differences. (b) A Kaguya TC derived DTM of the southern central crater floor looking towards north. Distinct albedo differences can be observed between the narrow lower unit and the more extensive and blocky high-albedo unit. (c) Kaguya TC image of the northern part of crater floor shows

large blocks and highly textured impact melt. (d) Kaguya TC image of the southern crater floor showing a strikingly smooth impact melt with no large blocks.

Figure 12 Mineralogical character of the floor impact melt deposits at Jackson crater. (a) M³ standard color composite showing distinctively feldspathic northern floor (blue) and weakly mafic southern floor (red arrow). (b) Spectra from the northern floor (blue) shows no detectable absorption bands while spectra from the southern floor (red) show a very weak absorption around 1000 nm.

Figure 13 Giordano Bruno crater (a) Location on the lunar far side (b) M³ image showing the crater with its almost no terraces. The crater also lacks any central peak although it is large enough to have one. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. Mineralogical differences on the crater floor are indicated in this composite. (d) Complementary color composite highlighting mafic walls and the ejecta (in pink and red). (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 14 Morphological diversity of impact melt at Giordano Bruno. (a) Context image of the crater showing locations for subsequent figures. (b) NAC view of the NW crater rim showing two distinctive materials. There is gray toned bifurcating impact melt flow in the top-middle section. In the immediate vicinity are pulverized low-albedo materials

which could be part of the ejecta from a localized lithology. (c) A very distinct low-albedo flow feature located about 1 crater radii away in the NW. (d) Ropy melt deposits are located in different parts of crater exterior. The image shows these deposits located in the west part of crater exterior. (e) The well known impact melt flow on the southern rim of the crater. Note that it looks morphologically quite fresh as compared to the flow shown in c despite the fact that both formed in the same cratering event. (f) Another well-documented and a unique feature occurs on the western floor region. The large melt pond shows a whirlpool morphology formed by local landslide. (g) The central part of the crater floor shows viscous, debris laden melt that flowed around a central elongated island. *Image Source: LRO NAC.*

Figure 15 Mineralogy of melt units at Giordano Bruno. (a) M^3 standard color composite overlain on a LRO NAC mosaic of the crater. Numbered locations represent the spectral sampling locations. (b) M^3 reflectance spectra of the various melt units which are either melt poor (in magenta) or melt-rich (in green). (c) Continuum-removed spectra illustrating that the melt-rich units display strong absorption bands as compared to melt-poor units.

Figure 16 Glushko crater (a) Location on the lunar western near side (b) M^3 image showing the crater with flat floor. The crater has a very small central peak and several large blocks on the floor. (c) M^3 standard color composite highlighting the crater scale mineralogical diversity. Note the mafic-rich northern wall and rim. (d) Complementary color composite highlighting the northern wall and rim as a distinctive unit. (e)

Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 2 by 0.05. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands. (1-N Wall, used in next figure as 1*).

Figure 17 Melt deposits at crater Glushko. (a) M^3 context image of the crater showing the distribution of impact melt deposits. The orange arrows indicate the viewing directions for the DTM shown in later figures. (b) Kaguya TC derived DTM of the crater floor region shows a hummocky terrain with large blocks and smooth impact melt occupying the local lows. The central peak appears as a pyramid shape structure. (c) Kaguya TC DTM of the northern rim of the crater showing an elongated melt pond. (d) The northern exterior deposits of the crater showing extensive impact melt deposits accumulated around an island (marked with a yellow arrow). (e) Radar images of the same area as d showing that impact melt is having higher surface roughness (bright region in left image and red color in right image) as compared to the nearby regions. Source: *Carter et al.*, [2012]

Figure 18 Mineralogical character of impact melt deposits at Glushko. (a) M^3 color composite of the crater showing the mafic northern unit in contrast to the dominantly feldspathic crater units. The thick orange arrow indicates the viewing direction for the DTM shown in later figures. (b) Kaguya TC derived DTM of the northern wall and rim region showing melt ponds which could be identified in M^3 data and therefore could be spectrally analyzed. (c) Kaguya DTM of the melt pond located on the northern wall. (d)

M³ reflectance spectra of the rim and wall ponds in comparison to the northern wall spectra (as shown in Figure 16). The pond spectra have relatively weak but well-defined absorption bands indicating their mafic character. (e) Continuum removed spectra showing detectable differences in the absorption band positions with rim pond and northern wall having short-wavelength bands as compared to the long wavelength (high-calcium pyroxene rich) bands of wall pond.

Figure 19 Ohm crater (a) Location on the lunar western near side (b) M³ image showing the crater with relatively flat floor and walls with terraces. The crater has a small central peak. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite highlighting a prominent halo (in magenta color) at the floor-wall interface. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 20 Impact melt deposits at crater Ohm. (a) M³ context image of the crater showing a flat floor and poorly formed central peaks. Letters represent locations of subsequent figures. (b) Large impact melt pond in the northern part of the crater floor. Note the melt-front draped onto the surrounding material in the NW wall and eastern crater floor. (c) The southernmost peak appears as a bright albedo unit with no observable evidence of impact melt. (d) The NE peak unit provides a morphological contrast with a thick cover of material, that appears fractured (center of the image) and is interpreted as impact melt here.

Figure 21 Distinctive mineralogical pattern in the crater interior at Ohm (a) M³ context image showing no discernable albedo patterns within the crater. (b) M³ standard color composite of the crater showing a high albedo but mafic poor floor region in contrast to the mafic-rich material (green, orange, yellow shades) starting from the wall-floor boundary and up the wall. (c) Similar pattern as described in b is also observed in the complementary color composite. The magenta shade representing high-calcium pyroxene dominated lithology is largely restricted in the crater floor-wall interface region (marked by black arrows).

Figure 22 King crater (a) Location on the lunar far side (b) LRO WAC image showing the crater with rough crater floor and prominent (and unusual) central peaks. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Color composite suggesting that melt unit on the floor and northern rim are distinct from the remaining crater. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 23 Melt distribution and morphology around King crater. (a) LRO WAC image of the region with King located in the bottom section. (b) WAC derived DEM draped on the WAC image showing a pervasive topographic low (cyan-teal colors) on King exterior in N-NW direction. White boxes show geographic locations of subsequent images. (c) The NW periphery of the topographic low shows several melt-fronts (marked by black

arrows). (d) Outside of the large topographic low, the melt-fronts could still be observed indicating that melt moved further north during King cratering event.

Figure 24 Kovalevskaya crater (a) Location on the lunar far side (b) M³ image showing the crater with relatively smooth floor and central peaks. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. Note the prominent mafic unit on the northern and eastern sections of the crater. (d) Color composite suggesting no major compositional differences on the crater floor. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 2 by 0.03 and spectrum 3 by 0.07. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 25 Melt deposits at crater Kovalevskaya. (a) LRO WAC context image showing some smooth areas in immediate vicinity (white arrow) and further west of the crater (yellow arrow). The latter could be a large impact melt deposit. (b) WAC derived DEM overlain on WAC image showing that the extensive western region (yellow arrow in a) is topographically flat but also higher in elevation than the Kovalevskaya floor.

Figure 26 Mineralogical variations on the floor of Kovalevskaya crater. (a) M³ context image of the crater. (b) M³ standard color composite showing the different mineralogy of the crater floor (mafic in the north and feldspathic in the south) (c) Spectral reflectance of some of the bright spots on the crater floor as observed in the two color composites. Each

of the spectra show distinct long wavelength absorption bands similar to the mafic northern material (noted in Figure 25, #4). The reflectance scale is offset for spectrum 3 by 0.07. (d) Complementary color composite showing small, bright regions (in magenta color), likely fresh impact craters on an otherwise mineralogically uniform looking crater floor.

Figure 27 Eratosthenes crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively rubbly floor and walls with terraces. The crater has a distinctive central peak. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting uniform melt mineralogy on the floor. The observed striping is due to residual photometric and thermal effects. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 28 Mineralogy of floor impact melt at Eratosthenes. (a) M³ context image of the crater. (b) M³ standard color composite of the crater showing highly heterogeneous central peak and a largely uniform crater floor. The striping is an artifact and is due to the residual of thermal and photometric corrections. (c) Soil spectra of the floor region shows very weak features (#1, #3) if any. The reflectance scale is offset for spectrum 4 by 0.02.

Figure 29 Aristillus crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively flat floor, wall terraces and central peaks. Note the low albedo linear

streak on the NE crater wall and rim region. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting a very uniform mineralogy on the crater floor that appears similar to the central peaks. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale refers to spectrum 3. All others are offset as follows: spectrum1: 0.01, spectrum 2: 0.05, spectrum 4: 0.06. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 30 Impact melt deposits at Aristillus. (a) M³ context image showing the crater. Lettered boxes represent locations of subsequent figures. (b) The northern wall of the crater shows smooth regions (marked by arrows) near the crater floor, likely representing a thick impact melt veneer. (c) The northern central peak region displays some extended melt veneer-like deposits at multiple locations (white arrows). (d) The southern crater floor shows cooling cracks with different geometries (e.g. radiating, parallel).

Figure 31 Melt mineralogy at Aristillus (a) M³ context image of the crater showing the locations of spectral sampling. (b) M³ standard color composite showing mafic central peaks and largely feldspathic/ noritic crater wall. (c) Spectra from different parts of the impact melt-rich floor show remarkable similarity. The reflectance scale is offset for spectrum 1 by 0.1, spectrum 2 by 0.2, spectrum 3 by 0.3, spectrum 4 by 0.4. (d) Continuum-removed spectra further illustrated the spectral and therefore mineralogical homogeneity of the impact melt deposits.

Figure 32 Burg crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively flat floor, wall terraces and central peaks. Note the possible connection between peak and the eastern wall through the floor. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting a very uniform mineralogy on the crater floor. In contrast, some of the wall sections (north and SW) look distinctly different from the surroundings. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 4 by 0.08. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 33 Probable impact melt deposits on the terraces of crater Burg. (a) Context image showing the locations analyzed at high resolution. Orange arrows indicate the viewing direction for the later images. (b) DTM of the western crater wall showing small pockets of smooth material with slightly lower albedo in comparison to the sloping and bright nearby material. (c) DTM of the northern wall terrace showing flat-lying, low-albedo smooth material in comparison to the slightly rougher material in the close vicinity (in lower part of the image). The upper part of the image represents northern wall.

Figure 34 Mineralogy of the impact melt on the crater floor (a) M³ context image of the crater. (b) M³ standard color composite of the crater showing feldspathic ejecta material and heterogeneous central peaks. Numbers represent spectral sampling locations. (c) Spectral reflectance of the impact melt soils and fresh craters indicate the mafic nature of

the impact melt. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.025, spectrum 3: 0.04, spectrum 4: 0.02, spectrum 5: 0.07, spectrum 6: 0.05. (d) Continuum-removed spectra illustrate the low calcium-pyroxene rich nature of the impact melt.

Figure 35 Theophilus crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively flat floor, walls with terraces and prominent central peaks. (c) M³ standard color composite highlighting the crater scale mineralogical diversity, mostly from the peak region. (d) Complementary color composite indicating largely uniform crater floor (melt) mineralogy. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 3 by 0.02 and spectrum 4 by 0.04. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 36 Mineralogy of impact melt on the floor of Theophilus. (a) M³ context image of the crater. Letters represent spectral sampling locations. (b) M³ standard color composite of the crater suggesting a largely uniform floor mineralogy. Numbers represent spectral sampling locations. (c) LRO NAC view of one of the spectral sampling locations (#6) which hosts a large Mg-Spinel occurrence on the crater floor, away from the peak. The white box represents the zone of Mg-spinel. (d) Soil spectra of impact melt on the crater floor shows predominantly featureless spectra. The reflectance scale is offset for spectrum 2 by 0.01 and spectrum 4 by 0.02. (e) Spectra from selected fresh craters on the floor show a dominantly mafic mineralogy with some glass. The reflectance scale is

offset for spectrum 4 by 0.08. (f) Spectral comparison of all the Mg-Spinel locations on the floor, compared to the strongest Mg-Spinel detection (magenta).

Figure 37 Lowell crater (a) Location on the lunar western near side (b) M³ image showing the crater with blocky floor and central peak. Note the small crater on the eastern rim which is also part of the study. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting high calcium pyroxene mineralogy of the melt-rich floor (in magenta color). The small crater on the eastern rim also has similar mineralogy. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

Figure 38 Mineralogy of impact melt deposits at Lowell crater. (a) M³ context image of the crater. White box represents region shown in e. (b) M³ standard color composite of the crater showing a prominently mafic central peak. Numbers represent spectral sampling locations. (c) Spectra from fresh surfaces (small craters) on impact melt-rich floor show a dominantly high-calcium pyroxene signature. The reflectance scale is offset for spectrum 2 by 0.06, spectrum 3 by 0.04 and spectrum 4 by 0.02. (d) Continuum removed spectra highlights the high-calcium pyroxene dominance across all the regions. (e) LRO NAC view of SE section of the crater showing the younger crater on the rim and associated magnificent impact melt flows. (f) A close-up view of the flow-structures on the walls show overlapping lobate ends. The morphological freshness of the features indicates their very young age.

Figures

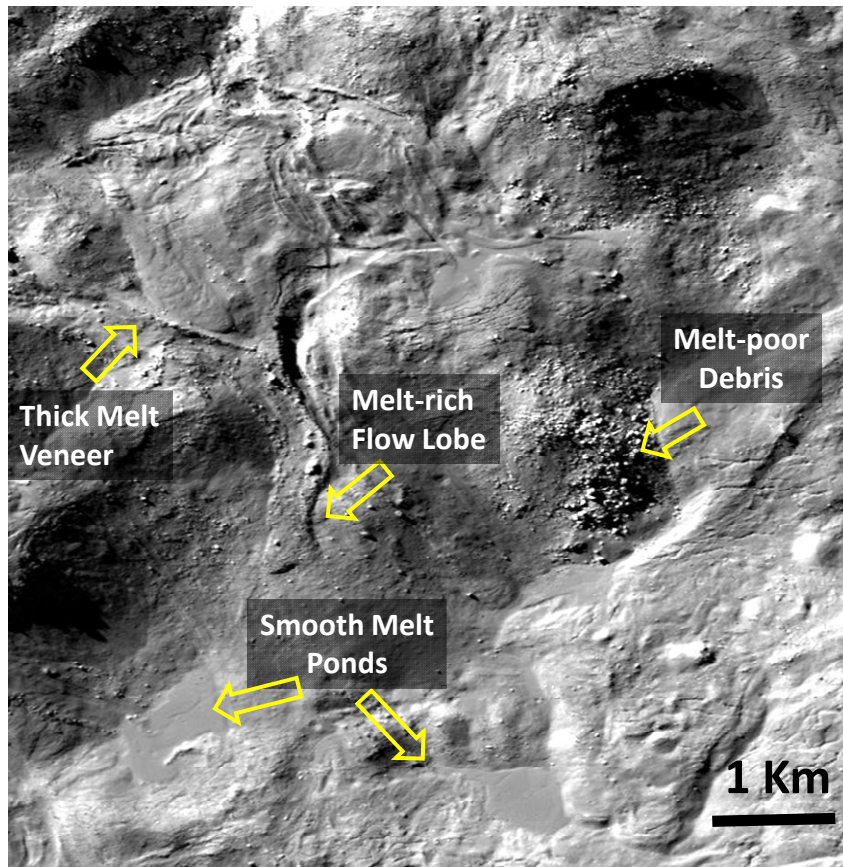


Figure 1 Morphological diversity of impact melt, over a very small spatial scale is illustrated in this image of the north-eastern wall of crater Tycho. *Image source: Kaguya Terrain Camera.*

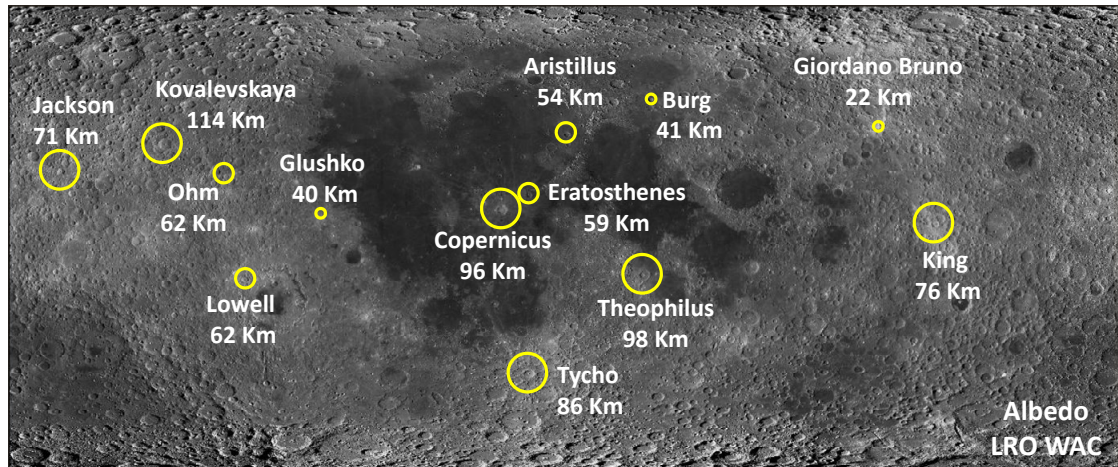
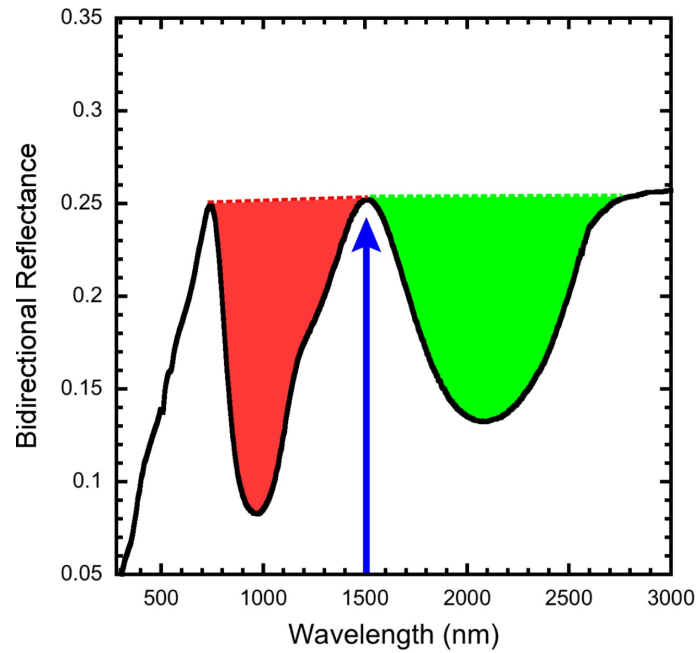
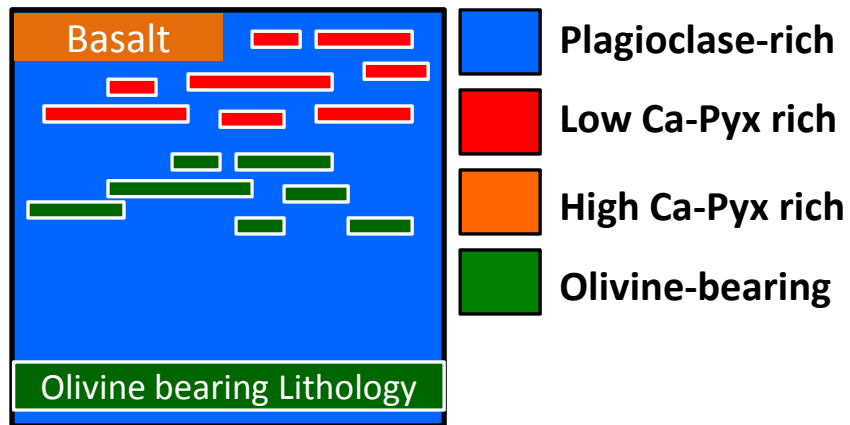


Figure 2 Location of craters analyzed in this study shown on albedo map derived from Wide Angle Camera (WAC) onboard Lunar Reconnaissance Orbiter (LRO). The yellow circles mark the locations of the crater and their sizes represent the relative crater diameters.



(a)



(b)

Figure 3 (a) Graphical representation of the spectral parameters used in generating standard color composite. Red colored region represents the IBD 1000 parameter and is the strength of absorption band around 1000 nm, Green colored region represents the IBD 2000 parameter and is the strength of absorption band around 2000 nm, Blue

arrow indicates the wavelength 1498 nm. These parameters and the corresponding colorations have been used to generate M³ standard color composite. (b) Schematic illustrating the likely nature of target geology at a given crater location.

Copernicus

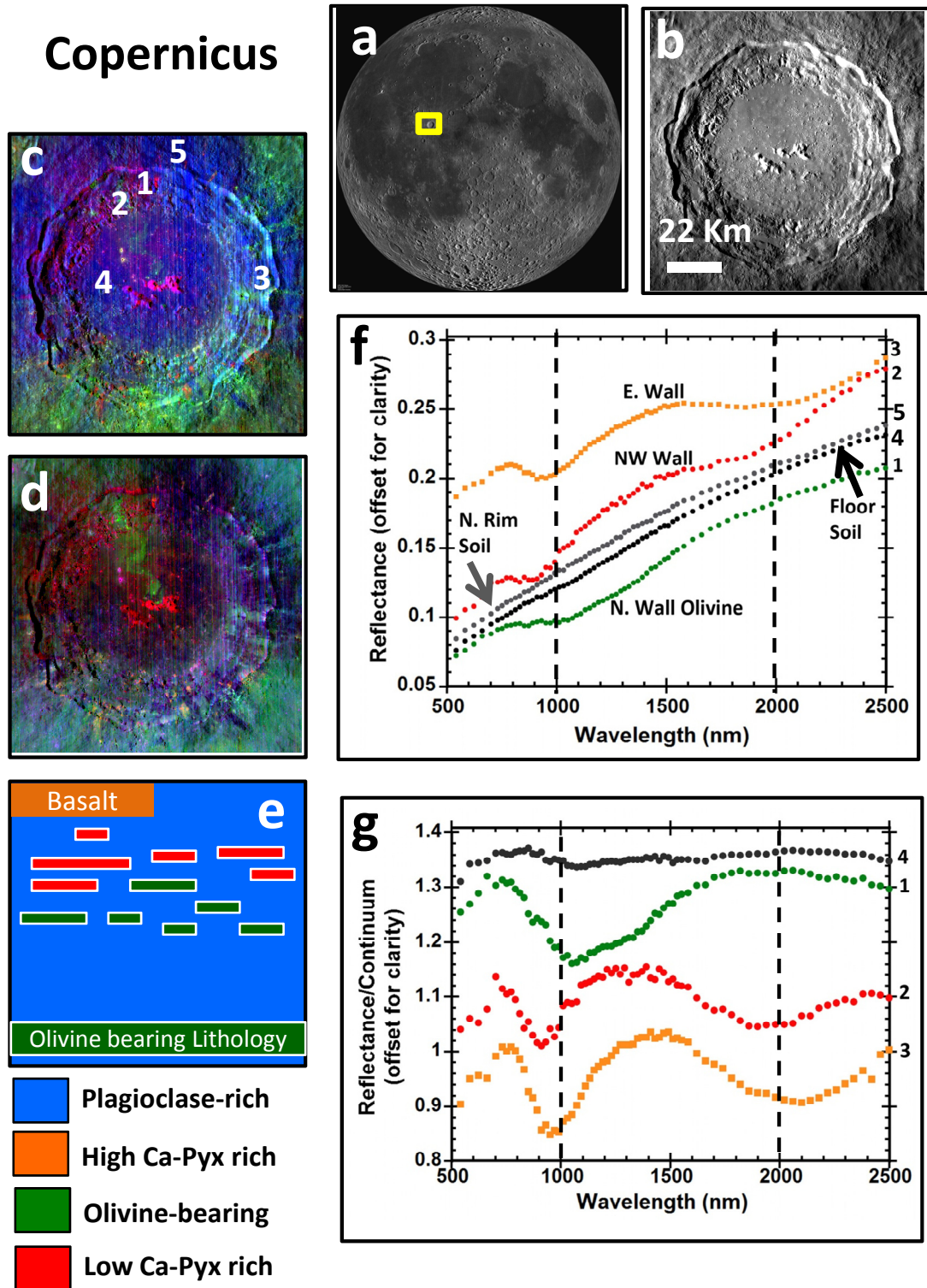


Figure 4 Copernicus crater (a) Location on the lunar side (b) Kaguya TMC image showing the crater with its well-formed terraces and cluster of central peaks on the

crater floor. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. North-south mineralogical heterogeneity (feldspathic-mafic) is clearly observed in this composite. (d) Complementary color composite highlighting the sinuous melt feature on the crater floor (in green) which was not distinct in the standard color composite. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. The reflectance scale is offset for Spectrum 3 by 0.1. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

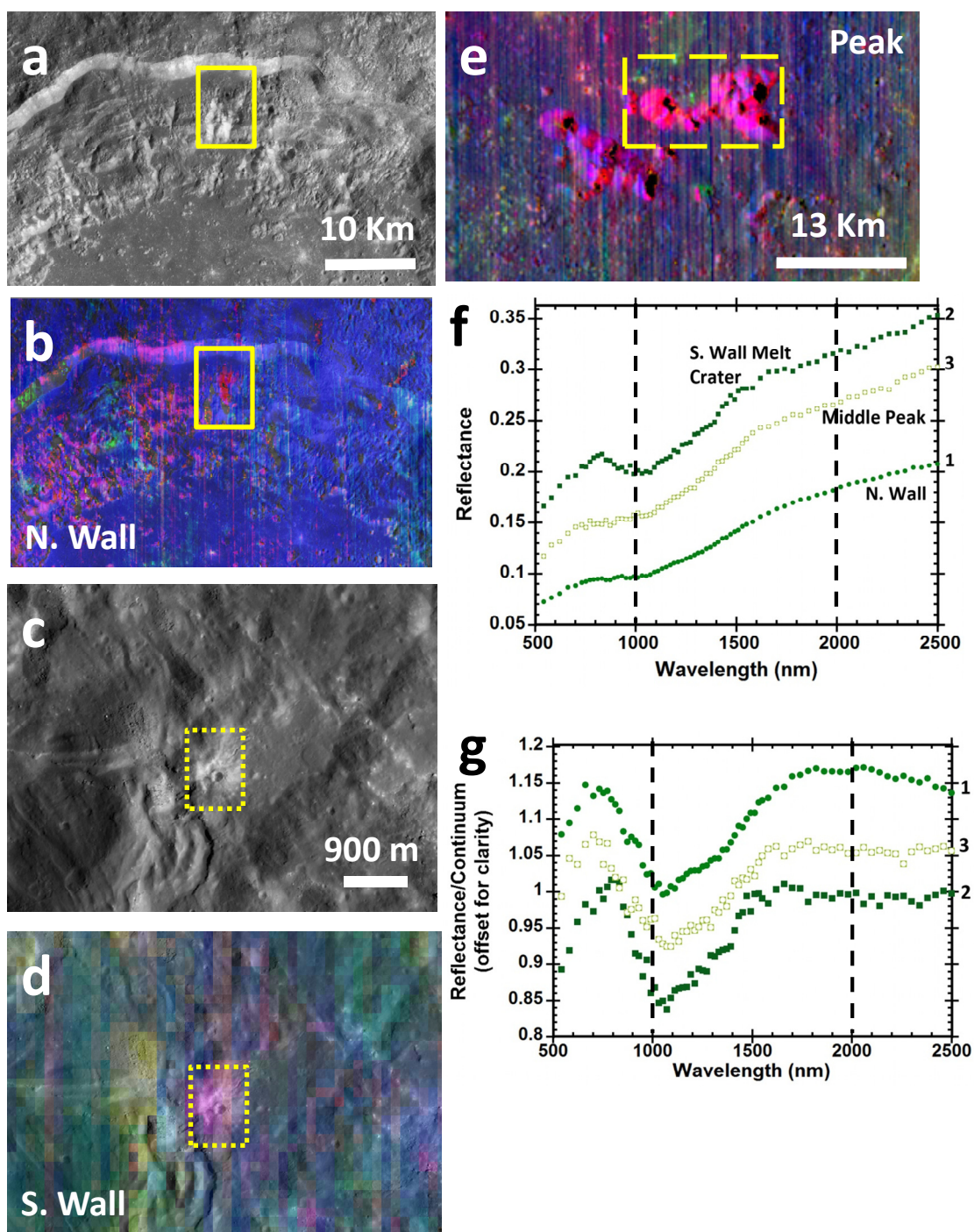


Figure 5 Diversity in geologic setting of olivine lithology at Copernicus crater (a) Kaguya TC image showing the northern wall with location of olivine exposure

marked by yellow box. (b) M^3 color composite overlain on Kaguya TC data showing the olivine-bearing exposure in deep red (within yellow box). (c) Kaguya TC image of impact melt on the terrace of southern crater wall with olivine-bearing exposure marked by yellow dotted box. (d) M^3 color composite overlain on Kaguya TC data showing that olivine-bearing material occurs in the ejecta of a fresh crater in impact melt deposit. (e) M^3 color composite overlain on Kaguya TC data showing olivine-bearing central peaks with the box indicating peaks that have more extensive olivine signatures. (f) Spectra of olivine lithology from the three locations described above showing similarity in spectral signatures, consistent with the presence of olivine. (g) Continuum removed spectra showing the same spectra as in f, highlighting the absorption band characteristics. The numbers correspond to the locations in the crater as marked in c.

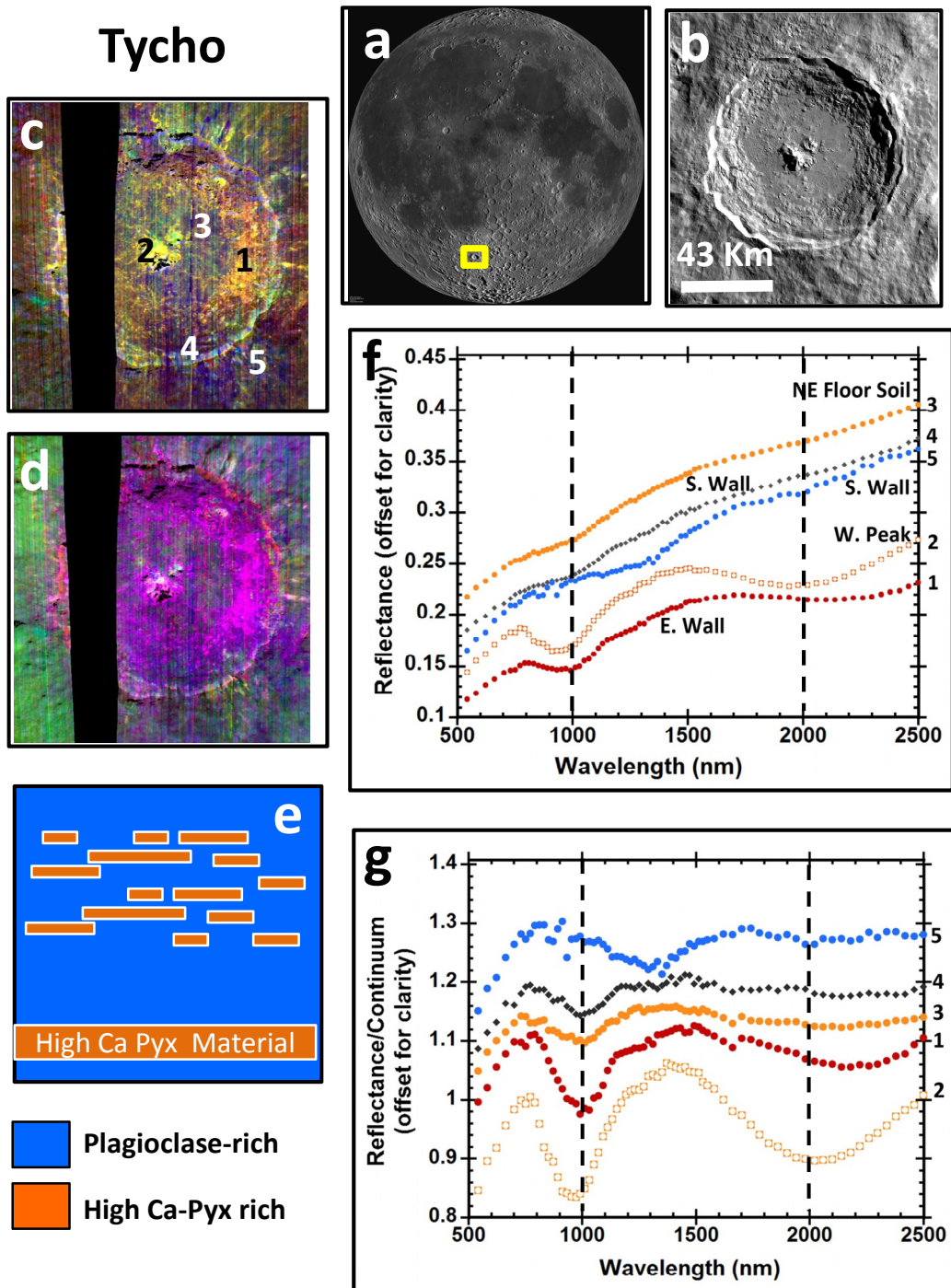


Figure 6 Tycho crater (a) Location on the lunar side (b) M³ image showing the crater with its well-formed terraces and central peaks. (c) M³ standard color composite

highlighting the crater scale mineralogical diversity. Note the distinct character of eastern wall (1) unit in yellow-orange as compared to the crater walls in the vicinity. (d) Complementary color composite of the region. Eastern wall is again observed as distinctive unit. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Tycho. The reflectance scale is offset for spectrum 3 by 0.1 and spectrum 4 by 0.08. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands for the various lithologies.

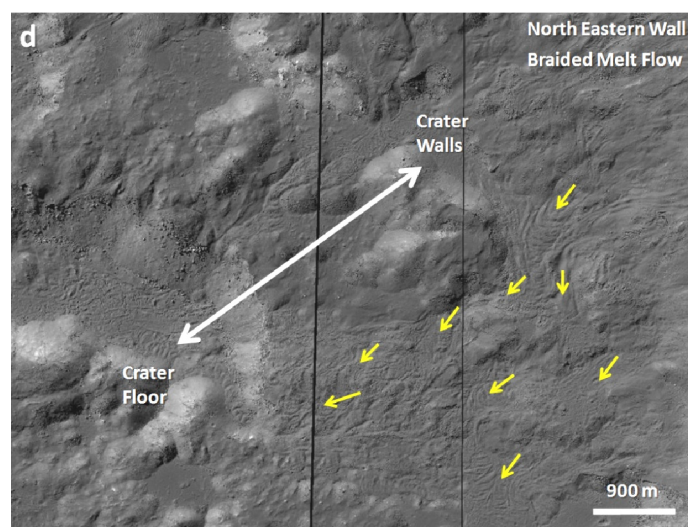
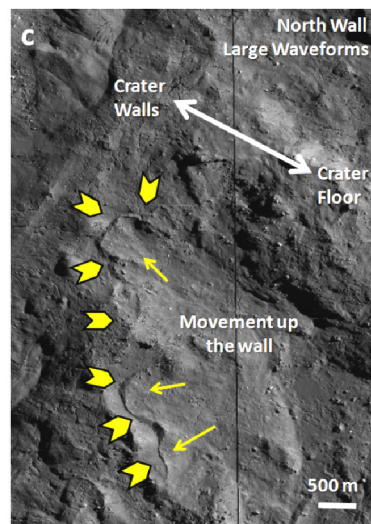
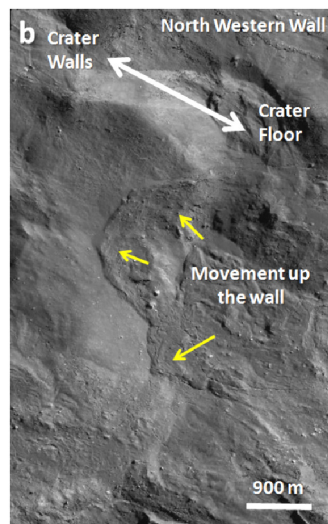
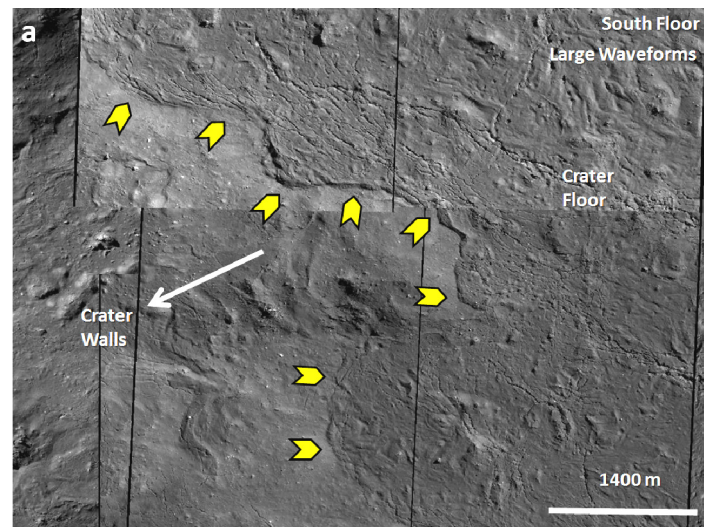


Figure 7 Morphological diversity of impact melt on the crater floor of Tycho (a) Melt fronts (marked by yellow arrows) draped on to the nearby crater wall indicating upslope flow towards the wall. (b) Similar melt fronts on the NW wall. (c) Another example of well-defined melt-fronts draping the high standing wall topography and oriented in up slope direction. (d) Large impact melt deposit on the NE wall of the crater showing several flow fronts moving down slope in a braided fashion. *Image source: LRO Narrow Angle Camera.*

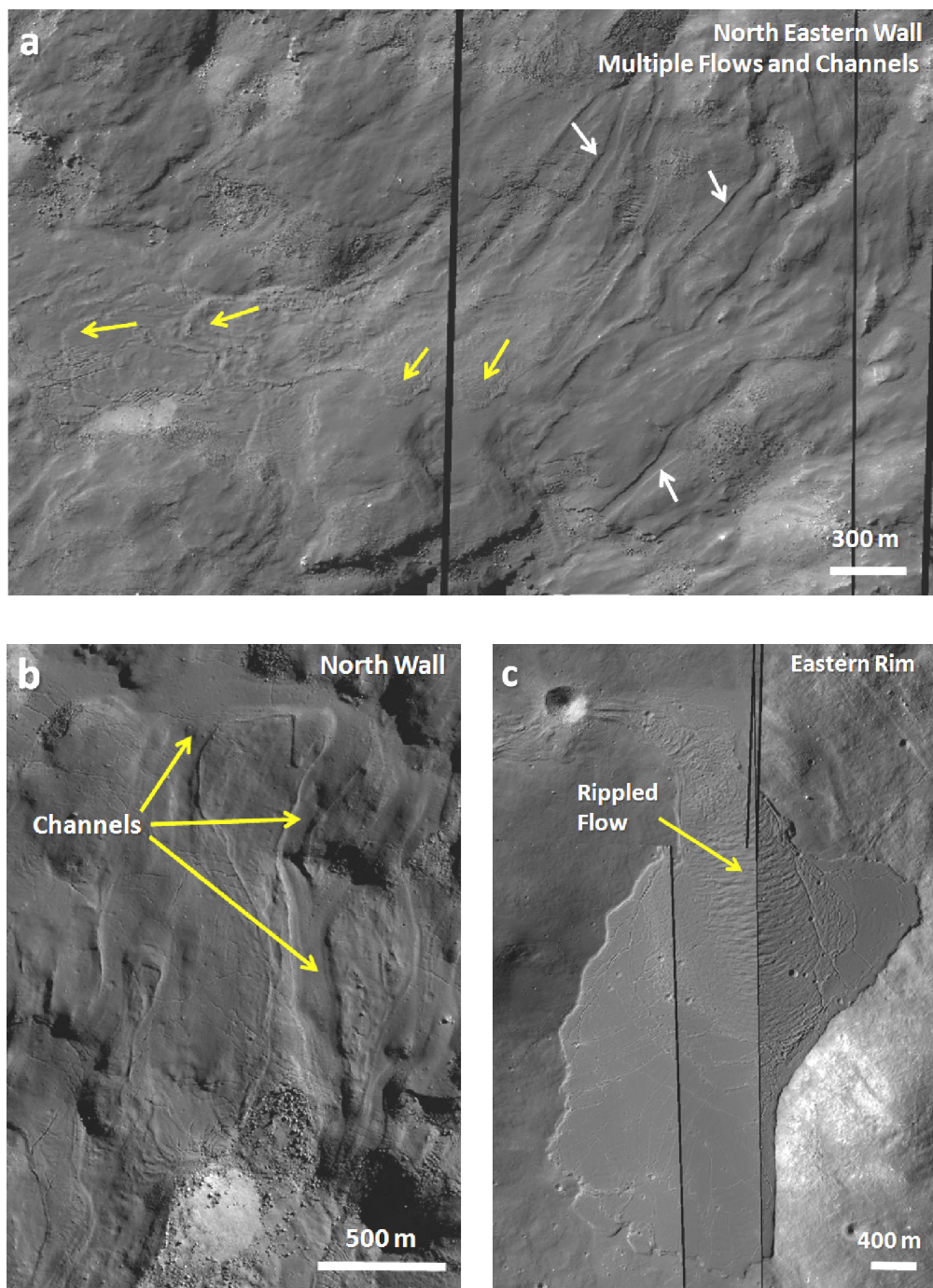


Figure 8 Morphological forms of impact melt at Tycho. (a) Multiple flow fronts, perhaps formed by draining through channels up slope on the NE wall. (b) Well-

marked channels and pervasive melt cover on the northern wall. (c) The eastern rim of Tycho shows this spectacular flow with a rippled surface, likely defined by break in slope. Image source: LRO Narrow Angle Camera.

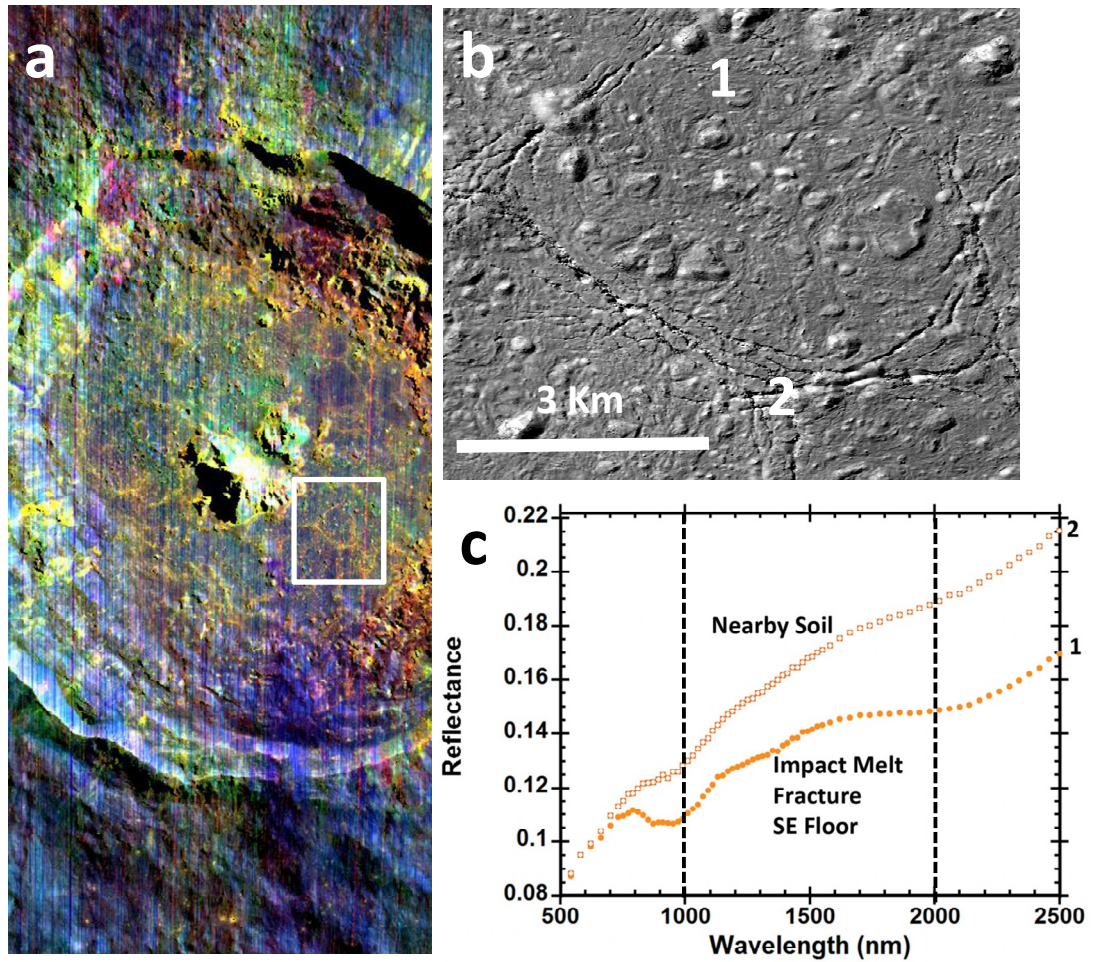


Figure 9 Large scale fractures in impact melt at Tycho.(a) M³ standard color composite showing the strong mafic character of polygonal floor fractures (as marked in white box). (b) LRO NAC image of a polygonal fracture (same as shown in white box in a). (c) Spectra comparison of melt within the fracture (1) and from the fresh fracture surface (2). The fresh fracture has much stronger spectral bands indicating high-calcium pyroxene mineralogy.

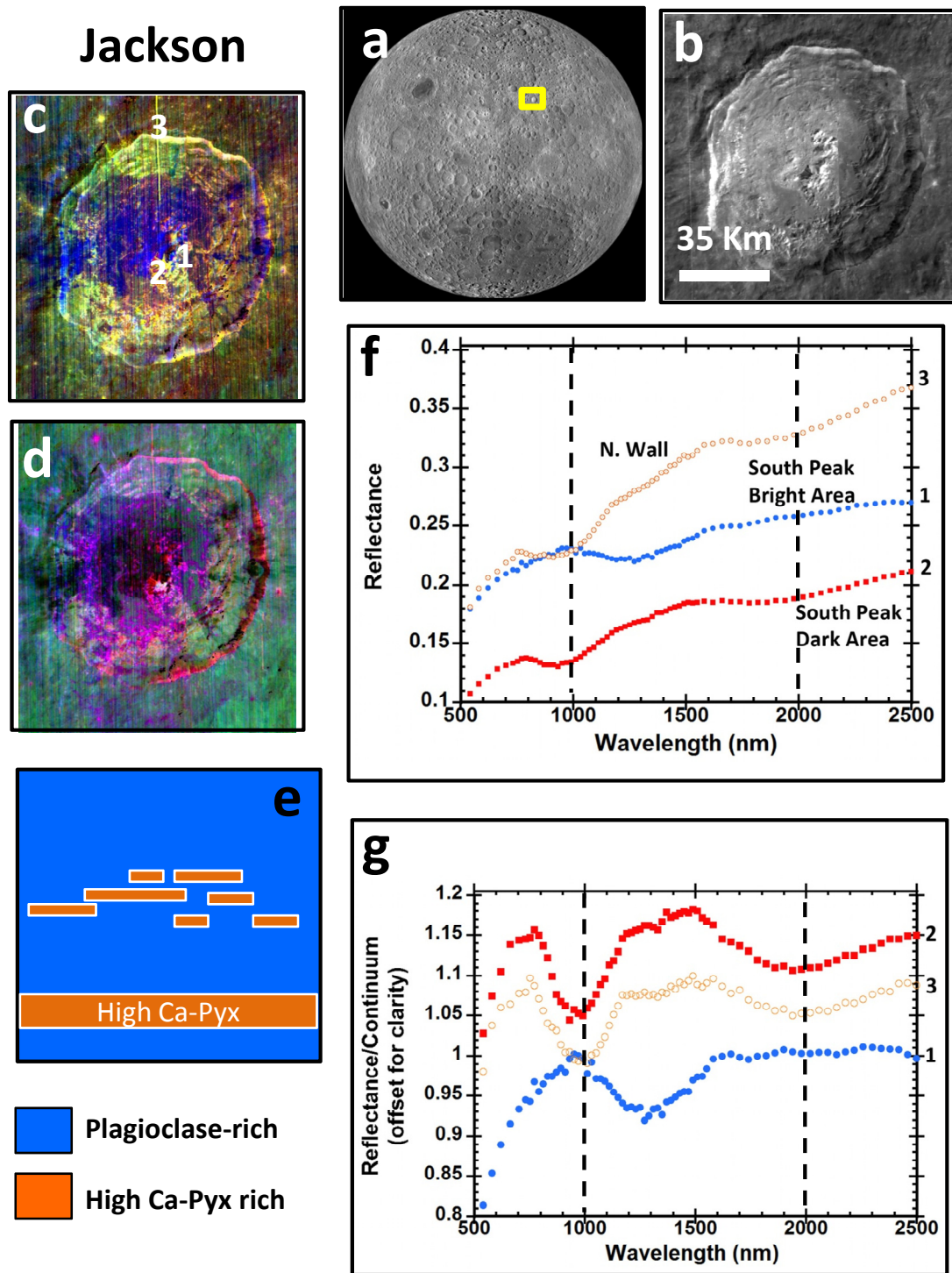


Figure 10 Jackson crater (a) Location on the lunar far side (b) M³ image showing the crater with its well-formed terraces and central peaks. (c) M³ standard color composite

highlighting the crater scale mineralogical diversity. North-south mineralogical heterogeneity (feldspathic-mafic) on the crater floor is indicated in this composite. (d) Complementary color composite highlighting mafic central peak and the southern crater floor (in pink and red). (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

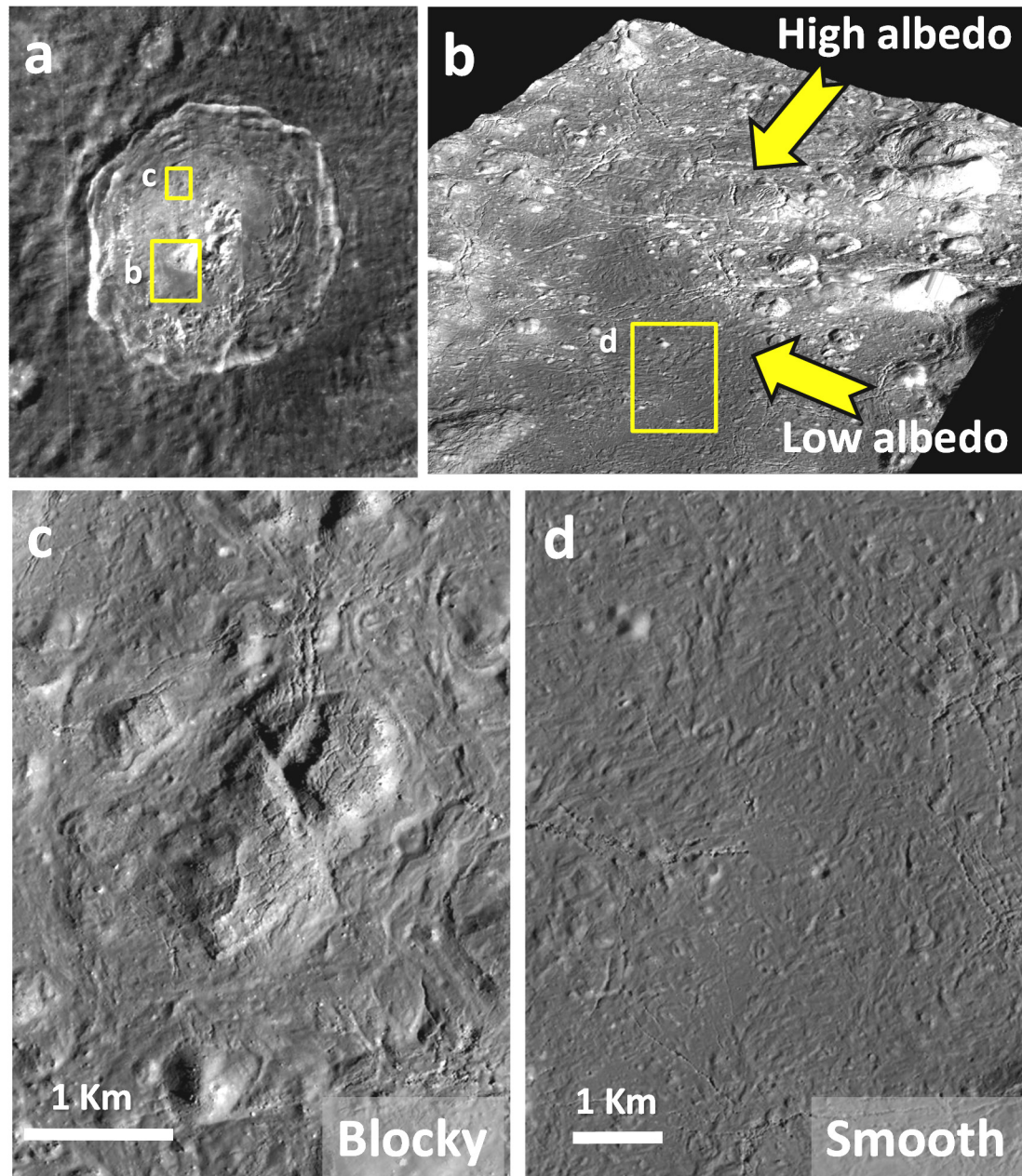


Figure 11 Character of floor impact melt deposits at Jackson crater. (a) M³ context image showing floor of Jackson crater with some albedo differences. (b) A Kaguya TC derived DTM of the southern central crater floor looking towards north. Distinct albedo differences can be observed between the narrow lower unit and the more extensive and

blocky high-albedo unit. (c) Kaguya TC image of the northern part of crater floor shows large blocks and highly textured impact melt. (d) Kaguya TC image of the southern crater floor showing a strikingly smooth impact melt with no large blocks.

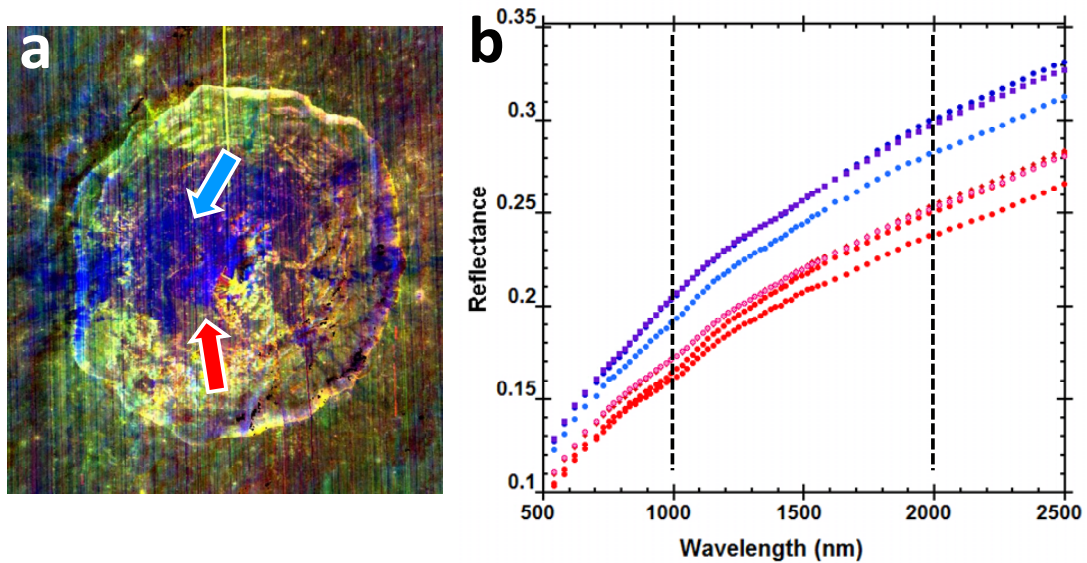


Figure 12 Mineralogical character of the floor impact melt deposits at Jackson crater. (a) M³ standard color composite showing distinctively feldspathic northern floor (blue) and weakly mafic southern floor (red arrow). (b) Spectra from the northern floor (blue) shows no detectable absorption bands while spectra from the southern floor (red) show a very weak absorption around 1000 nm.

Giordano Bruno

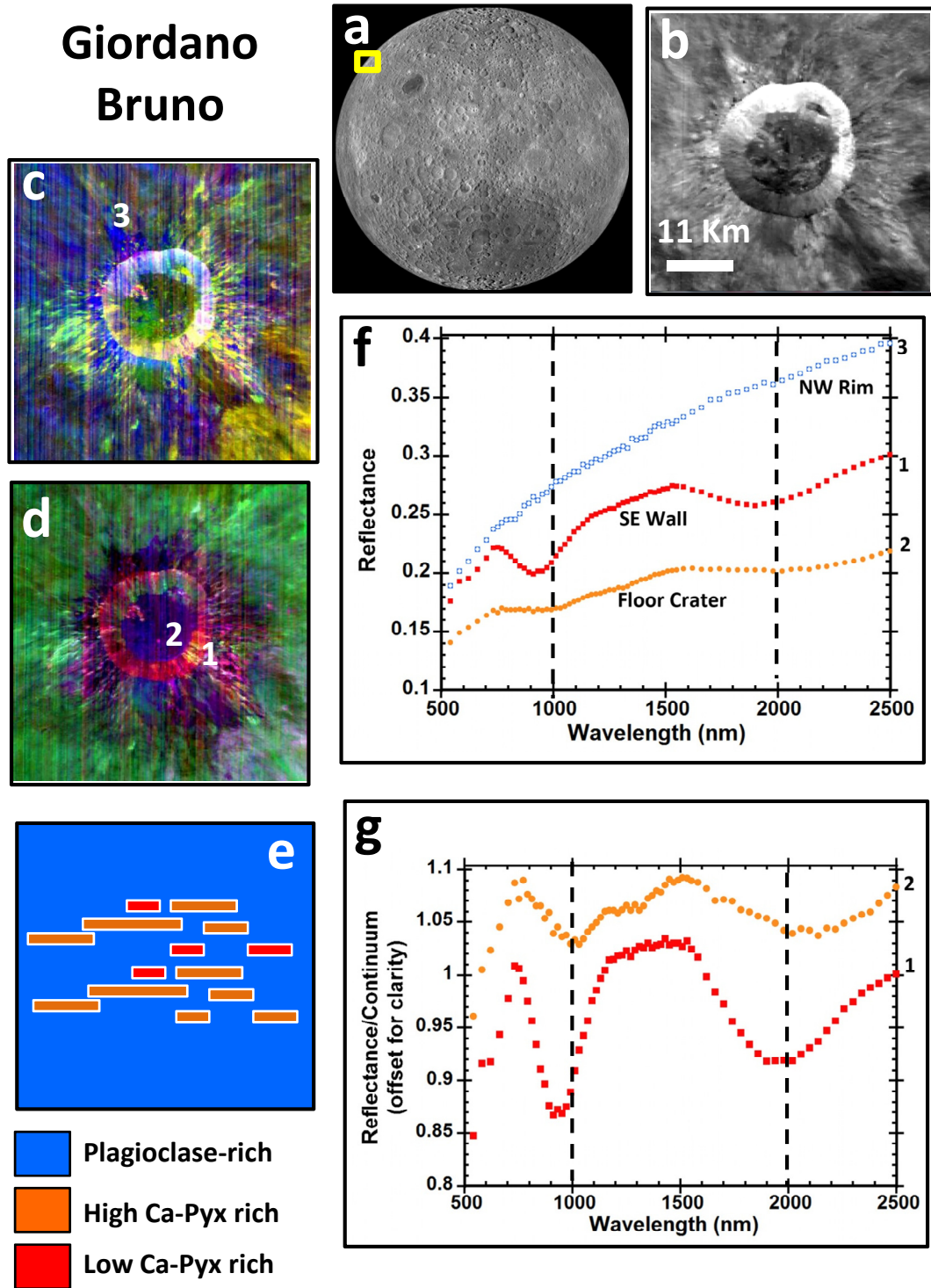


Figure 13 Giordano Bruno crater (a) Location on the lunar far side (b) M³ image showing the crater with its almost no terraces. The crater also lacks any central peak

although it is large enough to have one. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. Mineralogical differences on the crater floor are indicated in this composite. (d) Complementary color composite highlighting mafic walls and the ejecta (in pink and red). (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies at Copernicus crater. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

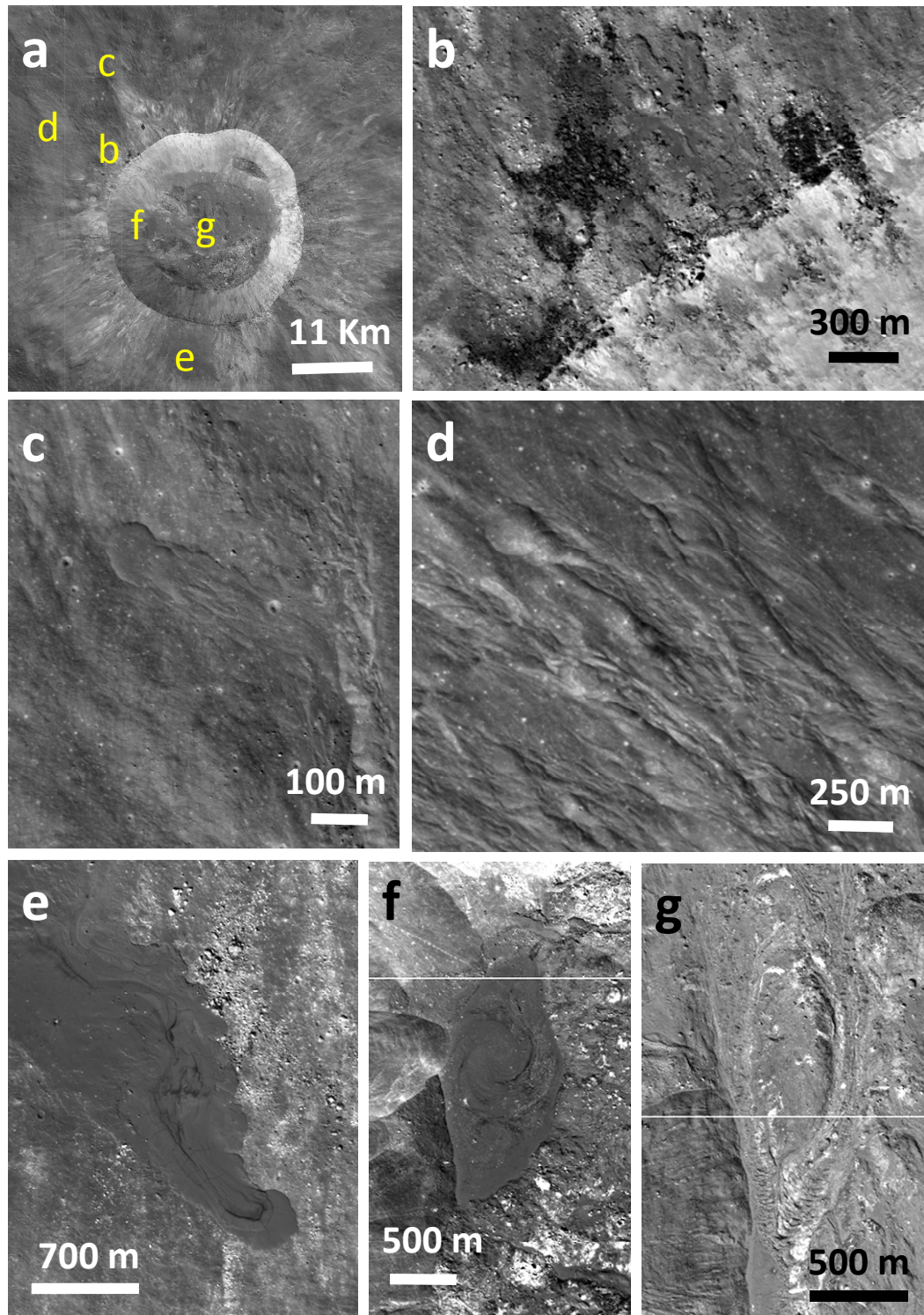


Figure 14 Morphological diversity of impact melt at Giordano Bruno. (a) Context image of the crater showing locations for subsequent figures. (b) NAC view of the NW crater

rim showing two distinctive materials. There is gray toned bifurcating impact melt flow in the top-middle section. In the immediate vicinity are pulverized low-albedo materials which could be part of the ejecta from a localized lithology. (c) A very distinct low-albedo flow feature located about 1 crater radii away in the NW. (d) Ropy melt deposits are located in different parts of crater exterior. The image shows these deposits located in the west part of crater exterior. (e) The well known impact melt flow on the southern rim of the crater. Note that it looks morphologically quite fresh as compared to the flow shown in c despite the fact that both formed in the same cratering event. (f) Another well-documented and a unique feature occurs on the western floor region. The large melt pond shows a whirlpool morphology formed by local landslide. (g) The central part of the crater floor shows viscous, debris laden melt that flowed around a central elongated island. *Image Source: LRO NAC.*

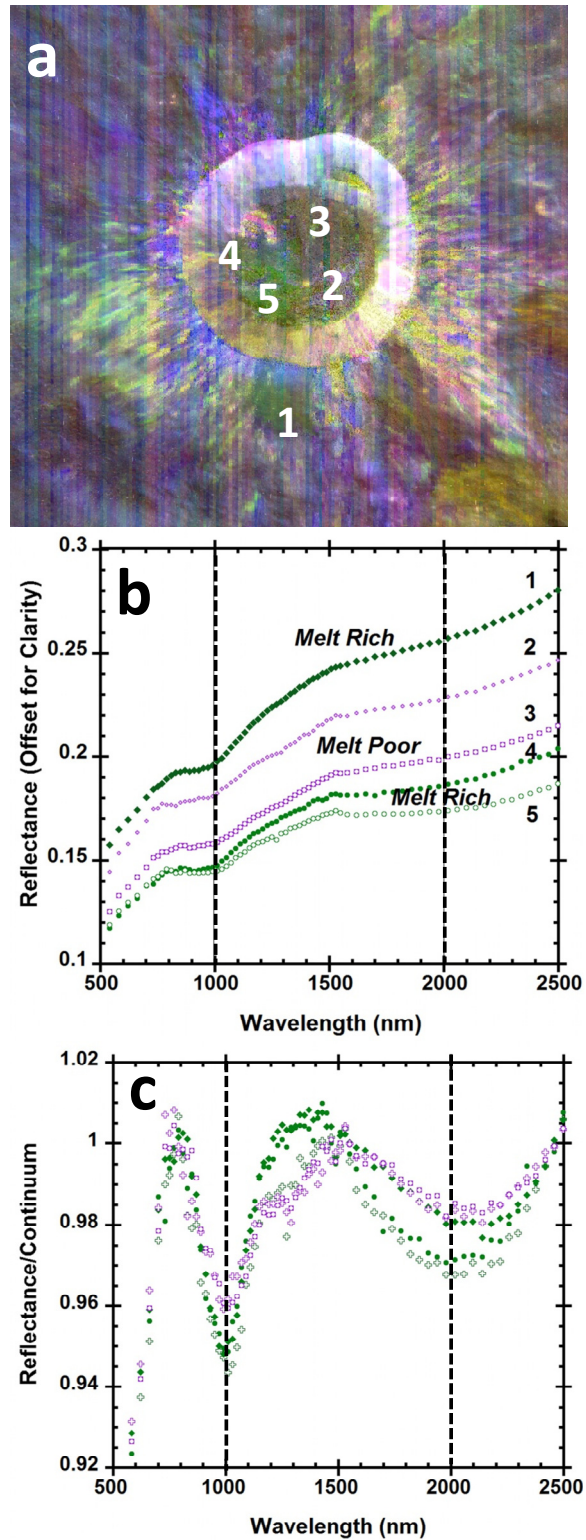


Figure 15 Mineralogy of melt units at Giordano Bruno. (a) M^3 standard color composite overlain on a LRO NAC mosaic of the crater. Numbered locations represent the spectral

sampling locations. (b) M^3 reflectance spectra of the various melt units which are either melt poor (in magenta) or melt-rich (in green). (c) Continuum-removed spectra illustrating that the melt-rich units display strong absorption bands as compared to melt-poor units.

Glushko

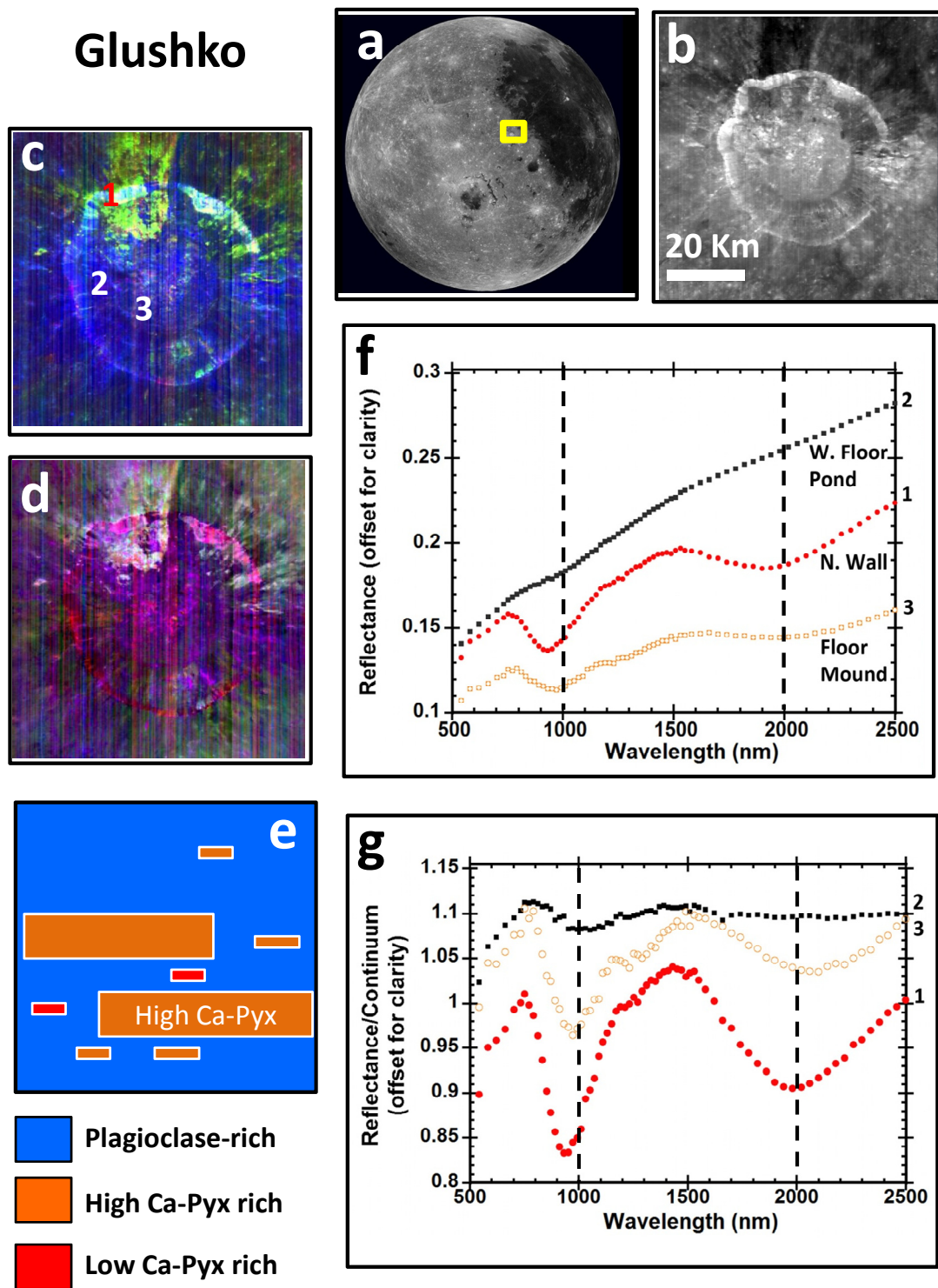


Figure 16 Glushko crater (a) Location on the lunar western near side (b) M³ image showing the crater with flat floor. The crater has a very small central peak and several

large blocks on the floor. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. Note the mafic-rich northern wall and rim. (d) Complementary color composite highlighting the northern wall and rim as a distinctive unit. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 2 by 0.05. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands. (1-N Wall, used in next figure as 1*).

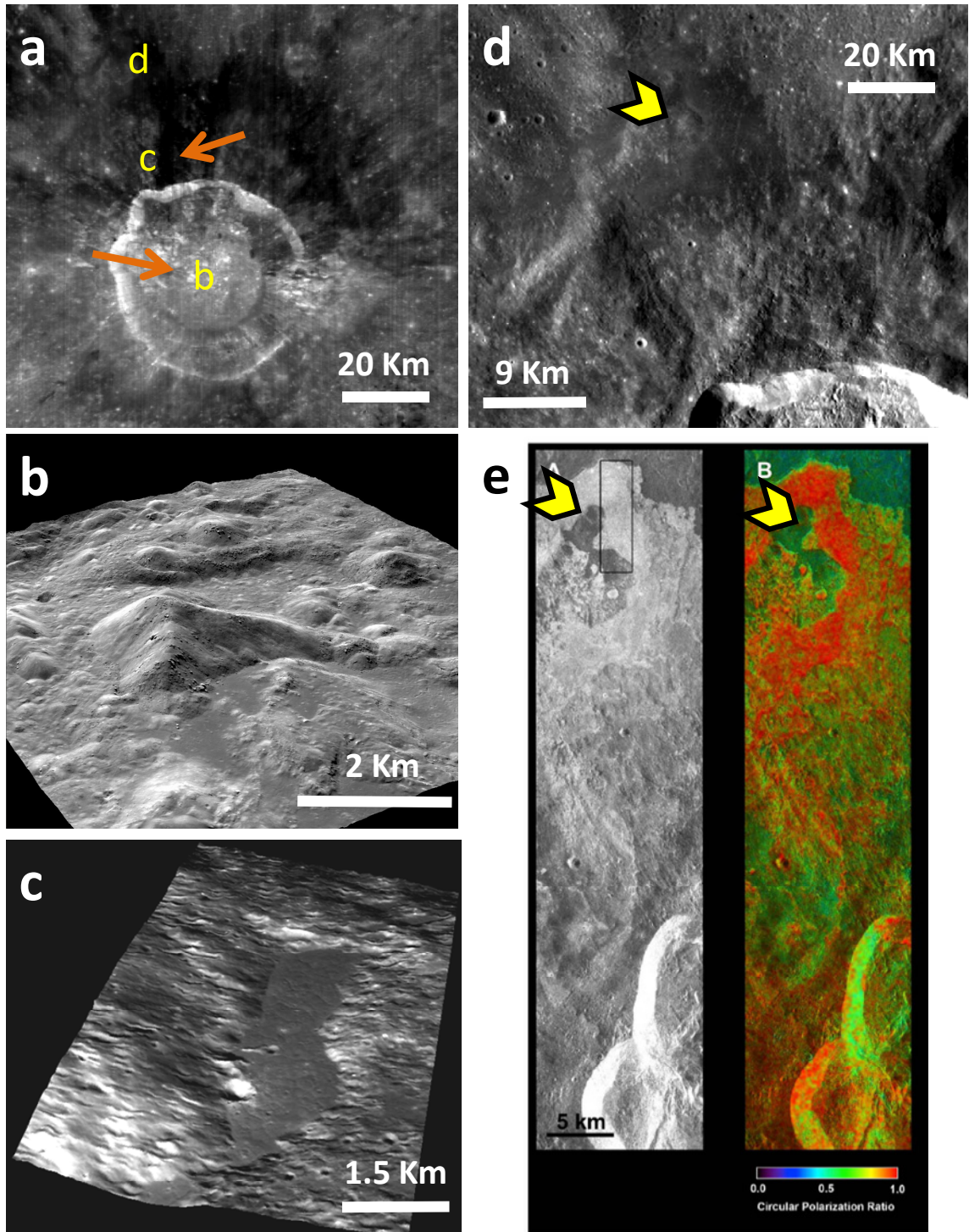


Figure 17 Melt deposits at crater Glushko. (a) M³ context image of the crater showing the distribution of impact melt deposits. The orange arrows indicate the viewing

directions for the DTM shown in later figures. (b) Kaguya TC derived DTM of the crater floor region shows a hummocky terrain with large blocks and smooth impact melt occupying the local lows. The central peak appears as a pyramid shape structure. (c) Kaguya TC DTM of the northern rim of the crater showing an elongated melt pond. (d) The northern exterior deposits of the crater showing extensive impact melt deposits accumulated around an island (marked with a yellow arrow). (e) Radar images of the same area as d showing that impact melt is having higher surface roughness (bright region in left image and red color in right image) as compared to the nearby regions. Source: *Carter et al.*, [2012].

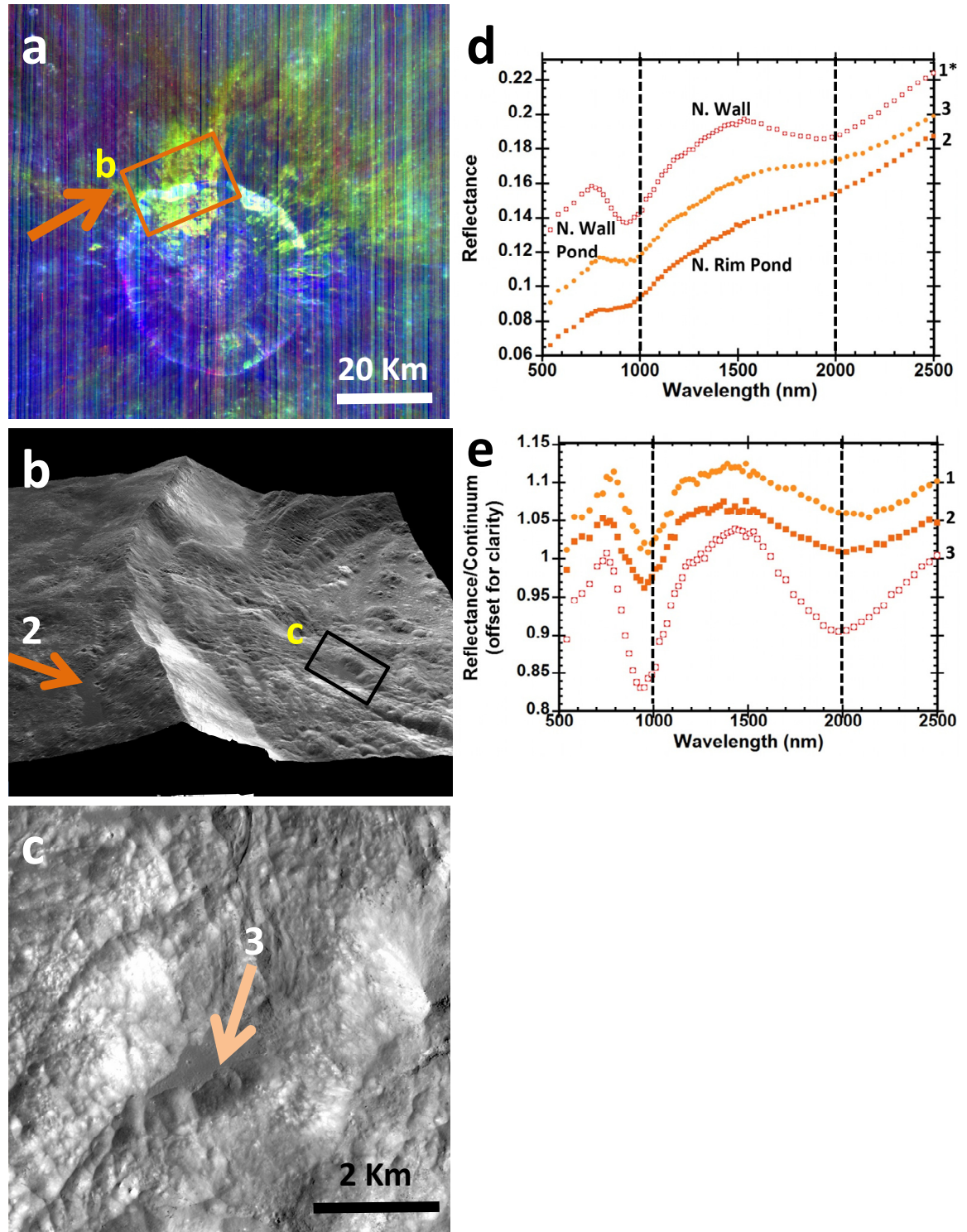


Figure 18 Mineralogical character of impact melt deposits at Glushko. (a) M³ color composite of the crater showing the mafic northern unit in contrast to the dominantly

feldspathic crater units. The thick orange arrow indicates the viewing direction for the DTM shown in later figures. (b) Kaguya TC derived DTM of the northern wall and rim region showing melt ponds which could be identified in M^3 data and therefore could be spectrally analyzed. (c) Kaguya DTM of the melt pond located on the northern wall. (d) M^3 reflectance spectra of the rim and wall ponds in comparison to the northern wall spectra (as shown in Figure 16). The pond spectra have relatively weak but well-defined absorption bands indicating their mafic character. (e) Continuum removed spectra showing detectable differences in the absorption band positions with rim pond and northern wall having short-wavelength bands as compared to the long wavelength (high-calcium pyroxene rich) bands of wall pond.

Ohm

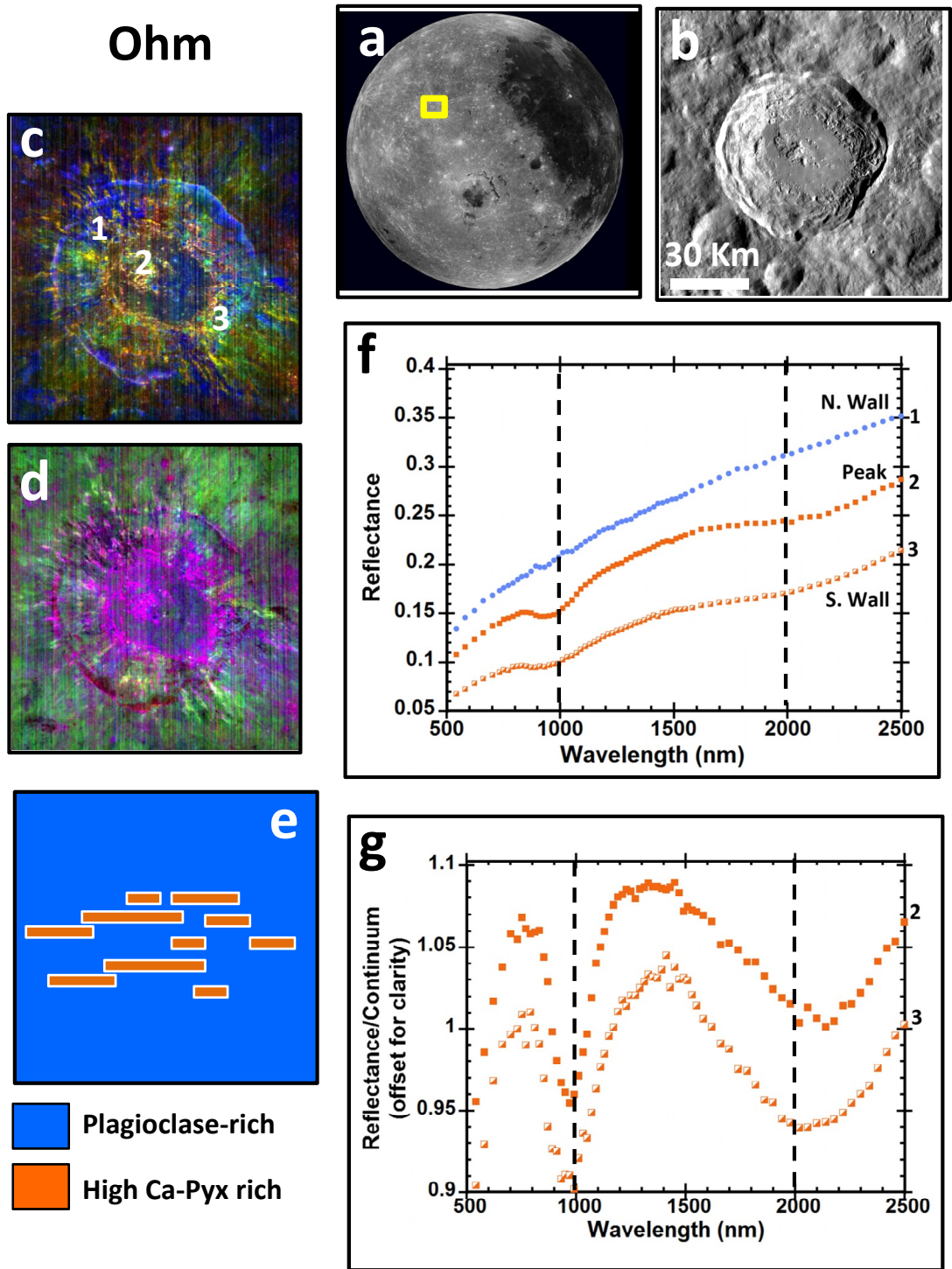


Figure 19 Ohm crater (a) Location on the lunar western near side (b) M³ image showing the crater with relatively flat floor and walls with terraces. The crater has a

small central peak. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite highlighting a prominent halo (in magenta color) at the floor-wall interface. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

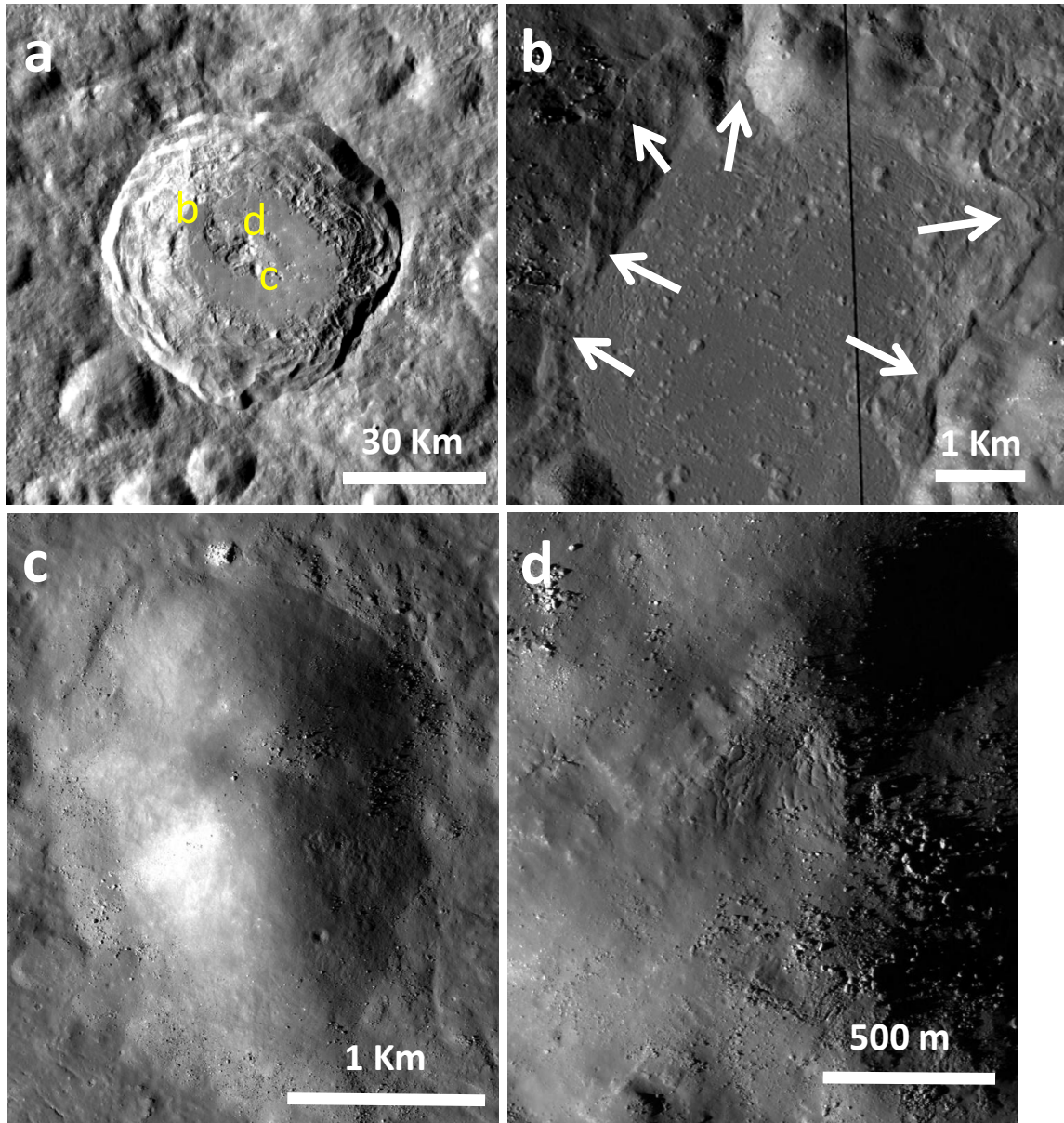


Figure 20 Impact melt deposits at crater Ohm. (a) M³ context image of the crater showing a flat floor and poorly formed central peaks. Letters represent locations of subsequent figures. (b) Large impact melt pond in the northern part of the crater floor. Note the melt-front draped onto the surrounding material in the NW wall and eastern crater floor. (c) The southernmost peak appears as a bright albedo unit with no observable crater floor. (d) The southernmost peak appears as a bright albedo unit with no observable crater floor.

evidence of impact melt. (d) The NE peak unit provides a morphological contrast with a thick cover of material, that appears fractured (center of the image) and is interpreted as impact melt here.

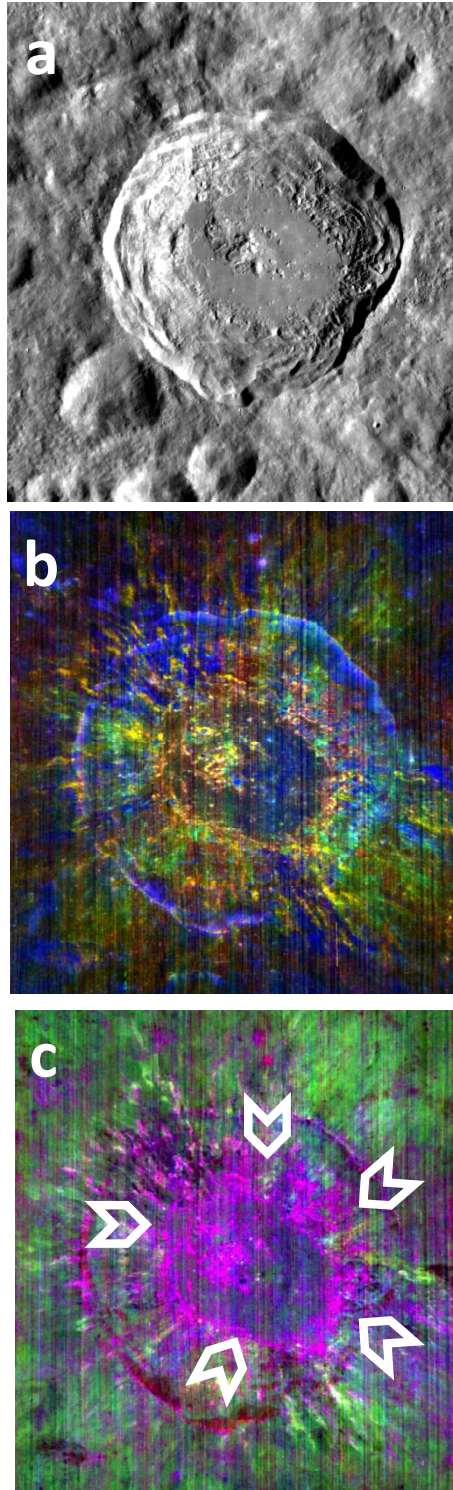


Figure 21 Distinctive mineralogical pattern in the crater interior at Ohm (a) M^3 context image showing no discernable albedo patterns within the crater. (b) M^3 standard color

composite of the crater showing a high albedo but mafic poor floor region in contrast to the mafic-rich material (green, orange, yellow shades) starting from the wall-floor boundary and up the wall. (c) Similar pattern as described in b is also observed in the complementary color composite. The magenta shade representing high-calcium pyroxene dominated lithology is largely restricted in the crater floor-wall interface region (marked by black arrows).

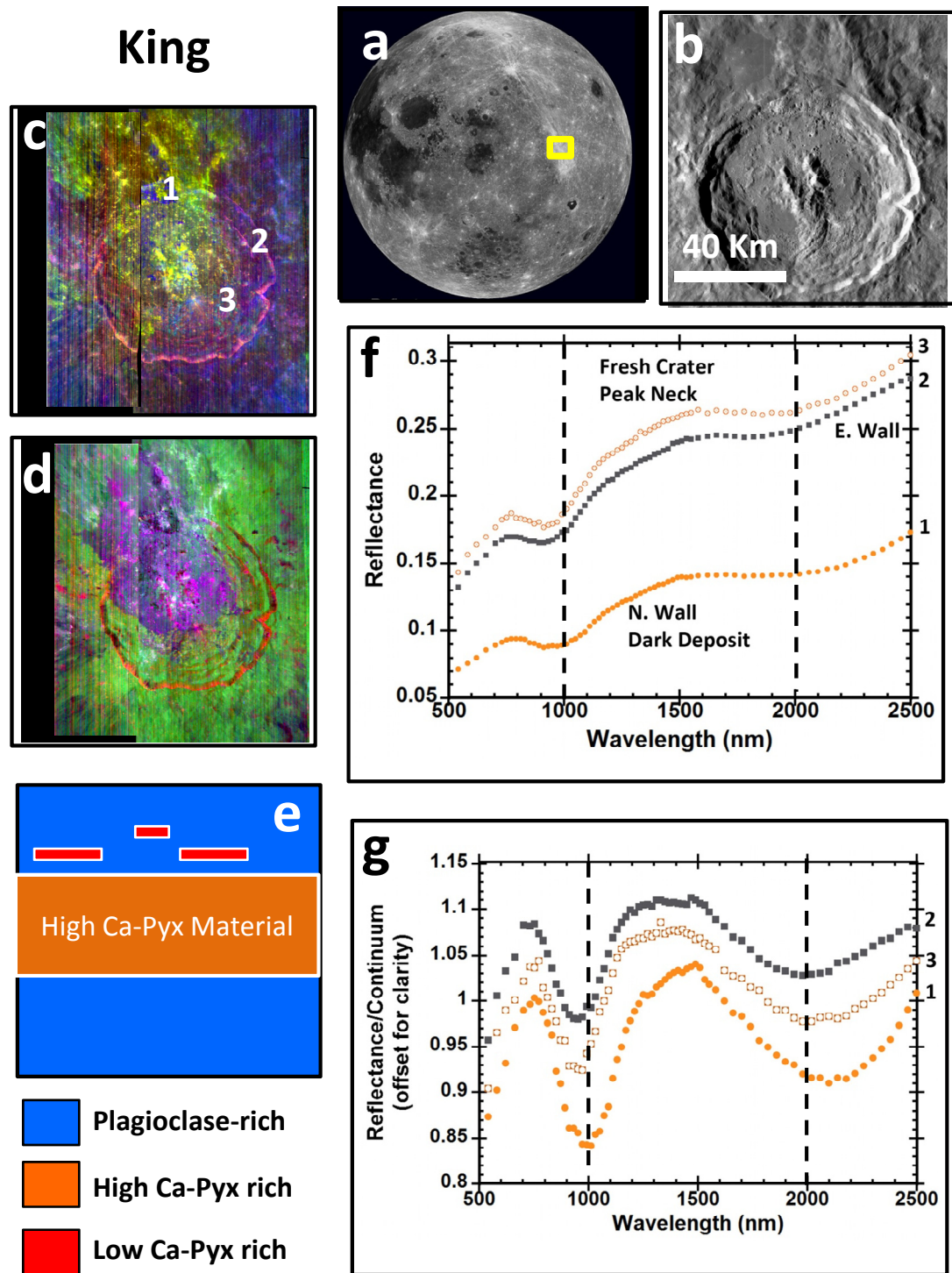


Figure 22 King crater (a) Location on the lunar far side (b) LRO WAC image showing the crater with rough crater floor and prominent (and unusual) central peaks. (c) M³

standard color composite highlighting the crater scale mineralogical diversity. (d) Color composite suggesting that melt unit on the floor and northern rim are distinct from the remaining crater. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

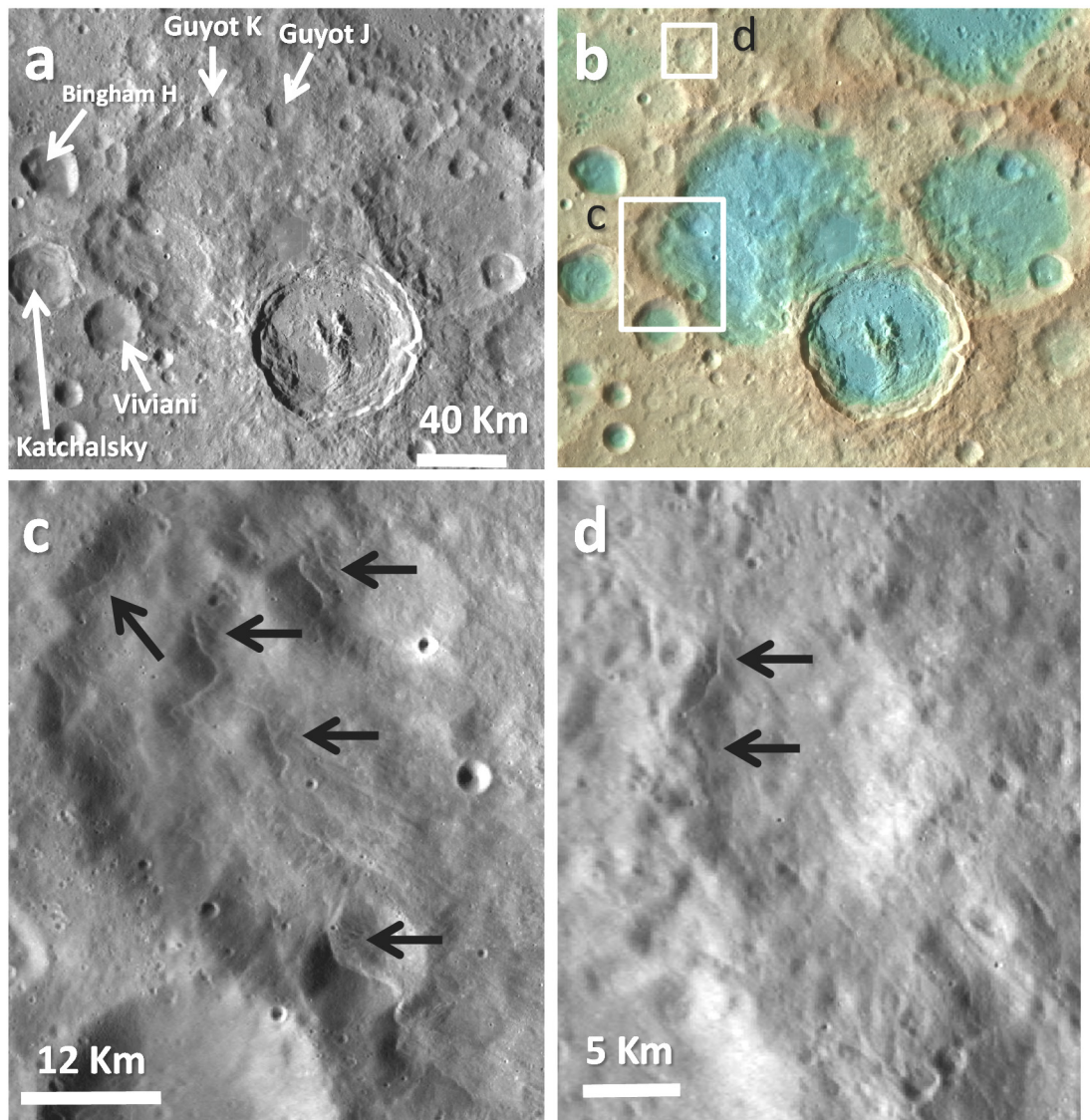


Figure 23 Melt distribution and morphology around King crater. (a) LRO WAC image of the region with King located in the bottom section. (b) WAC derived DEM draped on the WAC image showing a pervasive topographic low (cyan-teal colors) on King exterior in N-NW direction. White boxes show geographic locations of subsequent images. (c) The NW periphery of the topographic low shows several melt-fronts (marked by black arrows). (d) Outside of the large topographic low, the melt-fronts could still be observed indicating that melt moved further north during King cratering event.

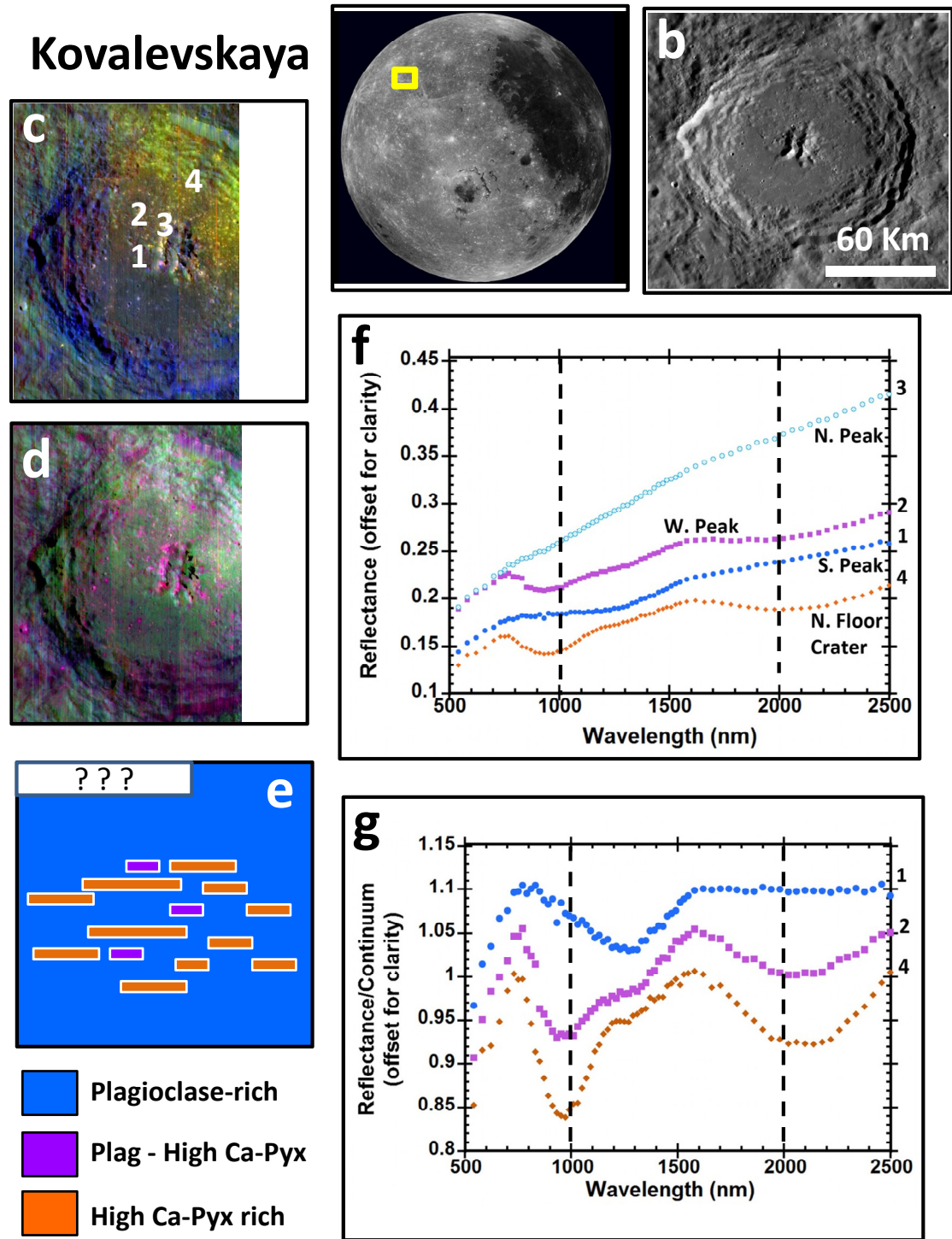


Figure 24 Kovalevskaya crater (a) Location on the lunar far side (b) M³ image showing the crater with relatively smooth floor and central peaks. (c) M³ standard color composite

highlighting the crater scale mineralogical diversity. Note the prominent mafic unit on the northern and eastern sections of the crater. (d) Color composite suggesting no major compositional differences on the crater floor. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 2 by 0.03 and spectrum 3 by 0.07. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

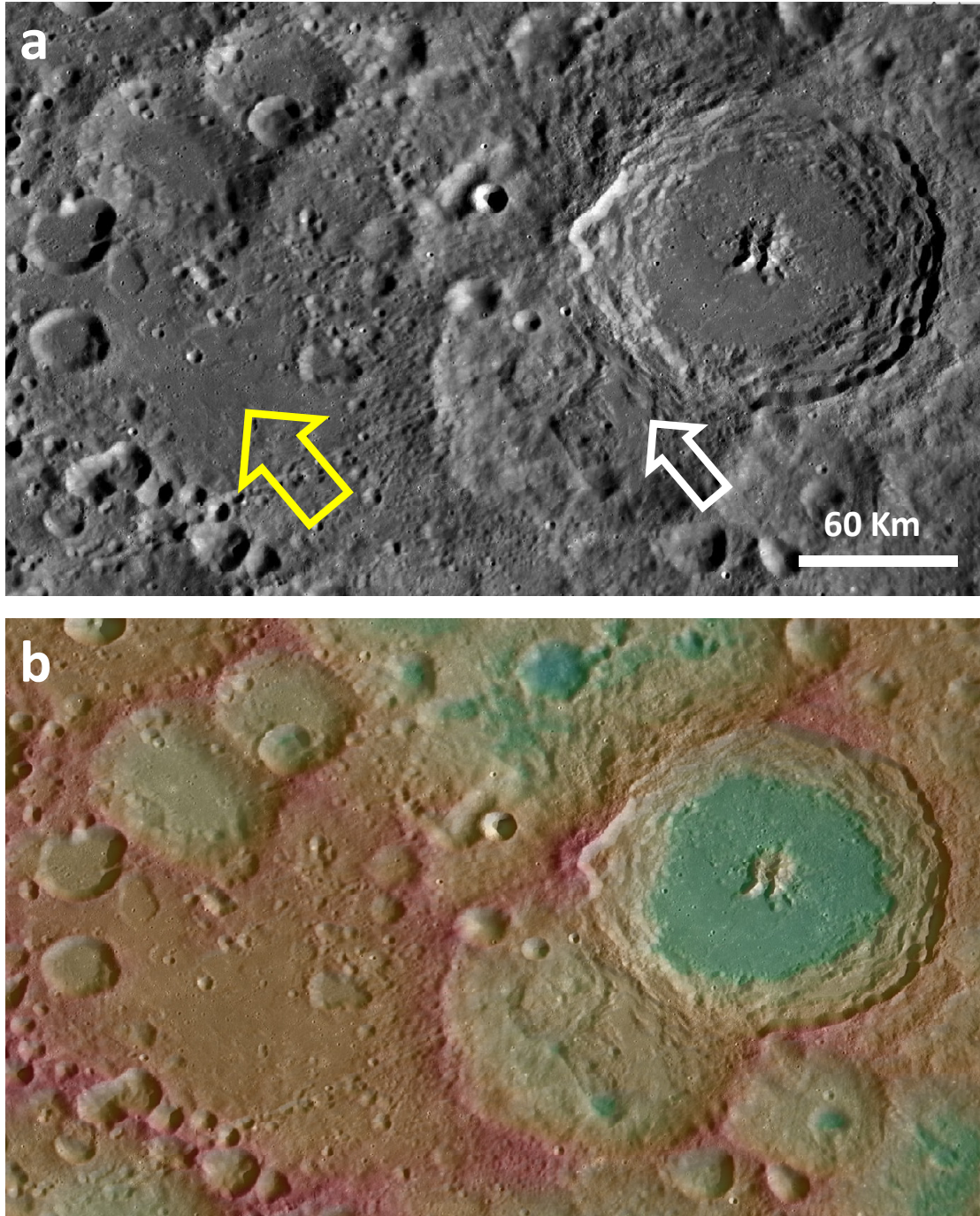


Figure 25 Melt deposits at crater Kovalevskaya. (a) LRO WAC context image showing some smooth areas in immediate vicinity (white arrow) and further west of the crater (yellow arrow). The latter could be a large impact melt deposit. (b) WAC derived DEM

overlain on WAC image showing that the extensive western region (yellow arrow in a) is topographically flat but also higher in elevation than the Kovalevskaya floor.

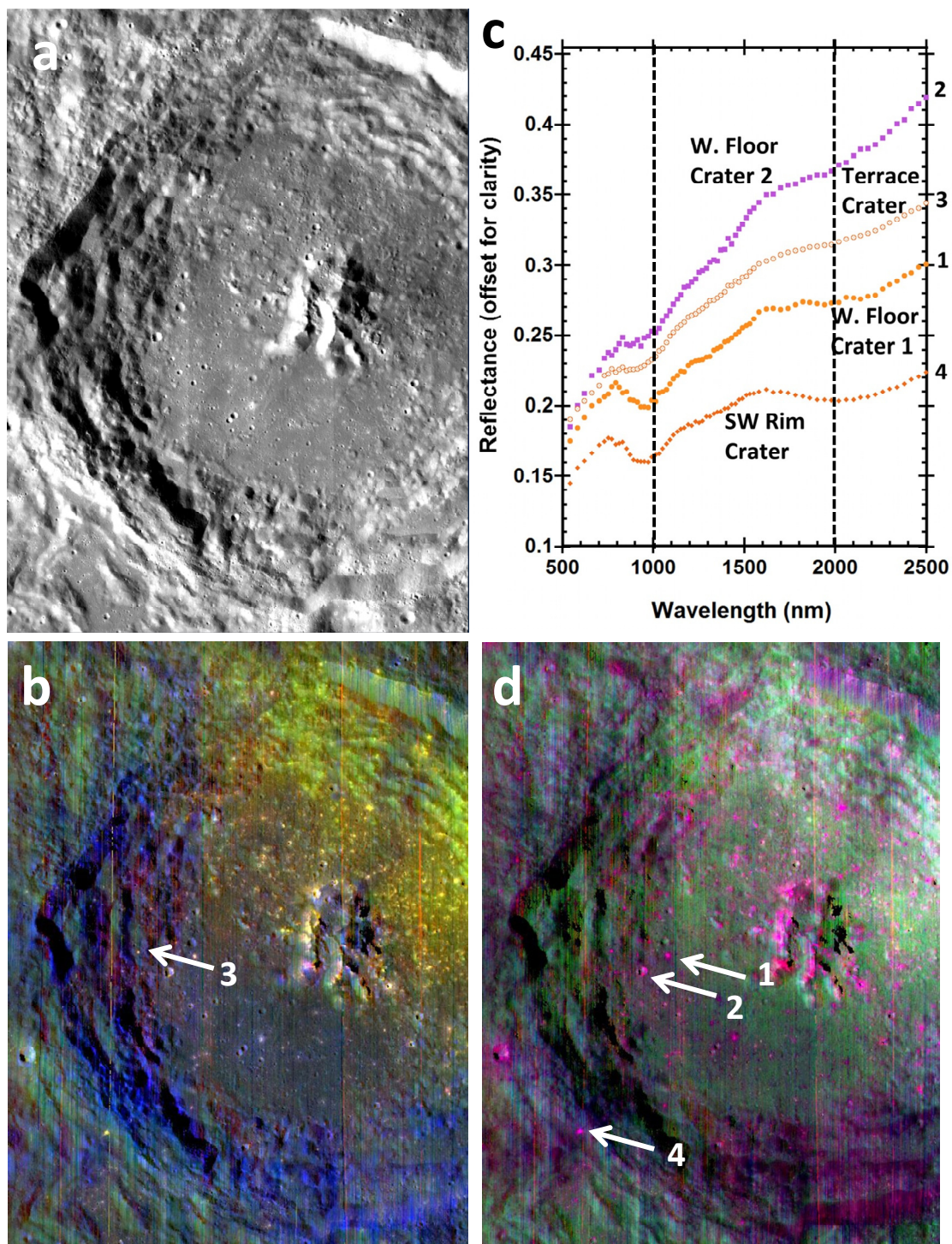


Figure 26 Mineralogical variations on the floor of Kovalevskaya crater. (a) M³ context image of the crater. (b) M³ standard color composite showing the different mineralogy of

the crater floor (mafic in the north and feldspathic in the south) (c) Spectral reflectance of some of the bright spots on the crater floor as observed in the two color composites. Each of the spectra show distinct long wavelength absorption bands similar to the mafic northern material (noted in Figure 25, #4). The reflectance scale is offset for spectrum 3 by 0.07. (d) Complementary color composite showing small, bright regions (in magenta color), likely fresh impact craters on an otherwise mineralogically uniform looking crater floor.

Eratosthenes

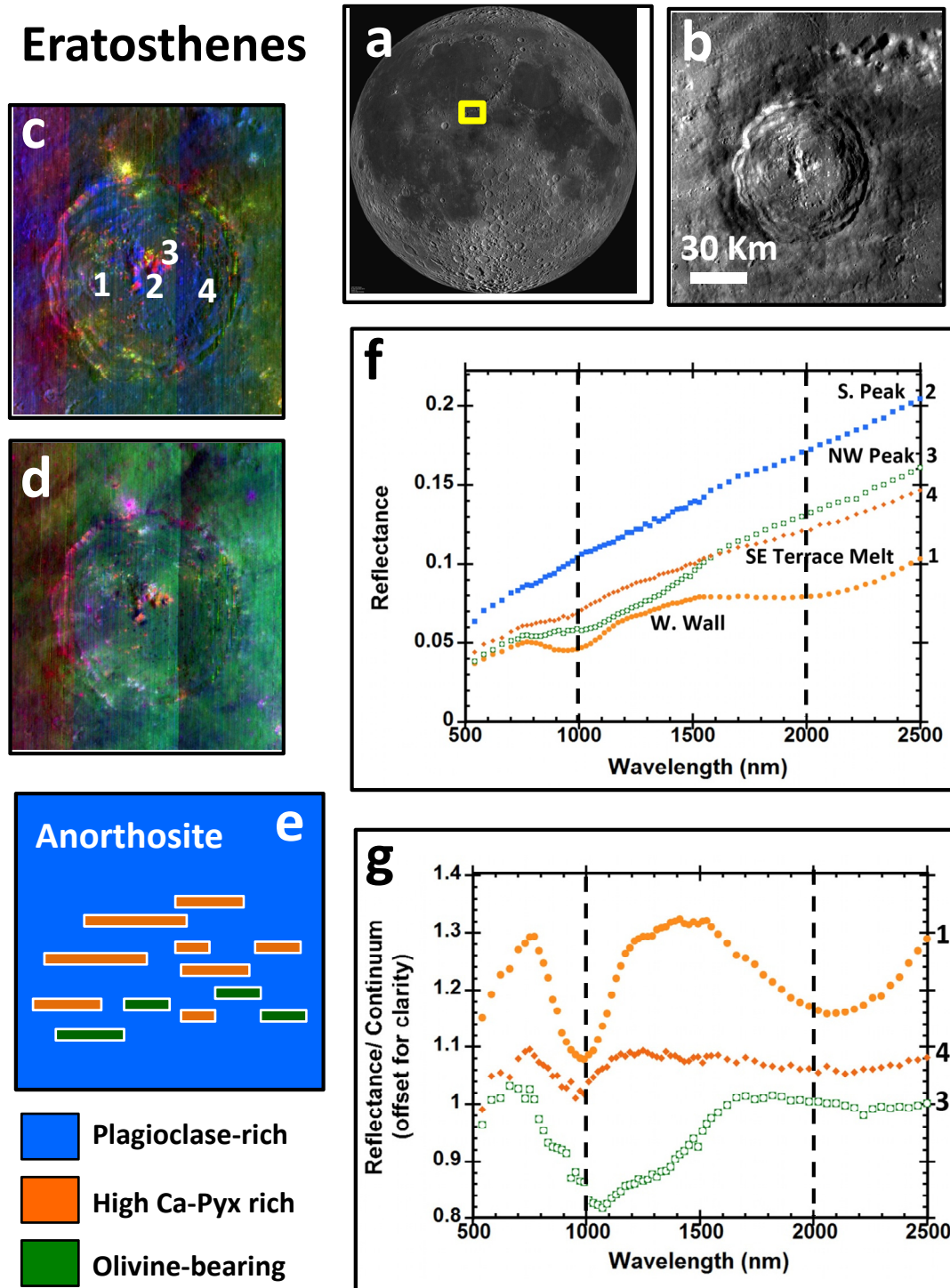


Figure 27 Eratosthenes crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively rubbly floor and walls with terraces. The crater has a distinctive central peak. (c) M³ standard color composite highlighting the crater scale mineralogical

diversity. (d) Complementary color composite suggesting uniform melt mineralogy on the floor. The observed striping is due to residual photometric and thermal effects. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

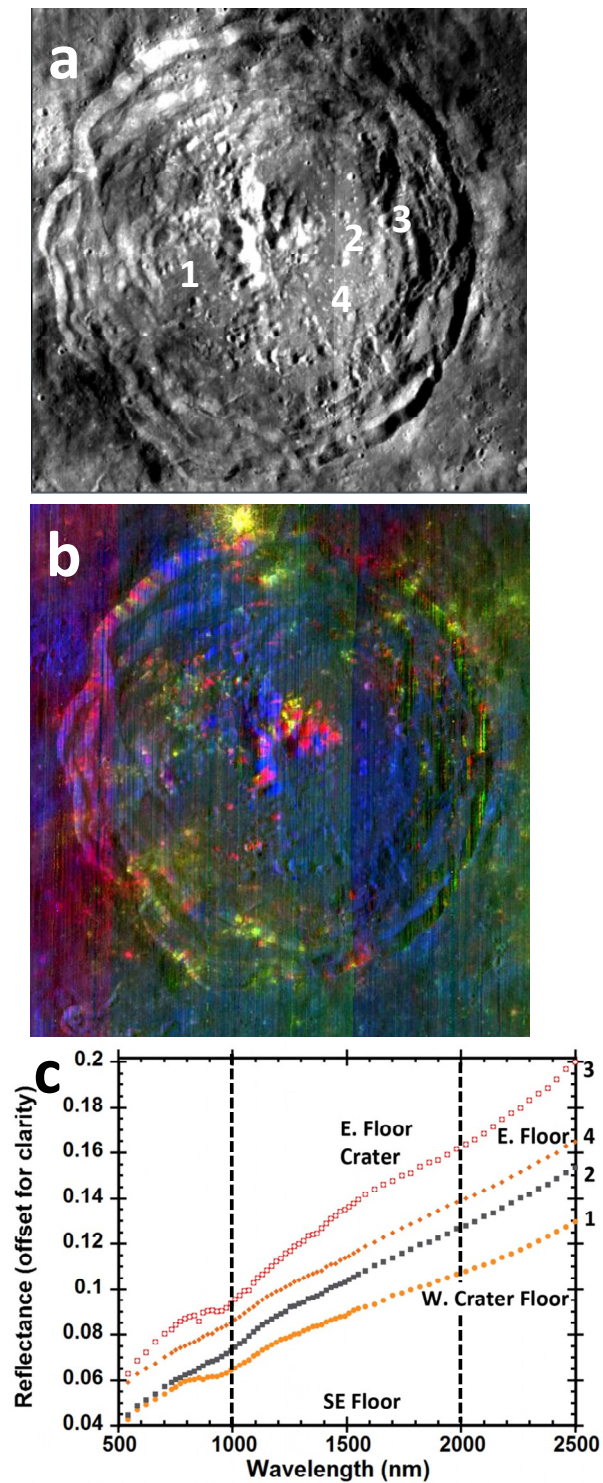


Figure 28 Mineralogy of floor impact melt at Eratosthenes. (a) M³ context image of the crater. (b) M³ standard color composite of the crater showing highly heterogeneous

central peak and a largely uniform crater floor. The striping is an artifact and is due to the residual of thermal and photometric corrections. (c) Soil spectra of the floor region shows very weak features (#1, #3) if any. The reflectance scale is offset for spectrum 4 by 0.02.

Aristillus

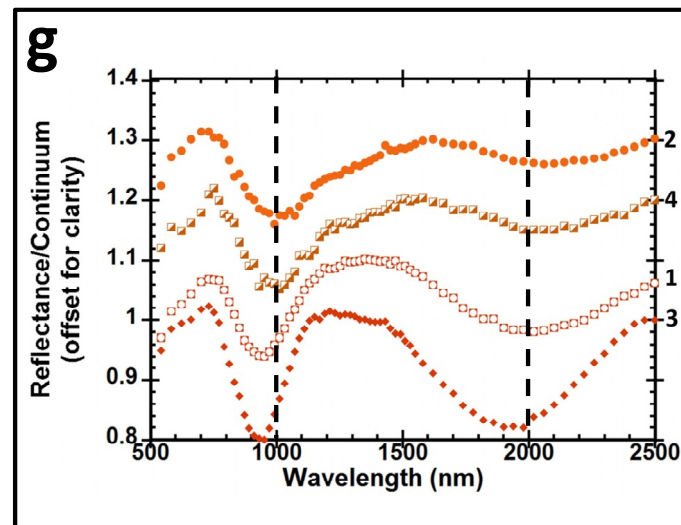
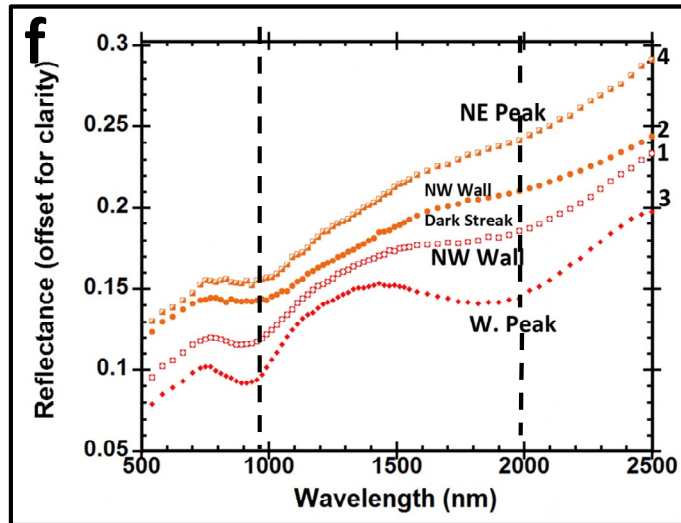
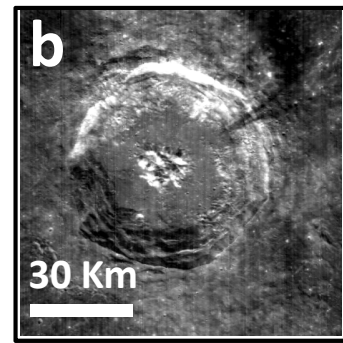
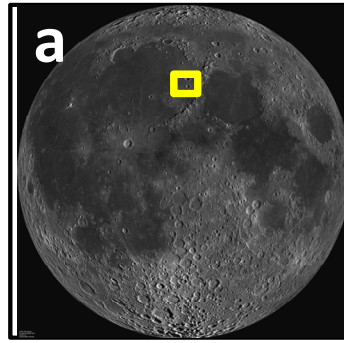
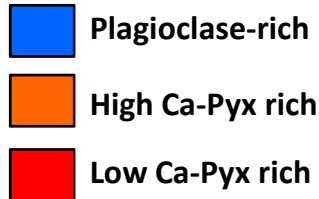
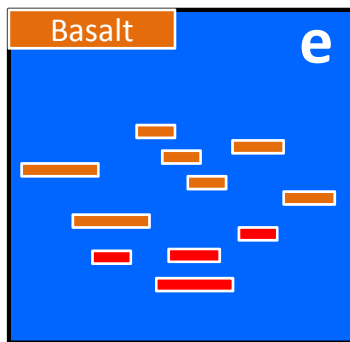
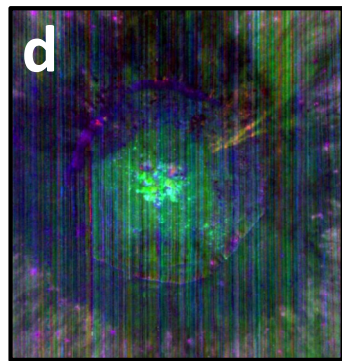
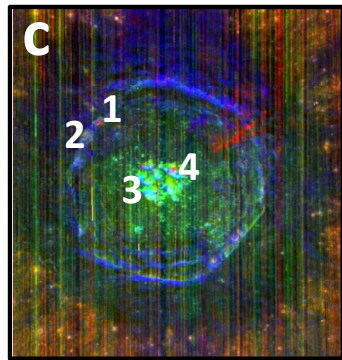


Figure 29 Aristillus crater (a) Location on the lunar near side (b) M^3 image showing the crater with relatively flat floor, wall terraces and central peaks. Note the low albedo linear streak on the NE crater wall and rim region. (c) M^3 standard color composite highlighting

the crater scale mineralogical diversity. (d) Complementary color composite suggesting a very uniform mineralogy on the crater floor that appears similar to the central peaks. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale refers to spectrum 3. All others are offset as follows: spectrum1: 0.01, spectrum 2: 0.05, spectrum 4: 0.06. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

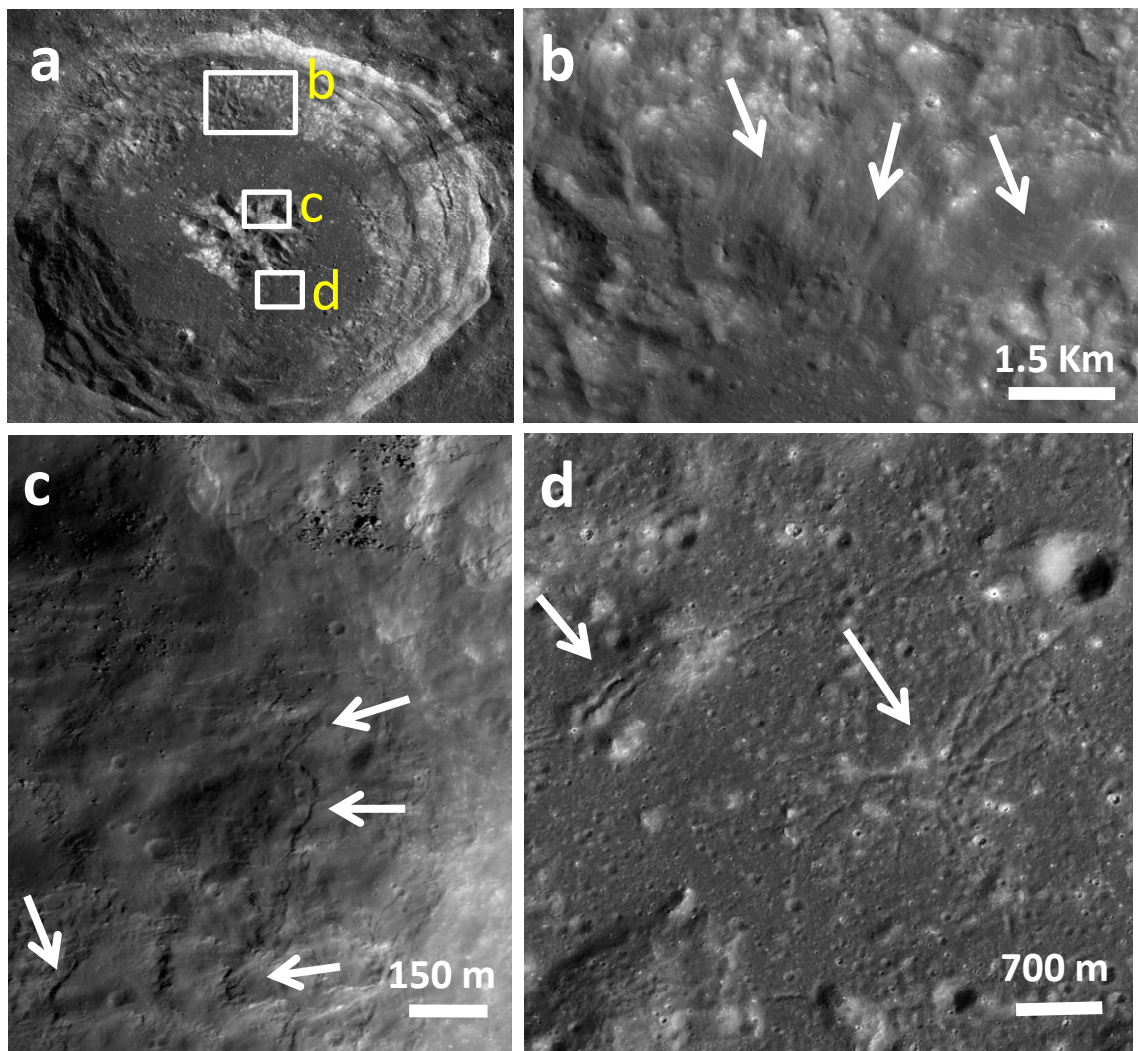


Figure 30 Impact melt deposits at Aristillus. (a) M³ context image showing the crater. Lettered boxes represent locations of subsequent figures. (b) The northern wall of the crater shows smooth regions (marked by arrows) near the crater floor, likely representing a thick impact melt veneer. (c) The northern central peak region displays some extended melt veneer-like deposits at multiple locations (white arrows). (d) The southern crater floor shows cooling cracks with different geometries (e.g. radiating, parallel).

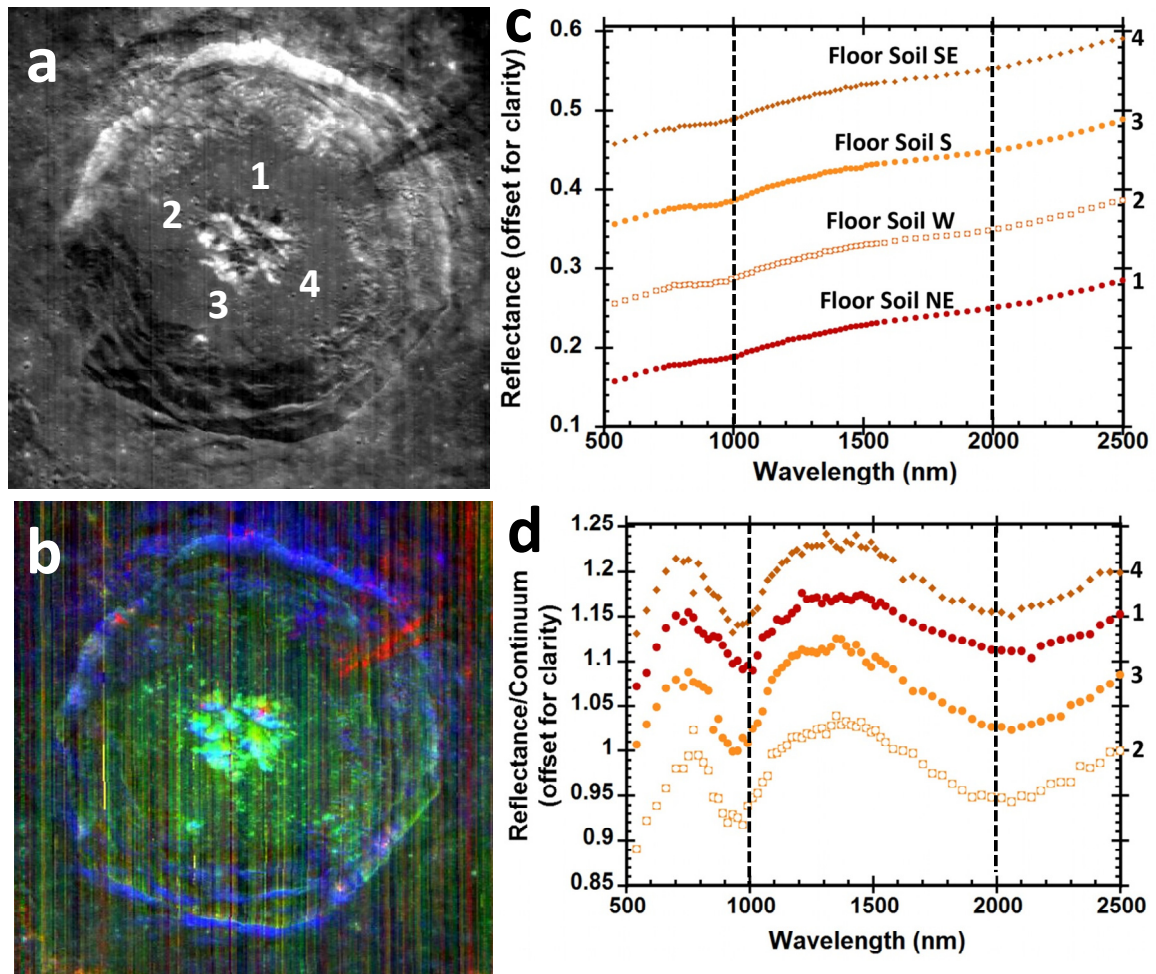


Figure 31 Melt mineralogy at Aristillus (a) M³ context image of the crater showing the locations of spectral sampling. (b) M³ standard color composite showing mafic central peaks and largely feldspathic/noritic crater wall. (c) Spectra from different parts of the impact melt-rich floor show remarkable similarity. The reflectance scale is offset for spectrum 1 by 0.1, spectrum 2 by 0.2, spectrum 3 by 0.3, spectrum 4 by 0.4. (d) Continuum-removed spectra further illustrated the spectral and therefore mineralogical homogeneity of the impact melt deposits.

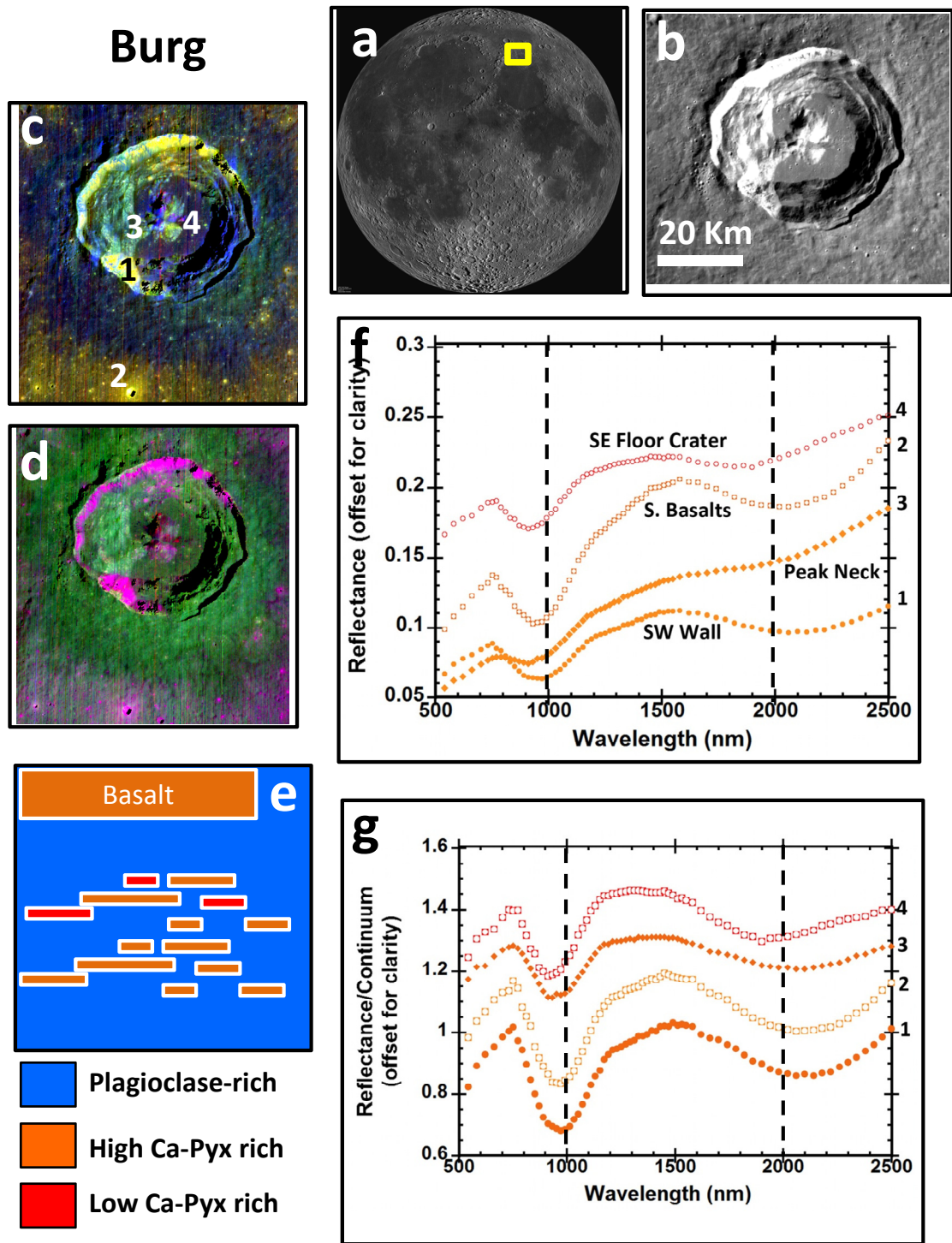


Figure 32 Burg crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively flat floor, wall terraces and central peaks. Note the possible

connection between peak and the eastern wall through the floor. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting a very uniform mineralogy on the crater floor. In contrast, some of the wall sections (north and SW) look distinctly different from the surroundings. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 4 by 0.08. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

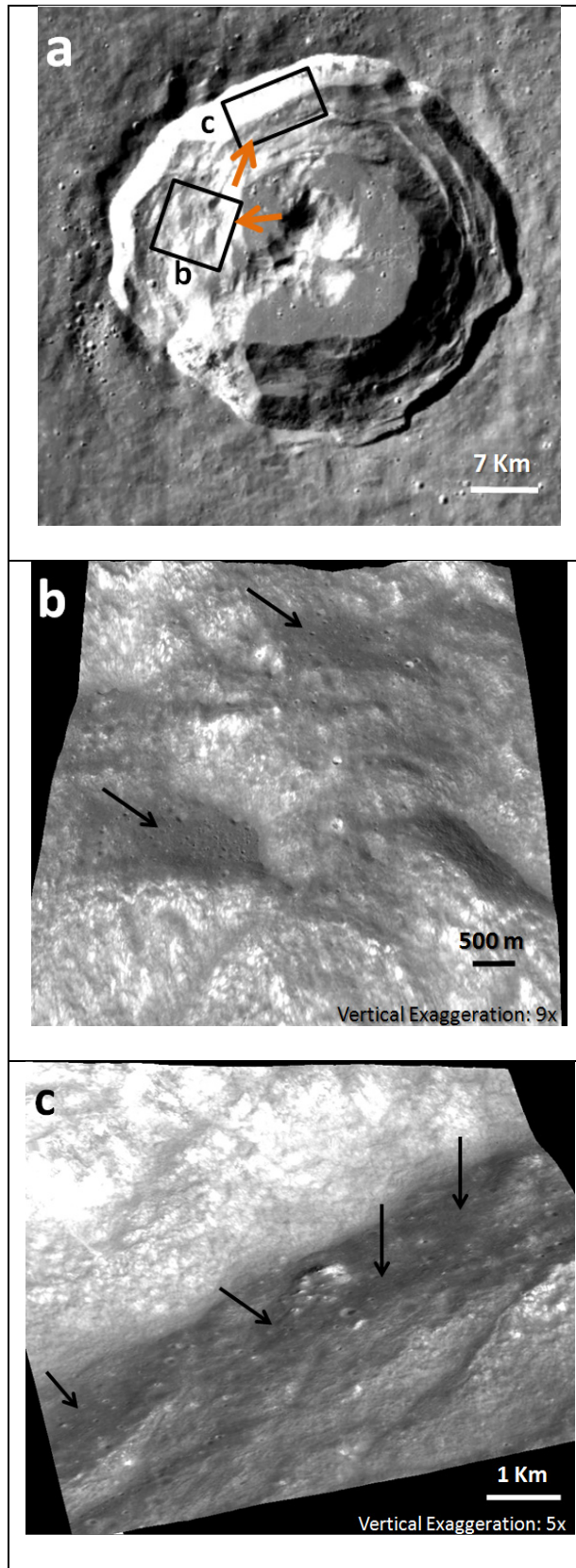


Figure 33 Probable impact melt deposits on the terraces of crater Burg. (a) Context image showing the locations analyzed at high resolution. Orange arrows indicate the viewing direction for the later images. (b) DTM of the western crater wall showing small pockets of smooth material with slightly lower albedo in comparison to the sloping and bright nearby material. (c) DTM of the northern wall terrace showing flat-lying, low-albedo smooth material in comparison to the slightly rougher material in the close vicinity (in lower part of the image). The upper part of the image represents northern wall.

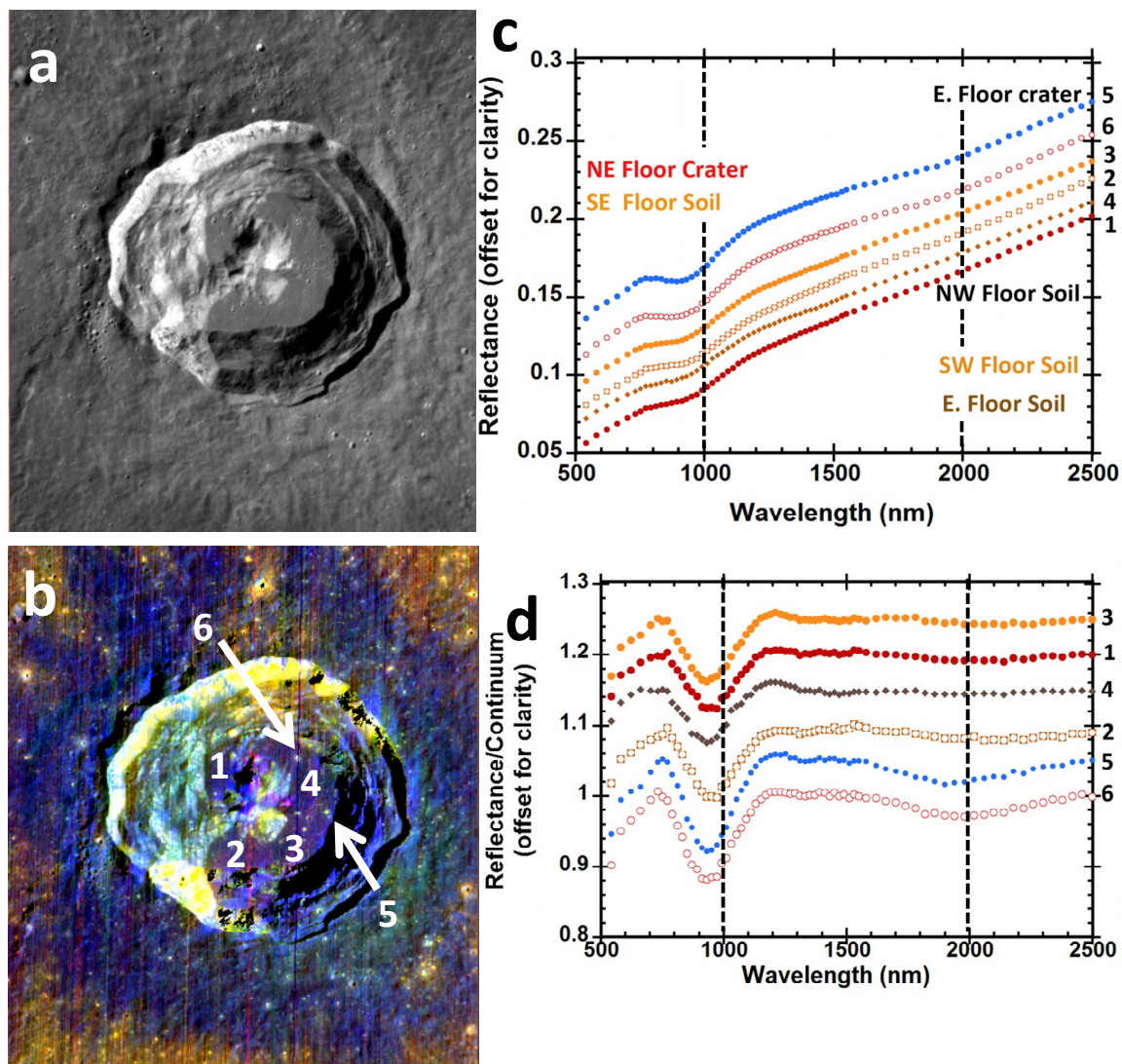


Figure 34 Mineralogy of the impact melt on the crater floor (a) M³ context image of the crater. (b) M³ standard color composite of the crater showing feldspathic ejecta material and heterogeneous central peaks. Numbers represent spectral sampling locations. (c) Spectral reflectance of the impact melt soils and fresh craters indicate the mafic nature of the impact melt. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.025, spectrum 3: 0.04, spectrum 4: 0.02, spectrum 5: 0.07,

spectrum 6: 0.05 (d) Continuum-removed spectra illustrate the low calcium-pyroxene rich nature of the impact melt.

Theophilus

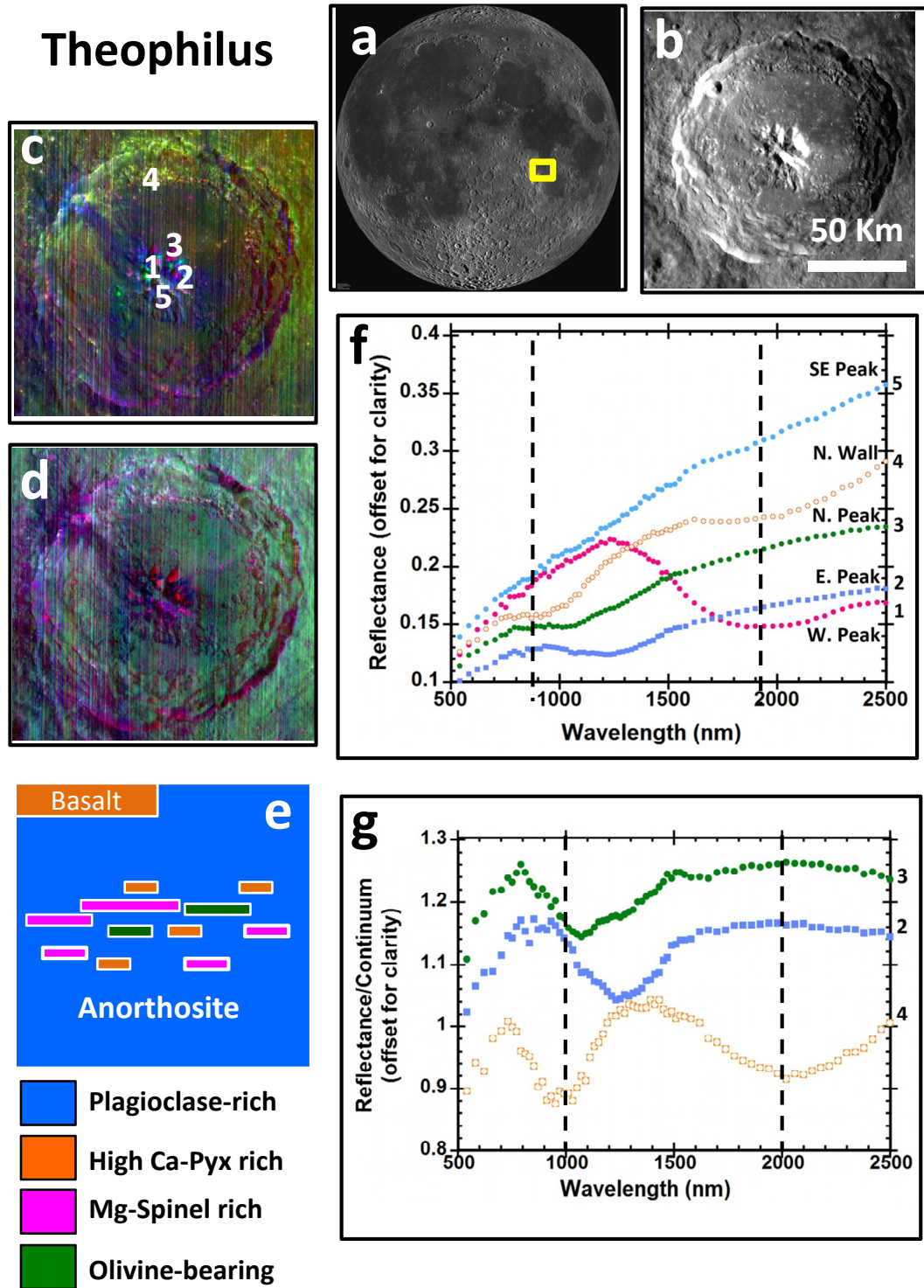


Figure 35 Theophilus crater (a) Location on the lunar near side (b) M³ image showing the crater with relatively flat floor, walls with terraces and prominent central peaks. (c)

M³ standard color composite highlighting the crater scale mineralogical diversity, mostly from the peak region. (d) Complementary color composite indicating largely uniform crater floor (melt) mineralogy. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. The reflectance scale is offset for spectrum 3 by 0.02 and spectrum 4 by 0.04. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

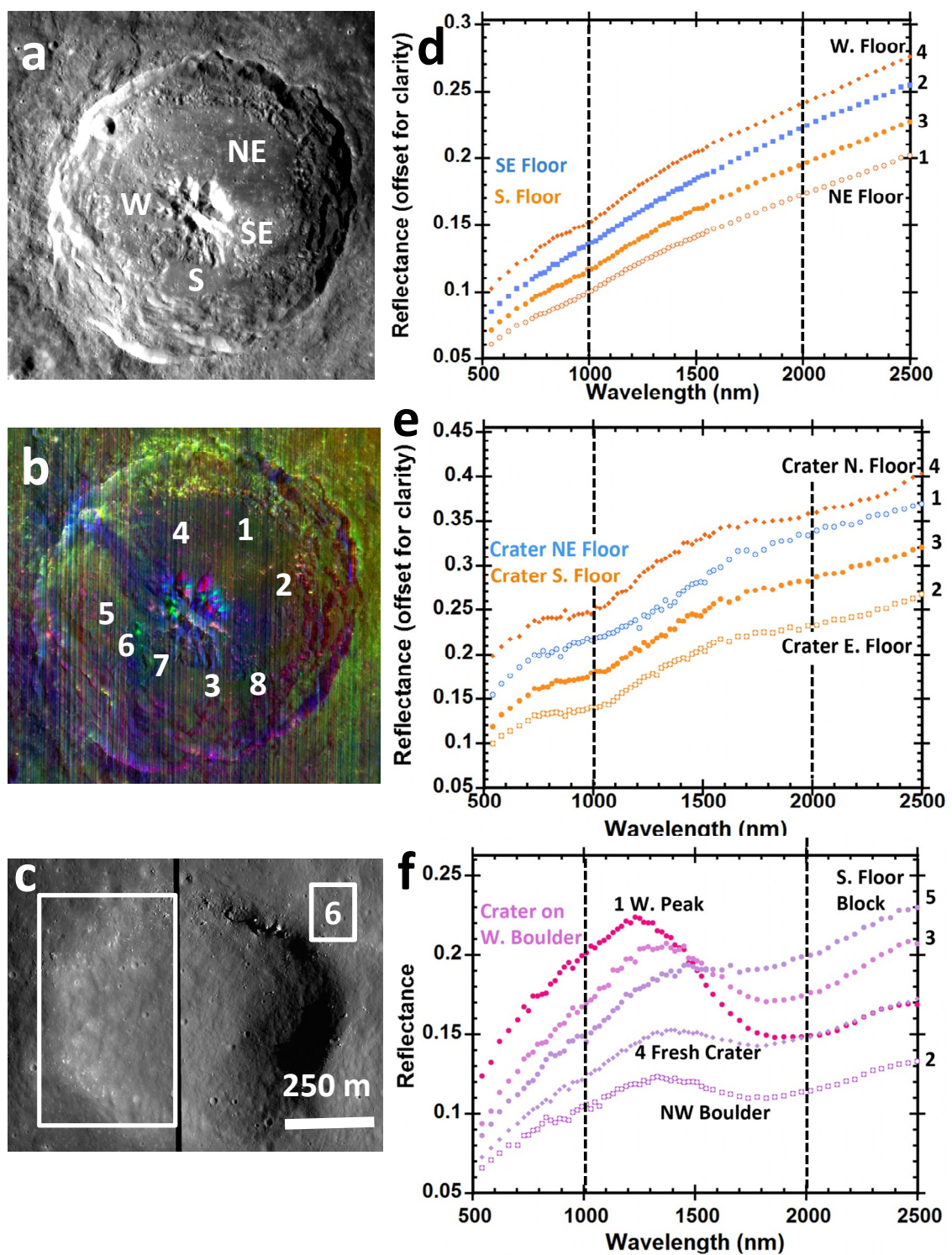


Figure 36 Mineralogy of impact melt on the floor of Theophilus. (a) M³ context image of the crater. Letters represent spectral sampling locations. (b) M³ standard color composite

of the crater suggesting a largely uniform floor mineralogy. Numbers represent spectral sampling locations. (c) LRO NAC view of one of the spectral sampling locations (#6) which hosts a large Mg-Spinel occurrence on the crater floor, away from the peak. The white box represents the zone of Mg-spinel. (d) Soil spectra of impact melt on the crater floor shows predominantly featureless spectra. The reflectance scale is offset for spectrum 2 by 0.01 and spectrum 4 by 0.02. (e) Spectra from selected fresh craters on the floor show a dominantly mafic mineralogy with some glass. The reflectance scale is offset for spectrum 4 by 0.08. (f) Spectral comparison of all the Mg-Spinel locations on the floor, compared to the strongest Mg-Spinel detection (magenta).

Lowell

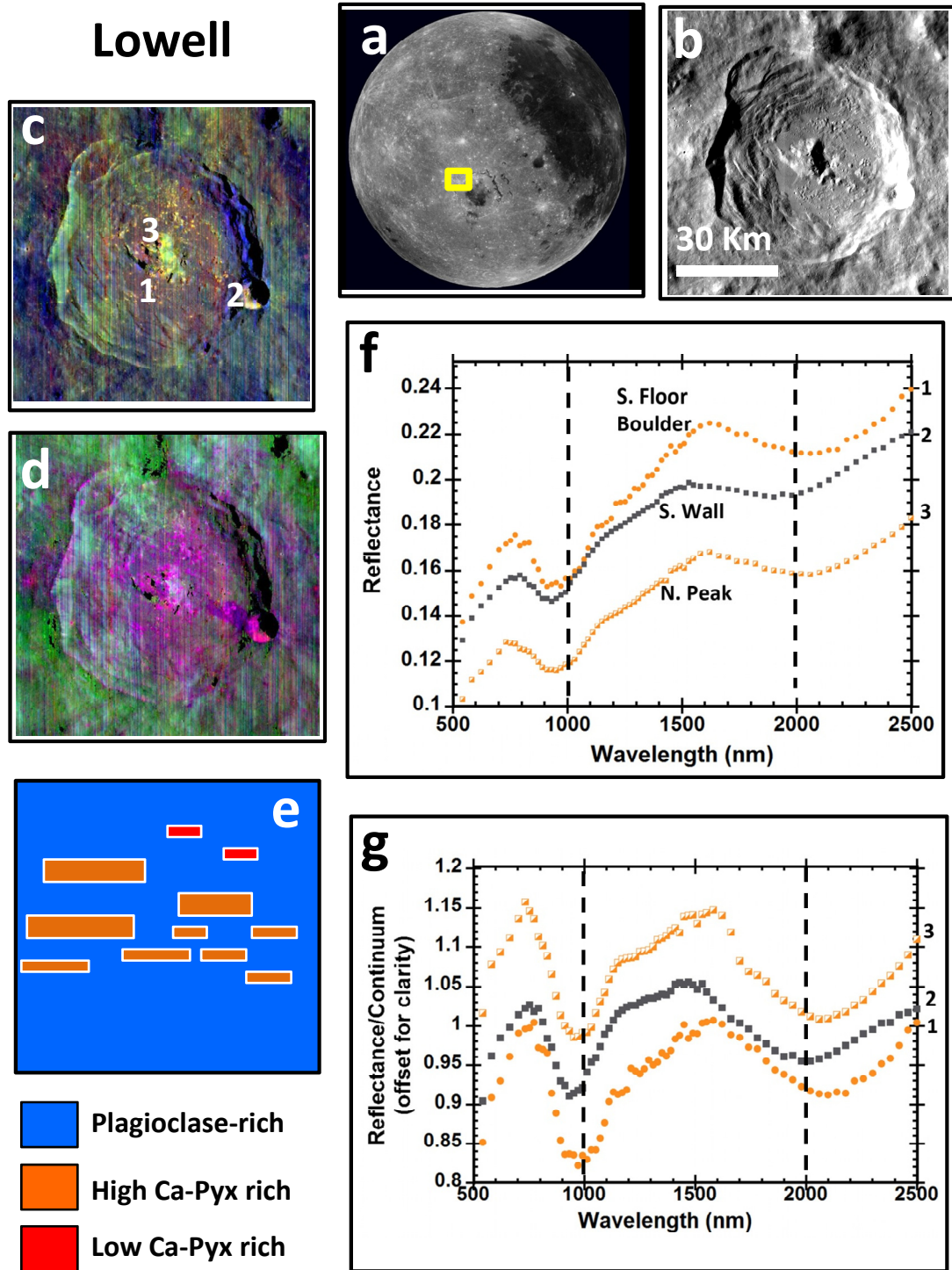


Figure 37 Lowell crater (a) Location on the lunar western near side (b) M³ image showing the crater with blocky floor and central peak. Note the small crater on the

eastern rim which is also part of the study. (c) M³ standard color composite highlighting the crater scale mineralogical diversity. (d) Complementary color composite suggesting high calcium pyroxene mineralogy of the melt-rich floor (in magenta color). The small crater on the eastern rim also has similar mineralogy. (e) Simplified geologic setting of the pre-impact target capturing the constituent rock-types. (f) Spectral character of the dominant lithologies. (g) Continuum-removed spectra highlighting the finer scale differences in the characters of absorption bands.

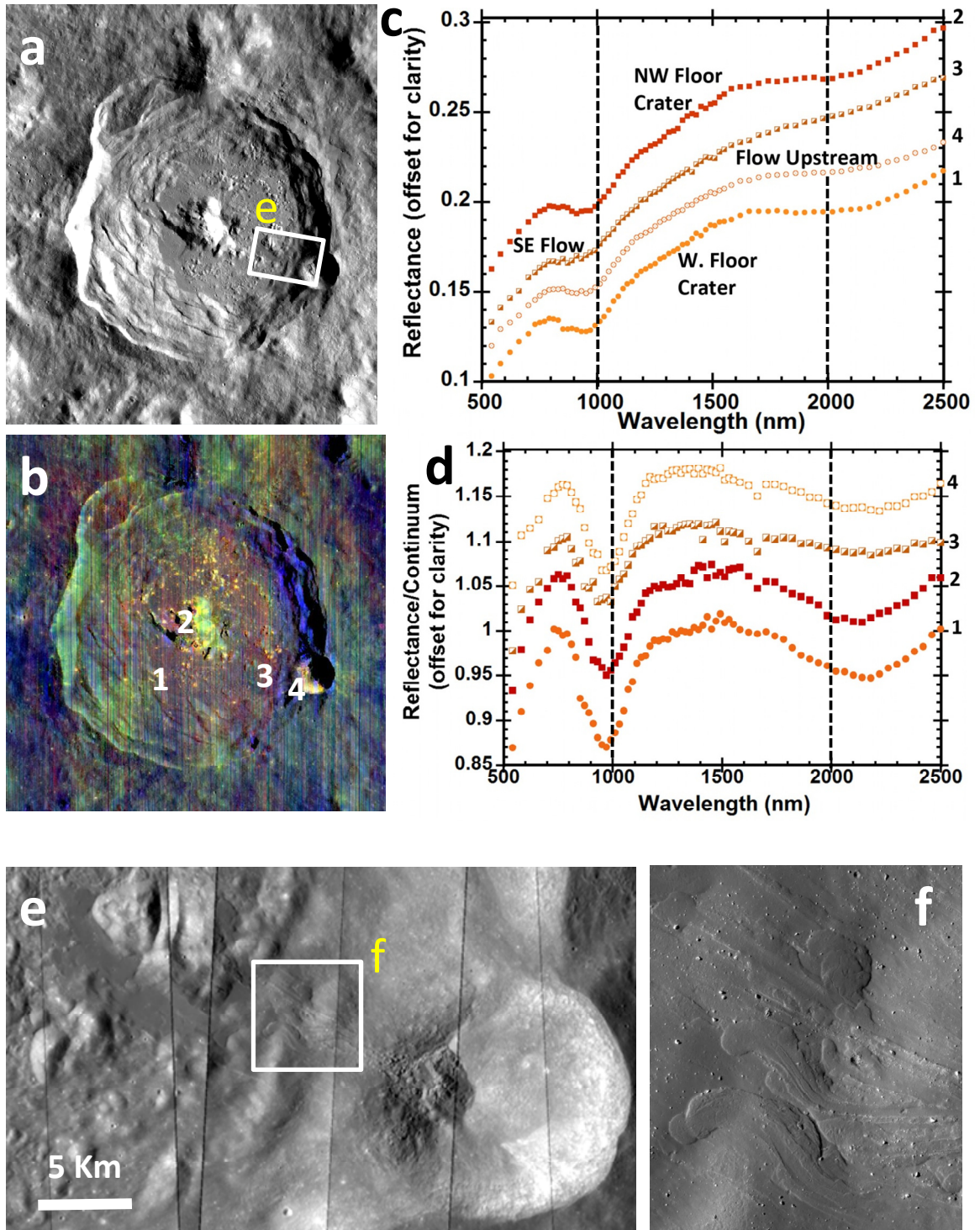


Figure 38 Mineralogy of impact melt deposits at Lowell crater. (a) M³ context image of the crater. White box represents region shown in e. (b) M³ standard color composite of

the crater showing a prominently mafic central peak. Numbers represent spectral sampling locations. (c) Spectra from fresh surfaces (small craters) on impact melt-rich floor show a dominantly high-calcium pyroxene signature. The reflectance scale is offset for spectrum 2 by 0.06, spectrum 3 by 0.04 and spectrum 4 by 0.02. (d) Continuum removed spectra highlights the high-calcium pyroxene dominance across all the regions. (e) LRO NAC view of SE section of the crater showing the younger crater on the rim and associated magnificent impact melt flows. (f) A close-up view of the flow-structures on the walls show overlapping lobate ends. The morphological freshness of the features indicates their very young age.

CHAPTER 2: Large Mineralogically-Distinct Impact Melt Feature at Copernicus Crater – Evidence for Retention of Compositional Heterogeneity

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Abstract

Despite several lines of evidence for efficient mixing of impact melt in complex craters, we document mineralogical heterogeneity in impact melt deposit on a scale of tens of kilometers on the Moon in the 96 km-diameter Copernicus crater. This heterogeneity is in the form of a large, sinuous impact melt feature on the floor and northern wall that is spectrally distinct from melt in its immediate vicinity. This melt feature spanning >30 km in length and 0.5-5 km in width has relatively short-wavelength, narrow ferrous absorption bands near ~900 nm and ~2000 nm indicating a more Mg-rich pyroxene composition as compared to impact melt deposit in the vicinity which is relatively rich in Fe/Ca-pyroxenes. This distinction provides evidence for the preservation of compositional heterogeneity in impact melt in complex craters on the Moon and documents an example of inefficient mixing of melt during the cratering process.

1. Introduction

Impact cratering is known to be a very rapid and dynamic process and is divided into three stages: 1) contact and compression, 2) excavation and 3) modification [e.g. *Gault et al.*, 1968]. Impact melt formation and emplacement are important components of the excavation and modification stages [e.g. *Grieve et al.*, 1977] and there is abundant evidence that impact melt is mobile during the short-term modification stage of the transient cavity [e.g. *Hawke and Head*, 1977; *Bray et al.*, 2010; *Osinski et al.*, 2011]. Highly chaotic and dynamic movement of superheated impact melt is predicted from theoretical considerations [e.g. *Melosh*, 1996]. Further, homogeneity of impact melt is reported in some terrestrial craters with diverse target substrates [e.g. *Floran et al.*, 1978; *Zieg and Marsh*, 2005] suggesting highly turbulent mixing that would homogenize any initial compositional heterogeneities. In contrast, some of the recent studies of terrestrial melt sheets have revealed heterogeneities associated with specific target lithologies [e.g. *Darling et al.*, 2010]. Heterogeneities in impact melt have also been reported for craters in sedimentary targets [e.g. *Osinski et al.*, 2008]. We report here the occurrence of a large impact melt feature at lunar crater Copernicus that is mineralogically distinct from surrounding impact melt deposits.

Copernicus is a 96 km diameter, young complex impact crater [~ 779 m.y.; e.g. *Hiesinger et al.*, 2012] located on the lunar near-side, extensively studied using telescopic [e.g. *Pieters*, 1982; *Lucey et al.*, 1991; *Pinet et al.*, 1993] and spacecraft observations [e.g. *Pieters et al.*, 1994; *Le Mouélic and Langevin*, 2001; *Ohtake et al.*, 2008; *Bugiolacchi et al.*, 2011]. The pre-impact stratigraphy (top to bottom) has been suggested to be [*Schmitt et al.*, 1967]: i) mare basalts ii) Imbrium ejecta (Fra Mauro Formation) and

iii) upper crustal material (pre-Imbrian megaregolith and anorthosites) [e.g. *Hiesinger and Head*, 2006, Figure 1.20]. Later, Earth-based spectroscopic measurements detected an olivine-bearing lithology in the central peaks [*Pieters*, 1982]. A noritic, thin upper crust and olivine-rich peak material from lower crust or even mantle was suggested by *Pieters and Wilhelms* [1985]. The crater shows a north-south compositional heterogeneity with more basaltic components detected along the southern wall [e.g. *Pieters et al.*, 1994]. Recently proposed east-west differences [*Arai et al.*, 2011] and identification of Mg-spinel [*Dhingra and Pieters*, 2011] at Copernicus have expanded this diversity. Impact melt deposits are extensively present in various parts of the crater, in the form of smooth ponds, debris-laden deposits and flows, some of which contain quenched glass [*Smrekar and Pieters*, 1985].

2. Newly Identified Impact Melt-Related Feature

Spectral reflectance analysis for the Copernicus crater interior has been carried out using high spectral resolution data from the Moon Mineralogy Mapper (M³) instrument onboard Chandrayaan-1 mission [*Goswami and Annadurai*, 2009]. M³ is a VIS-NIR imaging spectrometer [e.g. *Pieters et al.*, 2009] operating between 460 – 3000 nm in 85 spectral bands at a spatial resolution of 140-280 m. The data has been corrected for viewing geometry, thermal emission and ground truth. Supplementary datasets include data from the Terrain Camera (TC) [*Haruyama et al.*, 2008] onboard Kaguya mission, data from the Lunar Reconnaissance Orbiter Camera (LROC) [*Robinson et al.*, 2010] and the Lunar Orbiter Laser Altimeter (LOLA) [*Smith et al.*, 2010] onboard LRO mission.

2.1 Geologic Setting of the Study Region

The geologic context of the area is illustrated in Figure 1(a)-(d). The geological map of Copernicus shown in Figure 1(a) delineates two floor units that have been interpreted as impact melt deposits (ft – textured floor material, magenta color; fh – hummocky floor material, red color). Figure 1(b) shows an image of the crater from the Wide Angle Camera (WAC) onboard Lunar Reconnaissance Orbiter (LRO). Note the relatively smooth north-western crater floor which is believed to be comprised of thick melt deposits. The area outlined in black in both Figure 1(a) and 1(b) corresponds to the study region for which M³ data were analyzed (Figure 1c & d). The newly identified melt-related feature is not easily discernible in the albedo images and is outlined in red in the sketch of the study region (Fig. 1d) based on M³ spectral data.

2.2 Characteristics of the Proposed Sinuous Melt-related Feature

2.2.1 *Spectral and Compositional Properties*

The character of the melt-related feature is best represented in a RGB color composite (Fig. 2a-b). The red channel represents albedo variations at 1489 nm, green shows absorption band strength variations across the 2000 nm while blue captures band strength variations around 1900 nm (see Table 1 in auxiliary material for band parameter algorithm). The sinuous melt-related feature appears cyan-blue color while two fresh craters located west of this feature (but still within impact melt) appear green in this color composite. The spatial extent of the sinuous melt-related feature is marked with solid and broken lines based on the clarity of the spectral boundaries. Various perspectives of the region shown in Figure 2(b) provide better understanding of the geological setting and

the relationship of the melt feature with the surroundings. The parameter images can be observed individually in Fig. 2(d)-(f). The feature can also be seen in independent color composite of Kaguya MI multispectral data presented by Arai et al., [2011], although the authors did not comment on the possible origin of this feature.

The broad spectral variations observed in the color composite were further analyzed by obtaining representative spectra and studying the differences in shape, strength and center of the absorption bands. As mentioned above, the mineralogical diversity at Copernicus crater has been well studied. M³ spectra for these key lithologies are illustrated in Figure 3(a). We also include the recent detection of Mg-spinel (R4 in Figure 3a and marked by a green arrow in Figure 2a) at Copernicus [Dhingra and Pieters, 2011], a new component in the existing diversity.

Apart from diverse primary lithologies, impact melt deposits at Copernicus also exhibit compositional variability with some areas displaying relatively strong absorption bands while others having either weak or no absorptions altogether. Materials excavated by relatively young craters or exposed at steeply sloped surfaces have little soil accumulation and are referred here as ‘fresh surfaces’. Representative spectra from fresh surfaces (A2, A3; Figure 3b, c) within the newly identified melt feature have band centers at shorter wavelengths and a narrower 1 μm absorption band compared to spectrum (A1) from the fresh crater located outside the sinuous melt feature in the northwestern thick melt deposits (see Figure S1 in auxiliary material for location). The observed difference in band center implies a different pyroxene composition [e.g. Adams, 1974; Burns, 1993; Klima et al., 2007, 2011], specifically more Mg-rich pyroxenes for the sinuous melt feature and more Ca- and Fe-rich pyroxenes for the fresh crater to the west in widespread

impact melt deposits. The broader 1 μm absorption for #A1 may be solely due the presence of clinopyroxene; however, an additional component such as olivine or quenched glass is also possible. Although fresh material outside the sinuous melt feature is less common, the #A1 spectrum (Figure 3b, c) from impact melt deposit appears to be representative (see Fig. S2 in auxiliary material for various sampling locations used to validate compositional differences).

To further assess the compositional variability of the region, we sampled soils from various locations on the floor (see auxiliary material, Figure S1) since soil reflects a relatively well-mixed composition of an area (aided by micro-meteoritic impact gardening processes) and is therefore a more representative spectral sample (though it has weaker spectral bands). Spectra of soils sampled within the sinuous melt feature (Figure 3d and Figure S4 in auxiliary material) have a very consistent spectral character with short wavelength pyroxene bands comparable to those observed for fresh surfaces (A2, A3; Figure 3b, c) in the melt feature, indicating more Mg-rich pyroxene composition. Spectra of soils elsewhere within impact melt deposits either have no discernible absorptions or have very broad bands around 1000 nm. The latter (2, 3; Figure 3d and located outside of the melt feature) suggests the presence of quenched glass which is consistent with telescopic observations [Smrekar and Pieters, 1985]. A soil from the hummocky southern floor [1; Figure 3d] exhibits pyroxene features of comparable strength but has a distinct composition in view of the different 2 μm pyroxene band when compared to spectra of soil inside the sinuous melt feature [6-8; Fig. 3d].

Integrated analysis of fresh surfaces and soils in the study area indicate that the sinuous melt feature has a composition consistent with relatively Mg-rich pyroxenes

(commonly associated with norites) as compared to more Fe- and Ca-rich pyroxenes (commonly associated with basalts) in the surrounding melt deposit.

2.2.2 Surface Morphology and Texture

Topography derived from LOLA data shows a net relief of ~250 meters on the crater floor with the newly identified sinuous melt feature being located in a broad depression (blue region, Figure 4a). High spatial resolution images (10 m/pixel) from Kaguya TC were studied (Figure 4b and 4c) to identify brightness variations that may be linked with topographical differences between the sinuous melt feature and surrounding impact melt deposits. Subtle variations were noted in the northern part of the melt feature (also observed in Figure 1c, yellow arrow) but no differences were discernible in the central and southern part, suggesting overall low-relief in the area.

Radar observations at 12.6 cm wavelength from both ground (Arecibo) and spacecraft (LRO Mini-RF [Nozette *et al.*, 2010] total power images at higher spatial resolution) suggest a similar degree of roughness within and outside the sinuous melt feature making it indistinguishable from the surrounding melt deposit [B. Campbell and L. Carter, *Pers. Comm.*].

3. Discussion

There are several possible causes for the observed mineralogical heterogeneity including 1) melting of a heterogeneous target and insufficient time for mixing, 2) isolation of an impact melt component during initial stages of melt movement and its later incorporation to the floor, 3) variable cooling and differentiation of the melt perhaps

due to volume differences and/or abundance and mineralogical variability of lithic clasts and 4) impactor debris contamination [e.g. *Schultz et al.*, 1998].

We interpret the observed differences in the mineralogy of the sinuous melt-feature (Mg-rich pyroxenes) and the surrounding impact melt deposits (Fe- Ca-rich pyroxenes) on the crater floor as due to inefficient mixing of melt during the cratering process. Terrestrial examples of heterogeneous melt deposits [e.g. *Kring et al.*, 2004; *Lambert*, 2010] support this possibility. The two melt compositions are essentially mimicking pre-impact target composition (basalt, norite), which is known to be heterogeneous [e.g. *Pieters et al.*, 1994]. Therefore, heterogeneity of impact melt in the present case likely represents the original composition of the target rocks. Although some fractionation of the melted material may occur [e.g. *Vaughan et al.*, 2013], in the present case, compositional differences have not been observed to be linked to sampling depth (which would be expected in case of differentiation) and therefore we favor preservation of the target heterogeneity (#1 and #2 above) as the likely cause. In this scenario, the sinuous melt feature likely represents preservation of an outwardly (radial) streaming zone of impact melt derived from a mineralogically distinct (noritic) horizon of the target substrate. The observed sinuous nature could be attributed to deformation accompanying melt drain-back during the modification stage of the cratering event. Furthermore, the spatial relations are intriguing and may offer insights into melt dynamics; the sinuous melt-feature occurs on the floor and crater wall, north of the central peaks but no evidence is seen for the continuation of this feature on the floor to the south of central peaks.

4. Conclusions

The spectroscopically identified sinuous impact melt feature at Copernicus has provided a view of compositionally heterogeneous lunar impact melt on a scale of several tens of kilometers. There are at least two mineralogically distinct varieties of impact melt (Mg-rich pyroxene vs Fe-Ca-rich pyroxene) occurring in close proximity on the floor of Copernicus, over a distance of ~30 km. Pre-impact target stratigraphy plays an important role in the type and form of impact melt produced in a cratering scenario where an outward (radial) streaming melt (and its later drain-back) preserves the character of the source lithology. The Copernicus region thus provides compelling evidence for the preservation of impact melt heterogeneity in the context of an extremely dynamic cratering process, strengthening its potential as a future exploration site.

5. Acknowledgement

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Figure Captions

Figure 1 Geologic context of the study area. Similar colored arrows across the panels refer to the same features. Solid rectangle in (a) & (b) represent area analyzed using M³ data (presented in (c) & (d)). (a) Geological map of Copernicus area subset from *Howard*, [1975]. Units coded in magenta, orange, gray and red have been interpreted as melt coatings or pooled impact melt. (b) LRO Wide Angle Camera (WAC) image of Copernicus crater (subset from WAC_GLOBAL_E300N3150_100M). (c) M³ albedo image [M3G20090207T044515] at 1498 nm. (d) Sketch map of the study region based on M³ data. The large impact melt-related unit identified using M³ is shown in red color (solid where boundaries are clearly discernible and dashed where they are not clear). Yellow arrows mark a prominent boundary of the melt feature. Blue arrows indicate the location of the well-known impact melt flow on the northern wall. Above this flow is a large melt pond (marked as hashed unit in sketch) and indicated by purple arrows.

Figure 2 (a) RGB color composite based on spectral parameters prominently captures the sinuous impact melt feature as distinct unit (marked with solid and broken lines). Here, R= albedo at 1489 nm, G=IBD 2000 nm, and B= BD 1900. Green arrow points to the location of newly identified Mg-Spinel lithology. (b) Various perspectives of the study area. Here, M³ data is draped over LOLA topography. c) The M³ 1489 nm albedo image provides context, but does not explicitly show the sinuous impact melt feature. d) The IBD1000 parameter highlights the central peaks and fresh craters on the floor. (e) & (f) BD1900 and IBD2000 parameter images show the sinuous feature.

Figure 3 (a) Spectral diversity at Copernicus. R1- Olivine + Crystalline Plagioclase, R2- High Ca-pyroxene, R3-Low Ca-pyroxene, R4- Mg-spinel, R5-Olivine. **(b)** Fresh surface spectra of impact melt deposit within (A2, A3) and outside (A1) sinuous melt feature. **(c)** Spectra in (b) with continuum removed (derived after dividing the spectra with a straight line continuum between 730 nm and 1618 nm). **(d)** Continuum removed spectra of soils within and outside the sinuous melt feature (See auxiliary material Fig. S4 for soil spectra without continuum removal).

Figure 4 (a) Topography of the floor derived from LOLA data suggests a broad low in the northern floor. Black dotted boxes in the top and bottom part of the image represent areas in (b) and (c) respectively. **(b)** Kaguya TC DEM of the northern part of the sinuous melt feature. **(c)** Kaguya TC DEM of the southern part of the sinuous feature. Neither image suggests any significant morphological expression of the sinuous feature. Similar colored arrows in different panels refer to the same feature. Kaguya TC DEMs in (b) and (c) were derived from DTM_MAP_02_N12E339N09E342SC.img and TCO_MAP_02_N12E339N09E342SC.img

Figures

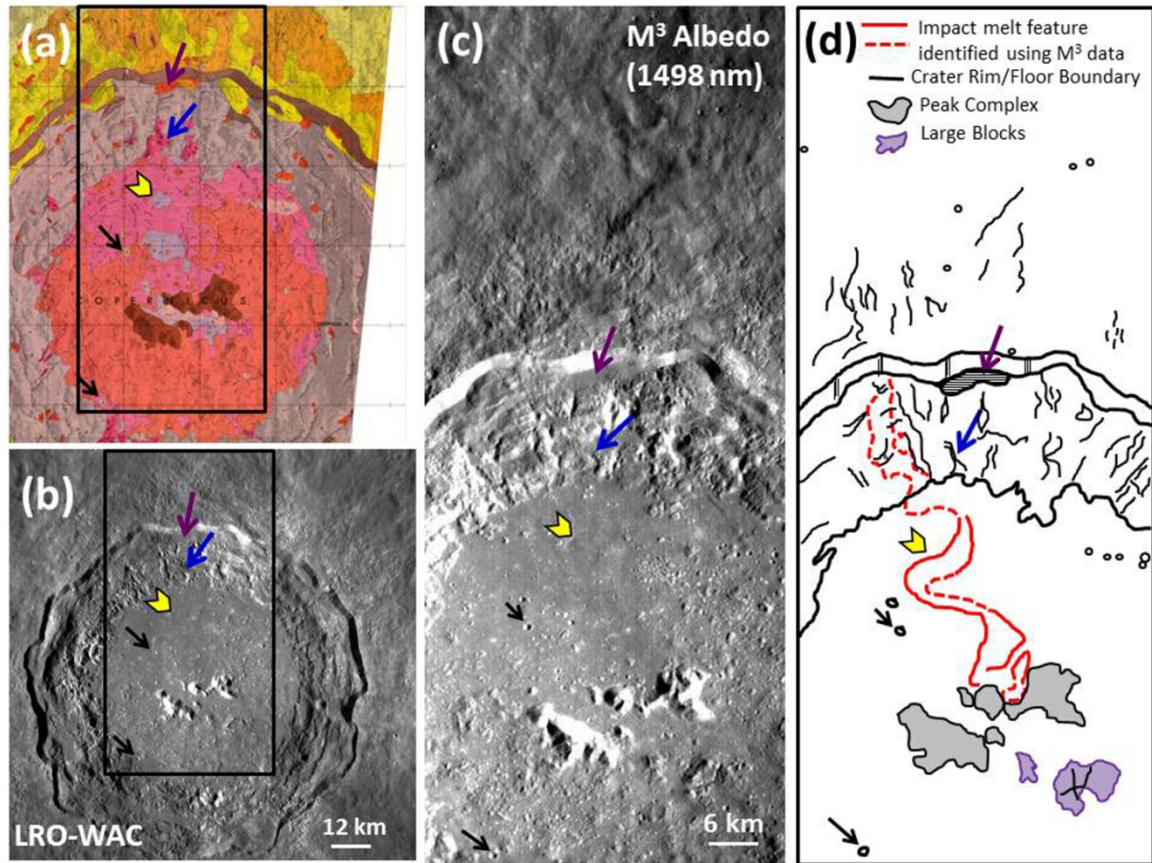


Figure 1 Geologic context of the study area. Similar colored arrows across the panels refer to the same features. Solid rectangle in (a) & (b) represent area analyzed using M³ data (presented in (c) & (d)). (a) Geological map of Copernicus area subset from *Howard*, [1975]. Units coded in magenta, orange, gray and red have been interpreted as melt coatings or pooled impact melt. (b) LRO Wide Angle Camera (WAC) image of Copernicus crater (subset from WAC_GLOBAL_E300N3150_100M). (c) M³ albedo image [M3G20090207T044515] at 1498 nm. (d) Sketch map of the study region based on M³ data. The large impact melt-related unit identified using M³ is shown in red color (solid where boundaries are clearly discernible and dashed where they are not clear). Yellow arrows mark a prominent boundary of the melt feature. Blue arrows indicate the

location of the well-known impact melt flow on the northern wall. Above this flow is a large melt pond (marked as hashed unit in sketch) and indicated by purple arrows.

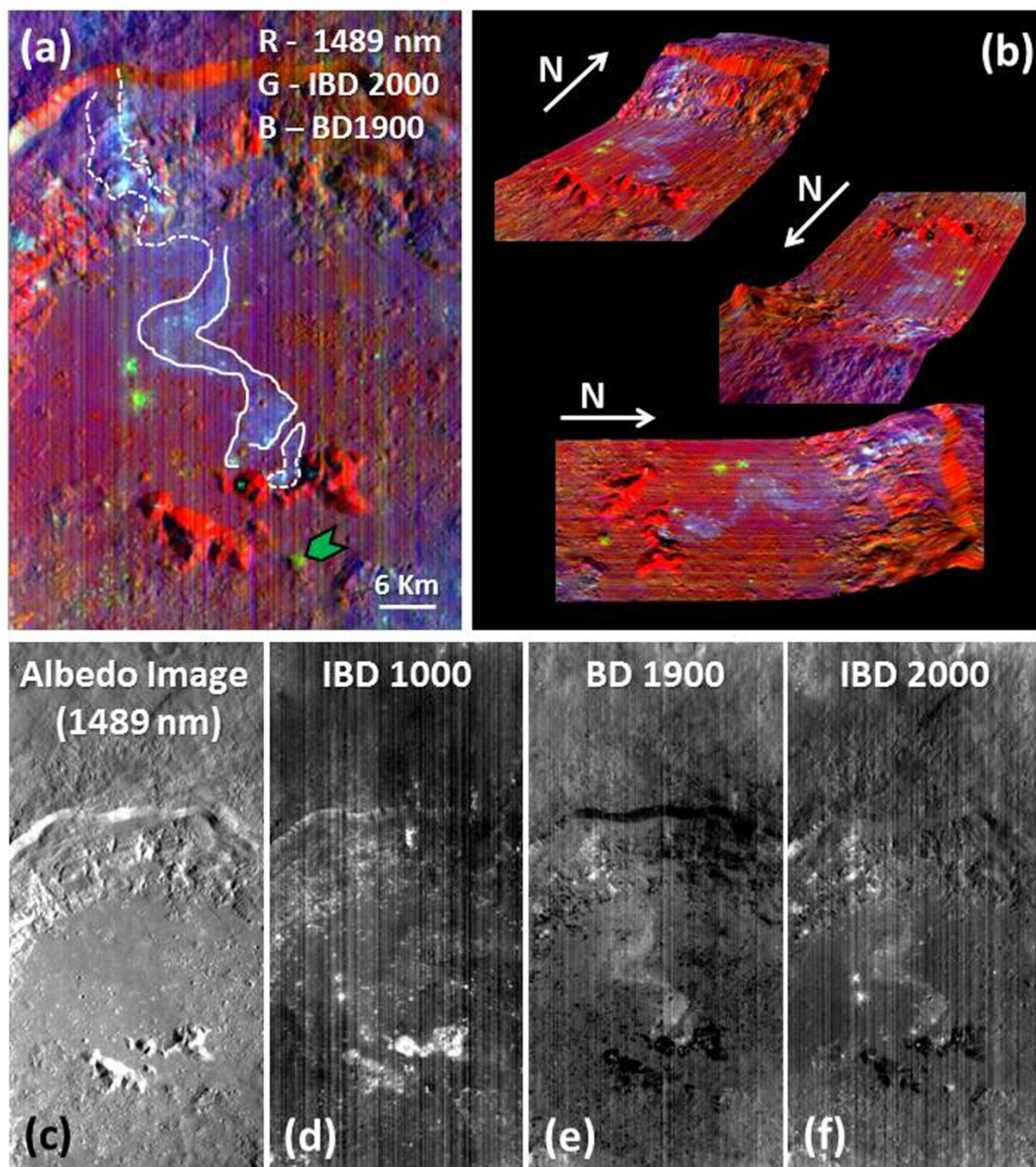


Figure 2 (a) RGB color composite based on spectral parameters prominently captures the sinuous impact melt feature as distinct unit (marked with solid and broken lines). Here, R= albedo at 1489 nm, G=IBD 2000 nm, and B= BD 1900. Green arrow points to the location of newly identified Mg-Spinel lithology. (b) Various perspectives of the study area. Here, M³ data is draped over LOLA topography. c) The M³ 1489 nm albedo image

provides context, but does not explicitly show the sinuous impact melt feature. d) The IBD1000 parameter highlights the central peaks and fresh craters on the floor. (e) & (f) BD1900 and IBD2000 parameter images show the sinuous feature.

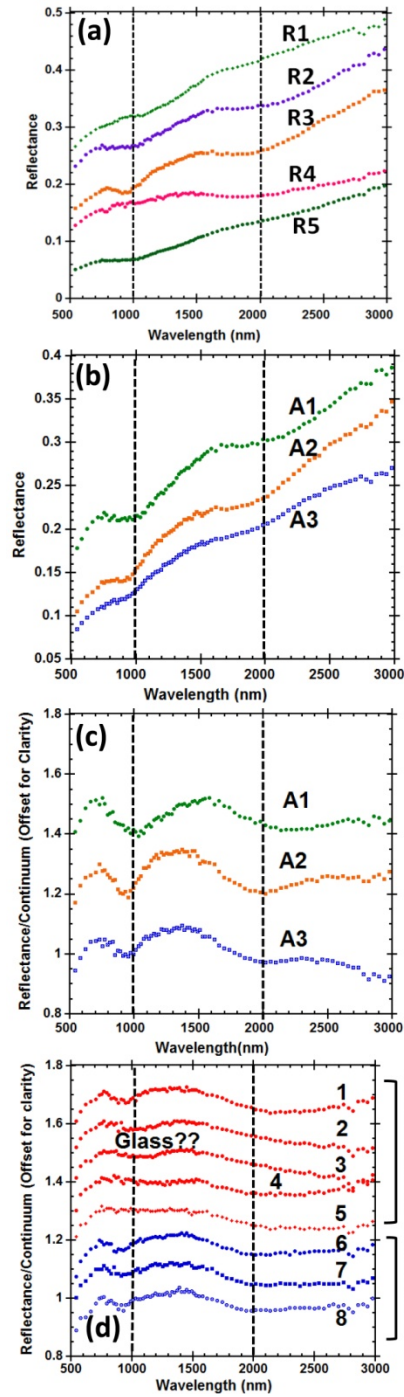


Figure 3 (a) Spectral diversity at Copernicus. R1- Olivine + Crystalline Plagioclase, R2- High Ca-pyroxene, R3-Low Ca-pyroxene, R4- Mg-spinel, R5-Olivine. **(b)** Fresh surface spectra of impact melt deposit within (A2, A3) and outside (A1) sinuous melt feature. **(c)**

Spectra in (b) with continuum removed (derived after dividing the spectra with a straight line continuum between 730 nm and 1618 nm). **(d)** Continuum removed spectra of soils within and outside the sinuous melt feature (See auxiliary material Fig. S4 for soil spectra without continuum removal).

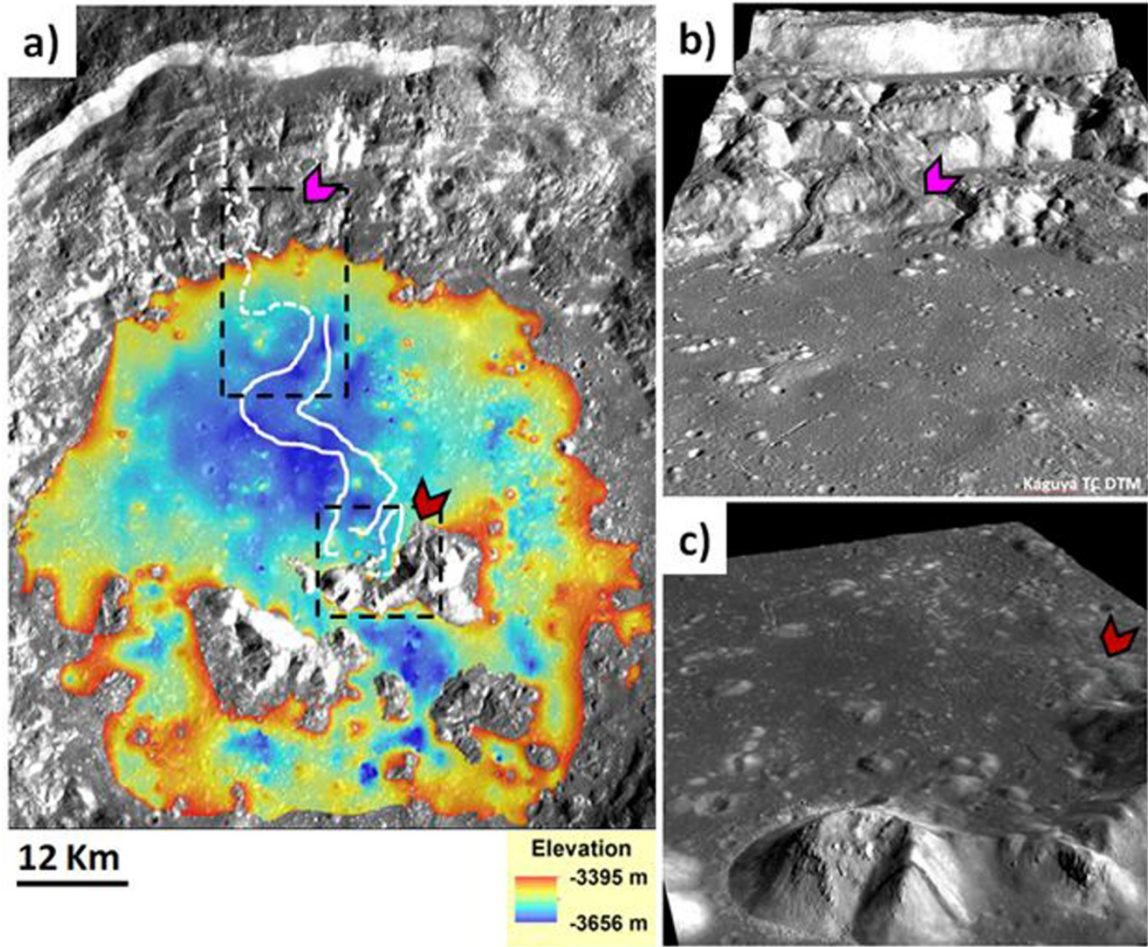


Figure 4 (a) Topography of the floor derived from LOLA data suggests a broad low in the northern floor. Black dotted boxes in the top and bottom part of the image represent areas in (b) and (c) respectively. (b) Kaguya TC DEM of the northern part of the sinuous melt feature. (c) Kaguya TC DEM of the southern part of the sinuous feature. Neither image suggests any significant morphological expression of the sinuous feature. Similar colored arrows in different panels refer to the same feature. Kaguya TC DEMs in (b) and (c) were derived from DTM_MAP_02_N12E339N09E342SC.img and TCO_MAP_02_N12E339N09E342SC.img

Supplementary Material

Large Mineralogically-Distinct Impact Melt Feature at Copernicus Crater – Evidence for Retention of Compositional Heterogeneity

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1. Representative nature of sampled spectra outside the sinuous melt feature

Spectral sampling locations used in this paper are shown in Fig.S1. We used the fresh crater located west of the melt feature as representative of the composition of the impact melt outside of the sinuous melt feature. It may be noted that another fresh crater of similar size (marked 'a' in Fig. S1), displays the same spectral properties when observed in the color composite (Fig. 2a). Since both of the craters are ~ 1 km in diameter there is a possibility that the observed spectral properties are more controlled by sampling depth and cooling history. We analyzed various collapse pits located within the sinuous melt feature on the crater floor) which are clearly exposing material deeper than that on the surface. The RGB color composite (Fig. S2) overlaid onto high-resolution LRO-NAC images provides a broad understanding of the mineralogical variations with geological context. The collapse pits/craters within the sinuous feature show signatures consistent with the mineralogy of the overall sinuous feature (shown in cyan), instead of the fresh craters outside (shown in green color). Selected spectra from these locations when compared with the fresh craters outside the sinuous feature show difference in mineralogy (Fig. S3) suggesting that the observed compositional differences are not likely to be related to different depth of sampling, but due instead to melt of different composition.

Table 1 Algorithm for deriving various spectral parameters.

R refers to the reflectance at a given wavelength, Rc is the continuum reflectance defined as a straight line across the absorption band, 20 and 40 (in algorithm for IBD 1000 and IBD 2000, respectively) specify the wavelength interval in nanometers, and n is the number of channels to be integrated over.

Spectral parameter	Algorithm
IBD 1000	$\sum_{n=0}^{26} 1 - \frac{R(789 + 20n)}{Rc(789 + 20n)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm
IBD 2000	$\sum_{n=0}^{21} 1 - \frac{R(1658 + 40n)}{Rc(1658 + 40n)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm
BD 1900	$1 - \frac{R1898}{\left(\frac{R2498 - R1408}{2498 - 1408}\right) * (1898 - 1408) + R1408}$
BD 2300	$1 - \frac{R2298}{\left(\frac{R2578 - R1578}{2578 - 1578}\right) * (2298 - 1578) + R1578}$

Figure Captions

Fig. S1 Spectral sampling locations in the study area.

Fig. S2 M³ color composite overlain on NAC mosaic of the study region highlighting the compositional units in the region. It is observed that several collapse pits and small craters located inside the newly identified impact melt feature and exposing material at depth, have a consistent coloration (cyan color) as compared to other impact melts in the vicinity (displayed in green and red color). Selected spectra from some of these are shown in Fig. S3. The mounds were sampled to verify the consistency in the spectral character of material within the sinuous melt feature.

Fig. S3 Spectral character of fresh craters outside the sinuous melt feature (green spectra) are similar and suggest uniform composition. Crater/collapse pits (cyan spectra) within the sinuous melt feature expose material deeper than the surface but are still spectrally different from fresh crater composition outside the melt feature.

Fig. S4 Spectral character of the sampled soils inside and outside of the sinuous melt feature.

Figures

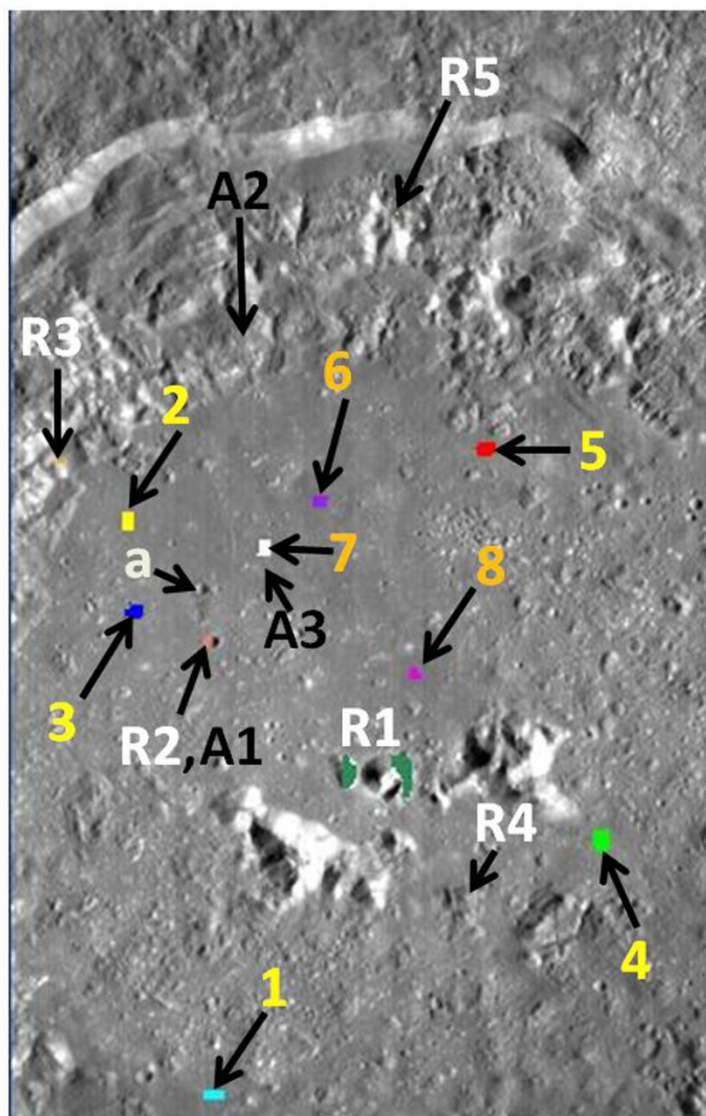


Figure S1 Spectral sampling locations in the study area.

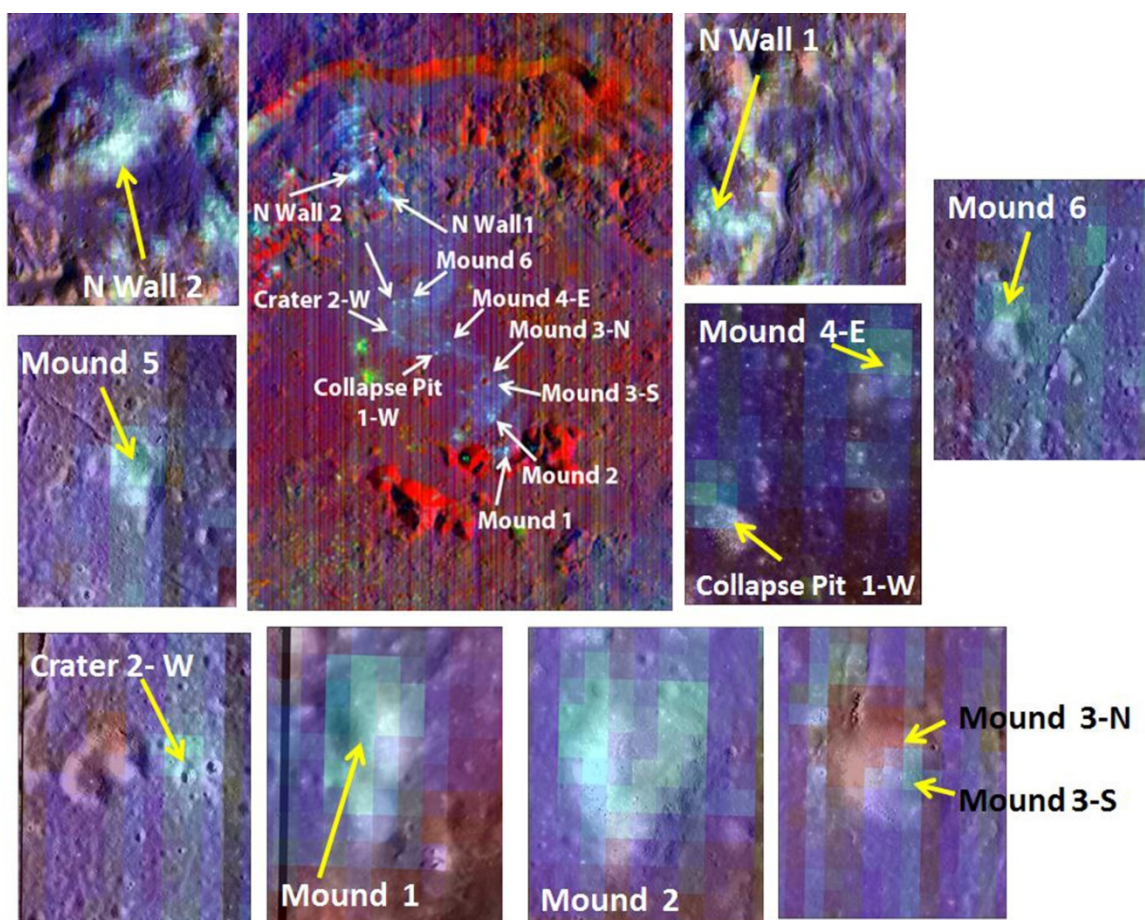


Figure S2 M^3 color composite overlain on NAC mosaic of the study region highlighting the compositional units in the region. It is observed that several collapse pits and small craters located inside the newly identified impact melt feature and exposing material at depth, have a consistent coloration (cyan color) as compared to other impact melts in the vicinity (displayed in green and red color). Selected spectra from some of these are shown in Fig. S3. The mounds were sampled to verify the consistency in the spectral character of material within the sinuous melt feature.

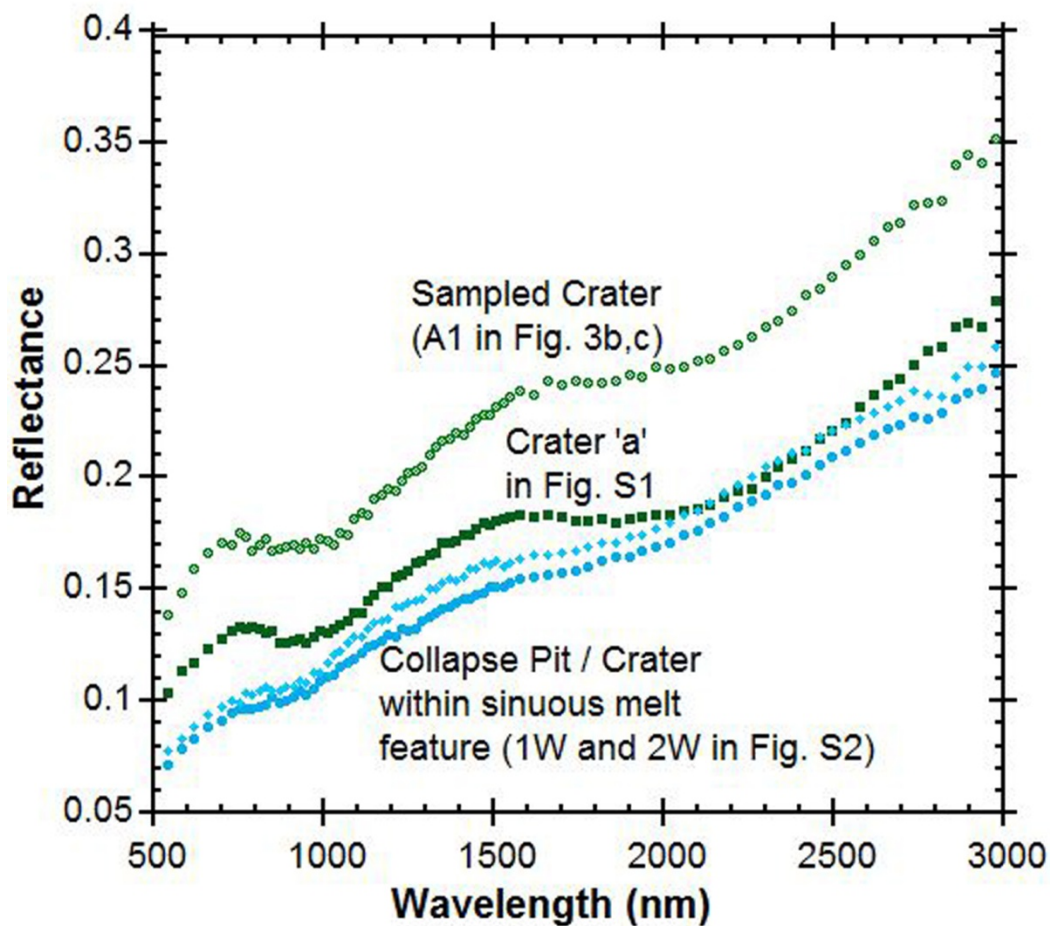


Figure S3 Spectral character of fresh craters outside the sinuous melt feature (green spectra) are similar and suggest uniform composition. Crater/collapse pits (cyan spectra) within the sinuous melt feature expose material deeper than the surface but are still spectrally different from fresh crater composition outside the melt feature.

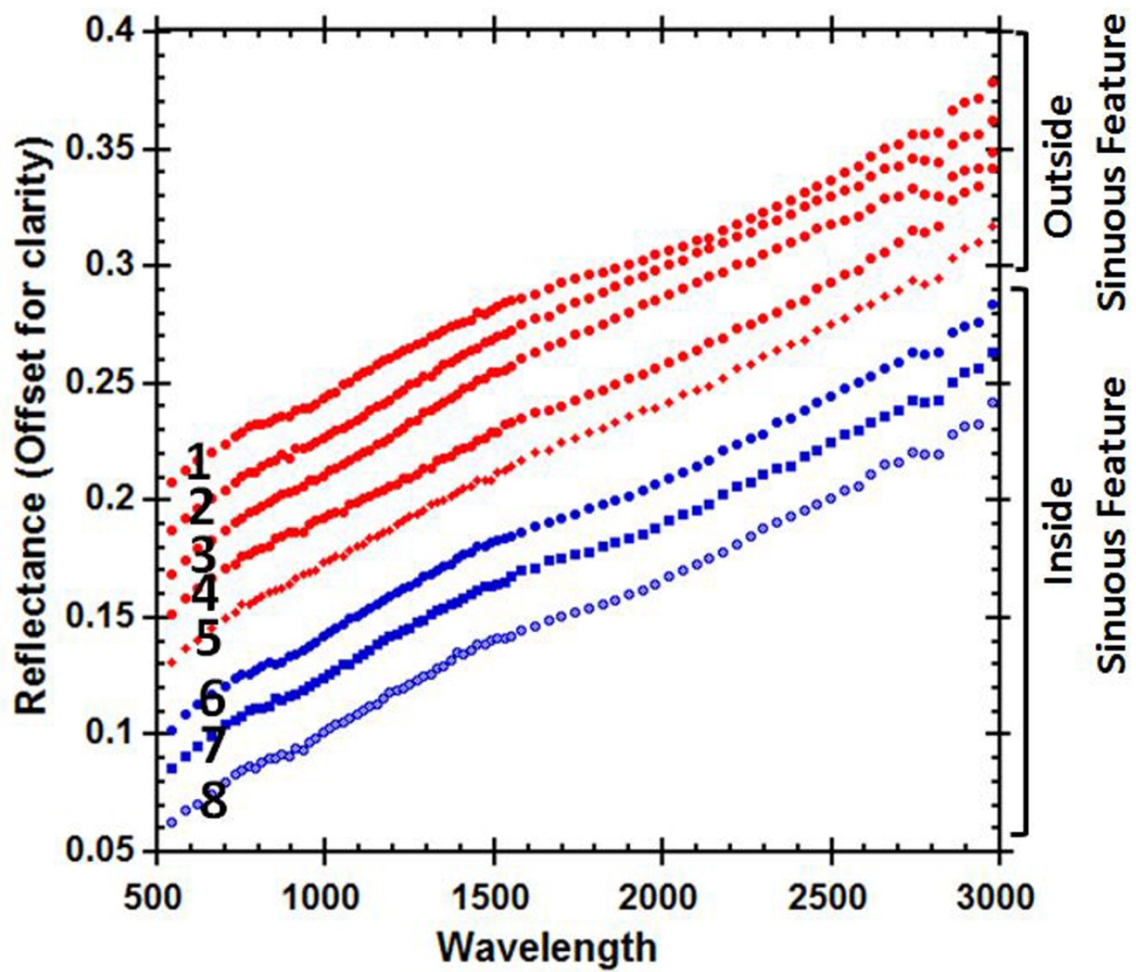


Figure S4 Spectral character of the sampled soils inside and outside of the sinuous melt feature.

CHAPTER 3: Multiple Origins for Olivine at Copernicus Crater

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Abstract

Olivine has been known to exist in the central peaks of Copernicus crater (9.62° 339.92°; 96 Km) located on the lunar nearside. Candidate olivine exposures in the northern wall were later identified and verified. Recent remote sensing missions have also identified olivine around lunar basins [*e.g. Yamamoto et al.*, 2010; *Pieters et al.*, 2011; *Kramer et al.*, 2013] and at other craters [*e.g. Sun and Li*, 2014], renewing strong interest in its origin and provenance. A mantle source is commonly suggested with global implications. Here we analyze olivine exposures at Copernicus crater using integrated data from Chandrayaan-1 Moon Mineralogy Mapper (M³), Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and Kaguya Terrain Camera (TC). We report several diverse forms of olivine lithology that require different origins. Prominent albedo differences exist between olivine-bearing exposures in the central peaks and a northern wall unit (the latter being ~40% darker). The low-albedo wall unit occurs as a linear mantling deposit and is interpreted to be of impact melt origin, in contrast with the largely unmodified nature of olivine-bearing peaks. Areas of olivine-rich lithology also occur on the impact melt-rich floor as small, localized exposures, representing another geologic setting. We expect that olivine exposures elsewhere on the Moon occur in diverse environments and are unlikely to all have a common mantle source.

1. Introduction

Olivine is commonly the first crystallizing solid during magmatic differentiation and resides largely in the mantle of differentiated planetary bodies (such as the Earth). Near-surface occurrences of olivine dominated lithologies are therefore unusual unless produced through secondary processes like volcanism (or plutonism). Impact craters, however, can expose or relocate subsurface mineralogy from various depths, with larger craters excavating relatively deeper than smaller craters. Central peaks of impact craters represent some of the deepest material excavated within a crater. Their steep slopes minimize soil retention and aid in the identification of constituent mineralogy, revealing compositions from depth [e.g. *Tompkins and Pieters*, 1999; *Cahill et al.*, 2009].

Olivine on the lunar surface was first discovered remotely in the central peaks of Copernicus crater [*Pieters*, 1982] and interpreted to be likely sourced from the mantle or a buried pluton [e.g. *Pieters and Wilhelms*, 1985]. Later studies suggested a possible shallow source region [e.g. *Lucey et al.*, 1991] based on potential olivine-bearing locations in the northern crater wall and the assumption that olivine in the wall and the peak had a common origin. A variety of geological scenarios have been proposed to invoke a mantle origin for olivine exposures on the Moon, including excavation through a thin crust [e.g. *Yamamoto et al.*, 2010], multiple impacts in a given region (allowing access to deeper material) [e.g. *Pieters and Wilhelms*, 1985], and a single giant impact event [e.g. *Yamamoto et al.*, 2010]. Diverse origins of olivine continue to be proposed [e.g. *Powell et al.*, 2012; *Corley et al.*, 2014; *Sun and Li*, 2014].

2. Data and Methods

The spectral and spatial data analyzed in this study are archived and available in public domain. Chandrayaan-1 M³ [e.g. *Pieters et al.*, 2009; *Goswami and Annadurai*, 2009] and LRO NAC [e.g. *Chin et al.*, 2007; *Robinson et al.*, 2010] datasets are available on Planetary Data System (PDS) (<http://pds-imaging.jpl.nasa.gov>) while Kaguya TC data [e.g. *Haruyama et al.*, 2008] is available on SELENE Data Archive (<http://l2db.selene.darts.isas.jaxa.jp/>).

M³ data was acquired in various phases known as optical periods and which represent various imaging conditions [*Boardman et al.*, 2011]. In this study, we used data from optical periods Op2c1 and Op2a. Mosaics were created for each optical period using imaging strips covering the area of study. The choice of the optical period was guided by the areal coverage, illumination conditions and spatial resolution. In this context, Op2c1 data was used for its better viewing geometry which minimized shadows and facilitated detection of albedo differences. Op2a data was helpful due to its high spatial resolution which could be used to identify small scale compositional differences. The spatial resolution of Op2c1 data is ~280 m/pixel while Op2a data has resolution of 140 m/pixel. We used the Level 2 data for both optical periods which is publicly available and has all major corrections [e.g. *Green et al.*, 2011] applied to it.

The reflectance data from M³ was initially used to derive various spectral parameters that allow general mapping of compositional differences in a spatial context. The M³ parameters used in this study are described in supplementary information. Subsequently, representative spectra from the study region were extracted to highlight the observed character of olivine lithology. The spectra have been presented with albedo

information and in a continuum removed form, the latter highlights fine-scale compositional differences. Continuum was estimated (for each spectrum) based on the spectral slope between 750 nm -1618 nm. The spectrum was divided by the continuum to remove it.

3. New Observations and Insights

We have carried out detailed spectral and morphological analyses at Copernicus crater. The prominent occurrence of olivine throughout the central peaks and a well-defined olivine exposure in the northern wall (outlined in red in Figure 1b) are readily recognized in M^3 spectra. Our analyses identify several new observations about olivine occurrences.

3.1. Major Albedo differences in olivine-bearing lithologies

Photometrically-corrected high sun (low-phase angle) images of the region indicate that the northern wall olivine exposure exhibits a dramatically lower albedo around 750 nm compared to the olivine in the peaks (Figure 1c). M^3 spectra of the two regions (Figure 1d) illustrate this brightness difference very well with the northern wall olivine exposure having a consistently low-albedo across the visible to near-infrared wavelength range. In fact, this unit exhibits the lowest albedo in the entire region when compared to the material near the peaks and the neighboring wall, highlighting its distinctive nature. Additional measurements of albedo differences are presented in Supplementary Figure S1.

3.2. Distinct morphology of the northern wall olivine unit

A second major observation documents the distinctive geologic context of the olivine-bearing, low-albedo northern wall unit, illustrated in Figure 2 with high spatial resolution data from LRO NAC (~1 m/pixel) and Kaguya TC (10 m/pixel). The low-albedo unit occurs as a relatively continuous, linear feature about 3.5 km long and 0.5-1 km wide, extending down slope from a prominent crater wall terrace that contains an impact melt pond (Figure 2a, b, c, f). The morphology of the lower section is quite distinct. At the very distal end, there is a sharp boundary between the low-albedo unit and the bright (boulder-rich) northern wall material. The low-albedo unit occurs as a dark apron with undulating boundaries spread across the wall, likely guided by the local topography (illustrated in Figure 2d). It mantles the wall as a thin-deposit with sub-surface topography visible through it. Occasionally, bright boulder material from the wall can be observed poking through the low-albedo unit or excavated by small craters (shown in Figure 2e). All these properties indicate that the low-albedo feature is an impact melt deposit.

A likely continuation of the low-albedo unit appears to extend beyond the crater rim and is best captured in Figure 2f. This rim unit also displays a broad (but weaker) absorption band near 1000 nm (black spectrum in Figure 3c and d). There are a few other low-albedo streaks in the vicinity and in other parts of the crater (e.g. eastern and southern rim) but many with spectrally different character. Additional details on these diverse features are provided in Supplementary Figure S2.

3.3. Olivine exposures on the crater floor away from central peaks

A third new observation is the identification of several small, isolated exposures of olivine on the impact melt-rich crater floor (Figure 3a with red and blue circles). These areas display distinctive spectral properties that are similar to the confirmed olivine exposures discussed above. This represents a third geological setting (in addition to the central peaks and northern wall) for olivine lithologies at Copernicus crater. The exposures are generally clustered in the north-west part of the crater floor (Figure 3a) and are associated with small, high standing mounds (Figure 3b) or fresh craters in the melt sheet. An evaluation of the geologic context for each occurrence and the nature of their spectra has been made and compared with the other olivine-bearing lithologies. Spectra of olivine exposures on the floor have higher albedo than the northern wall olivine spectrum (Figure 3c & d) making them more comparable to the central peaks spectrum.

The areas identified with filled red circles in Figure 3a display absorption bands centered around 1050 nm with no feature at 2000 nm and have comparable band strength (e.g. spectrum 9, 10 in Figure 3d) to the known olivine occurrences. We interpret these as olivine-bearing. Several other areas on the crater floor (blue filled circles in Figure 3a) also display a broad absorption band around 1000 nm confirming their slightly mafic character. These spectra are noisier and have variable band strength, making it difficult to confirm a composite nature of the 1000 nm absorption, which would be diagnostic of olivine. Despite the broad spectral similarity with known olivine-bearing occurrences, this group may also be interpreted as fully melted and quickly quenched glass [Bell *et al.*, 1976; Horgan *et al.*, 2014] which has a broad absorption around 1000 nm. However, a weak absorption short of 2000 nm, usually present in quenched glass, is not observable.

Since quenched glass might be present in impact melt deposits, we do not rule out its presence in some of these locations.

Nevertheless, the occurrence of olivine-bearing lithologies on the crater floor is clearly indicated by the spectral character of the first group (red colored circles) along with its well-defined geologic context (mounds/craters). The additional exposures (blue colored circles), if confirmed to be olivine-bearing instead of glass-rich, would further expand the spatial extent of olivine-bearing lithologies on the floor. The spatial distribution of small, localized exposures of olivine could indicate whether it was geographically extensive in the pre-impact target material or was rather limited. Detailed compositional mapping across the crater [*Chapter 4*] suggests that there are also a few small, isolated olivine-bearing exposures scattered in different parts of the crater, an indication of perhaps a broad distribution of olivine at Copernicus.

4. Discussion

Olivine-bearing lithologies have now been documented in three genetically different crater units of Copernicus (central peaks, wall deposits and the impact melt-rich floor), each sampling a different depth and/or having undergone different geological processing. An affiliation with impact melt is noted in two cases (northern wall and floor). Since recent geophysical results from GRAIL mission [*e.g. Zuber et al., 2013; Wieczorek et al., 2013*] do not indicate the presence of a thin crust at Copernicus, direct mantle access was unlikely during the cratering event.

The source of observed olivine at Copernicus thus appears to have originally been located within the crustal column and may be represented by previously deposited

basin ejecta (e.g. Imbrium or Insularum) or a buried shallow pluton [e.g. *Pieters and Wilhelms*, 1985; *Andrews-Hanna et al.*, 2013]. Alternatively, olivine could have originated in an impact melt by secondary processing of a heterogeneous crustal column. Mare basalt is known to be part of the pre-impact target geology at Copernicus and could have contributed a mafic component to the impact melt which later crystallized olivine as it cooled. In order to determine how the distinctly different olivine exposures recognized at Copernicus may be related, each needs to be evaluated separately in geologic context.

4.1 Possible origin of olivine in the central peaks and crater floor

In the case of olivine-bearing central peaks, their formation is believed to have involved transportation of material from ~15 km depth [e.g. *Cintala and Grieve*, 1998] in solid state, although likely in a highly shocked form [e.g. *Melosh*, 1982]. The bright peak material is interpreted to be a mixture of plagioclase and olivine in different proportions [e.g. *Pieters*, 1982]. The olivine exposures on the crater floor (mostly high standing mounds) likely represent broken, un-melted large fragments that became embedded in the impact melt, perhaps from the same source lithology as the central peaks. In this context, the source lithology could be occurring as a single layer or may be present in multiple zones in the crust.

4.2 Possible origin of olivine on the northern wall

On the other hand, the northern wall olivine exposure has no observable large boulders and instead appears quite smooth. The notable low-albedo requires a pervasive opaque component, an important distinguishing property. The strong, composite absorption band around 1050 nm (northern wall, Figure 3d) suggests that the crystalline olivine is relatively abundant or has a notably coarse grain size within a darker matrix.

These combined characteristics indicate that the olivine-bearing northern wall exposure is compositionally distinct from the olivine in the central peaks and on the floor.

There is no unique interpretation for the origin of the low-albedo olivine-bearing wall unit, although a mafic-rich component tapped by the impact and incorporated into the impact melt appears essential. One scenario could involve a cooling history in which large olivine crystals initially formed in a mafic melt but the melt was disturbed and it rapidly cooled forming a dark, glassy melt matrix (with embedded large olivine crystals). Adjustments during the modification stage of the crater, for example, could potentially disturb the cooling process of such a melt body allowing it to flow down the crater wall.

Another scenario could result from a quenched environment involving olivine crystals in an opaque-rich, fine-grained glassy matrix. Here, the olivine could be derived from the original target material in the form of un-melted, small clasts. Alternatively, devitrification of mafic glassy matrix could give rise to olivine needles. In either case, abundant olivine crystals are required to give an optical signature while the surrounding material is still largely opaque and/or strongly absorbing. A third scenario could involve excavation of a pre-existing olivine-rich pyroclastic deposit with partially quenched olivine-bearing mafic glass. Large pyroclastic deposits (e.g. Sinus Aestuum, Rima Bode) in close vicinity to Copernicus crater are consistent with such a geological environment.

5. Summary

The integrated analysis presented here documents different genetic affiliations for olivine occurrences within Copernicus crater. The distinctive albedo differences between the northern wall exposure of olivine and the central peaks indicate that different geological processes (and possible source regions) were involved in their formation.

Olivine lithologies in the northern wall exposure and the crater floor are associated with impact melt. As such, the bulk of these olivine-bearing materials were derived from a relatively shallow source depth in comparison to the central peaks. The presence of olivine is detected based on its diagnostic spectral signature in remote sensing data but the spectral detection does not address its petrographic form. Olivine can occur in a variety of forms such as un-melted primary mineral clast, recrystallized melt or devitrified glass. It is therefore also very important to analyze the geologic context of olivine-bearing locations at high spatial resolution and to identify morphological distinctions that may be related to the nature and genetic linkages of olivine.

The distinct differences in geologic context of olivine at Copernicus, document its genetic diversity that is likely prevalent across the lunar crust. In this context, Copernicus remains a scientifically high priority target for future missions.

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Figure Captions

Figure 1 Observed albedo differences between olivine-bearing central peaks and northern wall exposure. (a) M³ Op2c1 image highlighting bright central peaks and the relatively dark olivine-bearing northern wall. (b) The same image with the two locations outlined in red. Image Id: M3G20090610T030313. The phase angle for the acquired data was about 13°. Scale bar, 48 km. (c) M³ Op2c1 reflectance values measured at 750 nm for the olivine bearing central peaks (light green bars), northern wall (dark green bars) and nearby locations (brown bars) (d) M³ Op2a spectra illustrating the differences between olivine exposures in the low-albedo northern wall and the central peaks.

Figure 2 Geologic context of the low-albedo olivine-bearing northern wall unit. (a) Kaguya image of the northern wall containing the low-albedo olivine-bearing unit (yellow box). Scale bar, 4 km (b) M³ color composite overlain on the Kaguya image illustrating the correspondence of strong olivine signature in the wall (red color in yellow box) with the low-albedo deposit. Red= strength of 1000 nm absorption band, Green= strength of 2000 nm absorption, Blue = reflectance at 1489 nm. (c) LRO NAC image (M1101338216RE) of the region (marked by the yellow box in a & b) showing the distinctive low-albedo unit. Magenta box denotes area shown in d. Scale bar, 1 km. (d) Distal portion of the low-albedo unit in LRO NAC image (M127063668RE) illustrates the superposed nature of the deposit. Orange box denotes the area shown in e. Scale bar, 300 m. (e) LRO NAC view (M127063668RE) showing the subsurface topography poking through the deposit. A fresh crater exposes bright wall material from beneath the

deposit. Scale bar, 40 m. (f) Kaguya oblique image (SP_2B2_01_06758_N111_E3400P) showing the extension (green arrows) of the low-albedo wall unit beyond the rim (also partially captured in b). Scale bar, 800 m.

Figure 3 Nature and distribution of the olivine exposures at Copernicus crater. (a) The locations of olivine/quenched glass-bearing floor exposures marked as filled circles. Red outlines show olivine-bearing central peaks and the northern wall exposure. Spectra of the numbered floor locations are presented in (c) and (d) and colored the same way. (b) Kaguya TC image showing geologic context of two crater floor locations (7, 10) displaying strong 1050 nm absorption, M^3 color composite overlays are shown with same parameters as in Figure 2b. (c) Spectra of numbered crater floor exposures. The spectra from the central peaks, northern wall and rim above the wall exposure are provided for comparison. (d) Same spectra as c but with continuum removed. Vertical dotted line at 1050 nm in (c) and (d) marks the central absorption in olivine. Scale bars, 700 m.

Figures

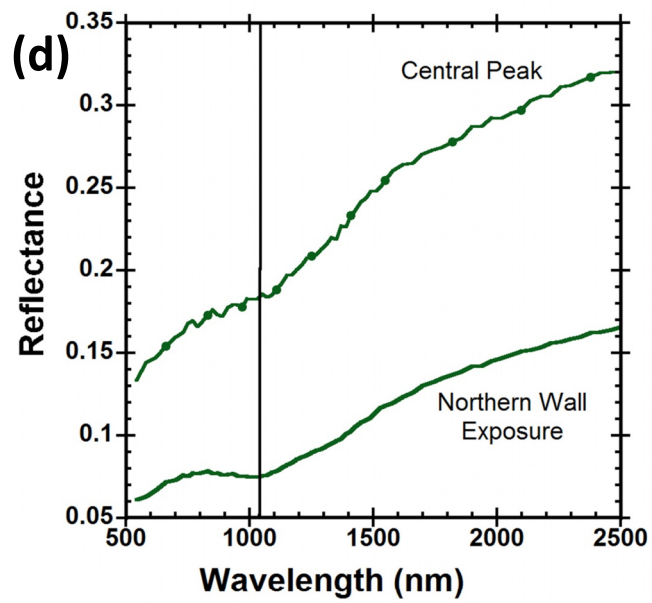
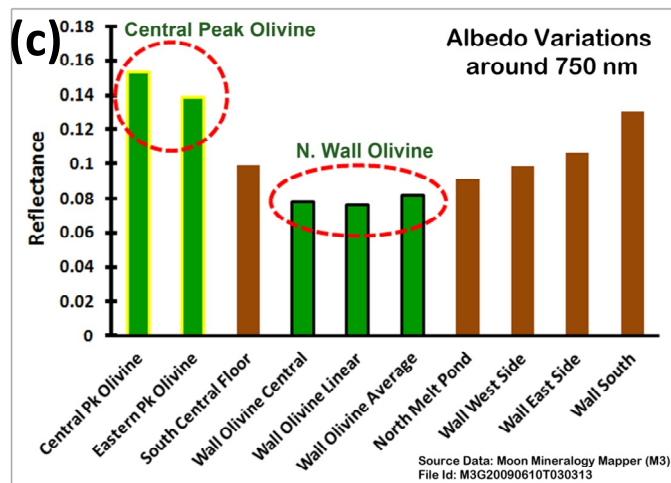
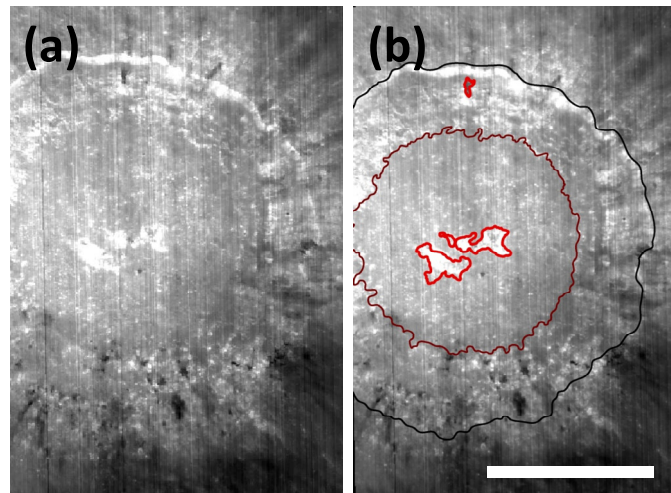


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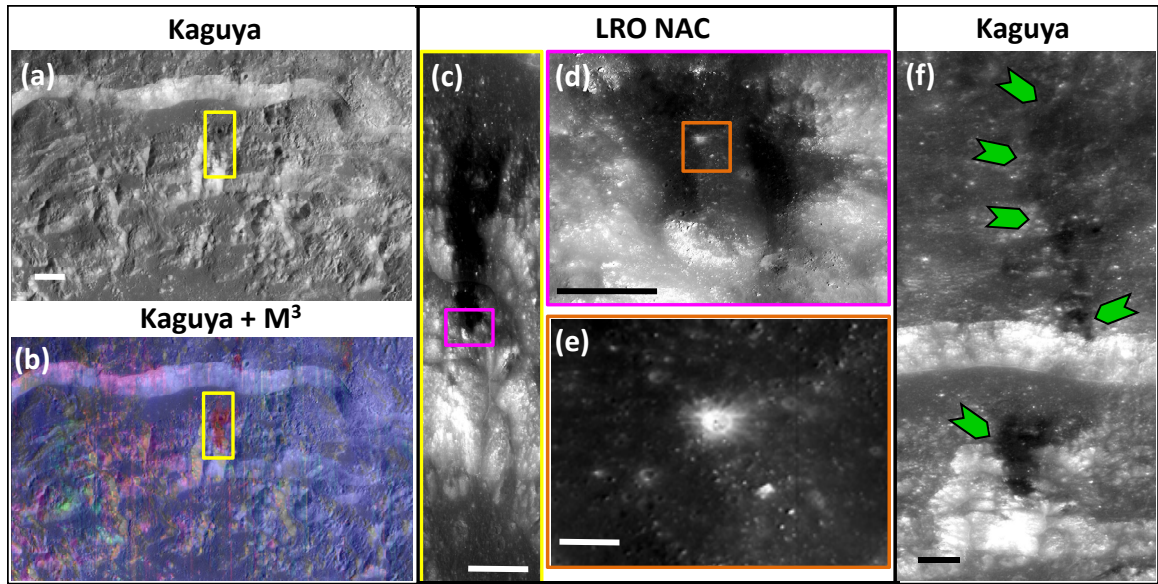


Figure 2 Geologic context of the low-albedo olivine-bearing northern wall unit. (a) Kaguya image of the northern wall containing the low-albedo olivine-bearing unit (yellow box). Scale bar, 4 km (b) M^3 color composite overlain on the Kaguya image illustrating the correspondence of strong olivine signature in the wall (red color in yellow box) with the low-albedo deposit. Red= strength of 1000 nm absorption band, Green= strength of 2000 nm absorption, Blue = reflectance at 1489 nm. (c) LRO NAC image (M1101338216RE) of the region (marked by the yellow box in a & b) showing the distinctive low-albedo unit. Magenta box denotes area shown in d. Scale bar, 1 km. (d) Distal portion of the low-albedo unit in LRO NAC image (M127063668RE) illustrates the superposed nature of the deposit. Orange box denotes the area shown in e. Scale bar, 300 m. (e) LRO NAC view (M127063668RE) showing the subsurface topography poking through the deposit. A fresh crater exposes bright wall material from beneath the deposit. Scale bar, 40 m. (f) Kaguya oblique image (SP_2B2_01_06758_N111_E3400P) showing the extension (green arrows) of the low-albedo wall unit beyond the rim (also partially captured in b). Scale bar, 800 m.

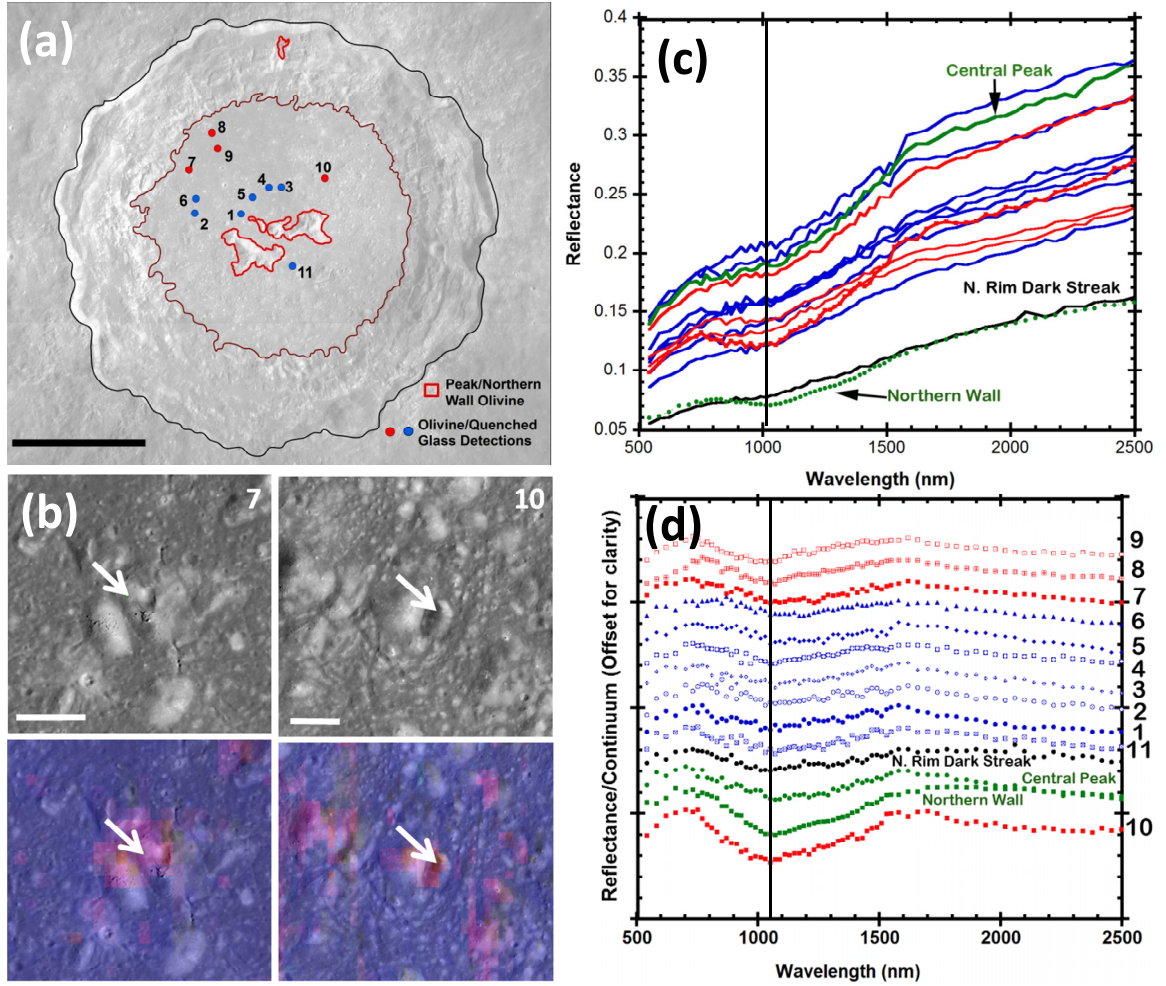


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Supplementary Material

Multiple Origins for Olivine at Copernicus Crater

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Table 1 Algorithms for spectral parameters used in this study

Spectral parameter	Algorithm
IBD 1000	$\sum_{n=0}^{26} 1 - \frac{R(789 + 20n)}{Rc (789 + 20n)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm
IBD 2000	$\sum_{n=0}^{21} 1 - \frac{R(1658 + 40n)}{Rc (1658 + 40n)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm

Figure Captions

Figure S1 Several east-west albedo profiles at 750 nm (Op2c1 data) across the northern wall of Copernicus crater containing the low-albedo olivine exposure (as shown in Figure 1 in the main text). Note the consistent drop in reflectance in the central part of the plot which represents the extent of the low albedo unit. Red curve is the average profile.

Figure S2 Comparison of the spectral character of the main low-albedo unit on the northern wall (labeled 1) with other low albedo exposures in other parts of the crater as observed in the Op2c1 image (acquired at low phase angle). The spectra have been extracted from the Op2a mosaic owing to their high spatial resolution which is necessary to identify the weak spectral features. Locations 5, 6, 7 are likely related to the basalts of the target region.

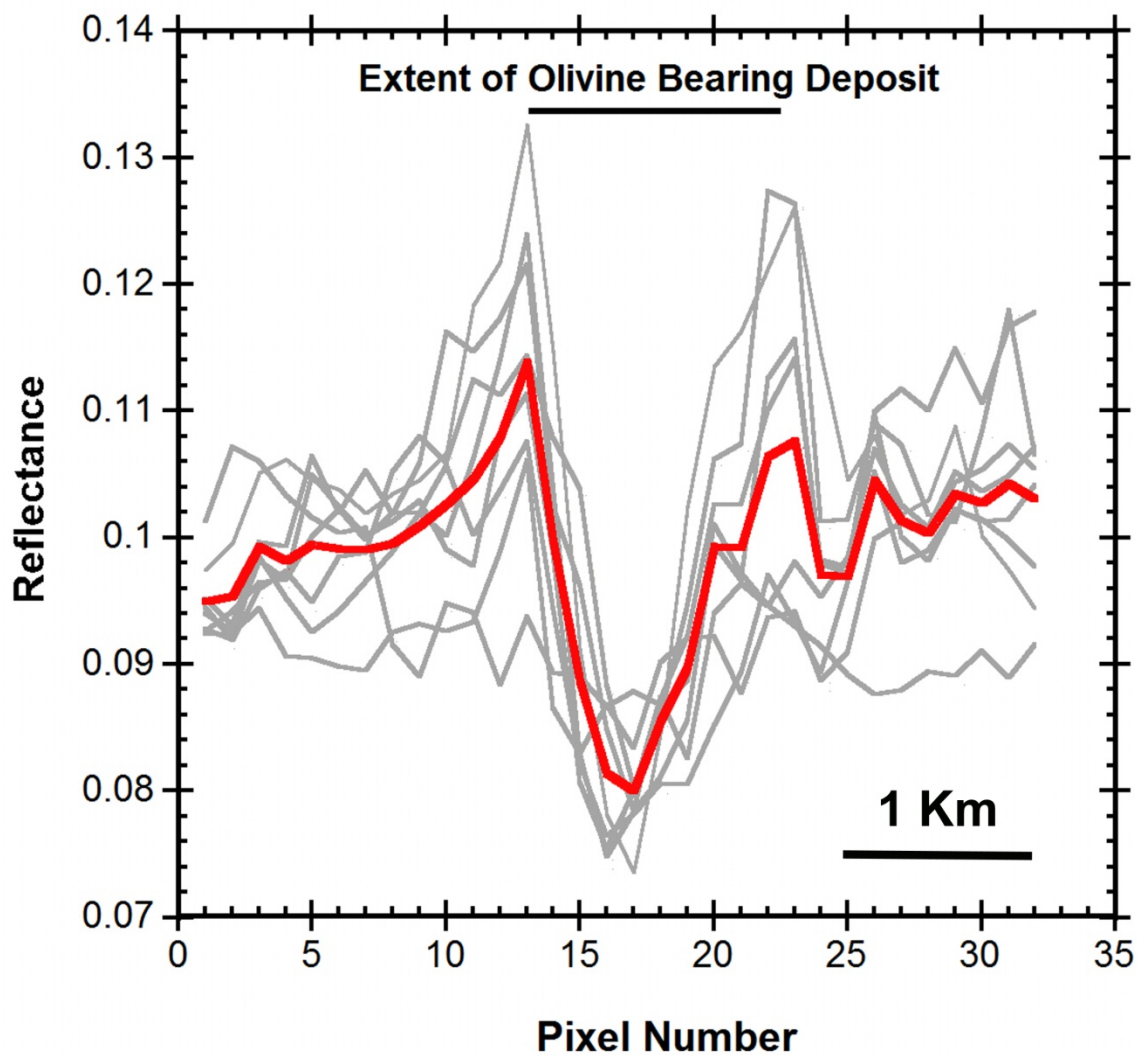


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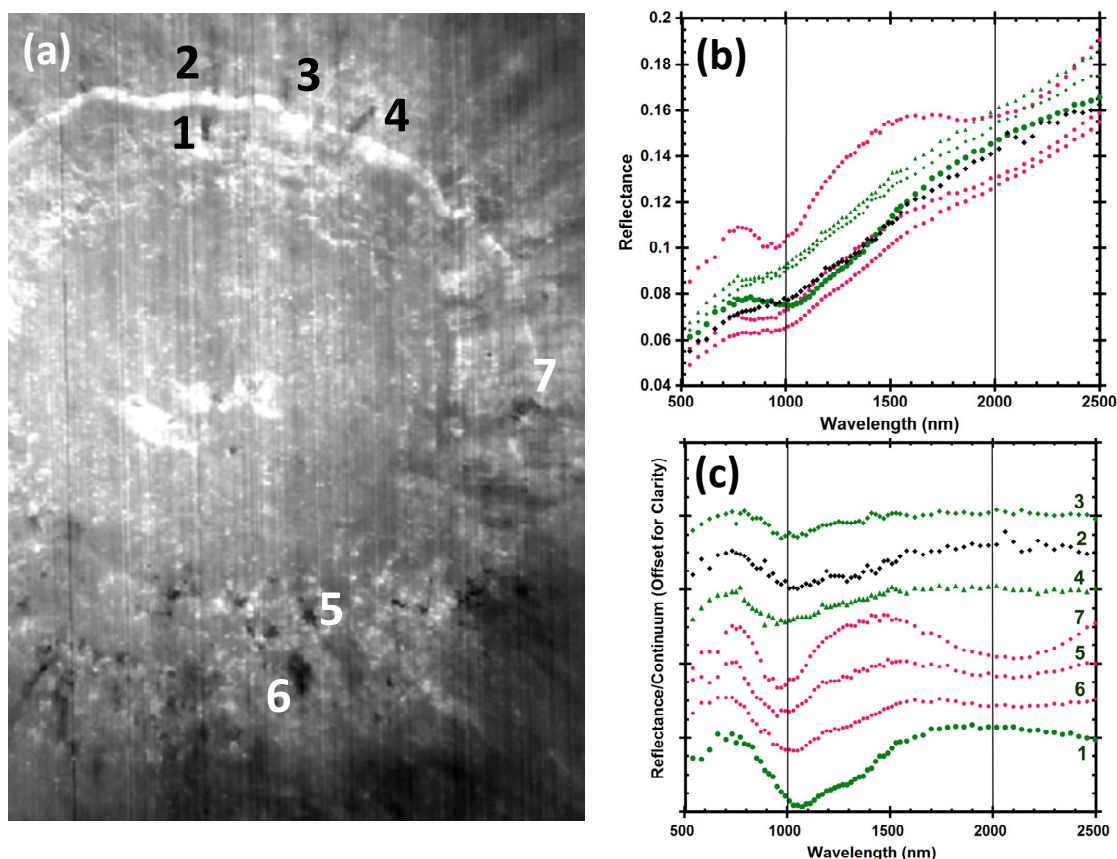


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CHAPTER 4: Impact Melt Distribution, Mineralogy and Morphology at
Copernicus Crater: Insights into Melt Character, Evolution and Pre-Impact
Geological Setting

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Abstract

Systematic spatial variation in the mineralogy of impact melt deposits at Copernicus crater is observed and subsequently used as a tracer to understand the impact melt emplacement, evolution and relationship with local target properties. The observed mineralogical heterogeneity is radially diverse and is reflected in the soil as well as geologically fresh surfaces within impact melt deposits (craters, collapse pits, large blocks). The observed radial trends are consistent across the floor, walls and rim regions of Copernicus. We interpret these trends to indicate that local vertical mixing of melt is the dominant process at crater scale while lateral mixing is relatively limited. High resolution morphological and compositional mapping of impact melt species across the crater highlights the diversity and distribution of melt forms including a 27 km long flow feature cutting through the ejecta blanket on the southern rim. The new information obtained in this study has been integrated with the existing knowledge of the area to reconstruct the pre-impact target geology at Copernicus. Among the distribution of various lithologies, we highlight multiple geological scenarios for olivine occurrence based on our observations. Copernicus continues to provide important new insights and holds a promise to answer several science questions, meriting its exploration by human/robotic missions in the near future.

1. Introduction

Melting is an inevitable product of the impact cratering process involving the recycling of the primary and/or secondary crust on a planetary body (i.e. magma ocean derived in contrast to the mantle derived partial melt). Impact melt deposits have either been observed or proposed to occur on variety of planetary bodies including the Earth, Moon, Mercury, Mars, Venus and the asteroid Vesta [e.g. *Dence, 1971; Howard and Wilshire, 1975; Phillips et al., 1991; Morris et al., 2010; Ostrach et al., 2012; Le Corre et al., 2013*] although the spatial extent of impact melt is different on each of them. The volume of melt generated, its distribution and subsequent preservation depends on variety of factors including gravitational energy of the planetary body, impact conditions (velocity, size, angle), physical properties of the projectile and the target material as well as state of the target body (geologically active/dead) [e.g. *Gault et al., 1968; Cintala and Grieve, 1998*].

Terrestrial occurrences of impact melt have been very well studied using remote sensing, field studies as well as laboratory analyses [e.g. *Grieve, 1975; Kring et al., 2004; Osinski et al., 2008*]. They have contributed immensely to the knowledge of impact melt character, formation and its subsequent evolution. Well-known examples include the impact melt occurrences at Manicouagan [e.g. *Floran et al., 1978*], Ries [e.g. *Shoemaker and Chao, 1961*] and Vredefort [*Reimold and Gibson, 2006; Cupelli et al., 2014*]. In the context of other planetary bodies (apart from the Earth) where large expanse of impact melt has been observed and remote sensing is the primary tool to study, extensive efforts have been devoted to understand the morphological character of impact melt deposits and the dominant governing factors [e.g. *Howard and Wilshire, 1975; Hawke and Head,*

1977]. New insights in this direction are being further provided [e.g. *Bray et al.*, 2010; *Carter et al.*, 2012; *Denevi et al.*, 2012; *Neish et al.*, 2014] by diverse datasets from recent and current lunar spacecrafts [e.g. *Chin et al.*, 2007; *Pieters et al.*, 2009, *Goswami and Annadurai*, 2009; *Haruyama et al.*, 2010]. However, very few studies have addressed the mineralogical character of impact melt deposits [e.g. *Smrekar and Pieters*, 1995; *Tompkins and Pieters*, 2010]. As a consequence, this has been largely an unexplored domain but has the potential to shed new light on the crustal mineralogy, its spatial diversity and its implications for the evolution of the Moon through time. We attempt to bridge this existing gap by carrying out a coordinated mineralogical-morphological study of impact melt deposits at geologically young craters like Copernicus.

1.1 Regional Geology and Earlier Work

Copernicus (9.62°N 21°W, 96 Km diameter) is a geologically fresh complex crater located on the lunar nearside (Fig. 1a, b) with an extensive ray system and pervasive deposits of impact melt. It defines the youngest unit of the lunar stratigraphic time scale (Copernican; 1.1 billion years - present) and has been extensively studied by telescopic and spacecraft datasets [e.g. *Pieters et al.*, 1982; *Lucey et al.*, 1991; *Pinet et al.*, 1993]. The Apollo 12 mission is believed to have sampled material from one of the Copernicus rays which was subsequently dated to be ~800 m.y. old [e.g. *Eberhardt et al.*, 1973], consistent with the most recent crater counts derived age of 770 m.y. [*Hiesinger et al.*, 2012].

The geology of the area is quite complex with Imbrium basin (located towards the North) and Mare deposits of the Procellarum basin forming the two major regional

geological entities. Numerous mapping efforts (Fig. 1d) using the lunar orbiter images have been carried out highlighting the major units in the area [*e.g. Schmitt et al.*, 1967; *Howard*, 1975]. Mineralogically, Copernicus appears to have excavated both highlands and basaltic material, the spatial distribution of which is quite non-uniform. The stratigraphic sequence at Copernicus crater before impact has been suggested [*Schmitt et al.*, 1967; *Pieters and Wilhelms*, 1985] to be (from top to bottom):

- i) Mare Basalts
- ii) Imbrium Ejecta
- iii) Noritic crust
- iv) Olivine-bearing lithology

Copernicus displays mineralogically heterogeneous ejecta deposits with feldspathic material (high albedo, no mafic bands) dominating the northern half and basaltic lithology (high Ca-Pyroxene rich) dominating the southern part (Fig. 1c). Olivine-bearing rocks, initially detected in the central peaks [*Pieters*, 1982] were later on also suggested in other locations of the crater [*e.g. Lucey et al.*, 1992; *Pinet et al.*, 1993; *LeMouéléc and Langevin*, 2001]. A deep-seated origin (lower crust or even upper mantle) was proposed based on the extensive occurrence of olivine in the central peaks and excavation as a result of multiple impact events (Procellarum, Insularum and Copernicus) [*e.g. Pieters and Wilhems*, 1985]. With the most recent availability of crustal thickness datasets [*e.g. Wiezoreck et al.*, 2013], the crust at Copernicus does not appear to be unusually thin and therefore a mantle origin could perhaps be ruled out. Our study of the region [*Dhingra et al.*, 2014] has suggested that olivine at Copernicus has multiple

origins and therefore could have diverse source regions. In the present study, we further discuss the various possible sources of olivine lithology (see section 4.3).

Earlier work on impact melt deposits at Copernicus using telescopic data suggested presence of a quenched glass absorption band on the NW wall and the crater floor [Smrekar and Pieters, 1985] which was explored further using Clementine multispectral data [Pieters *et al.*, 1994]. The Clementine color composite (Fig. 1c) mapped the NW quadrant of Copernicus (extending beyond the rim) as a distinct spectral unit. The spectral ratio (750/415 nm) was intended to map both quenched glass-rich regions as well as mature material. Since all the ejecta produced during the Copernicus event is expected to form over the same time period, the observed spectral variability would likely not be due to differential maturity. It was therefore interpreted to be a signature of quenched impact melt glass.

More recently, with the availability of high spatial and spectral resolution datasets from lunar remote sensing missions, several studies have re-looked at Copernicus [e.g. Araki *et al.*, 2011; Buggiolachi *et al.*, 2011] documenting its mineralogical diversity. Among the new set of information, our work [Dhingra *et al.*, 2013] has documented the large scale mineralogical heterogeneity of impact melt at Copernicus crater and interpreted it to be an evidence of inefficiency in melt mixing during the cratering process. It is consistent with some of the recent terrestrial observations [e.g. Osinski *et al.*, 2008; Lambert, 2010] but marks a departure from the common notion of homogenization of impact melt composition during the cratering process [e.g. Phinney and Simonds, 1977].

1.2 Scope of current research and specific objectives

Copernicus crater, with its laterally heterogeneous target rocks, provides an opportunity to track the fate of different lithologies after they were melted in the cratering event, thereby providing useful insights into the melt emplacement and its evolution, including melt mixing (lateral & vertical). The young age of this crater also enhances the possibility of identifying various morphological species of impact melt and their corresponding mineralogical signatures. The specific objectives of this research are:

- i) to systematically document the mineralogical character of impact melt at Copernicus crater, along with the corresponding geologic context. It would include observations of impact melt deposits located in different parts of the crater and having diverse morphologies and spatial dimensions.
- ii) to interpret this information in terms of impact melt evolution and emplacement during the cratering process.
- iii) to explore any correlations between impact melt mineralogy and target properties.
- iv) to understand the role of impact melt mineralogy in the observed compositional diversity of the lunar crust.

Synergistic use of spectral data with morphological information provides a powerful method for exploring the character of impact melt deposits and is critical for better interpretation of the observed compositional diversity of the lunar crust. We have used this integrated approach to initially capture regional trends and then local trends were studied. This unique ensemble of information was also used to identify exploration

targets, for future human and/or robotic missions at Copernicus that could address specific science questions.

2. Datasets & Methods

In this study, we have integrated information from morphology, mineralogy and topography sourced from various active and recent missions. These include monochrome optical datasets at couple of meters to sub-meter spatial resolution, topography data and mineralogy data based on the visible to near-infrared wavelengths. Table 1 documents the various datasets used, their mission affiliation and technical details.

2.1 Geological Mapping of Melt Deposits

Impact melt deposits at Copernicus crater have been mapped based on their morphological character on a scale of 1:25000. The geographical extent of the mapping effort primarily covers the crater floor and wall. The primary data used to map the melt deposits is Kaguya Terrain Camera (TC) at a spatial resolution of ~ 10 m [*e.g. Haruyama et al.*, 2008]. The data was downloaded as image tiles from the SELENE data archive (<http://l2db.selene.darts.isas.jaxa.jp/>) and subsequently imported into ArcGIS for generating the base image and then used for impact melt mapping. One of the important factors affecting the mapping of morphological features is the illumination geometry. It could affect the fine-scale delineation of the geographical extent of a feature as well as detection of subtle morphological structures. Efforts were made to map the entire Copernicus region using datasets obtained under similar illumination conditions. In view of this very important constraint, for albedo and morphological anomalies, the region of

interest was investigated under more than one illumination condition in order to make reliable interpretation. Occasionally, we have also utilized Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) datasets [e.g. *Chin et al.*, 2007; *Robinson et al.*, 2010] to resolve any ambiguities or to understand the finer details of any interesting morphology.

2.1.1. Impact Melt Units

The various morphological forms of impact melt identified at Copernicus are shown in Figure 2 and explained below. In this regard, the term ‘megaclasts’ has been used in the description of some of the classes. Megaclasts refer to meter to kilometer-sized boulders which occur along with the impact melt deposits on the crater floor. Megaclasts occur in a variety of settings and scales such as isolated mounds and clusters. They should not be confused with the term ‘clast’ in terms of scale (mm-cm versus kilometers here). However, these rock bodies are associated with the surrounding impact melt in a similar way as small-scale clasts are associated with melt and hence this term.

- i) *Hummocky Unit*: It is defined as a high relief unit comprising of abundant megaclasts along with relatively smaller proportion of smooth material. The hummocky unit primarily occurs on the crater floor and usually exists as a pervasive unit but sometimes is also observed to be interrupted by other units.
- ii) *Smooth Unit*: The smooth unit is usually devoid of any megaclasts and is the smoothest species among the impact melt deposits with minimal relief if any. It is quite extensive and occurs on the crater floor.

- iii) Intermediate Unit: The intermediate unit comprises of topographically subdued megaclast population. The megaclasts can be identified but the boundaries of individual clasts are indistinct and they occur more as continuous unit with low but observable relief.
- iv) Isolated Mounds: These are large megaclasts which are usually either not at all surrounded by other megaclasts or they stand out as distinct unit among the surrounding low relief megaclasts.
- v) Mega-Blocks: These are very large blocks occurring on the crater floor attaining the size and elevation similar to the central peaks and therefore have been mapped separately than other megaclasts. These are very sparse but significantly different in their extent and morphology as compared to the isolated mounds.
- vi) Collapse Pits: These are rim-less depressions of various sizes and shapes mostly, circular to semi-circular in shape. While some of them appear geologically fresh and have sharp boundaries with outcrops, others are more subdued.
- vii) Smooth Ponds: These deposits are defined as smooth material that is confined by high standing topography on almost all sides. The smooth ponds commonly occur in topographic lows on the walls as well as the rim region.
- viii) Unconfined Perched Deposits: This unit is defined as smooth in its nature but is most often not surrounded by high standing topography on all sides; rather it occurs at various locations as a perched deposit. This unit occurs most extensively on the slopes of the crater walls.

- ix) Interrupted Smooth Deposits: These are overall smooth deposits but are interrupted locally by surface material that pokes through the smooth material. This material occurs mostly on the walls as well as the rim region.
- x) Flows: These are linear to sinuous features extending from crater wall to the floor and show either a central depression with raised walls or lobate deposits draped on the underlying topography. This unit is usually quite restricted but sometimes large deposits are observed from the wall all the way to the floor. Other times, the unit manifests itself as small linear depressions terminating into smooth ponds on the crater walls.
- xi) Curvilinear Striations: These are commonly associated with the flows and occur as irregular, small, sinuous striations on the terminal part of the flow units.
- xii) Cracked Material: This unit is characterized by extensive semi-circular cracks occurring in a relatively limited part of the crater, commonly at the interface between the walls and the crater floor.
- xiii) Cracks: These are isolated markings of limited lateral extent on various morphological units including smooth ponds and interrupted smooth unit.

2.1.2. Mapping Rules

There are certain set of rules which were defined while mapping the above mentioned units to ensure a systematic and effective approach. In an effort to avoid over-interpretation of the datasets, ambiguous impact melt regions were not mapped. At the same time, we note that the surface is anyways about a billion year old and has been

modified through large and small impacts (although less frequently) as well as micro-meteoritic bombardment and solar wind. The mapping effort has therefore been a mix of objective criteria and subjective intuition that builds over time. Following are the general rules followed while mapping:

- i) The unit boundaries are primarily defined based on differences in physical characteristics such as albedo, texture and structure.
- ii) The morphological units should have sufficient spatial coherence in order to be mapped as a unit. Chaotic units which display a mixed character on small spatial scales are classified as ‘undivided’.
- iii) The geomorphological units are broadly classified into floor and wall sub-units for simplicity and to accommodate variability that is specific to these broad units. This convention is followed even when certain units in these classes share similar morphological character. Accordingly, central peaks are mapped as a different unit although they are located on the crater floor.
- iv) In case where one unit transitions into the other (e.g. unconfined perched deposits transitioning sometime into flow deposits), the unit with the larger extent is used for assigning unit classification.

2.2 Spectral Mapping and Analysis

Individual Chandrayaan-1 Moon Mineralogy Mapper (M³) [e.g. *Pieters et al.*, 2009; *Goswami and Annadurai*, 2009] data cubes for the Copernicus region were downloaded from Planetary Data System (PDS) and mosaicked in ENVI software to obtain seamless coverage of the study area. Mosaics for optical period Op1b and Op2a

have been used in this study. The mineralogical analysis of impact melt occurring at Copernicus has been carried out in numerous ways:

i) *Spectral parameter mapping*: This effort involved using some standard parameters like strength of absorption bands and albedo to map the general mineralogical variability and also to identify locations of interest for further detailed analysis. We used the algorithms developed jointly by the M³ team for data analysis. The parameter maps were commonly used in the form of color composites by combining selected parameters (described in Table 2). The broad variations were mapped as specific units for understanding the general setting. The purpose however, was not to suggest that every pixel in the unit has the same mineralogy. Representative spectra were extracted from various regions to understand the mineralogy in detail.

The absorption band strength parameters were calculated in two ways. The specific formulation is presented in Table 2 and the procedure is described here. In the first case, an integrated band depth (IBD) was calculated by first removing the continuum slope from the spectrum and then adding up the estimated band strength values (with respect to the continuum of 1) at all wavelengths that were covered by the absorption band. The absorption band strength around 1000 and 2000 nanometers were estimated in this way and the corresponding parameters are mentioned as IBD1000 and IBD2000.

The second way of estimating the band strength was to partially cover the absorption bands and guided by the short wavelength (900-950 nm and 1950-2000 nm) absorption for the low Ca-pyroxenes and long wavelength (950-1000 nm and 2000-2500 nm) absorption for the high Ca-pyroxenes. The second procedure for band strength estimation was aimed at separating out the contributions from these two different types of

pyroxenes. In this study, we have used this parameterization only for the long wavelength absorption bands (around 2000 nm) since the differences are more apparent there.

ii) *Radial soil sampling*: The soil sampling was carried out for impact melt units occurring on the floor, wall and the rim; wherever impact melt units can be identified with confidence. We understand that certain smooth areas could simply be fluidized ejecta. Accordingly, we have carried out soil sampling near pervasive melt deposits and assumed that all smooth areas are either only impact melt or it is the major component. The spectra were extracted by drawing regions of interest in areas devoid of any craters (observable at Kaguya TC resolution of 10 m) which could contaminate the sample with fresh (immature) material.

iii) *Localized sampling at interesting locations*: Several interesting locations identified either based on their morphology or due to strong spectral signature, as observed in spectral parameter mapping, have been sampled to extract mineralogy information. The geological context (local and regional) for such locations at the highest possible resolution has also been studied while understanding the relevance of the mineralogical signatures.

Systematic high resolution study of the entire crater floor was carried out to gather mineralogical insights from the extensive impact melt deposits. In this context, the study area was divided using a grid (Figure 3). Subsequently, each grid unit was analyzed mineralogically followed by a morphological study to ascertain the nature of the feature and the corresponding geologic context.

2.2.1 Spectral Mapping Rules

Spectral mapping rules were defined for a systematic and reliable analysis. In view of M³ data related issues such as residual thermal component, small variations in repeat coverage and spectral instability in the short wavelength region (typically 540 -750 nm), the analysis strategy was made as rigorous as possible. At the same time, the rules were also made flexible enough to accommodate the diversity of situations that come up during such detailed analyses. The general guidelines followed are described below:

- i) The sampled spectra should be reproducible in at least one other optical period (repeat coverage data) unless repeat coverage is not available. Otherwise, it is generally not sampled.
- ii) The spectra should be identifiable across at least few pixels to be regarded as representative. There is flexibility to allow how many pixels depending whether terrain is comprised of boulders or is a continuous outcrop.
- iii) As an exception, single pixel spectrum is admissible if the spectrum is too strong to be an artifact and can be identified in another optical period (repeat coverage data).
- iv) In some cases, single pixel spectrum is selected despite the fact that it is noisy, just because geologic context clearly supports an identifiable feature such as crater, collapse pit or mound.

3. Results

3.1 Regional Analysis

3.1.1 North-South Differences

Copernicus crater displays a prominent north-south variation in its surface properties and the same has been known based on earlier studies [e.g. *Pieters et al.*, 1994]. The variability can be observed in the albedo (Figure 4a) with the northern part appearing relatively brighter than the southern part of the crater. The differences appear much more pronounced when observed in a color composite highlighting mineralogical differences (Figure 4b). The mineralogical insights reveal that the northern part of Copernicus (actually including the whole crater floor) is dominantly composed of feldspathic material based on higher albedo and lack of strong mafic absorption bands. M³ data supports this general interpretation on crater scale. However, by virtue of its much higher spectral resolution (10-20 nm) and extended wavelength coverage (540 nm – 3000 nm), several new observations have been made including the distinct observation of a large, mineralogically distinct, sinuous melt feature on the crater floor (Figure 4c; green wavy feature of the floor) [*Dhingra et al.*, 2013]. An interesting aspect of this observation is that although, mineralogically the sinuous feature is very distinct, it does not have any morphologically detectable signatures. Spectral information could therefore be very useful in the study of such impact melt deposits. It may also be noted here that the dominantly feldspathic material in the northern part of the crater occurs as a coherent unit. In contrast, the dominantly mafic material in the southern part of the crater is more scattered, interrupted by either feldspathic units or mixtures of feldspathic and mafic material. It might be linked to the physical state of target lithology prior to the impact.

The mapped distribution of impact melt deposits in the same region provides a very different perspective (Figure 5). The nature of impact melt units on the crater walls and floor do not have a unifying character in contrast to their shared feldspathic nature. We also do not see the NW part of the crater floor and wall sharing similar melt characteristics. While this lack of correlation between the spectral and morphological units may not be surprising given that the two observations are based on very different surface properties, it is nevertheless important to take note of such differences in spatial patterns while making interpretations. This is especially important since we have reported an observable correlation between morphologic and spectral units at crater Giordano Bruno (*Chapter 1, Figure 15*) where melt-rich (megaclast-poor) units displayed relatively stronger absorption bands and appeared green in the M³ standard color composite while melt-poor (megaclast-rich) units displayed relatively weak absorption bands and appeared in magenta-blue tones.

The morphological map (Figure 5) however, highlights a different kind of asymmetry, namely in the melt distribution on the crater floor. The NW floor region is dominated by smooth melt unit (smooth texture, fewer megaclasts) while the remaining floor is largely represented by hummocky and intermediate units (abundant megaclasts). The smooth character of NW floor has been known from earlier studies and suggested to indicate thicker melt sheet. Our detailed mapping effort carried out here captures the diversity of impact melt deposits, their distribution and association with other geologic units. Several small melt flow features have been mapped which may not have been discernable with the low resolution datasets earlier. Our mapping shows that the smooth unit, although most pervasive in the NW crater floor, also occurs on the fringes of the

eastern and southern parts of the floor (mainly restricted to the floor-wall interface region) which is consistent with previous mapping efforts [Howard, 1975]. In addition, we also note that almost all the collapse pits mapped on the crater floor are associated with the smooth unit.

3.1.2 Radial Asymmetry in Soil Mineralogy of Impact Melt

One of the well-known peculiarities of the NW quadrant of Copernicus is its distinctly red tone in a color ratio composite based on Clementine 5 band spectral data (Figure 1c) where red represents the ratio of reflectance at 750 nm and 415 nm. The red coloration of the NW region was suggested to be due to the presence of quenched impact melt glass [e.g. Pieters *et al.*, 1994] which is also consistent with earlier observations [Smrekar and Pieters, 1985]. In the present study, we use Moon Mineralogy Mapper's 85 spectral bands in order to tie the spectral observations to specific geological entity. Melt deposits on the floor, wall and rim were identified for spectral sampling and their soil composition was analyzed to shed more light on the nature of material in the NW quadrant in contrast to the melt deposits in other parts of the crater.

It is interesting to note that irrespective of the melt deposit location on the crater floor, wall or rim, the soil composition of melt in the NW quadrant is remarkably devoid of any detectable mafic absorption bands within instrumental noise (Figure 6). There does appear to be a very broad dip around 1000 nm which could be due to the presence of quenched glass but it is ambiguous based on the available data. In contrast to the NW quadrant, the melt deposits in the NE and SW parts of the crater show a mixed character with certain melt deposits showing detectable mafic absorption bands while other

deposits showing either very weak or no absorption bands at all (Figure 6). However, the SE part of the crater is distinctive with almost all the melt deposits displaying identifiable mafic absorptions at 1000 nm and 2000 nm (Figure 6). The band positions are suggestive of high Ca-pyroxene as the dominant species. The analysis thus shows that not only NW quadrant has a very distinctive spectral signature; the SE part of the crater too is very different and distinguishable from rest of the crater.

An important point to note is that the reported differences are evident in soil composition over a large area. Since soils are known to be a time averaged sample, they are quite representative and the observed differences essentially capture the regional differences in impact melt mineralogy. As suggested earlier on, by the occurrence of the mineralogically distinct, sinuous melt feature [*Dhingra et al.*, 2013], the observed radial differences in soil mineralogy form another robust piece of evidence supporting heterogeneity in the impact melt deposits at Copernicus. This observation has obvious implications for the emplacement and evolution of the melt and is dealt in Section 4.

3.1.3 Distribution of Melt Ponds and Flow Features

The occurrence of smooth ponds (in localized depressions) and flow features are the strongest evidences for identification of melt deposits. The mapping of these features highlights some of the main melt-bearing bodies, their distribution and any peculiarities in terms of morphology and mineralogy. While the melt ponds are largely observed to be uniformly distributed across the crater wall, the flow units are principally observed on the northern wall (Figure 7) and the southern rim (Figure 8).

The north-central wall segment has at least 3 morphologically identifiable flow units. Flow unit 1 has a tongue-like morphology that appears to be draped over the wall material and then spreads out on the floor. The textural fabric of the flow feature appears rough which may indicate a viscous melt (probably laden with clasts). Flow unit 2 is perhaps the most well-known feature documented in previous studies [e.g. *Howard and Wilshire*, 1975]. This flow unit has a fork like, bifurcating morphology possibly suggesting very fluid-like melt material (in contrast to the probably viscous flow unit 1) that may have been partially aided by steeper slopes. Flow unit 3 occurs as a broad protruding lobe onto the crater floor, probably aided by the massive melt accumulation at the bottom terrace of the crater wall. This flow unit occurs as a natural extension of the accumulated melt. The morphology of the unit either is guided by the very gentle slope of the terrain or might also be affected by heavy load of clasts. An additional set of sinuous features could be observed on this flow unit (observable in the geological map in Fig. 7b, red striations) and could be the second generation flow features formed towards the end of the emplacement process. It is interesting to note such diversity in the morphology of melt flows located in close proximity and emphasizes the highly chaotic nature of cratering process. Mineralogically, none of the three flows have any distinctive features as is illustrated in the color composite in Figure 7c where it is hard to identify the individual flows.

Perhaps the least discussed flow unit (to the best of our knowledge) is the massive, 27 km long melt flow (Figure 8) located on the southern rim of Copernicus. The melt unit carved out a huge channel which is narrow near the crater's southern rim and broadens out towards its distal end where it displays digitate protrusions (Figure 9a, b).

The melt channel near the rim region shows a step-like topography dropping by about 400 meters before merging into the larger segment of the flow downstream (Figure 9c, d). It is however not clear as to how much of the observed topography is a result of crater adjustment during the modification stage. Accordingly, it is difficult to decipher the relative sequence of formation of the flow feature with respect to the step-like topography. The melt flow also seems to have cut through the ejecta blanket which is striking keeping in view the extremely short time span of the cratering event. The massive melt feature is largely coherent with no major branching out of the melt channels. Mineralogically, the melt flow displays distinctly mafic character with prominent absorption bands at 1000 nm and 2000 nm (Figure 10). The band positions indicate dominance of high Ca-pyroxene. The character of the nearby material (strength and position of the absorption bands) is similar to the flow unit suggesting probably similar source. There are other smaller flow features in the area along with, what appears to be melt-laden debris. Since it is difficult to unambiguously distinguish the latter as melt flows or fluidized ejecta, they have not been mapped as melt flows.

3.1.4. High Resolution Studies of the Crater Floor

The extensive melt deposits on the crater floor were probed at the highest available resolution (probing at pixel level) to characterize the fine scale mineralogy of the melt units and gather any new insights. In order to systematically analyze the various locations, a grid approach was followed (see Figure 3 and associated description). Several interesting trends have emerged from this analysis (Figure 11) emphasizing some kind of *order among the chaos* that is generally expected on the melt-rich crater floor:

i) *Potential olivine-bearing exposures on NW crater floor* – The systematic survey identified numerous exposures in the NW region which display a broad 1000 nm absorption band centered around 1050 nm and no detectable absorption bands at 2000 nm. The spectral signatures of these exposures (red and blue colored spectra in Figure 12a) are comparable to the olivine-bearing central peaks while some are similar to northern wall olivine exposure. These observations are divided into two broad classes: a) exposures displaying very strong and noise-free signatures are colored in red and likely olivine-bearing, b) exposures displaying weak or noisy signatures are colored in blue. They could be olivine-bearing or quenched glass since the latter also has a broad absorption band around 1000 nm (along with a weaker 2000 nm absorption which is not observed here). These observations have been documented in *Dhingra et al.*, [2014] in great detail along with discussion on the implications for the origin of olivine lithology at Copernicus and elsewhere. However, we have provided a brief description here for the sake of completeness and to discuss some additional details.

An interesting aspect of the occurrence of these exposures (both red and blue) is their clustering largely in the NW region and only sporadic occurrences elsewhere. It is important because unlike the NW region where there are very limited megaclasts which would contribute fresh surfaces to be mineralogically detectable, the remaining crater floor (notably NE and SW region) has abundant megaclasts and therefore potentially much more fresh surfaces available. Still, a very miniscule number of olivine-like exposures could be documented from the rest of the crater (which is also generally true for other lithologies, described below). The detection and distribution of these potentially

olivine-bearing exposures have also contributed towards determining several geologic settings in which olivine source regions could occur (see section 4.3).

ii) *Pyroxene dominance in the southern crater floor*: The pyroxene-bearing exposures (both low Ca-pyroxene and high Ca-pyroxene) also appear to be largely clustered in their spatial distribution on the melt-rich floor (Figure 11). Our earlier report [Dhingra *et al.*, 2013] on the existence of mineralogically distinct low Ca-pyroxene sinuous impact melt feature is well captured in this survey (Figure 11, Brown circles) by the clustering of low Ca-pyroxene exposures in the north-central part of the crater.

There is a small but notable high Ca-pyroxene cluster occurring in the SW crater floor, close to the westernmost central peak. Spectra from this cluster is shown in Figure 12c. Apart from these distinct detections, there are several exposures where the identification of pyroxene nature can be confidently made based on the existence of absorption bands around 1000 nm and 2000 nm but the bands are weak (especially 2000 nm band) making it difficult to unambiguously determine their specific pyroxene affiliation (low Ca-pyroxene or high Ca-pyroxene). Therefore, these exposures are classified simply as pyroxene-bearing. They are clustered mostly around the S-SE margin of the crater floor. Spectra showing these characteristics are shown in Figure 12d.

iii) *Crystalline plagioclase exposures*: There are two crystalline plagioclase exposures detected in the crater floor survey, located in the eastern and south-western part of the crater floor (Purple squares in Figure 11, spectra shown in Figure 12b). These are additional new detections, to the best of our knowledge, apart from what has been already reported [*e.g. Donaldson Hanna et al.*, 2014].

3.2 Local Analysis

Several small-scale observations have been made around the crater based either on a strong spectral signature, a peculiar morphology or both. Together they represent wealth of new information. Some of it documents the diversity in the mineralogy and morphology while others have direct broad scale implications for the target geology.

3.2.1 Discrete/Isolated Olivine Exposures

In addition to the olivine-bearing central peaks, earlier studies also suggested potential exposures along the northern wall [*e.g. Lucey et al.*, 1991; *Pinet et al.*, 1993]. In particular, there is an elongated low-albedo deposit extending from a prominent terrace down the crater wall. It has a very strong olivine spectral signature and had been assumed to be a primary wall exposure and interpreted to be indicating relatively shallow source region for olivine at Copernicus [*e.g. Lucey et al.*, 1991]. We have reported [*Dhingra et al.*, 2014] that this specific olivine-bearing deposit has an impact melt affiliation based on its significantly low albedo as compared to the olivine-bearing central peaks and distinct morphological characteristics indicating a thin-mantling nature rather than a fresh wall outcrop (Figure 13c). Accordingly, the northern wall olivine exposure cannot be directly compared with central peak olivine lithology in terms of source depth.

There are two additional isolated exposures of potentially olivine-bearing mineralogy. One of them occurs within a fresh crater in an impact melt pond. It is located on the SE crater wall and has a relatively strong absorption band around 1050 nm (Figure 13f). The geologic context in terms of melt association is clear in this exposure (Figure 13d). The second exposure occurs on the NW wall and has a distinct broad absorption around 1050 nm along with a moderate albedo (Figure 13f). The geologic extent of this

exposure is quite small and therefore the relevant context is unclear. With the available information, it seems to be associated with an impact melt veneer (Figure 13e). These isolated occurrences of olivine along with the potential olivine exposures on the crater floor illustrate a much more widespread distribution of this lithology than previously thought.

3.2.2. Nature of Mg-Spinel Exposure

Mg-spinel lithology, the newly identified rock type on the Moon [Pieters *et al.*, 2011] has initiated an active area of research with numerous new occurrences reported in recent times [e.g. Dhingra *et al.*, 2011; Lal *et al.*, 2011; Bhattacharya *et al.*, 2012; Dhingra *et al.*, 2013]. In addition to our initial report about Mg-spinel occurrence at Copernicus [Dhingra *et al.*, 2013], we have found a mafic lithology located very close to the Mg-spinel site, on the opposite face of the same mound that hosts the Mg-spinel exposure (pink color in Figure 14b and e). The spectral signature of this mafic lithology is defined by a very broad absorption band centered slightly beyond 1000 nm (pink spectrum, Figure 14d). There is no detectable 2000 nm absorption band. This is in contrast to the strong absorption band shortward of 2000 nm observed in the Mg-spinel lithology (green spectrum, Figure 14c, d). Although the mafic feature is too weak for an unambiguous identification of the specific mineralogy, it is distinct enough to be identified as mafic in character. In view of lack of sufficient information, the spectrum is classified as Olivine/Quenched Glass. Irrespective, this is perhaps the first distinct detection of Mg-spinel in close association of another mafic lithology.

In context of the origin of Mg-spinel lithology, the large number of detections has highlighted different flavors of this lithology on the lunar surface [Pieters *et al.*, 2014].

One of the new possibilities is the formation of Mg-spinel by melt reaction of rocks rich in plagioclase feldspar and olivine [e.g. *Prissel et al.*, 2014]. It has been further suggested that a high Mg# rock could drive such a reaction after interacting with plagioclase at relatively shallow depths. In the present case, it is possible that the mound-like feature hosting Mg-spinel might be a part of central peak in which case, it might be rich in olivine and plagioclase (troctolite). Subsequently, local melting and interaction with surrounding impact melt could have led to the formation of Mg-spinel. In this regard, we explored the morphology of the mound to ascertain any specific association of impact melt and the Mg-spinel lithology. The limited spatial extent of the Mg-spinel and morphologically subdued nature of the mound did not allow any straight forward conclusions to be drawn.

3.2.3 Small Scale Features

Numerous small scale features are distributed across the crater highlighting different aspects of the impact melt activity and subsequent modifications. Among them, small flows (1km or less) are reminiscent of the melt movement and deposition that must have continued for some time after the formation of the crater. These features are in addition to the fewer but highly chaotic large flow features described earlier in Section 3.1.3. The small-scale flow features comprise of neatly carved channels with well-defined levees and sometimes observed to have emptied into the nearby melt ponds (Figure 15). In other cases, they appear to have fed melt flows (lobes) that eventually reached the crater floor (Figure 16).

Another common feature observed at impact melt deposits, especially in ponded melt, is the occurrence of cooling cracks. Geologically very young craters such as Giordano Bruno, Tycho, Jackson and Glushko (*as discussed in Chapter 1*) provide ample evidence for the presence of cooling cracks. At Copernicus, cooling cracks do occur in various ponded deposits but are rather subdued and difficult to map (e.g. in Figure 17). However, large scale fractures are still identifiable on the melt-rich crater floor and span across the surface melt units (Figure 18). While some of them could be cooling cracks, other are likely collapse features due to subsurface drainage of impact melt.

Another observation unrelated to impact melt deposits but still worth documenting is the occurrence of a crater that likely impacted onto the vertical crater wall and appears to be hanging like a vertical crater! The 450 m diameter crater is located in the middle section of NE crater wall (Figure 19). It is interesting to note that the ejecta pattern seems to be held in place, partly on the vertical wall face and remaining on the adjacent horizontal wall terrace with clearly identifiable bright albedo material. Unfortunately, it is too small to be readily detected in M³ data and so there is no mineralogy information available for this feature at the moment.

4. Discussion

The integrated mineralogical and morphological analyses of impact melt deposits at Copernicus using high spectral and spatial resolution datasets have provided new insights on diversity of issues. Here is a discussion of new perspectives gained on some of the aspects.

4.1 Compositional heterogeneity of impact melt

The extensive analyses carried out in this study have demonstrated the heterogeneity in the mineralogy of impact melt deposits at various spatial scales thereby highlighting their contribution to the commonly observed mineralogical diversity of the crust. The regional soil survey (Figure 6) clearly elucidates the radial variation in the mineralogy of impact melt with soils in the NW being most deficient in the mafic mineralogy while the soils in SE display strongest mafic absorptions. At the same time, local analysis of the crater floor has provided a different perspective. Our earlier study [Dhingra *et al.*, 2013] highlighted the presence of low Ca-pyroxene rich sinuous melt feature, part of which occurs in the NW quadrant. In contrast, two fresh craters (~1 Km diameter) in the NW quadrant are notably rich in high Ca-pyroxene component. These contrasting observations (regional radial variation and local floor variation) would perhaps require more than one process. However, the processes might also be taking place at different spatial scales such that they can mutually contribute to the observed trends without contradicting each other.

The observed variation in impact melt mineralogy of soils is likely the result of a regional process since the differences occur on the crater scale and also because soils represent a large average accumulated over billion year time scale. Accordingly, the observed radial variation in the mineralogy of impact melt deposits suggest that melt composition was non-uniform and that the extent of lateral mixing was not significant enough to homogenize the large volume of melt produced during the cratering event. The observed heterogeneity in the impact melt could be interpreted in two ways:

- i) It represents a general case emphasizing the fact that in a large cratering event, there is minimal lateral mixing of the melt and any differences in the original target composition are retained for the most part. Therefore, compositional heterogeneity in the impact melt should be expected at other craters where the target is composed of more than one type of lithology.
- ii) The observed heterogeneity of impact melt at Copernicus is a special case where the component target lithology was so diverse that the available impact energy was insufficient to homogenize the melt sheet completely. In such a case, compositional heterogeneity in the impact melt would solely depend on the degree of contrast between the compositional units and may or may not be commonly observed.

Earlier work on impact cratering has clearly favored the homogeneity of impact melt [e.g. *Phinney and Simonds*, 1977]. A recent report [*Spudis et al.*, 2013] based on the analysis of Orientale and Nectaris impact melt sheets also supports this case. However, some of the terrestrial literature including impact melt deposits at Rochechart crater [e.g. *Lambert et al.*, 2011] and other occurrences [e.g. *Osinski et al.*, 2008] have reported occurrence of heterogeneous impact melt. Crater Jackson on the lunar far side also displays heterogeneity in the mineralogy of impact melt [e.g. *Ohtake et al.*, 2009; *Hirata et al.*, 2010; *Dhingra et al.*, 2012] although it is not as distinct as observed in the case of Copernicus. Since the volume of impact melt produced in a cratering event increases non-proportionally with respect to the crater diameter [e.g. *Grieve and Cintala*, 1992], the homogenous vs heterogeneous nature of the melt may be affected by the melt volume. At

this stage, it does not seem obvious to favor one possibility more than the other. But, certainly it is worth taking note that there is clear evidence of compositional heterogeneity in impact melt on Earth as well as on the Moon which contributes to the mineralogical diversity. Our studies at 12 other complex craters, as part of our survey to characterize lunar impact melt deposits, also indicates that mineralogical heterogeneity in melt is pervasive but not universal [*as reported in Chapter I*]. There are also craters with homogeneous melt mineralogy despite evidence for likely heterogeneous targets (e.g. Eratosthenes).

4.2 Re-constructing the Pre-Impact Target Geology

This study has revealed that in spite of the seemingly chaotic nature of the cratering process and more specifically, the impact melt emplacement, mineralogy of impact melt seems to preserve the character of pre-existing local geology. Accordingly, careful mineralogical study of impact melt deposits in different parts of the crater could be used in conjunction with mineralogy of the ejecta deposits to reconstruct the pre-impact target geology. It should be noted that the emphasis here is on the broad aspects of geological setting (on crater scale). We acknowledge that minor components could be lost in the process and therefore cannot be deciphered through this approach.

Here, we have integrated our observations (carried out on regional and local scale) to guide our intuition in an attempt to reconstruct the stratigraphy at the Copernicus impact site. Our principle observations are as under:

- i) The entire NW quadrant was dominantly feldspathic and perhaps either devoid of any basaltic cover or the basalts formed an insignificant part. The

NW quadrant had some unknown amounts of mafic material, namely low Ca-pyroxene and possibly some amount of olivine. The low Ca-pyroxene component could either be occurring as breccia deposits from previous impact events such as Imbrium, Serenitatis and possibly Insularum. It is also possible that there were limited noritic exposures. Olivine could simply be occurring at depth as a coherent unit, part of the brecciated material from earlier impact events or could also be sourced from olivine-rich pyroclastic deposits.

- ii) The NE quadrant was also likely comprised of feldspathic and noritic material but for the same amount of excavation depth, the proportion of these lithologies seem to be different with lesser extent of feldspathic terrain and increased extent of low-calcium pyroxene-rich material. Minor olivine could also be part of the terrain. In addition, M³ standard color composite displays discrete ray-like emplacement of feldspathic and mafic material which suggests a non-coherent feldspathic target that got sparsely emplaced during excavation process.
- iii) The SE quadrant seems to be dominated by basaltic components and some feldspathic/noritic component (again in the form of discrete ray-like material). Minor olivine could be present. It may be noted that this mineralogy is displayed for the same excavation depth as the northern part of the crater so the target had a different mineralogy in the southern part, namely in terms of thicker basalts, low abundance of feldspathic material and relatively higher proportions of low-calcium pyroxene bearing material.. The SW quadrant seems to be covering two spatially coherent terrains. The W-SW part is

dominantly feldspathic while S-SW region is more mafic, dominated by basaltic material. Some minor olivine could be present.

- iv) As has been hypothesized by previous workers [e.g. Pieters and Wilhelms, 1985], there seems to be a coherent, dominantly olivine-bearing unit at some depth (likely lower crust) which has been excavated and exposed in the central peaks. However, in view of the identification of several potential olivine exposures in our study (crater floor, NW wall, SE wall) along with the olivine exposure in the northern wall, it is possible that multiple olivine-bearing horizons occur at Copernicus crater [*Dhingra et al., 2014*]. It is discussed in further detail in the next section.

We have incorporated the above information into a geological cross-section at Copernicus impact site. In this context, we have taken 2 transects (A-B, C-D) to highlight the lateral variability observed in two different directions (Figure 20). We propose that the thickness of the feldspathic target material is radially variable such that north and north-west sectors have a thicker pile while the NE sector has a thinner layer of these materials and/or may be less coherent. This is well illustrated in the ejecta properties with background feldspathic ejecta material overlain by mafic materials in ray-like pattern that is observable in mineralogical color composite (Figure 4b) but not distinct in albedo images. Irrespective, a distinct variation in mineralogy is indicated in the NE as compared to NW sector.

The southern sector shows distinct affiliation with high calcium-pyroxene and has been noted in the ejecta as well as impact melt deposits including the melt ponds in SE and also at the southern melt flow feature. There are however some evidences of

admixture of feldspathic/noritic material suggesting a thin feldspathic layer was sampled in the southern part of the crater target as well.

It may seem a little difficult to reconcile the radial differences in the thickness of feldspathic and basaltic lithologies at Copernicus impact site. However, considering the proximity of Copernicus to ejecta deposits from Imbrium and Serenitatis basins, such variability can be understood although not confirmed.

4.3 Source Regions of Olivine Lithology at Copernicus

There have been two new developments in the context of olivine lithology at Copernicus [Dhingra *et al.*, 2014]. We have identified several potential olivine-bearing exposures on the crater floor and walls which were not known earlier. These new detections expand the distribution of olivine lithology at Copernicus. Additionally, we have shown that olivine exposures at Copernicus have multiple origins with one of them (the northern wall exposure) being associated with impact melt.

These observations also have implications for the possible source regions of olivine lithology since the identifications have been made in three genetically different crater units, namely, the central peaks, crater walls and the crater floor. Each of these units taps a different depth in the target. The central peaks are believed to represent material uplifted from the deepest horizons during crater rebound [*e.g.* Melosh, 1982]. An important point here is that the peak forming material comprises of a relatively coherent (although heavily shocked) rock that was originally located deeper than the melt/transient cavity [*e.g.* Cintala and Grieve, 1998]. Therefore, the coherent peak forming material is not necessarily the same as the material producing melt in the cratering event. In this

scenario, it is ambiguous whether an olivine lithology associated with the melt (observed on the crater floor and the wall) could have any relation at all with the olivine in the central peak (in terms of source depth). As a consequence, a unique deep-seated source for all of the reported olivine occurrences may not always be the case. In addition, it is also apparent from the recently available geophysical data [Wieczorek *et al.*, 2013] that source of olivine at Copernicus is likely located in the crust and direct mantle excavation is unlikely [Dhingra *et al.*, 2014]. We describe two end-member geological scenarios with respect to occurrence of olivine in the crust which could represent the original geologic setting at Copernicus:

A) Multiple horizons of olivine lithology in the crust (Figure 21a): Olivine may have occurred independently at a variety of depths in the crust (shallow to deep) making it feasible for it to be tapped directly by the transient cavity (relatively shallow depths) during the cratering process. At the same time, deeper olivine horizons (unrelated to the shallow olivine) could form the central peaks during crater rebound and uplift. These olivine-bearing zones could occur either as part of multi-component basin ejecta deposits or as a coherent unit (e.g. differentiated products of magmatic pluton). In this multiple horizons scenario, no genetic relation is required between any of the observed olivine exposures.

B) Single, deep-seated olivine-bearing lithology in the crust (Figure 21b): In this scenario, a unique olivine-bearing horizon may have occurred at depth, not readily accessible to the transient cavity during the Copernicus impact event. The observed olivine occurrences in this case might be genetically related (since there is a single

source). There are, at least two possible geological settings in this case, distinguished by the proximity of the transient cavity and the olivine-bearing horizon:

- i. Distal olivine horizon un-sampled by the transient cavity – In this end-member scenario, the deep-seated olivine-bearing lithology would have formed the central peaks (by crater rebound) but was located deeper as compared to the transient/melt cavity sampling depth and therefore could not have directly contributed olivine fragments to the melt. An indirect sampling of olivine could however still be facilitated, in principle. Fragments of olivine bearing lithology may have been incorporated into the impact melt while the peak material was emerging through a thick column of impact melt during crater rebound.
- ii. Olivine bearing horizon is partially sampled by the transient cavity – A variant of i) could be such that olivine-bearing layer is deep but its uppermost part was still reachable by the transient/melt cavity during the Copernicus impact. As a consequence, a part of the olivine lithology could have been incorporated into the impact melt while the remaining (un-melted, coherent) part formed the central peaks during crater rebound.

These scenarios clearly highlight the non-unique nature of source regions for olivine lithology and provide the motivation for further studies in this regard.

4.4 Copernicus as a Future Exploration Target

Copernicus crater was one of the proposed landing sites during the Apollo missions. Ever since, several significant findings have been made there including the discovery of olivine in the central peaks [Pieters, 1982], later in the crater wall [e.g.

Lucey et al., 1991] and now at numerous other possible locations [*Dhingra et al.*, 2014], occurrence of Mg-Spinel lithology on the crater floor [*Dhingra and Pieters*, 2011], discovery of mineralogically distinct sinuous feature [*Dhingra et al.*, 2013] and heterogeneous impact melt deposits [*Dhingra and Pieters*, 2013]. Such an impressive diversity together with its young age makes Copernicus an extremely interesting target for exploration in the near future.

We therefore feel compelled to utilize the detailed investigations carried out in this study (along with the existing knowledge) to identify potential target locations which would be scientifically productive and efficient from an exploration standpoint. We have shortlisted 3 regions based on their scientific value as well as inter-target proximity. It should be noted that the ideas presented here are mainly based on the scientific importance of various targets. Several other considerations need to be given and therefore these suggestions should at best be considered as a starting point for planning any exploration activities in the future.

i) *Crater Center, in the vicinity of central peaks* - This region has probably the maximum scientific return in view of the rich diversity of targets (Figure 22). It includes several high quality exposures of olivine lithology in the peak which is the deepest exposed material in the region. There is also a likely pseudo-tachylite exposure on the centre-most peak which would be available for sampling and could help in dating the Copernicus event. The unique exposure of Mg-spinel could be sampled along with the low Ca-pyroxene bearing sinuous melt feature. There are several collapse pits in the area which could be explored for human habitation potential, for obtaining a vertical profile of impact melt pile at that location as well as studying possible subsurface drainage

pathways of impact melt. The region also boasts of one of the largest megablocks in the crater, comparable in size to the central peaks. We have suggested it to be likely a morphologically subdued part of the central peak cluster. Accordingly, its analysis could shed light about its provenance. All the exploration targets are situated in close proximity. The floor topography is relatively flat. This location however might provide some challenges for spacecraft landing as it has some high standing topography viz. the central peaks.

ii) *NW Crater floor* – This location captures most of the diversity including an olivine-bearing exposure, low Ca-pyroxene bearing sinuous melt feature, high Ca-pyroxene bearing melt but misses out Mg-spinel lithology and olivine in the central peaks (Figure 23). It however has collapse pits for carrying out the detailed analysis as described above. The region provides easy accessibility to the target locations with relatively flat-lying floor. In fact, this is the smoothest part of the crater floor. The region is devoid of any high standing topography and therefore could be less challenging for spacecraft landing. However, the exploration targets are located relatively far from each other and therefore in comparison to the first region of interest, it would take more time to sample the same diversity of targets.

iii) *NE Crater Floor* – This location would be useful to explore almost the same set of science targets excluding Mg-spinel and central peak olivine. However, it would add an exposure of crystalline plagioclase to the diversity. This region is more undulating but not surrounded by high standing topography (Figure 24). An interesting advantage of this location is that it is closest to one of the largest impact melt flows at Copernicus (located on the northern wall; shown in Figure7; feature#2) and therefore

could support their exploration. We would place this location as the third option which can be used in case the previous two locations do not work out.

With the rapid advances in space exploration, it would perhaps be possible to undertake scientific exploration of all the three sites and many more at Copernicus. It should be emphasized that all the major findings presented here as a motivation for Copernicus exploration have been carried out using remote sensing. Suitable ground truth for all these major findings would greatly help in putting stronger constraints on the interpretation of these remote sensing observations.

We duly acknowledge that selection of landing sites involves critical assessment of numerous engineering and scientific aspects and require a lot of inputs. In this study, we are not suggesting the three regions of interest as landing sites but wish to provide relevant scientific information based on our analysis that could feed into landing site selection studies.

5. Conclusions

This study provides a comprehensive view of impact melt mineralogy at Copernicus crater, adequately supplemented by the geologic context and provides new insights into diversity of aspects:

- i) The detailed spectral sampling demonstrates mineralogical heterogeneity of impact melt at various spatial scales emphasizing the fact that large variation in melt composition could be retained in Copernicus-size impact event due to limited lateral mixing of the material. This varied mineralogy of melt effectively contributes to the observed diversity of the lunar crust.

- ii) Several new insights about the nature of olivine lithology at Copernicus have been provided by the discovery of potential olivine-bearing exposures (on the crater floor and elsewhere) and the impact melt association of olivine-bearing northern wall unit. We have presented several scenarios under which olivine source regions could occur at the Copernicus impact site which would affect the genetic relationships between the observed olivine occurrences. Sampling of these locations by future exploration missions would perhaps be a very productive scientific activity.
- iii) The mapping of melt deposits highlights the occurrence of large melt flows restricted to the northern wall and southern rim of the crater. Detailed characterization of a ~27 km long melt flow on the southern rim revealed that it displays step-like topography near the rim, has digitate protrusions at the distal end and appears to have cut through the ejecta deposits. This large flow feature represents an important component of impact melt emplacement and could be explored in the future to understand the dominant controlling factors and the sequence of events that led to its formation.
- iv) The integrated and detailed analysis of melt mineralogy has been used as an input to reconstruct the pre-impact target geology taking advantage of the fact that local target characteristics have been largely preserved in the impact melt at Copernicus. Apart from crater ejecta mineralogy, impact melt composition has been demonstrated to be an important contributor in understanding the target heterogeneity.

- v) The information from detailed mineralogical and morphological mapping was utilized in identifying potential science targets for future exploration missions that could feed into further detailed analysis of these locations.

Copernicus holds clues to numerous scientific questions about the evolution of the lunar landscape, including some recent findings and is an excellent location to revive our quest to know the Moon (and by analogy other planetary bodies) better.

6. Acknowledgements

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Table 1 Details of various datasets used in this study

No.	Sensor	Mission	Spatial Resolution	Spectral resolution	Wavelength Range
1.	Moon Mineralogy Mapper (M ³)	Chandrayaan-1	140-280 m	10-20 nm	460-3000 nm
2.	Terrain Camera (TC)	Kaguya/SELENE	10 m	N/A	
3.	LRO Narrow Angle Camera (NAC)	Lunar Reconnaissance Orbiter (LRO)	0.5-1 m	N/A	
4.	LRO Wide Angle Camera (WAC)	LRO	~ 100 m		

Table 2 Algorithms for spectral parameters used in this study

Spectral parameter	Algorithm
IBD 1000	$\sum_{n=0}^{26} 1 - \frac{R(789 + 20n)}{Rc(789 + 20n)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm
IBD 2000	$\sum_{n=0}^{21} 1 - \frac{R(1658 + 40n)}{Rc(1658 + 40n)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm
BD 1900	$1 - \frac{R1898}{\left(\frac{R2498 - R1408}{2498 - 1408}\right) * (1898 - 1408) + R1408}$
BD 2300	$1 - \frac{R2298}{\left(\frac{R2578 - R1578}{2578 - 1578}\right) * (2298 - 1578) + R1578}$
M³ Standard Color Composite	Red – IBD 1000; Green – IBD 2000 ; Blue – Albedo at 1489 nm
Complementary Color Composite	Red – IBD 1000 ; Green – BD 1900 ; Blue – BD 2300

Figure Captions

Figure 1 Copernicus crater a) Global context b) Regional perspective c) Clementine data compositional perspective. Color composite highlights that the NW quadrant is distinctly different from remaining crater. R=750/415, G=750/950, B=415/750. d) Morphological perspective provided by a geological map from *Howard*, [1975]. Note the two broad units (magenta in the north, orange elsewhere) mapped on the melt-rich crater floor.

Figure 2 Impact melt morphological units observed and mapped at Copernicus crater. The scale bar is 1 km in each of the units.

Figure 3 Methodology for high resolution mineralogical studies (a) & (b) Crater was divided into grid units for systematic spectral sampling (c) Regional and (d) Local geological context was derived respectively, using high spatial resolution datasets (e.g. Kaguya TC, LROC NAC) (e) Spectral signature of interesting lithology was extracted.

Figure 4 Synoptic view of mineralogical and morphological diversity of Copernicus region. (a) Kaguya TC albedo (b) M³ standard color composite overlain on Kaguya TC data. (c) M³ complementary color composite (see Table 2 for spectral parameters) highlighting the presence of mineralogically distinct sinuous melt feature on the northern crater floor.

Figure 5 Morphological map of various impact melt units at Copernicus.

Figure 6 Sector-wise characterization of the impact melt ponds in and around Copernicus. Mineralogy extracted from soils varies radially indicating local melt heritage and minimal lateral mixing. North-west sector impact melt deposits display weak to non-existent spectral bands perhaps contributing to its identification as a distinct unit in various datasets. NE and SW sectors show some ponds with weak absorptions while others are featureless. Melt ponds occurring in the SE sector consistently show detectable mafic absorption bands. The color composite in the center is derived from M³ data using the similar band ratios as in case of Clementine data namely Red= 750/540 nm, Green= 750/950 nm, Blue= 540/750 nm. It displays the unique character of NW quadrant as was captured initially using Clementine data.

Figure 7 Melt flows on the northern wall of Copernicus Crater (a) Albedo image of the northern wall (b) Geological map of impact melt units (c) M³ standard color composite overlain on the Kaguya Terrain Camera image of the region display dominant mineralogy of the region. The flow features do not seem to have any distinctive spectral signature.

Figure 8 Melt feature on the southern rim of Copernicus Crater (a) Albedo image showing the melt feature (b) Geological map showing the extent of the melt flow (c) M³ color composite overlain on the Kaguya Terrain Camera image of the region display dominant mineralogy of the region. The flow feature seems to share the mafic mineralogy indicated by surrounding terrain.

Figure 9 (a) Kaguya TC image showing the massive scale of the flow feature and digitate morphology at the distal ends. Black arrow indicates a drop in elevation within the feature. Orange arrow indicates the viewing direction for the 3D perspective shown in next image. (b) Close-up 3D view of the flow feature. The step in topography is indicated by the black arrow (c) Image of the flow features closer to the crater rim. A-B indicates the profile along which local topography was measured. (d) Topographic profile along A-B as indicated in c using LRO WAC derived digital elevation model (GLD100). A significant drop of ~ 400 m is indicated.

Figure 10 Spectral character of the southern melt flow feature and the surrounding material. (a) M³ albedo mosaic of the region showing the sampling locations. Red is the flow feature, orange and magenta are fresh craters in the Copernicus ejecta and Green is a dark halo crater that has excavated the underlying basalts. (b) Spectra of the sampled locations indicate high Ca-pyroxene signatures. The spectral character of all the locations is very similar indicating that impact melt in the flow feature was likely locally derived. spectra are color coordinated with the figure above.

Figure 11 High resolution mineralogical mapping of the crater floor. Map showing the distribution of various mineralogies on the crater floor. Note that NW sector is dominated by olivine (red and blue star symbols) and low Ca-pyroxene (brown circles) bearing lithologies. In contrast, high Ca-pyroxene bearing lithology (green circles) is relatively more common in the southern part of the crater floor. Brown-green circles represent

pyroxene exposures where specific affiliation (low calcium/high calcium) could not be unambiguously determined.

Figure 12 Spectral character of the crater floor lithologies. (a) Potential olivine-bearing exposures. Spectra from the known olivine occurrences from central peak and northern wall are provided for comparison. Red and blue colors represent the two populations mapped in Figure 11. (b) Crystalline plagioclase spectra from NE and SW parts of the crater floor. (c) Pyroxene spectra from the SW region of the crater floor showing high calcium pyroxene signature. Some quenched glass might also be present as is indicated by the very broad absorption around 1000 nm. (d) Pyroxene spectra from the SE region of the crater floor showing identifiable long wavelength absorption beyond 1000 nm but very weak bands at 2000 nm.

Figure 13 Distribution of discrete/isolated olivine exposures at Copernicus. (a) Kaguya TC image showing the spatial context of sampled locations (b) M^3 standard color composite draped over Kaguya TC showing the regional mineralogical context of the sampled locations. (c) The northern wall olivine-bearing exposure is observed here as a low-albedo deposit with color composite indicating strong absorption around 1000 nm. (d) The southern wall olivine occurrence showing association with fresh crater in impact melt. (e) Small potential olivine-bearing exposure on the NW wall showing a likely association with melt veneer. (f) Spectra from the observed locations highlight long wavelength absorption at 1000 nm and no detectable absorption around 2000 nm.

Figure 14 Nature of Mg-Spinel lithology (a) Albedo image of the crater with a zoomed version showing the location of Mg-spinel exposure. (b) M³ standard color composite of the region. The zoomed version shows the contrasting lithologies on the sides of the large mound-like structure (green represented by Mg-spinel and pink represented by mafic lithology). (c) Spectral character of the Mg-Spinel lithology. (d) Mg-Spinel lithology (in green) contrasted with the other mafic lithology (in pink). (e) Kaguya TC derived DTM showing the spatial setting of the two lithologies situated on the mound on the crater floor.

Figure 15 Small scale flow features at Copernicus crater (a) Kaguya TC image showing melt channels ending into a large melt pond on the southern crater wall. (b) Same image showing mapped extent of the channels.

Figure 16 Melt channels leading a flow from the wall to the crater floor (a) Kaguya TC image showing multiple melt channels feeding a melt flow on the southern crater wall. Eventually melt is observed on the crater floor with distinctive lobe morphology. (b) Same image showing mapped extent of the channels and lobes.

Figure 17 Cooling cracks in impact melt. (a) Kaguya TC image showing perched melt deposits on the southern crater wall with fine-scale cooling cracks indicated by arrows. They are difficult to see but are present throughout the melt deposits. (b) Same image showing mapped extent of the cracks.

Figure 18 Large scale fractures on the crater floor (a) Kaguya TC image showing fractures of various sizes on the impact melt-rich floor. (b) Same image showing mapped extent of the cracks (black discontinuous lines).

Figure 19 Crater preserved on vertical wall. (a) Kaguya TC image showing the location of the 450 m diameter crater (marked by yellow box) on the NE crater wall of Copernicus. (b) Enlarged view of the crater showing not only preservation of the crater rim but also bright ejecta around it.

Figure 20 Reconstructed Pre-impact geological setting of the Copernicus target region. (a) Albedo image (1489 nm) of the Copernicus region. (b) M³ standard color composite of Copernicus showing mineralogical variability. A-B and C-D represent the two transects along which the geologic cross-sections have been generated below.

Figure 21 End member scenarios for occurrence of olivine source regions in the lunar crust as indicated by the distribution of olivine lithology at Copernicus crater. (a) Multiple olivine horizons scenario. Sampling and incorporation of olivine lithology in the melt would be possible by shallow-occurring olivine sources. The deeper, unrelated olivine horizon would be sampled by the central uplift. (b) Single deep-seated olivine horizon scenario. No direct sampling of olivine lithology would be possible by the transient melt cavity. The central uplift would still be able to directly excavate the deep seated olivine source.

Figure 22 Scientific exploration site #1 with locations of interesting target regions.

Figure 23 Scientific exploration site #2 with locations of interesting target regions.

Figure 24 Scientific exploration site #3 with locations of interesting target regions.

Figures

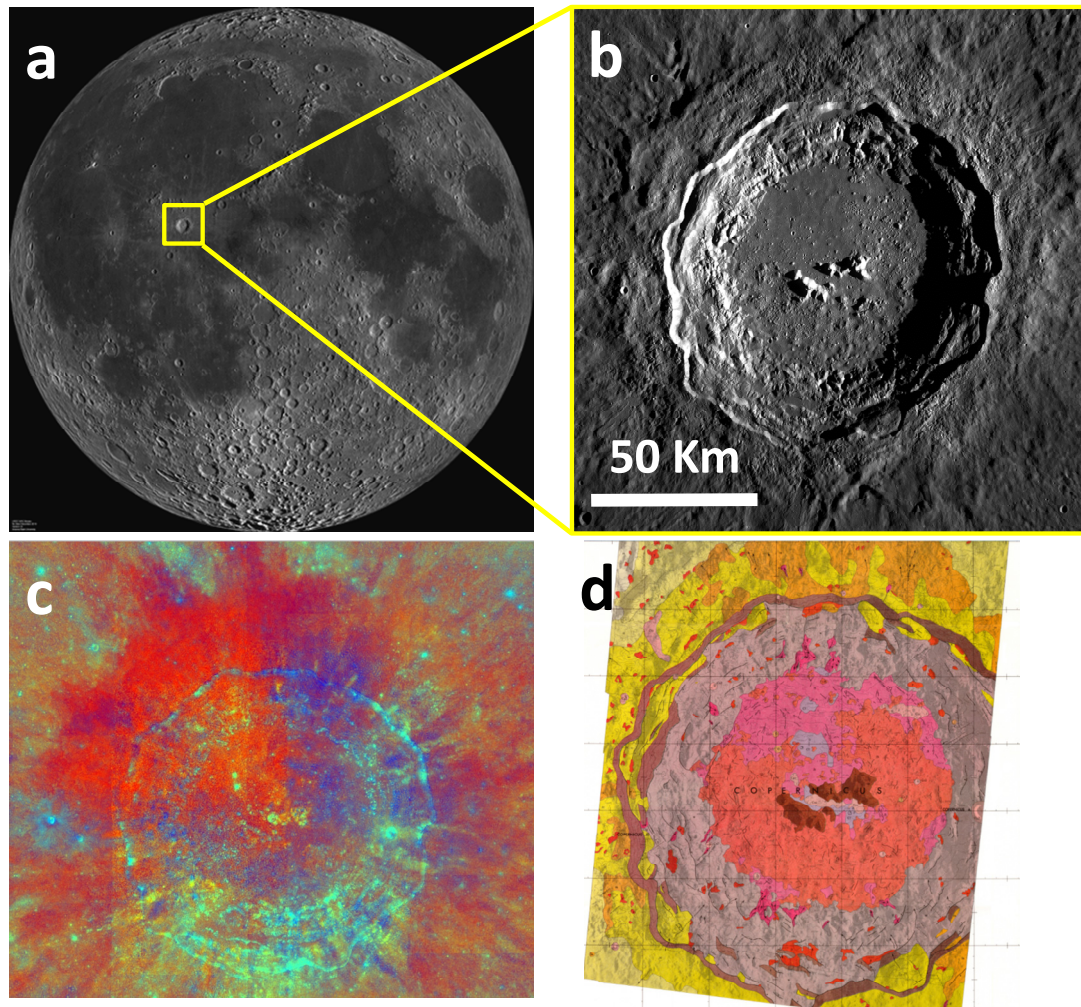


Figure 1 Copernicus crater a) Global context b) Regional perspective c) Clementine data compositional perspective. Color composite highlights that the NW quadrant is distinctly different from remaining crater. $R=750/415$, $G=750/950$, $B=415/750$. d) Morphological perspective provided by a geological map from *Howard*, [1975]. Note the two broad units (magenta in the north, orange elsewhere) mapped on the melt-rich crater floor.

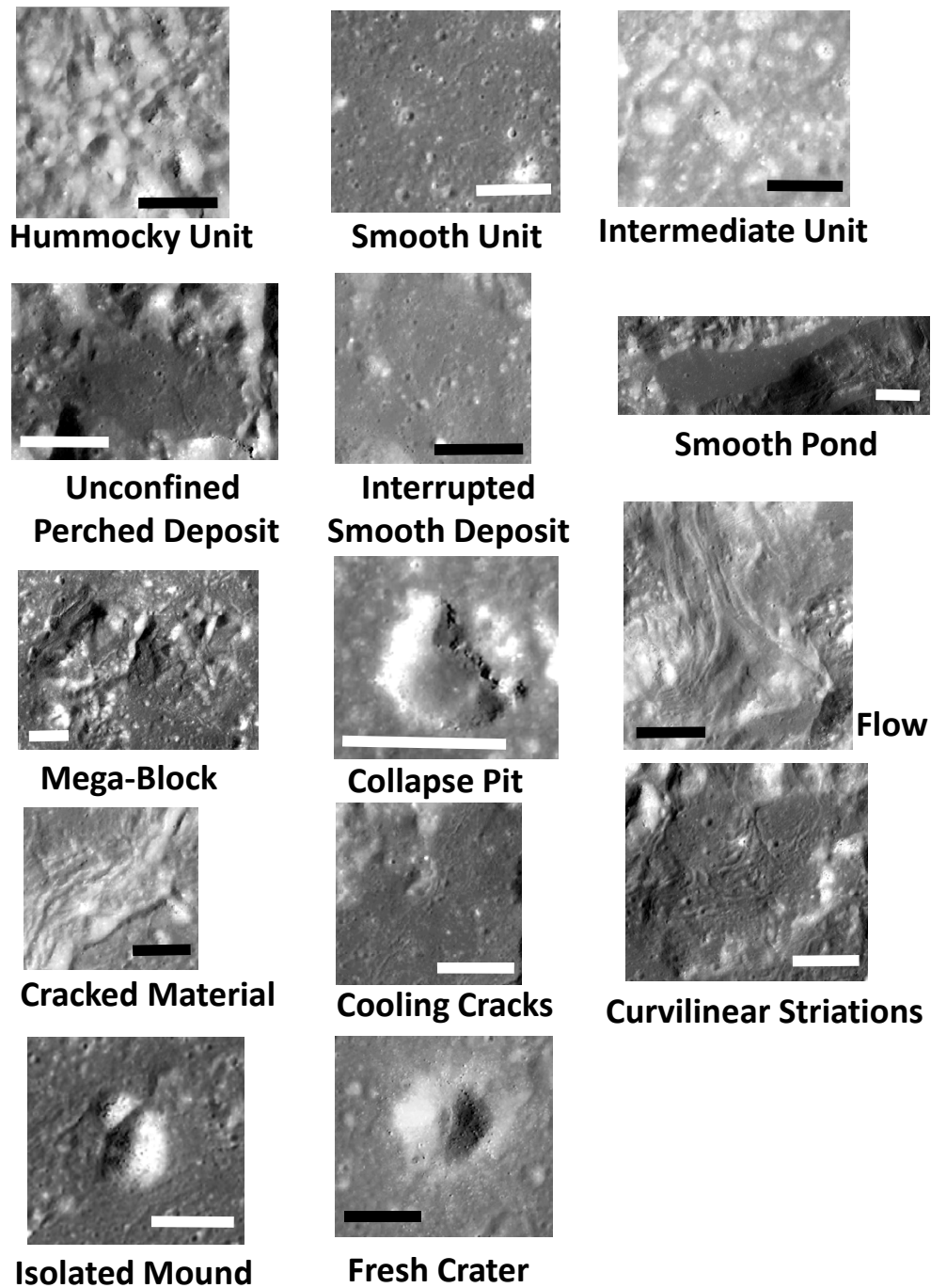


Figure 2 Impact melt morphological units observed and mapped at Copernicus crater.

The scale bar is 1 km in each of the units.

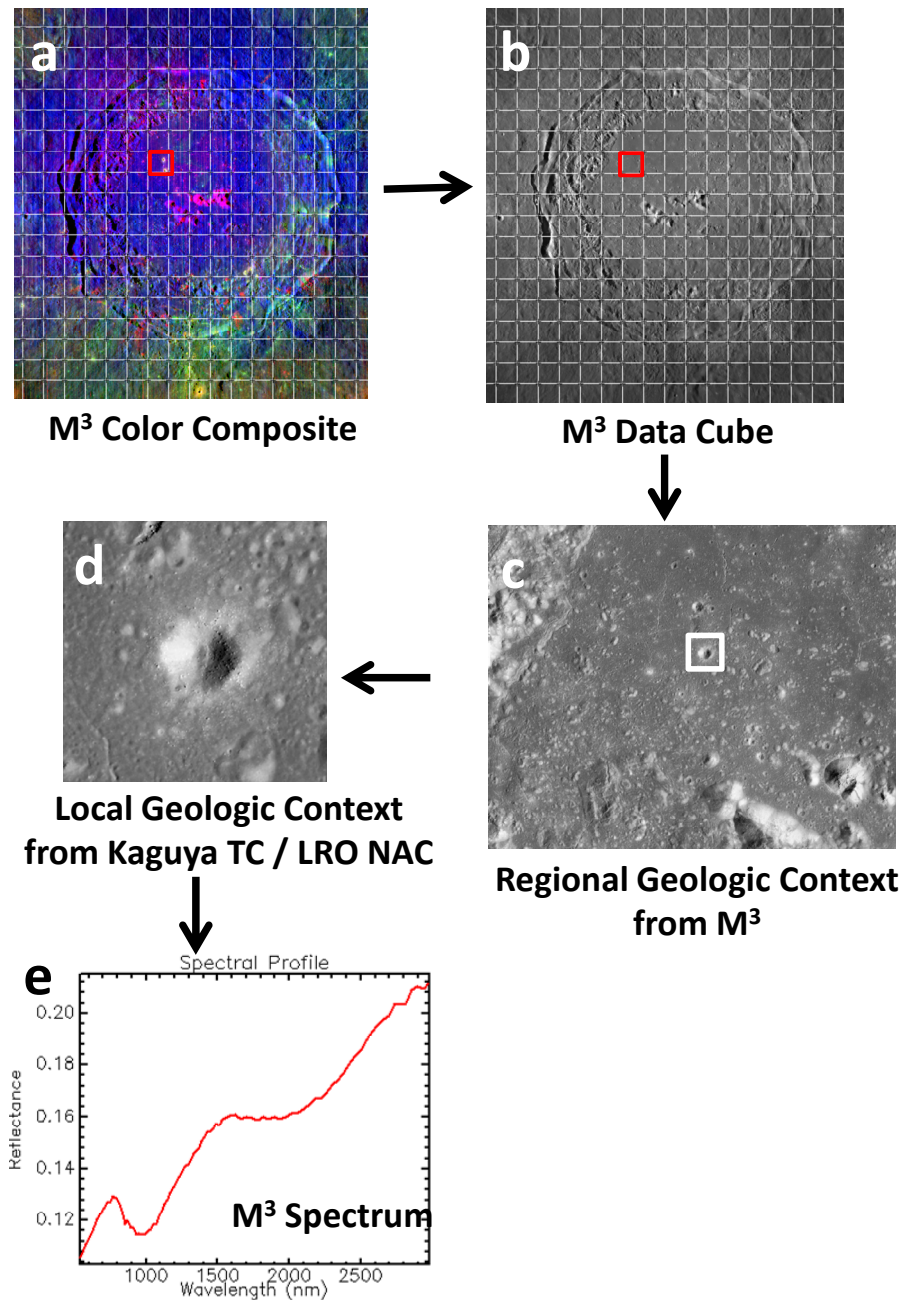


Figure 3 Methodology for high resolution mineralogical studies (a) & (b) Crater was divided into grid units for systematic spectral sampling (c) Regional and (d) Local geological context was derived respectively, using high spatial resolution datasets (e.g. Kaguya TC, LROC NAC) (e) Spectral signature of interesting lithology was extracted.

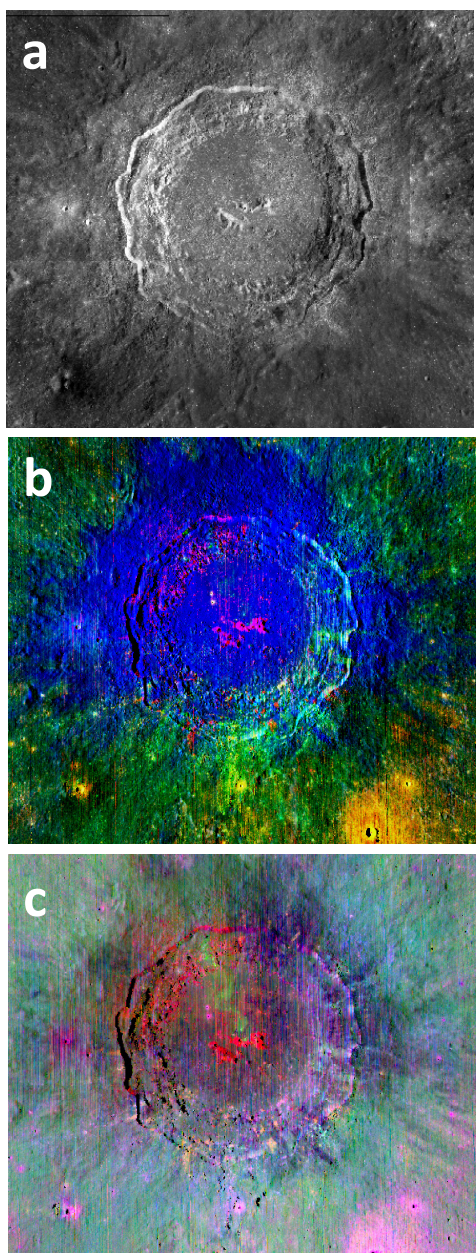


Figure 4 Synoptic view of mineralogical and morphological diversity of Copernicus region. (a) Kaguya TC albedo (b) M³ standard color composite overlain on Kaguya TC data. (c) M³ complementary color composite (see Table 2 for spectral parameters) highlighting the presence of mineralogically distinct sinuous melt feature on the northern crater floor.

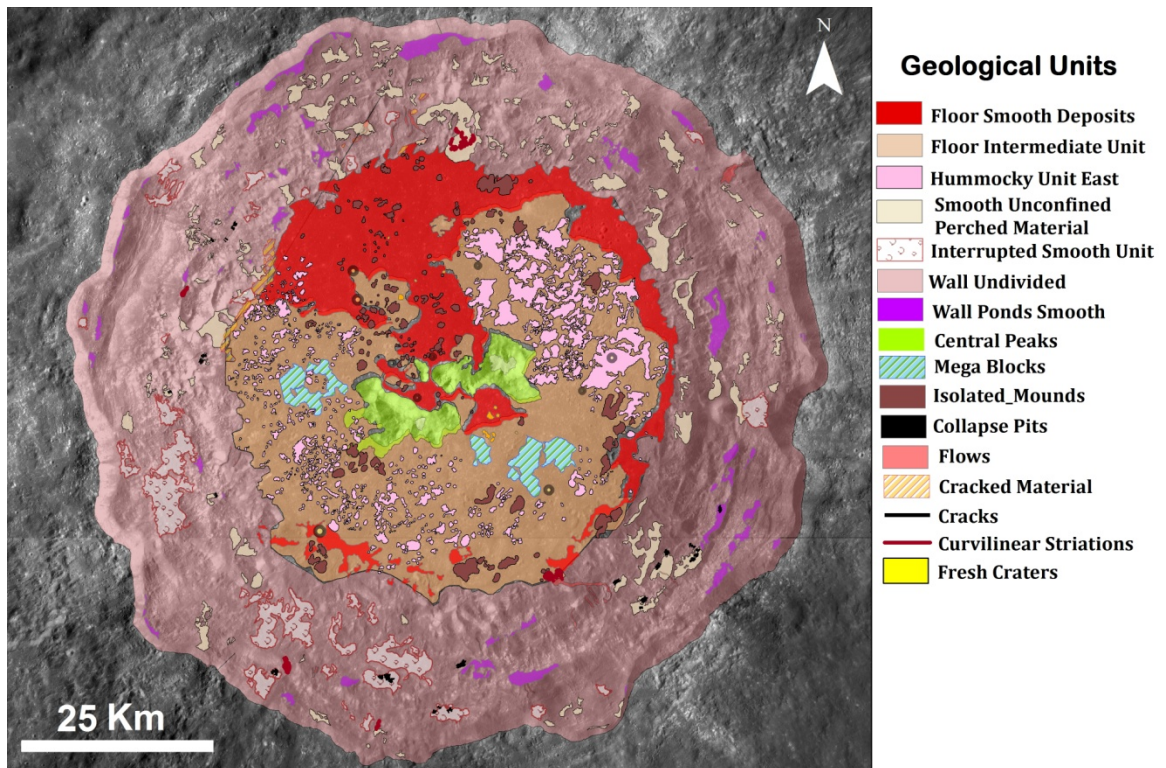


Figure 5 Morphological map of various impact melt units at Copernicus.

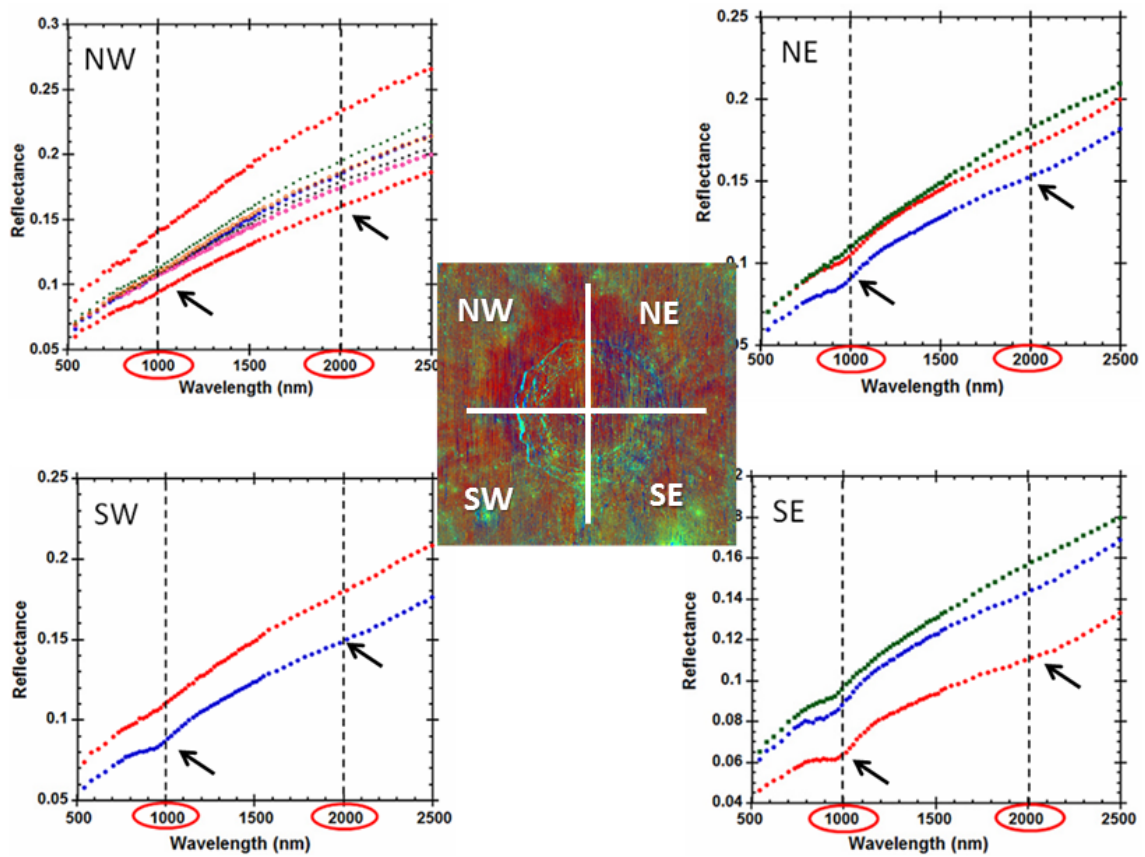


Figure 6 Sector-wise characterization of the impact melt ponds in and around Copernicus. Mineralogy extracted from soils varies radially indicating local melt heritage and minimal lateral mixing. North-west sector impact melt deposits display weak to non-existent spectral bands perhaps contributing to its identification as a distinct unit in various datasets. NE and SW sectors show some ponds with weak absorptions while others are featureless. Melt ponds occurring in the SE sector consistently show detectable mafic absorption bands. The color composite in the center is derived from M^3 data using the similar band ratios as in case of Clementine data namely Red= 750/540 nm, Green= 750/950 nm, Blue= 540/750 nm. It displays the unique character of NW quadrant as was captured initially using Clementine data.

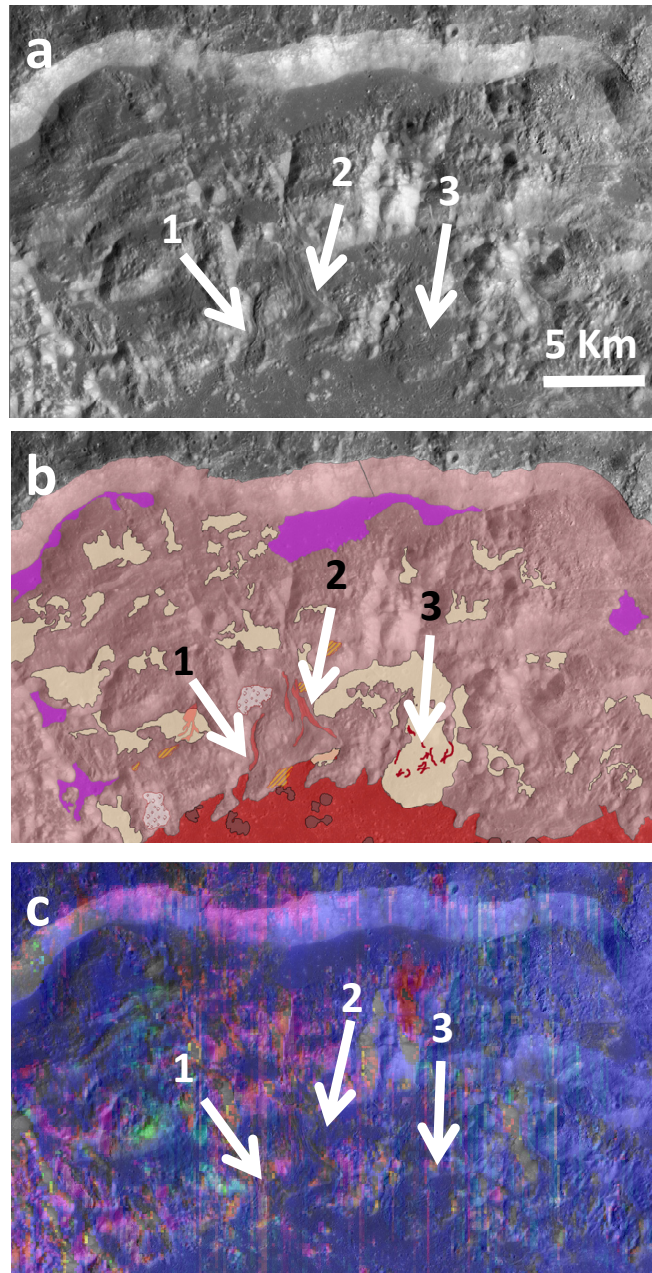


Figure 7 Melt flows on the northern wall of Copernicus Crater (a) Albedo image of the northern wall (b) Geological map of impact melt units (c) M^3 standard color composite overlain on the Kaguya Terrain Camera image of the region display dominant mineralogy of the region. The flow features do not seem to have any distinctive spectral signature.

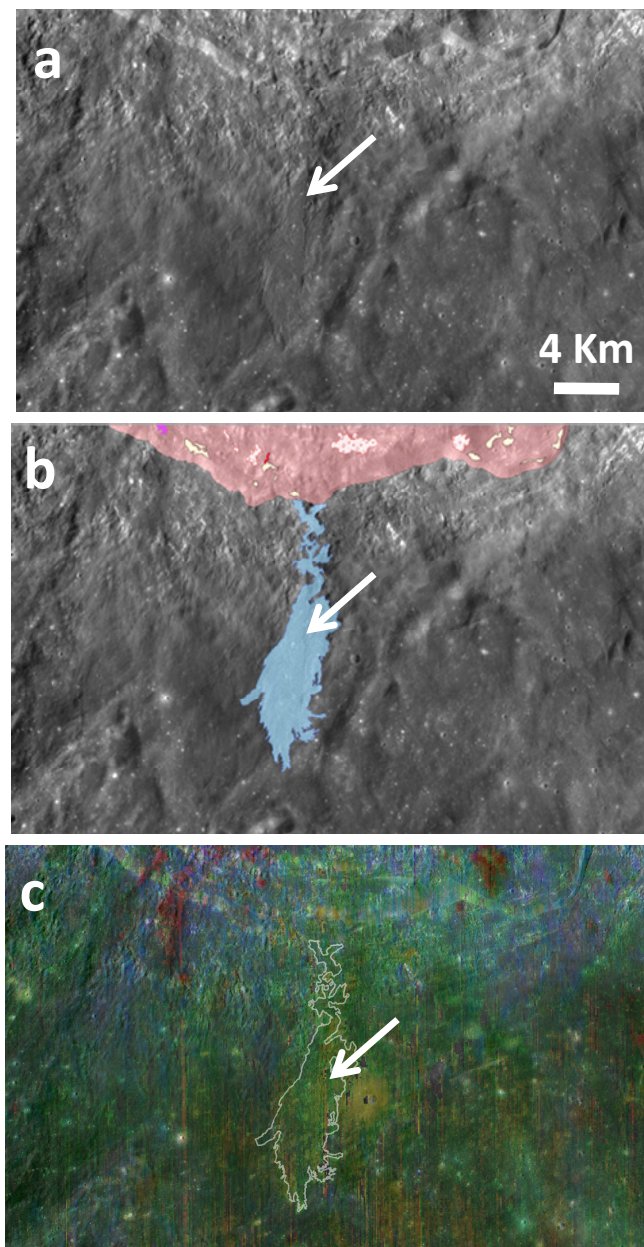


Figure 8 Melt feature on the southern rim of Copernicus Crater (a) Albedo image showing the melt feature (b) Geological map showing the extent of the melt flow (c) M^3 color composite overlain on the Kaguya Terrain Camera image of the region display dominant mineralogy of the region. The flow feature seems to share the mafic mineralogy indicated by surrounding terrain.

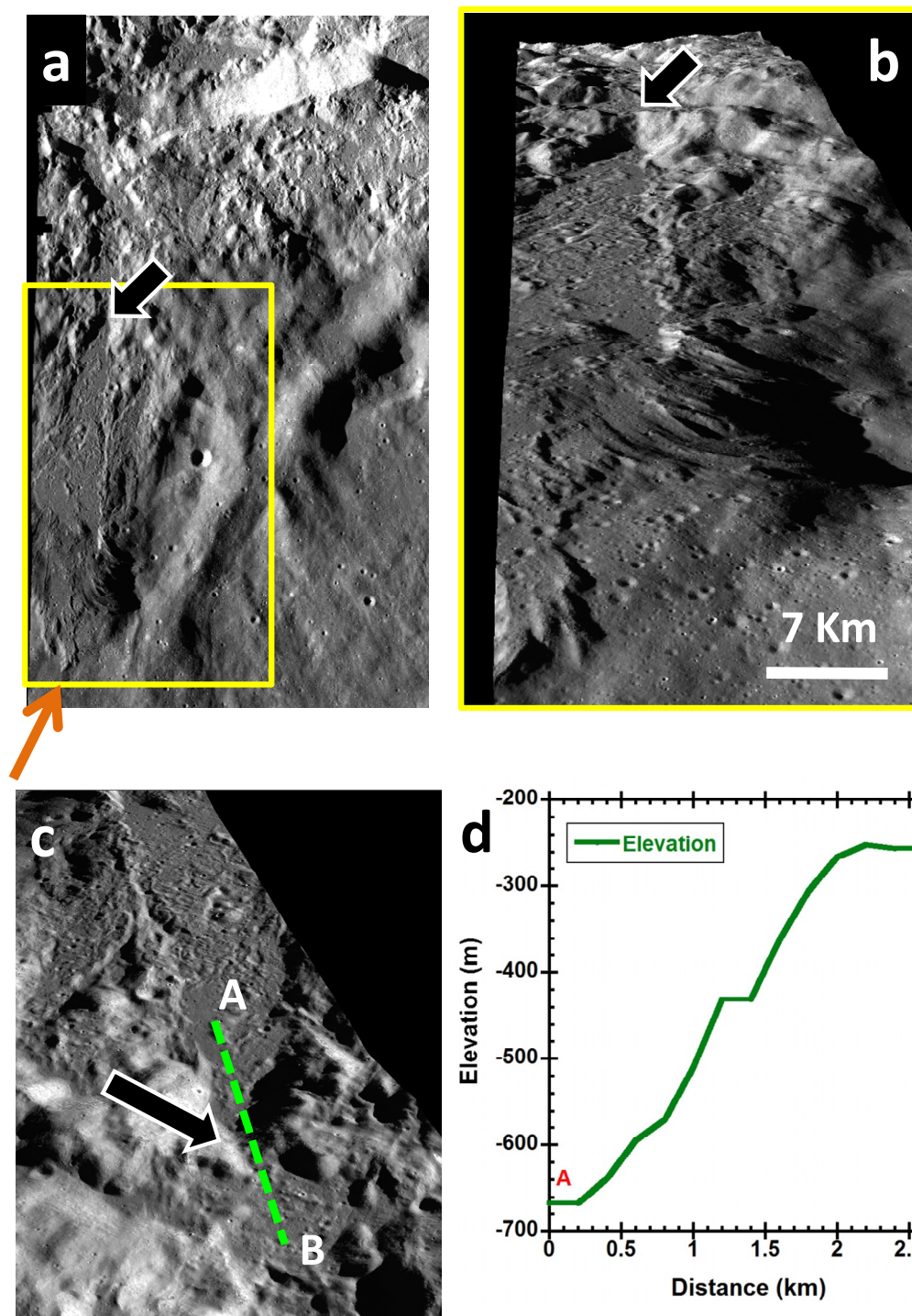


Figure 9 (a) Kaguya TC image showing the massive scale of the flow feature and digitate morphology at the distal ends. Black arrow indicates a drop in elevation within the feature. Orange arrow indicates the viewing direction for the 3D perspective shown in

next image. (b) Close-up 3D view of the flow feature. The step in topography is indicated by the black arrow (c) Image of the flow features closer to the crater rim. A-B indicates the profile along which local topography was measured. (d) Topographic profile along A-B as indicated in c using LRO WAC derived digital elevation model (GLD100). A significant drop of ~ 400 m is indicated.

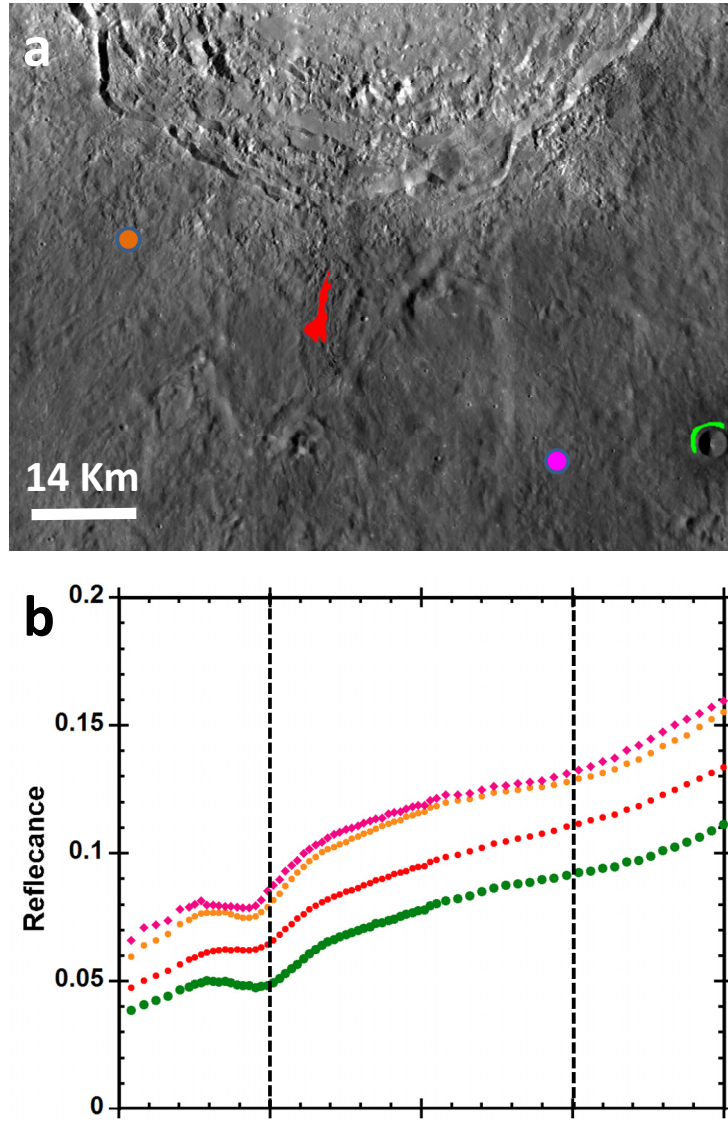


Figure 10 Spectral character of the southern melt flow feature and the surrounding material. (a) M³ albedo mosaic of the region showing the sampling locations. Red is the flow feature, orange and magenta are fresh craters in the Copernicus ejecta and Green is a dark halo crater that has excavated the underlying basalts. (b) Spectra of the sampled locations indicate high Ca-pyroxene signatures. The spectral character of all the locations is very similar indicating that impact melt in the flow feature was likely locally derived. spectra are color coordinated with the figure above.

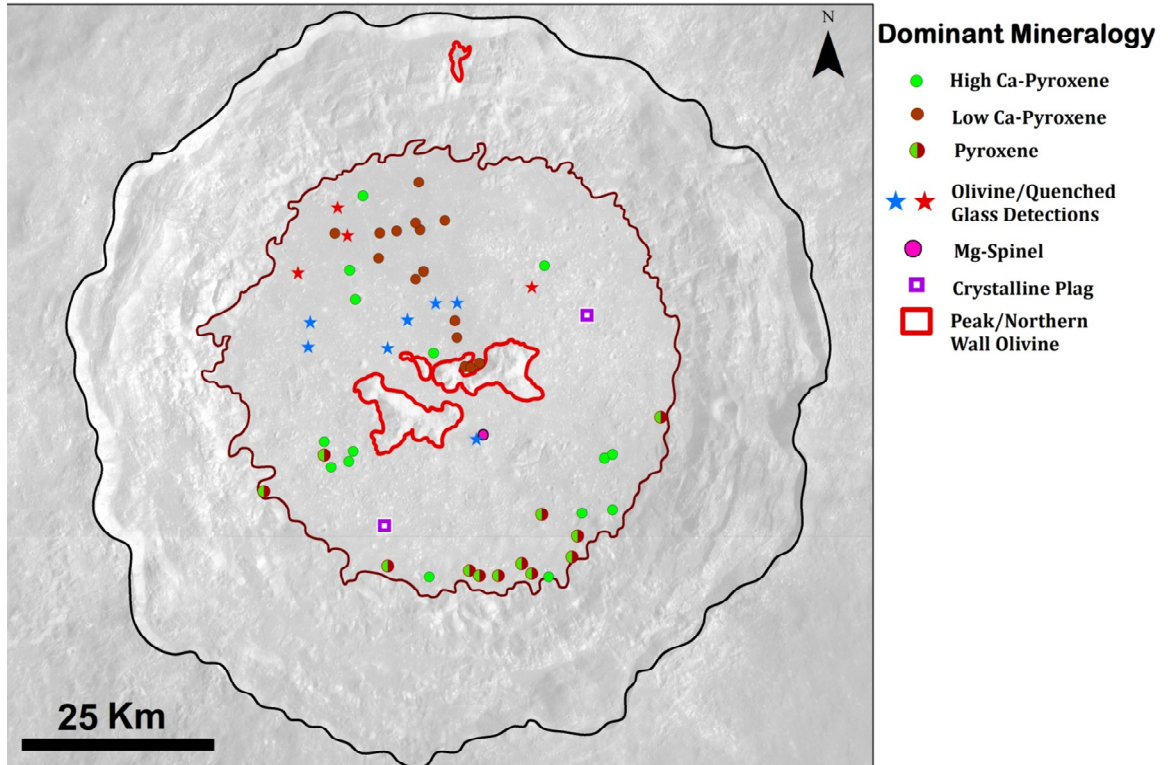


Figure 11 High resolution mineralogical mapping of the crater floor. Map showing the distribution of various mineralogies on the crater floor. Note that NW sector is dominated by olivine (red and blue star symbols) and low Ca-pyroxene (brown circles) bearing lithologies. In contrast, high Ca-pyroxene bearing lithology (green circles) is relatively more common in the southern part of the crater floor. Brown-green circles represent pyroxene exposures where specific affiliation (low calcium/high calcium) could not be unambiguously determined.

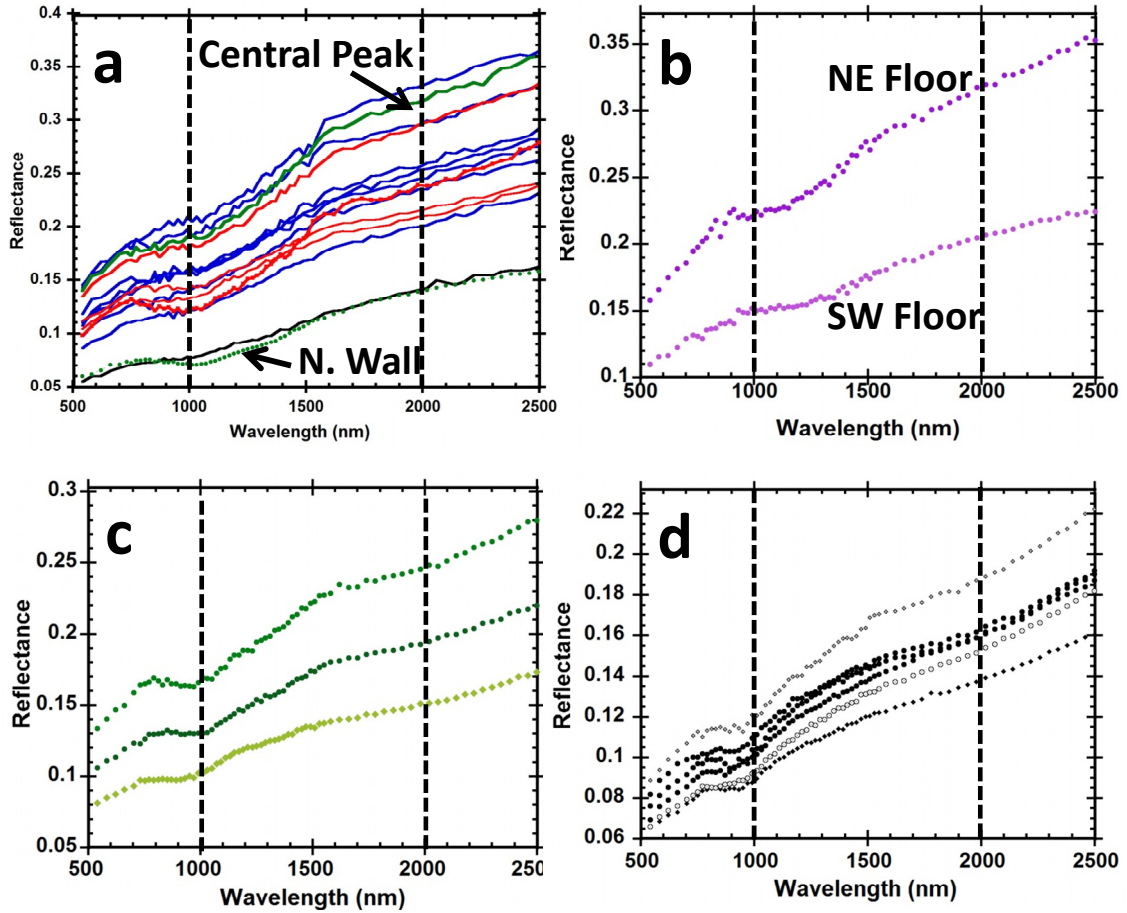


Figure 12 Spectral characteristics of the crater floor lithologies. (a) Potential olivine-bearing exposures. Spectra from the known olivine occurrences from central peak and northern wall are provided for comparison. Red and blue colors represent the two populations mapped in Figure 11. (b) Crystalline plagioclase spectra from NE and SW parts of the crater floor. (c) Pyroxene spectra from the SW region of the crater floor showing high calcium pyroxene signature. Some quenched glass might also be present as is indicated by the very broad absorption around 1000 nm. (d) Pyroxene spectra from the SE region of the crater floor showing identifiable long wavelength absorption beyond 1000 nm but very weak bands at 2000 nm.

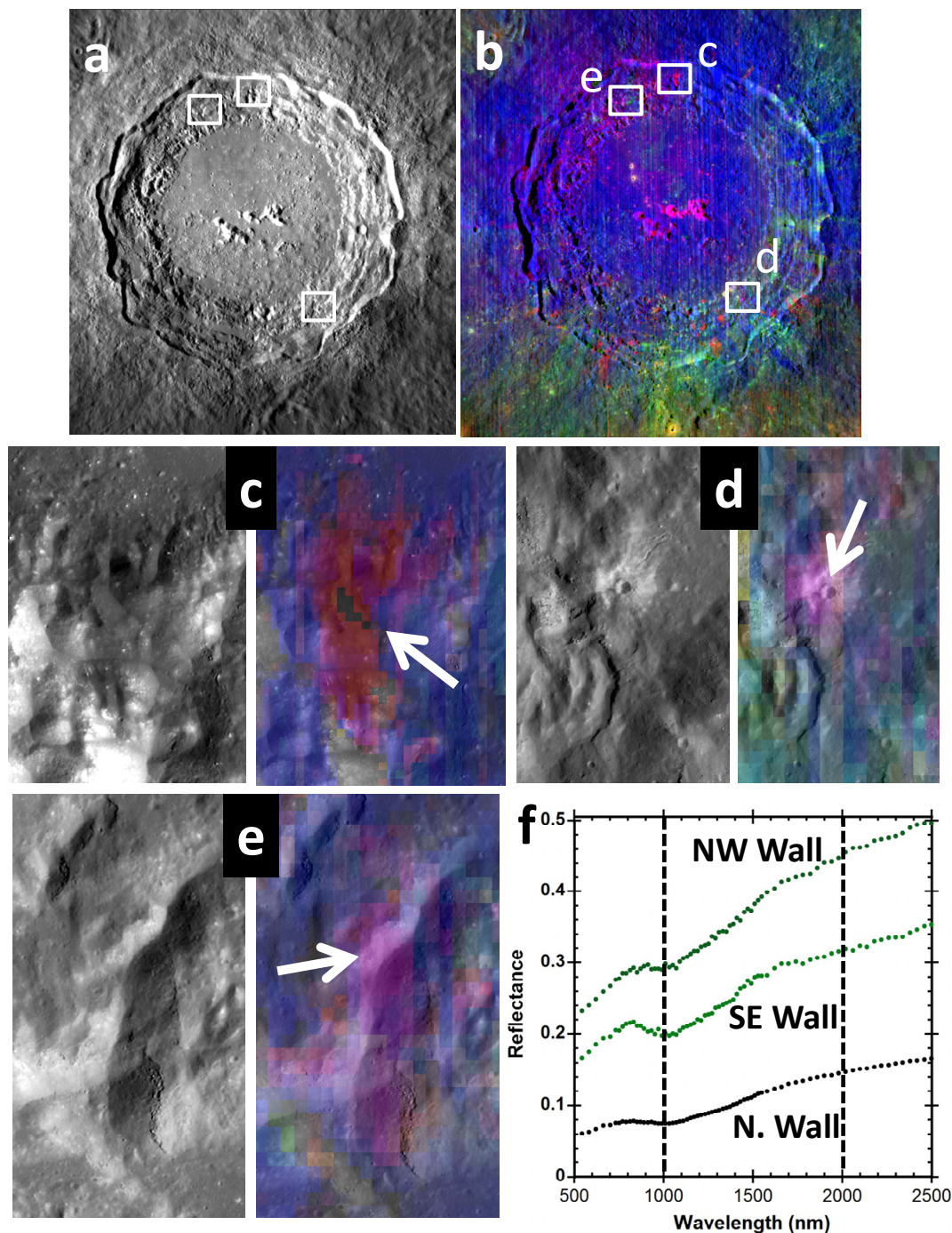


Figure 13 Distribution of discrete/isolated olivine exposures at Copernicus. (a) Kaguya TC image showing the spatial context of sampled locations (b) M³ standard color composite draped over Kaguya TC showing the regional mineralogical context of the

sampled locations. (c) The northern wall olivine-bearing exposure is observed here as a low-albedo deposit with color composite indicating strong absorption around 1000 nm. (d) The southern wall olivine occurrence showing association with fresh crater in impact melt. (e) Small potential olivine-bearing exposure on the NW wall showing a likely association with melt veneer. (f) Spectra from the observed locations highlight long wavelength absorption at 1000 nm and no detectable absorption around 2000 nm.

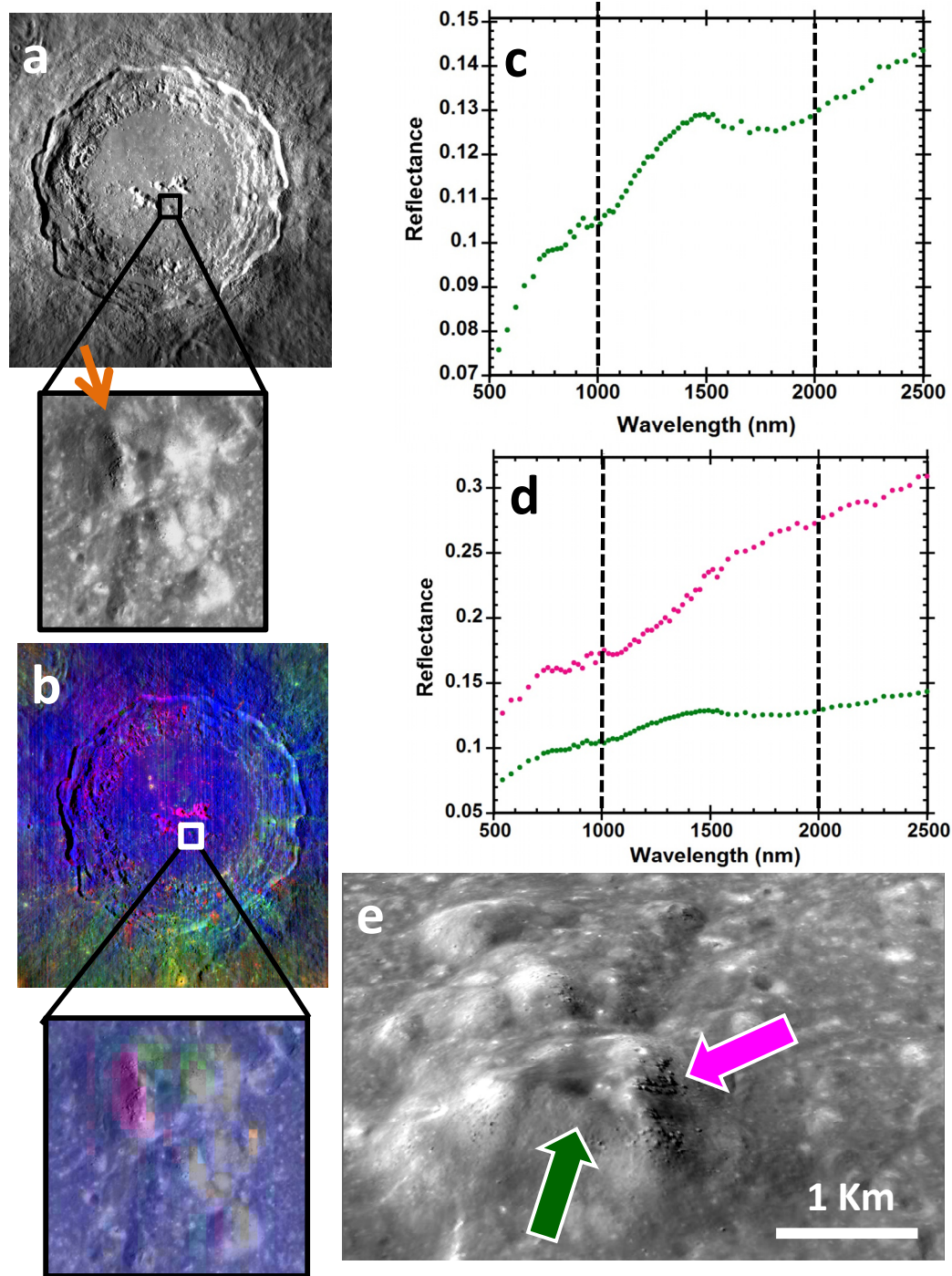


Figure 14 Nature of Mg-Spinel lithology (a) Albedo image of the crater with a zoomed version showing the location of Mg-spinel exposure. (b) M³ standard color composite of the region. The zoomed version shows the contrasting lithologies on the sides of the large

mound-like structure (green represented by Mg-spinel and pink represented by mafic lithology). (c) Spectral character of the Mg-Spinel lithology. (d) Mg-Spinel lithology (in green) contrasted with the other mafic lithology (in pink). (e) Kaguya TC derived DTM showing the spatial setting of the two lithologies situated on the mound on the crater floor.

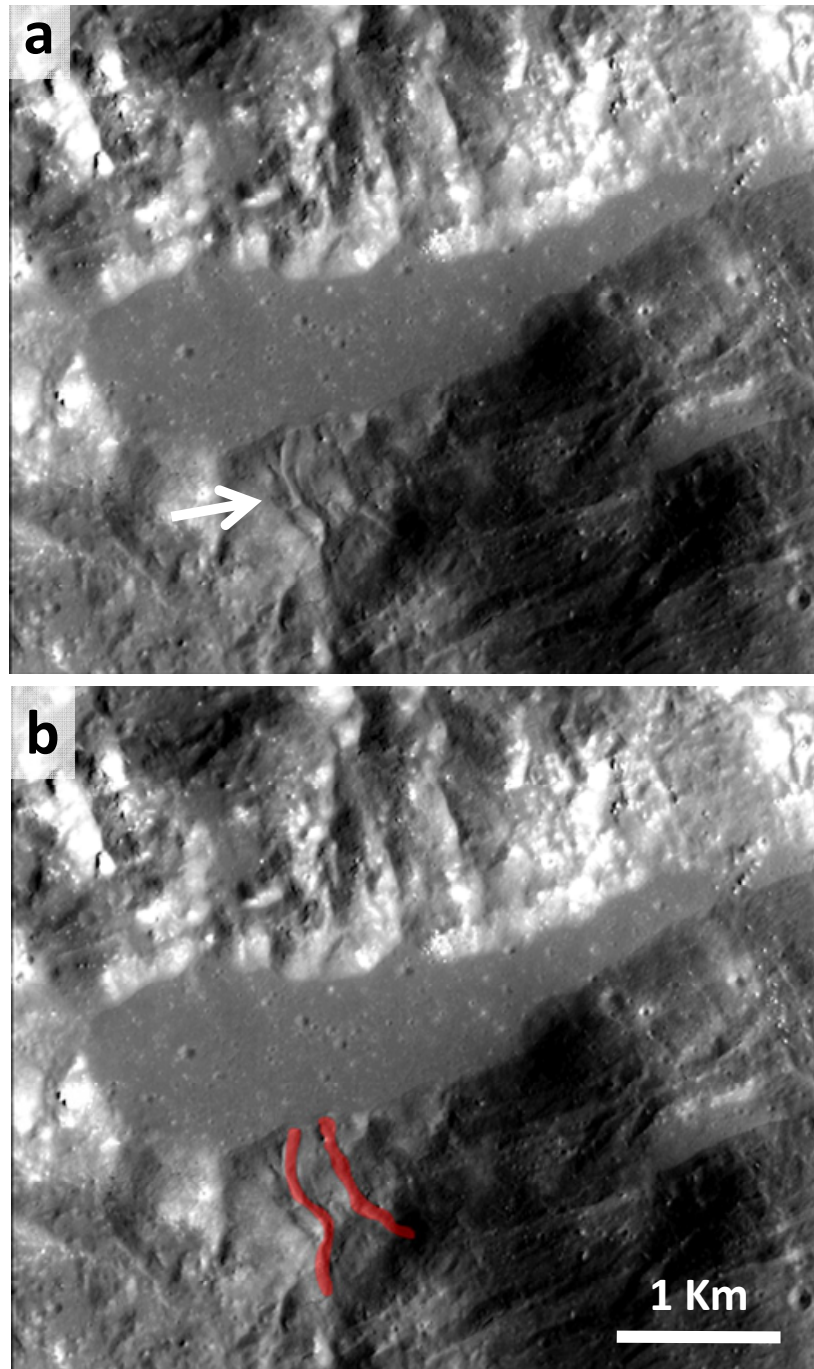


Figure 15 Small scale flow features at Copernicus crater (a) Kaguya TC image showing melt channels ending into a large melt pond on the southern crater wall. (b) Same image showing mapped extent of the channels.

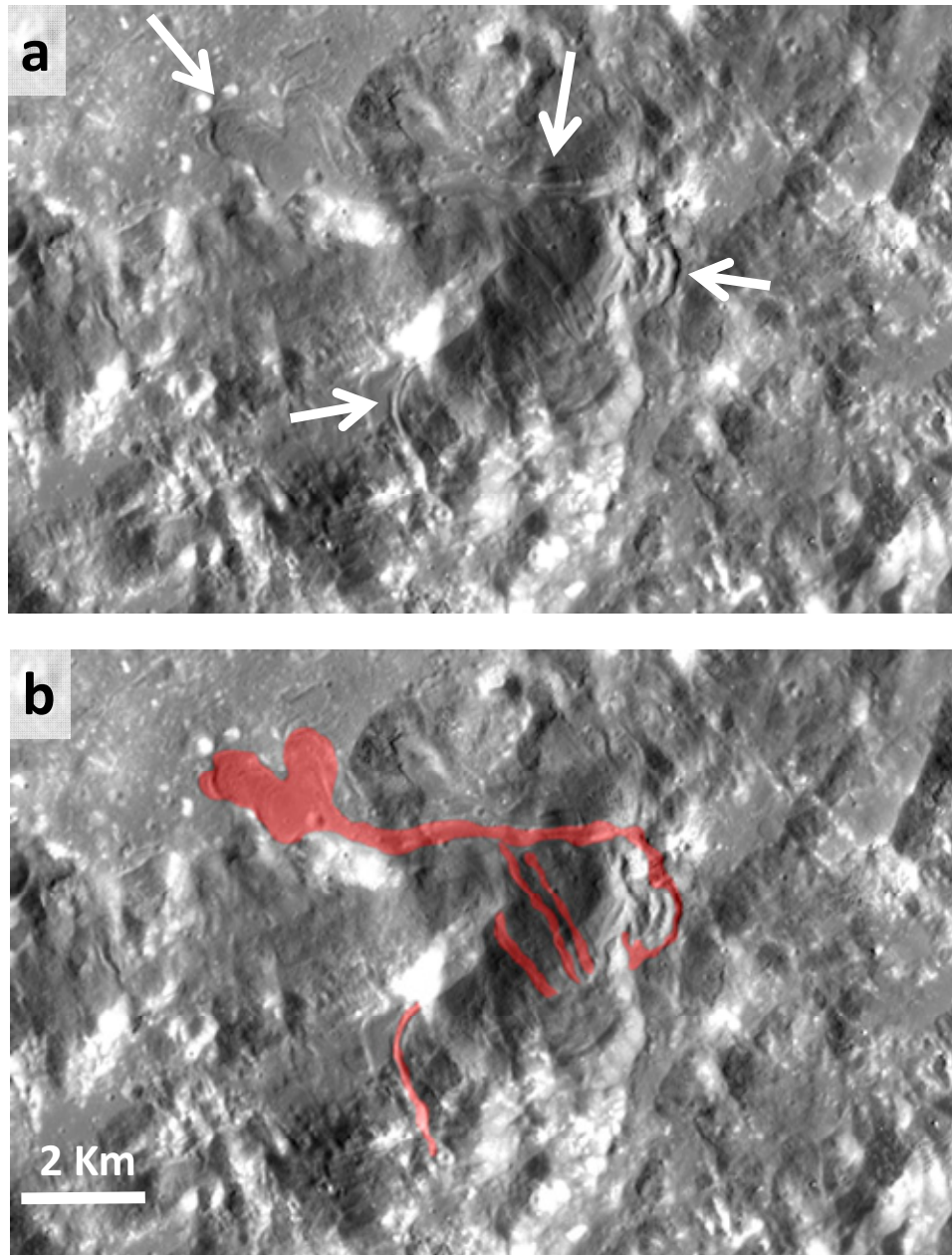


Figure 16 Melt channels leading a flow from the wall to the crate floor (a) Kaguya TC image showing multiple melt channels feeding a melt flow on the southern crater wall. Eventually melt is observed on the crater floor with distinctive lobe morphology. (b) Same image showing mapped extent of the channels and lobes.

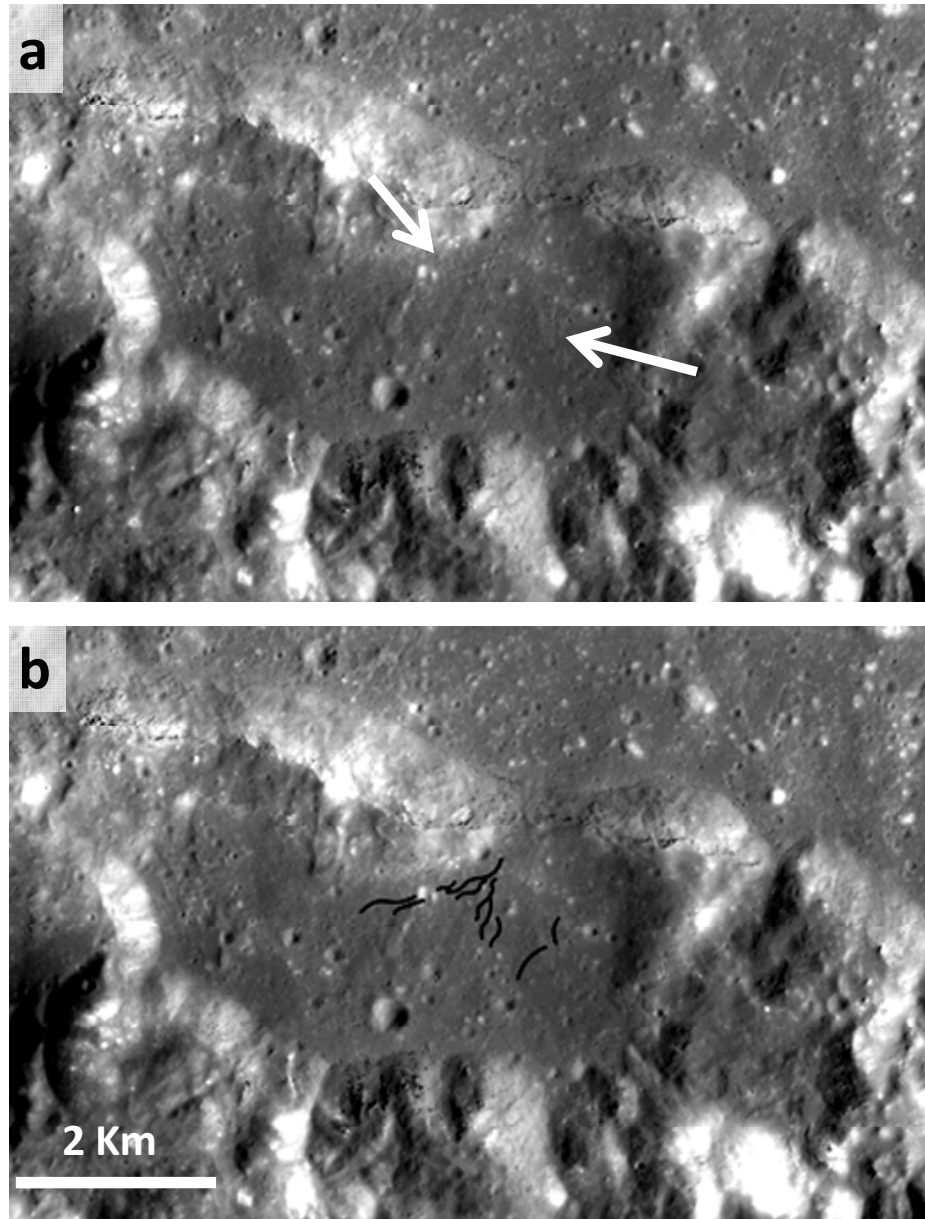


Figure 17 Cooling cracks in impact melt. (a) Kaguya TC image showing perched melt deposits on the southern crater wall with fine-scale cooling cracks indicated by arrows. They are difficult to see but are present throughout the melt deposits. (b) Same image showing mapped extent of the cracks.

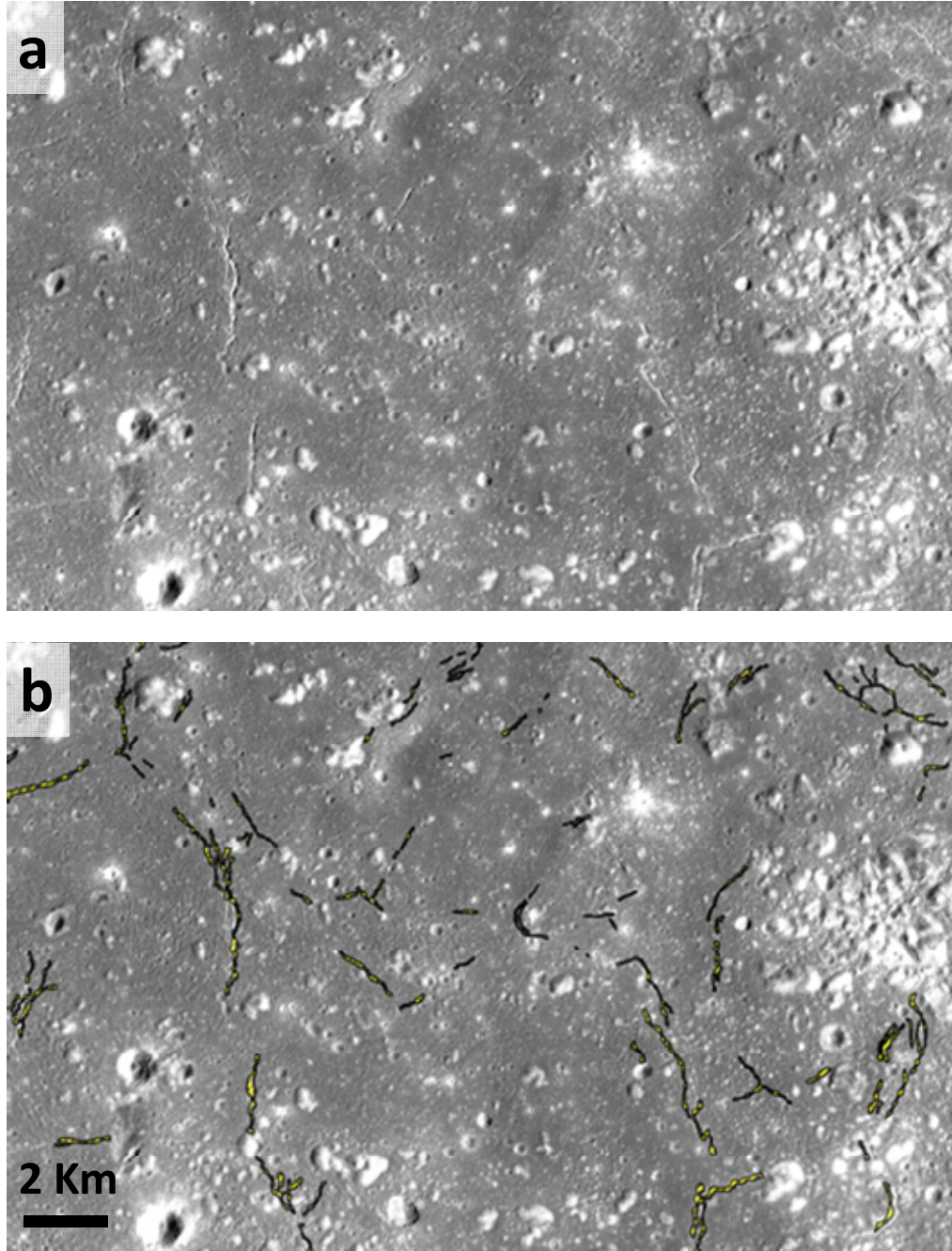


Figure 18 Large scale fractures on the crater floor (a) Kaguya TC image showing fractures of various sizes on the impact melt-rich floor. (b) Same image showing mapped extent of the cracks (black discontinuous lines).

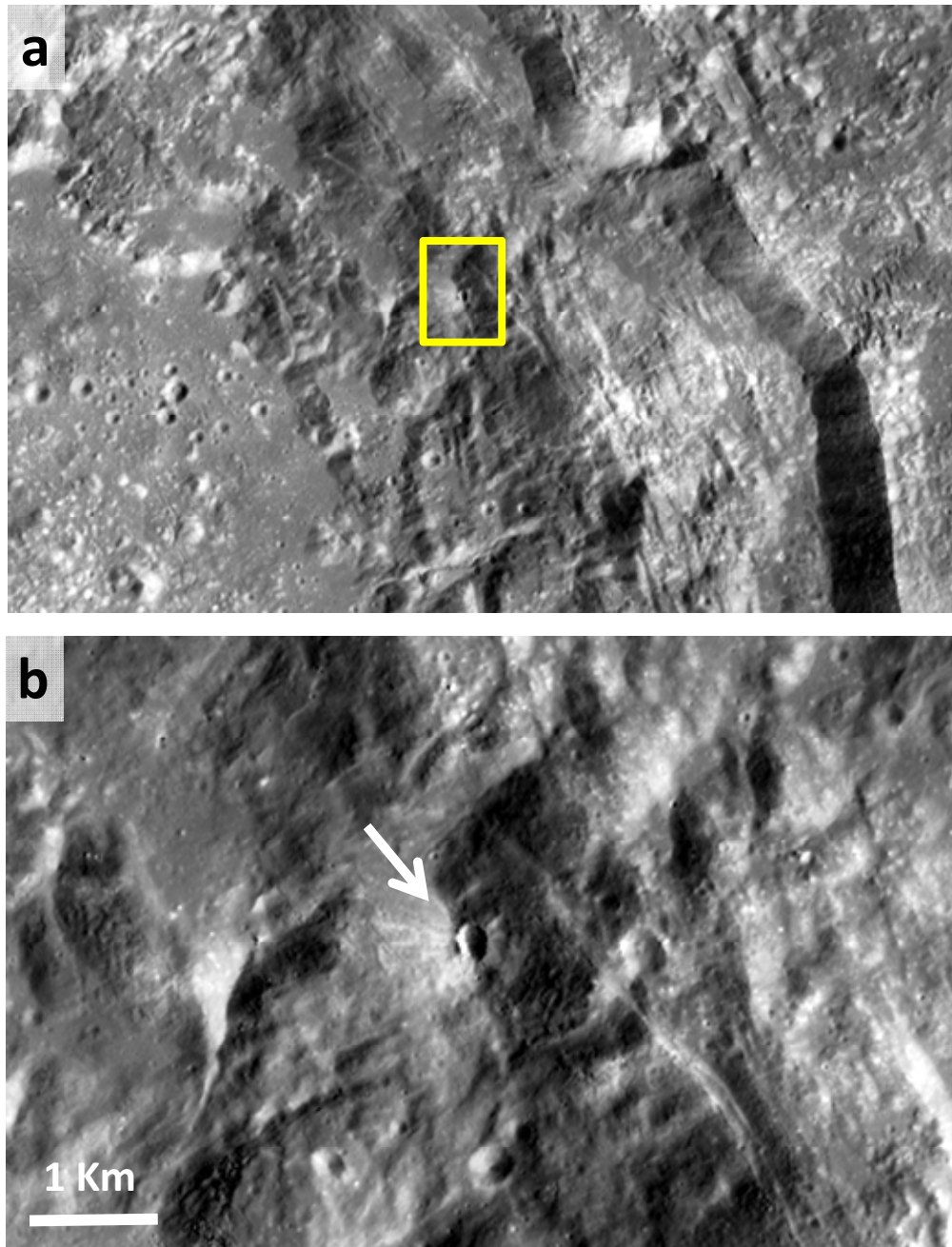


Figure 19 Crater preserved on vertical wall. (a) Kaguya TC image showing the location of the 450 m diameter crater (marked by yellow box) on the NE crater wall of Copernicus. (b) Enlarged view of the crater showing not only preservation of the crater rim but also bright ejecta around it.

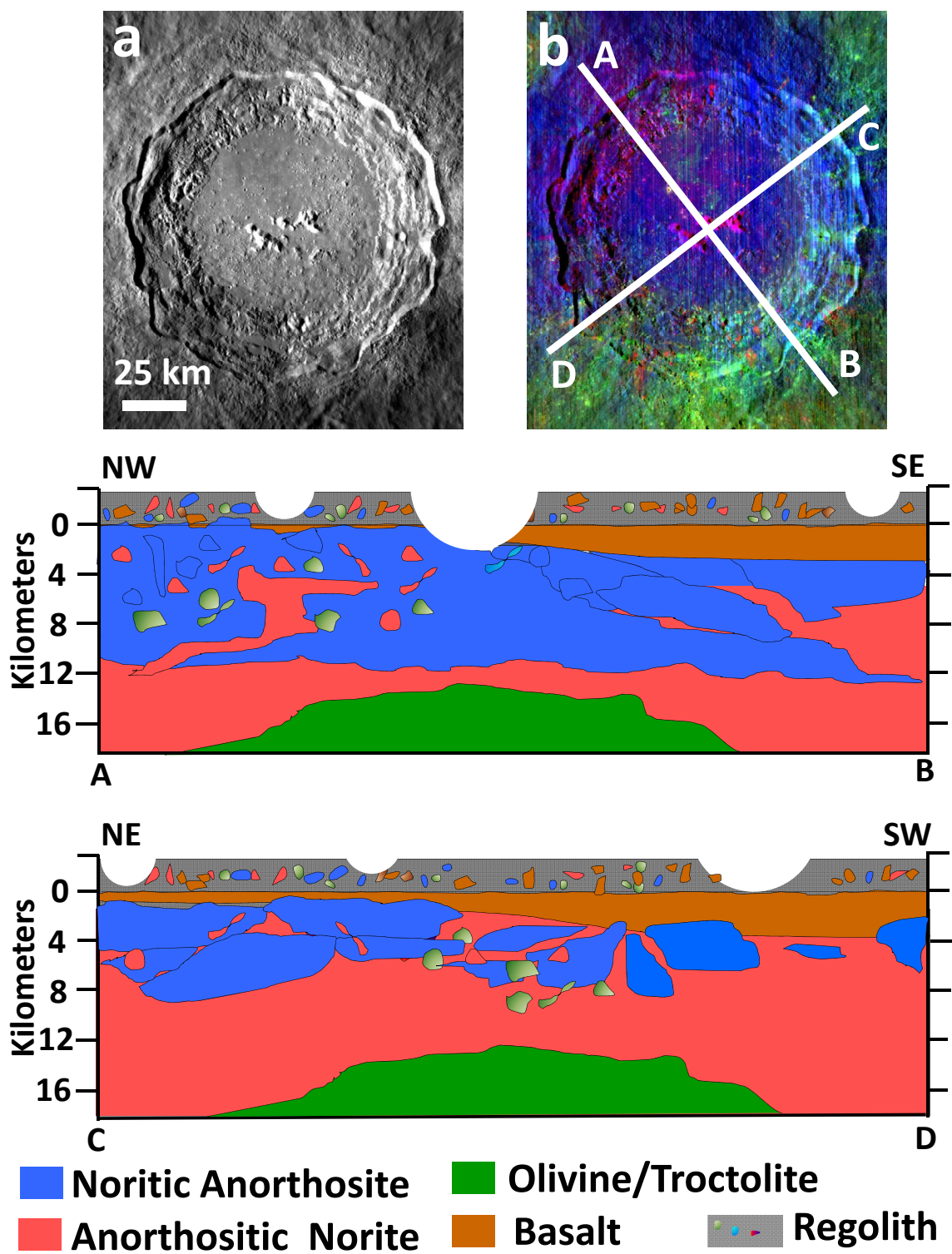


Figure 20 Reconstructed Pre-impact geological setting of the Copernicus target region.

(a) Albedo image (1489 nm) of the Copernicus region. (b) M³ standard color composite

of Copernicus showing mineralogical variability. A-B and C-D represent the two transects along which the geologic cross-sections have been generated below.

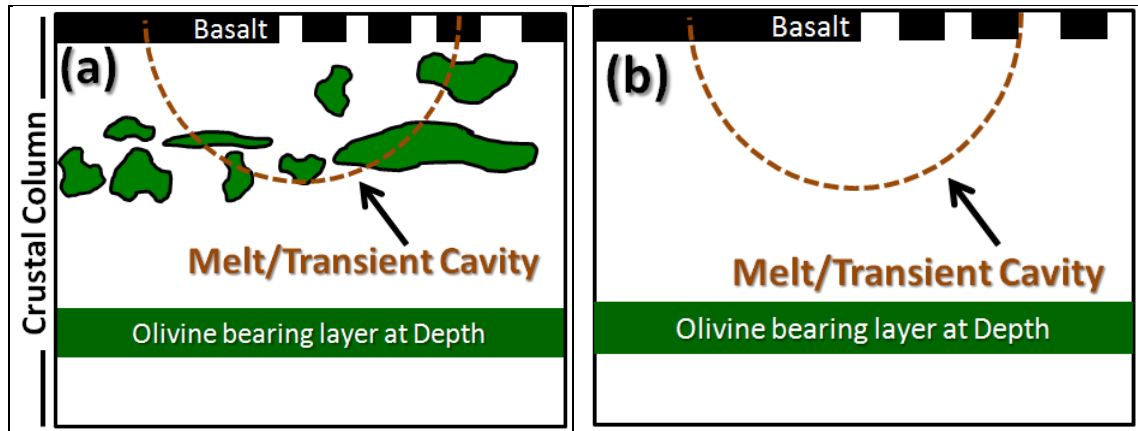


Figure 21 End member scenarios for occurrence of olivine source regions in the lunar crust as indicated by the distribution of olivine lithology at Copernicus crater. (a) Multiple olivine horizons scenario. Sampling and incorporation of olivine lithology in the melt would be possible by shallow-occurring olivine sources. The deeper, unrelated olivine horizon would be sampled by the central uplift. (b) Single deep-seated olivine horizon scenario. No direct sampling of olivine lithology would be possible by the transient melt cavity. The central uplift would still be able to directly excavate the deep seated olivine source.

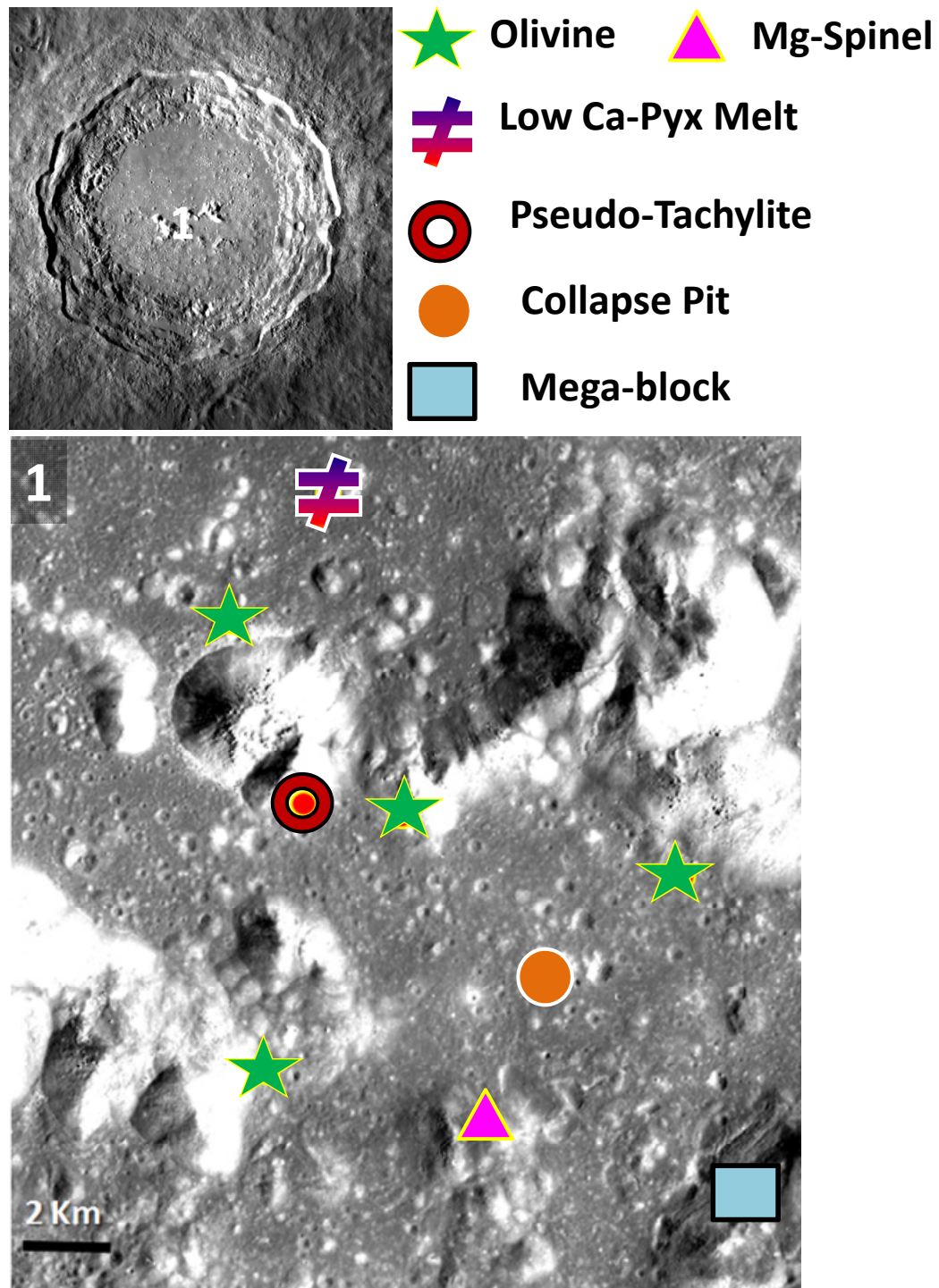


Figure 22 Scientific exploration site #1 with locations of interesting target regions.



- ★ Olivine
- ≠ Low Ca-Pyx Melt
- ⊕ High Ca-Pyx Melt
- Collapse Pits

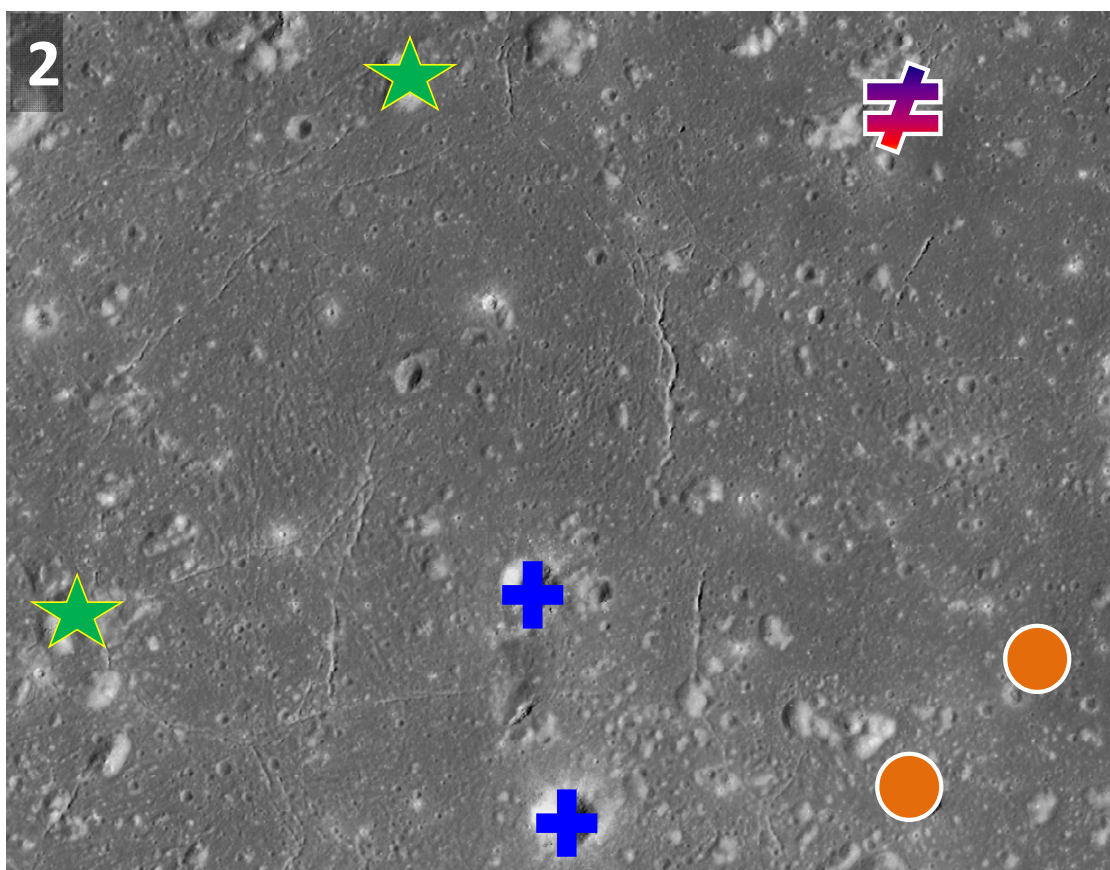


Figure 23 Scientific exploration site #2 with locations of interesting target regions.

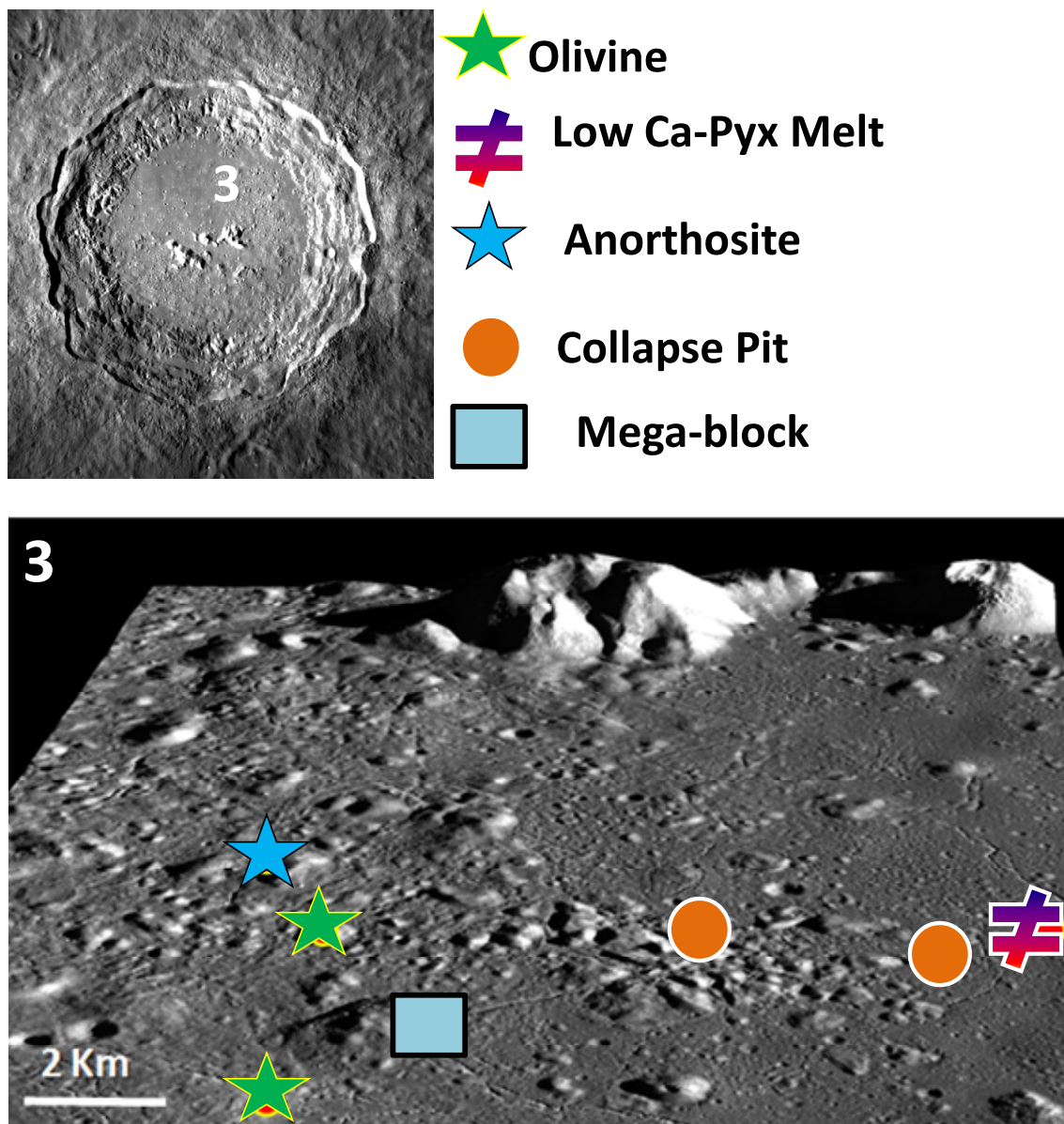


Figure 24 Scientific exploration site #3 with locations of interesting target regions.

CHAPTER 5: Impact Melt Characteristics of Highland Craters Jackson and Tycho: Evaluating the Role of Similar Geologic Setting

Deepak Dhingra, Carle M. Pieters and James W. Head

Abstract

Impact melt properties at two craters, Jackson and Tycho were studied and contrasted based on the premise that similar size craters, formed in similar targets would have comparable impact energy available during their formation. Geological mapping of the impact melt deposits coupled with detailed mineralogical assessment at the two craters have provided wealth of insights into the character of various impact melt units. This information is used to interpret salient aspects of the impact melt formation and emplacement process. We report two elevation levels on the crater floors of Jackson and Tycho and provide observational support for structural subsidence, apart from subsidence occurring as a result of cooling of the impact melt. The mineralogy of the impact melt is heterogeneous at both the craters although the specific flavor is different. Tycho displays mineralogical variations within the high calcium-pyroxene suite while Jackson exhibits weakly mafic and non-mafic character of impact melt. We propose a likely coherent pre-impact target at Tycho as compared to the more fractured nature of target at Jackson based on the character and distribution of the boulder units on their respective crater floors. Physical nature of the target is suggested as one of the principal cause for different nature of the boulder units and an additional factor that affects the properties of impact melt and associated products even when impact energy is expected to be comparable. Morphologically, both the craters show evidence for prominent impact melt fronts in different parts hinting at the large scale mobility of impact melt during the cratering process.

1. Introduction

The process of impact cratering and the associated impact melt production is known to be dependent on several parameters [e.g. *Gault et al.*, 1968; *Cintala and Grieve*, 1998; *Melosh*, 1989; *Pierazzo and Melosh*, 2000]. Some of the commonly considered parameters include planetary gravity, target/projectile strength, projectile size, velocity, angle of impact and pre-impact geological setting including the topography. The complex interplay of such parameters leads to diversity in impact crater morphology and the associated products. One of the most commonly observed diversity is correlated with a progression in crater size (Figure 1) from simple (bowl shape, flat floor, and steep walls) to complex craters (floor with central uplift, terraced walls) and later basins at very large sizes (concentric rings with or without peaks) [e.g. *Pike*, 1988; *Baker et al.*, 2011]. The transition across the mentioned categories changes with the planet and is determined by the planetary gravity.

Impact melt production and distribution during a cratering event is another aspect of the cratering process that shows quite a bit of diversity and has been extensively studied [e.g. *Hawke and Head*, 1977]. Recent studies from newly available planetary mission data have provided some fresh insights in this direction, especially, on impact melt occurrences at smaller craters [e.g. *Plescia and Cintala*, 2012; *Stopar et al.*, 2013]. The new data have also considerably expanded the morphological diversity of impact melt deposits and led to better appreciation of their pervasive nature [e.g. *Bray et al.*, 2010; *Denevi et al.*, 2012]. Radar data has led to the identification of previously unknown impact melt deposits further highlighting their spatial extent and distribution [e.g. *Carter et al.*, 2012; *Neish et al.*, 2014].

The most recent contribution in this field has been by the mineralogical studies of impact melt deposits using high spatial and spectral resolution data from recent missions [e.g. *Ohtake et al.*, 2008; *Pieters et al.*, 2009; *Mall et al.*, 2009; *Green et al.*, 2011]. Detailed studies of impact melt deposits at several craters have provided new perspectives on the impact melt properties [e.g. *Hirata et al.*, 2010; *Dhingra and Pieters*, 2011; *Dhingra and Pieters*, 2013a; *Dhingra and Pieters*, 2013b; *Wöhler et al.*, 2014; *Öhman et al.*, 2014], some of which have very important implications for the interpretation of lunar crustal composition as well as the impact cratering process [e.g. *Dhingra et al.*, 2013; *Dhingra et al.*, 2014].

The geological setting of the target is one of the important parameters directly affecting the impact melt properties. Our recent work has highlighted a strong correlation between target lithology and impact melt mineralogy at several craters with impact melt mineralogy mimicking the compositional heterogeneity of the target [e.g. *Dhingra et al.*, 2013; also in *Chapters 1 and 4*]. Some of the terrestrial craters also show such compositional heterogeneity [e.g. *Kring et al.*, 2004; *Osinski et al.*, 2008; *Lambert*, 2010]. An important next question is whether craters in similar geologic setting would be expected to have broadly similar impact melt characteristics? If yes, what is the nature of the similarity? If no, what might be other important processes contributing to the differences? In this study, we attempt to evaluate this possibility.

2. Motivation and Major Objectives

The research presented in earlier chapters has highlighted that properties of impact melt can not only contribute to an understanding of the mineralogical diversity of

the crustal column, there is also considerable scope in using impact melt as a tracer in deciphering many aspects of the impact cratering process itself. It includes an understanding of how the target mineralogy gets incorporated into the impact melt, the scale to which heterogeneities can be retained, the relative extent of melt mobility in different parts of the crater and the relationship of melt emplacement with respect to the central peak formation. Despite the complex nature of the cratering process, we see some order that can be usefully interpreted. In this context, we use impact craters as our natural laboratory to understand and evaluate the effects of various parameters on its products such as impact melt, ejecta and crater morphometry.

Our interest is in developing an observational perspective for evaluating the various parameters controlling impact melt properties. A simple case in this endeavor is to compare impact melt properties at craters of similar diameters and which formed in a similar target. The similar crater size and target lithology would ideally lead to similar volume of impact melt which can then be studied and compared to understand the processes involved. The relatively pristine lunar surface is an important repository for the products of impact cratering including impact melt. Compared to the terrestrial occurrences of impact craters which are in various stages of degradation as a result of dynamically active nature of the Earth, lunar impact craters, especially the geologically young, Copernican (and may be Eratosthenian) craters, host an impressive and complete record that is waiting to be extensively mined. The availability of sufficiently high spatial and spectral resolution datasets for the Moon makes it even more compelling proposition. With an extensive array of craters on the Moon, we have the ability to select craters of similar size which formed in broadly similar targets. We acknowledge that natural

settings are not controlled environments and at scales of several tens of kilometers, there are many degrees of freedom. However, we are motivated by our earlier observations of some systematic trends in impact melt properties. This study is therefore based on the premise that the selected targets are comparable but we would exercise caution in the interpretations knowing that certain cratering parameters (e.g. angle of impact, mechanical nature of the target)) are likely going to be different at the selected craters.

The major objective of this study is to carry out a detailed documentation of the melt properties at the selected craters. Although it would be most beneficial to study impact melt deposits all over the crater, for the scope of this study, we are restricting certain efforts, namely geological mapping, to the impact melt deposits on the crater floor. The melt-rich crater floor is the single largest melt-bearing unit and therefore would have a large impact on the observed melt properties. Although small-scale differences in impact melt properties would be occurring in different parts of the crater and would be important, the floor melt deposits would still provide us the big picture. Our earlier experience with Copernicus crater supports this possibility. We would however extend this analysis to other crater units in the near future. The specific aspects studied here are:

- i) Detailed morphological mapping of impact melt deposits on the crater floor including any deposits on the central peaks.
- ii) Detailed assessment of associated mineralogy of various impact melt units on the crater floor.

- iii) We also document the mineralogy of impact melt on the crater walls, rim and nearby region to get an overall assessment of the mineralogical nature of these deposits.
- iv) A comparison of these properties among the selected craters is then carried out assessing similarities and differences with the aim to evaluate whether similar target lithology and impact energy gives rise to similar melt properties.

3. Data and Methods

In this study, we have evaluated impact melt properties at complex craters Jackson and Tycho (Figure 2). The craters have similar size (71 km and 86 km, respectively), both are Copernican in age and formed in a pre-dominantly highlands terrain. Both the craters have an extensive ray system, have majestic central peaks and show extensive impact melt occurrences. These set of similarities make them a good pair for comparing and contrasting the nature of impact melt deposits.

3.1 Geological Mapping

Impact melt deposits at both the craters have been mapped based on their morphological character on a scale of 1:25000. The geographical extent of the mapping effort in this study covers the crater floor. The primary data used to map the melt deposits is Kaguya Terrain Camera (TC) at a spatial resolution of ~10 m [Haruyama *et al.*, 2008]. The data was downloaded as image tiles from the SELENE data archive (<http://l2db.selene.darts.isas.jaxa.jp/>) and subsequently imported into ArcGIS for

generating the base image which was then used for impact melt mapping. The morphological details mapped out in this study are dependent on the illumination geometry as has been discussed earlier in *Chapter 4*. We have therefore taken care that images selected for mapping have comparable illumination conditions across the two selected craters as well as to Copernicus where we also carried out morphological mapping. In this study, we used elevation information from Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) [Chin *et al.*, 2007; Smith *et al.*, 2010] as an additional input in defining the floor units thus increasing the information content of the geological map. We show that integrating such information might provide some additional insights compared to the morphological details alone.

3.1.1 *Geologic Units*

The various morphological forms of impact melt identified at Jackson and Tycho are shown in Figure 3 and explained below. Since the morphological subdivisions are broadly similar to Copernicus crater, we retain the observed morphologies there as our template but added any new units that we have defined at Jackson or Tycho. We continue to use the term ‘megaclasts’ as has been done in the case of Copernicus crater (*Chapter 4*). To reiterate, Megaclasts refer to meter to kilometer-sized boulders which occur along with (usually embedded in) the melt deposits on the crater floor. Megaclasts occur in variety of settings and scales such as isolated mounds and hummocky clusters. They should not be confused with the term ‘clast’ in terms of spatial scale (mm-cm versus kilometers here). However, these rock bodies appear to be associated with the surrounding impact melt in a similar way as small-scale clasts are associated with melt

and hence this term. The individual description of the mapped units is provided below. It should be noted that we have introduced some sub-units in comparison to the geological units defined at Copernicus crater. These sub-units are based on elevation and relative albedo which do not have any additional morphological character. Therefore, the description below is restricted to the main units based on morphological variations observed at these craters.

- i) *Hummocky Unit*: It is defined as a high relief unit comprising of abundant megaclasts along with relatively smaller proportion of smooth material. The hummocky unit primarily occurs on the crater floor and usually exists as a pervasive unit but sometimes is also observed to be interrupted by other units.
- ii) *Smooth Unit*: The smooth unit is usually devoid of any megaclasts and is the smoothest species among the impact melt deposits with minimal relief if any. Here, we have two additional smooth units based their roughness as well as relative elevation on the crater floor.
- iii) *Intermediate Unit*: The intermediate unit comprises of topographically subdued megaclast population where individual clast boundaries are indistinct and they occur more as continuous unit with low but observable relief. In this study we have divided intermediate unit into two sub-units: a) Low Elevation High Albedo Intermediate Unit; b) High Elevation Low Albedo Intermediate Unit. The basic character of both the units is similar in terms of low-relief but rough unit. However, the sub-classification is based on their respective elevation on the crater floor and some albedo differences.

- iv) Isolated Mounds: These are large megaclasts which are usually either not at all surrounded by other megaclasts or they stand out as distinct unit among the surrounding low relief megaclasts.
- v) Mega-Blocks: These are very large blocks occurring on the crater floor attaining the size and elevation similar to the central peaks and therefore have been mapped separately than megaclasts. These are very sparse but significantly different in their extent and morphology as compared to the isolated mounds.
- vi) Flows: These are linear to sinuous features extending from crater wall to the floor and show either a central depression with raised walls or lobate deposits draped on the underlying topography. This unit is usually quite restricted but sometimes large deposits are observed from the wall all the way to the floor. Other times, the unit manifests itself as small linear depressions terminating into smooth ponds on the crater walls.

We introduce some additional morphological units than what were mapped at Copernicus crater. It includes new units on the crater floor and a separate set of classification for the central peaks. Similar to our philosophy of separating out the units located in major parts of the crater (viz. floor, walls, peaks), we classify impact melt units on the central peaks separately.

- vii) Melt Fronts: These are large, continuous sheet-like structures occurring in different parts of the crater floor, sometimes enveloping the large boulders while on other occasions, they appear to climb up the central peaks.

- viii) Melt Front Striations: These are similar to the *Melt fronts* in their morphology but can only be defined on their leading side while the lagging side is merged with the background floor melt deposits.
- ix) Central Peak Low Albedo Coating: This central peak unit is very thin, low-albedo in character and is found principally associated with one of the peaks. It has also been determined to be mineralogically distinct. It is only observed at Jackson crater.
- x) Central Peak Boulder Regions: This central peak unit is comprised of boulder fields which occur almost throughout the peak. Although boulders are much more abundant, we have focused on locations with boulder clusters.
- xi) Central Peak Unconfined Perched Deposits: This central peak unit is defined as largely smooth in its nature but could be locally rough in texture. It occurs at various locations as a perched deposit, generally occurring on the slopes of the peaks but also sometimes in lows, not surrounded by high standing topography on all sides.
- xii) Central Peak Undivided: This unit includes the remaining area on the peak that did not have any specific morphologic character associated with it except surfaces with different surface albedo and texture but not in a coherent way. It also includes areas in shadow or saturated with illumination.

3.1.2 Mapping Rules

There are certain set of rules which were defined while mapping the above mentioned units to ensure a systematic and effective approach. In an effort to avoid over-

interpretation of the datasets, ambiguous impact melt regions were not mapped. At the same time, the mapping effort has been a mix of objective criteria and subjective intuition that builds over time. Following are the general rules followed while mapping:

- i) The unit boundaries are primarily defined based on differences in physical characteristics such as albedo, texture and structure. In this study, we also used regional elevation differences.
- ii) The morphological units should have sufficient spatial coherence in order to be mapped as a unit. Chaotic units which display a mixed character on small spatial scales are classified as ‘undivided’.
- iii) The geomorphological units are broadly classified into floor and peak sub-units for simplicity and to accommodate variability that is specific to these broad units. This convention is followed even when certain units in these classes share similar morphological character. In case where one unit transitions into the other (e.g. unconfined perched deposits transitioning sometime into flow deposits), the unit with the larger extent is used for assigning unit classification.

3.2 Spectral Mapping

Individual Data cubes from Moon Mineralogy Mapper (M^3) [*e.g. Pieters et al., 2009*] were downloaded from Planetary Data System (PDS) for the selected craters and mosaicked in ENVI software to obtain seamless coverage of the study area. Mosaics for optical period Op2c2 in case of Jackson and Op2c1 for Tycho have been used in this study. The mineralogical analysis of impact melt occurring at Copernicus has been carried out in numerous ways:

i) *Spectral parameter mapping*: This effort involved using some standard parameters like strength of absorption bands and albedo to map the general mineralogical variability and also to identify locations of interest for further detailed analysis. We used the algorithms developed jointly by the M³ team for data analysis. The parameter maps were commonly used in the form of color composites by combining selected parameters. Representative spectra were extracted from various regions to understand the mineralogy in detail.

The absorption band strength parameters were calculated in two ways. The specific formulation is presented in Table 1 and the procedure is described here. In the first case, an integrated band depth (IBD) was calculated by first removing the continuum slope from the spectrum and then adding up the estimated band strength values (with respect to the continuum of 1) at all wavelengths that were covered by the absorption band. The absorption band strength around 1000 and 2000 nanometers were estimated in this way and the corresponding parameters are mentioned as IBD1000 and IBD2000.

The second way of estimating the band strength was to partially cover the absorption bands and guided by the short wavelength (900-950 nm and 1950-2000 nm) absorption for the low Ca-pyroxenes and long wavelength (950-1000 nm and 2000-2500 nm) absorption for the high Ca-pyroxenes. The second procedure for band strength estimation was aimed at separating out the contributions from these two different types of pyroxenes. In this study, we have used this parameterization only for the long wavelength absorption bands (around 2000 nm) since the differences are more apparent there.

ii) *Soil sampling*: The soil sampling was carried out for impact melt units occurring on the floor, wall and the rim; wherever impact melt units could be identified

with confidence. We understand that certain smooth areas could simply be fluidized ejecta. Accordingly, we have carried out soil sampling near pervasive melt deposits and assumed that all smooth areas are either only impact melt or it is the major component. The spectra were extracted by drawing regions of interest in areas devoid of any craters (observable at Kaguya TC resolution of 10 m) which could contaminate the sample with fresh (immature) material.

iii) *Localized sampling at interesting locations*: Several interesting locations identified either based on their morphology or due to strong spectral signature, as observed in spectral parameter mapping, have been sampled to extract mineralogy information. The geological context (local and regional) for such locations at the highest possible resolution has also been studied while understanding the relevance of the mineralogical signatures. However, it should be realized that the spectral data at 140 m per pixel when draped on a 10 m per pixel data is stretched to its limits making straightforward interpretations difficult at times. The inherent data striping starts to show up making it difficult to identify fine scale differences that might be present. Therefore, wherever possible, we supplement such observations with the actual spectra to make a judgement.

3.2.1 Spectral Mapping Rules

Spectral mapping rules were defined for a systematic and reliable analysis. In view of M³ data related issues such as residual thermal component, small variations in repeat coverage and spectral instability in the short wavelength region (typically 540 -750 nm), the analysis strategy was made as rigorous as possible. At the same time, the rules

were also made flexible enough to accommodate the diversity of situations that come up during such detailed analyses. The general guidelines followed are described below:

- i) The sampled spectra should be reproducible in at least one other optical period (repeat coverage data) unless repeat coverage is not available. Otherwise, it is generally not sampled.
- ii) The spectra should be identifiable across at least few pixels to be regarded as representative. There is flexibility to allow how many pixels depending whether terrain is comprised of boulders or is a continuous outcrop.
- iii) As an exception, single pixel spectrum is admissible if the spectrum is too strong to be an artifact and can be identified in another optical period (repeat coverage data).
- iv) In some cases, single pixel spectrum is selected despite the fact that it is noisy, just because geologic context clearly supports an identifiable feature such as crater, collapse pit or mound.

4 Results

We present the impact melt properties of the two selected craters, Jackson and Tycho in separate sections for each of the observed aspects.

4.1 Geologic Setting

4.1.1 Jackson

Jackson (22.4°N 163.1°W; 71 km) is a young crater (Copernican age) located on the lunar far side, east of Mare Moscoviense and north of SPA basin (Figure

4a, b). The crater has a spectacular ray system on the far side (Figure 2), has well-formed terraces as well as a cluster of central peaks with varying degrees of morphological freshness. The crater is located in the deep far side highlands and therefore the geologic setting is principally feldspathic. The southernmost central peak of Jackson has been reported to host a mafic lithology surrounded by a notable occurrence of crystalline plagioclase [e.g. *Ohtake et al.*, 2009]. The mafic lithology has been proposed to be likely of impact melt origin [e.g. *Ohtake et al.*, 2009]. The mineralogy of the region is dominated by crystalline and shocked plagioclase and likely a mixture of low and high-calcium pyroxene.

The crater diameter suggests an excavation depth of about 11 km [e.g. *Cintala and Grieve*, 1998] indicating the thickness of the crustal column that was modified (excavated and melted) during the event. The peaks likely came from below this depth.

4.1.2 Tycho

Tycho (-43.29° 348.78°, 86 Km) is also a Copernican age (108 million years) crater located in the southern highlands region on the lunar near side (Figure 4c, d). However, some large mare basalt exposures occur in the north and west of the crater about 200 km away. Tycho has an extensive ray system (Figure2) that is observable with a naked eye, a majestic central peak and spectacular impact melt deposits that occur almost everywhere on the crater including the rim, walls, floor and even the central peak [e.g. *Dhingra and Pieters*, 2011]. Mineralogically, Tycho has high-calcium pyroxene bearing central peaks [e.g. *Tompkins and Pieters*, 1999] which has been an enigma owing

to the primarily highland setting of the crater. The high-calcium pyroxene signatures have been suggested to be representing an exposure of a buried pluton [e.g. *Tompkins et al.*, 1999]. More recently, Mg-spinel bearing lithology has been reported [e.g. *Kaur et al.*, 2012; *Pieters et. al.*, 2014] from various locations in the crater. Tycho is also known for its dark halo observable under high solar illumination and has been suggested to be representing quenched glass [e.g. *Smrekar and Pieters*, 1985]. The crater diameter suggests an excavation depth of about 13 km [e.g. *Cintala and Grieve*, 1998].

4.2 Impact melt distribution and morphology

The young age of both the craters allows confident identification of variety of impact melt deposits located on the crater floor, wall and rim region. We have carried out a detailed mapping of the floor impact melt deposits as it forms the single largest impact melt unit and could provide useful information about the character of the melt. The distribution of impact melt deposits in other parts of the crater, although not specifically mapped has been analyzed and a documentation of their character is also presented here.

4.2.1 *Jackson*

4.2.1.1 Floor Impact Melt

The floor of Jackson crater provides a diverse variety of impact melt units. We have mapped 15 geological units on the crater floor based on the surface texture, overall albedo and local elevation. The latter was included due to a distinct elevation pattern observed on the floor (Figure 5b). There are 5 continuous melt units (Figure 6). The three extensive units are *Low Elevation High Albedo Intermediate Unit* (N, NW

crater floor), *High Elevation Low Albedo Intermediate unit* (N, E crater floor) and *Low Elevation Low Albedo Smooth unit* (SW crater floor). Each unit usually occurs as a coherent entity. However, in case of the *Low Elevation Low Albedo Smooth unit*, it extends into the *Low Elevation High Albedo Intermediate Unit*. Relatively smaller scale continuous units include the *Smooth Unit* and *High Elevation Low Albedo Smooth Unit*. These units are more limited in their spatial extent and are principally located in parts of the southern and eastern crater floor.

The second important set of units includes the megaclasts. These include very large-sized *Megablocks*, comparable to the central peaks. There are two Megablock units mapped, one located in the northern crater floor and the other is close to the crater center. Both are extensively draped with impact melt with the latter showing extensively fractured melt layer (Figure 7a, b). The next megaclast unit comprise of *Isolated Boulders*. They are mostly located in the western part of the crater floor although some boulders are also scattered in other parts of the floor. As with the *Megablocks*, these also seem to be covered with impact melt. Some of them are only partial exposed with the remaining part covered by a melt front (Figure 7c). Many of the mapped boulders have high standing topography with poorly-defined boundaries (Figure 7d). The last set of megaclasts form the *Hummocky unit* on the crater floor and are spatially more extensive. However, these are usually much smaller in size and tend to occur in clusters. A major cluster is located in the NW crater floor (observable in Figure 6) surrounded by *Isolated Mounds*. Relatively smaller clusters, sometimes widely scattered, are located in remaining part of the crater floor and can be found associated with all the major continuous units discussed above.

Central peaks also host small impact melt occurrences mainly as *Unconfined Perched Deposits* which include melt with variable texture occurring mostly on sloping surfaces, not surrounded by well-defined topography on all sides. Major occurrences are on the southern central peaks. Another prominent melt occurrence is on the apex of the southernmost peak. Owing to the different morphological character of this unit, a smooth low-albedo coating, it has been classified separately as *Central Peak Low Albedo Coating*. In addition, there are numerous boulder clusters (*Central Peak Boulder Regions*) distributed throughout the central peak on flat as well as sloping surfaces.

One of the most interesting impact melt morphology on the Jackson floor comprises of a set of coherent melt fronts (Figure 8). Although they are not abundant in the region but a prominent cluster is mapped on the central peaks with melt-front boundaries facing the upslope direction. Relatively small melt fronts have also been mapped elsewhere on the floor, sometimes as well-defined units and on other occasions, only the leading edge could be mapped (as *Melt Front Striations*; see black lines in Figure 8b).

4.2.1.2 Impact Melt Deposits Elsewhere

Distinctive impact melt deposits in other parts of the crater largely occur in terms of melt ponds. Relatively large, elongate melt ponds (4-7 km) are located on the north eastern and eastern wall sections while small melt ponds are scattered throughout the crater walls. Other notable occurrences are on the western and south-western rim region where small melt ponds are present. The remaining region at best can be described as resurfaced by the Jackson cratering event but specific impact melt morphologies like

large flows around the rim region are not observed. The crater walls of Jackson however, do exhibit a thick veneer with occurrence of cooling cracks, scalloped margins and channelized small flows on the wall-floor interface (Figure 9).

4.2.2 Tycho

4.2.2.1 Floor Impact Melt

The impact melt on the floor of Tycho occurs at two different elevations with the western crater floor at a relatively higher elevation than the eastern crater floor (Figure 5 c, d). This two floor-level setting is similar to Jackson which has an elevated eastern crater floor as compared to the western floor. We mapped 15 geological units on the floor with 4 continuous and extensive units and 11 units of limited extent or discontinuous nature. Among the latter, 4 are central peak units (Figure 10).

Among the 4 continuous units, 2 units (*High Elevation Low Albedo Intermediate Unit* and *Low Elevation Intermediate Albedo Smooth Unit*) have protrusions into nearby units (*High Elevation High Albedo Intermediate Unit* and *Low Elevation Intermediate Albedo Intermediate Unit*). The 11 discontinuous or limited extent units are located across these continuous units and display identifiable patterns, sometimes similar to the trends observed at Jackson while at other times, they are different. Among the megaclasts (*Isolated Mounds*, *Hummocky Unit* and *Megablocks*), the *Isolated Mounds* unit is scattered throughout the crater but we note that they are especially concentrated in the northern crater floor. The *Hummocky Unit* is quite extensive on the crater floor. The low elevation region on the eastern crater floor, with the exception of *Low Elevation Intermediate Albedo Smooth Unit* (brown color), has a notably higher concentration of

Hummocky Unit (magenta color) as compared to the high elevation region on the west. The *High Elevation Low Albedo Smooth Unit (light pink)*, located in the south-western crater floor is almost devoid of *Hummocky Unit* and *Isolated Mounds*. The crater floor has some *Megablocks* located in the western part which are draped completely by the impact melt. Although they are large and coherent in nature, these *Megablocks* appear relatively subdued as compared to the observations of this unit at Jackson crater.

Tycho displays *Flow* features and *Melt Fronts* (and *Melt Front Striations*). We note that the latter units are concentrated only in the western part of the crater except one isolated feature on the central peak. Several distinct *Melt Fronts* can be observed lining the edges of the floor (Figure 11a, 12) with well-preserved curvilinear fronts oriented in upslope direction. At times, we could identify multiple *Melt Fronts* at the same location but different elevations. Interestingly, we did not observe any *Melt Fronts* or *Melt Front Striations* in the entire eastern section of the crater floor. Instead, this region is laden with extensive *Flows* extending from the crater walls at different levels and show diversity of morphologies some of which were highlighted in *Chapter 1 (Figures 7, 8)*.

The central peaks of Tycho display an extensive melt cover, mainly in the form of *Unconfined Perched Deposits*. There is also a large melt pond in the northern section of the main central peak unit. Many impact melt locations on the peak display extensive set of cooling cracks. An interesting observation is the occurrence of a large *Melt Flow Striation* on the eastern part of the main central peak unit. The feature spans across the peak unit and can be observed on either side (Figure 11a, b). The *Boulder Regions* are mostly associated with the distal ends of the mapped melt occurrences.

4.2.2.2 Impact Melt Elsewhere

The melt diversity at Tycho extends beyond the crater floor to the walls and the rim with some notable occurrences. The rim and continuous ejecta deposits host large number of melt ponds scattered around the crater, the distribution of which has been found to be asymmetric and interpreted to be likely associated with the direction of impact [e.g. *Kruger et al.*, 2012]. Notable impact melt occurrences are located on the eastern rim where melt has accumulated in low-lying regions (Figure 13b). The southeastern rim also hosts an impact melt flow feature about 20 km long flow with extensive set of cooling cracks of various dimensions (Figure 13c). A smaller flow, guided by the local topography occurs further south of this feature.

The crater walls at Tycho exhibit a different set of impact melt features with extensive melt cover in the form of thick coating or veneer. Several sections of the crater wall are inundated with melt forming ponds on the terraces as well as multiple flows, some of which indicate the highly chaotic nature of the event (Figure 14, 15).

4.3 Mineralogical trends

The mineralogical character of impact melt at the two selected craters provides an interesting contrast and some similarities. The mineralogical observations have been substantially strengthened with the integration of high spatial resolution imaging data. This methodology allows trends and details that could not otherwise be resolved with the coarser resolution spectral data. Imaging data provides the crucial geological context for the mineralogical observation as presented below. At the same time, it should be realized that the spectral data (140 meters/pixel) is stretched to its limits when draped on imaging

data (10 meters/pixel), the latter having two order of magnitude higher resolution. Accordingly, the presented results might have data stripes but can still be comprehended along with the corresponding spectra from the target of interest.

4.3.1 Jackson

4.3.1.1 Mineralogically Heterogeneous Melt on the floor

The mineralogy of the floor impact melt at Jackson is distinctively heterogeneous when observed on a M³ standard color composite (Figure 4b, 16a) with the northern crater floor dominated largely by a high albedo (Figure 4a), feldspathic melt and the southern floor primarily indicating a mafic signature. This spatial duality is supported by very subtle spectral evidence (Figure 16b). The northern crater floor soils display featureless spectra while the southern floor impact melt exhibits a weak but discernable absorption band around 1000 nm (slightly longer). This is the second documented example of large scale mineralogical heterogeneity in impact melt after Copernicus crater [Dhingra et al., 2013; Wöhler et al., 2014]. Although this distinction has been noted earlier in various forms [*in Chapter 1, also in Ohtake et al., 2009; Hirata et al., 2010*], there are very interesting finer details that have never been discussed.

The first interesting observation is the small protrusion of the *Low Elevation Low Albedo Smooth Unit (brown color)* into the *Low Elevation High Albedo Intermediate Unit (bright yellow)*. This relationship is consistently observed in the mineralogy as well as the morphological mapping (as reported earlier in section 4.2.1.1). The melt feature is discernible in the color composite (yellow arrows in Figure 16c) as well as spectra (Figure 16d). A fracture running across the units (white arrows in Figure

16c) provides a good sampling point and shows mafic mineralogy (red spectrum) in contrast to the featureless spectra further away from it (blue/purple spectra) and the mafic unit.

The second interesting observation is the occurrence of mafic melt exposures scattered throughout the otherwise feldspathic impact melt in the northern crate floor. The mafic exposures are associated with high standing topography defined by the megaclasts (*Hummocky Unit*, *Isolated Mounds* and *Megablocks*) but not all of them seem to carry the mafic signatures (Figure 17). In fact, there are several examples where only a part of the megaclast exhibits a mafic signature while the other part is featureless (Figure 17, black filled arrow with yellow outline; Figure 18a, orange spectrum). This is surprising given the fact the morphological character of the entire megaclast looks uniform.

4.3.1.2 Melt Ponds

There are melt ponds occurring in different parts of the crater as described in section 4.2.1.2. Majority of them are relatively small (1-2 km) and usually difficult to locate on M³ images. However, we were able to sample some larger ponds on the crater wall and rim (Figure 18b). The spectral character of the ponds has very weak signatures making it difficult to discern the mineralogy. However, within the available constraints, they seem to show some variability in their properties. The melt ponds on the western rim and eastern wall show weak features beyond 1000 nm and have higher overall reflectance. In contrast, a small pond on the western wall appears largely featureless and has a lower albedo. Comparing these spectra with the general soil spectra of the two major units on the crater floor provides an interesting insight (Figures 18b and

16b respectively). Usually high albedo spectra is featureless and low albedo spectra has the weak absorption at 1000 nm. However, in case of the melt ponds, it is the opposite. In view of these observations, it is possible that the weak absorption in high albedo spectra from melt ponds on the western rim and eastern wall is being contributed crystalline plagioclase fragments. The character of the spectra only allows us to speculate this at the moment but the same cannot perhaps be confirmed with the available data. However, the suggested interpretation is feasible given the abundance of crystalline plagioclase exposures in the central peak of Jackson crater [e.g. *Ohtake et al.*, 2009; *Donaldson-Hanna et al.*, 2014]

4.3.1.3 Character of Pyroxenes at Various Locations

The detailed analysis of the crater has highlighted the prevalent nature of pyroxenes in the region associated with multiple crater units, ejecta and impact melt. The spectral signatures of various exposures display small differences which could indicate differences in mineralogy but could also result from variable degree of maturity as well as mixture of other components (e.g. small amounts of crystalline or shocked plagioclase, quenched glass and non-crystalline material). Spectra from some of the prominent pyroxene exposures are shown in Figure 19. Almost all the locations have strong absorption bands around 1000 nm but relatively weaker 2000 nm absorptions, except the fresh crater on the northern rim (Figure 19, black spectrum) where both 1000 nm and 2000 nm are equally strong. Although there are some differences in the relative width of the absorption bands at 1000 nm, the band is generally wide in all the sampled spectra and likely has more than one component.

There is additional diversity in terms of spectacular occurrences of crystalline plagioclase surrounding a mafic exposure at the central peaks. The same is discussed separately under section 4.4.1.

4.3.2 Tycho

The extensive impact melt deposits at Tycho were spectrally sampled at numerous locations to evaluate their mineralogical character. It includes obtaining spectra of the floor impact melt, wall melt ponds, melt deposits on the central peaks and the crater rim region. The impact melt mineralogy is dominated by high calcium-pyroxene. In addition, we report distinctive differences within the high calcium-pyroxene suite based on variations in band positions of the sampled impact melt deposits.

4.3.2.1 Distinct Mineralogy of the Eastern Wall

On a regional scale, the eastern wall of the crater stands out on the M^3 spectral color composites (Figure 20b, c, white arrows) as a distinctive unit when compared to the remaining wall sections. The spectra extracted from multiple locations across Tycho, clearly illustrate this difference in mineralogy (Figure 20a, d). The character of a spectrally coherent unit on the eastern wall (#6, magenta spectrum) has a distinctively long wavelength absorption bands at 1000 nm and 2000 nm compared with the remaining impact melt deposits. It is interesting to note that impact melt deposits in the SW crater floor (#4, pink squares) and south wall (#8, green spectrum) seem to share some spectral similarity with the eastern wall deposits, although they have much weaker absorptions around 2000 nm to make specific interpretations. The remaining melt

deposits, although high calcium-pyroxene rich, have band positions slightly shorter than the melt deposits of the eastern wall. A pertinent question at this point is about the source of this heterogeneity which can perhaps be answered by the geologic association.

In order to answer this specific association of the distinctive high calcium-pyroxene signature of the eastern wall, we located an area in M³ data where impact melt could be differentiated from high standing mounds which represent the wall material. This high resolution spectral sampling indicates that the wall material (Figure 21) has relatively short-wavelength absorption bands (#2, 3, 4, 5) compared to the enclosed impact melt unit (#1) suggesting that the signatures are likely associated with impact melt. Due to the difficulty in finding additional suitable locations where such evaluations could be confidently carried out, we would tentatively assign the long wavelength high calcium-pyroxene signature to the impact melt unit on the eastern wall.

4.3.2.2 Melt Ponds

As described earlier, Tycho has extensive deposits of impact melt ponds scattered in different parts of the crater. However, owing to the coarse resolution of spectral data, we are limited to determining the mineralogical composition of the more prominent occurrences. Even at this scale, these represent some of the very first observations of impact melt mineralogy and therefore an important new input to the study of impact melt deposits on the Moon. We obtained spectra from impact melt ponds on the northern and southern walls as well as the eastern rim, the latter hosting some of the large melt deposits (Figure 22).

The melt ponds distinctively show their affiliation with a high calcium-pyroxene source material (Figure 23). As observed with large scale melt deposits, the spectral diversity can be observed at the relatively small scale melt ponds as well. The differences in band positions at 1000 nm and 2000 nm are quite evident although in some cases, the 2000 nm band is not strong enough for making comparisons. The best contrast is presented by the large flow located on the SE rim (Figure 22, locations 5, 6, 7). The spectral signature of the flow feature sampled at two locations (#5, #6 in Figure 23) distinctively show long wavelength absorption band positions. In contrast, a 400 m diameter crater that impacted onto a small melt channel connecting two large ponds, shows slightly short wavelength absorption bands that can be noted at both 1000 nm and 2000 nm (#7 in Figure 23). This observation is consistent with the results from high spectral resolution study of the eastern wall presented above.

4.4 Character of the Central Peaks

Central peaks represent the exposure of some of the deepest materials within a crater [*e.g. Melosh, 1982*] and therefore have been extensively used to decipher the subsurface mineralogy [*e.g. Tompkins and Pieters, 1999; Cahill et al., 2009; Song et al., 2013*]. The peaks of Jackson and Tycho contain some exposures of impact melt and represent another geologic setting where impact melt deposits can be studied.

4.4.1 Jackson

The central peaks of Jackson have been well-known recently due to the occurrence of extensive crystalline plagioclase exposures [*e.g. Ohtake et al., 2009*;

Donaldson-Hanna et al., 2014; also shown here in Figure 24c, blue spectrum]. A mafic melt exposure was also documented earlier and suggested to be of either impact melt origin or a megaregolith layer overlying a crustal component [*e.g. Ohtake et al.*, 2009]. It has also been shown that the peak contains mixtures of crystalline plagioclase and pyroxene at many places.

We document the wide existence of the mafic component on the central peaks than has previously been noted. The mafic component is not uniquely associated with the low-albedo unit (marked in Figure 24a and mapped in 24b) but is much more pervasive on the peaks as captured by the yellow coloration in the M³ standard color composite (Figure 24b). In particular, a coherent and extensive lithological unit (marked with yellow arrows in Figure 24a) located very close to the main central peak is dominantly mafic (Figure 24b, c) with no other detectable mineralogy and shares similar spectral signatures as the peak. In fact, further north there is another lithological unit on the floor which shares the same mafic character but which has a less prominent topography. We think that these two extensions of the wall unit (especially the larger, coherent unit) are connected to the two central peaks, similar to the association observed at King crater and at Eratosthenes. Based on the distinct similarity in mineralogy and the geological association of these units, we have mapped the larger unit in the south (marked with yellow arrows in Figure 24) as part of the central peaks. The smaller unit further north is likely having the same relationship but it is less obvious and therefore we have not yet mapped it as part of the central peaks.

The specific melt accumulations on the central peaks are relatively smaller from the perspective of spectral sampling by M³ data. Spectra from one of the

impact melt unit large enough to be sampled (Figure 25a, blue/orange arrows), provided a mixed signature with part of the melt showing a weak absorption at 1000 nm (Figure 25, blue spectrum) while the remaining melt being largely featureless (Figure 25, orange spectrum).

4.4.2 *Tycho*

The extensive melt cover on the central peaks of Tycho also shows some spectral diversity within the high calcium-pyroxene suite. The spectral diversity is best observed in the M^3 complementary color composite highlighting pyroxene differences (Figure 26). In particular, the distal end of the smaller peak located NE of the main peak appears to show distinctive spectral units. Incidentally, this is also one of the locations from where Mg-spinel has been reported [*e.g. Kaur et al.*, 2012; *Pieters et al.*, 2014].

The spectral signatures of various units on the peaks have very strong absorption bands enabling the detection of differences in band positions. The reported differences long ward of 1000 nm and 2000 nm are also observed here. Impact melt occurrences located close to the small peak unit capture both the long (#5 in Figure 26c) and short wavelength absorption band varieties (#6 in Figure 26c) complementing the spectral diversity discussed earlier in the section.

4.5 Mineralogy-Textural Linkages

Our integrated analysis combining compositional information with morphological form led to several observations where the two parameters appeared to be

linked in some form. The relatively young age (Copernican, <1 billion years) of Jackson and Tycho has preserved a lot of textural information that can be analyzed in documenting the relationship between mineralogy and texture. We present a few examples here in this regard.

4.5.1 Jackson

The first example is of a smooth impact melt patch located in the NE corner of the crater floor which is impacted by a 400 m diameter crater (Figure 27a, orange arrow), sufficiently large to be analyzed by M^3 data. It is observed that the smooth impact melt around the fresh crater (Figure 27a, brown and green arrows) displays weak to non-existent absorption bands while the fresh crater exhibits very distinctive absorption around 1000 nm and a weak absorption band at 2000 nm that is centered at longer wavelengths (Figure 27c). We interpret the spectra to represent a high calcium-pyroxene mineralogy which is interesting in view of the location of this melt in close proximity to the dominantly feldspathic northern melt deposits as indicated in the color composite in Figure 27b.

The second example comprise of a set of observations all over the crater where spectral signatures seem to be directly correlated with either large scale fractures or high standing features on the crater floor when observed in M^3 color composite in conjunction with high spatial resolution Kaguya TC data (Figure 28b). Both the morphological/structural features seem to have a coarser texture than the background crater floor material (Figure 28a). Although at times, the spectral data is stretched to the extremes for highlighting these observations with abundant visible striping (which may

be distracting), the spectra from some of these features (Figure 28c, #1, #2 versus #3, #4) support the observations based on color composite alone. Apart from the presence of relatively strong absorption bands, we also note variation in the spectral slope of these two set of features. The pervasive occurrence of this correlation is interpreted to be emphasizing the close link between surface texture of the melt and the corresponding mineral signatures.

While the effects of space weathering are well-known in the lunar community and such observations of fresh surfaces giving strong spectral signatures may not come as a big surprise, it is nevertheless interesting to see the spatial scale at which mineralogical signatures are more prominent on the fresh, textured surfaces. An important observation concerns the mafic signatures linked to the high standing features (#1, #2) draped in impact melt similar to the melt on the background floor material. No fresh craters or large fractures seem to be contributing to the mafic signatures here. The only notable difference observed in this case is that the mounds appear to have a rougher texture than the background melt.

4.5.2 *Tycho*

An interesting example of morphologically observable textural contrast in impact melt deposits exists on the floor of Tycho where the spectral signatures seem to be affected by the texture of the impact melt. A very small, smooth impact melt deposit occurs north of the central peak on the floor (Figure 29a, #1). In contrast, the northern edge of the smaller peak unit has a rough textured impact melt (Figure 29a, #2). Spectral signature of the two regions show stronger absorption bands associated with the rough

textured melt and relatively weaker signatures associated with the smooth deposit (Figure 29, #2 versus #1 respectively). The mineralogy of the two impact melt deposits however appears to be similar as indicated by their respective absorption band positions at 1000 nm and 2000 nm.

5 Discussion

The vast array of observations: mineralogical, morphological and integrated, at the two craters Jackson and Tycho, provide us the opportunity to compare some key aspects of their impact melt properties and evaluate whether there are similarities that could be linked to broadly similar targets and amount of impact energy involved in their creation. We present here a summary of major observations in this direction.

5.1 Pre-Impact Target Properties

The character of the target lithology is known to affect the products of the cratering including volume of melt produced and its distribution. Although it is non-trivial to interpret the nature of the target lithology, we provide some observations that could be useful in deciphering the likely character of the target rocks.

5.1.1 *Physical Nature of the Target*

The physical character of the target includes individual mineral stability to high level of shock and disintegration as well as macro-porosity of the target. Jackson and Tycho present a striking contrast in the occurrence and distribution of the megaclast units, namely *Isolated Mounds* (dark brown) and the *Hummocky Unit* (magenta). At Jackson, the *Isolated Mounds* are quite pervasive, appear to be mostly

large sized and are concentrated in the low elevation western section of the crater floor. In contrast, the *Isolated Mounds* at Tycho although equally pervasive, are quite scattered with no prominent clustering is observed. They also don't seem to bear any association with the floor elevation and are uniformly distributed across the high elevation western floor and low elevation eastern floor. The average size of the mounds also appears smaller as compared to the average size of these mounds at Jackson.

These observations are somewhat correlated with the character of the *Hummocky Unit* where Jackson appears to have a very small proportion of this unit. At Tycho, *Hummocky Unit* is relatively much more pervasive, especially in the low elevation eastern crater floor (with the exception of *Low Elevation Intermediate Albedo Smooth Unit*). The size of each sub-unit within the *Hummocky Unit* also seems to grade to very small sizes at Tycho compared to Jackson crater.

While this nature and distribution of the megaclasts (*Isolated Mounds* and *Hummocky Unit*) could be interpreted in many ways, our preferred interpretation is that these observations suggest a relatively coherent target at Tycho which led to an efficient and more uniform distribution of the impact energy. As a consequence, we observe evenly distributed occurrence of *Isolated Mounds* and *Hummocky Unit*. The smaller sizes of the individual sub-units also seem to be consistent with this interpretation. In contrast, we believe that the pre-impact target at Jackson crater was likely extensively fractured due to which the impact energy was preferentially funneled along weak zones (large scale fractures). As a consequence, the impact could not finely pulverize the target leading to smaller proportion of *Hummocky Unit*. The fractured nature of the target led to higher macro-porosity which only allowed the impact

event to cause a first-order breakdown of rocks and thereby led to larger sizes of boulders at Jackson compared to the observations at Tycho.

These observations although nascent at the moment could be documented systematically across different craters to evolve a consistent methodology for evaluating the nature of the pre-impact target lithology. An additional set of observations that could potentially validate such interpretations based on the character of megaclasts, include an assessment of impact melt volume produced at each of the craters. It is known that other parameters being equal, impact melt volume varies with respect to rock porosity. A correlation of estimated impact melt volume and the boulder sizes may help validate the argument presented above.

5.1.2 Mineralogical Character

The mineralogical makeup of the target rocks is another factor that controls the nature of the products in a cratering event. It is known that plagioclase is much more susceptible to shock and physical disintegration and that olivine and pyroxenes are relatively more persistent mineralogies. Jackson has significant proportion of crystalline plagioclase exposures observable in the central peaks. The high albedo material on the northern crater floor is also likely composed in part of shocked or crystalline plagioclase material. Thus, Jackson target rocks could be considered as a heterogeneous mixture of plagioclase and high calcium pyroxene. Some local variations in pyroxene mineralogy were also noted and hint at small occurrences of low calcium pyroxene lithology. Considering this information alone, Jackson would perhaps be

expected to display a higher proportion of impact melt since it has a larger proportion of the weaker plagioclase-bearing lithology.

In contrast, Tycho is dominated by different varieties of high calcium-pyroxenes. Although small exposures of crystalline plagioclase have been reported from the central peak [*e.g. Ohtake et al., 2009*], plagioclase does not seem to form a major part of the pre-impact target lithology. This interpretation is in contrast to the highland setting of Tycho. Based on our observations, it seems that Tycho might not have formed in highland rocks or alternatively, the highland rocks at Tycho impact site were heavily intruded so that the crustal column had very thin cover of highland material.

Irrespective of the relative differences in mineralogy of the target rocks at Jackson and Tycho, it is amply clear that although both the craters appear to have formed in highland settings, the abundance of high calcium-pyroxene at both the craters, as highlighted by our detailed observations, indicate an intruded crustal setting. Further analysis of these regions using complementary datasets such as from GRAIL mission [*Zuber et al., 2013; Andrews-Hanna et al., 2013*] could help evaluate this hypothesis in more detail.

5.2 Impact Melt Mineralogical Heterogeneity

The mineralogy of impact melt at various craters has been highlighted in *Chapter 1* and has been shown in detail at Copernicus crater [*Dhingra et al., 2013*]. The mineralogy of impact melt at Jackson is broadly similar to the observations at Copernicus with the northern and southern floors bearing slightly different but detectable mineralogical signatures. We have also shown that differences in melt mineralogy exist at

smaller spatial scales. At Tycho, the mineralogical heterogeneity certainly exists as shown by the differences within the high calcium-pyroxene suite. However, instead of well-defined regions on the crater floor, the regional heterogeneity is observed in terms of distinctive eastern wall mineralogy. It is still unclear as to why this signature is concentrated on the eastern crater wall. Additional work is required to ascertain whether the melt mineralogical heterogeneity at Tycho is similar to the distinct melt mineralogies reported at Copernicus crater [*Dhingra et al.*, 2013; *Chapter 3, 4*] associated with the nature of locally melted target rocks or is caused by some other mechanism.

5.3 Impact Melt Emplacement and Evolution

The production of impact melt during the cratering event, its movement across the crater in various stages, the final emplacement and subsequent evolution depends upon numerous parameters. Impact energy is one of the important parameters. Since Tycho and Jackson have similar crater sizes which were formed in largely similar targets, we assume that the amount of impact energy available for the event was comparable to a first order. In such a scenario, it would be interesting to compare the dominant impact melt morphologies, their distribution and any specific trends.

5.3.1 *Evolution of the crater floor*

The crater floors of both Jackson and Tycho show two elevation levels. We have earlier on also documented a local topographic low the floor of Copernicus crater [*Dhingra et al.*, 2013]. Earlier studies have shown significant subsidence occurring in large impact melt deposits [*e.g. Wilson and Head*, 2011] subsequent to their emplacement due to cooling. A similar interpretation could be made

in case of the observed elevation differences at Jackson and Tycho craters. However, some of the observations made in this study indicate that apart from subsidence of impact melt, there are probably other contributing factors to the observed elevation differences.

The first observation is the largely coherent nature of the elevation units. In view of the highly chaotic nature of the impact cratering process, where large scale slumping of material occurs along with melting, the floor is expected to be a random mixture of melt and rock lacking coherence. Any subsequent subsidence should therefore lead to local elevation differences (jagged topography?). However, it is not the case at Jackson or Tycho at the observed spatial scale. Our observations suggest some level of coherence in the two floor levels.

The second observation, in support of other parameters controlling elevation differences, is related to the distribution of *Hummocky Unit* at Tycho. If floor elevation differences occurred during early stages of the crater modification (although how early is in relative sense here), then melt is expected to move towards the lower elevation floor unit thereby inundating the region and submerging any small scale topography. Contrary to this expectation, the low elevation floor units at Tycho (eastern crater floor) have an observationally high density of the *Hummocky Unit*. The high elevation units have comparable or lower density of the *Hummocky Unit*. While differential subsidence during cooling of impact melt could be explained due to differences in the melt to rock ratio in the two floor units, it is difficult to reconcile the lack of melt movement to lower topography once elevation differences were in place.

An alternative explanation for this observation could be ‘structural subsidence’ during the modification stage. In such a scenario, it is possible that a part of

the crater floor may have subsided due to structural weaknesses after most of the melt became viscous enough to stay in place. However, we are still not able to explain the relatively higher abundance of *Hummocky Unit* in the low elevation crater floor region.

5.3.2 Diversity and Distribution of Impact Melt Morphologies

The two craters show similar degrees of diversity in the morphology of impact melt deposits. There are however, observable differences in their distribution. As discussed in section 5.1, the nature of occurrence and properties of *Isolated Mounds* and *Hummocky Unit* is different in the two craters. Besides these observations, we have also documented the occurrence of *Melt Fronts* and *Melt Front Striations* at the two craters. It is interesting to note that while these units are mainly observed on the floor-wall interface at Tycho (specifically the western section), Jackson displays prominent *Melt Fronts* and *Melt Front Striations* on the central peaks and some other large boulders within the crater. These differences in the occurrence of the two units might indicate different dynamics of impact melt during the emplacement process.

A possible explanation of lack of *Melt Fronts*/*Melt Front Striations* on the floor-wall interface at Jackson could be that the abundant / dense distribution of *Isolated Mounds* may have impeded the movement of *Melt Fronts* and restricted them to the crater floor interior. We acknowledge the fact that the current distribution of various geological units on the crater floor represents the final configuration which may be very different than the initial crater setting when impact melt was produced and being moved around. However, the large boulders were likely incorporated into the melt on very short time scales and played a role in the distribution and emplacement of impact melt. Irrespective coherent melt movement is indicated by

these features which has important implications for understanding the impact melt mobility.

5.3.3 *Central Peak – Impact Melt Relationship*

Impact melt represents an integrated product of lithologies present in the crustal column which may not share any mineralogical link with the central peak lithologies since the two units represent different sampling depths [*e.g. Dhingra et al., 2014, Chapter 4*]. The occurrence of impact melt on central peaks therefore could misguide interpretations of the subsurface mineralogy. Jackson and Tycho represent excellent examples where central peaks have clearly been affected by impact melt cover. The mapped impact melt distribution at the two craters illustrates the fact that central peaks, although pristine by their inherent formation mechanism, need to be examined with high resolution imaging data for isolating melt-free regions before being used to determine the mineralogy of deeper horizons in the crust.

6 Summary

The detailed investigations presented in this study document the impact melt properties at two young craters, Jackson and Tycho and use these observations in evaluating the impact melt deposits occurring at craters with similar sizes and formed in similar targets. The salient findings from this study are as under:

i) We find that the similar impact energy available during the formation of the two craters was inadequate to homogenize the impact melt generated from a heterogeneous lithological target. The nature of mineralogical heterogeneity is different at Tycho and Jackson with the former showing differences principally within the high

calcium-pyroxene suite. The latter displays evidence for two contrasting lithologies: anorthosite and high calcium-pyroxene bearing lithology. The detailed mineralogical investigations capture mineralogical differences in impact melt deposits at large and small spatial scales supporting the observations made earlier at Copernicus crater. In particular, we document the distinctive character of the eastern crater wall of Tycho and the north-south mineralogical heterogeneity at Jackson crater.

ii) The diversity of mapped geological units on the melt-rich floors of both the craters is similar but they have slightly different specific properties in terms of spatial distribution and average observational sizes. These observations have been linked to the physical nature of the target (e.g. spatial coherence) and the large scale mineralogical character. We suggest a likely coherent target at Tycho and more fractured target at Jackson crater.

iii) The study highlights the morphological diversity of impact melt including the melt fronts which occur in different parts of the two craters and are likely affected by the local geological setting. Melt mobility on large spatial scales is inferred by the presence of these morphological features.

iv) Detailed mineralogy of melt ponds, floor melt deposits, crater walls and peaks highlight the dominant occurrence of high calcium-pyroxene bearing mineralogy at the two craters suggesting an intruded crust at both locations.

v) We observe two coherent floor levels in both the craters. The observed differences in the distribution of geological units across the two craters are used to investigate and understand the cause of elevation differences on the crater floor. We infer

that apart from possibly differential floor subsidence during the cooling of the melt sheet, structural subsidence along weak zones might also be an additional contributing factor.

We acknowledge that some of the inferences presented here are speculative in nature and would certainly benefit from additional analysis as well as observations at other craters. At the same time, these observations illustrate that impact melt studies could provide wealth of insights for understanding the cratering process as well as their role in contributing to the mineralogical diversity of the lunar crust.

7 References

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Table 1 Spectral parameters used in the study

Spectral parameter	Algorithm
IBD 1000	$\sum_{n=0}^{26} 1 - \frac{R(789 + 20n)}{Rc(789 + 20n)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm
IBD 2000	$\sum_{n=0}^{21} 1 - \frac{R(1658 + 40n)}{Rc(1658 + 40n)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm
BD 1900	$1 - \frac{R1898}{\left(\frac{R2498 - R1408}{2498 - 1408}\right) * (1898 - 1408) + R1408}$
BD 2300	$1 - \frac{R2298}{\left(\frac{R2578 - R1578}{2578 - 1578}\right) * (2298 - 1578) + R1578}$
M³ Standard Color Composite	Red – IBD 1000; Green – IBD 2000; Blue – Albedo at 1489 nm
Complementary Color Composite	Red – IBD 1000; Green – BD 1900; Blue – BD 2300

Figure Captions

Figure 1 Progression in crater morphology with increasing size. *Image source:* Baker et al., [2011]

Figure 2 Spatial context of Jackson and Tycho craters on the lunar surface. Jackson is located on the lunar far side while Tycho is located on the nearside of the Moon. Both show prominent crater rays. *Image Source:* LRO WAC.

Figure 3 Morphological units mapped at the two craters. The scale bar is 1 km for each of the units.

Figure 4 Local geologic context of craters Jackson and Tycho. (a) M³ Op2c2 image of Jackson crater at 1489 nm. (b) M³ standard color composite (see Table 1 for details) of Jackson crater showing contrast in the mineralogy of the northern (feldspathic) and southern floor (weakly mafic). (c) M³ Op2c1 image of Tycho crater at 1489 nm. (d) M³ standard color composite of Tycho crater showing distinctive eastern wall unit (in orange-yellow tones).

Figure 5 Elevation differences observed on the crater floors of Jackson and Tycho. (a) Kaguya TC albedo image of the floor region of Jackson crater (b) LRO LOLA derived DEM overlain on Kaguya TC dataset showing elevation differences between eastern and western crater floors. (c) Kaguya TC albedo image of the floor region of Tycho crater (d)

LRO LOLA derived DEM overlain on Kaguya TC dataset showing elevation differences between eastern and western crater floors.

Figure 6 Geological map of impact melt-rich floor of Jackson crater.

Figure 7 Morphological details of selected megaclast units. (a) *Megablock* located close to the crater center shows extensive melt cover on its surface. (b) *Megablock* located in the northern part of crater floor showing thick melt covering all over the region. Very few clear exposures of the underlying rock unit are otherwise visible. (c) An *isolated mound* located in the north western crater floor partially covered by a *melt front*. (d) *Isolated mounds* located in the southern crater floor showing indistinct boundaries due to extensive melt cover. Also note the sinuous feature in the center-bottom of the image. It could be representing a flow deposit which is now covered by the impact melt.

Figure 8 *Melt Fronts* and *Melt Front Striations* observed on the Jackson crater floor. (a) Kaguya TC image without mapped units. The yellow arrows indicate the inferred direction of movement of the melt fronts. (b) Mapped extent of the *Melt Fronts* and *Melt Front Striations*. Note the large melt front cluster overlain onto the steeply sloping central peaks. Individual melt fronts are marked in black lines.

Figure 9 Melt ponds and flows on the south-eastern crater wall of Jackson. Yellow triangles indicate the melt pond locations. Orange arrows indicate a channel carved out in

the wall which eventually empties on to the crater floor. Multiple lobate flows can be observed on the crater floor (marked with arrows on the floor).

Figure 10 Geological map of impact melt-rich floor of Tycho crater.

Figure 11 *Melt Fronts* and *Melt Front Striations* at Tycho crater. (a) Context image showing the distribution of *Melt Fronts* and *Melt Front Striations* on the crater floor. Note the predominance of these morphological features in the western section and their absence in the eastern crater floor. White boxes with letters and numbers indicate regions shown in enlarged view. (b) Enlarged view of the central peak region showing a prominent melt front overlain on the eastern section (marked by yellow arrows) of the main peak.

Figure 12 *Melt Front* and *Melt Front Striations* in the north western crater floor-wall interface. (a) Kaguya TC image showing several melt fronts at different elevations overlain to various extents on the crater walls. The yellow arrows point to the leading edges of the melt fronts. (b) Mapped extent of the *Melt Fronts* and *Melt Front Striations*.

Figure 13 Impact melt deposits on the eastern rim of Tycho (a) Kaguya TC context image showing notable occurrences of impact melt on the eastern rim. Boxes represent locations of the enlarged views shown in other images. (b) Enlarged view of the NE rim regions showing numerous impact melt ponds formed in low-lying areas (c) Enlarged view of the SE rim region showing part of a 20 km long flow showing abundant cooling

cracks. Note the small crater on the right edge of the image which impacted on part of the melt body. Spectra from this crater, the northern and southern part of the impact melt flow were extracted and compared.

Figure 14 Kaguya TC derived 3D view of the NE crater wall of Tycho showing extensive melt cover and diversity of morphologies. Yellow triangles indicate locations of melt ponds. White boxes indicate locations of enlarged views present in Figure 15. Orange arrows indicate the viewing direction for the enlarged DTMs. Vertical exaggeration is 5x.

Figure 15 High resolution 3D views of the impact melt deposits. (a) Enlarged view of the bottom part of the crater wall showing melt veneer across a scalloped margin, small melt flow on the top and textured melt on the bottom. (b) Enlarged view of an area above a, showing braided impact melt with ropy texture. There is also smooth melt unit adjacent to these chaotic melt deposits. Vertical exaggeration is 5x.

Figure 16 Melt mineralogical heterogeneity on the floor of Jackson crater. (a) M^3 standard color composite overlain on Kaguya TC image shows feldspathic northern floor and weakly mafic character of the southern floor. (b) The corresponding spectra from the northern and southern units indicate featureless spectra for the northern part and weak absorption around 1000 nm for the southern unit. White box shows location for enlarged image shown in c. (c) Image showing the protrusion of weakly mafic southern unit into the feldspathic unit. Yellow arrows indicate the boundary of the two melt units. White

arrowheads indicate a fracture exhibiting mafic character attesting to the protrusion. (d) Spectra across the fracture confirms the observations from color composite. The fracture surface and an adjacent location in the north (red and orange spectra respectively) indicate mafic character while remaining surfaces are featureless (blue and purple spectra).

Figure 17 Contrasting mineralogy exhibited by melt covered boulders at Jackson crater. (a) Kaguya TC image showing boulders covered by impact melt. (b) M^3 standard color composite overlain on Kaguya TC image showing the dominant mineralogy of the boulders. Boulders labeled with yellow arrows suggest mafic character while black arrows indicate boulders with feldspathic character. The boulder unit in the center of the image marked with a filled black arrow and yellow outline was selected for extracting spectra shown in Figure 18.

Figure 18 Spectral variability in the impact melt occurrences at small spatial scales at Jackson crater. (a) Spectra from northern and southern section of the same isolated mound (marked with filled black arrow in Figure 17). (b) Spectra from melt ponds located on the crater wall and rim.

Figure 19 Spectral variability in the pyroxene occurrences at Jackson crater and nearby region.

Figure 20 Mineralogically distinctive eastern wall of Tycho crater. (a) M³ Op2c1 albedo image at 1489 nm. Numbers indicate spectral sampling locations. (b) M³ standard color composite (see Table 1 for spectral parameters) highlighting the mafic nature of the eastern wall. (c) M³ complementary color composite suggests high calcium-pyroxene occurrence at eastern wall, peaks and parts of crater floor. (d) Spectra of melt soils from various locations as marked in a. Note the long wavelength absorption bands of the bottom two spectra (#6 eastern wall , #4 SW floor). White arrows in b and c indicate the location of #6. The reflectance scale refers to spectra 6 and 8. All others are offset as follows: Spectrum 1: 0.01, spectrum 2: 0.07, spectrum 3: 0.07, spectrum 4: 0.01, spectrum 5: 0.035, spectrum 7: 0.02

Figure 21 High resolution spectral studies of the eastern wall melt-rock exposures at Tycho crater. (a) Kaguya TC image of eastern section of Tycho. (b) M³ standard color composite (see Table 1 for spectral parameters) overlain on Kaguya TC image. The image shows the distinctive mafic character of the eastern wall. Black boxes in both a and b show the location of area selected for high resolution study. (c), (d) Enlarged view of the study location. Numbers in c indicate the spectral sampling locations. (d) is M³ standard color composite overlain on Kaguya TC data for the study region. (e) Spectra of the melt-rich (#1) and melt-poor (#2 - #5) locations. Magenta arrows indicate the distinctly longer wavelength absorption bands of the melt-rich region (#1). The reflectance scale is offset for spectrum 2 by 0.02, spectrum 4 by 0.04 and spectrum 5 by 0.06.

Figure 22 Impact melt ponds at Tycho crater selected for mineralogical analysis. (a) M³ Op2c1 image of Tycho providing context for the melt pond locations. (b) NE rim region. (c) SE rim region. (d) Northern wall region. (e) Southern wall region. Scale bar in b-e is 1 km.

Figure 23 Mineralogical character of the impact melt ponds at Tycho crater. The numbers correspond to the locations shown in Figure 22. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.01, spectrum 3: 0.02, spectrum 4: 0.04, spectrum 5: 0.01, spectrum 6: 0.07, spectrum 7: 0.08, spectrum 8: 0.06, spectrum 9: 0.1, spectrum 10: 0.05

Figure 24 Extensive mafic character of the central peaks of Jackson. (a) Kaguya TC image of the central peaks highlighting the location of the previously documented mafic unit (white arrow). Hollow yellow arrows point a likely connection of the peak (neck) with the wall. (b) M³ standard color composite overlain on the Kaguya TC image. The extent of previously documented mafic unit is also mapped in black. Note that mafic character extends beyond the black mapped unit and is also shared by the neck region. (c) Spectra from selected locations on the central peak and the neck region. The high calcium-pyroxene rich character of the peak and the neck region is comparable. The blue spectrum represents crystalline plagioclase exposure on the peak.

Figure 25 Mineralogical variations within a melt unit on the central peak neck region at Jackson crater. (a) Kaguya TC image of the central peaks showing the melt unit whose

spectra was obtained. Arrows indicate the two sampling locations. (b) M³ standard color composite overlain on the Kaguya TC image. The melt pond is surrounded by mafic exposures. (c) Spectra from the two locations within the melt pond show variations in spectral signatures. Spectrum labeled as south pond is offset by 0.01.

Figure 26 Mineralogical diversity on the peak of Tycho crater. (a) M³ Op2c1 albedo image at 1489 nm showing locations selected for spectral sampling. Numbers correspond to spectra shown in c. (b) M³ complementary color composite used for discriminating within pyroxenes shows different tones on the peaks. (c) Spectra of the selected locations based observed variations in the color composite shown in b. Note the distinctly long wavelength absorption of the impact melt on the crater floor (#5, magenta spectrum) compared to other melt signatures. The reflectance scale refers to spectra 5 and 6 1. All others are offset as follows: spectrum 1: 0.02, Spectrum 2: 0.02, spectrum 3: 0.05, spectrum 4: 0.02

Figure 27 Variation in melt mineralogy in the NE smooth floor deposits at Jackson crater. (a) Kaguya TC image of the NE crater floor showing fresh crater (orange arrow) in impact melt. The brown and green arrows indicate spectral sampling locations of the smooth melt deposits. (b) M³ standard color composite overlain on Kaguya TC showing the dominant mineralogy of the region. Note the strong mafic character of the fresh crater. (c) Spectra from the locations marked in a. High calcium pyroxene character of the

melt is indicated by the fresh crater in contrast to the dominantly feldspathic character of the melt in this part of the crater floor.

Figure 28 Impact melt textural linkages with spectral signatures at Jackson crater. (a) Kaguya TC image of the southern part of the crater floor showing raised mounds(#1, #2) with coarser texture relative to the nearby melt (#3, #4). (b) M³ standard color composite overlain on Kaguya TC data suggesting that raised mounds have strong mafic character (yellow coloration). (c) Spectra from two mounds (#1, #2) and background melt (#3, #4) show systematic variations in band strength. Note the subtle differences in their respective continuum slopes. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.04, spectrum 3: 0.02, spectrum 4: 0.03

Figure 29 Evaluating relationship between morphological texture and spectral signature of impact melt at Tycho crater. (a) Kaguya TC image showing a smooth melt near the central peak (#1) and fractured melt (#2). (b) M³ standard color composite (see Table 1 for spectral parameters) overlain on Kaguya TC image showing broad scale mineralogical character of the two locations. (c) Spectral properties of the two selected locations. Textured melt has relatively stronger absorption bands although mineralogical composition appears similar.

Figures

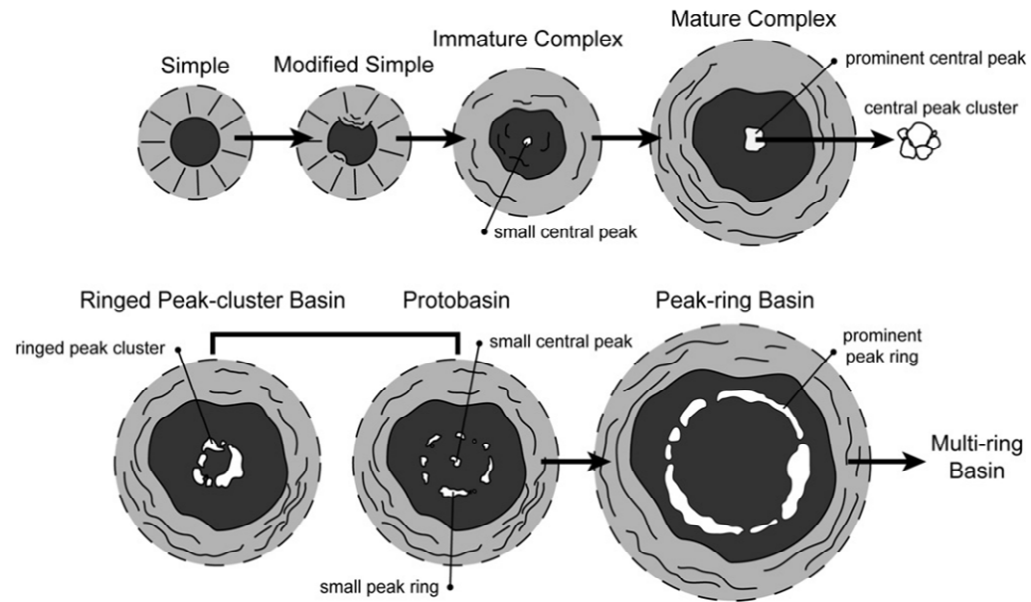


Figure 1 Progression in crater morphology with increasing size. *Image source:* Baker et al., [2011]

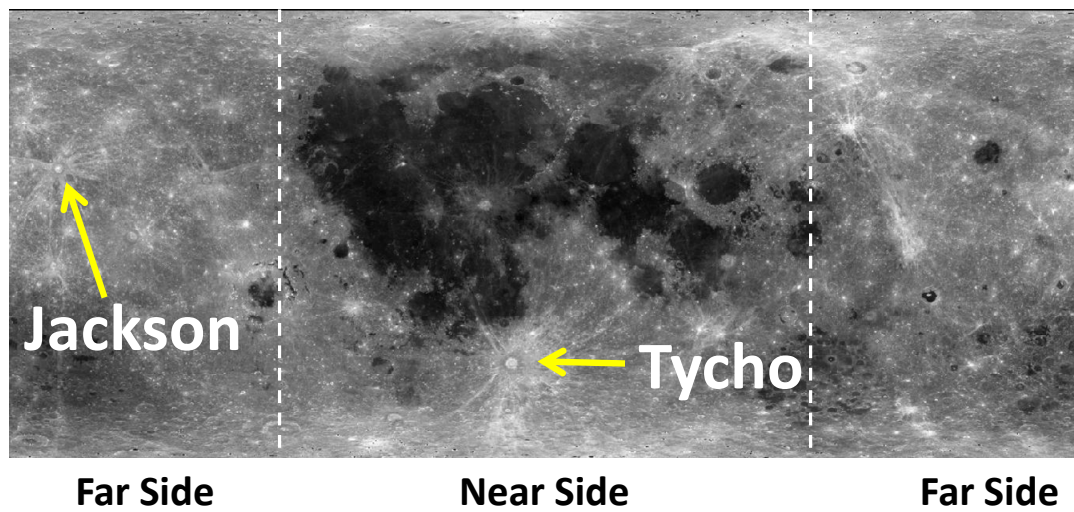


Figure 2 Spatial context of Jackson and Tycho craters on the lunar surface. Jackson is located on the lunar far side while Tycho is located on the nearside of the Moon. Both show prominent crater rays. *Image Source: LRO WAC.*

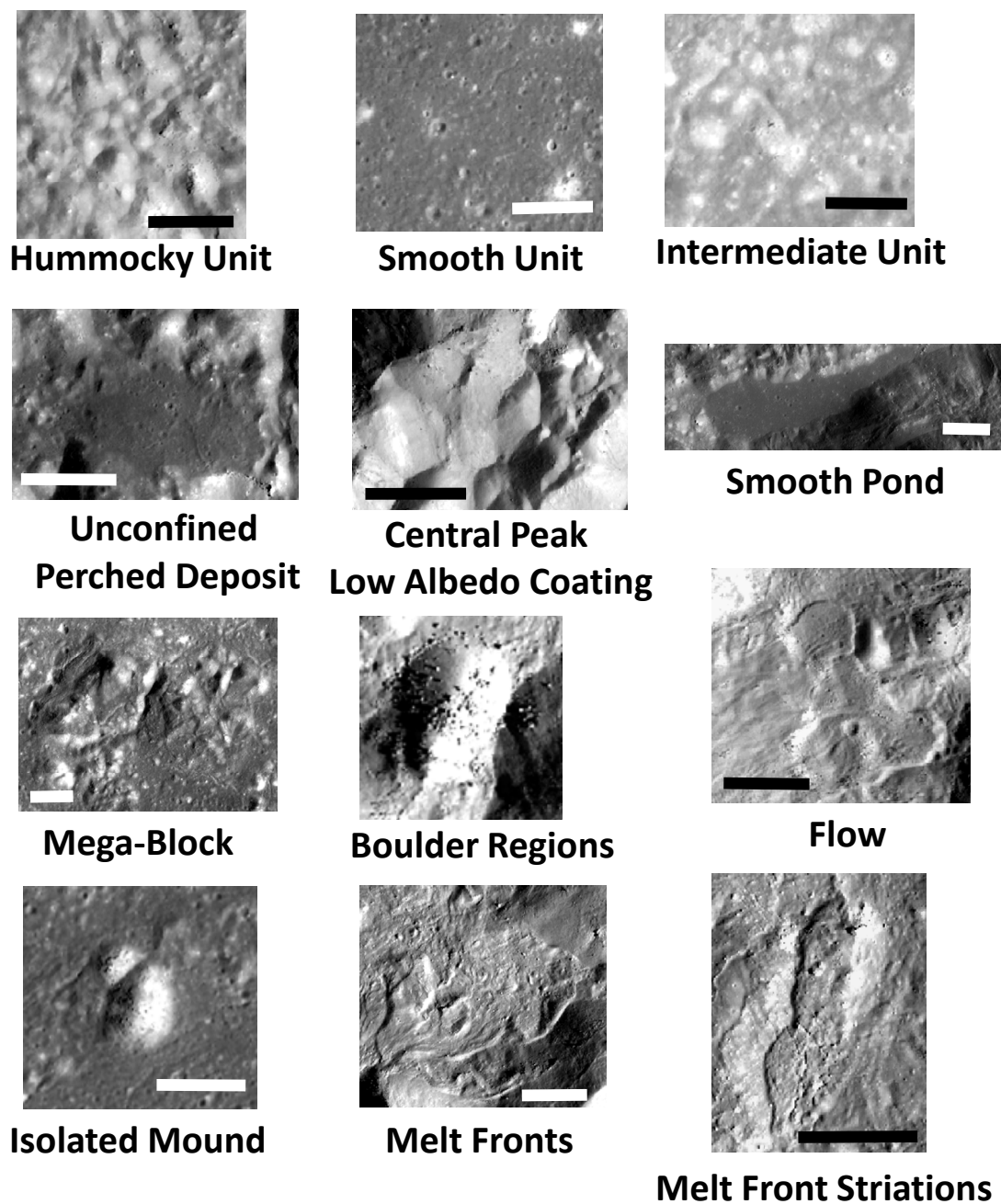


Figure 3 Morphological units mapped at the two craters. The scale bar is 1 km in each of the units.

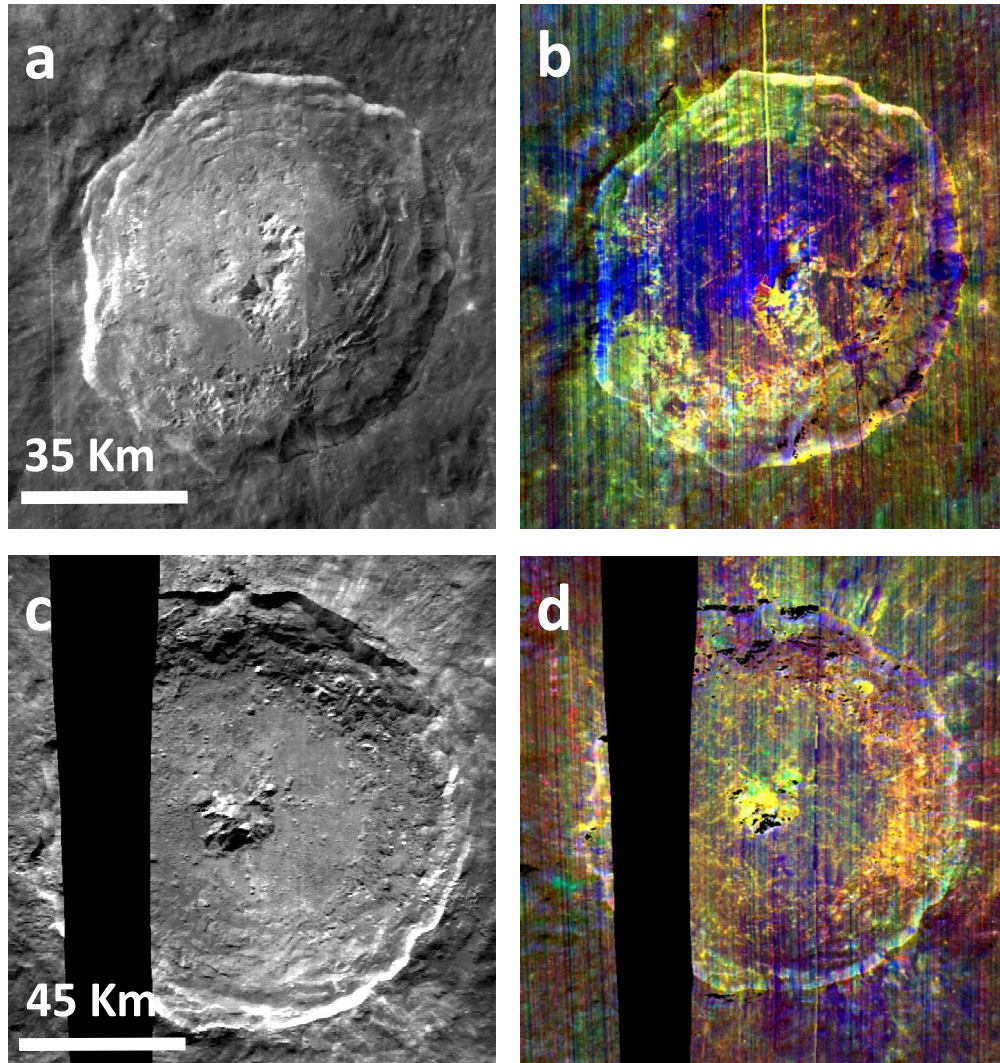


Figure 4 Local geologic context of craters Jackson and Tycho. (a) M³ Op2c2 image of Jackson crater at 1489 nm. (b) M³ standard color composite (see Table 1 for details) of Jackson crater showing contrast in the mineralogy of the northern (feldspathic) and southern floor (weakly mafic). (c) M³ Op2c1 image of Tycho crater at 1489 nm. (d) M³ standard color composite of Tycho crater showing distinctive eastern wall unit (in orange-yellow tones).

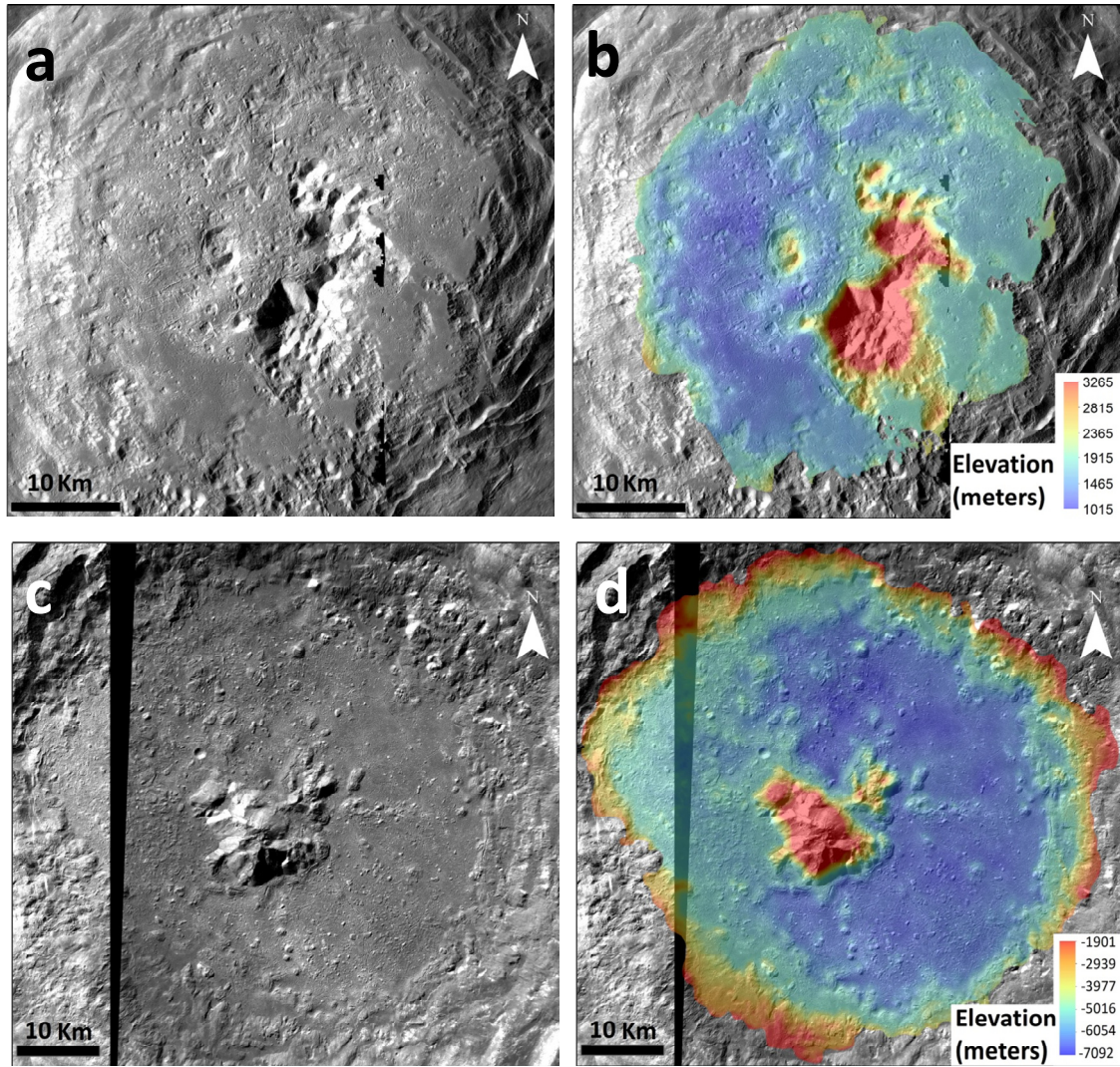
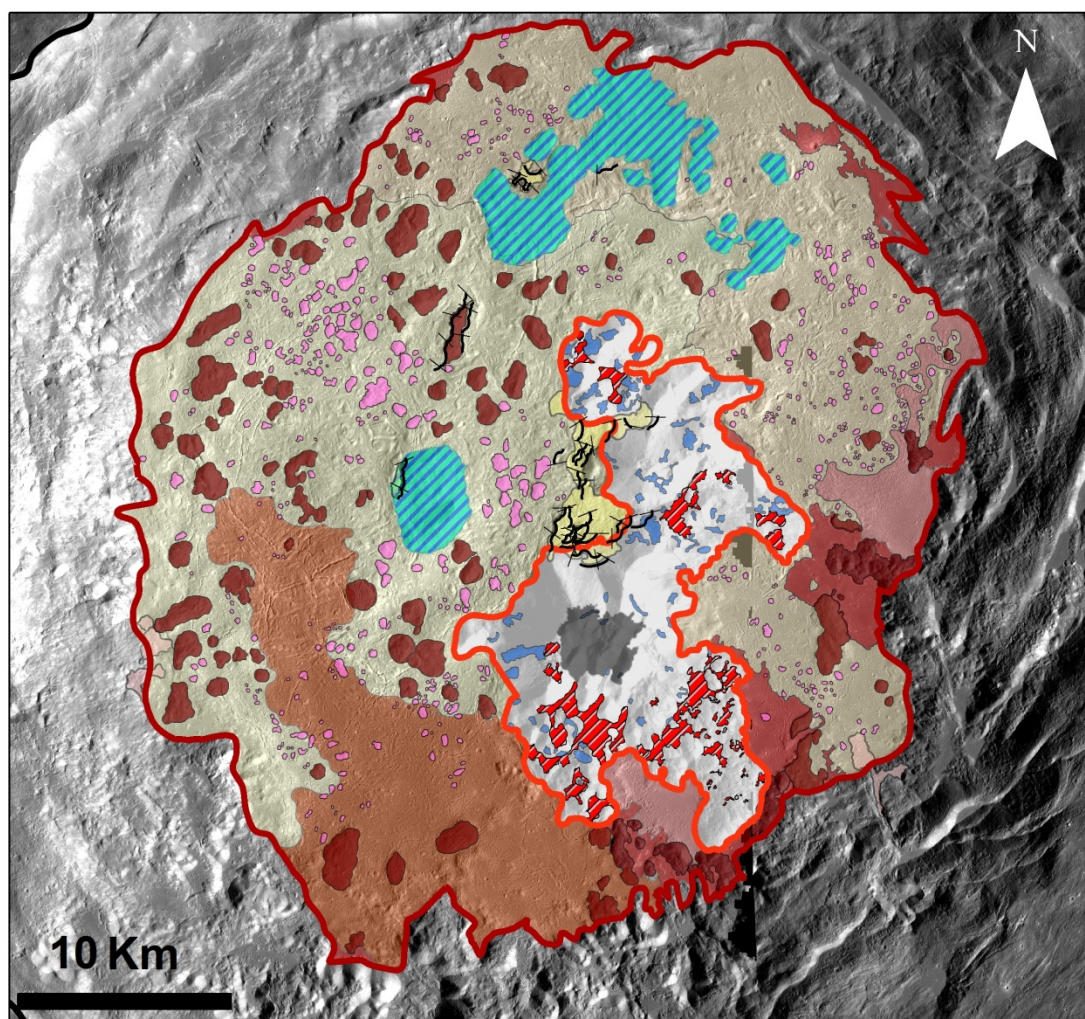


Figure 5 Elevation differences observed on the crater floors of Jackson and Tycho. (a) Kaguya TC albedo image of the floor region of Jackson crater (b) LRO LOLA derived DEM overlain on Kaguya TC dataset showing elevation differences between eastern and western crater floors. (c) Kaguya TC albedo image of the floor region of Tycho crater (d) LRO LOLA derived DEM overlain on Kaguya TC dataset showing elevation differences between eastern and western crater floors.



Floor Geological Units

 Low Elevation High Albedo Intermediate Unit	 Isolated Mounds
 Low Elevation Low Albedo Smooth Unit	 Hummocky Unit
 High Elevation Low Albedo Intermediate Unit	 Flows
 High Elevation Low Albedo Smooth Unit	 Melt Fronts
 Smooth Unit	 Megablocks
 Central Peak Boulder Regions	 Melt Front
 Central Peak Melt Coating	 Striations
 Central Peak Unconfined Perched Deposit	 Floor
 Central Peak Undivided	 Central Peaks

Figure 6 Geological map of impact melt-rich floor of Jackson crater.

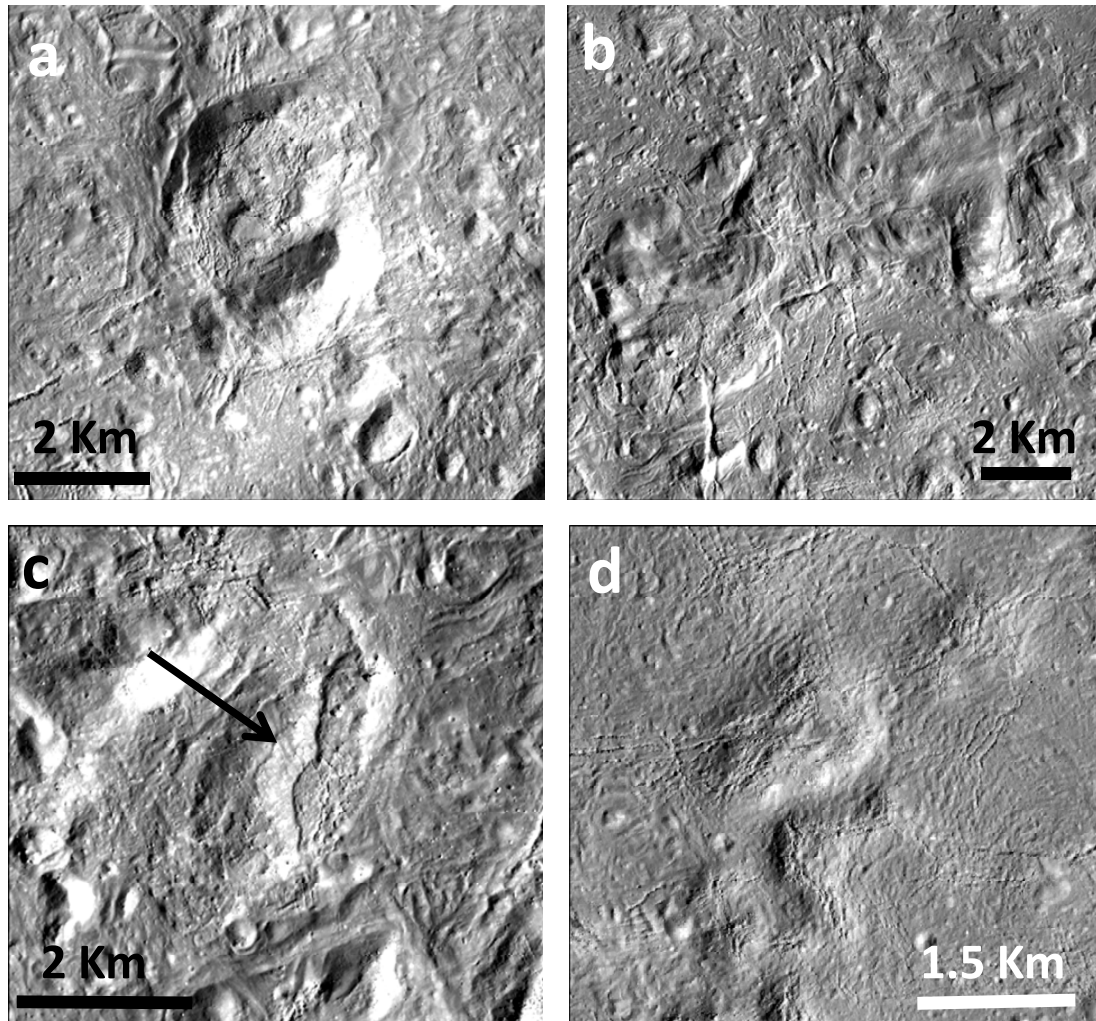


Figure 7 Morphological details of selected megaclast units. (a) *Megablock* located close to the crater center shows extensive melt cover on its surface. (b) *Megablock* located in the northern part of crater floor showing thick melt covering all over the region. Very few clear exposures of the underlying rock unit are otherwise visible. (c) An *isolated mound* located in the north western crater floor partially covered by a *melt front*. (d) *Isolated mounds* located in the southern crater floor showing indistinct boundaries due to extensive melt cover. Also note the sinuous feature in the center-bottom of the image. It could be representing a flow deposit which is now covered by the impact melt.

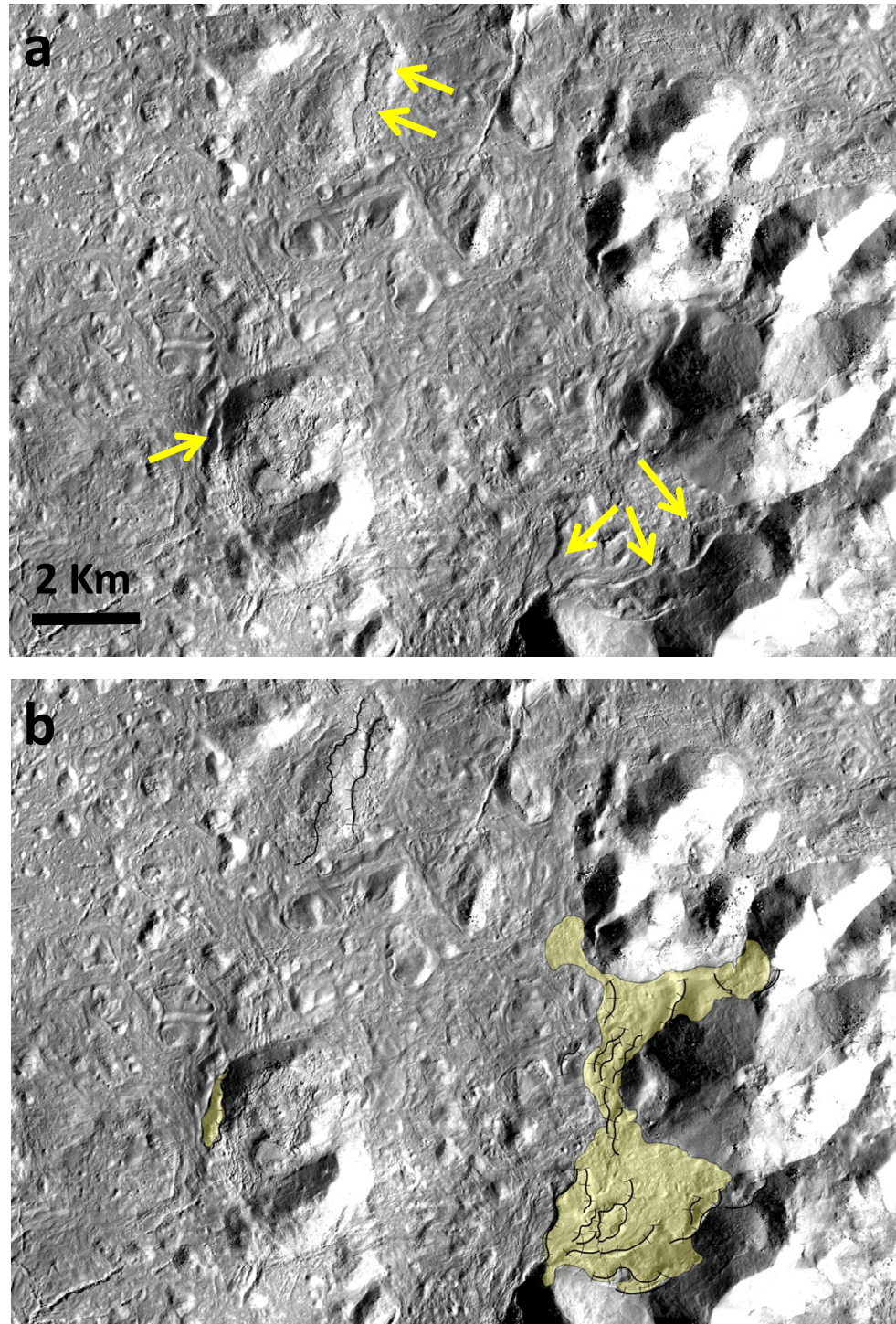


Figure 8 *Melt Fronts* and *Melt Front Striations* observed on the Jackson crater floor. (a) Kaguya TC image without mapped units. The yellow arrows indicate the inferred

direction of movement of the melt fronts. (b) Mapped extent of the *Melt Fronts* and *Melt Front Striations*. Note the large melt front cluster overlain onto the steeply sloping central peaks. Individual melt fronts are marked in black lines.

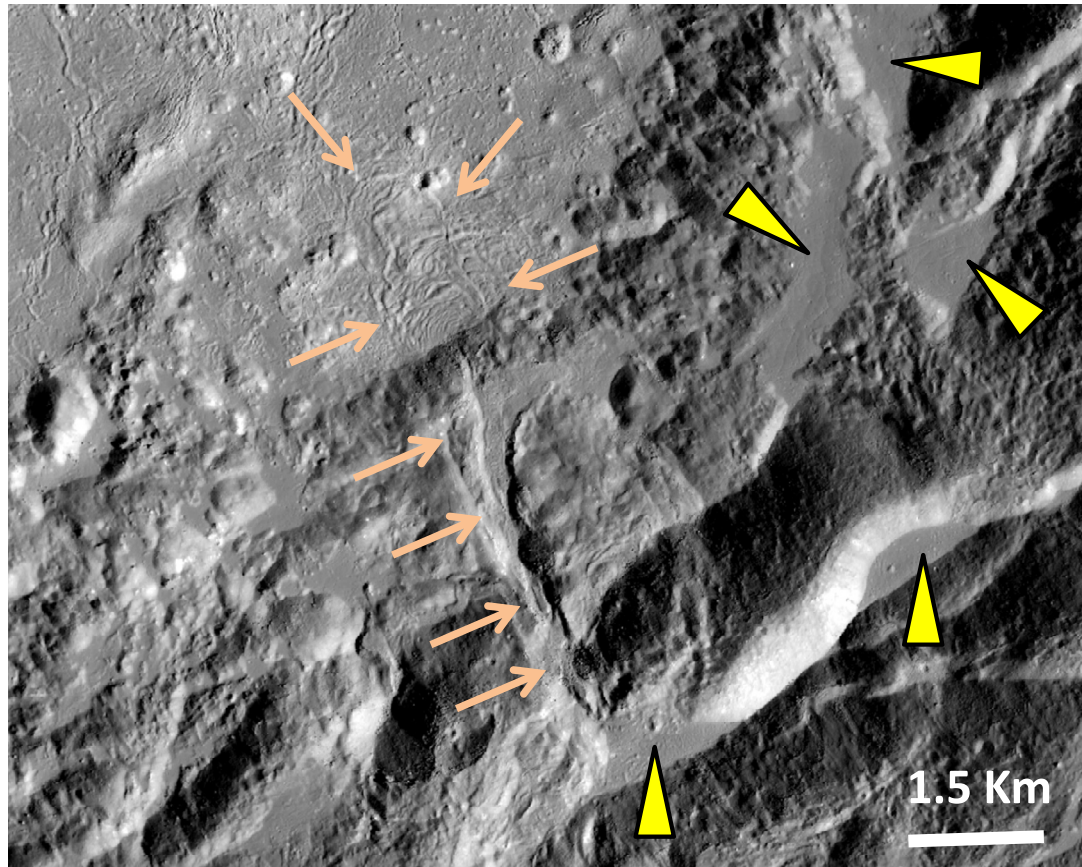
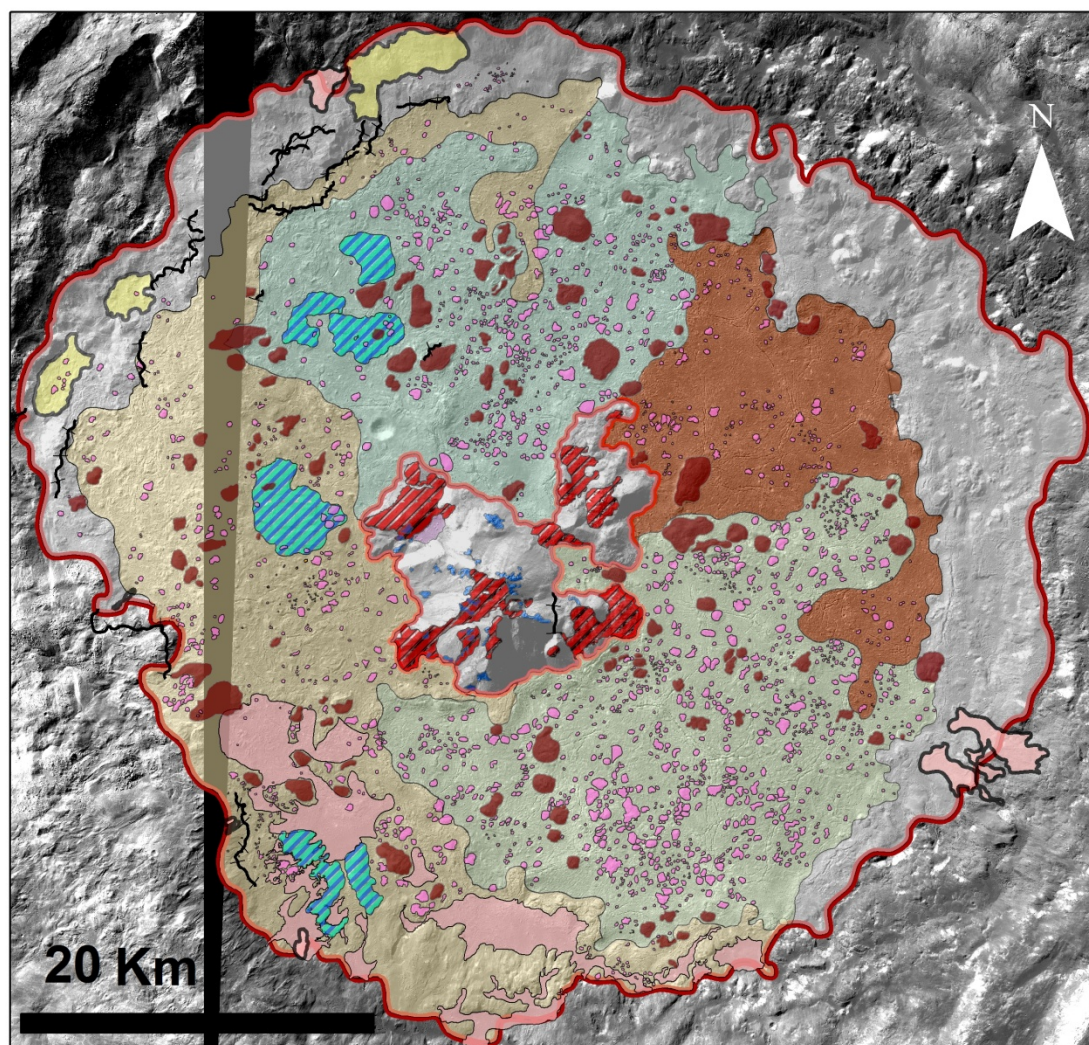


Figure 9 Melt ponds and flows on the south-eastern crater wall of Jackson. Yellow triangles indicate the melt pond locations. Orange arrows indicate a channel carved out in the wall which eventually empties on to the crater floor. Multiple lobate flows can be observed on the crater floor (marked with arrows on the floor).



Floor Geological Units

 Low Elevation Intermediate Albedo Intermediate Unit	 Flows
 Low Elevation Intermediate Albedo Smooth Unit	 Melt Fronts
 High Elevation High Albedo Intermediate Unit	 Isolated Mounds
 High Elevation Low Albedo Smooth Unit	 Hummocky Unit
 High Elevation Low Albedo Intermediate Unit	 Mega Blocks
 Central peak Boulder Regions	 Melt Front
 Central Peak Melt Ponds	 Striations
 Central Peak Unconfined Perched Deposits	 Central Peaks
 Central Peak / Floor Undivided	 Floor

Figure 10 Geological map of impact melt-rich floor of Tycho crater.

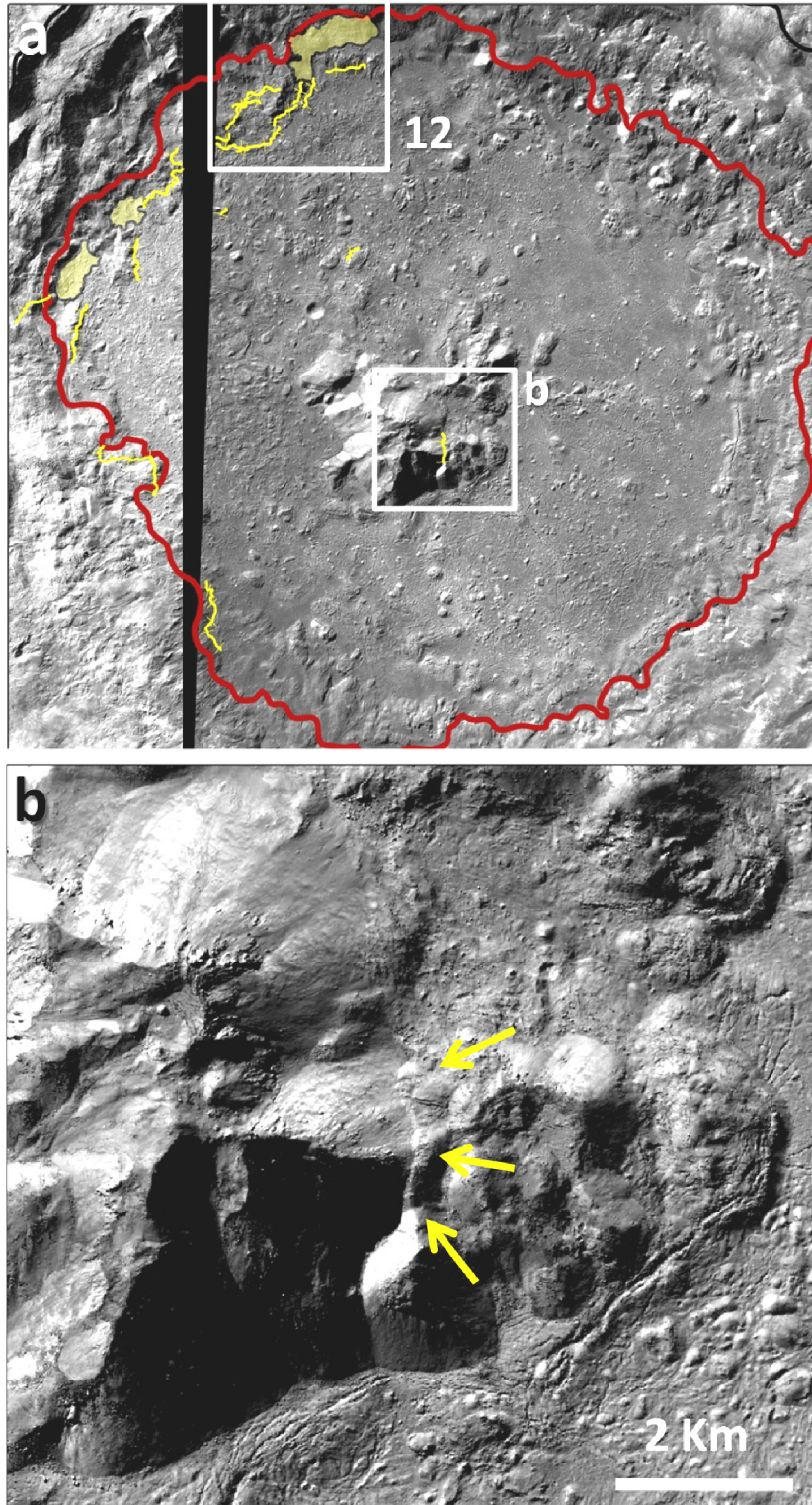


Figure 11 *Melt Fronts and Melt Front Striations at Tycho crater. (a) Context image showing the distribution of Melt Fronts and Melt Front Striations on the crater floor.*

Note the predominance of these morphological features in the western section and their absence in the eastern crater floor. White boxes with letters and numbers indicate regions shown in enlarged view. (b) Enlarged view of the central peak region showing a prominent melt front overlain on the eastern section (marked by yellow arrows) of the main peak.

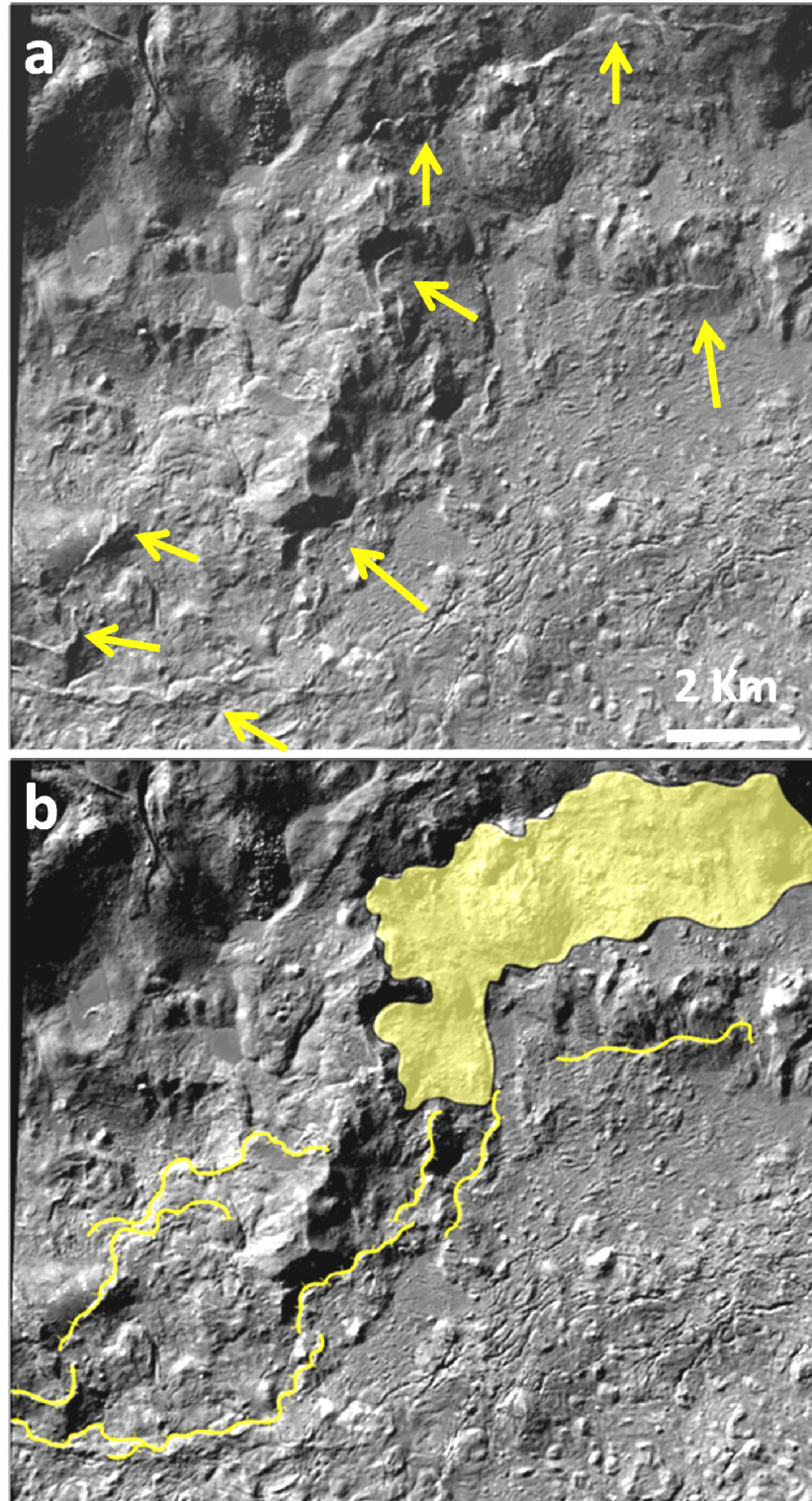


Figure 12 *Melt Front and Melt Front Striations* in the north western crater floor-wall interface. (a) Kaguya TC image showing several melt fronts at different elevations

overlain to various extents on the crater walls. The yellow arrows point to the leading edges of the melt fronts. (b) Mapped extent of the *Melt Fronts* and *Melt Front Striations*.

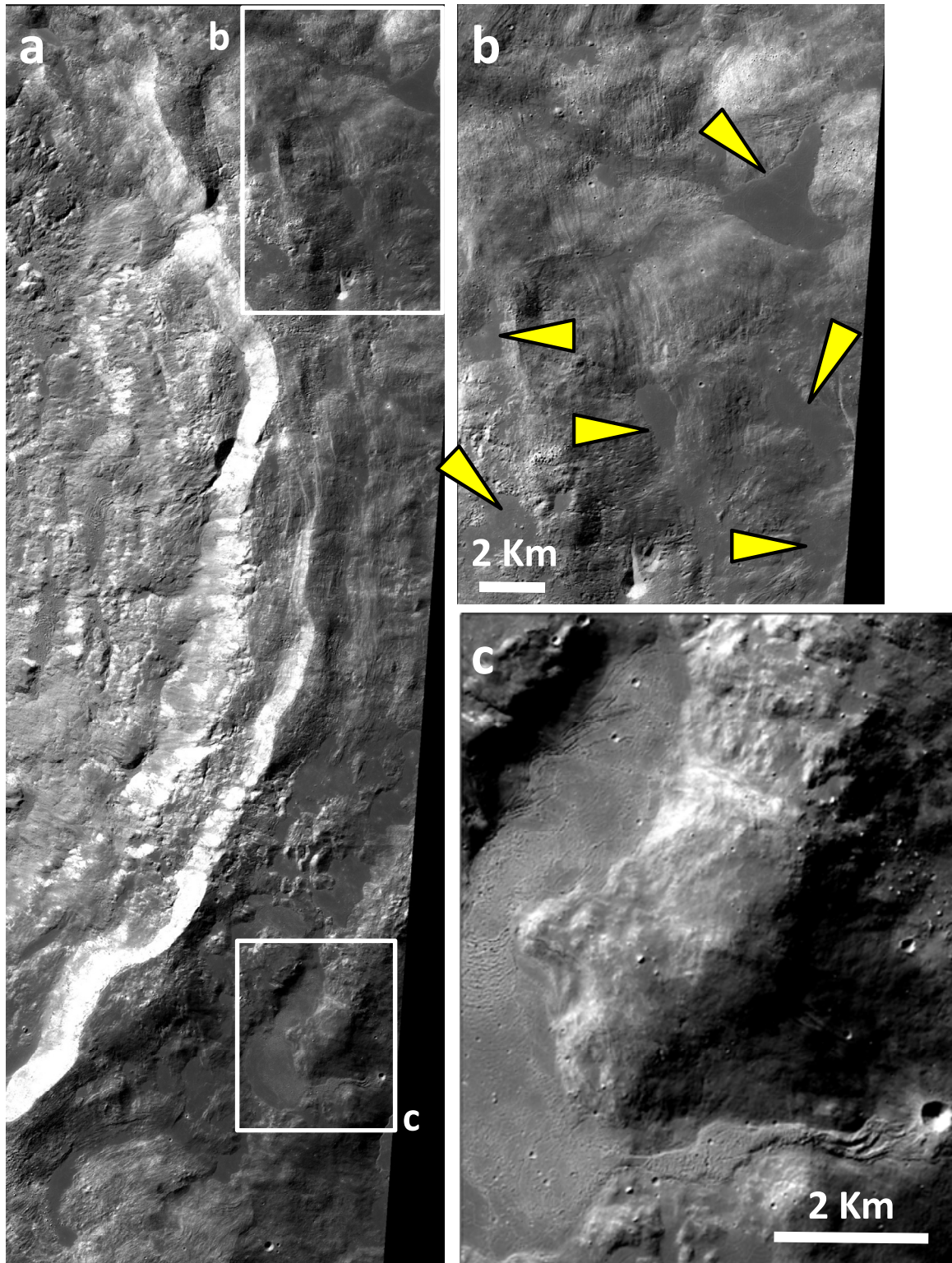


Figure 13 Impact melt deposits on the eastern rim of Tycho (a) Kaguya TC context image showing notable occurrences of impact melt on the eastern rim. Boxes represent

locations of the enlarged views shown in other images. (b) Enlarged view of the NE rim regions showing numerous impact melt ponds formed in low-lying areas (c) Enlarged view of the SE rim region showing part of a 20 km long flow showing abundant cooling cracks. Note the small crater on the right edge of the image which impacted on part of the melt body. Spectra from this crater, the northern and southern part of the impact melt flow were extracted and compared.

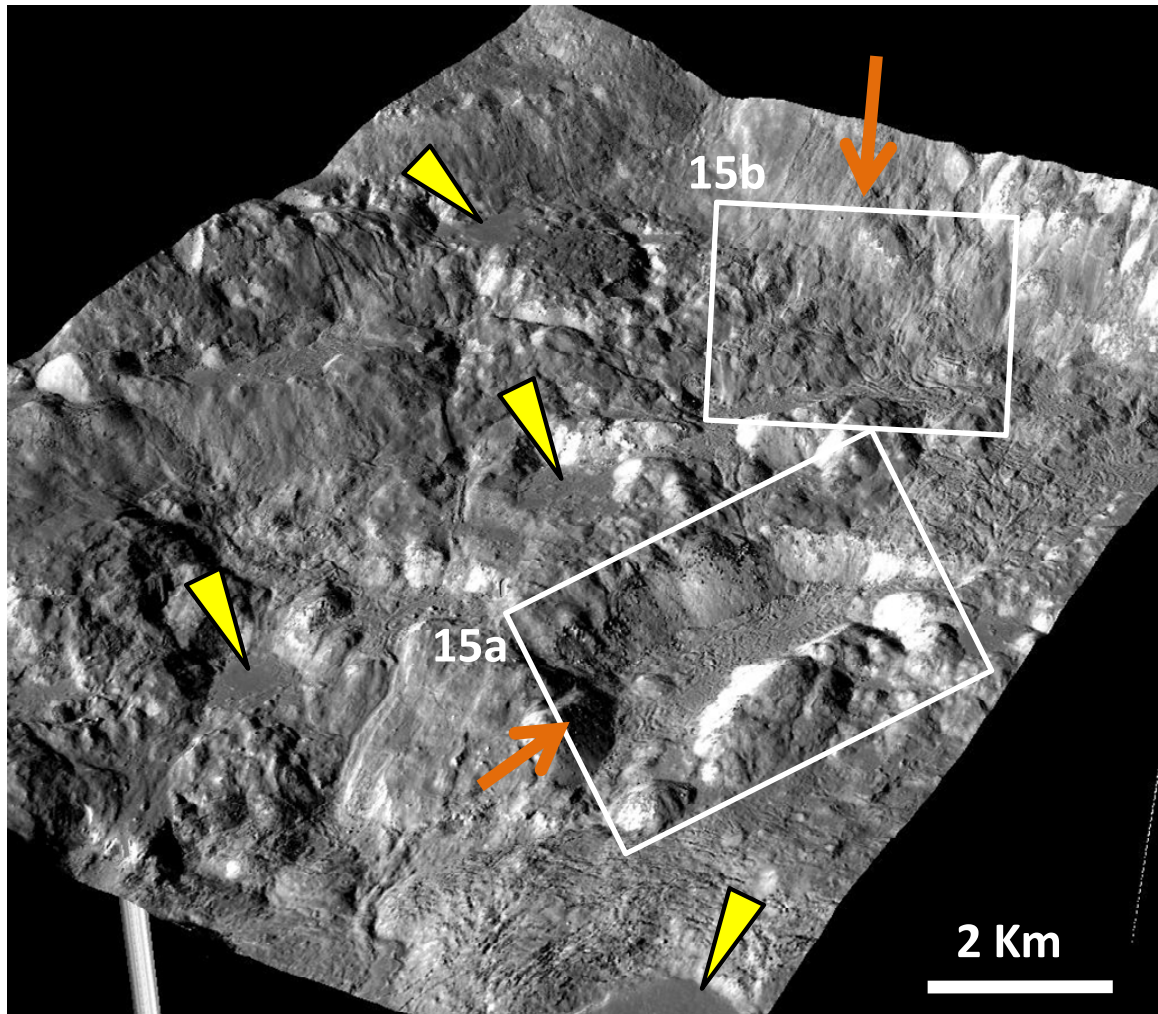


Figure 14 Kaguya TC derived 3D view of the NE crater wall of Tycho showing extensive melt cover and diversity of morphologies. Yellow triangles indicate locations of melt ponds. White boxes indicate locations of enlarged views present in Figure 15. Orange arrows indicate the viewing direction for the enlarged DTMs. Vertical exaggeration is 5x.

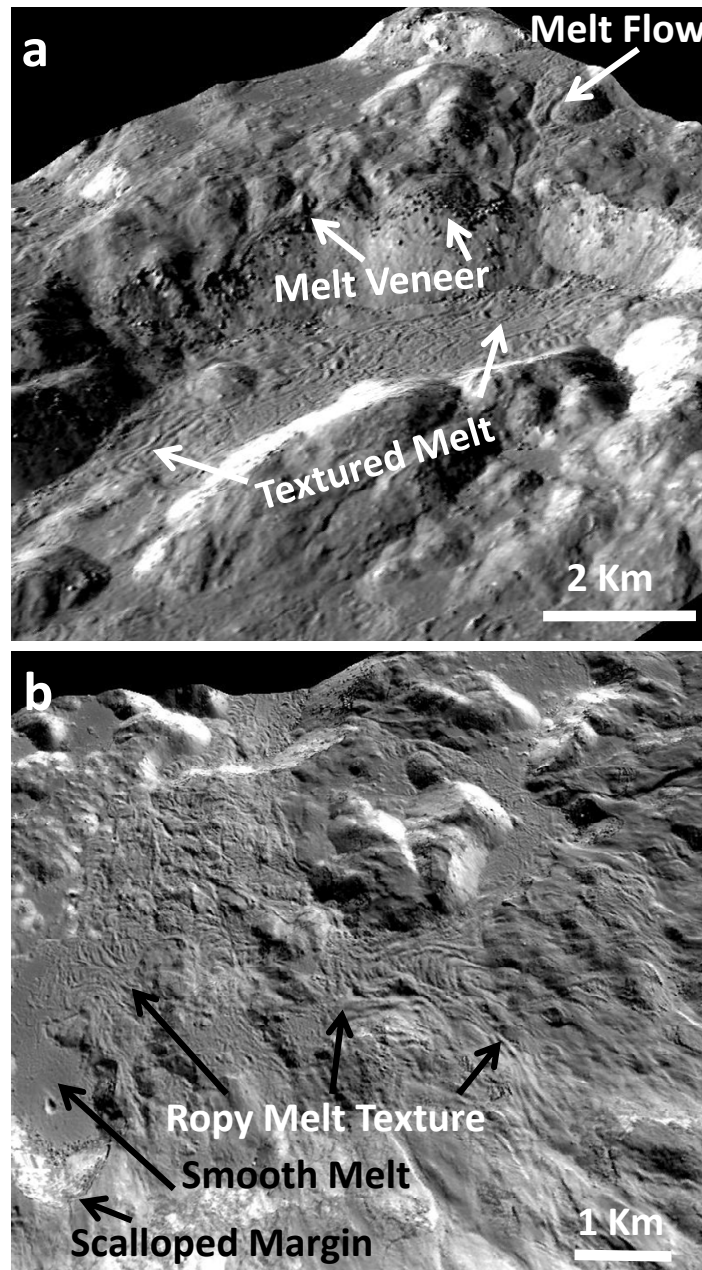


Figure 15 High resolution 3D views of the impact melt deposits. (a) Enlarged view of the bottom part of the crater wall showing melt veneer across a scalloped margin, small melt flow on the top and textured melt on the bottom. (b) Enlarged view of an area above a, showing braided impact melt with ropy texture. There is also smooth melt unit adjacent to these chaotic melt deposits. Vertical exaggeration is 5x.

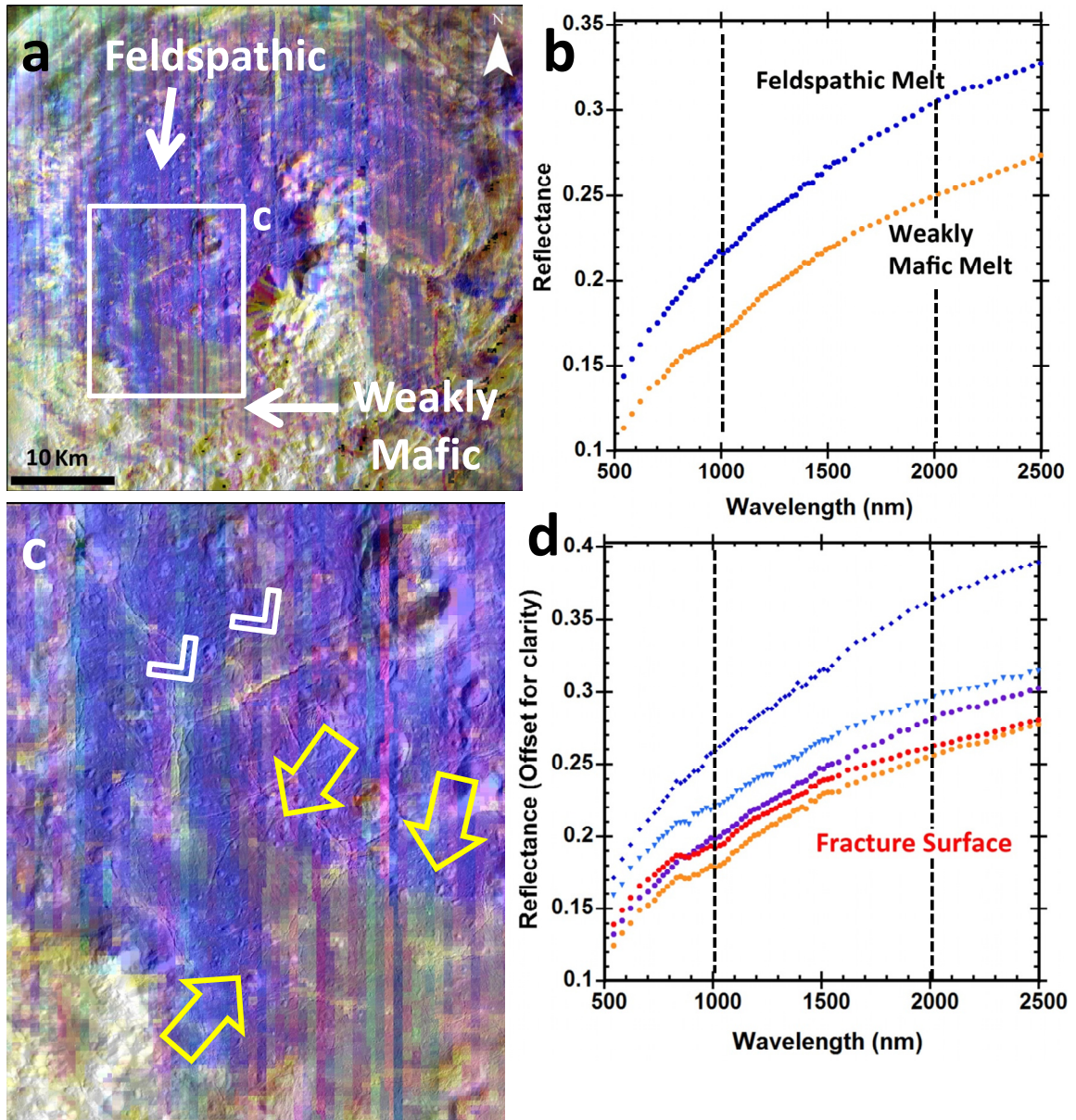


Figure 16 Melt mineralogical heterogeneity on the floor of Jackson crater. (a) M^3 standard color composite overlain on Kaguya TC image shows feldspathic northern floor and weakly mafic character of the southern floor. (b) The corresponding spectra from the northern and southern units indicate featureless spectra for the northern part and weak absorption around 1000 nm for the southern unit. White box shows location for enlarged

image shown in c. (c) Image showing the protrusion of weakly mafic southern unit into the feldspathic unit. Yellow arrows indicate the boundary of the two melt units. White arrowheads indicate a fracture exhibiting mafic character attesting to the protrusion. (d) Spectra across the fracture confirms the observations from color composite. The fracture surface and an adjacent location in the north (red and orange spectra respectively) indicate mafic character while remaining surfaces are featureless (blue and purple spectra).

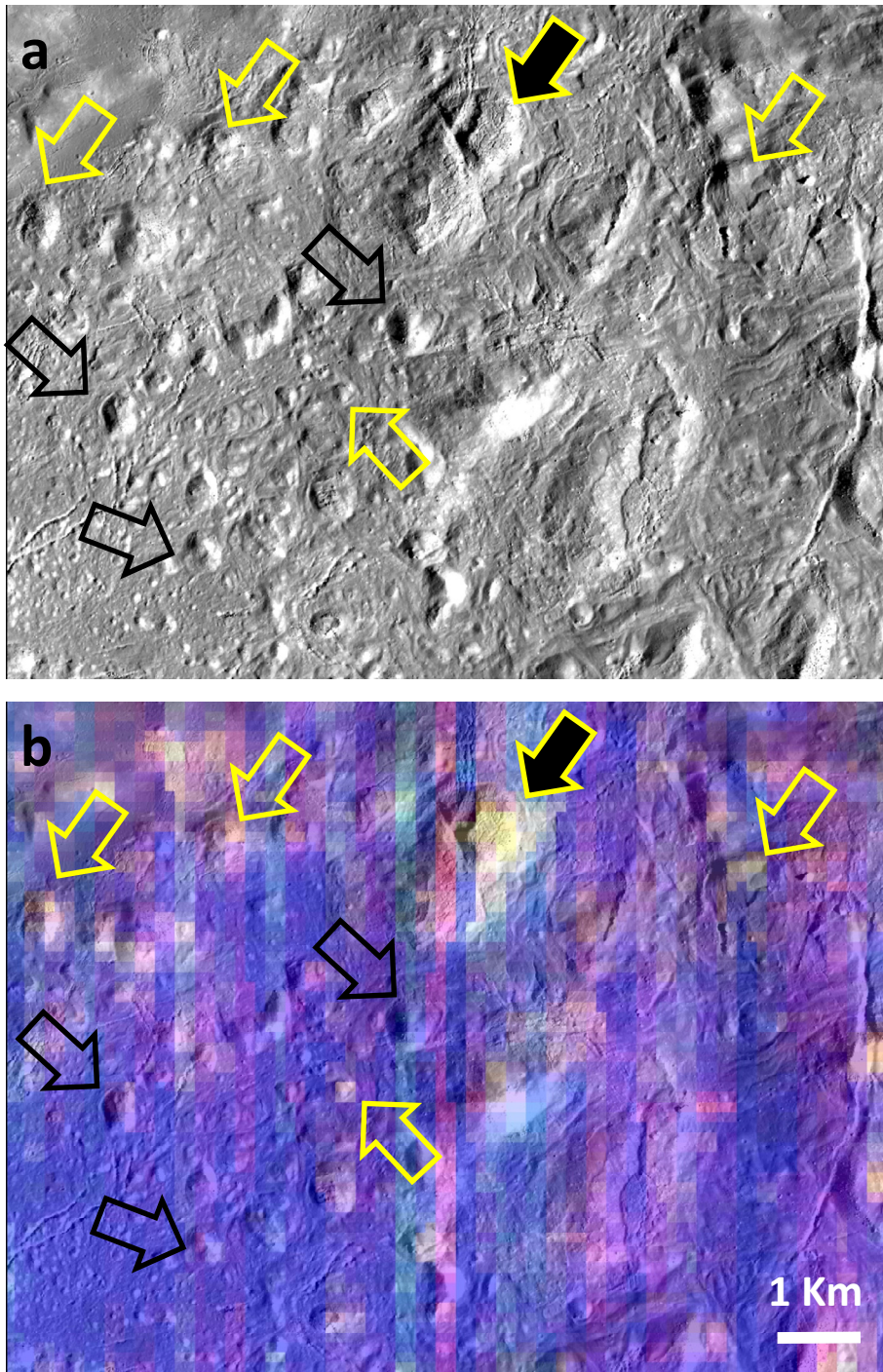


Figure 17 Contrasting mineralogy exhibited by melt covered boulders at Jackson crater. (a) Kaguya TC image showing boulders covered by impact melt. (b) M³ standard color composite overlain on Kaguya TC image showing the dominant mineralogy of the

boulders. Boulders labeled with yellow arrows suggest mafic character while black arrows indicate boulders with feldspathic character. The boulder unit in the center of the image marked with a filled black arrow and yellow outline was selected for extracting spectra shown in Figure 18.

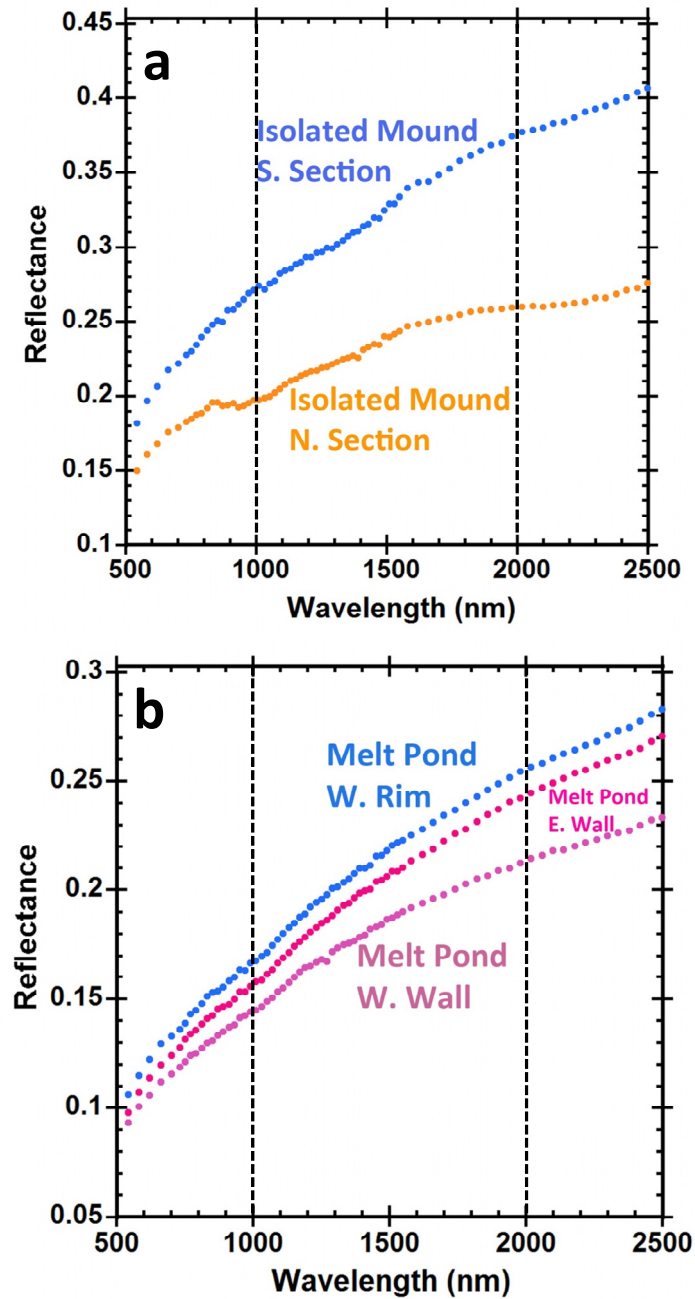


Figure 18 Spectral variability in the impact melt occurrences at small spatial scales at Jackson crater. (a) Spectra from northern and southern section of the same isolated mound (marked with filled black arrow in Figure 17). (b) Spectra from melt ponds located on the crater wall and rim.

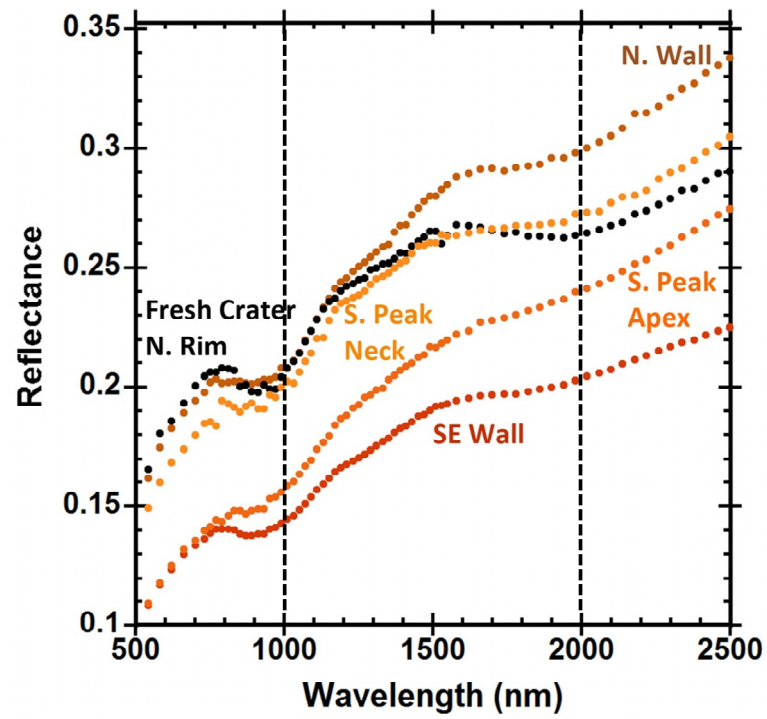


Figure 19 Spectral variability in the pyroxene occurrences at Jackson crater and nearby region.

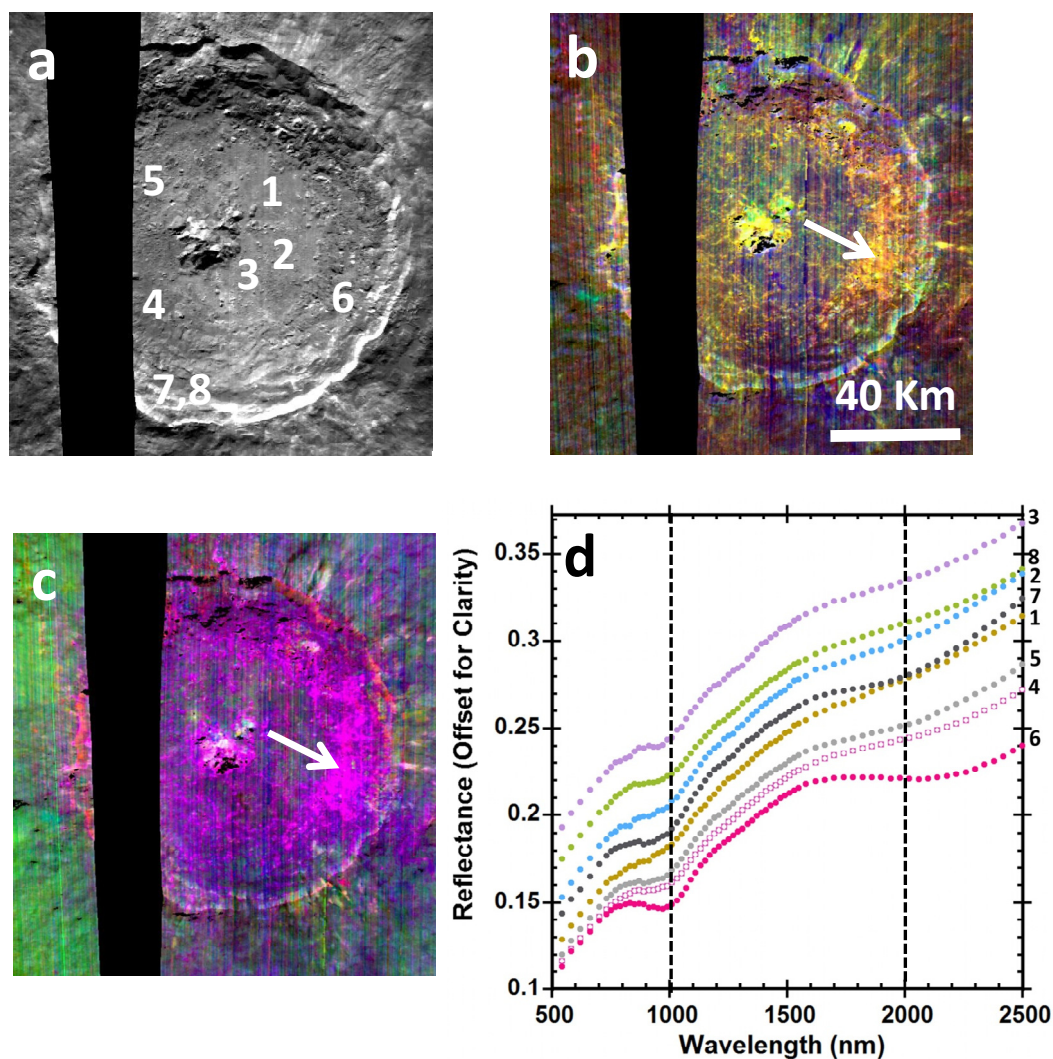


Figure 20 Mineralogically distinctive eastern wall of Tycho crater. (a) M³ Op2c1 albedo image at 1489 nm. Numbers indicate spectral sampling locations. (b) M³ standard color composite (see Table 1 for spectral parameters) highlighting the mafic nature of the eastern wall. (c) M³ complementary color composite suggests high calcium-pyroxene occurrence at eastern wall, peaks and parts of crater floor. (d) Spectra of melt soils from various locations as marked in a. Note the long wavelength absorption bands of the bottom two spectra (#6 eastern wall , #4 SW floor). White arrows in b and c indicate the location of #6. The reflectance scale refers to spectra 6 and 8. All others are offset as

follows: Spectrum 1: 0.01, spectrum 2: 0.07, spectrum 3: 0.07, spectrum 4: 0.01,
spectrum 5: 0.035, spectrum 7: 0.02

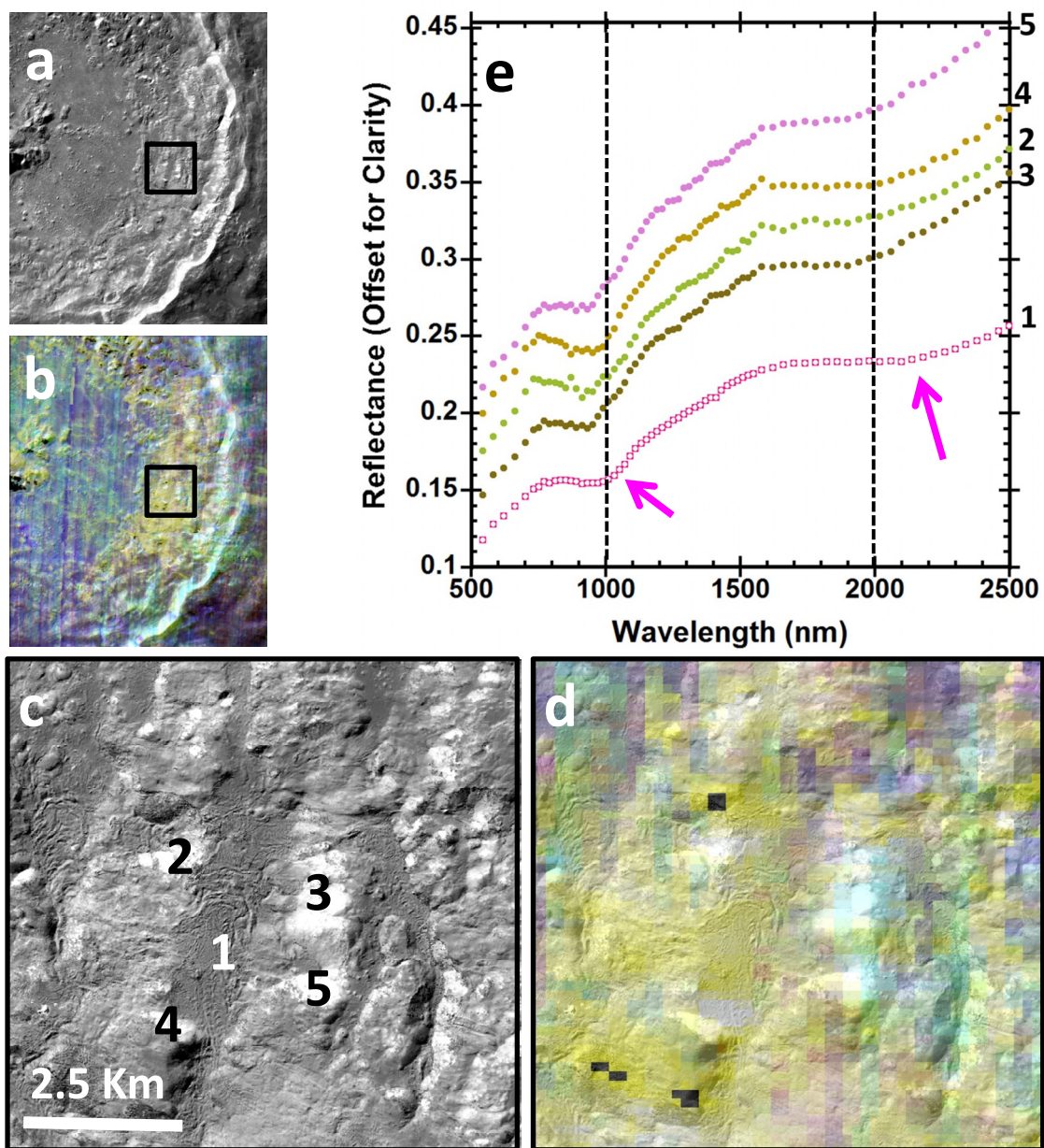


Figure 21 High resolution spectral studies of the eastern wall melt-rock exposures at Tycho crater. (a) Kaguya TC image of eastern section of Tycho. (b) M³ standard color composite (see Table 1 for spectral parameters) overlain on Kaguya TC image. The image shows the distinctive mafic character of the eastern wall. Black boxes in both a and b show the location of area selected for high resolution study. (c), (d) Enlarged view

of the study location. Numbers in c indicate the spectral sampling locations. (d) is M³ standard color composite overlain on Kaguya TC data for the study region. (e) Spectra of the melt-rich (#1) and melt-poor (#2 - #5) locations. Magenta arrows indicate the distinctly longer wavelength absorption bands of the melt-rich region (#1). The reflectance scale is offset for spectrum 2 by 0.02, spectrum 4 by 0.04 and spectrum 5 by 0.06.

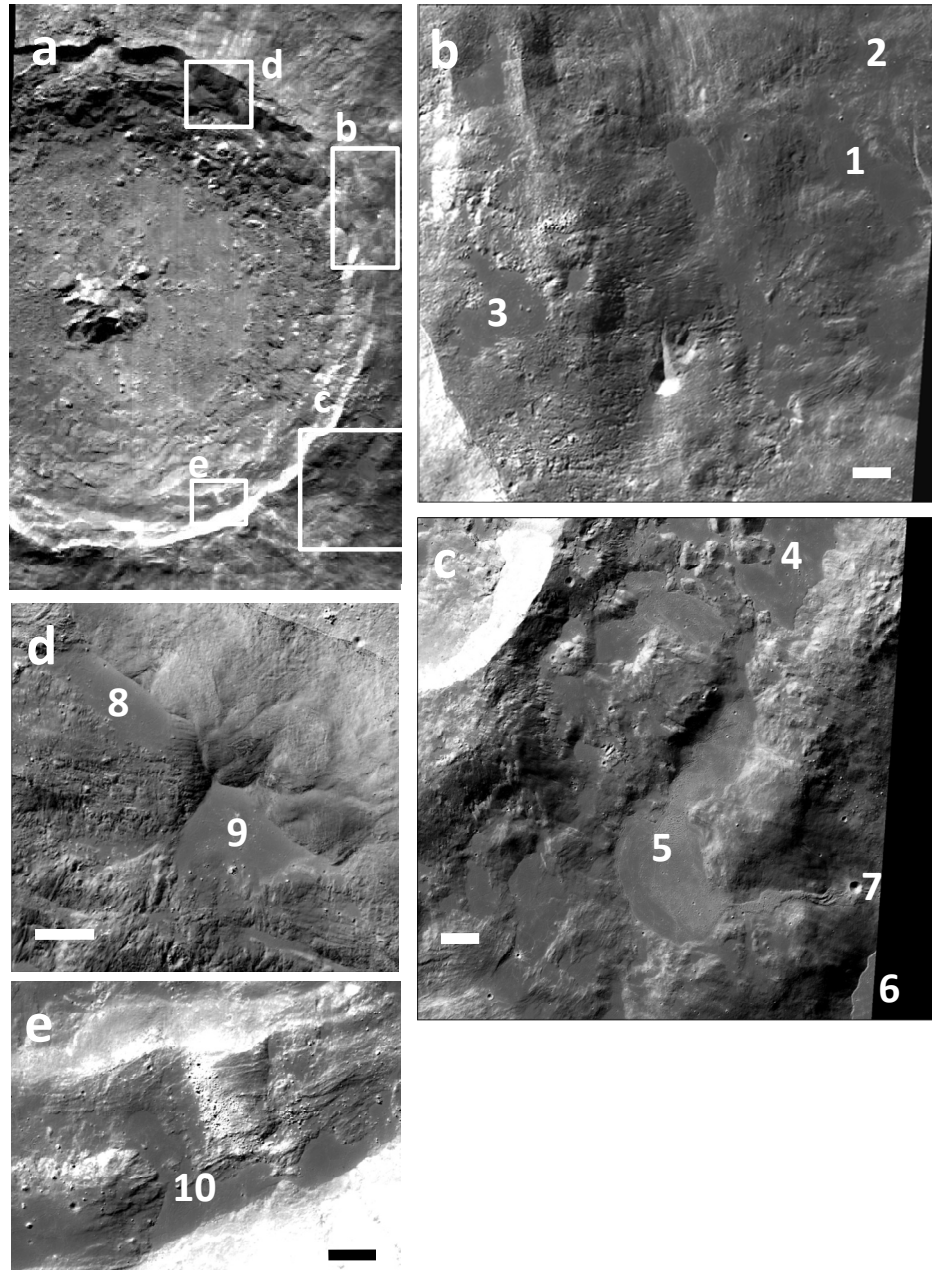


Figure 22 Impact melt ponds at Tycho crater selected for mineralogical analysis. (a) M³ Op2c1 image of Tycho providing context for the melt pond locations. (b) NE rim region. (c) SE rim region. (d) Northern wall region. (e) Southern wall region. Scale bar in b-e is 1 km.

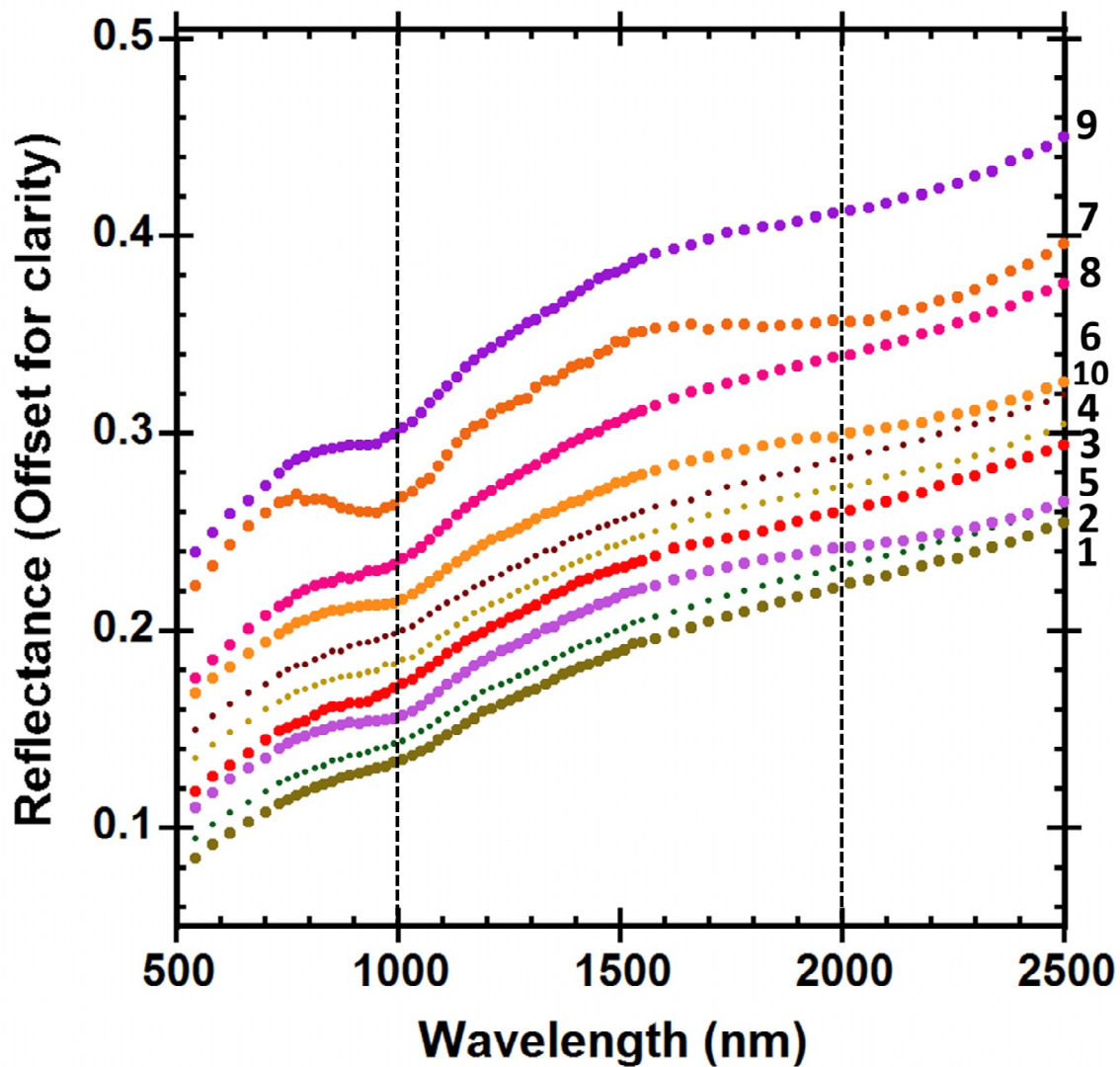


Figure 23 Mineralogical character of the impact melt ponds at Tycho crater. The numbers correspond to the locations shown in Figure 22. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.01, spectrum 3: 0.02, spectrum 4: 0.04, spectrum 5: 0.01, spectrum 6: 0.07, spectrum 7: 0.08, spectrum 8: 0.06, spectrum 9: 0.1, spectrum 10: 0.05

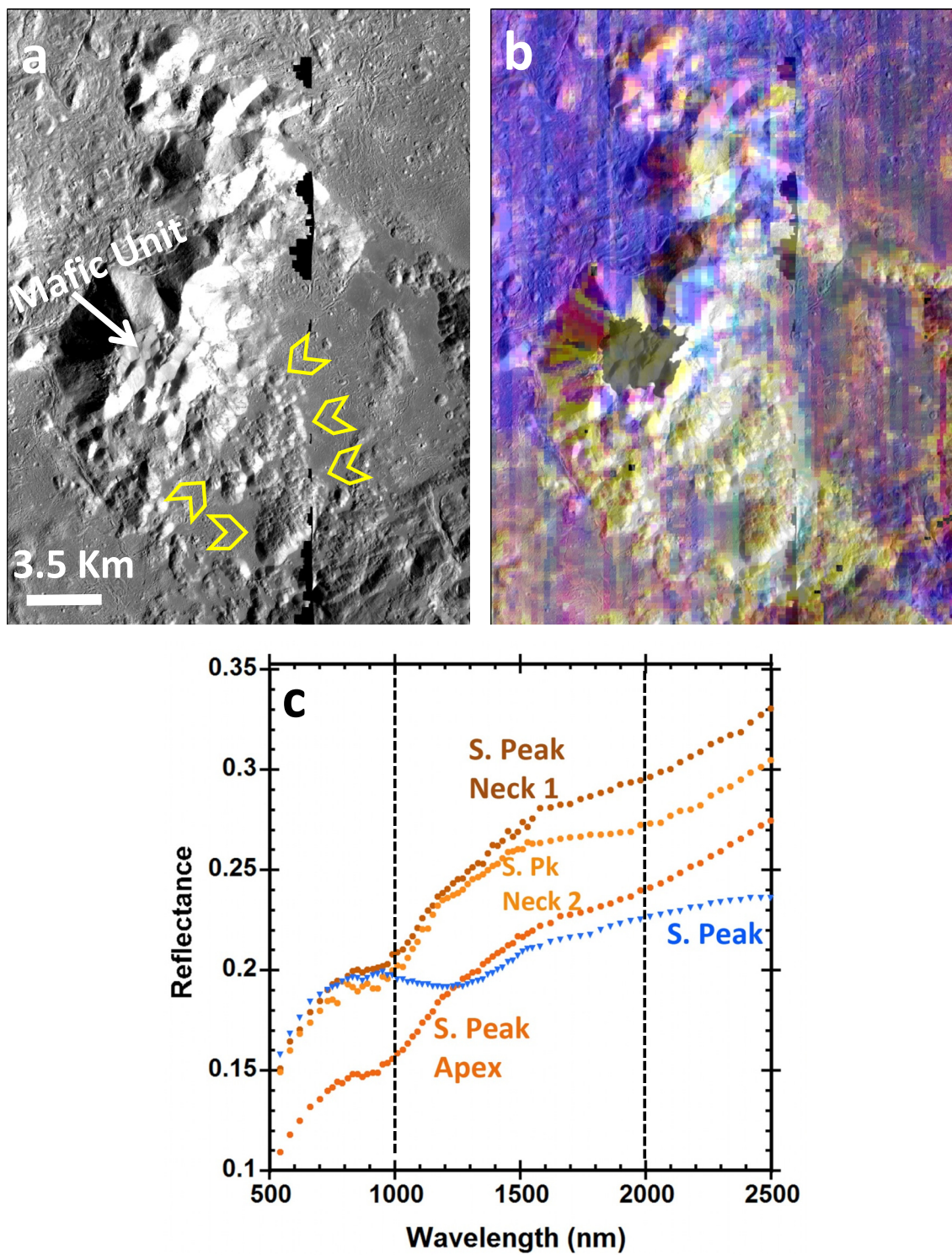


Figure 24 Extensive mafic character of the central peaks of Jackson. (a) Kaguya TC image of the central peaks highlighting the location of the previously documented mafic

unit (white arrow). Hollow yellow arrows point a likely connection of the peak (neck) with the wall. (b) M^3 standard color composite overlain on the Kaguya TC image. The extent of previously documented mafic unit is also mapped in black. Note that mafic character extends beyond the black mapped unit and is also shared by the neck region. (c) Spectra from selected locations on the central peak and the neck region. The high calcium-pyroxene rich character of the peak and the neck region is comparable. The blue spectrum represents crystalline plagioclase exposure on the peak.

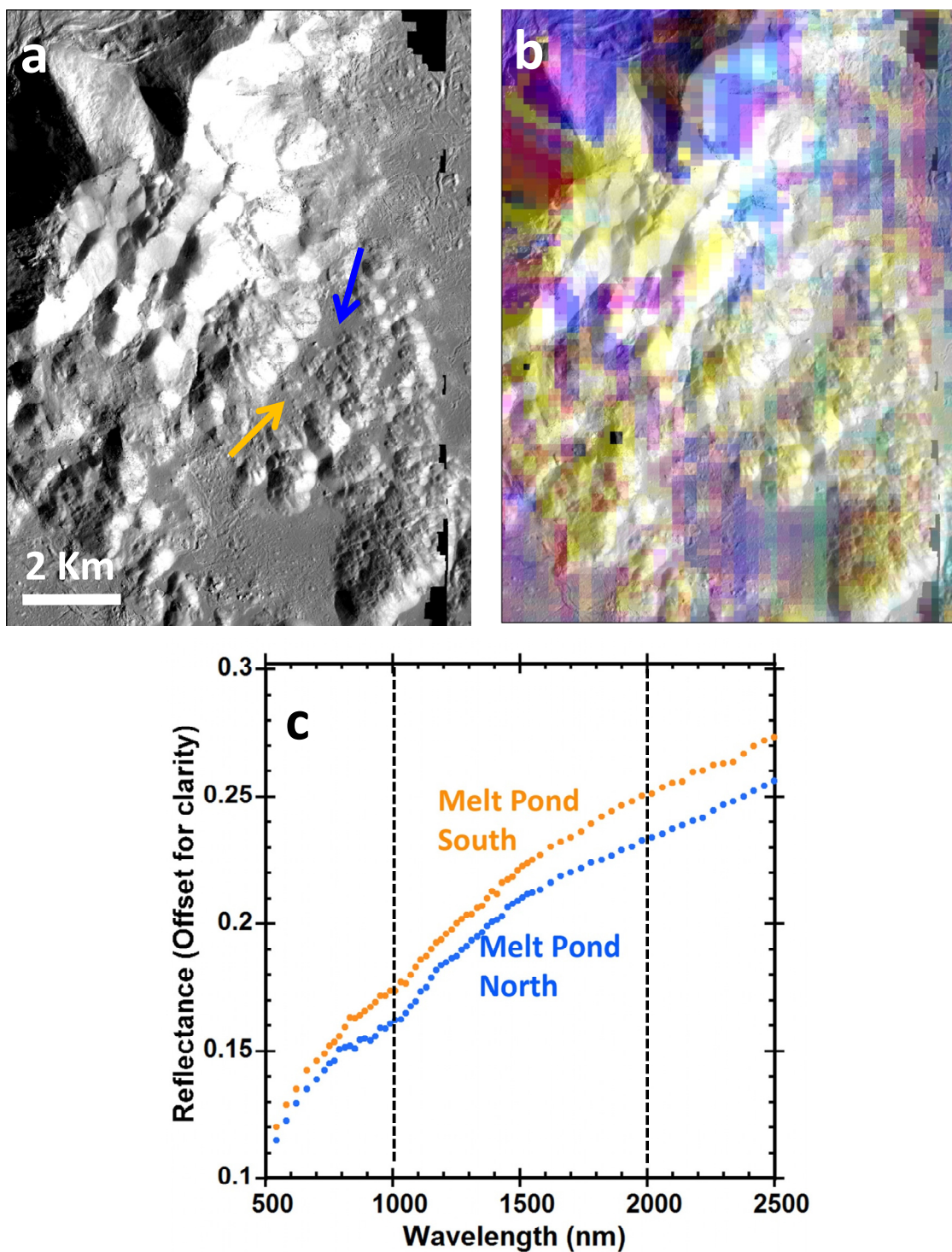


Figure 25 Mineralogical variations within a melt unit on the central peak neck region at Jackson crater. (a) Kaguya TC image of the central peaks showing the melt unit whose

spectra was obtained. Arrows indicate the two sampling locations. (b) M^3 standard color composite overlain on the Kaguya TC image. The melt pond is surrounded by mafic exposures. (c) Spectra from the two locations within the melt pond show variations in spectral signatures. Spectrum labeled as south pond is offset by 0.01.

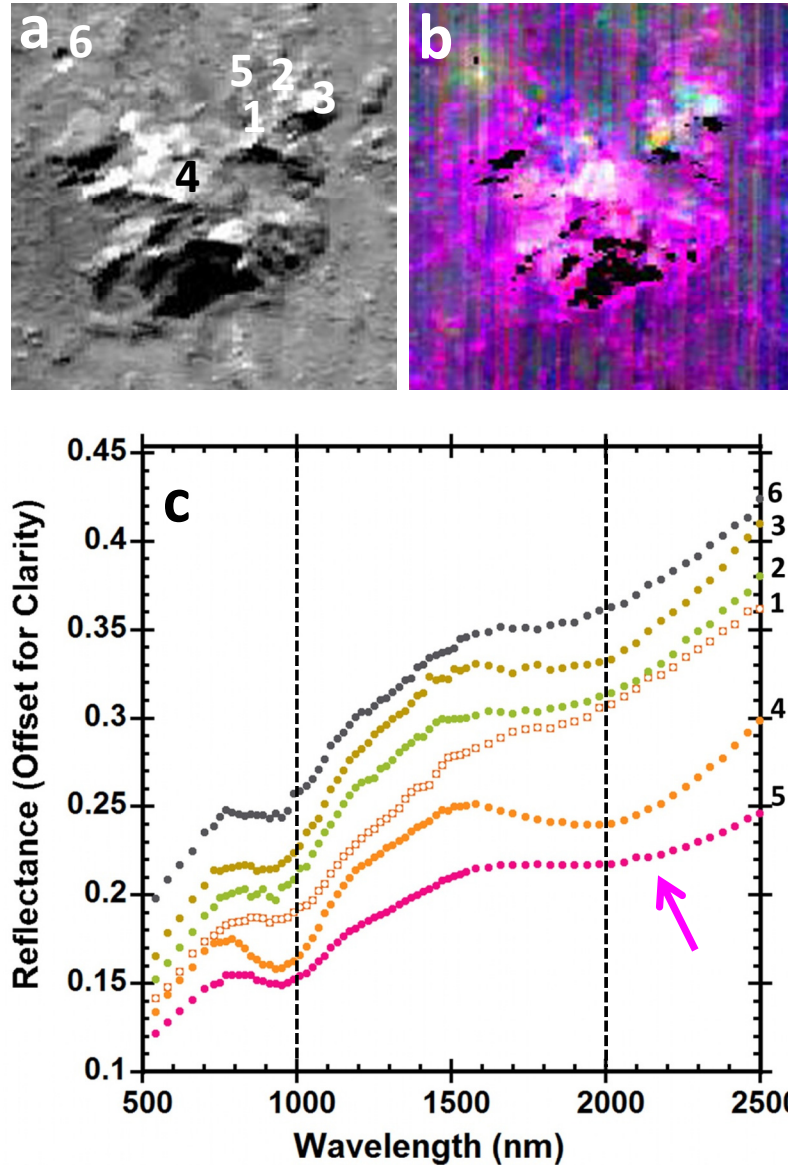


Figure 26 Mineralogical diversity on the peak of Tycho crater. (a) M³ Op2c1 albedo image at 1489 nm showing locations selected for spectral sampling. Numbers correspond to spectra shown in c. (b) M³ complementary color composite used for discriminating within pyroxenes shows different tones on the peaks. (c) Spectra of the selected locations based observed variations in the color composite shown in b. Note the distinctly long wavelength absorption of the impact melt on the crater floor (#5, magenta spectrum) compared to other melt signatures. The reflectance scale refers to spectra 5 and 6 1. All

others are offset as follows: spectrum 1: 0.02, Spectrum 2: 0.02, spectrum 3: 0.05,
spectrum 4: 0.02

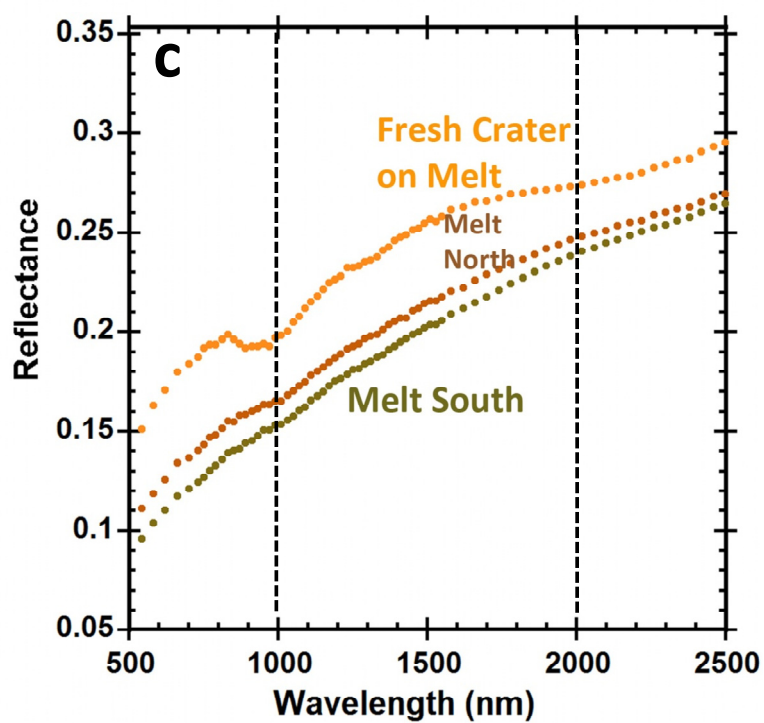
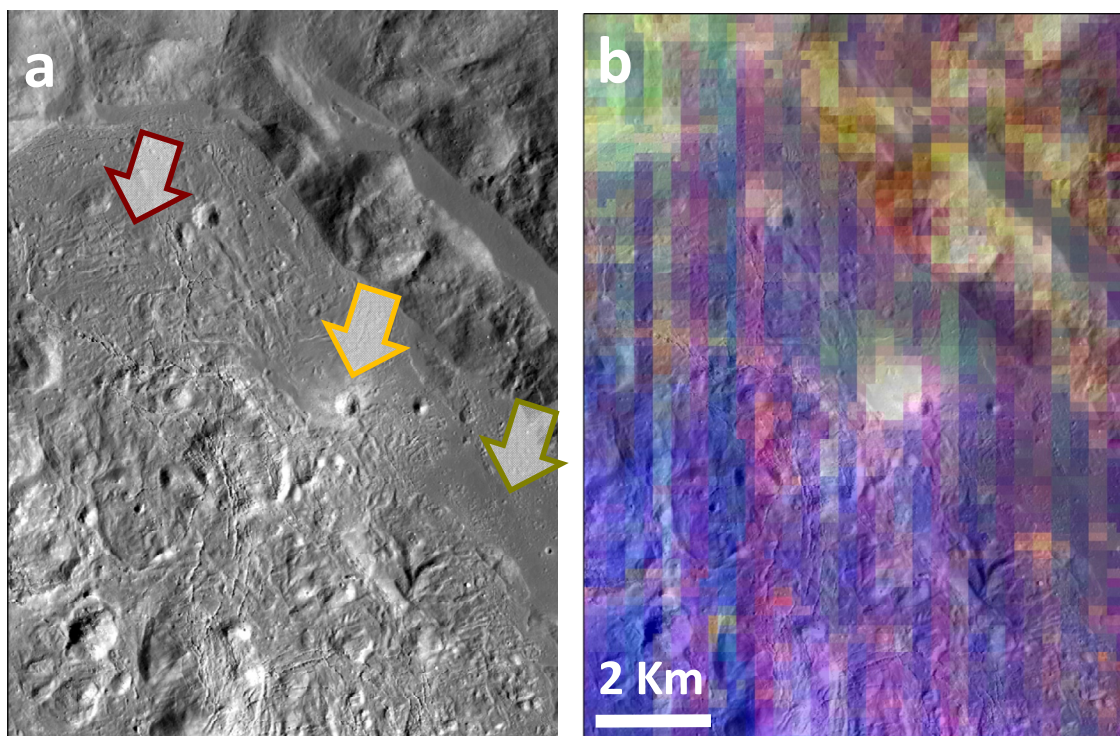


Figure 27 Variation in melt mineralogy in the NE smooth floor deposits at Jackson crater. (a) Kaguya TC image of the NE crater floor showing fresh crater (orange arrow) in

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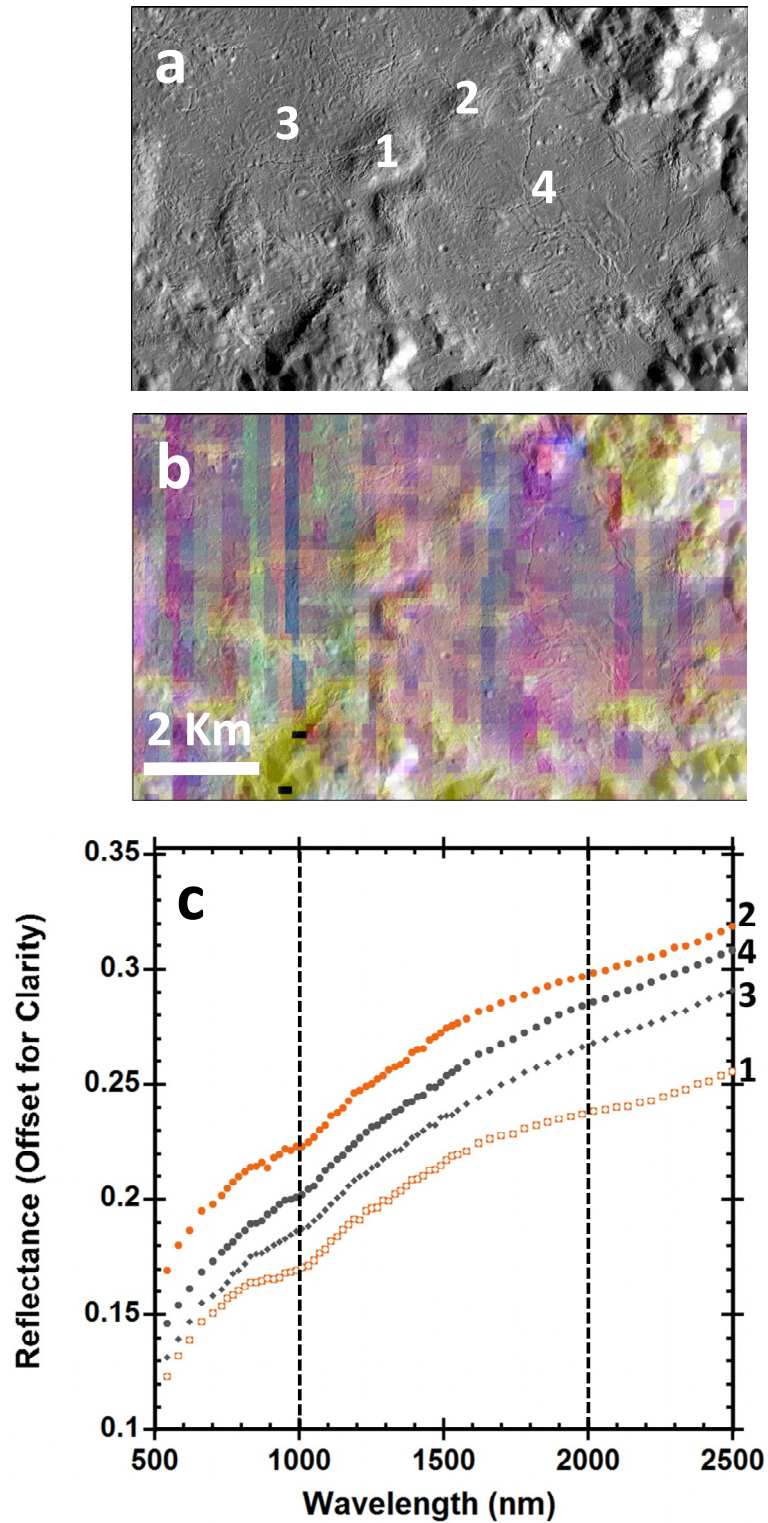


Figure 28 Impact melt textural linkages with spectral signatures at Jackson crater. (a) Kaguya TC image of the southern part of the crater floor showing raised mounds(#1, #2)

with coarser texture relative to the nearby melt (#3, #4). (b) M^3 standard color composite overlain on Kaguya TC data suggesting that raised mounds have strong mafic character (yellow coloration). (c) Spectra from two mounds (#1, #2) and background melt (#3, #4) show systematic variations in band strength. Note the subtle differences in their respective continuum slopes. The reflectance scale refers to spectrum 1. All others are offset as follows: Spectrum 2: 0.04, spectrum 3: 0.02, spectrum 4: 0.03

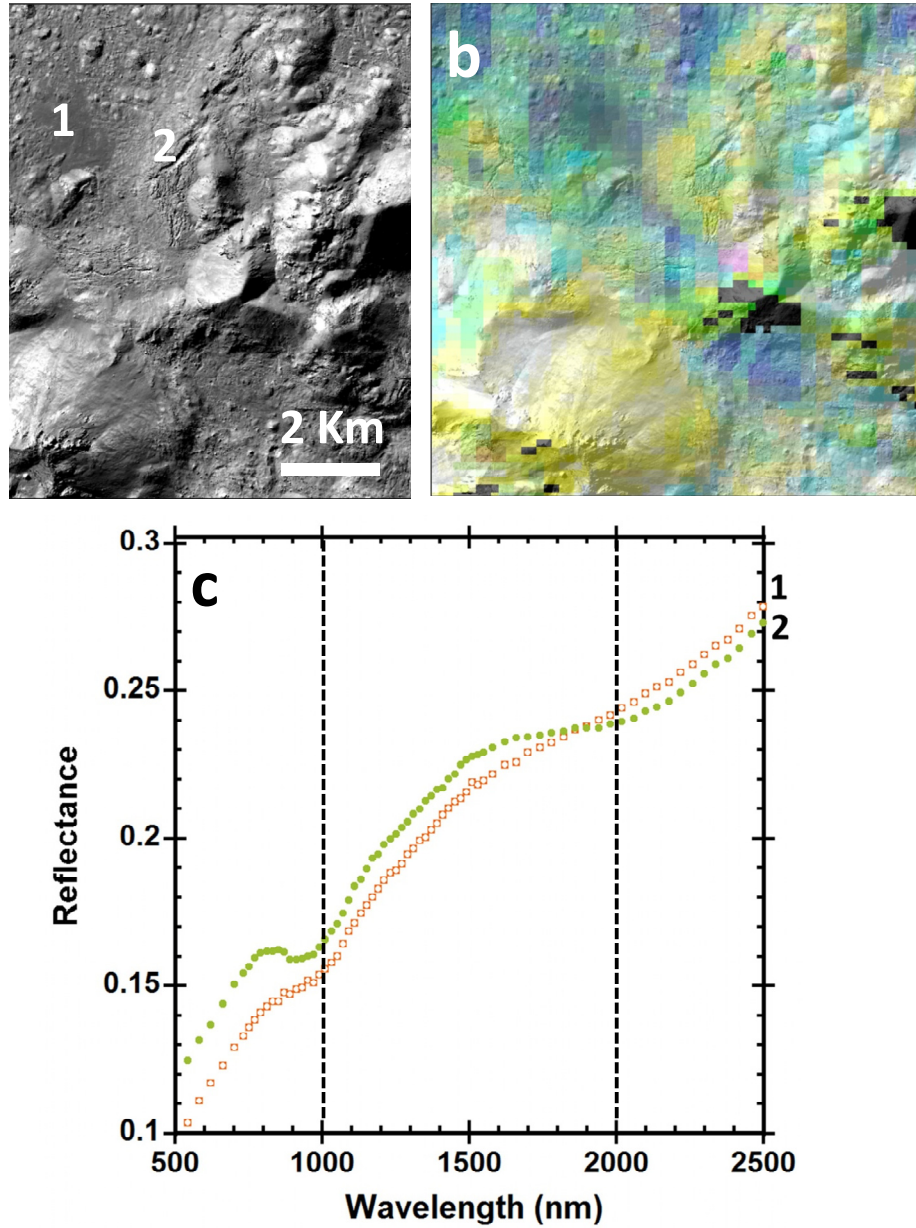


Figure 29 Evaluating relationship between morphological texture and spectral signature of impact melt at Tycho crater. (a) Kaguya TC image showing a smooth melt near the central peak (#1) and fractured melt (#2). (b) M^3 standard color composite (see Table 1 for spectral parameters) overlain on Kaguya TC image showing broad scale mineralogical character of the two selected locations. (c) Spectral properties of the two selected

locations. Textured melt has relatively stronger absorption bands although mineralogical composition appears similar.

CHAPTER 6: Synthesis and Future Directions

Deepak Dhingra

1. Summary of Major Results

This work is perhaps the first major study integrating mineralogical and morphological properties of lunar impact melt deposits using the new generation remote sensing data. Our research has provided diversity of new perspectives on the character and distribution of impact melt deposits at complex craters on the Moon and has important implications for the lunar surface composition and the impact cratering process. We highlight some of the salient findings here.

1.1 Impact Melt Deposits – No unique spectral signature

Remote spectral reflectance studies of a wide variety of impact melt deposits at various craters presented here have illustrated the fact that there is no unique spectral signature associated with impact melt which can be used for its identification. Similar inference was also drawn from laboratory spectral measurements of selected lunar impact melt samples [Tompkins and Pieters, 2010]. Impact melt, especially from a remote sensing perspective, is an umbrella term for melt deposits with variable proportions of un-melted rock fragments or clasts. The mineralogy of such deposits is therefore determined by the mineralogy of the rock fragments and the melted material. Mineralogy of the pre-impact target material largely dominates the melt mineralogy to the extent that melt seems to mimic the same composition in many cases. There are however secondary contributing factors such as the degree of crystallization of the melt component, amount of opaques and the surface texture.

Quenched glass, defined as fast cooled, poorly crystalline glass with weak spectral bands, is expected to be associated with impact melt deposits [e.g. Smrekar and

Pieters, 1985; Tompkins and Pieters, 2010]. In our studies, spectral character of some of the impact melt soils seem to bear the signatures of quenched glass (e.g. in Copernicus NW quadrant, [*Dhingra et al., 2013; Dhingra et al., 2014*]) but we could not uniquely identify them due to the very weak spectral features. In general, we did not identify quenched glass as an abundant impact melt species among the various craters that were studied. In majority of the cases, where a confident morphological identification of the impact melt deposit could be made, the spectral signatures were similar to a crystalline lithology. It should however be noted that even if quenched glass is unambiguously identified spectroscopically, it would represent only one component of impact melt among the vast diversity that has been documented in the presented research.

Laboratory studies of impact melt samples have suggested the possibility of 600 nm absorption band being associated with certain types of impact melt deposits [*Tompkins and Pieters, 2010*]. It has been suggested to be caused by fine grained ilmenite dispersed in a relatively transparent mineral such as plagioclase. In our studies, we did not specifically find this feature to be commonly associated with impact melt. Unfortunately, there are uncertainties in the obtained M³ spectral data in the wavelength region short of 750 nm which may have also affected the detection of this feature in our studies. The occurrence of 600 nm absorption in remote measurements of lunar impact deposits thus remains open to future studies with better datasets, especially in this wavelength region.

1.2 Mineralogy of Impact Melt across Craters - Strong spectral signatures more common than bland

The survey of impact melt deposits at various lunar complex craters and further detailed studies at some of them have illustrated the fact that impact melt deposits, in most cases, share spectral similarity with crystalline rocks. Our studies have shown strong absorption bands being commonly associated with morphologically identifiable impact melt deposits. Some noteworthy examples include impact melt ponds on the southern crater wall of Copernicus crater, melt pond on western crater floor of Giordano Bruno, melt ponds on northern wall and eastern rim of Tycho and the melt accumulations on the eastern wall of Tycho crater. We have also reported weak to spectrally bland signatures from certain melt deposits but they are relatively less common. In addition, some of the featureless spectra are due to specific lithology (e.g. shocked plagioclase at Jackson crater floor) while in other cases, it could be an effect of the geological age (spectral maturity).

Among the diversity of spectral signatures that have been observed to be associated with impact melt deposits, a comparison with the spectral measurements of impact melt in the laboratory [e.g. *Tompkins and Pieters, 2010*] suggests that most of the observations reported in this research would fall in the category 1A/2A, that is spectra with strong, well-defined absorption bands similar to primary igneous rocks (Figure 1a, d). In certain cases, we also found indications of the likely presence of quenched glass/olivine in a pre-dominantly pyroxene spectra [e.g. *Dhingra et al., 2013*]. In such cases, the pyroxene band around 1000 nm was much broader indicating additional components (Green spectrum – A1, Figure 1e, f) and making the spectra look similar to

spectral class 2B. However, this possibility was also supported by the geological context in that the spectral sampling was carried out on the melt-rich crater floor. It is difficult to confirm the presence of quenched glass in the presence of other minerals owing to contributions from several minerals in this wavelength region including plagioclase, fast cooled pyroxenes and olivine.

1.3 Prevalence of Mineralogical Heterogeneity in Impact Melt Deposits at Various Spatial Scales

This has been the key observational finding coming out of our research. It includes the first documented evidence of large scale mineralogical heterogeneity in lunar impact melt deposits [Dhingra *et al.*, 2013]. It may seem obvious to have heterogeneous mineralogy in different parts of an impact melt deposit due to the chaotic nature of the cratering process. In fact, many of the impact melt hand samples (except differentiated impact melt) appear highly heterogeneous in their mineralogy. However, what distinguishes our observations from these known facts is that there is *an observable order in the chaos*. Further, this orderly behavior is reflected at different spatial scales.

The 30 km long, spectrally prominent, low calcium-pyroxene rich sinuous impact melt feature on the Copernicus crater floor in the vicinity of high calcium-pyroxene rich melt is perhaps the best example of large scale mineralogical heterogeneity in impact melt deposits [Dhingra *et al.*, 2013]. In contrast, the coherent mineralogy within the large sinuous melt deposit represents a certain degree of order in impact melt composition which is interesting. Besides, the melt deposit also has the distinction of not being easily detectable on albedo images or topography data.

On a different spatial scale, 2-5 km melt ponds scattered inside and outside of Copernicus, Glushko and Tycho [*Chapters 1, 4 and 5*] exhibit variability in melt mineralogy that is systematic in nature and at times could be clearly linked with the local target mineralogy. These observations are not only brand new, they have several important implications. Some of them are discussed in the later sections.

1.4 Impact Melt Mineralogy - Contributor to the Observed Compositional Diversity

The strong spectral signatures associated with impact melt deposits and their pervasive mineralogical heterogeneity at different spatial scales makes impact melt deposits an important contributor to the observed mineralogical diversity of the lunar crust [*e.g. Pieters et al., 1991*]. This realization from our research marks an important departure from the generally assumed *primary* nature of the crustal mineralogical diversity. Our work has extensively documented the fact that a lot of mineralogical diversity is, in fact, *secondary* in nature. It is important to distinguish the primary vs secondary contributions. The best example to illustrate the importance of making this distinction is the distribution of olivine at Copernicus crater. Spectral identification of olivine in the central peaks and the northern wall were equated based on mineralogical similarity and it was assumed that both olivine occurrences had the same origin. This information was used to suggest a shallow source depth of olivine at Copernicus.

Our mineralogical investigations coordinated with high spatial resolution geologic context indicate multiple origins of olivine lithology at Copernicus crater [*Dhingra et al., 2014*]. We have shown that olivine occurrence on the northern crater wall is associated with impact melt and therefore *secondary* in origin compared to the *primary* origin of

olivine in the central peaks of Copernicus. Since central peaks have been suggested to originate below the melting zone, the two olivine occurrences, one derived from melt zone vs the other derived from region below it, *cannot be directly compared* and likely had different sources.

1.5 Impact Melt Cover on Central Peaks - Implications for the interpretation of mineralogy at depth

Central peak mineralogy as a key to explore the compositional structure of the crust was pioneered by *Tompkins and Pieters*, [1999] based on the premise that central peaks represent material excavated from great depths which is otherwise not directly accessible. The idea has later been followed extensively by many workers [*e.g. Cahill et al.*, 2009; *Song et al.*, 2013]. However, in view of our identification of impact melt deposits on the central peaks of many craters and the common association of strong, crystalline absorption bands with impact melt deposits, it is now important to ascertain whether the dominant mineralogical signatures on the central peaks are being contributed by the relatively pristine material uplifted from great depths or the impact melt derived from shallow depths? This potential confusion was also acknowledged in the initial spectral analysis of the crater central peaks [*Tompkins*, 1997]. However, the available resolution of the various datasets was perhaps insufficient at that time in order to decipher the dominant sources of spectral signatures on the central peaks.

The currently available data has helped alleviate that confusion to a certain extent. Extensive impact melt cover has been mapped on Tycho and Jackson [*Chapter 5*]. Some other recent studies have documented impact melt on central peaks of many other craters

[*e.g. Kuriyama et al., 2013; Dhingra et al., 2014*] suggesting impact melt to be pervasive on the peaks. Accordingly, it is now important to isolate melt-free regions on central peaks and revise the mineralogical assessment of the crust.

1.6 Integrated Impact Melt Studies - Tool to understand the impact cratering process

The process of impact cratering is not only chaotic, it is also extremely short-lived making it difficult to document each stage of the process in detail even in a laboratory. Besides, the nature of the process changes with the scale of the event (simple craters to complex craters to basins). Although experiments and modeling efforts have contributed a great deal to our understanding of the impact cratering process, even now the computational resources are insufficient to model many geological observations including observations of melt mineralogical heterogeneity presented here.

The observational capabilities provide an alternative way to explore some of these difficult to handle problems. Earlier workers have used field and remote sensing observations to understand diversity of aspects related to the cratering process including the role of pre-impact target topography [*e.g. Hawke and Head, 1977*] and deciphering the impact direction of the projectile [*e.g. Kruger et al., 2012*]. The new generation sensors have made this option even more productive. Our research has illustrated several examples where detailed high resolution mineralogical and morphological observations could be used to understand the dynamics of melt formation, its emplacement and subsequent evolution. Our results on radial asymmetry in the mineralogy of impact melt ponds were interpreted to indicate that impact melt, at least in certain cases, seems to locally derived thereby preserving the local mineralogical character of the target rock.

We have compared nature and distribution of megaclasts at Jackson and Tycho craters to propose that pre-impact target rocks at Jackson were likely highly fractured giving rise to the larger average size and abundant nature of the isolated mounds. In contrast, the target at Tycho was perhaps more coherent and led to smaller size of the isolated mounds and their relatively sporadic occurrence. We acknowledge that these efforts still represent the *first steps* in the direction of understanding the conditions during the cratering event and subsequent dynamics of material modification. There is considerable scope to improvise and refine since many such interpretations are non-unique and need to be validated extensively. Nevertheless, our research has highlighted new parameters that could be used in understanding the cratering process as well as the target characteristics.

2. Outstanding Issues

The research presented here has raised several questions, some of which remain to be answered and would benefit from incorporating additional data as well as expanding the analysis to other craters.

2.1. Quenched glass

Although not specifically detected in our study regions, quenched glass of different composition has been synthesized and measured in the lab [e.g. *Bell and Mao*, 1976; *Tompkins and Pieters*, 2010] and has also been reported from some locations on the Moon [e.g. *Mustard et al.*, 2011]. The nature of occurrence of quenched glass is unclear at the moment and could be affected by many parameters including the presence

of other mineralogical components and preservation. Dark haloes have been noticed around many craters (e.g. Tycho) under high solar elevation conditions and suggested to be indicative of quenched glass occurrences. However, some recent work has suggested that dark haloes around small craters are related to differences in texture [*e.g. Kaydash et al.*, 2014]. Work needs to be done to evaluate whether similar textural differences at large craters could be the cause of dark haloes. An additional complexity associated with the detection of quenched glass is the difficulty in distinguishing its origin from impact process vs volcanic fire fountaining activity since glass is produced in both the events.

2.2. Relationship of Impact Melt Texture to Mineralogical Signatures – Role of clasts

Our research has consistently shown strong spectral signatures to be commonly associated with impact melt deposits. These include smooth ponds on the crater walls, flows on the crater interior and exterior as well as fractured melt on the crater floor. It is however difficult to say what commonly dominates the spectral signatures – is it the crystallized melt or the un-melted rock fragments (clast)? We tried to use surface texture as a proxy to decipher melt to clast ratio within the constraints of spatial resolution of our remote sensing data. In this direction, we could identify (and map in selected craters) impact melt deposits with different surface texture (e.g. smooth, rough, intermediate, cracked). However, we have documented strong spectral signatures from some of the smoothest melt deposits (e.g. melt pond on southern wall of Copernicus) and lack of spectral features (bland spectra) in case of rough textured melt occurrences (e.g. hummocky unit on Copernicus crater floor). It is also interesting to note that some of the

textured melt on isolated mounds at Jackson crater display mafic absorptions compared to smooth melt deposits in the immediate vicinity.

In view of this contrast in observations, there does not seem to be a directly observable link between impact melt texture and the corresponding mineralogical signatures. Therefore, at this point, both crystallized melt as well as un-melted rock fragments (clasts) are assumed to be equally contributing to the spectral signature. There are however, exceptions where one component is more preferable than the other. An important example in this case is the low-albedo olivine bearing deposit on the northern wall of Copernicus crater. The strong spectral signature of this proposed impact melt deposit [Dhingra *et al.*, 2014] along with its significantly low albedo, makes olivine bearing clasts as the likely dominant contributor to the observed absorption bands while the melted component is likely contributing to the low-albedo through the presence of abundant opaques. However, this is a non-unique interpretation and more work is required to shed light in this direction.

2.3. Effect of Age on Impact Melt Deposits: Constraints on Mineralogical Characterization

Impact melt deposits are expected to age with time just as the other material on the Moon with space weathering being an important process that weakens the spectral signatures [*e.g.* Hapke *et al.*, 1970; Pieters *et al.*, 1993]. Our work, although focused on geologically young Copernican craters (<1 billion years), has tried to contrast the results by including a few relatively older Eratosthenian craters (1-3.2 billion years). We have shown that not only it becomes morphologically difficult to identify impact melt deposits

at the older craters (e.g. Aristillus, Eratosthenes), wherever melt deposits can be identified, the spectral signatures are usually bland with no detectable absorption bands associated with them (e.g. Burg). As a result, it is almost impossible to capture any mineralogical differences. At this point, it is then difficult to ascertain whether the impact melt at a given crater is homogeneous and amorphous or is it heterogeneous and crystalline but the space weathering effects have muted the spectral signatures?

We have shown that older craters (Eratosthenian age) tend to lose the spectacular morphological diversity associated with impact melt deposits and therefore this aging seems to limit the scope of spectral and morphological studies. It is still unresolved if all the impact melt morphologies (viz. flows, melt ponds, veneer, cracked melt) age at the same rate or they differentially weather and so some features could still potentially be usable for our studies.

3. Future Directions

3.1. Integrating Information from Other Remote Sensing Techniques

Data is currently available from several other remote sensing techniques offering the potential of being integrated with spectral and imaging datasets used in this study. These include data from radar, gravity and thermal infrared measurements. These data would provide wealth of complementary information that will help in better characterization of the impact melt deposits and might be able to answer some of the questions raised by our work. We plan to include these datasets in future studies for carrying out targeted study of interesting impact melt deposits. Some of the mafic observations made in this study far away from mare occurrences could be investigated

further using GRAIL data [e.g. Zuber *et al.*, 2013; Andrews-Hanna *et al.*, 2013]. Radar data has already been used to identify impact melt deposits [e.g. Carter *et al.*, 2012; Neish *et al.*, 2014] which could not otherwise be detected based on their morphology. We can therefore use it at older craters to identify potential impact melt occurrences.

3.2. Laboratory Spectral Reflectance Studies of Impact Melt/ Radiative Transfer Modeling

Ground truth has always been an integral component of remote sensing studies and the same cannot be overlooked in our case. Spectral measurements of impact melt samples have been undertaken in the past [e.g. Tompkins and Pieters, 2010] and are being actively pursued more recently [e.g. Cannon *et al.*, 2014]. Our work has provided plenty of motivation for some targeted ground truth measurements of impact melt samples that we would like to coordinate with radiative transfer modeling in the near future. A key study would include spectral measurements and comparison of different melt components with the same mineralogy. Such measurements are possible by in-situ measurements where a suitable impact melt rock might show the progression from unaffected clast to partially melted and shocked rock to melt. Laboratory imaging spectroscopy provides the ability to measure different melt components in-situ and could be instrumental in such studies.

3.3. Expanding the Analysis to other Craters and Basins

We feel that our research of impact melt deposits on the Moon would benefit immensely by expanding our analysis to other complex craters and to basins. The

presented research has focused on the impact melt properties at complex craters but basins present an entirely different level of complexity and spatial extent with regard to impact melt. Some recent studies have focused on analyzing mineralogy and modeling the differentiation of impact melt sheets at basins [e.g. *Vaughan et al.*, 2013; *Spudis et al.*, 2014; *Hurwitz et al.*, 2014]. Observational studies of large impact melt sheets at basins on the lines of the integrated analysis presented here would vastly expand our knowledge about impact melt generation, diversity and evolution. In addition, further studies at other complex craters would allow us to build on the various geomorphological observations made here aimed at deciphering target properties and understanding impact melt evolution.

3.4. Comparative Planetology of Impact Melt Deposits

Impact cratering has occurred across the solar system. It is therefore important to compare the impact melt properties observed on the Moon to other planetary bodies. Variation in gravity alone affects the dynamics of melt generation as well as its preservation. Rock porosity is another important factor affecting melt generation. We would like to carry out comparative planetology studies of impact melt deposits to expand the knowledge from their occurrence on the Moon. Although Moon is one of the best places to study impact melt deposits, the close neighbor Mercury and large asteroid Vesta might be good additions to our knowledge soup.

3.5. Motivation For Flying Advanced Spectrometers on Future Missions

Several observations presented in this work stretched the spectral data to its limits and which was at times, a hindrance to the detailed mineralogical analysis. Selected

examples include characterizing the spectral properties of impact melt along crater scale fracture zones (e.g. Tycho, Jackson), observations of small impact melt ponds on the crater rim (e.g. Tycho) and characterization of mafic mineralogy of isolated mounds located within largely feldspathic impact melt at Jackson crater. Such observations would benefit from spectral observations obtained at higher spatial resolution. Although M³ instrument provided a remarkable improvement in spectral resolution, significant improvement in spatial resolution is still awaited and is required. It should be noted though that data from M³ instrument at 70 meters/pixel (and 260 bands) is available for a small number of targeted observations as compared to the 140 meters/pixel resolution of majority of M³ data strips [e.g. *Boardman et al.*, 2011; *Green et al.*, 2011]. While it would have been great to obtain global lunar data at this spatial resolution, we would still need to think of much higher spatial resolution in order to bridge the data gaps highlighted above.

We realize the associated practical issues pertaining to available signal at small spatial footprints while still maintaining high spectral resolution. A workable trade-off could be going for a spectral imager, with slightly less number of spectral bands (20-30) than M³ but higher spatial resolution of 10-20 meters. The closest match to this specification among the currently available datasets is the multi-band imager (MI) which was onboard the SELENE spacecraft [e.g. *Ohtake et al.*, 2008]. It has 9 bands with spatial resolution between 20-62 meters. However, the restricted wavelength range (415 -1550 nm) as well as variable spatial resolution still needs a more desirable instrument.

4. Final Remarks

The work presented here together with some other recent research [e.g. *Bray et al.*, 2010; *Denevi et al.*, 2012 ; *Neish et al.*, 2014; *Stopar et al.*, 2013; *Wöhler et al.*, 2014] has highlighted the relatively widespread occurrence of impact melt on the lunar surface, spectacular diversity in its morphological form and mineralogical diversity. The latter is not only limited to presence of strong spectral signatures but is also represented by mineralogical heterogeneity at different spatial scales. Impact melt deposits produced by the cratering process dot the lunar landscape and in essence form a pervasive cover which should perhaps be regarded as a separate global unit on the lines of megaregolith and regolith. The formation of impact melt deposits by recycling of the primary and/or secondary lunar crusts makes it suitable to be referred as a type of ‘tertiary crust’ in the generic sense. This designation is different than the generally accepted definition of tertiary crust, that being produced at convergent plate margins] on the Earth [*Taylor*, 1989]. However, the realization of impact melt deposits as an important contributor to the crustal mineralogy as demonstrated by our research and their vast spatial occurrence merits their acceptance as the lunar tertiary crust.

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Figure Captions

Figure 1 Comparison of laboratory spectral reflectance data with remotely obtained spectra of impact melt deposits. (a) Spectra from Apollo crystalline impact melt breccias. Note spectral classes 1A and 1B. (b) Spectra of the synthetic glasses generated from same samples as a, under lunar-like conditions. (c) Spectra of the impact melt samples from several locations on the Moon exhibiting a consistent absorption feature around 600 nm. This is classified as spectral class 2C (d) Spectra from the lunar impact melt suite showing broad absorption around 1000 nm and weak band around 2000 nm (spectral class 2B); strong absorptions at 1000 nm and 2000 nm (dotted spectrum, spectral class 2A) (e) Spectra of impact melt deposits on the Copernicus crater floor. Note the broad absorption band around 1000 nm in the green spectrum (A1) taken from fresh crater in impact melt. It shares some similarity with Class 2B spectra shown in d (marked with black arrows). The orange and blue spectra (A2, A3) are from a sinuous melt feature and do not seem to have the broad absorption, besides having a different pyroxene composition. (f) Continuum removed version of the spectra in e show the same differences. Spectra in a-d are laboratory measurements taken from Tompkins and Pieters, [2010]. Spectra in e-f are remote sensing measurements from M³ and have been taken from Dhingra et al., [2013]

Figures

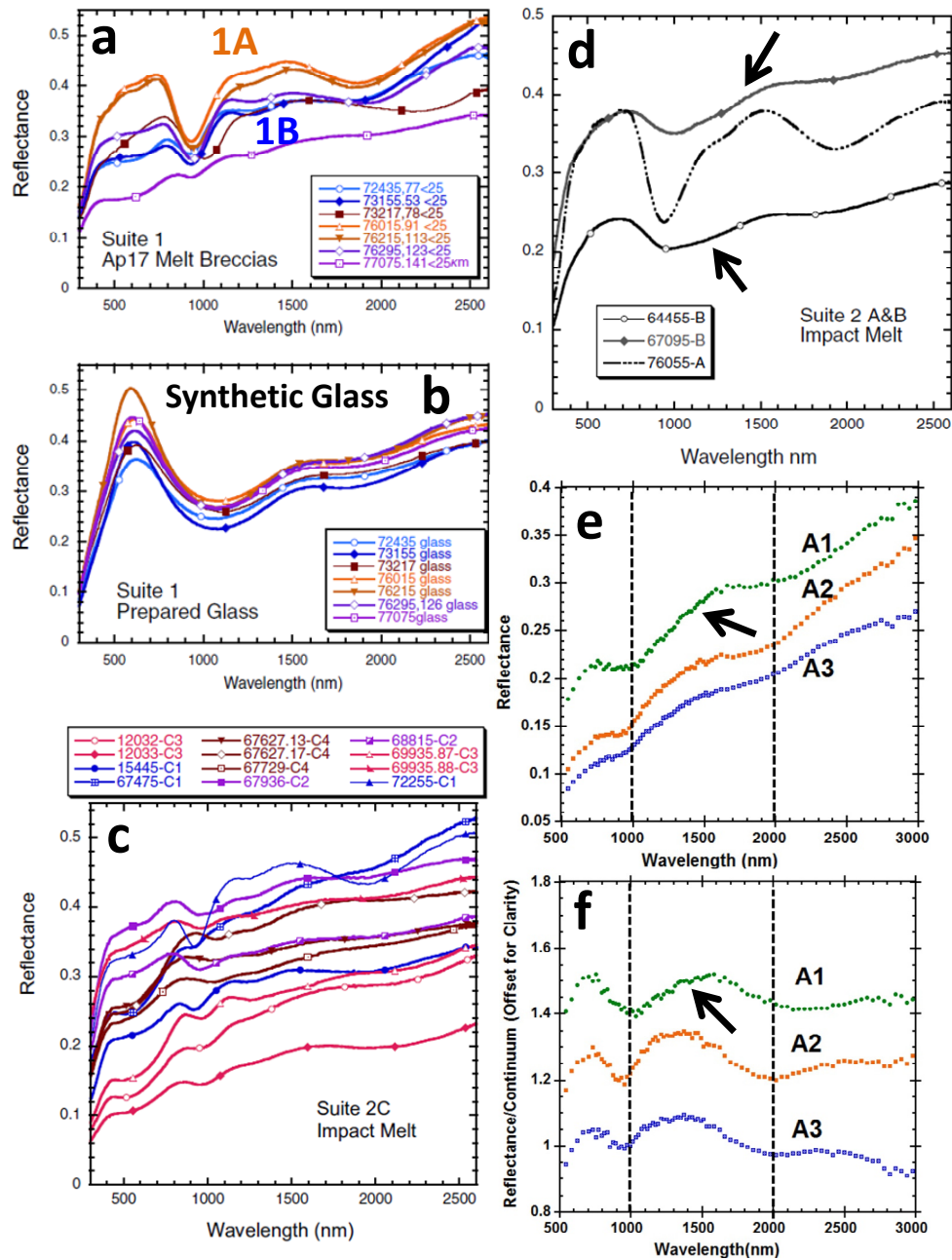


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APPENDIX – I: Non-Linear Mixing Analysis of Impact Melt at Copernicus
Crater Floor using Hapke’s Radiative Transfer Model

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Abstract

A radiative transfer based approach is taken to study the mineralogical diversity of impact melt at Copernicus crater using Hapke's theory. Optimized image-derived end members have been selected for modeling the observed variations in mineralogy. Two approaches are implemented to independently generate the observed contrast in the spectral character of various mineralogical units. The first approach uses linear unmixing of spectral data cube in single scattering albedo space to obtain end member distribution on the Copernicus crater floor. The second approach compares spectral data cube with synthetically generated mineral mixtures (created in single scattering albedo and then converted back to reflectance) in order to obtain the distribution of mineralogical end members. Both the approaches are able to reproduce the observed spectral diversity in the impact melt namely, in the form of mineralogically distinct low calcium-pyroxene bearing sinuous impact melt feature and high calcium-pyroxene signatures in nearby impact melt exposed through two fresh craters. The second approach, which is more desirable, needs to be developed further in order to provide realistic estimates of mineral abundances associated with various impact melt deposits.

1. Introduction

Rocks are an *intimate mixture* of component minerals where the individual grains from different minerals are in contact with each other. Photons of light falling onto such a target are multiply scattered and in the process interact with more than one type of mineral (Figure 1). The reflected photons received at the detector therefore carry information from multiple components present in the mixture, with individual components contributing to the reflected photons, not in proportion of their abundance but in proportion to the number of times a photon interacted with an individual component. The probability of this interaction is not strictly defined by the mineral abundance alone. It also depends on other factors such as the degree to which the mineral is dispersed in the rock, the grain size, presence of other minerals etc.

This non-linear nature of photon interaction with the matter makes it difficult to quantify the proportions of components present in the mixture using linear combination of contributions from individual components. Non-linear mixing models [*e.g. Hapke, 1981; Shkuratov et al., 1999*] provide possible solution to this problem and aid in computing proportions of component minerals in a mixture which are more realistic. It is therefore a useful approach for identification and quantification of components in intimate mixtures.

Impact melt is a common product of the cratering process in the solar system and therefore occurs on numerous planetary bodies. Impact melt on the Moon has been well studied in terms of the morphology and still forms an active field of research in view of the high resolution datasets from recent remote sensing missions. However, very few

studies have dealt with the mineralogical character of impact melt on the Moon especially on large spatial scales [*Smrekar and Pieters, 1985; Tompkins and Pieters, 2010*].

We have carried out a systematic mineralogical assessment of lunar impact melt deposits using high spectral resolution data from Moon Mineralogy Mapper (M³) onboard Chandrayaan-1 mission. The geologic context of the observations is also documented using high spatial resolution data from Kaguya Terrain Camera (TC) and Luna Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC). Our results have documented compositional heterogeneity in impact melt at different spatial scales ranging from a few kilometers to several tens of kilometers on the Moon [e.g. *Dhingra et al., 2013*]. Some of these observations have fundamental implications for understanding the impact melt formation and evolution on spatial and temporal scales with respect to composition. It is therefore important to develop a quantitative mineral abundance estimation approach for characterizing the mineralogical diversity of impact melt.

2. Scope of Research

We wish to develop a radiative transfer model based approach in order to use it for identifying the dominant impact melt mineralogical species and later on, quantify their relative abundances and map their spatial distribution. The approach has been successfully applied to variety of lunar mineralogy related problems both for laboratory data as well as remotely acquired datasets [e.g. *Denevi et al., 2008; Cahill et al., 2009*]. The degree of success however, varies and depends upon numerous factors such as appropriate selection of end-members, their physical properties and the nature of the iterative process carried out in the modeling of mixtures etc. Non-linear un-mixing is an

especially important tool in providing first-cut information for the interpretation of planetary remote sensing datasets where the availability of ground truth is always a problem.

Here, we intend to develop an approach geared towards impact melt mineralogical characterization. We are using the case of impact melt deposits on the floor of Copernicus crater where a mineralogically distinct impact melt feature (Figure 2) has been identified recently [Dhingra *et al.*, 2013]. The melt mineralogy of nearby deposits is different than this feature. Impact melt deposits encompass a wide variety of materials including glass, opaques along with mineral grains, all with varying degrees of crystallinity. It could therefore be challenging in modeling the spectra from such rock materials.

The scope of the presented research here is restricted to development of the approach and its preliminary validation. It is not the intent here to provide robust quantitative estimates but to compare results of non-linear mixing with other methods of identifying mineralogical species.

3. Data and Methods

We have used spectral reflectance data from the Moon Mineralogy Mapper (M³) instrument for this study. M³ is an imaging spectrometer operating between 460 – 3000 nm in 85 spectral bands with a spatial resolution of 140-280 meters per pixel [e.g. Pieters, 2009]. We model the mineralogy of impact melt occurring on the floor of Copernicus crater using Hapke's radiative transfer model [Hapke, 1981] applied to end member spectra selected from the image data (scene derived end members).

3.1 Hapke's Model and Assumptions

The model presents light interaction with matter as a combination of single and multiple scattering components where each component is primarily expressed in terms of single scattering albedo (ssa or ω defined as ratio of scattering to extinction for a light photon bouncing of a single particle) along with several other parameters that define the viewing geometry (e.g. angle of incidence, angle of emission, phase angle) and directionality of the light scattering (e.g. backscattering function(B(g)), single particle phase function (P(g))). The model provides analytic solution to derive ω from reflectance and vice versa and has been extensively used across scientific disciplines for modeling light interaction with matter.

There are several assumptions inherent in the model and some additional assumptions that we make in the present study which provide a framework in which one should interpret the obtained results:

- i) The model assumes that size of the interacting particle is always 'larger' than the interacting wavelength of light (typically, at least 10 times λ). This assumption may not be entirely true in our case since majority of the crater floor that we intend to model is comprised of soils (physically pulverized rock material that has subsequently been exposed to weathering processes in space environment for millions of years). Soils represent a continuum of grain sizes ranging from nanometer size metallic iron particles (formed by space weathering) to sizes much larger than wavelength of interacting light and each of them contributes to the scattered light. It has been shown that majority of the scattered light signal is contributed by the finest fraction (typically $<45 \mu\text{m}$) [Pieters *et al.*, 1993]. However, no firm estimates are available (to the best of author's knowledge)

for how much of the finest fraction ($<45\ \mu\text{m}$) is comprised of particles with size less than the light wavelengths at which spectral reflectance measurements are commonly made (400 nm – 2500 nm). We therefore acknowledge that we may be violating this basic assumption and accordingly may not be correctly modeling part of the target material.

ii) It is assumed that the target material comprises of closely spaced particles which makes contribution from diffraction insignificant. This assumption is true in our case.

iii) The model assumes that the imaginary index ('k') of complex index of refraction of the interacting material is much less than 1. Since we are using reflectance spectra in the VIS-NIR wavelength range (460 – 3000 nm), 'k' values do have values less than 1 and so the model can be used.

iv) Isotropic scattering is assumed (i.e. $P(g) = 1$). Since we are dealing with a randomly oriented, multi-component mixture, it is true in general. We do acknowledge that modest improvements in results can be obtained using better approximations as suggested by *Mustard and Pieters*, [1989] but for simplification, we are assuming isotropic scattering.

v) No contribution from backscattering (i.e. $B(g)$) is assumed. It has been shown [*Mustard and Pieters*, 1989] that $B(g)$ can be ignored if the phase angle is greater than 15° . This is a valid assumption and is applicable in our case where the phase angle of measured reflectance spectra is 30° .

vi) The basic version of the model (that we are using) does not account for the effects of topography (which would change the viewing geometry) and space weathering (which would affect the spectral character despite having the same basic composition).

We are modeling a relatively flat surface (crater floor) so topographical effect would be minimal, if any. However, space weathering effects are observed in our data and in that sense, we are violating the assumption. Although not implemented right now, we have a few ways to minimize the effects of space weathering to our dataset that we plan to implement in the later part of this project.

The first option is to choose a soil end member for every fresh surface end member that is selected (both having similar composition) and later adding their contributions to obtain an estimate of a compositional unit that has variability due to space weathering effects. Another option, though less effective (and more complicated) is to remove the continuum of the spectra before modeling. It would partially take care of the space weathering in terms of change of the spectral slope. However, it would introduce an artifact in the sense that it would artificially bring the real albedo maxima to a single value of '1'. In our case, it would still be acceptable since we are mainly concerned change in composition as observed in the shifting of absorption band positions.

vii) Our study assumes that the selected end members are unique in their composition (not mixtures of other components) as well as other properties and are adequate in number to explain the observed variation in composition of the study area. This is assumption needs to made to do the modeling but at the same time, is one of the toughest to obey *senso stricto*. This is especially true in our case where we are using image end members for which no ground truth is available. We try to circumvent this problem to a certain extent by using statistical methods of image end member extraction followed by manual filtering of spectral end members. The same is discussed in the next

section (3.2.2). However, in the present implementation, for testing of the modeling code, we used hand-picked spectra as end members based on spectral sampling experience in the study area. We intend to use the statistically derived end members in the later part of this project.

3.2 Implementation

3.2.1 End member Selection and Optimization

Image end members were used in the present study since no ground truth is available for the study region making it hard to devise criteria for selecting laboratory end members. Another advantage of using image end members is that it takes care of modeling (to a certain extent), the inherent noise that is part of any remote sensing dataset. End member selection is an iterative process and one needs to explore using different end members in order to obtain the best results possible.

Five image end members have been used (Figure 3) for mixing calculations: low calcium-pyroxene (EM1), high calcium pyroxene (EM2), olivine (EM3), low-albedo component (EM4) and high-albedo component (EM5). The latter two do not have any mineralogical significance but have been included to compensate for differences solely in albedo. Further, in order to realistically capture compositional variations and not just albedo differences (which could also be caused by factors not related to composition), the crystalline end member spectra were scaled to have similar albedos and spectral analysis range (700-2500 nm) was restricted.

3.2.2 Modeling steps

The basic modeling steps are illustrated in Figure 4 and have been implemented in IDL. The melt-rich crater floor (after masking the central peaks) has been analyzed by two approaches using image end members selected from the region. The first approach involves converting M3 reflectance of the target region into single scattering albedo (SSA) using Eq. 11.6 and 11.3 from Hapke, [1993]. Because the SSAs of multiple components in a mixture combine linearly, the SSA image can be unmixed using linear unmixing techniques. The image data were analysed using ENVI linear unmixing routine. This approach provides an efficient way of evaluating whether selected end members are adequate to explain the observed variation and produces end member proportion maps. However, the results from this approach need to be interpreted with caution because the ENVI algorithm does not strictly apply constraints such as end member proportions sum to unity and allows negative proportions (which is unrealistic). The results therefore cannot be interpreted in an absolute sense.

In the second approach, image end members were selected and their reflectance converted to single scattering albedo (SSA) using Hapke's formulation [*e.g.* Hapke, 1993]. The end members were linearly added to generate mixtures, in specified proportions (10% increments in our case), providing a look-up table encompassing the range of observed spectral diversity in the study region. Subsequently, the mixture array was converted back to reflectance using Eq. 11.5 from [Hapke, 1993] to enable comparison of the reflectance spectra from the study region with the synthetically generated mixture library.

For each pixel in the study region, a spectrum is selected from the mixture array that gives the least rms error. Finally, the selected mixture spectrum for a given location is decomposed into corresponding end member proportions to understand the mineralogical diversity. Needless to say, this process is iterative and even with best set of end members, mismatch in the observed vs modeled spectra usually remains because of the several simplifying assumptions made in the model and the particular study. The obtained results should be interpreted with these caveats.

4. Results & Discussion

The obtained results from both the approaches support the observations made earlier about the occurrence of distinct mineralogical character of the sinuous melt feature on the floor of Copernicus.

Un-mixing results from the first approach (linear un-mixing of M^3 spectral image cube in single scattering albedo space) are able to reproduce the observed mineralogical heterogeneity in impact melt at Copernicus crater and essentially capture the same spectral contrast among the various end member as had been observed independently (Figure 5). Low calcium-pyroxene rich sinuous impact melt feature (EM 1) occurs as distinct compositional unit from surrounding impact melt deposits. High Ca-Pyroxene rich fresh craters outside sinuous feature are also observed. The results also suggest that the 5 selected end members are able to explain the observed variability.

Forward modeling results from the second approach (converting end-member spectra to single scattering albedo, creating synthetic mixtures and inverting them into reflectance to compare with impact melt spectra on the crater floor) are also able to

distinctly capture the low calcium-pyroxene signature of the sinuous impact melt feature as well as high calcium pyroxene rich craters on the floor of Copernicus (Figure 6). However, as described earlier, the obtained results are only valid in relative sense and do not have any realistic abundances associated with them due to the option of negative abundances in the ENVI algorithm.

The output images of this un-mixing approach are not as coherent in their contrast as obtained by the first approach and have large areas which do not seem to have found a good spectral match from the synthetic spectral mixture matrix generated in this approach. Lack of smooth variation in abundances across the end member images in output of the second approach is probably affected by the selected end members as well as the limited number of discrete values generated in mixture matrix. As a consequence, these results are more limited in their scope at the moment. However, they do demonstrate the occurrence of the distinct mineralogical unit on Copernicus floor, effectiveness of the selected end members as well as the feasibility of the algorithm.

We hope to obtain better results with this approach by implementing improvements in the algorithm including expansion of the mixture matrix to smaller abundance intervals, better spectral comparison routine (to find the best spectral match) and adding more versatility to end member selection procedure.

5. Summary

We attempt to model the observed spectral variability in the impact melt deposits on Copernicus crater floor using Hapke's formulations. Preliminary results obtained from two independent approaches capture the major compositional variability reported from

other observations. The analysis would benefit from improvements in the modeling algorithm and could provide realistic first order abundance estimates of mineral species present in the impact melt deposits.

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Figure Captions

Figure 1 Light interaction with matter. Top Panel: Linear interaction where target components are spatially apart allowing photons to interact with only one component. Bottom Panel: Non-linear interaction where individual components are intimately mixed and the photons are scattered around interacting with multiple components before being received at the detector.

Figure 2 Mineralogically distinct impact melt feature on the floor of Copernicus crater. (a) Spatial context of Copernicus crater. Yellow boxes refer to the same geographic location. Orange box represents the extent of region shown in b. (b) M^3 color composite illustrating the presence of a distinct mineralogy of a sinuous impact melt unit on the crater floor. Red = albedo at 1489 nm, Green= strength of absorption at 2000 nm, B strength of absorption band around 1900 nm.

Figure 3 Scaled spectra of selected end members used for unmixing.

Figure 4 Flow chart showing the general steps involved in the modeling process.

Figure 5 Results from linear un-mixing in single scattering albedo space. (a) Albedo at 1489 nm. (b) – (d) Individual end member images EM1, EM2, EM3 (e) Color composite generated from EM1 (Blue), EM2 (Red) and EM3 (Green). (f) - (g) Albedo end members EM4, EM 5 (h) RMS image

Figure 6 Results from non-linear mixing in reflectance space. (a) Albedo at 1489 nm. (b) – (f) individual end member images (g) RMS image

Figures

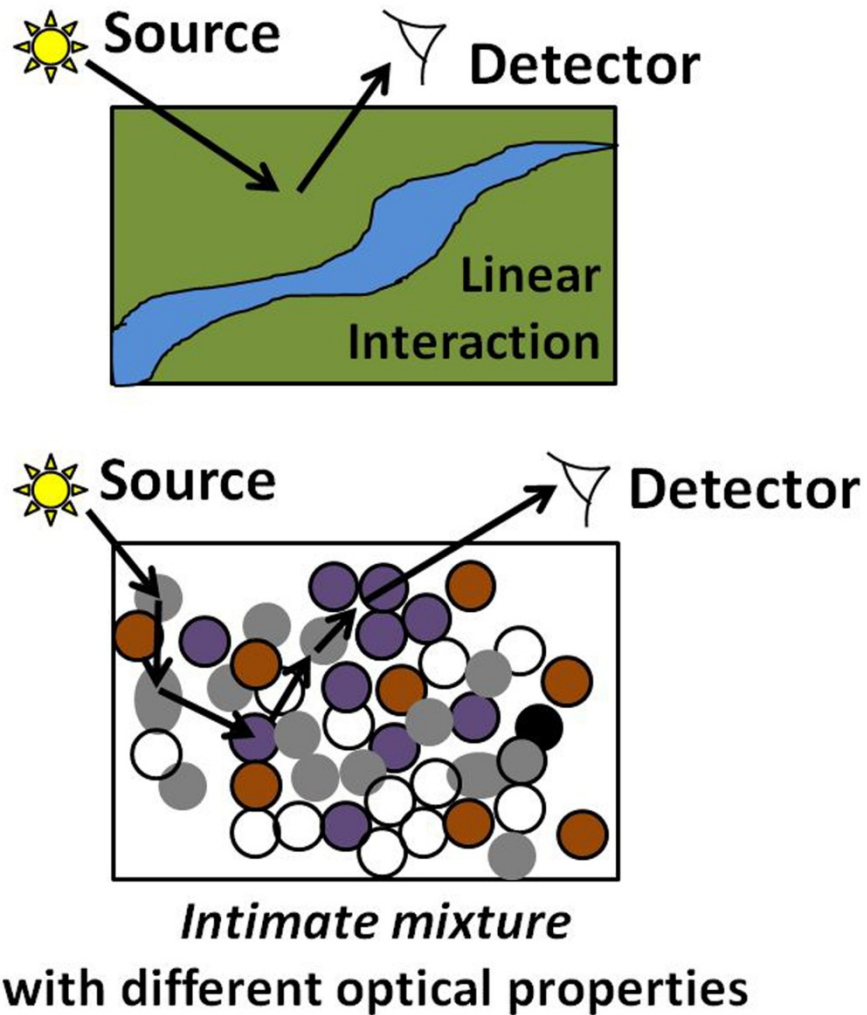


Figure 1 Light interaction with matter. Top Panel: Linear interaction where target components are spatially apart allowing photons to interact with only one component. Bottom Panel: Non-linear interaction where individual components are intimately mixed and the photons are scattered around interacting with multiple components before being received at the detector.

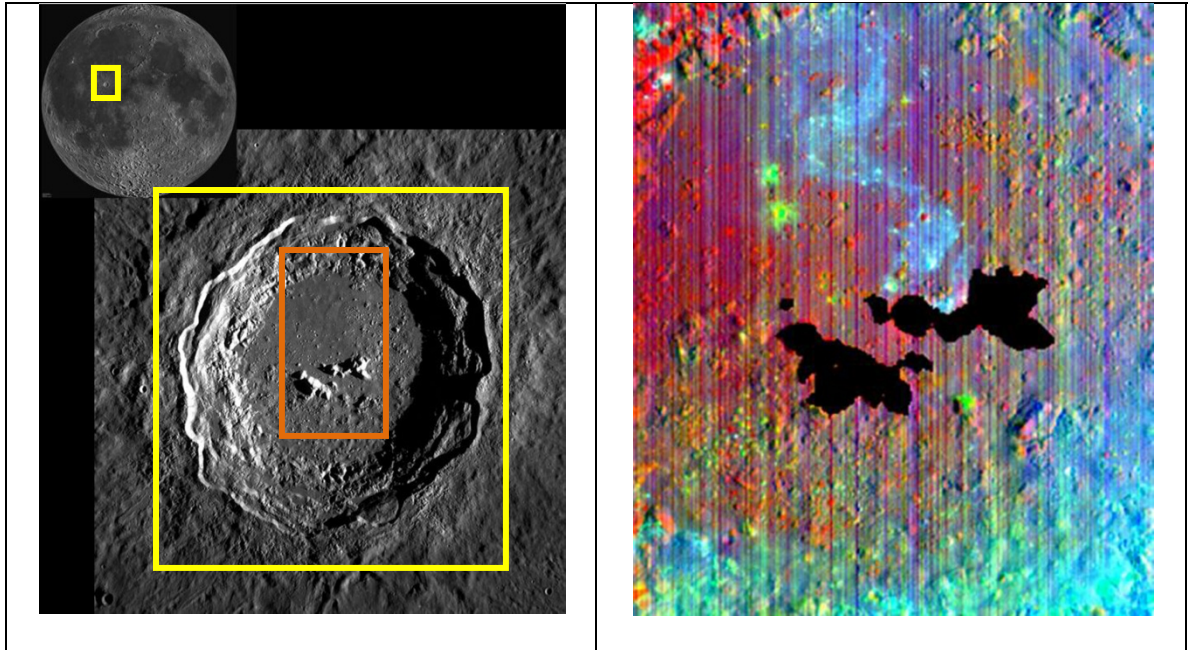


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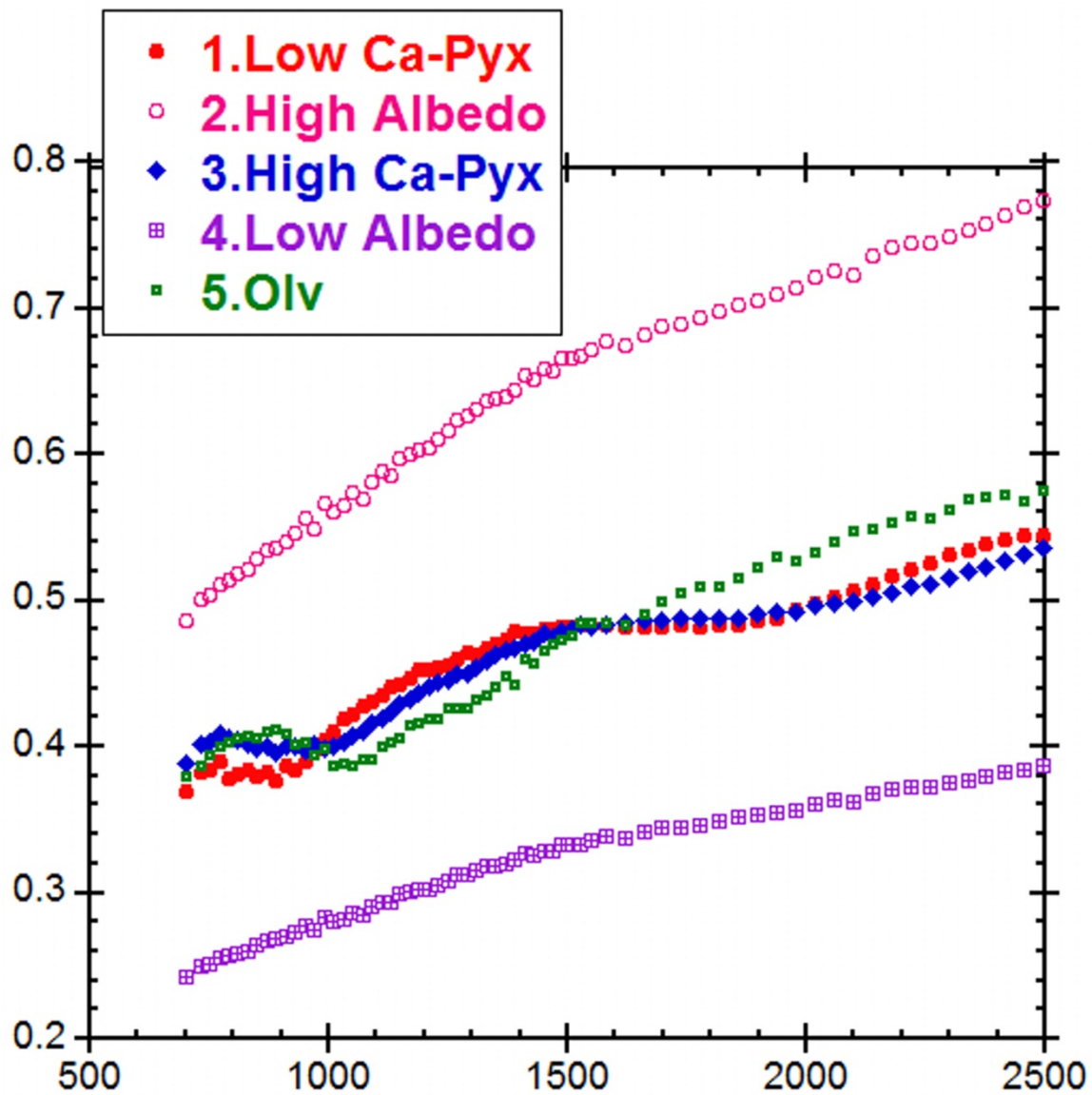


Figure 3 Scaled spectra of selected end members used for unmixing.

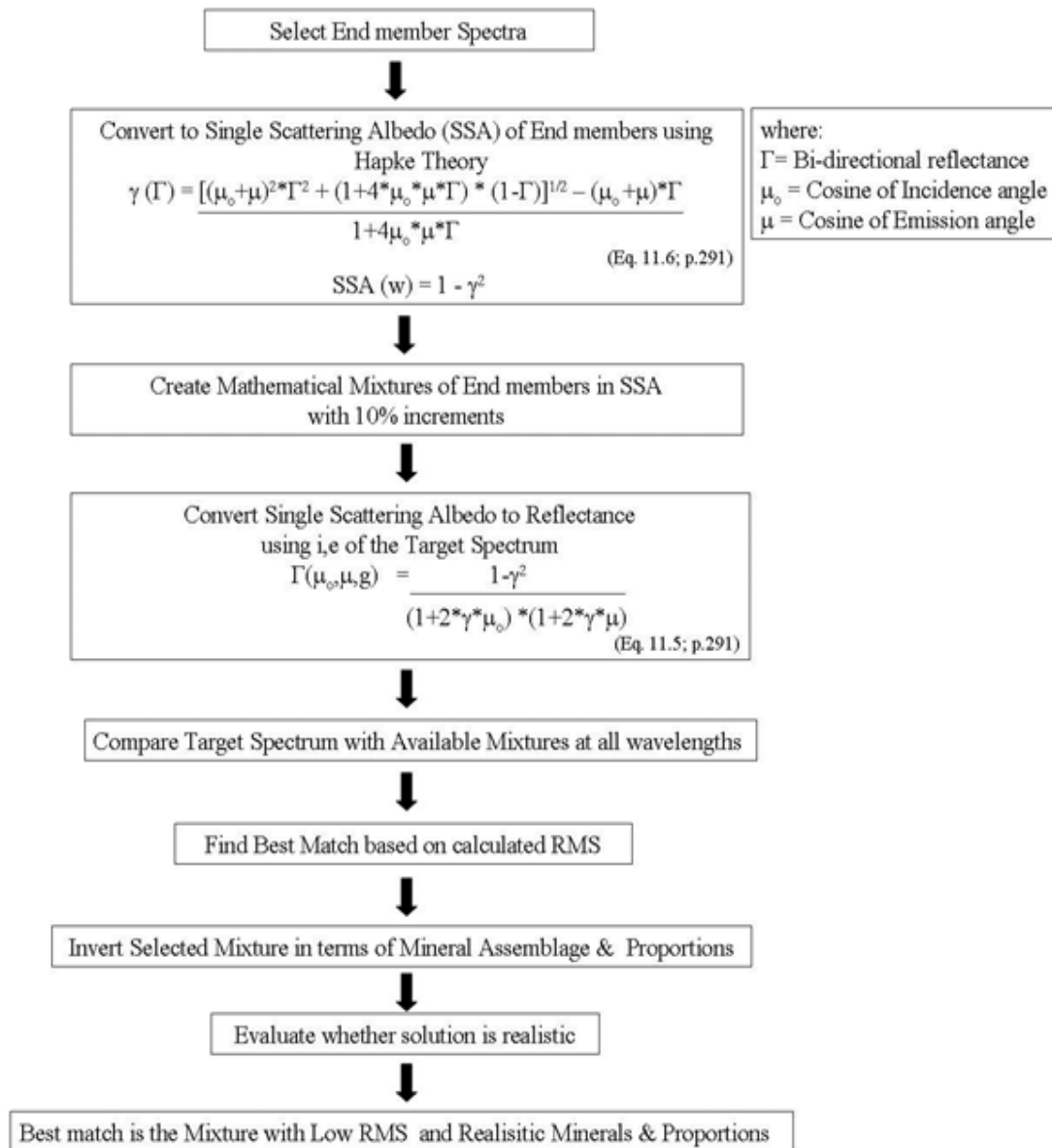


Figure 4 Flow chart showing the general steps involved in the modeling process.

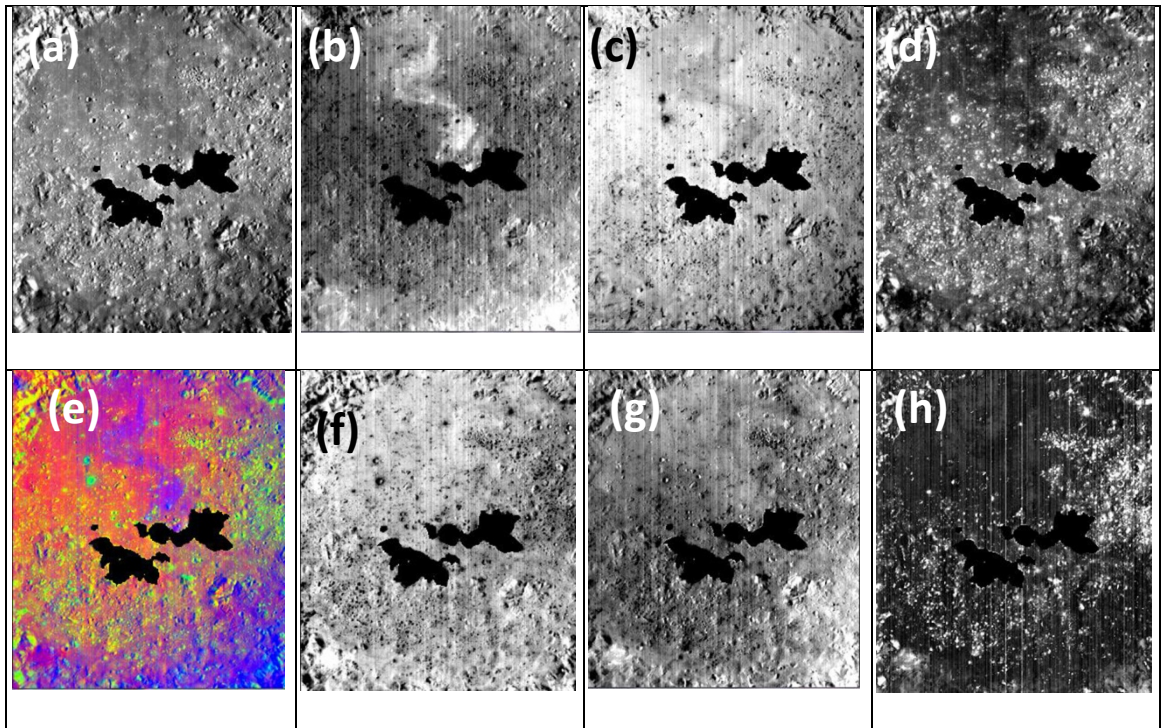


Figure 5 Results from linear un-mixing in single scattering albedo space. (a) Albedo at 1489 nm. (b) – (d) Individual end member images EM1, EM2, EM3 (e) Color composite generated from EM1 (Blue), EM2 (Red) and EM3 (Green). (f) - (g) Albedo end members EM4, EM 5 (h) RMS image

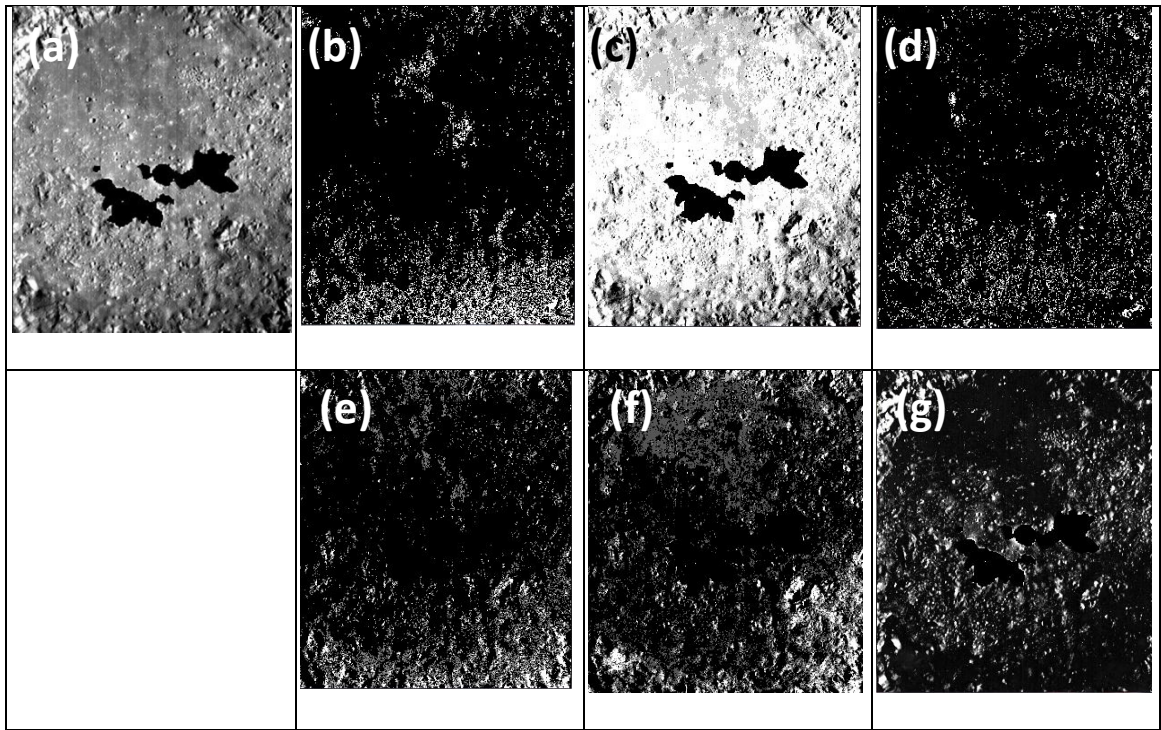


Figure 6 Results from non-linear mixing in reflectance space. (a) Albedo at 1489 nm. (b) – (f) individual end member images (g) RMS image

APPENDIX – II Spectroscopic Signatures of Basalts in Mare Tranquillitatis:
Observations by the Moon Mineralogy Mapper (M³) onboard Chandrayaan-1

Deepak Dhingra and M³ Team

Abstract

Basalts of diverse compositions and ages have been studied in Mare Tranquillitatis using high spectral and spatial resolution datasets from the Moon Mineralogy Mapper (M³) instrument. The nearly continuous spectral coverage across the visible and near-infrared region has enabled distinct spectral differences among basalts at Mare Tranquillitatis to be identified and analyzed in great detail. Analysis of mature soils and several hundred fresh craters indicate that these spectral differences are likely linked to the inherent mineralogical variations between the basalts. Two possible sources of compositional differences (most likely contributing together) are: 1) variability in the abundance of ilmenite and 2) variability in the composition of clinopyroxene. The dominant spectral variations observed are related to the character of the absorption band at 1000 nm and include differences in band strength, continuum slope ratio and band shape at longer wavelengths. Variations have also been observed at shorter wavelengths (across ultraviolet to visible region) and overall albedo.

1. Introduction

Basaltic volcanism, covering about 17% of the lunar surface, has been an important constituent of lunar evolution [Head, 1976]. The composition of the basalts provide valuable clues about their source regions in the lunar interior and form an important input for the thermal and chemical evolution models of the Moon. Lunar basalts vary in composition as well as age, with no definite evolutionary link observed between the two parameters [Hiesinger *et al.*, 2010]. Titanium is one of the important constituents of lunar basalts, exhibiting wide range of variation and has therefore been principally used to classify lunar basalts into very low-Ti (<2 wt%), low-Ti (2-6 wt%) and high-Ti (>6 wt%) basalts [Papike *et al.*, 1976; Neal and Taylor, 1992]. The spatial distribution of mare basalts is also heterogeneous as they have been concentrated on the nearside of the Moon with limited exposures on the farside, suggesting a possibly heterogeneous internal structure of the Moon. Mare Tranquillitatis region (Figure 1) was the site of the first Apollo landing and comprises one of the most titanium-rich basaltic terranes on the Moon as revealed by various observations. These include laboratory analysis of returned samples [Papike *et al.*, 1976] and data obtained from various remote-sensing techniques [Charette *et al.*, 1974; Pieters, 1978; Metzger & Parker, 1979; Davis, 1980; Prettyman *et al.*, 2006].

The Tranquillitatis basin is a ~ 800 km diameter, pre-Nectarian (>3.9 b.y.), non-mascon basin, situated on the equatorial nearside of the Moon. It has experienced several events of basaltic volcanism of different compositions ranging in age from about ~ 3.3 - 3.8 b.y. [Wilhems, 1987; Hiesinger & Head, 2000] with estimated basalt thickness of several hundred meters [Rajmon *et al.*, 1999] although thicker basalts (~2.5 km) have also been reported locally [Staid *et al.* 1996]. There is also a broad topographic slope from east

to the west observed by spacecraft laser altimetry [Zuber et al., 1994; Smith et al., 2010] and shown in Figure 2b. Compositionally, ground truth in the form of samples returned by the Apollo 11 Mission from the southwestern border of Tranquillitatis revealed a variety of high-Ti basalts including high-K and low-K basalts [Papike et al., 1976] with ilmenite being the principle carrier of titanium. Interestingly, basalts of similar composition and age were also detected in the samples brought back by the Apollo 17 Mission from southern Serenitatis, indicating a possible link between the Apollo 11 and Apollo 17 high-Ti basalts [Snyder et al., 2002]. The high-Ti character of Tranquillitatis basalts has also been observed by gamma-ray spectroscopy which is a more direct measure of elemental abundance among the various available remote sensing techniques.

Spectral mixture analysis for the Tranquillitatis region [Staid et al., 1996] using multispectral remote sensing data indicated four varieties of basalts based on the fractional abundance of the selected end-members in the study. Titanium abundances were subsequently estimated for these units using the UV-Vis ratio empirical relation for mare soils [Charette et al., 1974]. However, in view of the observed inconsistencies [Gillis et al., 2003] between derived TiO₂ abundances from multispectral datasets [Lucey et al., 1998] and from gamma-ray spectroscopy [Prettyman et al., 2006], it is desirable to explore the spectroscopic differences between basalts with varying titanium abundances.

2. Scope of Work

The basaltic units at Mare Tranquillitatis have been primarily distinguished by their estimated titanium content [Neal and Taylor, 1992]. The analysis of the spectral character of these basalts in the present study provides new information in the form of key spectral

differences and further uses those differences in the context of evaluating the mineralogical variability of these basalts. Earlier workers [Pieters et al., 1978] have used telescopic data to identify spectral differences between Tranquillitatis and nearby Serenitatis basalts which are understood to have very different titanium concentration. Ilmenite being the principal carrier of titanium on the lunar surface, it might be an important contributing factor to the spectral variation in basalts with different titanium concentrations. The dominant role of ilmenite is derived from its opaque properties which affect albedo and spectral contrast. The origin of spectral properties of ilmenite has been studied by earlier workers [Loeffler et al., 1975] and recent detailed work [Riner et al., 2009; Isaacson et al., 2010] has provided new insights into its near-IR properties. Specifically, mineral separates of ilmenite exhibit a local reflectance maximum around 1000 nm and significantly increased reflectance at longer wavelengths (>1800 nm). In the case of ilmenite-bearing lunar samples, this variation is clearly observed only for immature samples (coarse-grained mare basalts) [Isaacson et al. 2010]. Mature Ti-rich basaltic soils, which contain abundant space weathering products, do not show strong evidence for such features relative to Ti-poor basaltic soils [Taylor et al., 2001]. Further, the finer grain size fractions of ilmenite have been observed to have a disproportionately strong effect on the spectral properties of bulk sample [Isaacson et al., 2010]. The M^3 dataset is well suited to evaluate these properties using the near-continuous spectral coverage for the Moon.

3. Datasets and Methods

The present work utilizes the high spectral and spatial resolution data acquired by the Moon Mineralogy Mapper (M^3) instrument onboard Chandrayaan-1, India's first

mission to Moon [Goswami & Annadurai, 2009; Pieters et al., 2009]. The M^3 (M-cubed) instrument is a pushbroom imaging spectrometer operating between $\sim 430 - 3000$ nm. It obtained near global coverage of the Moon [Boardman et al., 2010] in 85 spectral bands at a spatial resolution of 140-280 m/pixel. For certain selected areas, M^3 obtained data at much higher spectral (259 bands) and spatial resolution (~ 70 m/pixel). The present dataset has been radiometrically corrected and geometrically rectified. Radiance data were converted to apparent reflectance through division by the solar spectrum scaled to the Sun-Moon distance. Further, a cosine correction was applied to take care of the latitude dependent variation in illumination to a first order. This provides an apparent reflectance for the entire dataset used in this study. A complete description of the radiometric and geometric correction procedures as applied to the dataset can be found in accompanying papers [Green et al., 2010; Boardman et al., 2010]. Development of detailed photometric and thermal correction (significant after 2400 nm) procedures is in progress [Hicks et al., 2010; Clark et al., 2010; Buratti et al., 2010]. The data presented in this paper therefore have been corrected only for the latitudinal variations. The lack of these corrections (although certainly desirable), do not affect the interpretations made in this paper. The M^3 spectra evaluated in this study have been truncated at 2400 nm to avoid significant contribution from thermal emission, although a minor thermal emission component may remain below 2400 nm, particularly for dark surfaces near the equator such as Tranquillitatis.

To account for the photometric variations, most of our interpretations are based on continuum-removed spectral data, which mitigates the wavelength dependent variability as a function of phase angle. In the present work, we focus on the data obtained during optical

period 1b [Boardman et al., 2010]. This dataset shown in Figure 2a, was obtained in a continuous sequence of orbits. Thus, the variation in phase angle across data strips is less significant than in other optical periods. Also shown in Figure 2b is the topography of the Tranquillitatis basin and the nearby Serenitatis region generated using the Lunar Orbiter Laser Altimeter (LOLA) instrument onboard Lunar Reconnaissance Orbiter (LRO). The M³ dataset was evaluated in a variety of ways. The initial (reconnaissance) analysis was carried out using a low-resolution mosaic of the study area where 10x10 pixels were averaged. This mosaic has a spatial resolution of 1.4 km/pixel across 85 spectral bands. The evaluation involved comparison of the different regions in Tranquillitatis in various spectral parameters and focused on capturing the regional differences which are dominated by mature soils. The identified regions in Tranquillitatis were also compared to the basalts in nearby Serenitatis basin, as overall, Serenitatis exhibits substantially different spectral properties from Tranquillitatis [Pieters, 1978]. These comparisons were performed regionally (dominated by soils) and for selected fresh craters observable in this low-resolution mosaic.

Further studies involved working at full spatial resolution of 140 m/pixel looking at the finer-scale variations within and across different basaltic units. In this case, spectral variations were studied for about 300 small (< 1km), immature craters from different basaltic units in Mare Tranquillitatis to evaluate and understand spectral properties least affected by the process of space weathering. A sample set of fresh craters was also extracted from the nearby Serenitatis region for comparison. The methodology of extracting representative spectra from small craters involved locating the craters with strong mafic absorptions, taking a traverse around each crater, looking for a smooth

spectrum (least affected by noise) that had the strongest absorptions and gentle spectralslope (as redder slopes indicate relatively mature material). The spectrum, in most cases, was an average of 3x3 pixels. However, in certain cases, where the crater was very small or where the spectrum was distorted, a single pixel was used. Apart from fresh craters, spectra were also extracted from steep-sloped features like the walls of rilles and grabens, in order to provide additional data points from fresh un-weathered surfaces.

4. Discussion

4.1 Basaltic Variability Observed in Spectral Parameters

The regional variability in composition of basalts at Mare Tranquillitatis was evaluated at low spatial resolution using various spectral parameters. It is observed that there is a variation in the strength of the absorption band at 1000 nm for various basaltic regions in Tranquillitatis as shown in Figure 3a. This band strength is measured in the form of an integrated band-depth (IBD 1000) which is a summation of all the band strengths between 789 nm and 1308 nm relative to a local continuum. Compared to the use of band-ratios as a proxy for band-strength in multispectral datasets, integrated band depth is a much more robust measure of the strength of the 1000 nm ferrous absorption feature. Comparison with the nearby Serenitatis basalts indicates that most of the basalts at Tranquillitatis have a weaker IBD at 1000 nm, although some local units have stronger absorptions. The areas with weaker absorptions also have lower overall albedo and are referred to as dark regions (“DWfl” in the subsequent discussion).

Similarly, the areas with stronger absorption are also higher in overall albedo and are referred to as bright regions (“BSst” in the subsequent discussion). The variation in

IBD at 1000 nm can be used in delineating various basaltic units within Mare Tranquillitatis and has been illustrated in Figure 3b. It is also noted that visual detection of fresh craters in the 1000 nm IBD parameter for Mare Tranquillitatis is much lower than the craters at Mare Serenitatis, which appear to be peppered with numerous fresh craters. This apparent difference is highlighted in Figure 4 where abundance of fresh craters as observed in the IBD 1000 nm image are compared for Tranquillitatis and Serenitatis. Both the illustrated regions form part of the same data strip and have been contrast stretched in the same way. Even with an increase in contrast, there is no appreciable increase in the detection of fresh (immature) craters in the Tranquillitatis region relative to the Serenitatis region. This observation is not related to the formation age of these surfaces since both regions should encounter comparable abundance of recent impacts (< 1 b.y.). The cause for this observation could be the differences in composition of the basalts (possibly ilmenite abundance) that might cause a preferential suppression of the absorption at 1000 nm as well as possibly lead to different maturity trends for one set of basalts.

4.2 Basaltic Variability in Spectral Profile

Further insight into the variability in spectral character of different basaltic units is provided by the differences in spectral profile of the soils and fresh craters in Tranquillitatis and Serenitatis at low spatial resolution. The spectra have been truncated at 2400 nm to minimize the effects due to thermal emission. The soils in Tranquillitatis differ from soils in Serenitatis in two ways as illustrated in Figure 5: a) uniformly lower reflectance across all the wavelengths (though to different extents) and, b) flatter continuum slope-ratio in the near-IR. The spectral variability between fresh craters from

both regions is illustrated in Figure 6. The spectra have been averaged from a large number of samples drawn from different parts of the two basins. It can be observed from the spectra that the variations observed for soils (uniformly low reflectance, flatter NIR slope) also holds true for the fresh craters. Variation in spectral profile is also observed at the long-wavelength end of the 1000 nm absorption band, between 1209 to 1618 nm. The same is discussed below in detail under the small, fresh crater analysis.

4.3 Interpretations based on Full resolution Dataset

The Tranquillitatis region was subsequently studied at the highest available spatial resolution by analyzing spectral variability across small, fresh craters (<1 km) sampled from different basaltic units mapped earlier using variable IBD1000 parameter (as illustrated in Figure 3b). The spectra of small, fresh craters are expected to be least affected by the process of space weathering and would, therefore provide the most reliable constraints on mineralogical variations [e.g. McCord et al., 1981]. The spectral reflectance data has been continuum-removed to allow analysis of subtle variations in spectral character. The continuum removal process involved dividing the spectrum by a straight-line continuum fit tangent to the original spectrum between 730 nm and 1618 nm. Based on the spectral data from about 300 craters spread across Tranquillitatis, systematic variations are observed in the character of the 1000 nm absorption band. It should be mentioned here that the nature of variation at the 2000 nm absorption band could not be explored reliably due to the effects of thermal emission. Analyses of the 2000 nm absorption are thus not presented here. With effective thermal and photometric corrections, it is expected that the longer wavelength region will be better utilized in future studies.

In case of observed differences around 1000 nm within Tranquillitatis basin, it is noted that certain areas have relatively weaker band strengths compared to the other areas. This observation is in general agreement with the results from the low spatial resolution analyses discussed above. The second variation occurs in terms of difference in the 1000 nm band-shape at longer wavelengths. It has been observed that for one group of spectra, there exists a long wavelength shoulder for the 1000 nm band, making it asymmetric. This shoulder is notably absent from spectra of other units. For these units, the absorption feature is relatively symmetric. The variations at shorter wavelengths (400-730 nm) were also evaluated for the collected fresh-crater spectra though these variations need to be interpreted with caution as M^3 data in its present form, suffer from scattered light contamination. Efforts are underway for correcting this artifact. These issues are discussed in Green et al. [2010].

In the present study, variations at shorter wavelengths have been interpreted in conjunction with other variations rather than in isolation, mitigating the scattered light concern as systematic differences can be confirmed by variations in other wavelength regions. It is observed that at shorter wavelengths, best described as variations between UV-VIS region, spectra of some units are relatively flat (high UV-Vis ratio) whereas spectra of other units have more pronounced slopes towards the UV region (shorter wavelengths). This variation occurs noticeably between wavelengths 580 nm and 730 nm.

The observed variations for the fresh-crater spectra are presented in Figure 7 for a representative region of Tranquillitatis which comprise of both the bright and dark regions. The observed differences do not occur in isolation but are correlated. Specifically, the darker spectra with flatter UV-Vis ratios (580 nm/730 nm) also exhibit weaker absorptions

at 1000 nm as well as relatively symmetric 1000 nm absorptions (higher 1209 nm / 1618 nm ratio). The other spectral group exhibit lower UV-Vis ratios, stronger absorption at 1000 nm and relatively asymmetric 1000 nm absorptions (lower 258 1209/1618 ratios). Based on the set of differences observed for the dark and bright regions in Tranquillitatis, we introduce a naming convention for these units for easy reference.

We are considering three parameters, namely, overall albedo (Bright-B; Dark – D), strength of the absorption band at 1000 nm (Weak – W; Strong - S) and the NIR slope (1209 263 nm/1618 nm) signifying asymmetry of the 1000 nm absorption (Steep – st; Flat - fl). It is interesting to note that the asymmetric absorptions are dominantly associated with the units identified as medium- to low-Ti in abundance [Th and Tl in Staid et al., 1996]. The relatively high-Ti units [TvhB in Staid et al. 1996] largely tend to exhibit more symmetric bands. This difference in band-shape extends to a wavelength range 1209–1618 nm. Although this band symmetry appears to be correlated with estimated titanium abundance, it may also be due to the differences in the relative strength of a 1200 nm pyroxene absorption feature [Klima et al., 2007; 2010]. Irrespective of the specific cause of these variations, they are important distinguishing characteristics for the basaltic units and are linked to mineralogical differences.

Comparison of the simplified map of various basaltic units in Tranquilltatis (illustrated in Figure 3b) with a much more detailed map of spectral units identified and dated by Hiesinger et al. [2000] also provides insight into the possible stratigraphic relationships that these different spectral (and likely compositional) units might be sharing. Table 1 summarizes the possible links between the units mapped by different workers. As can be seen, the high-Ti units show considerable scatter in ages [Hiesinger et al., 2000] and

comprise probably both the youngest and the oldest basaltic units in the basin which makes the geologic setting quite complex.

The Tranquillitatis basin is also complex in terms of its topography as is illustrated by the LOLA generated Digital Elevation Model (DEM) [Smith et al., 2010] in figure 2b. As compared to other basins, Tranquillitatis does not display a prominent circular boundary making the basin shape quite irregular. Significant viscous relaxation of the basin prior to the oldest episode of volcanism in the basin has been proposed as one of the main reason for the present topographic profile [Solomon et al., 1982]. Within the basin, the central and eastern regions are topographically higher. It could either result from a thicker accumulation of basalts in these regions or due to variable pre-existing topography of the basin or both. Kipukas and islands of small basaltic units as illustrated in Figure 8 (b) are frequently observed indicating the possibility of thin basalts. Representative spectra from the region illustrate the differences between various units and are shown in Fig. 8(c) and (d).

The spectrum from fresh surface in the basaltic island (labeled 1) is similar to the bright regions (BSst) while the spectra of small, fresh craters in the surrounding basalts (labeled 2, 3) represent the dark regions (DWfl). It should also be noted that spectrum of one of the kipukas (spectrum 4) has band minimum at significantly shorter wavelengths indicative of a more noritic composition. Spectra from a ~10 km diameter crater nearby appears similar to the island basalts (bright regions –BSst) suggesting possible occurrence of these basalts as a pervasive thick unit at the sampled location. This overall geological setting demonstrates the complex stratigraphy in this region.

4.4 Spatial Setting of Spectrally Different Regions

The observed spectral variations discussed in the previous sections for various basaltic units in Tranquillitatis are based on the analysis of selected sets of fresh, immature craters and soils. Though they are expected to be representative of the basaltic units at Tranquillitatis, it needs to be evaluated if these observed differences occur in a coherent manner when observed for the whole Mare Tranquillitatis. In order to evaluate the spatial variation of these observed spectral differences, a color composite of the area has been made by assigning parameters (sensitive to the observed spectral differences) to the three (RGB) color channels. These spectral differences are derived both from the regional studies using low resolution mosaics as well as studies of small, fresh craters at full resolution.

The color composite shown in Figure 9 represents the combination of continuum-slope ratio (1618 nm/730 nm) in red, integrated band-depth at 1000 nm in green and variable band-shape around 1000 nm band (1209 nm/1618 nm) in blue. The differences mapped out in the color composite are spatially coherent and correlate well with the basaltic units identified previously by Staid et al. [1996]. The near-continuous spectral coverage from M³ provides new insight into the spectral differences between these different units. The small, immature craters in dominantly blue regions in the color composite have a higher value for 1209/1618 ratio and therefore represent a more symmetrical 1000 nm absorption band. Since these regions lack significant red or green shades in the color composite, it confirms that the band strength at 1000 nm (assigned green color in the composite) for these regions is weaker and also that they have a flatter

continuum slope ratio (assigned red color in the composite), which agrees with the spectral variations observed for the Tranquillitatis based on the analysis of low-resolution mosaic.

Comparisons with Mare Serenitatis in this color scheme show appreciably red to orange shades in Serenitatis, indicating steeper continuum slopes as well as stronger band strengths at 1000 nm. The color composite image suggests that the spectral variations observed for small, fresh craters (selected from various basaltic units in Tranquillitatis) are representative of the differences that occur on regional scale, which are otherwise dominated by mature soils. The exact cause of these observed differences needs additional refining of spectral properties of these basalts which may include deriving absorption band parameters using deconvolution algorithms (e.g. MGM). Several lines of evidence also point to a dominant role of ilmenite. Laboratory reflectance data have indicated the suppression of the band-strength around 1000 nm as well as flattening of the long wavelength shoulder around 1000 nm for samples containing abundant ilmenite [Riner et al., 2009; Isaacson et al., 2010].

Additionally, laboratory experiments have demonstrated contrasting differences between ilmenite and pyroxene in their response to space weathering processes [Christofferson and Keller, 2007]. For same degree of space weathering, ilmenite appears to be more resistant to space weathering [Pieters and Taylor, 2003] and may therefore have an increasingly dominant effect on the overall spectral character of the target material. Both of these factors point toward ilmenite as one of the possible cause for the observed spectral variations across the study area. It is also possible that a difference in pyroxene composition contributes to the differences between fresh crater spectra of Tranquillitatis and those in Serenitatis. As observed in Fig. 6, both spectra exhibit band centers just short

of 1000 nm and 2200 nm. The more distinctive, sloping shoulder near 1200 nm in Serenitatis could imply a higher proportion of high-Ca pyroxene or higher iron content in these basalts relative to Tranquillitatis [Klima et al., 2010]. The band-depth at 1000 nm can be related to the amount of iron in a pyroxene, but it is not explicitly diagnostic of pyroxene composition because it also depends on the pyroxene structure and, in the case of basalts, on grain size and the other minerals present.

The correlation between UV-Vis ratio (580 nm/730 nm) and the variable band shape around 1000 nm absorption band, represented by the 1209/1618 ratio has been found to be useful in distinguishing the compositional units in Tranquillitatis. This relationship is illustrated in a scatter plot for these two parameters for the Tranquillitatis and Serenitatis regions in Figure 10. The two regions, which have notably different compositions, plot in distinct regions of this scatterplot. The dense regions of the data cloud represent mature soils. The fresh craters plot on the periphery of the plot. The variations within Tranquillitatis would be at a much finer scale (i.e. most of Mare Tranquillitatis plots as a single cluster in this plot) and would require more focused scatterplots to be subdivided into smaller units. Figure 11 shows the nature of this variation observed for the sampled small, fresh craters in Mare Tranquillitatis.

5. Conclusions

The high spatial and spectral resolution data from M³ has enabled “analysis of spectral profiles” for target regions and thereby aided in identification of subtle spectral differences between basalt units that could not be observed with limited spectral coverage from the previous lunar orbital missions. The high-titanium character of the Tranquillitatis

basalts, confirmed by gamma-ray spectroscopy, is now observed in terms of differences in spectral profiles of Tranquillitatis and nearby basalts. Detailed analysis of several hundred small (<1km), immature craters including continuum-removed spectral analysis, has helped determine the dominant spectral differences in basalts within Mare Tranquillitatis as well as nearby basalts. Many differences are observed which include the strength of 1000 nm absorption band, albedo, variable band-shape at longer wavelength around 1000 nm as well as continuum-slope ratio.

All these differences correlate with each other and form spatially well-defined units, making the interpretation of these differences as being due to variable mineralogy more robust. Significant complexity of Tranquillitatis basalts, in terms of diverse mineralogy and stratigraphy as observed in this study, merits further detailed examination. It will be the focus of later studies with the availability of fully calibrated and complete M³ dataset. Future work involves MGM and non-linear spectral mixture analyses using this new dataset which would help constrain spectral contributions from various mineral components and their physical nature (e.g grain size, mode of occurrence).

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Table 1 Comparison of various units within Mare Tranquillitatis as mapped by different workers. The units in the present study have been defined based on the strength of 1000 nm absorption band

This Study	Staid et al. [1996]		Hiesinger et al. [2000]	
<i>Unit</i>	<i>Unit</i>	<i>Est. TiO₂ (wt%)</i>	<i>Unit</i>	<i>Age (b.y.)</i>
BSst	Tl	<3%	T19	3.6
	Th	3 – 5%	T4	3.75
			T7	3.7
			T14	3.66
DWfl	TvhB	5 – 8 %	T2	3.76
			T5	3.74
			T8	3.7
			T10	3.69
			T13	3.67
			T21	3.57
			T24	3.5
			T25	3.5
			T27	3.39

Figure Captions

Fig. 1 Mare Tranquillitatis on the near side of the Moon. The studied area is outlined by a dotted line (Image Credit: NASA)

Fig. 2 (a) M^3 1489 nm albedo image from low resolution mosaic showing M^3 coverage of Mare Tranquillitatis and nearby regions in optical period 1b. (b) Topography of the Tranquillitatis and nearby Serenitatis Basin as measured by LOLA instrument on LRO (Smith et al., 2010)

Fig. 3 (a) 1000 nm integrated band depth (IBD 1000) image for Mare Traquillitatis and nearby areas. It may be noted that apart from differences between Tranquillitatis and Serenitatis, there are differences within Tranquillitatis as well. The most prominent are marked by different colored units in Fig. 3 (b).

Fig. 4 Variation in visual detection of fresh craters in Serenitatis (a, b) and Tranquillitatis (c, d) in band strength images. Fig. 4 (a) and (b) represent thermal band (2976 nm) and IBD 1000 nm images from Mare Serenitatis while Fig. 4 (c) & (d) represent the corresponding images for Tranquillitatis region at full resolution.

Fig 5. (a) Comparison of average basaltic soil spectra from Mare Tranquillitatis (High Ti) and Mare Serenitatis. (b) Spectra scaled to unity at 750 nm illustrating the flatter NIR slope of the Tranquillitatis spectrum.

Fig. 6 Comparison of average spectra from immature craters in Mare Tranquillitatis (High-Ti) and Mare Serenitatis from low-resolution mosaic. (a) Apparent Reflectance (b) Continuum removed reflectance spectrum using a straight line continuum. The variation in the long wavelength shoulder between two regions is observed here and is marked by arrows. The UV-Vis (580 nm / 730 nm) and NIR slope (1209 nm / 1618 nm) as defined in the figure form important distinguishing criteria and are discussed in later figures.

Fig. 7 Continuum-removed spectra for the bright (red spectra) and dark (blue spectra) basaltic units from small, immature craters sampled from the full resolution mosaic.

Fig. 8 (a) Regional mosaic of the study area showing location of area discussed in (b) in full resolution. The area located in central Mare Tranquillitatis contains kipukas and two varieties of basalts of which one occurs as small islands. Note that the mosaic has not been photometrically corrected. (c) Apparent reflectance of selected locations as marked in (b). (d) Continuum removed reflectance spectra of selected locations. The spectra indicate that the three terranes have distinctive compositions.

Fig. 9 RGB color composite of the study area. The composite is comprised of continuum slope ratio (1618 nm / 730 nm) in Red, IBD 1000 nm in Green and variable band shape around 1000 nm (1209 nm/1618 nm) in Blue. Central Mare Tranquillitatis is dominantly blue with sparse regions in orange shades while the edges are dominantly represented in orange shades. Also note the abundant fresh craters (represented in green colors) in the orange units while blue units have visually fewer number of detectable fresh craters

Fig. 10 Scatter plot of UV-Vis (580 nm / 730nm) and 1000 nm band shape variability ratios (1209 nm / 1618 nm) for the study area. It is possible to separate the basalts at Tranquillitatis and Serenitatis based on differences in these ratios. The clusters dominantly represent soils while data points for the fresh craters lie at the edges and have a distinct relation with respect to each other.

Fig. 11 The nature of variation exhibited by fresh (immature) craters in bright (BSst) and dark (DWfl) regions in Tranquillitatis (as discussed in Fig. 7) in terms of UV-Vis ratio and NIR slope. The gray circles represent bright unit craters while black squares represent dark unit craters. Note that all the craters in dark regions (DWfl) have flatter long wavelength shoulder of the 1000 nm absorption band (more symmetrical bands in Fig. 7(b)). The immature craters in brighter basaltic regions show considerable scatter.

Figures

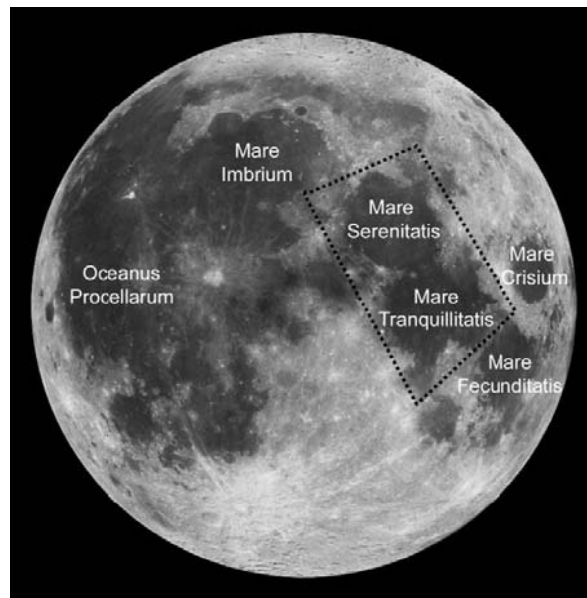


Fig. 1 Mare Tranquillitatis on the near side of the Moon. The studied area is outlined by a dotted line (Image Credit: NASA)

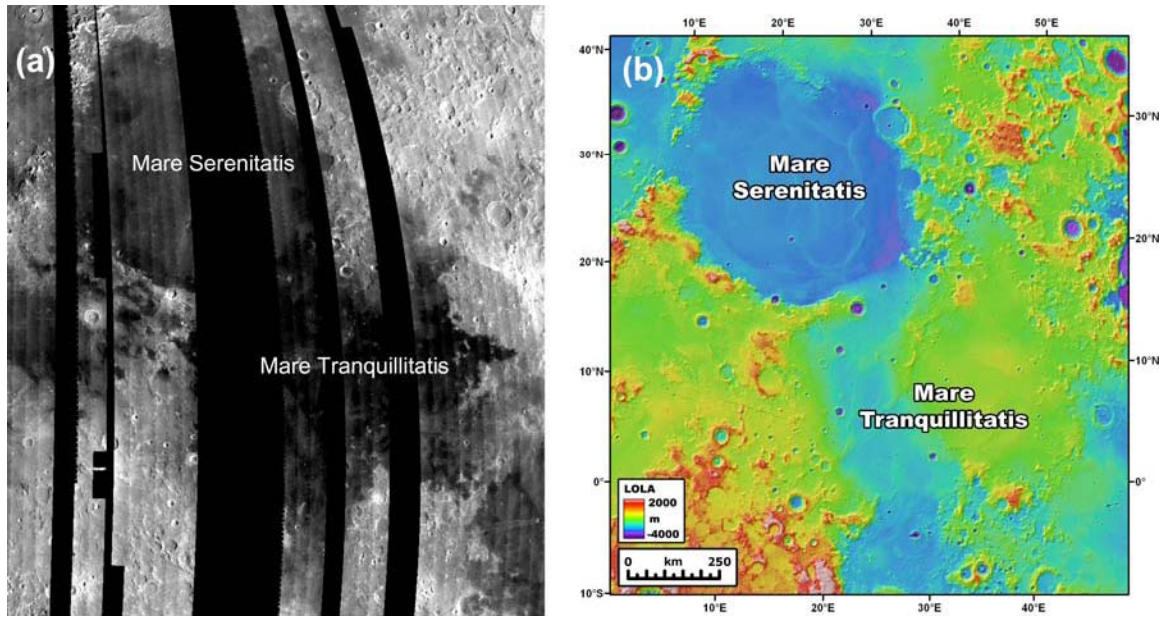


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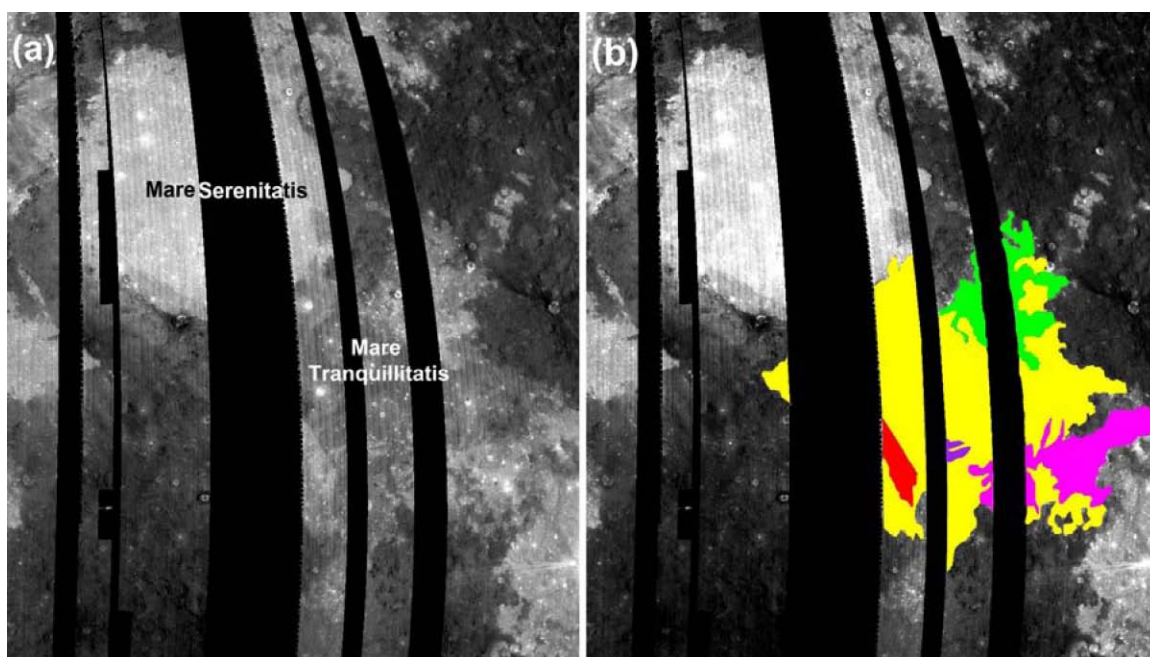


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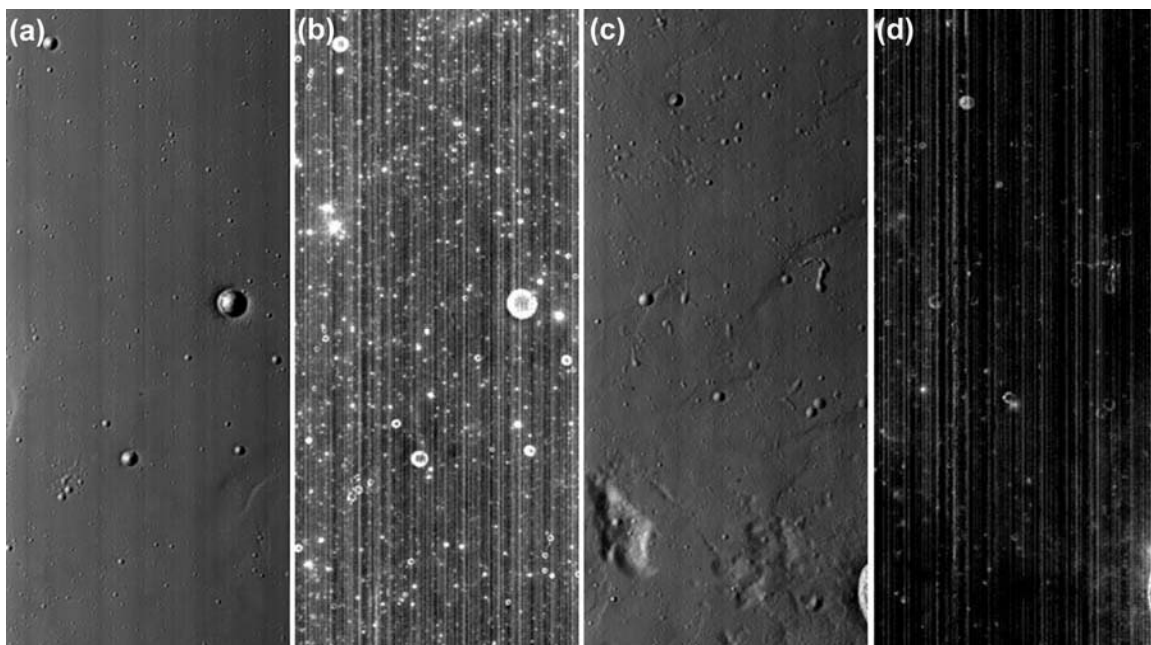


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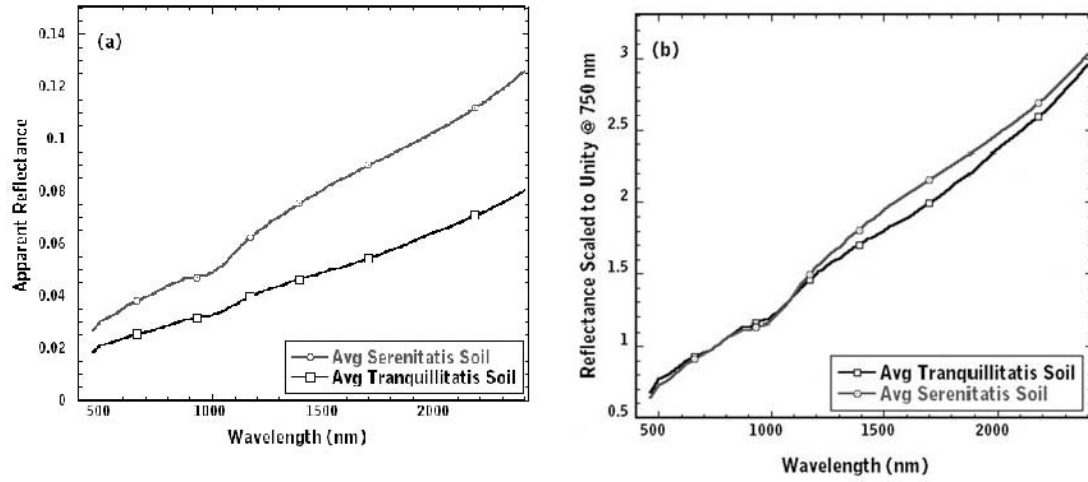


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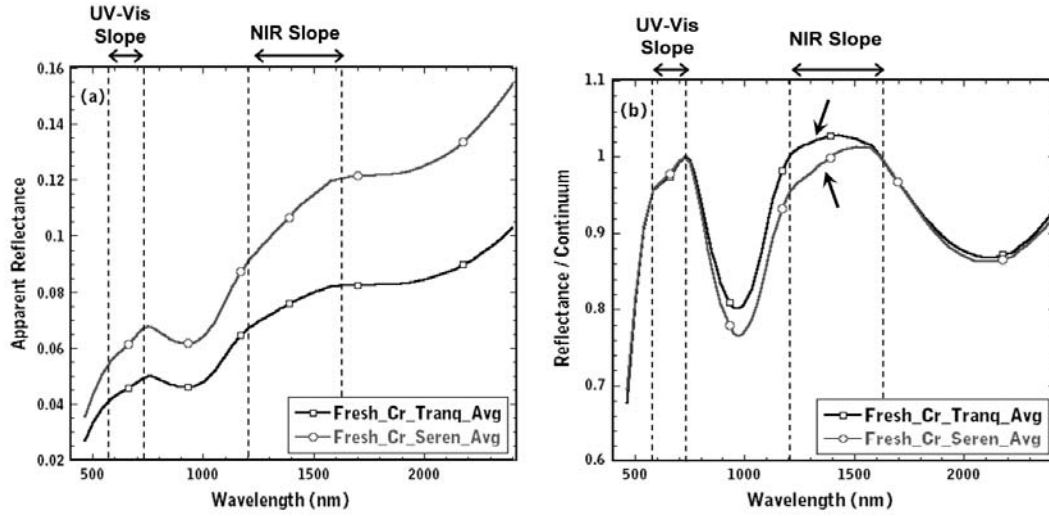


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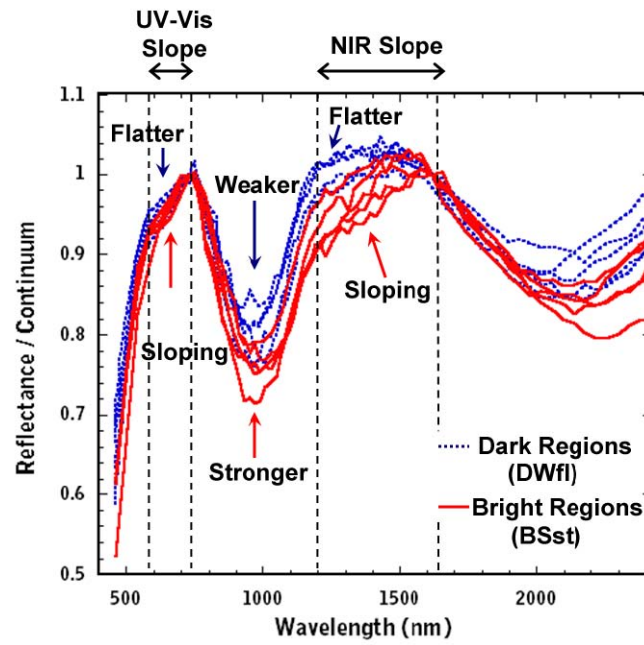


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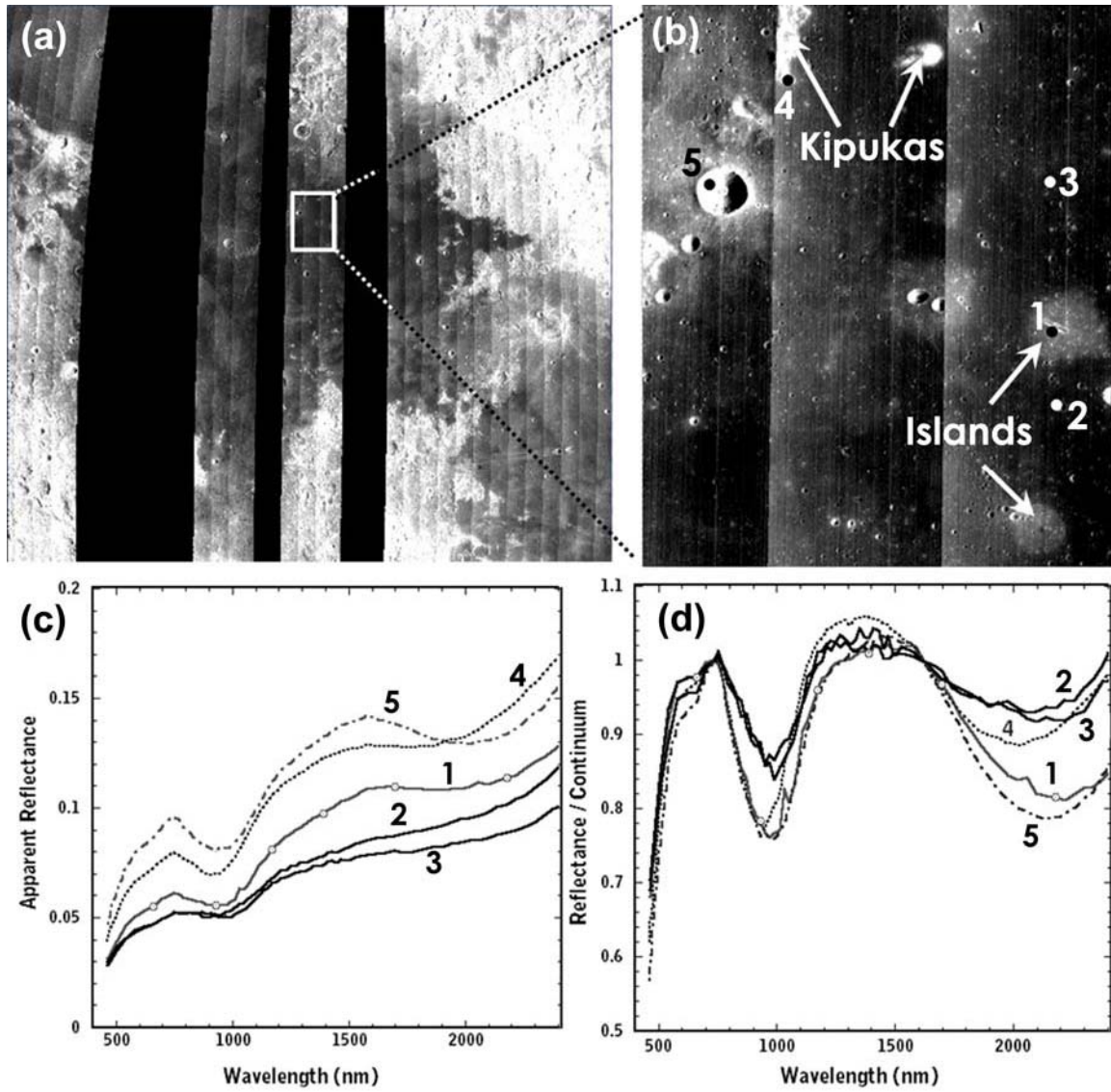


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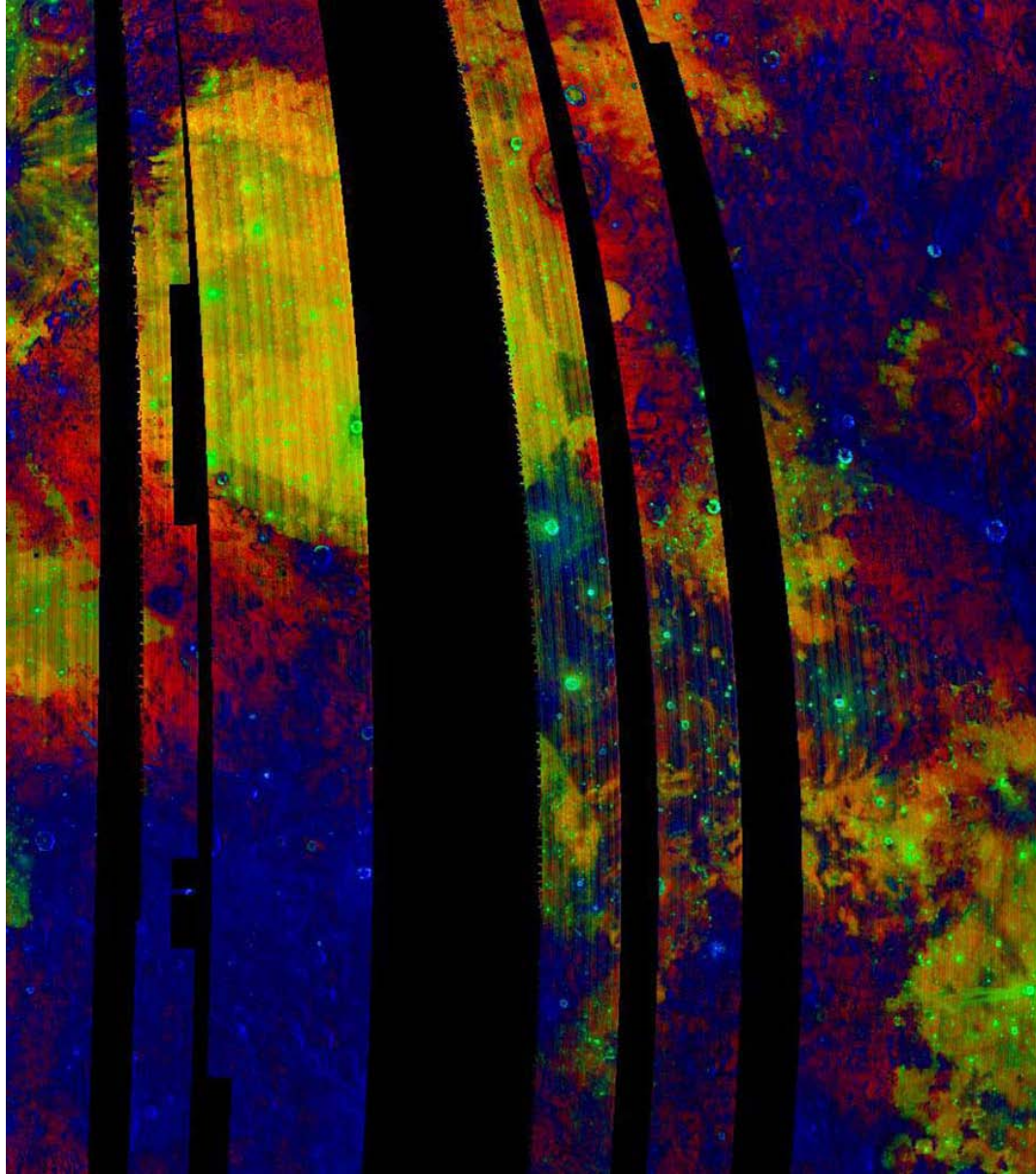


Fig. 9 RGB color composite of the study area. The composite is comprised of continuum slope ratio ($1618 \text{ nm} / 730 \text{ nm}$) in Red, IBD 1000 nm in Green and variable band shape around 1000 nm ($1209 \text{ nm} / 1618 \text{ nm}$) in Blue. Central Mare Tranquillitatis is dominantly blue with sparse regions in orange shades while the edges are dominantly represented in orange shades. Also note the abundant fresh craters (represented in green colors) in the orange units while blue units have visually fewer number of detectable fresh craters.

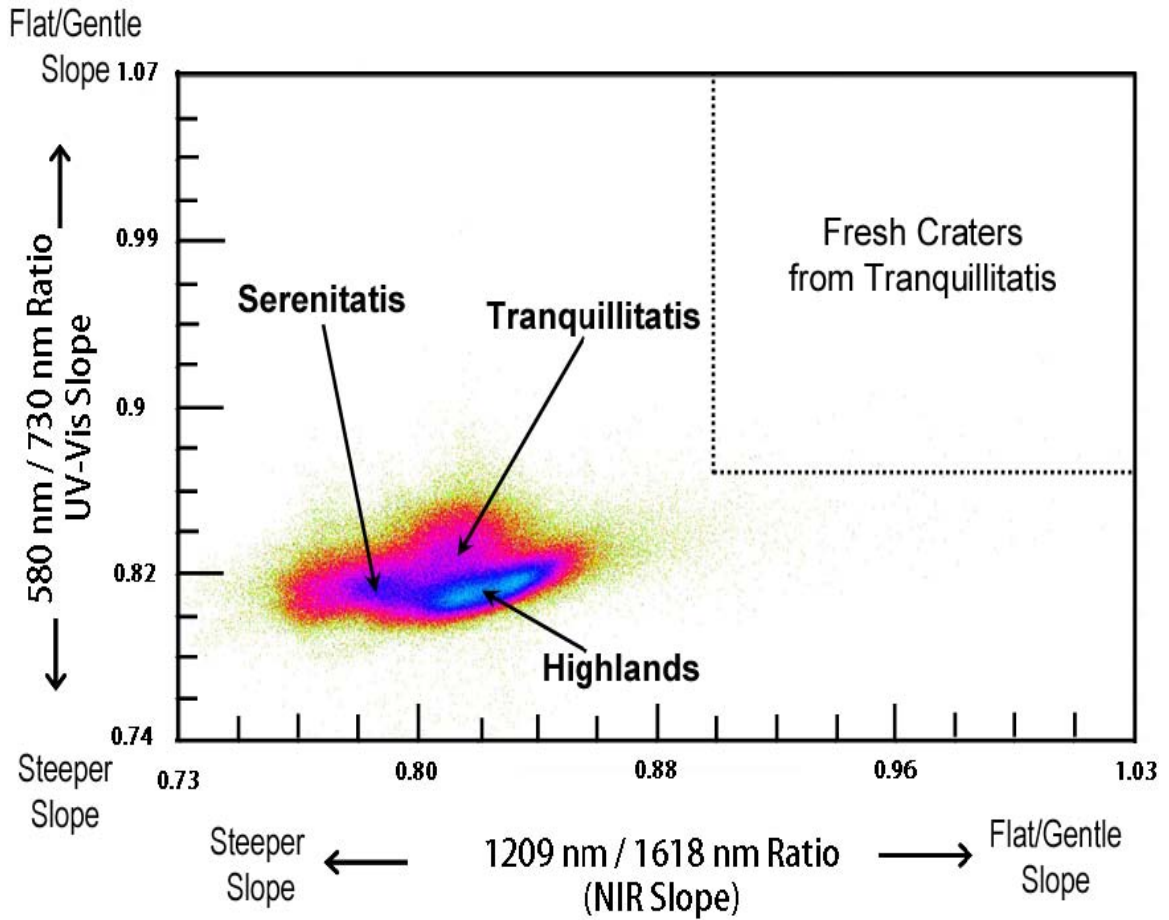


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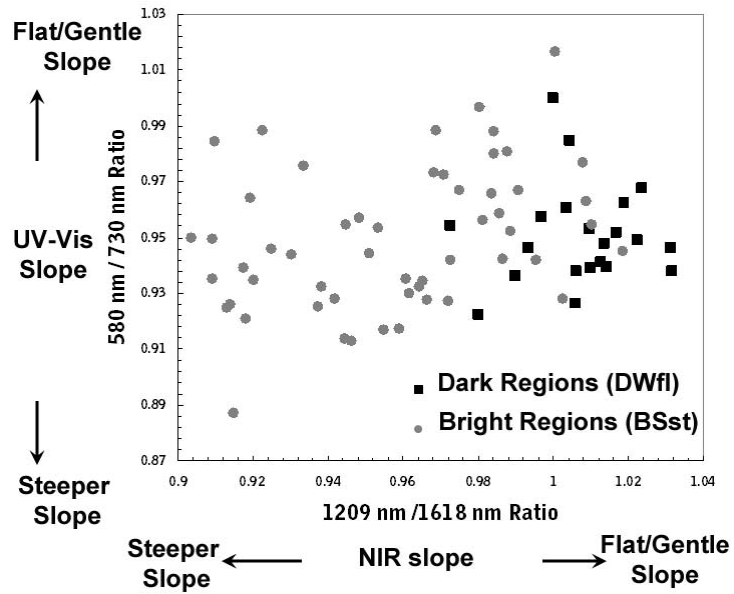


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