Chandrayaan-1 Lunar Science Atlas

Space Applications Centre
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Chandrayaan-1 Lunar Science Atlas

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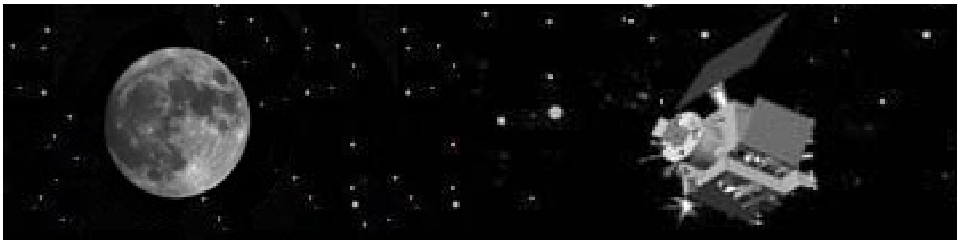

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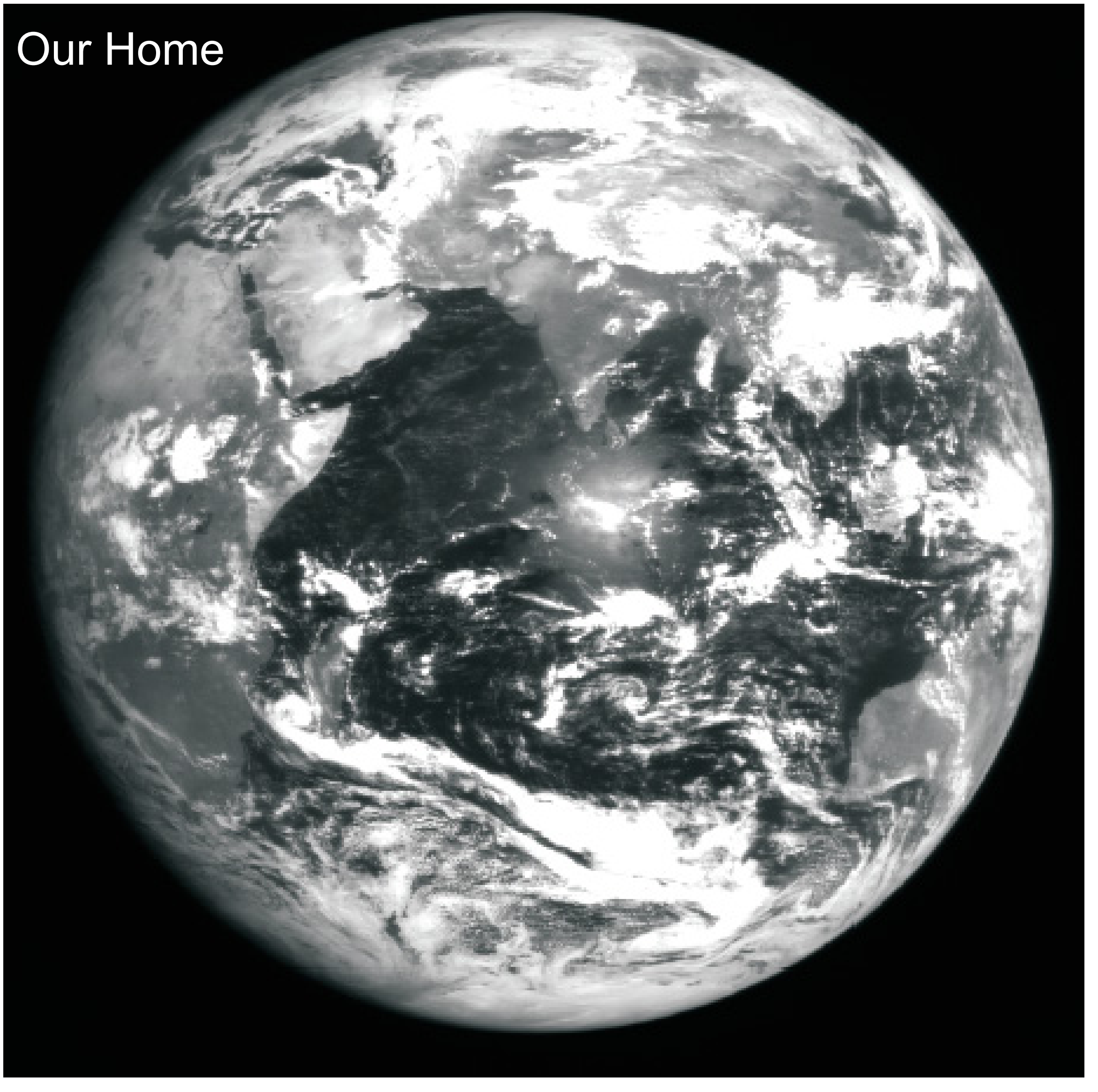

India and its surroundings viewed by Terrain Mapping Camera (TMC) of Chandrayaan-1 from Lunar orbit on March 25, 2009. The image of the Sun is seen as prominent sunglint over Indian ocean is captured at the centre of this image.

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FOREWORD

Moon - a celestial object in the night sky - has fascinated humans since time immemorial. Driven by the innate human inquisitiveness, many missions to Moon have taken place over the decades to understand about its evolution and to know about its surface and interior. Many such missions have provided valuable data on various scientific aspects of Moon.

India has successfully attempted its first mission to explore Moon by sending Chandrayan-1 with eleven instruments onboard which provided large amount of scientific data on surface geology, morphology, mineralogy, topography and magnetic properties of Moon. Scientific analyses of these data have led to various new discoveries including presence of water and new minerals on Moon. Most of the new findings from Chandrayaan-1 data have been published as peer reviewed papers and are now available in public domain. This mission has evoked fresh enthusiasm among the student and research community in the country towards carrying out planetary science studies. A good number of academic institutions have initiated planetary science research in their campuses after the success of this mission. Further in this direction, ISRO has started working towards its Chandryaan-2 mission, which will have an orbiter, a lander and a rover, being developed indigenously.

At this juncture, it is heartening to note that the Space Applications Centre, Ahmedabad is bringing out the second edition of compilation of science results obtained using Chandrayaan-1 data in the form of Lunar Science Atlas. Importantly, this atlas contains results of the work mainly done by Indian researches on different themes of lunar science. I acknowledge the efforts in bringing out this unique science atlas and congratulate all those who have contributed to this compilation. I am sure; this atlas will serve as a good reference volume to planetary scientists, research students and lunar enthusiasts in their pursuit to understand Moon.

Bangalore
April 30, 2015

आ सी किरण कुमार
(आ. सी. किरण कुमार)
(A. S. Kiran Kumar)

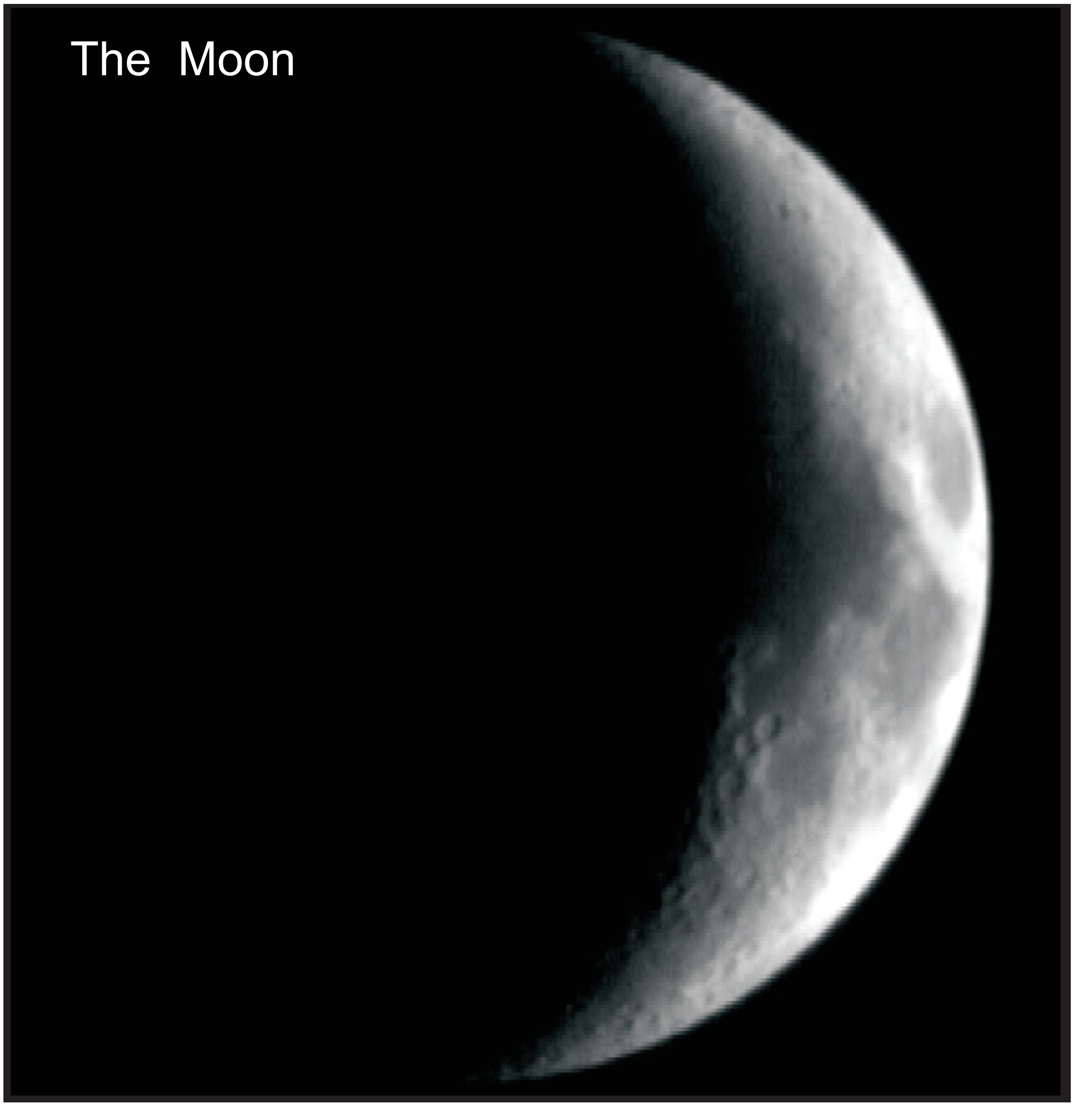

Image of the crescent Moon taken by TMC sensor of Chandrayaan-1 enroute to Moon on November 04, 2008 from a distance of ~311200 km. Prominent Lunar impact basins, highland and impact craters are distinctly visible in the image.

तपन मिश्रा
निदेशक
Tapan Misra
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PREFACE

Observing celestial objects and their movement, to understand and seek answers to the fundamental questions about the origin and evolution has been an exciting field of science. Space technology since its advent in the second half of the 20th century has made significant difference in our understanding about our celestial neighbours. India's first planetary mission Chandrayaan-1, has contributed significantly to enhance knowledge about Moon's surface and various processes, affecting its surface evolution. High quality data from various instruments of the Chandrayaan-1 in different spectral range of electromagnetic spectrum have provided an opportunity to observe Moon from close quarters. The scientific analysis of these data sets have led to various new scientific discoveries including that of water/hydrology molecules, new mineral findings, discovery of water ice etc. The mission has also successfully ignited minds of younger generation of Indian students and is hopefully attracting them to pursue Space as career option. Space Applications Centre is currently working towards sensor development for Chandrayaan-2 mission for detailed investigations on issues like water/ice on Moon.

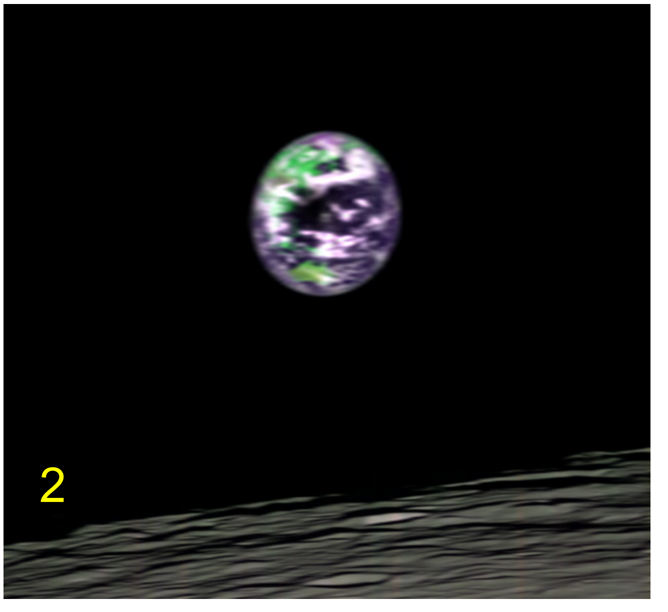
The high spatial and spectral resolution images from Terrain Mapping Camera (TMC) and Hyperspectral Imager (HySi), respectively, have provided newer insights into the formation of lunar impact craters, lunar mare basins, geological structure and Polar Regions of the Moon. This lunar Science atlas, is a compilation of science results obtained using Chandrayaan-1 data, obtained through work done mainly by Indian researches. I would like to place on record my appreciation to the team at the Space Applications Centre for bringing out this unique science atlas and completing this task in time.

Tapan Misra

(तपन मिश्रा)
(Tapan Misra)

Ahmedabad
29 April 2015

Earth rise over the Lunar Surface



This spectacular Image of the Earth rise over the Moon surface captured by 1) Terrain Mapping Camera (TMC), and 2) by Moon Mineralogy Mapper (M3) instrument of NASA/JPL onboard Chandrayaan-1 on July 22, 2009. Entire continent of Australia is seen in the southern portion of the Earth's image, while the left portion of the image shows eastern parts of Asia in the M3 image. The water of the Pacific ocean is seen in blue colour.

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ACKNOWLEDGEMENT

Chandrayaan-1 spacecraft acquired a large volume of data of the Moon surface on various aspect of Lunar Geosciences. High spatial and spectral resolution data from Terrain Mapping Camera (TMC), hyperspectral Imager (HySI) and Moon Mineralogy Mapper (M3) are like gold mine for lunar geoscientists. The topographic information provided by TMC and Lunar laser Ranging Instrument (LLRI) have significantly enhanced the interpretation of these data sets for exploring lunar geomorphology and surface composition. The present lunar science atlas is a collection of various interesting and new scientific findings in the broad field of lunar geosciences using Chandryaan-1 data.

We are extremely thankful to Shri Tapan Misra, Director, Space Applications Centre, for his initiative in bringing out this second edition of this atlas and his constant encouragement. The entire Chandryaan-1 science data analysis team expresses, our thanks to Shri A. S. Kiran Kumar, Chairman, ISRO and former Director, SAC for his keen interest in Lunar science and providing us continuous motivation. We are thankful to Dr P. K. Pal, Deputy Director, EPSA for his support and guidance in executing this work. We are grateful to entire Chandryaan-1 mission team for excellent coordination in executing Chandryaan-1 project and providing the scientists opportunity to study Moon. I also thank the payload and data product teams at SAC and all my colleagues in supporting this activity.

(Prakash Chauhan)

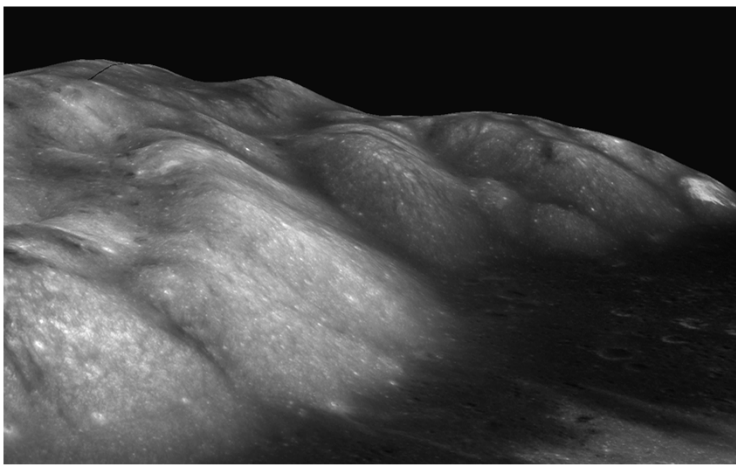
Ahmedabad

May 02, 2015

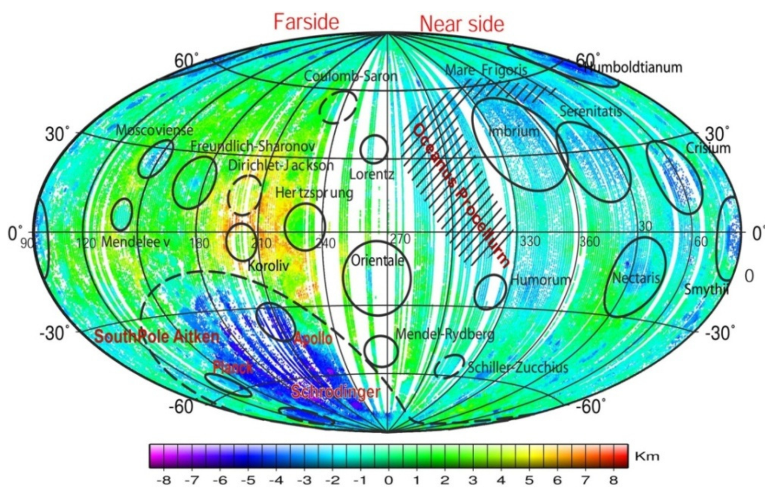
Lunar Science using Chandrayaan-1 : Summary

Laboratory studies of lunar samples brought back by earlier landing missions like APOLLO and LUNA and remote exploration of the Moon, particularly by CLEMENTINE and LUNAR PROSPECTOR missions have provided a considerable amount of data to understand the formation and subsequent chemical and geological evolution of the Moon. The key questions of lunar science about the surface evolution, radiation environment, permanently shadowed areas in poles and presence of water/ice are not yet fully understood. With the launch of Chandrayaan-1 in October 2008, India ushered into a new era of Planetary Exploration. The larger amount of data provided by eleven instruments on-board Chandrayaan-1 have now been analyzed. Many new discoveries and findings have been reported using Chandrayaan-1 data from different instruments. The major findings include discovery of water/hydroxyl molecules in lunar poles, findings on new minerals, confirmation of lunar magma hypothesis, mineralogy and morphology of complex craters, detection of lunar domes, sinuous rilles, lobate scarps and detection of water ice in polar regions of the Moon. All these findings have ultimately lead to enhanced understanding of the evolution of the Moon and associated processes.

This present scientific lunar atlas provides glimpses of the important scientific achievements using mainly imaging instruments such as Terrain Mapping Camera (TMC), Hyperspectral Imager (HySI), Moon Mineralogy Mapper (M3), Mini SAR, Lunar Laser Ranging Instrument (LLRI), SARA and C1XS. In spite of many illustrations presented in this atlas, the lunar exploration using Chandrayaan-1 data is still continuing.



Three dimensional view of lunar mountains



Global lunar topography using LLRI instrument

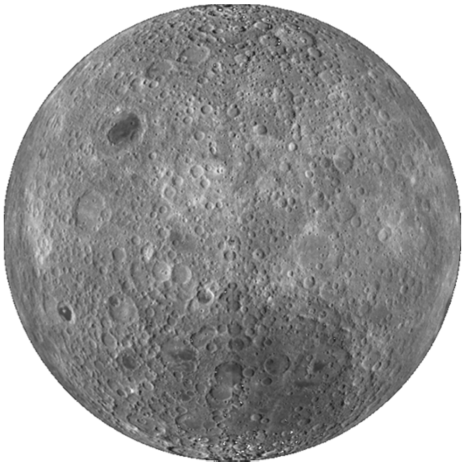
Contents

The Moon

Looking up on clear nights, the Moon is the familiar face for all of us which has looked the same throughout since human history. It is believed that, the Moon formed about 4.4 billion years ago after the collision of a Mars sized impactor body with Earth. The distance of Moon from the Earth is about 384,403 km. The Moon revolves around the earth at an average speed of 3,700 km/h and completes one revolution in an elliptical orbit around earth in 27 days 7 hours 43 minutes 11.5 seconds. For the Moon to go from one phase to the next similar phase, or one lunar month, requires 29 days 12 hours. The diameter of Moon is about 3,480 km. Temperature on the moon surface ranges from -158º to 130ºC. The gravitational pull at the lunar surface is only one-sixth that of Earth, which is one of the main reason for the Moon not having a dense atmosphere around it.

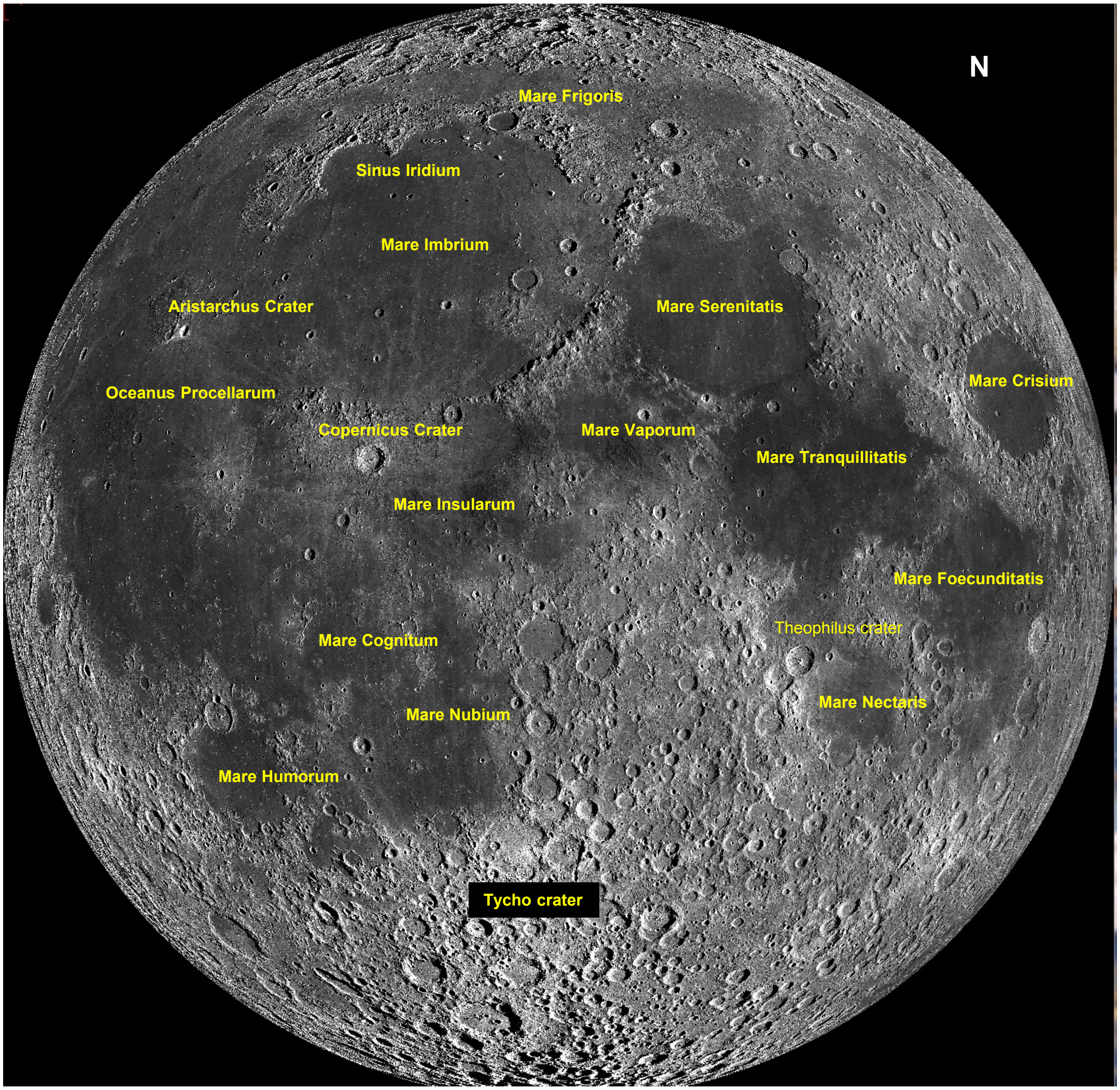
Near Side of the Moon

The Earth facing side is named as near side of the Moon, whereas the other side not visible from Earth's surface is called far side and is heavily cratered as compared to the near side. Early telescopic and subsequent space based observations revealed two major terrains on the Moon, the old heavily cratered highlands and the younger large dark plains filled by basalt flows known as 'Mare Basins'. The most enigmatic question exist in lunar science is the origin and evolution of the Moon. Since many decades scientists around the world trying to envisage the question of lunar evolution. Before the spacecraft exploration, lunar science was untouched by mankind, also speculations about lunar composition and origin were unconstrained. The data obtained remotely by past Lunar missions like Galileo, Clementine, and Lunar Prospector missions, including lunar meteorites have resulted in major change in our views about the evolution history of the Moon. New scientific ideas about the evolution of the Moon have been firmed up using the new datasets from recent lunar missions like Chandrayaan-1, Kaguya/SELENE, Changé and Lunar Reconnaissance Orbiter (LRO).



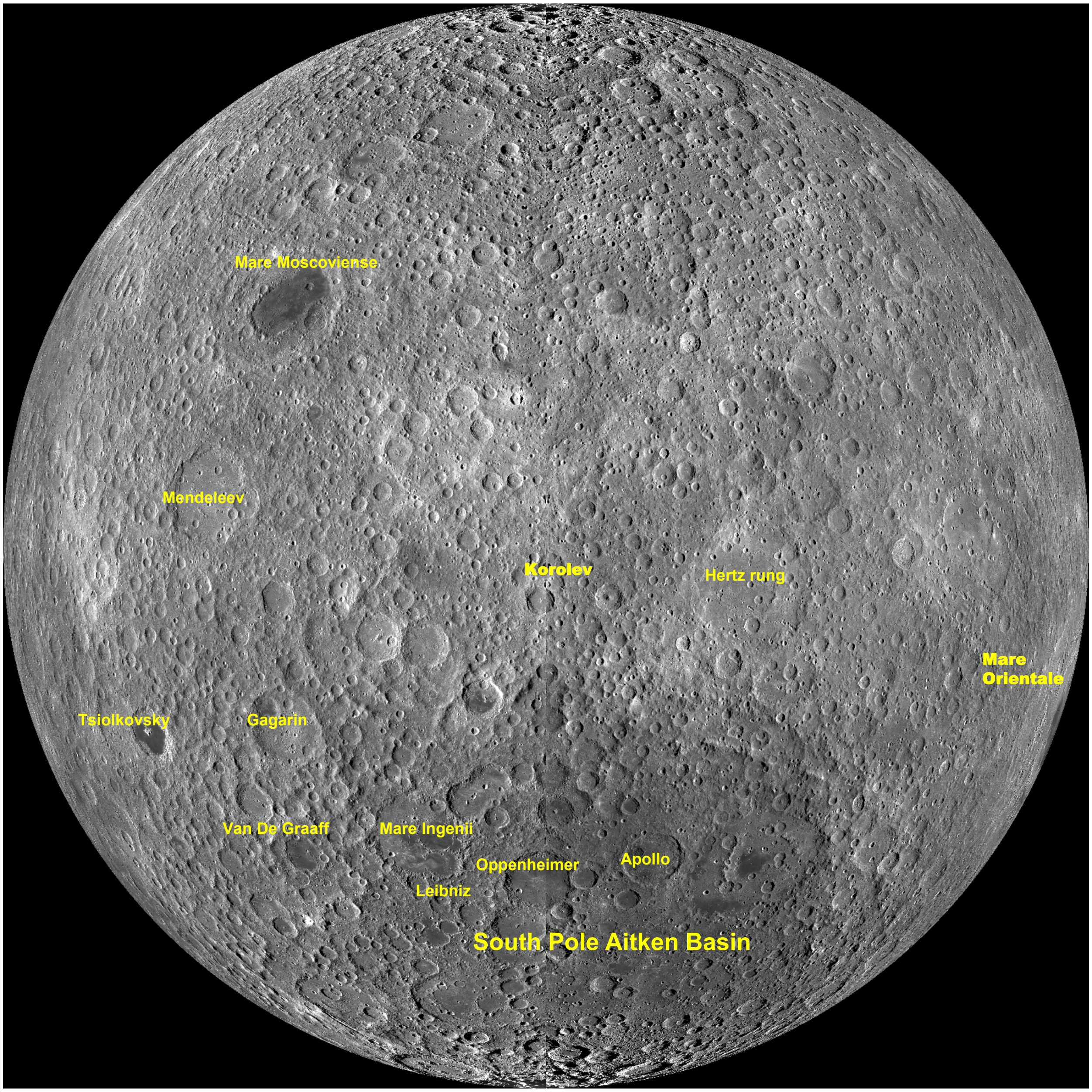
Far Side of the Moon

Near Side of the Moon



Major Mare basins and craters of the near side

Far Side of the Moon



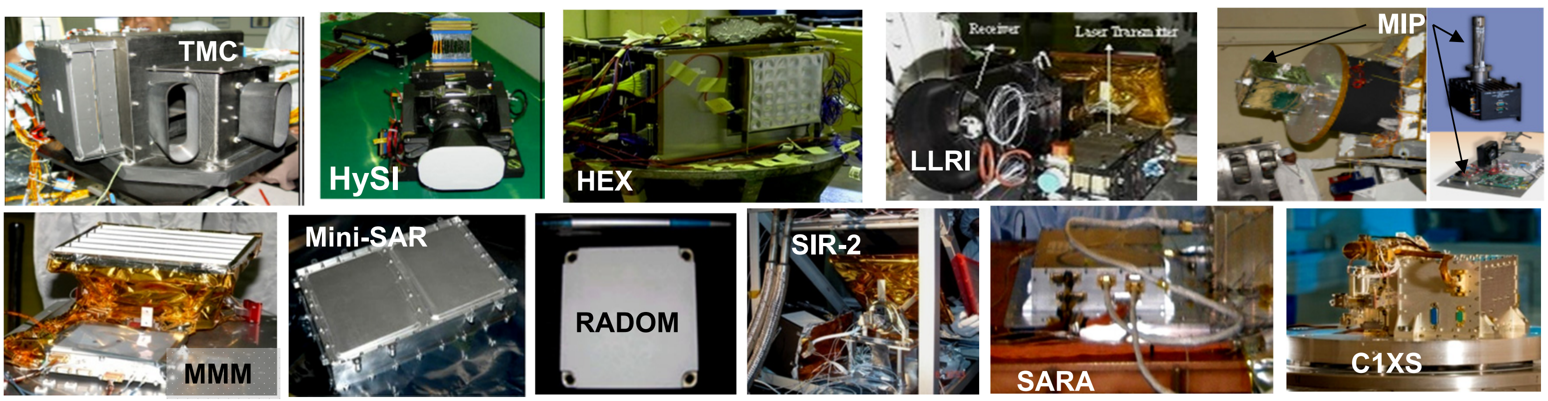
Major Mare basins and craters of the far side

The Chandrayaan-1 Mission & Payloads

Chandrayaan-1 has been the first Indian lunar mission launched on 22nd October, 2008 and was designed to study the lunar surface in terms of photo-geology, chemical and mineralogical mapping, elemental abundance, radiation environment and exploration of polar regions of the Moon. The satellite had 11 instruments onboard which were selected to meet the specific science objectives. During the last three years, a significant contribution to newer aspects of lunar geosciences had been addressed using data provided by different Chandrayaan-1 instruments.

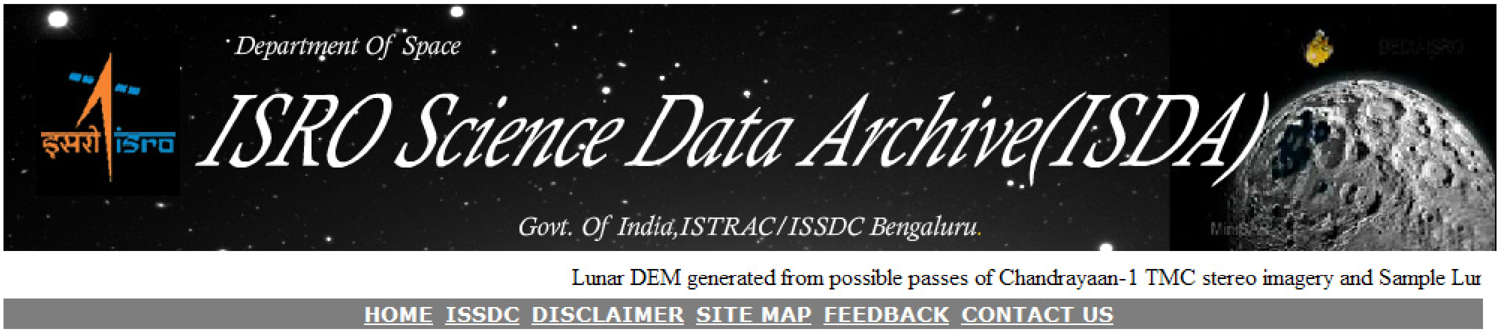
Terrain mapping Camera (TMC) mapped the lunar surface in panchromatic mode and provided the three dimensional images of the lunar surface for morphological studies. Hyperspectral Imager (HySI) with a spatial resolution of ~ 80m mapped the lunar surface in 0.42-0.96 μm spectral range (64 spectral bands) for extracting the mineralogical information.

Moon Mineralogical Mapper (M3) was an guest instrument from NASA for mineralogical mapping of the lunar surface in visible-near infrared region (0.5-3.0 μm) with 85 spectral bands. Infrared Spectrometer (SIR-2) was a non-imaging point spectrometer and guest instrument from Max-Planck Institute, Germany which has mapped the lunar surface in the spectral range of 0.94 – 2.4 μm. Mini SAR, a miniature Synthetic Aperture Radar was meant for mapping the properties of the plausible water-ice deposits on the basis of Circular Polarized Ratio (CPR) in the permanently shadowed polar-regions. Low energy C1XS did the chemical mapping in terms of elemental abundance of the lunar surface based on Solar X-Ray induced fluorescence emission. High Energy X Ray induced (HEX) payload studied the volatile transport on the Moon through detection of low-energy gamma-rays. Lunar Laser Ranging Instrument (LLRI) had mapped the global topographic field of the Moon. Moon Impact Probe (MIP) studied the transient lunar atmosphere using mass spectrometer and also discovered water molecules in the near lunar surface atmosphere. SARA was used for studying solar wind interactions with Moon surface, while RADOM was used for radiation budget monitoring.



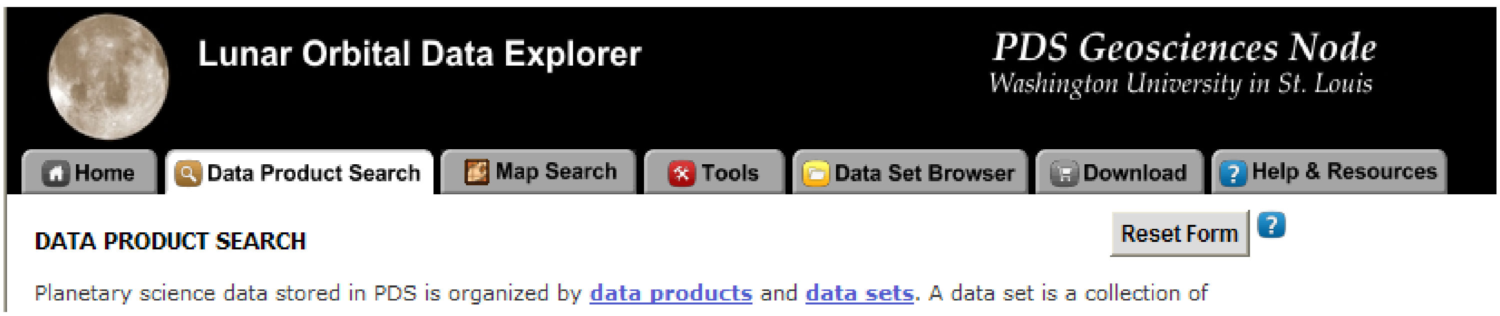
Different payloads of Chandrayaan-1 satellite

Chandrayaan-1 Data Archive



Chandrayaan-1 data from different instruments is now available from ISRO Science Data Archive (ISDA) web site of ISSDC/ISRO. The data has been put after a peer review process. The data can be downloaded from http://www.issdc.gov.in. The site contains data from TMC, HySI and Moon Mineralogical Mapper (M3) payloads of Chandrayaan-1. Data products like raw PDS data, Ortho images, TMC DEM data, TMC North and South pole mosaics can be downloaded from this site.

Data from instruments like Moon Mineralogy Mapper (M3) and Mini SAR are also available from PDS Geosciences Node of Washington University, USA.

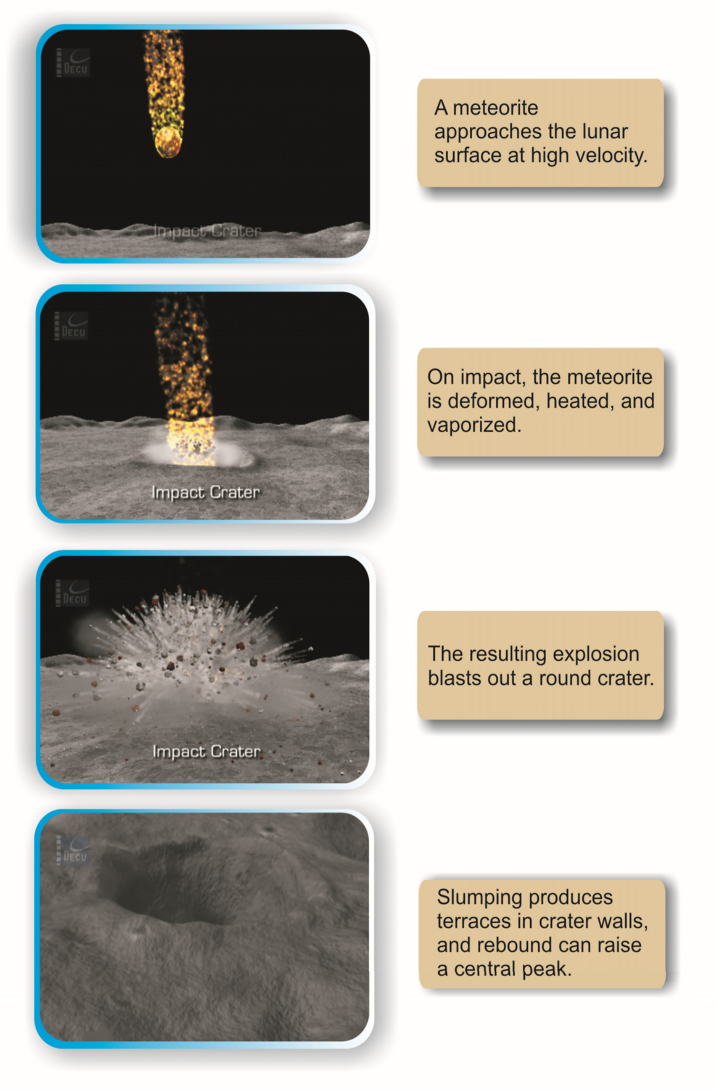


Lunar Impact Craters

02 Lunar Impact Craters

Due to lack of atmosphere on Moon, meteorites or projectiles directly hit the lunar surface and result into the formation of pits or bowl shaped depressions surrounded by a raised rim. These circular to non-circular features present on the Moon surface are called impact craters. Craters can have different diameters, geologic settings, morphologies and variations in composition covering the entire surface of the Moon. The impact generates large amount of debris of fresh bright material called ejecta, which surrounds the circular cavity and also produces bright streaks of target material called rays thrown to large distances. One such fascinating very bright youngest rayed crater named as Tycho crater can be seen in the southern highlands of the Moon. Craters can vary in their appearances and morphology having well developed crater floor, presence or absence of central uplift, terraced walls, type of ejecta pattern etc. depending on the size and velocity of impactors and the nature of the target material. Ejecta produced from the primary craters at lesser velocities can create morphologically varied *secondary craters* over large distances. Secondary craters are mainly present in clusters or as a long continuous chain of small craters.

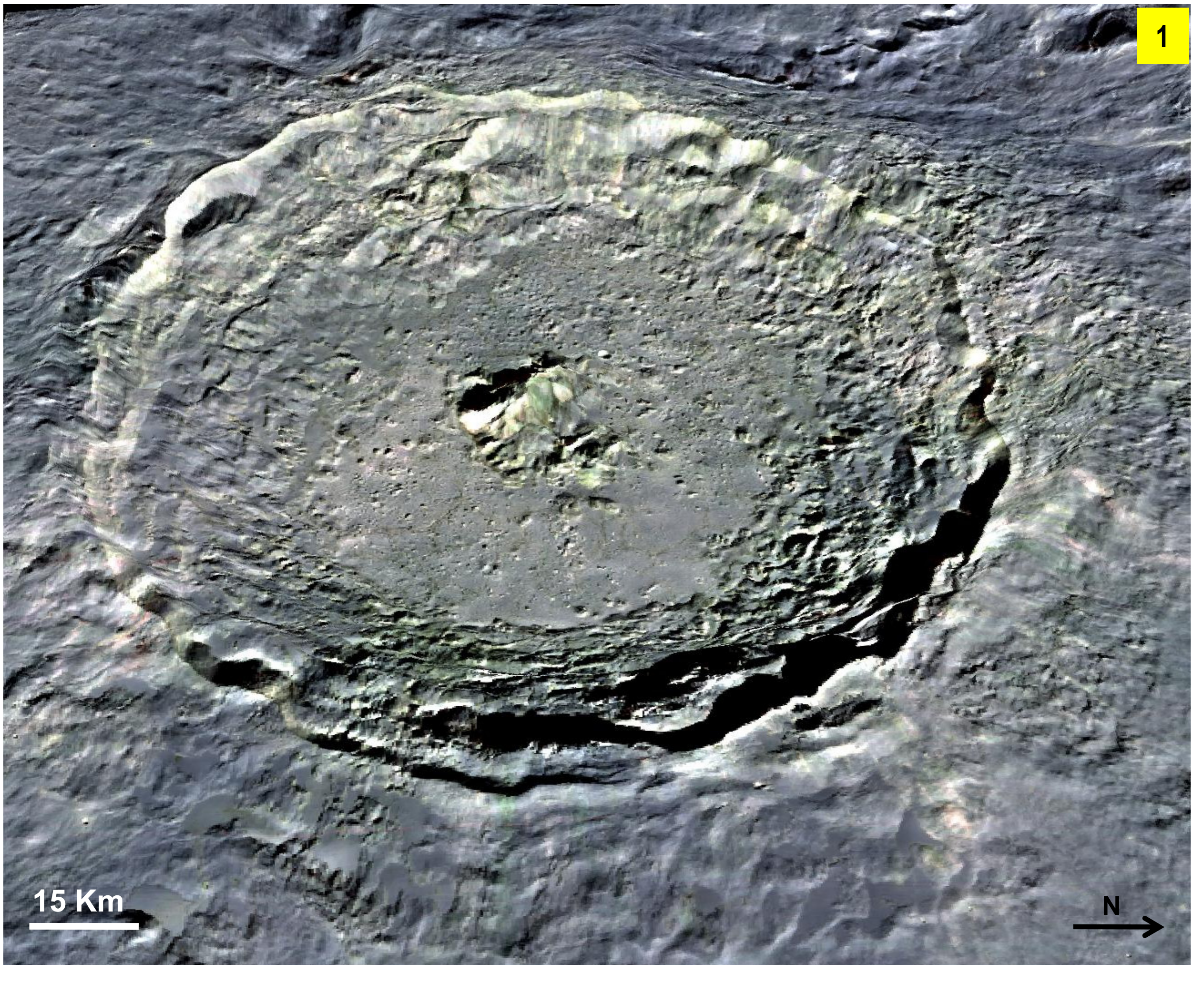
Lunar craters can be classified as: 1. *simple crater* which are generally bowl shaped with rounded or, in some cases, small flat floors 2. *complex craters* are characterized by terraced and crenulated rims and an uplifted central bulge or peak, and 3. *basins* formed when the diameter becomes lager than 200 km. By recording the numbers and size of the craters, chronology of the lunar surface can be reconstructed. In general, the older surfaces are likely to have larger crater sizes with more crater counts. Complex lunar craters are also important science targets as their central peaks can also provide information about interior rocks of the Moon.



Graphics: courtesy DECU/ISRO

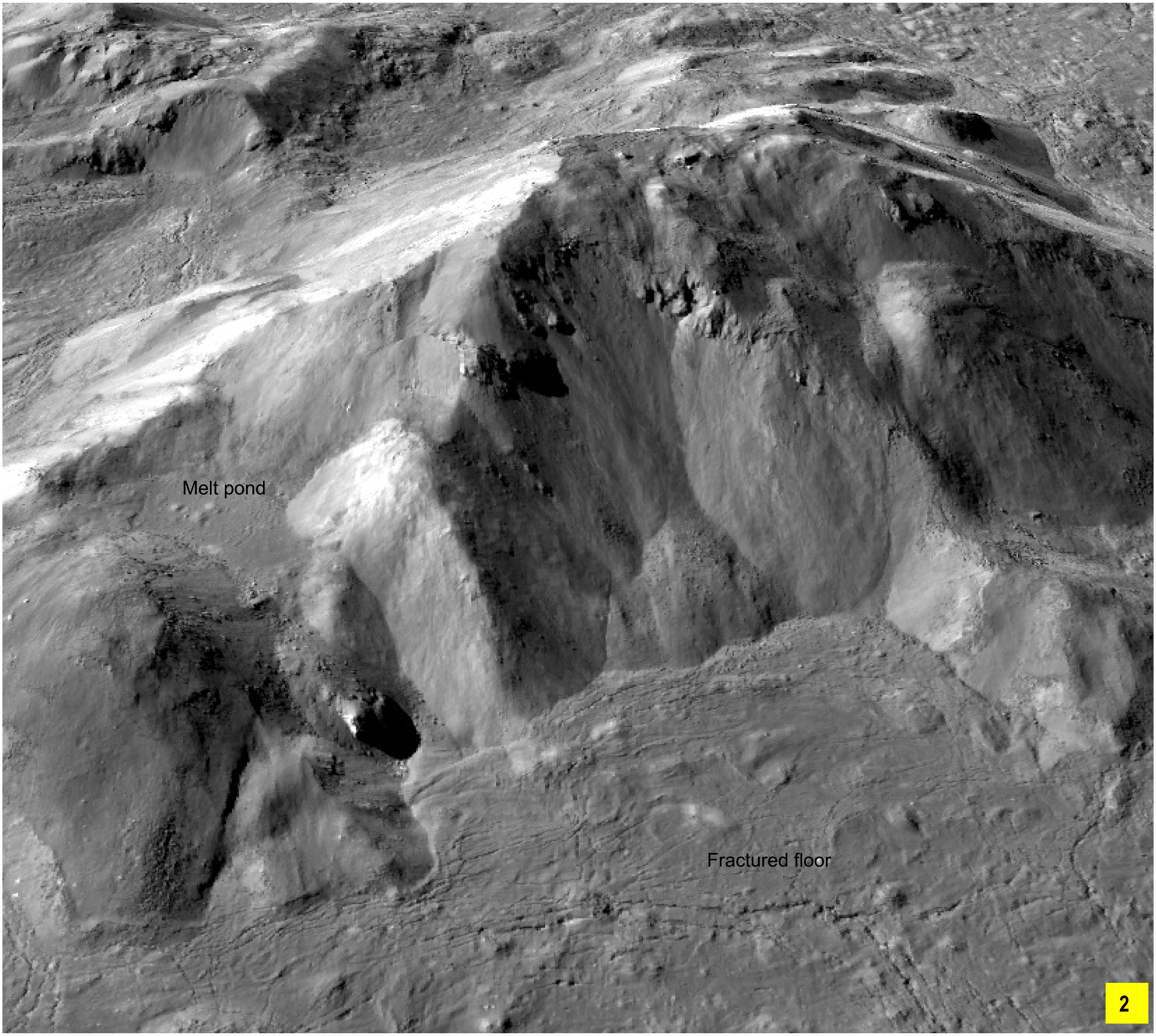
Tycho: A Complex Lunar Crater

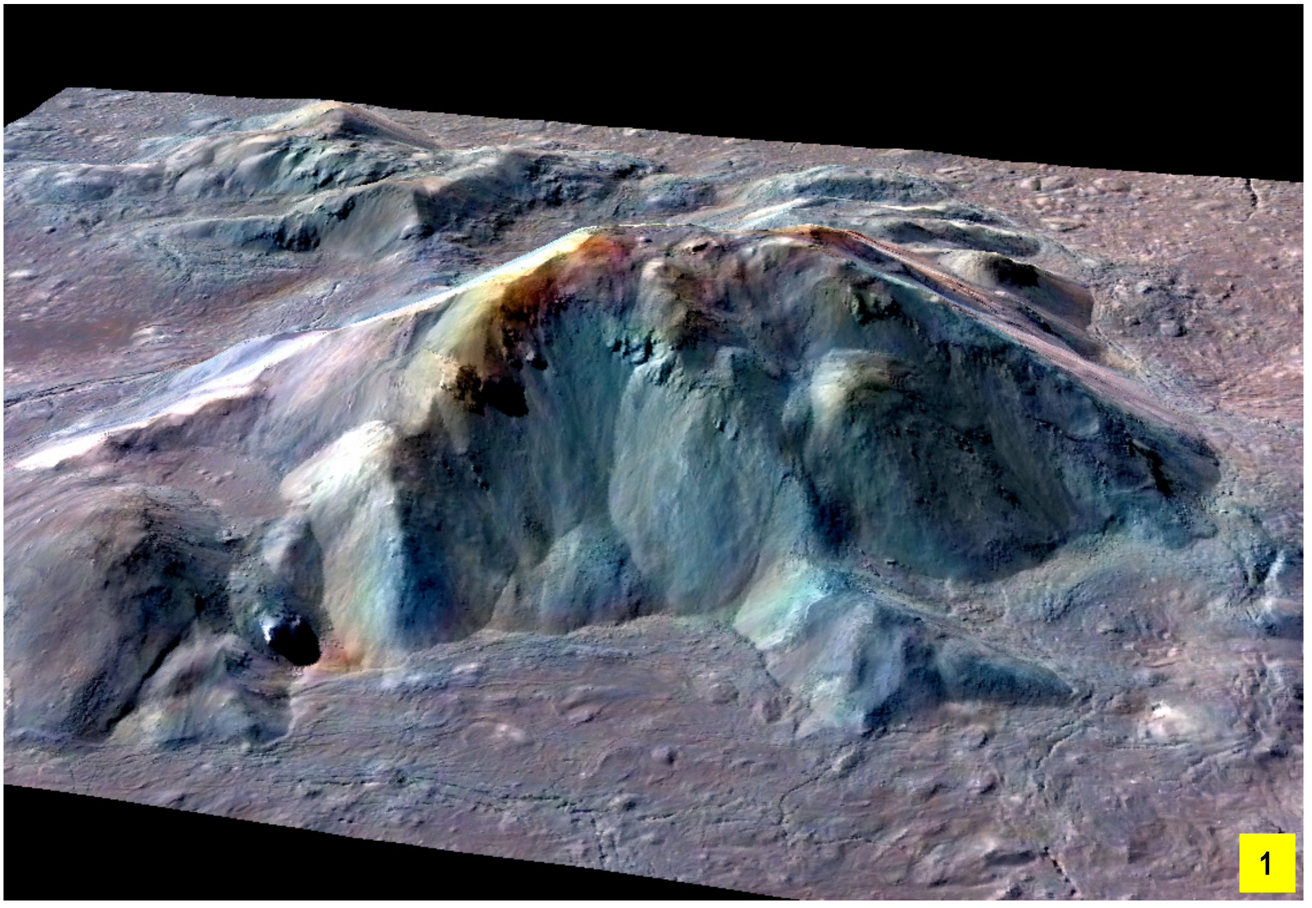
Tycho is a young impact crater of Copernican age (~100 million years) having 85 km diameter, situated on the southern highlands of the Moon. Tycho is considered to be the youngest complex crater on Moon having well developed central peak of ~2 km height and sharp traced crater rims. Chandrayaan-1 TMC data have shown details of fractured crater floor and impact melt pools in and around Tycho crater. HySI and Moon Mineralogy Mapper (M3) data have revealed mafic composition (rich in iron bearing rocks) of central peak of Tycho crater, which is in contrast with surrounding geological settings.

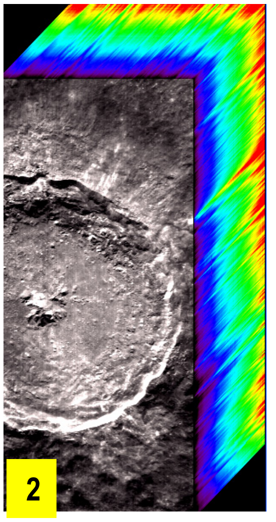


1. Color composite image (1009 ,1249 & 2000 nm bands) over Tycho crater as observed by Moon Mineralogy Mapper (M3). Light green-yellow color shows presence of iron rich rocks

2. Three dimensional view of Tycho crater from Chandrayaan-1 TMC data .


Melt pond
Fractured floor
2



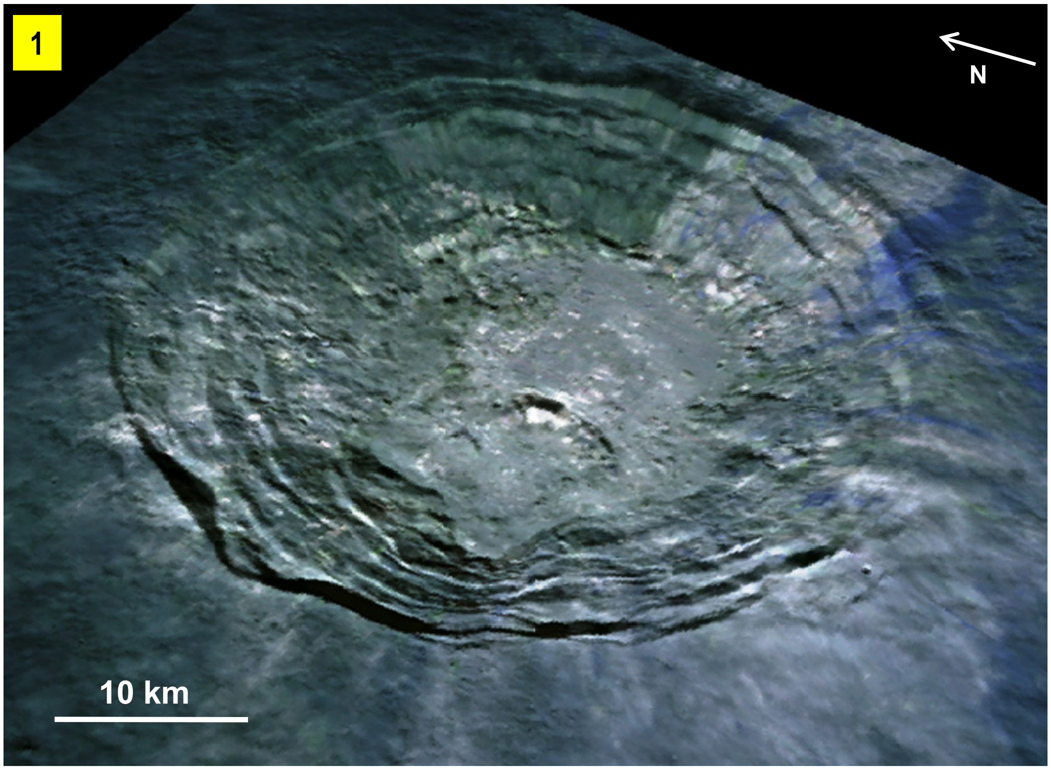


Composition of Tycho Crater

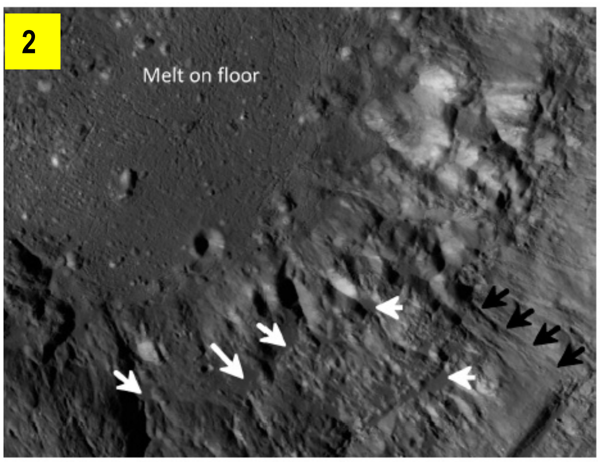
1. Color composite image of the central peak of Tycho created by fusion of HySI and TMC data. The image shows lithological variations in terms of mineralogy on the central peak of Tycho. Blue shades shows mafic composition while brown shade shows impact melt flows.

2. Hyperspectral cube of Chandrayaan-1 HySI data for Tycho carter

Aristarchus : Geologically diverse Lunar Crater



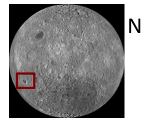
The Aristarchus crater is ~ 450 million years old crater situated on the western near side of the Moon. The crater has anomalous brightness relative to other craters of the similar age. The crater is situated at the contact between Oceanus Procellarum basalts and an uplifted lunar crustal block known as Aristarchus plateau. This crater is known for its complex and diverse geology.

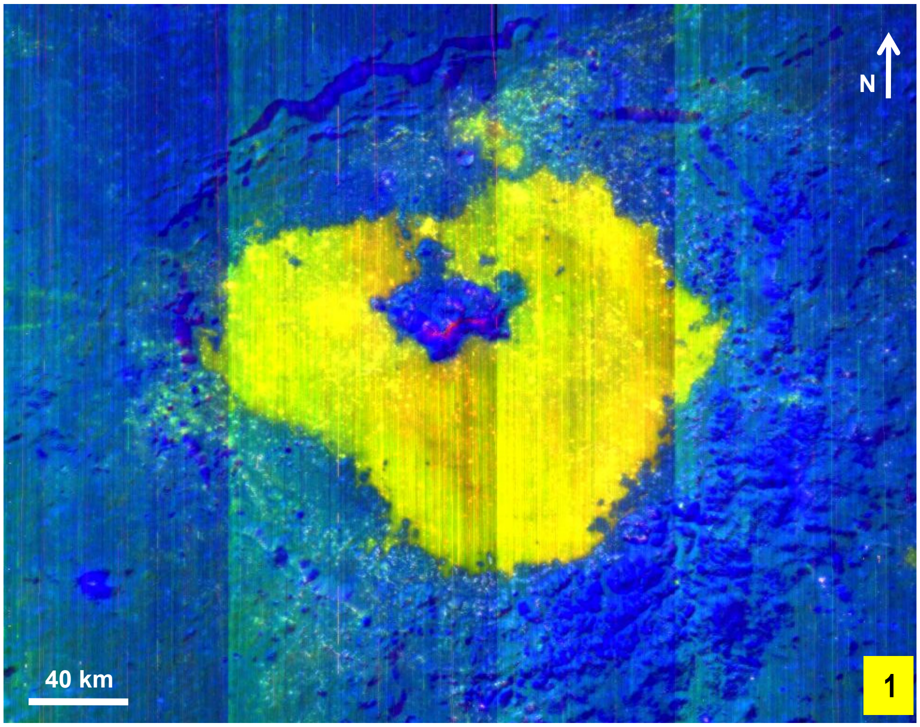


1. Color composite of Aristarchus crater generated using M3 data showing major mineralogy. Blue color represents olivine and/or glass deposits, while green color represents pyroxenes. The central peak exposures seen in white color represents plagioclase.

2. TMC image of the one of the portion of the crater showing melt flows on the crater floor and melt pools on the crater wall terraces.

Tsiolkovsky: Plagioclase exposures on Central Peak



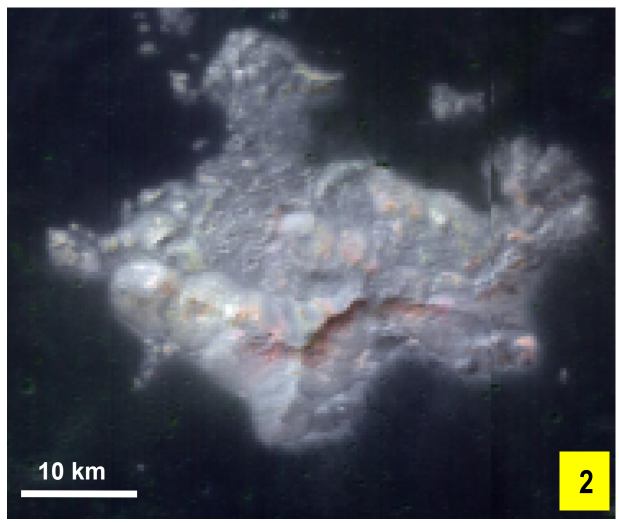


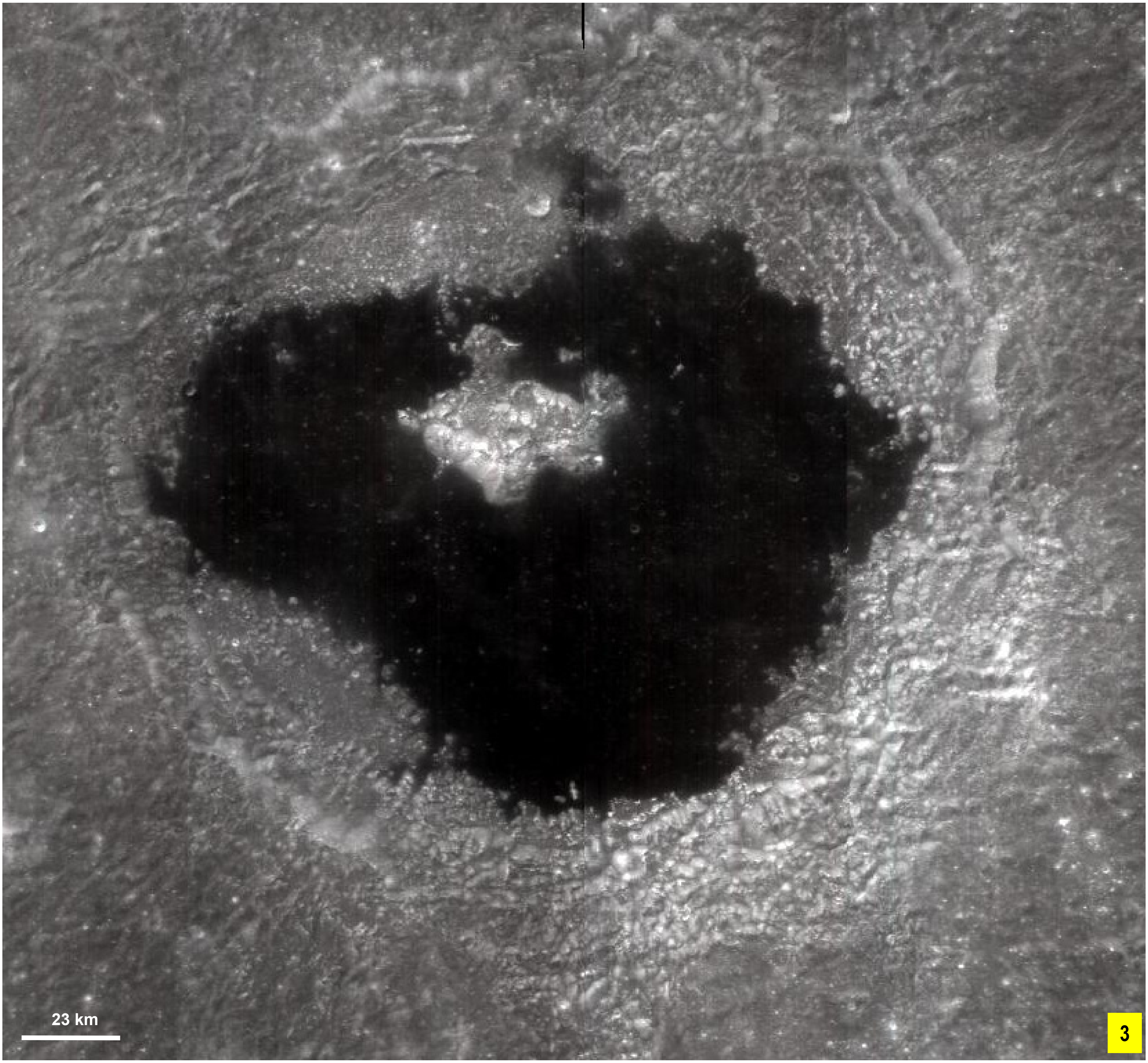
1. Image indicating major mineralogy of the Tsiolkovsky crater. Blue color represents mafic mineral free highland rocks, pink color are crystalline plagioclase exposures on central peak and yellow to green color represents basalts *(iron rich dark colored rock*) on the crater floor.

2. Central peak of the Tsiolkovsky crater with crystalline plagioclase exposures seen in pink color.

3. Tsiolkovsky crater as observed by Chandrayaan-1 in high resolution.

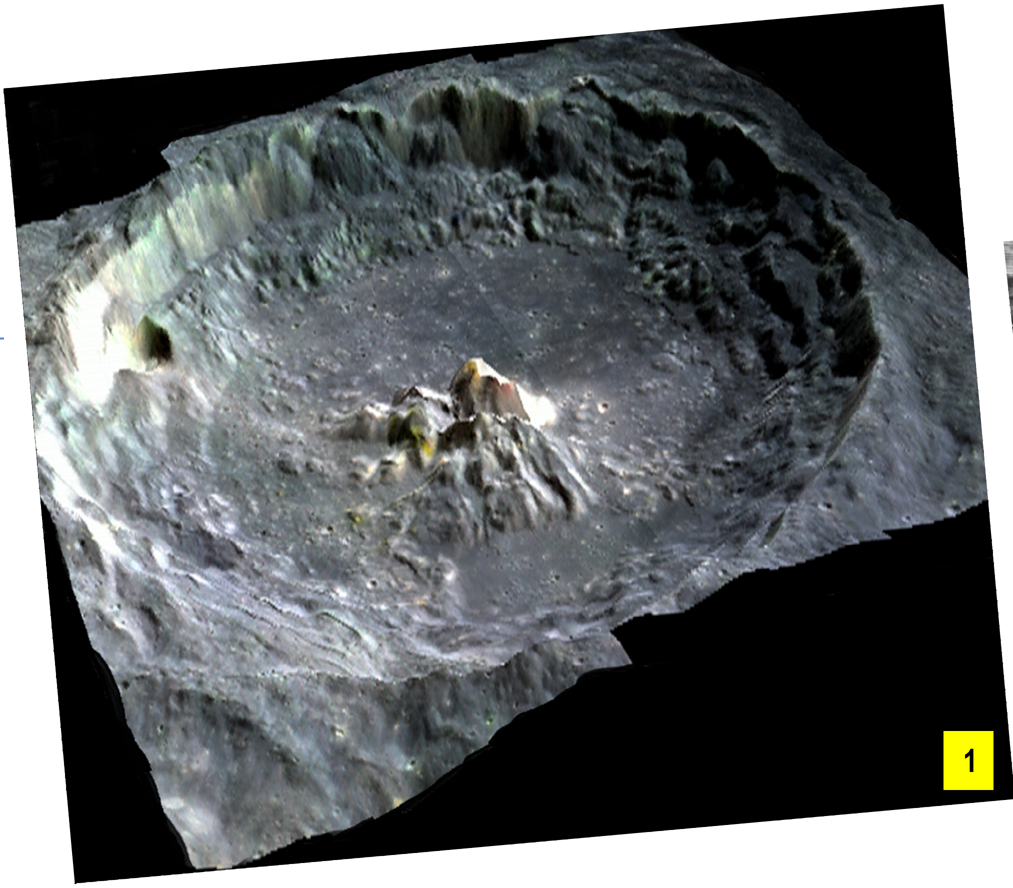
Tsiolkovsky is a ~185 km diameter crater situated on the lunar far side (20º S, 129º E), filled with dark mare deposits. The crater exhibits terraced walls and steeply sloping central peak ridges. The central peak of the crater has exposed fresh plagioclase rich material from within the crust. The crater floor is filled with basalts and peppered with numerous small impact craters. Lunar far side has more crustal thickness as compared to the near side and devoid of large scale mare volcanism. Tsiolkovsky crater represents an excellent example of far side lunar volcanism.

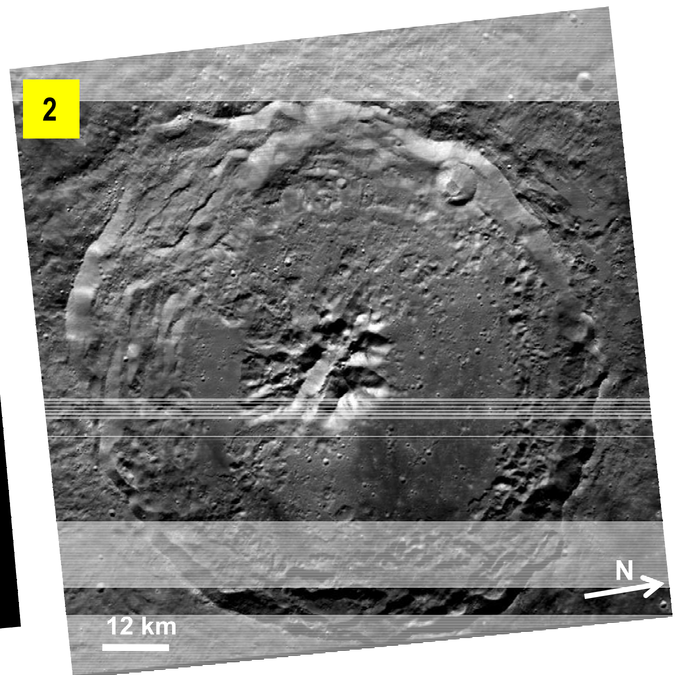



23 km
3

Theophilus : Large scale exposure of a new Lunar Mineral

Theophilus is a classic example of complex impact crater. It is of about 100 km in diameter and is located to north-west of the Mare Nectaris basin on the near side of the Moon. The crater has a well developed central peak with steep and terraced walls. The central peak of the crater is of ~ 3 km height and exposure of deep seated inner crustal material have been found on this peak. The crater is highly diverse in terms of mineralogy which is best exposed on the central peak. A new mineral Mg-Spinel has been detected using spectroscopic data of M3 instrument. The reflectance spectra of Mg-Spinel is identified on the basis of characteristic absorption around 2 micrometer wavelength and a lack of 1 micrometer absorption.





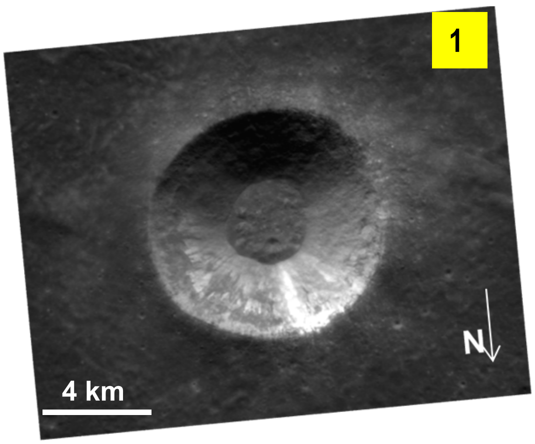
1. 3D color composite (1009 ,1249 & 2000 nm bands) view of the Theophillus crater from M3 sensor. Yellow color represents exposures of Mg-Spinel whereas pink color represents crystalline plagioclase exposures. Terraced walls of the crater is clearly visible.

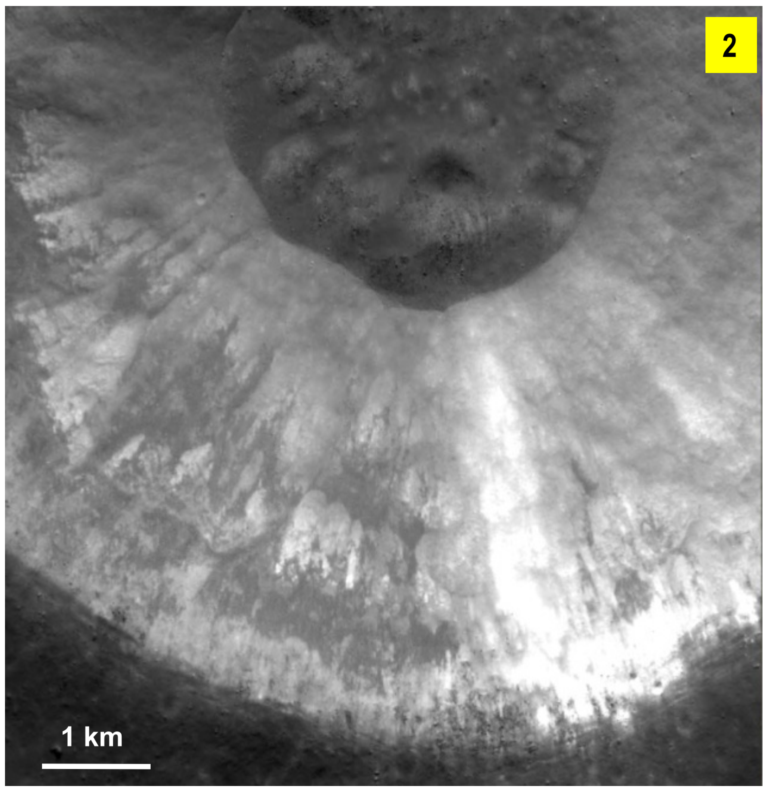
2. Albedo image of the crater at 750 nm wavelength

Letronne F: Fresh Impact crater

High resolution data from Terrain Mapping camera (TMC) at 5m resolution has imaged detailed morphology of many small and relatively young lunar impact craters. Young impact craters are immature craters and have been characterised by bright appearance having high albedo, sharp rim and contains fresh rock exposures. Due to interaction of lunar surface with solar wind and micro-meteoritic bombardment lunar soil becomes darker and black. Such surfaces are called mature and losses their spectral absorption properties. This process also known as space weathering is responsible for turning the freshly exposed surface to dark mature surface with time. The fresh impact craters expose the buried original subsurface bright material and are therefore, important in studying the original lithology of the Moon.

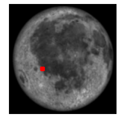
Letronne F is ~8 km diameter crater situated in the Oceanus Procellarum on the near side of the Moon. This crater is an example of fresh crater. Debris flow and the slumping of the loose material is one of the prominent process observed using TMC images. The loose material has flowed down the slopes of the craters and deposited on the crater floor. The TMC image presented below of Letronne F crater provide glimpse of the debris flow or slumping of material from crater wall.



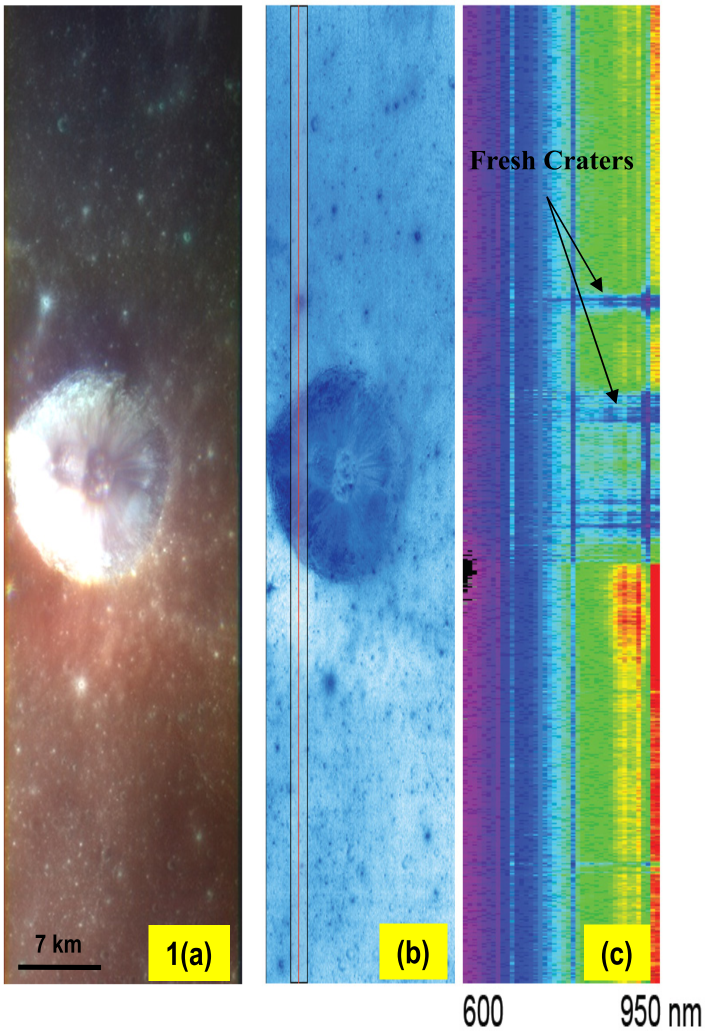


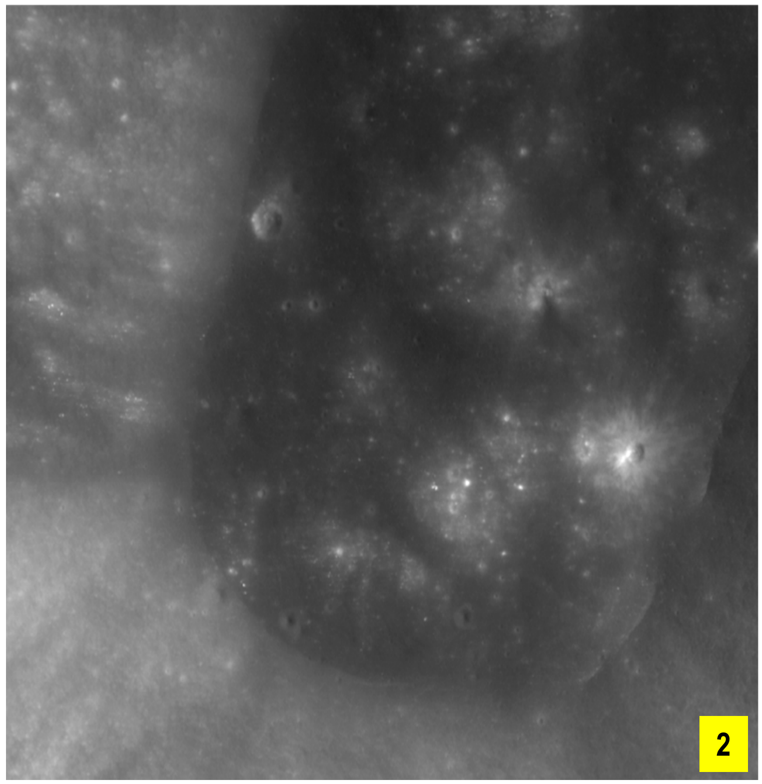
1. TMC image of fresh impact crater Letronne F situated in Oceanus Procellarum on the near side of Moon.
2. Bands of grey and white shades showing debris flow on the crater wall in high resolution mode.

Damoiseau E : Fresh Impact crater



Crater Damoiseau E is another example of fresh crater situated west of Oceanus Procellarum and just north of the main Damoiseau crater on the near side of the Moon. The reflectance values in the spectral region of 700 to 950 nm shows reduction due to presence of iron bearing minerals as shown in Figure 1 (c) of HySI data. This spectral information provides clues about the immaturity or freshness of the impact crater.

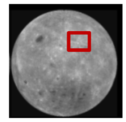




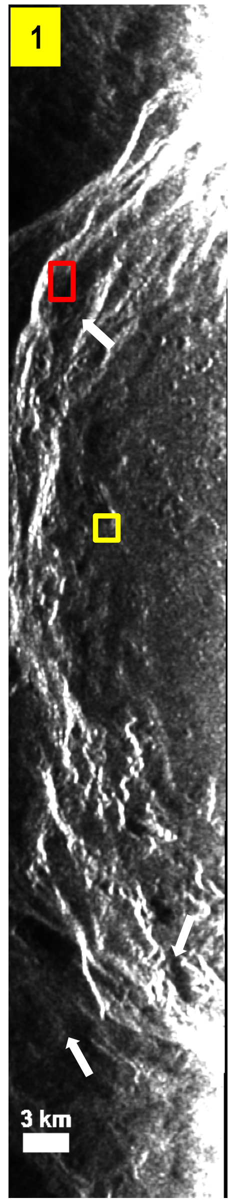
1. (a) Color composite of HySI data for Damoiseau E crater, (b) ratio of 750/950 nm bands of HySI data darker tone showing presence of fresh lunar material, (c) spectral plot for reflectance in 600 to 950 nm bands.

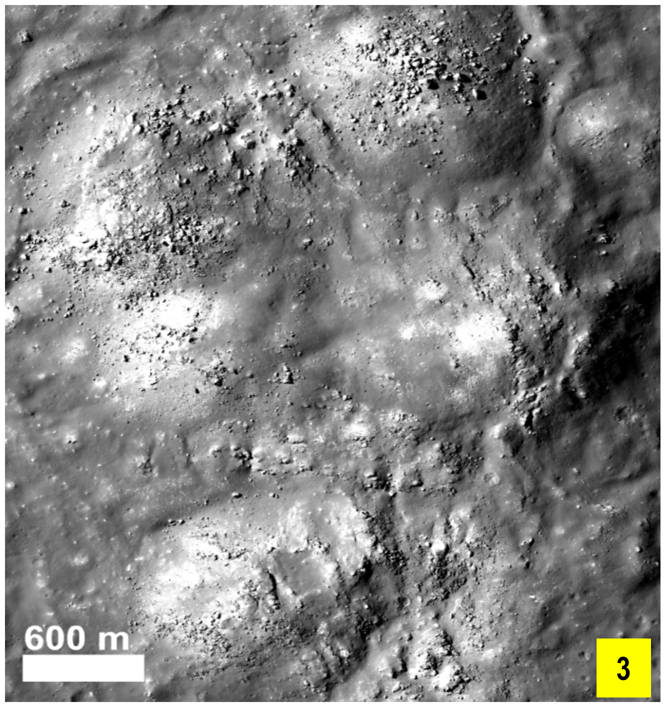
2. TMC image of the crater floor showing small young impact craters

Jackson: Fresh Impact Crater observed from Mini-SAR



Jackson crater is one of the most significant features in the northern hemisphere of lunar far side. Bright rays originated from Jackson crater streak for hundreds of kilometers across the lunar surface. Jackson crater is a classical example of a large fresh crater containing abundant surface rock population that gave rise to very high backscatter and Circular Polarization Ratio values in Mini SAR data. Along with abundant few-centimeter scale surface rocks, the ejecta deposits surrounding Jackson crater consist of a heterogeneous distribution of impact melt ponds. These features are revealed in great detail by the Mini-SAR and the corresponding high resolution optical imagery.

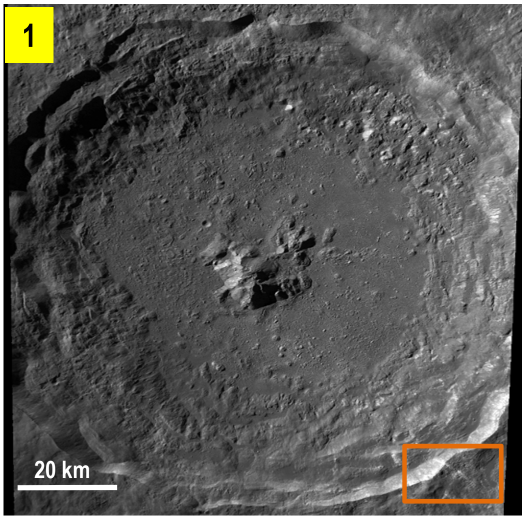


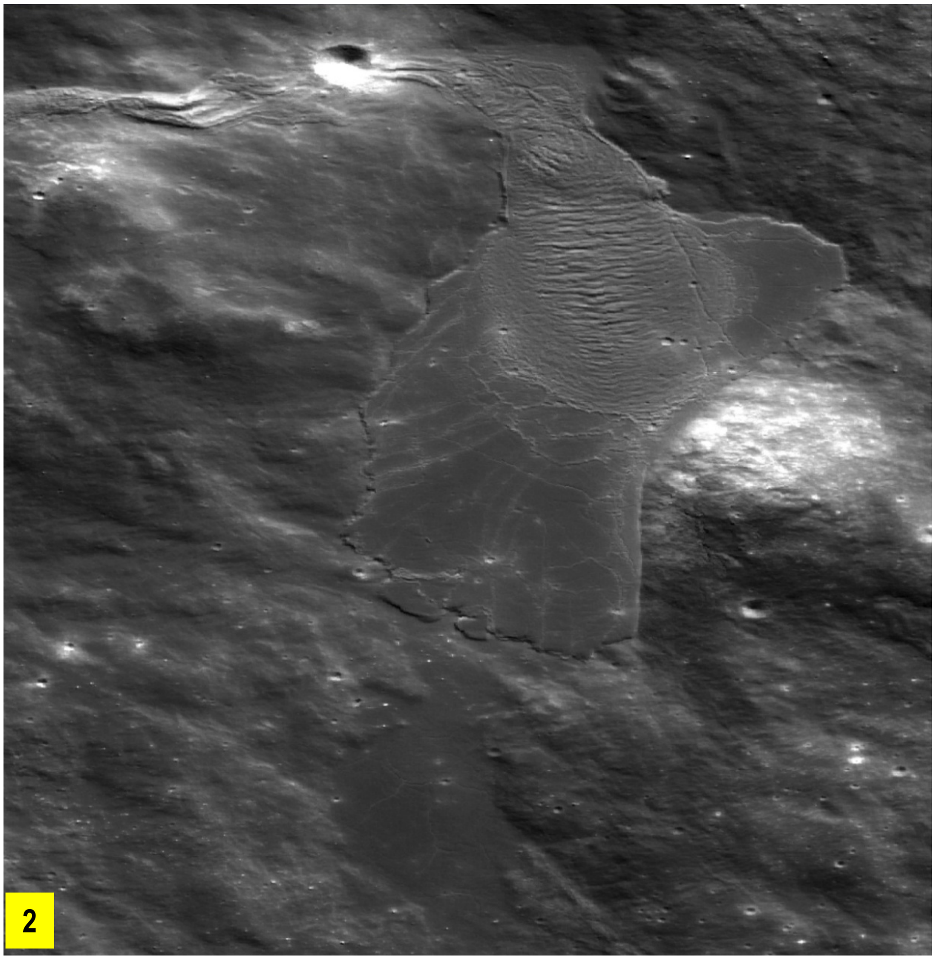


1. Jackson crater as seen by the Mini-SAR in total backscattered power image. The impact melt ponds can be seen as dark patches in the radar image indicated by arrows. The positions of Fig. 2 and 3 are marked by red and yellow boxes, respectively.
2. Optical image shows terraced walls and shadows formed inside the crater. Easily visible impact melt ponds and flow directions within the crater cavity are marked with arrows.
3. Portion of another optical image shows the highly disrupted interior of the crater.

Impact Melts: Tycho Crater

Impact melts are completely molten material produced by the shock waves generated during large impacts on lunar surface and are mixtures of pre-existing target materials. Such impact melts encompass completely non-crystalline glassy texture. Below is an example of an impact melt flow captured in TMC image of south-eastern rim of the Tycho crater. The melt generated has flowed down and deposited in a depression. A small impact crater overlying the flow feature suggests the flow has happened much before the formation of this small crater which is younger than the flow feature. The flow feature exhibits wrinkles or ropy texture suggestive of the less viscous nature of the flow.

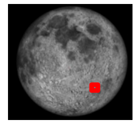




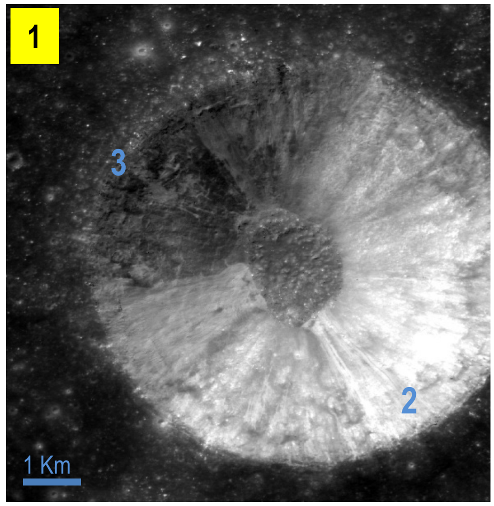
1. TMC mosaic of the Tycho crater. Orange box represents the location of figure 2.

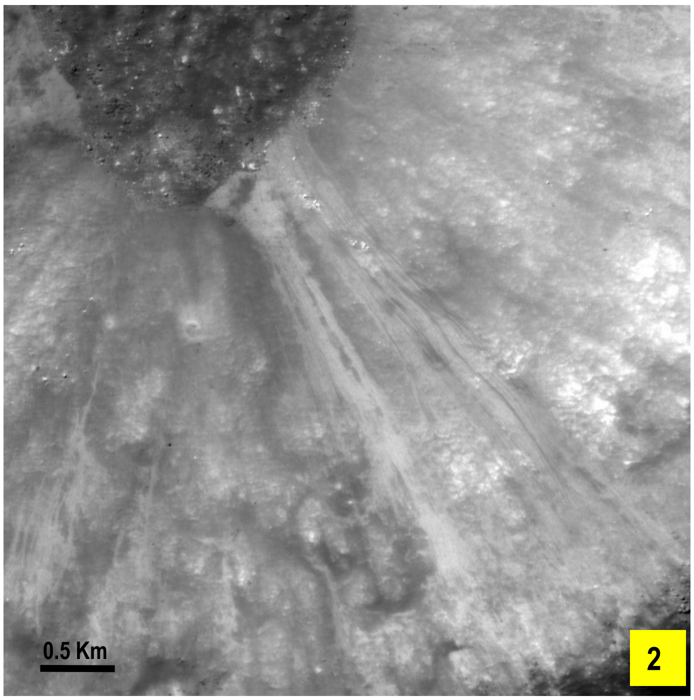
2. Image showing impact melt flow feature present near the south-eastern rim of the Tycho crater captured in TMC image.

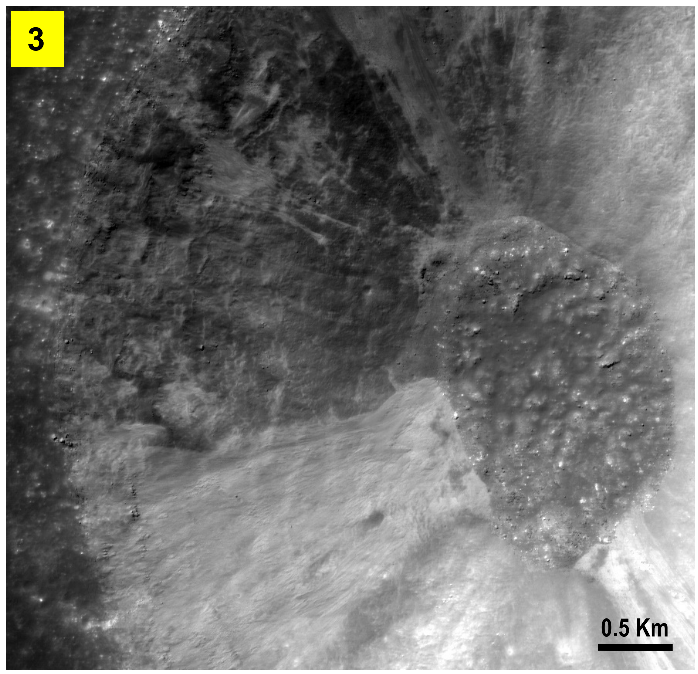
Piccolomini F: Fresh Impact crater with impact melt



Piccolomini F crater is a fresh impact crater with circular rim and circular floor situated south of Mare Nectaris on the near side. The crater has a diameter of ~7 km. TMC image of this crater shows presence of impact melt flows on the crater walls. The impact melt has mixed with the bright and dark material and flowed down the walls of the crater forming streaks of grey and dark tones. The mixed material has collected as a fan deposit near the floor of the crater thereby modifying the circular shape of the crater floor.



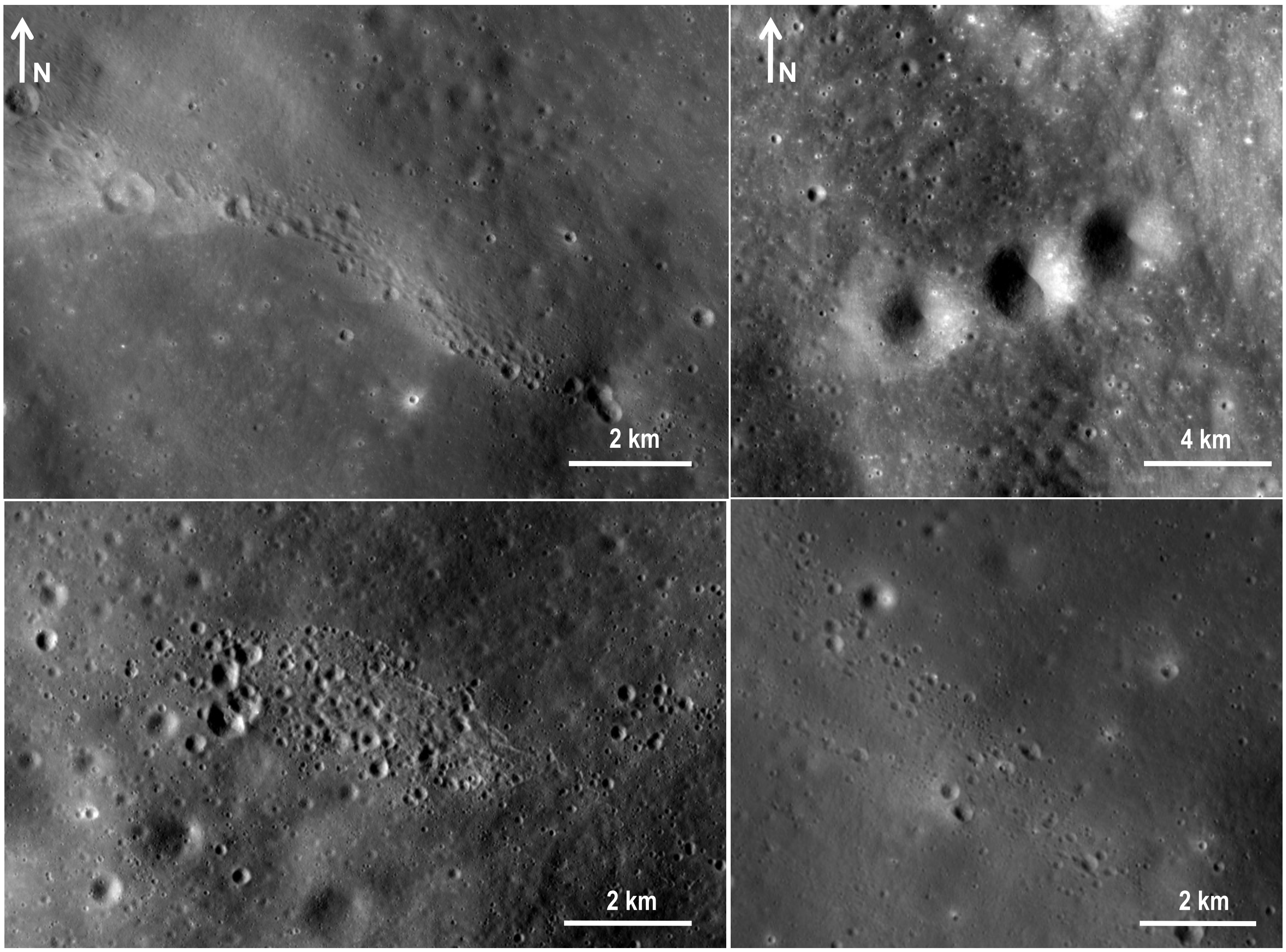




1. TMC image of fresh impact crater Piccolomini F situated south of Mare Nectaris on the near side of the Moon.
2. Linear streaks of impact melts flow on the crater wall.
3. Impact melt deposition on the crater floor.

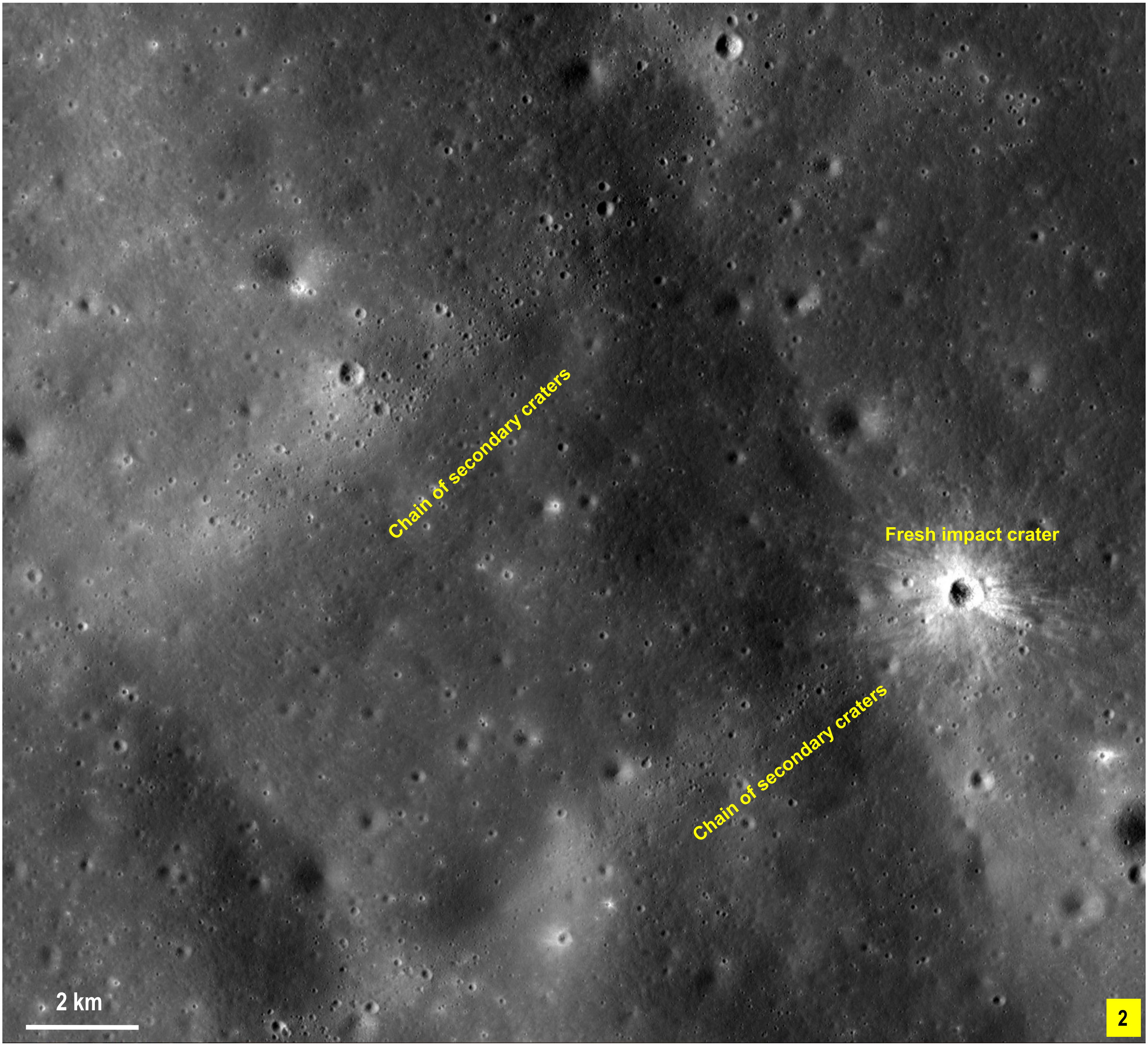
Secondary Craters

Secondary craters are formed by the ejecta from large primary impact craters that fall far from the parent crater. These craters radiate away from the point of the main impact. Secondary craters often form chains or found in clusters.

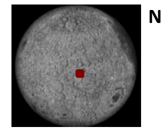


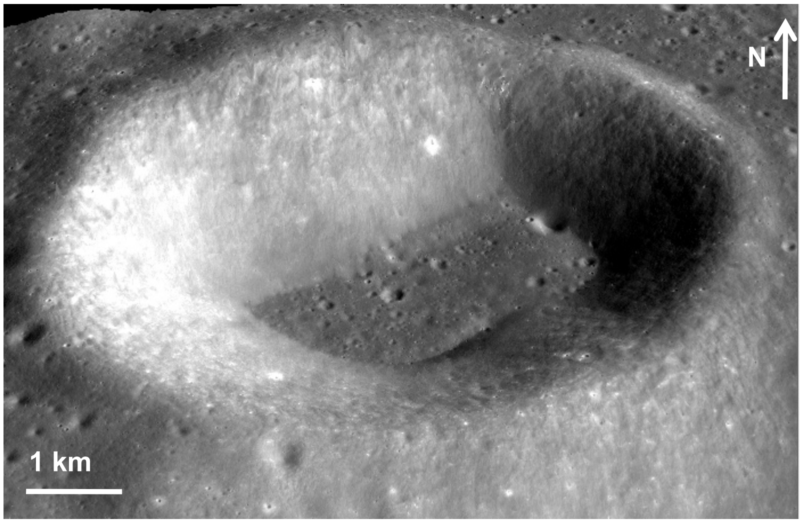
1

1. The above TMC image shows linear chains and clusters of secondary craters from a highland region just above the Orientale basin on the far side of the Moon.
2. High resolution image of linear chain of secondary craters. The lower part of the image shows a fresh impact crater with the associated chain of secondary craters possibly formed by the ejecta of the fresh crater.


Chain of secondary craters
Fresh impact crater
Chain of secondary craters
2 km
2

Unusual shaped Impact Craters

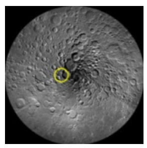




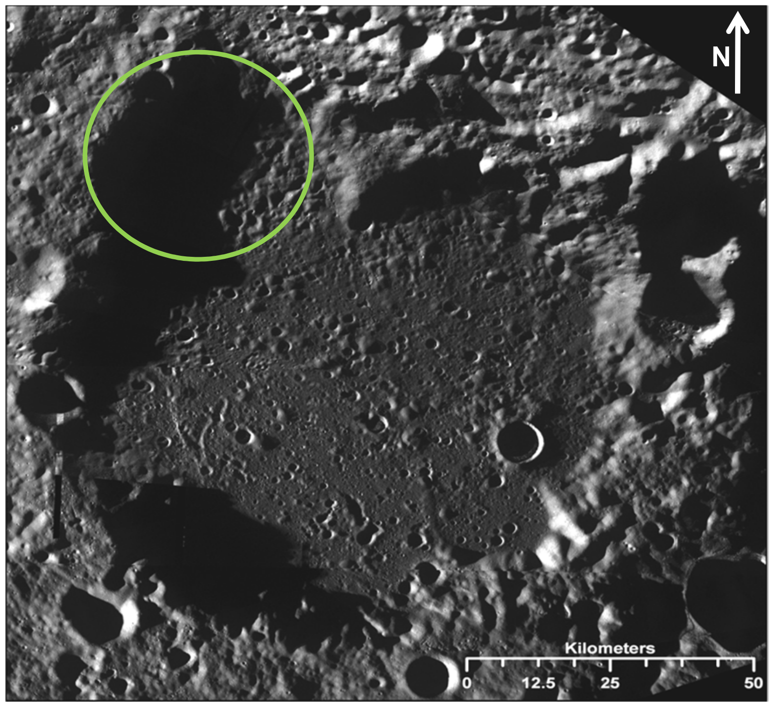
An unnamed crater

This is an unnamed crater situated on the far side of the Moon at 14°N 221°E just below a large crater Kekulé. The crater has an unusual elliptical/elongated shape. This type of craters have been produced due to low-velocity oblique impact. When the impact angles are less than 10 degrees, the craters will be of asymmetrical shape and become elongated. The floor of this crater is relatively leveled and many tiny craterlets have pitted the floor. No signs of fresh material, slumping and debris flow and other features associated with a fresh carter have been noticed, suggesting that the crater is old in age.

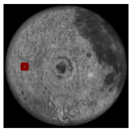
Hermite crater



Hermite crater of ~104 km diameter is situated near the north pole of the Moon was first discovered in 1964 and recently this crater has been mentioned by NASA as the coldest place recorded in the solar system with temperature at around 25^{0}K. The shape of this crater place it in the category of unusual craters. The crater floor has been modified or resurfaced by a large number of impacts creating tiny craterlets and low hills. The peculiar shape of this crater have been formed due to the merging of an old eroded crater (marked by circle) that overlies the south-western rim. The two craters have been merged to form a single crater giving rise to its unusual shape.



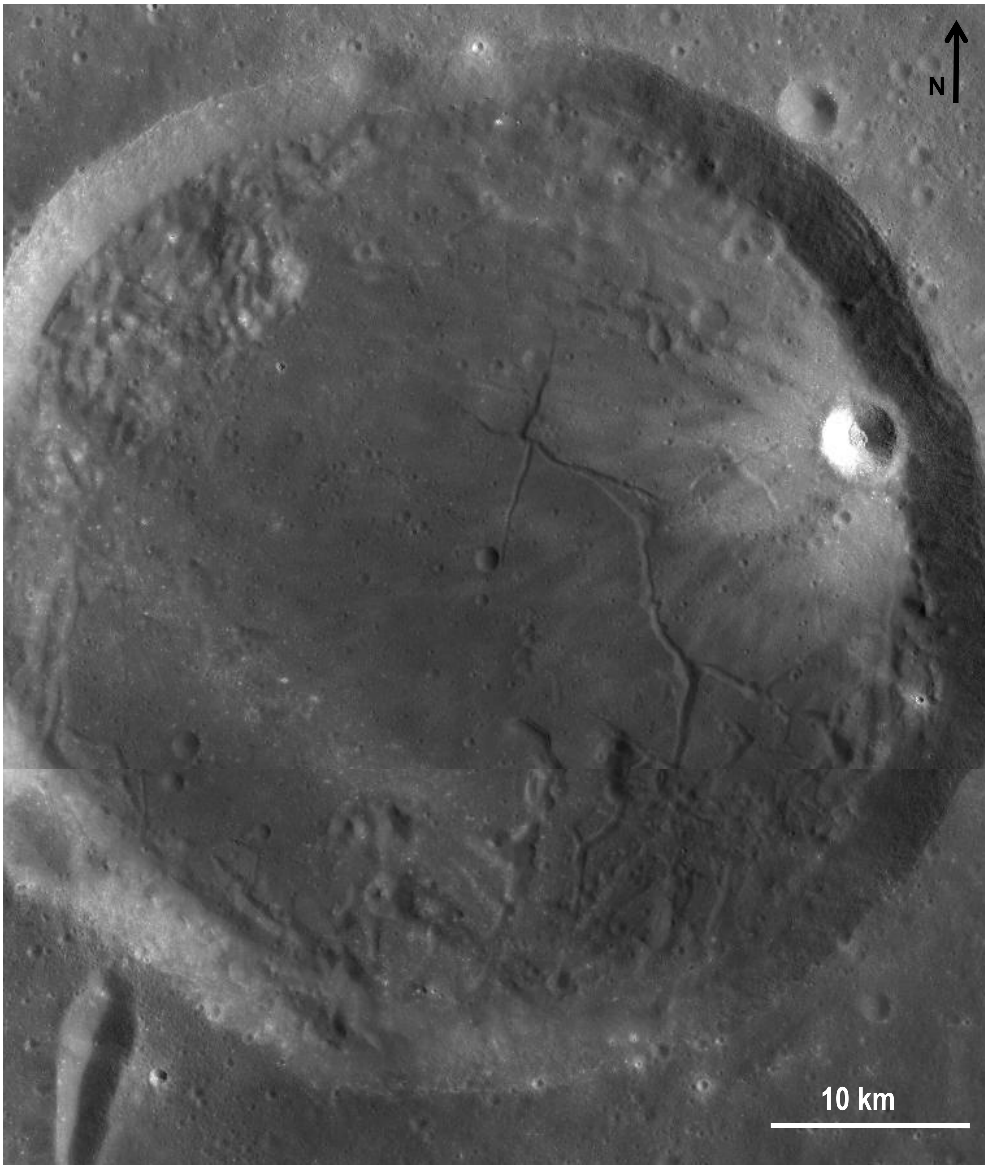
Unusual shaped Impact Crater



Kopff Crater

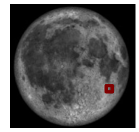
This crater is an example of floor-fractured unusual crater. Such type of craters generally occurs along the margins of the basins. Kopff Crater lies along the eastern edge of the inner Mare Oriental impact basin. The crater has ~40 km diameter with no central peak, no wall terraces, an unusual rim shape, and no apparent secondary craters. Kopff crater is supposed to have formed from an impact into partially molten material that was later volcanically modified.

The southeast part of the floor is fractured with a series of narrow rilles. Shock waves generated during impact creates zones of weakness. The magma underneath the crater floor exerts sufficient pressure that leads to rapture or failure of the floor, thus creating these fractures.

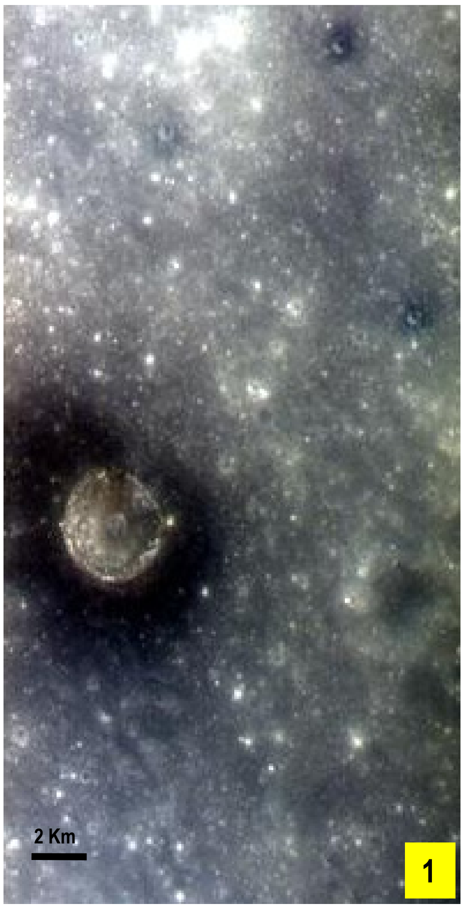


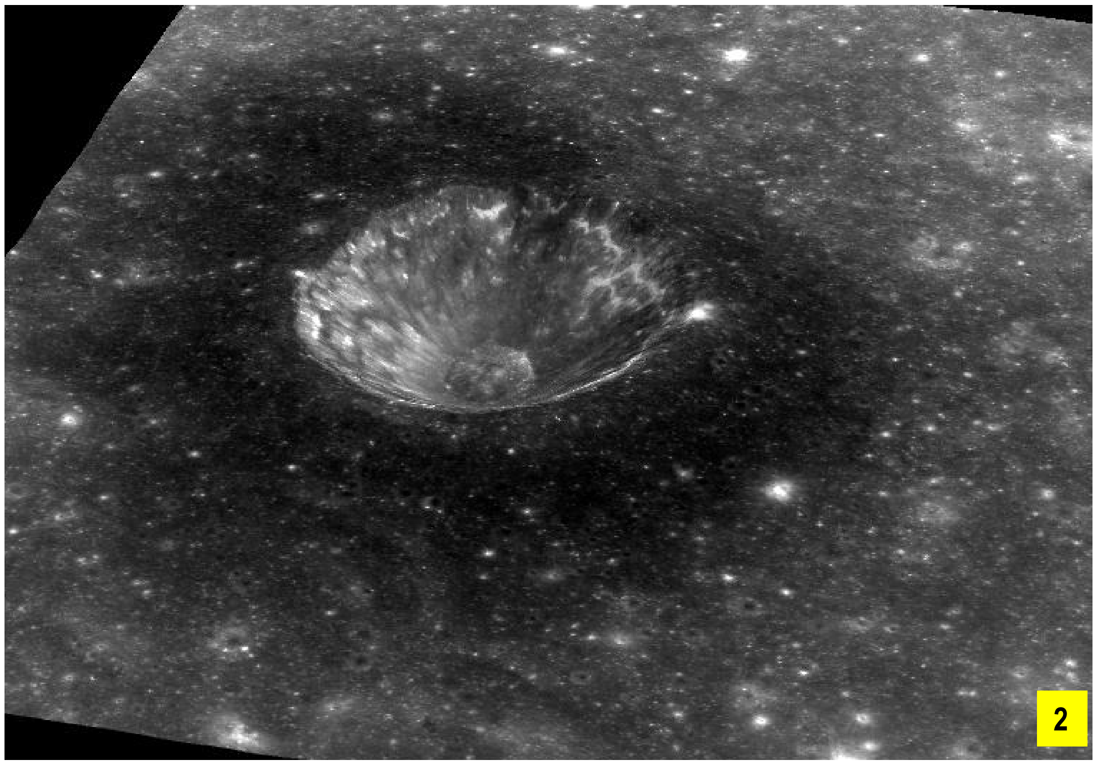
TMC image of Kopff crater

Dark Haloed Craters : Beaumont-L

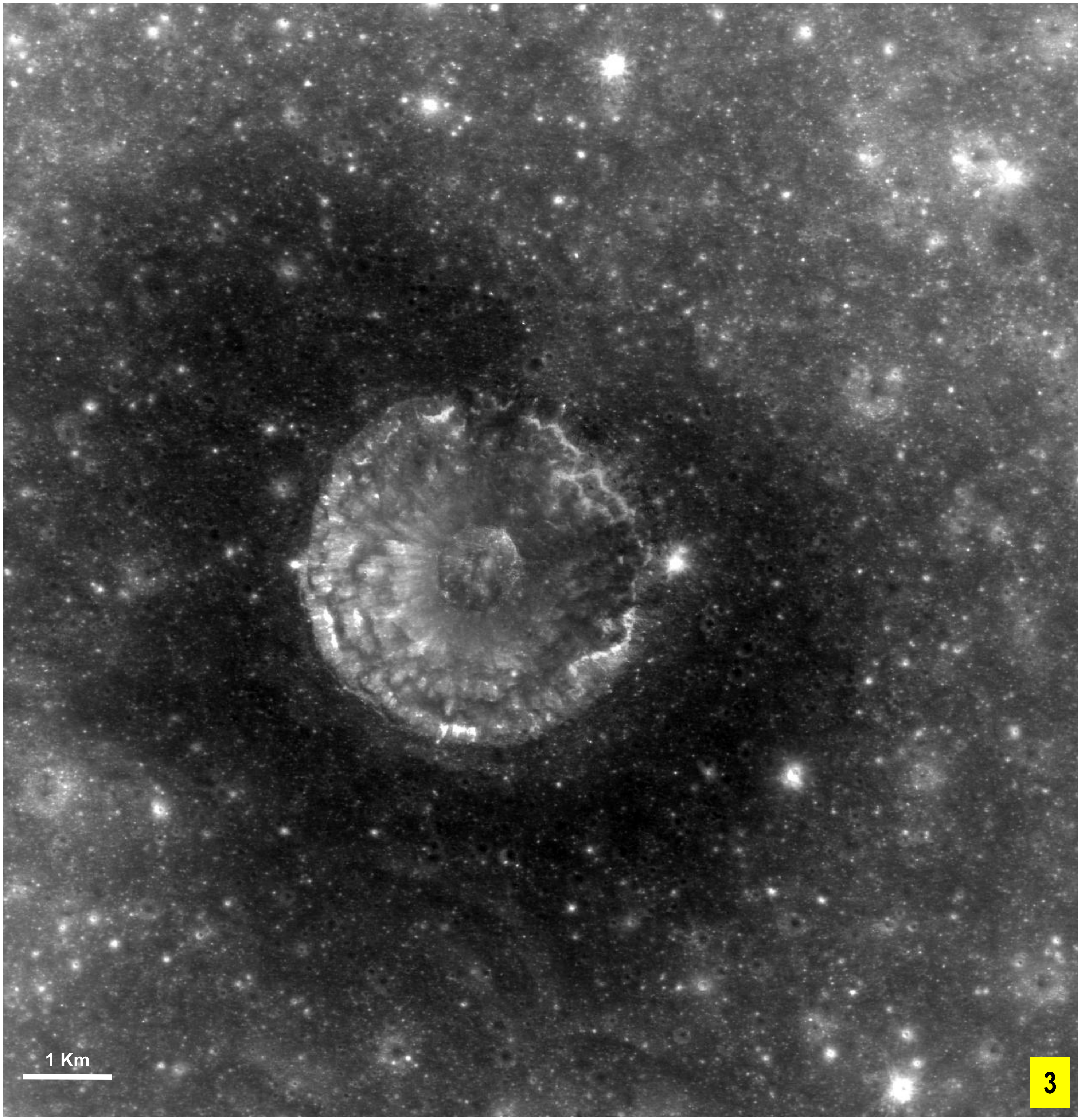


Early observations revealed presence of some atypical crates surrounded by deposits of low-albedo material interpreted as ash deposits surrounding volcanic vents. Later studies suggested that such craters show existence of buried or hidden mare deposits. Beaumont-L is one of dark halo crater situated on the western flank of Mare Nectaris and has been noted first due to its anomalous color during Apollo-14 mission and later on from Chandrayaan-1 HySI data. The morphological details captured by TMC data suggest that Beaumont-L is of impact origin. The low albedo material surrounding the crater must have been resulted due to excavation of mare basalt from beneath the lighter deposits, emplaced by ejecta of Theophilus and Madler crater located in the close vicinity of Beaumont-L.

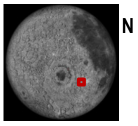




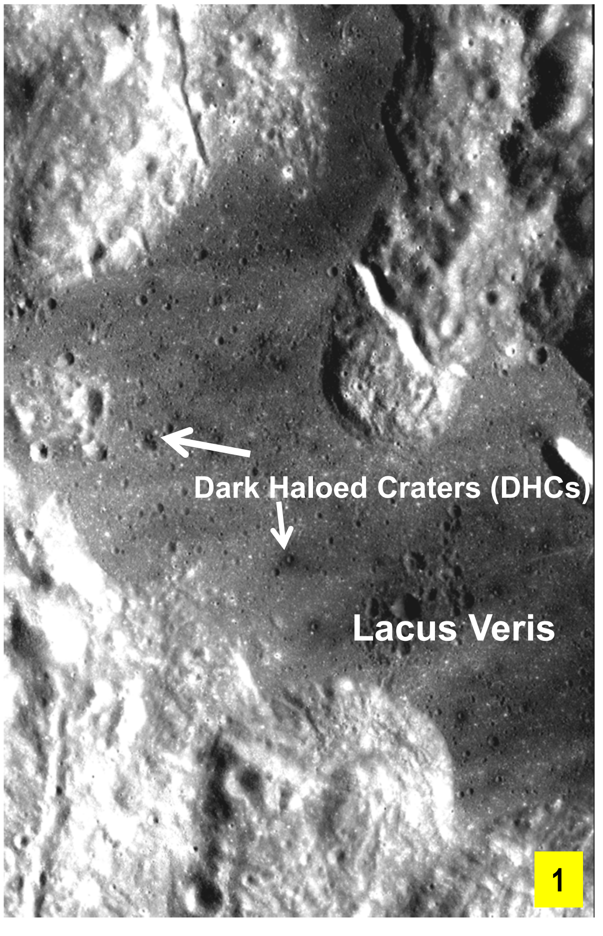
1. Color composite of HySI data showing brown colour anomaly around dark haloed crater Beaumont - L
2. Three dimensional view of Beaumont-L using TMC data showing raised rims, terraced walls and circular floor suggesting impact origin of this crater.
3. High resolution view of the crater using TMC data.


1 Km
3

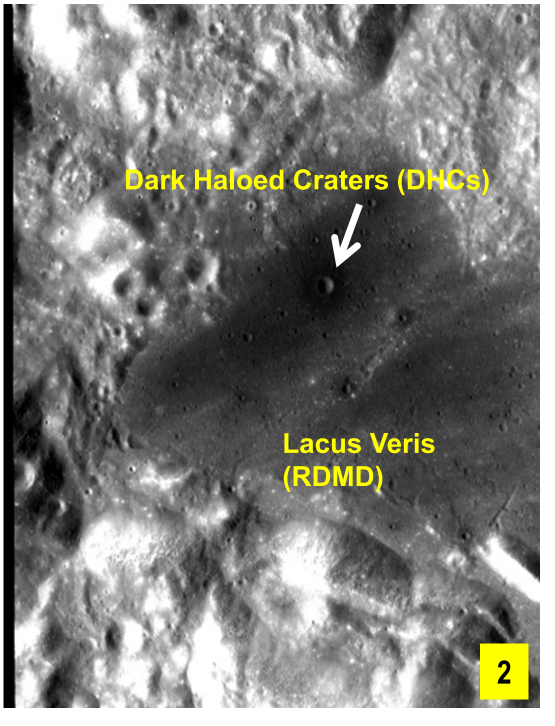
Dark Haloed Craters & regional dark mantling deposits in Mare Orientale



Dark mantle deposits (DMDs) refer to diffuse deposits having very low albedo than mantle mare and highland regions. The low reflectance of the regional DMDs are due to presence of volcanic beads having high iron (Fe) and titanium (Ti) content. The localized DMDs tend to concentrate on crater floors in association with small pit craters aligned on linear rilles, while the regional DMDs are located adjacent to the major basins and are superimposed on the older mare and highlands. Dark mantling areas were formed by the process of **'fire fountaining'**, jet like sprays of molten lava. Gases like carbon monoxide or carbon dioxide trapped in the lava act as propellants and shoot the lava high above the surface forming glass beads. These glassy beads on falling to the ground produce large patches of 'dark mantling'.

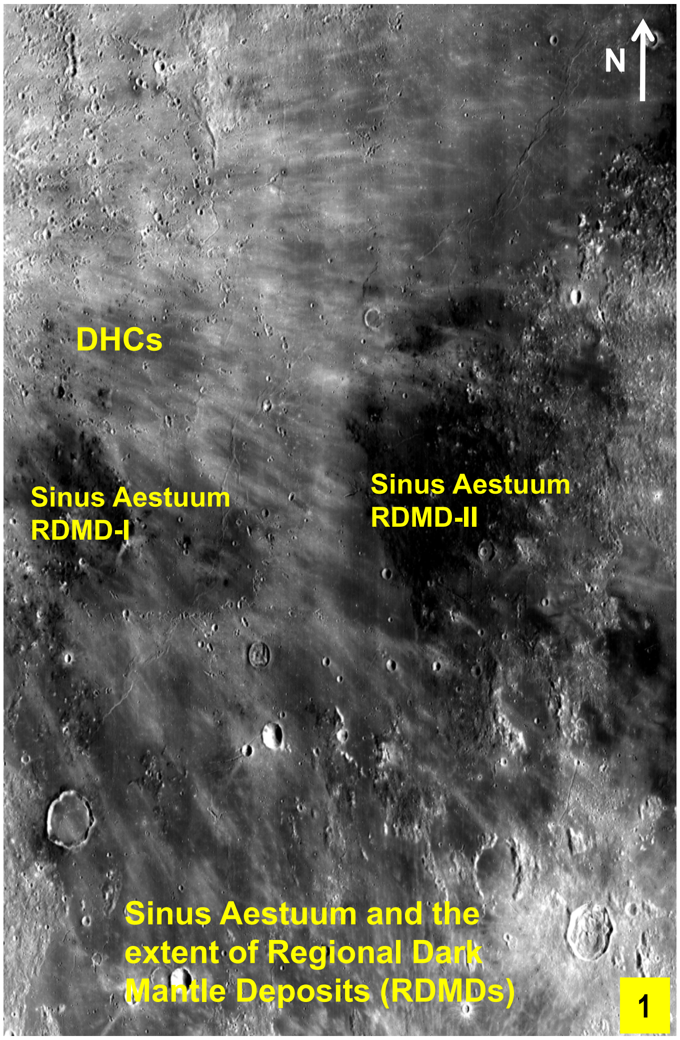


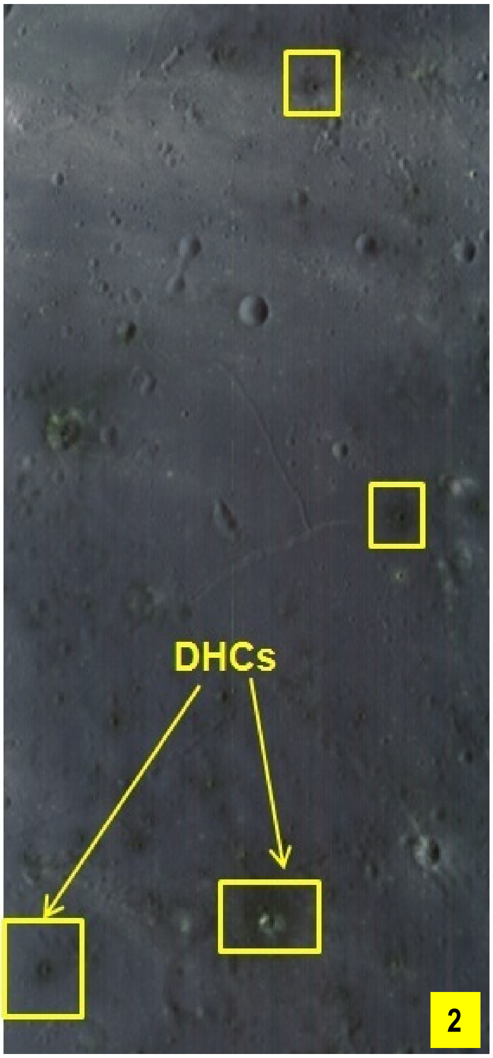
1 & 2 : Lacus Veris region on Moon enclose the basalt patches that were emplaced along the base of the Outer Rook Ring formation of Mare Orientale basin. TMC images of the Lacus Veris showing dark-haloed craters surrounded by low-albedo dark material and the regional dark mantled material.



Regional Dark Mantle Deposit (RDMD) of Sinus Aestuum

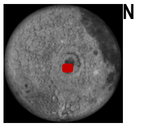
Sinus Aestuum regional DMDs are scattered around the southern edge of the Aestuum basin. It consists of two large dark mantle deposits namely Sinus Aestuum I and Sinus Aestuum II. Sinus Aestuum I DMD extents is ~90 km and is situated on small highland hills. Sinus Aestuum II DMD is located 130 km to the east of Sinus Aestuum I DMD. Crater ejecta and rays from the nearby Copernicus crater located northwest of the image have blanketed the whole region.

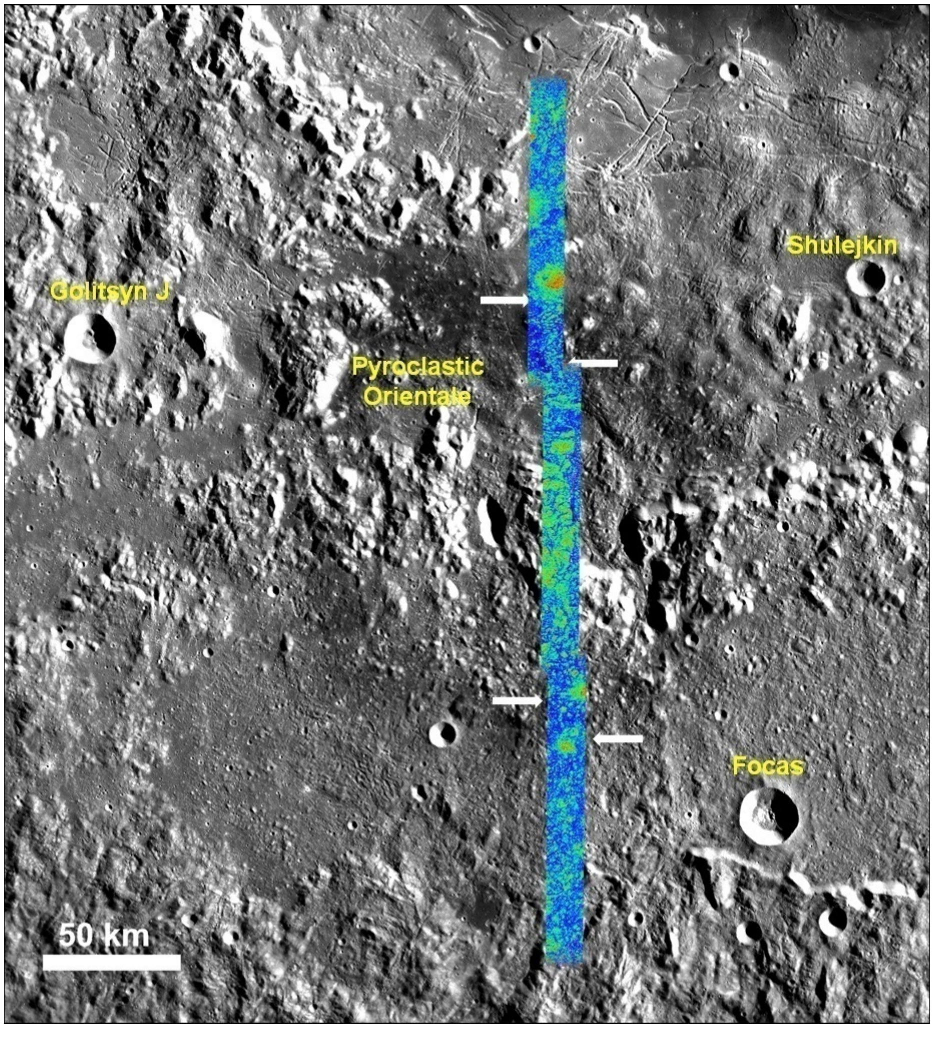




1. M3 mosaic of the Sinus Aestuum showing extent of the regional DMDs and dark haloed craters in the region.
2. Close view of the dark haloed craters using M3 False color composite (R = 1009 nm, G = 1249 nm and B = 2000 nm).

Pyroclastic Orientale ring seen in Mini SAR data





The Pyroclastic Orientale deposit is about 154 km across, lies on the southwest side of Orientale basin. These dark Pyroclastic ring deposits were found to have low backscatter and low circular polarization ratio (CPR) values. This indicates that the Orientale pyroclastic deposits are smooth at the S-band wavelength of the Mini-SAR radar, and have few embedded wavelength-sized scatterers.

Relatively high backscatter and CPR values are observed at the southern part of the dark mantle regional deposits (DMRD), due to its significant mixing with the highlands material. This suggests that the pyroclastic deposit is fairly thick in the southern portion.

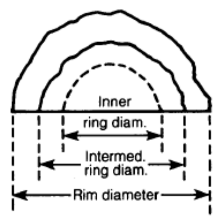
Part of an Orientale mosaic showing the Pyroclastic Orientale ring. The Mini-SAR Circular Polarization Ratio (CPR) image has been overlaid on the optical image for geological context. The Mini-SAR strip crosses the eastern half of the ring deposit at the northern and southern edges; the approximate extent is indicated by arrows. The CPR values span the color spectrum from purple through red for values between 0.1 and 1.

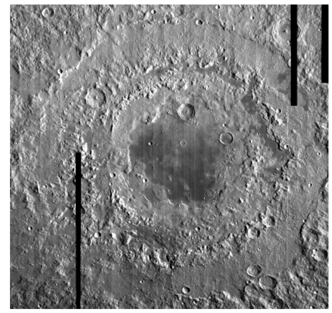
Mare Basins

03 Mare Basins: Large scale magma spill on the Moon

The dark-colored flat plains visible on the Moon are called Mare basins which are large depressions generally > 200 km in diameter mostly concentrated on the near side of the Moon. Famous astronomer Galileo compared the smooth basins to water i.e. “oceans” and hence the Latin word “mare” was used. These basins were formed by large-volume eruptions of low viscosity basaltic lavas. Due to sharp contrast between highland terrain exposures and mafic mare basalt, the maria or the mare basins are discernable even with naked eye. Mares albedo generally range from 0.07 to 0.10, i.e. mare basalts reflect 7 to 10 percent of the incident visible light. Large basins on near side are Mare Serenitatis, Mare Imbrium, Mare Tranquillitatis, Mare Nubium, Mare Vaporum, Mare Crisium, Mare Humboldtianm, Mare Nectaris, Mare Frigoris and Oceanus Procellarum. Far side of the Moon, however, encompass less basins like Mare Moscoviense, Mare Ingenii, Mare Marginis, Mare Smythii, Mare Orientale and Mare Australe.

Multiring Basin

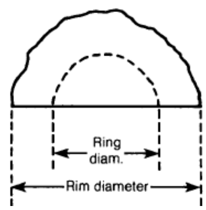


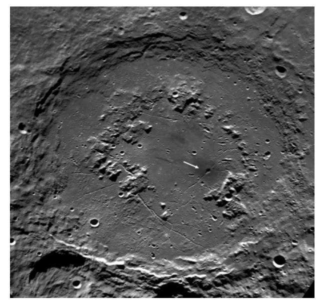


Orientale Basin

Impact basins have been divided into three morphological types: *Central peak basins*, such as Compton are relatively small basins with a fragmentary ring of peaks surrounding a central peak and occur in the 140–175 km diameter range and are transitional to peak-ring basins. *Peak-ring basins,* which have a well-developed ring but lack a central peak, are found in the 175–450 km diameter range; a well-known example is the Schrödinger Basin. The largest basins are *multiring basins, which have as many as six concentric rings and* are generally more than 400 km in diameter. The perfect example is the Orientale Basin.

Peak Ring Basin

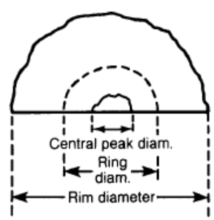


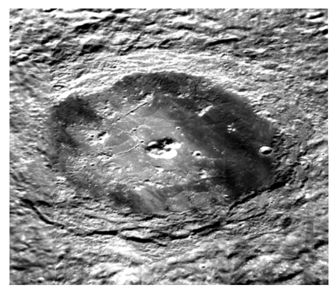


Schrödinger Basin

Mare basins hosts many morphological features and landforms like sinuous rilles, mare domes, types and number of small impact craters, dark-haloed craters, pyroclastic deposits, wrinkle ridges etc. which provide clue of the thermal and volcanic history of the Moon. Mare basins differ from each other in terms of relative age i.e, volcanic emplacement history, albedo difference, maturity, morphological landforms and slight compositional and spectral differences which are studied to know the thermal and evolutionary history of basins.

Central Peak Basin

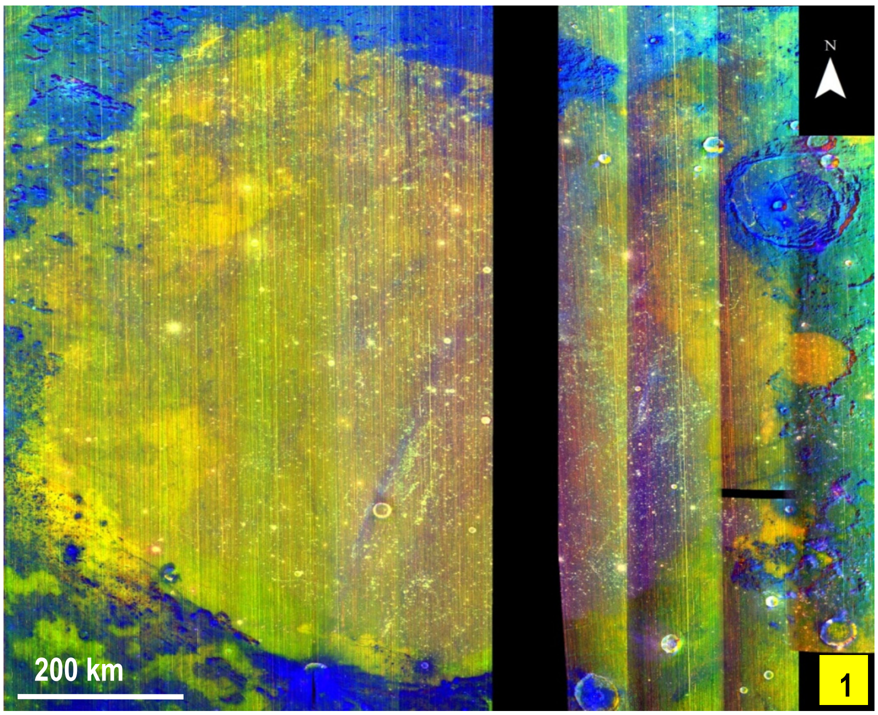


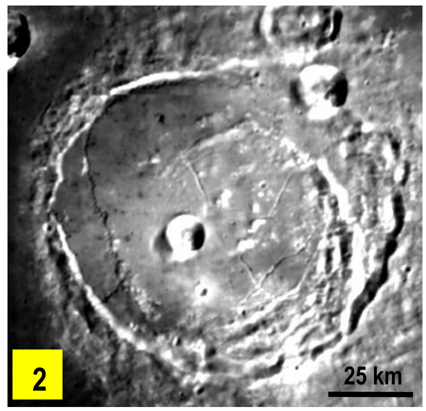


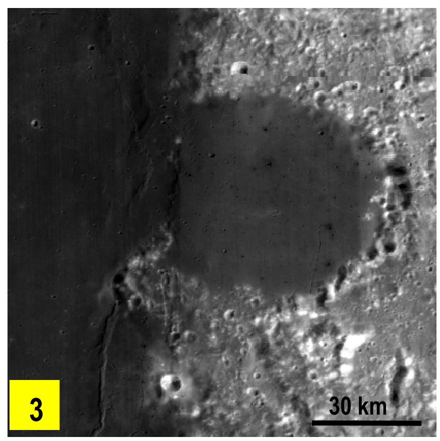
Compton Basin

Mare Serenitatis

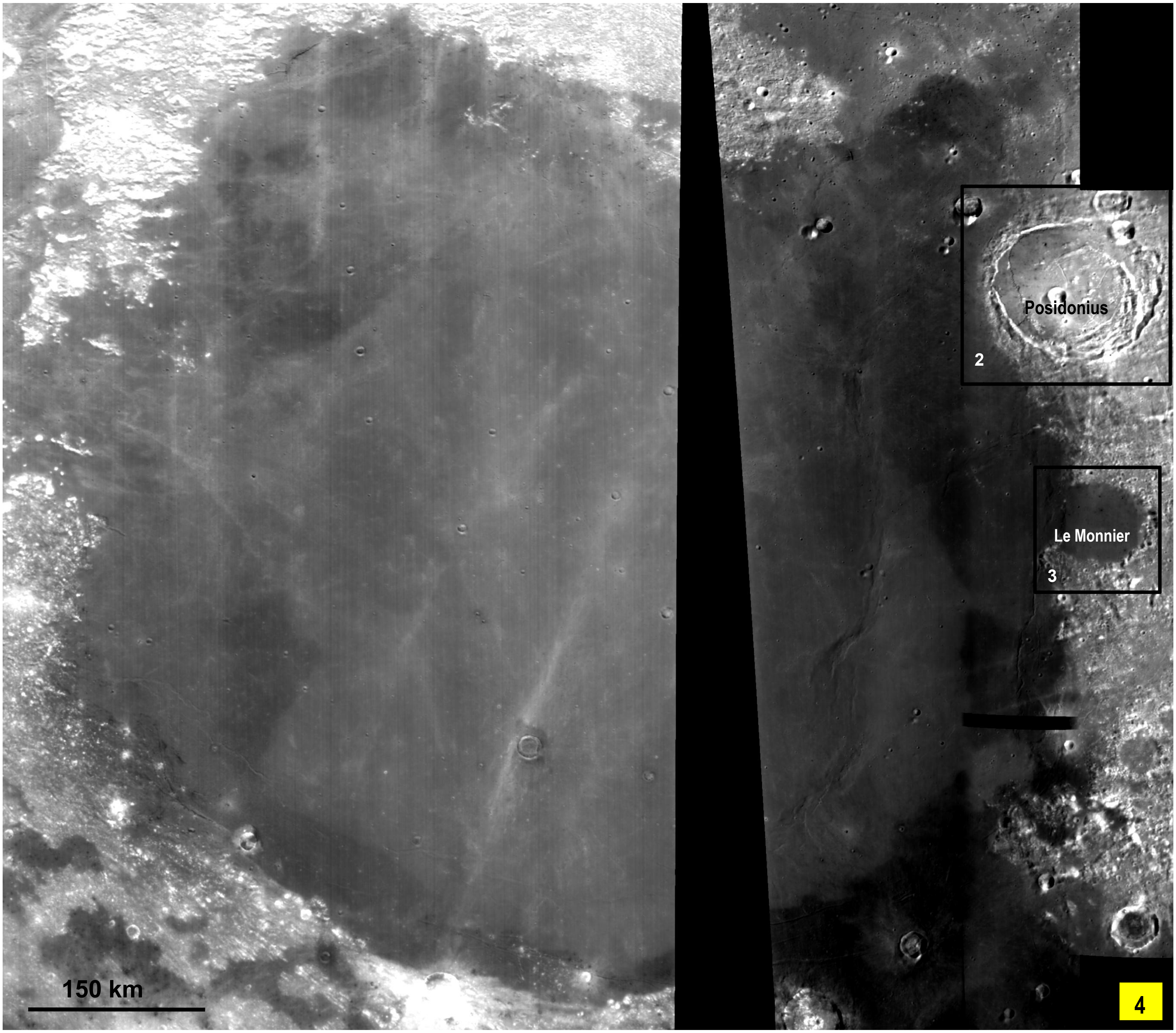
Mare Serenitatis (Sea of Serenity), is 740km diameter basin located at 27ºN, 19ºE on near side of the Moon. Samples returned by Apollo-17 mission indicated that the basin is 3.56 to 3.79 billion years old and the large part of the basin is filled with mare basalts. A valley namely Tarus - Littrow at the eastern border of Mare Serenitatis was the Apollo-17 landing site. Mare Serenitatis basin is an host of various morphological features like riles, wrinkle ridges, dark-mantle deposits and impact craters. An impact crater of 60 km diameter named Le Monnier (25º51'N, 30º27'E), completely flooded with basalt has obliterated the basin rim on the eastern side. Another impact crater of around 99 km, namely Posidonius is situated just above the Le Monnier crater. This basalt flooded crater hosts a long sinuous rille crossing north-south, a network of cross cutting fractures in the east and many impact craters peppering the crater floor.





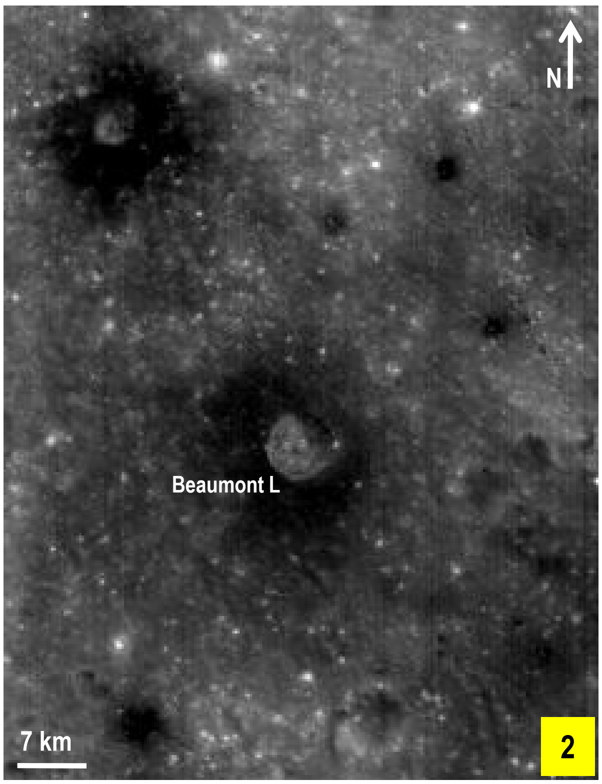


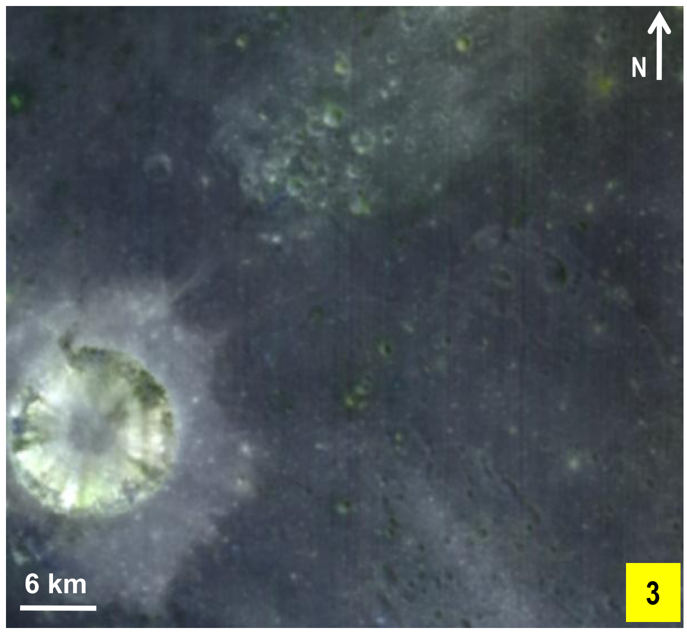
1. Mineralogical map of Mare Serenitatis – yellow color signifies basalt with pyroxenes as dominant phase and blue color signifies mafic free highland rocks.
2. Rille within flooded impact crater Posidonius
3. Impact crater Le Monnier
4. Mosaic of Mare Serenitatis


Posidonius
2
Le Monnier
3
150 km
4

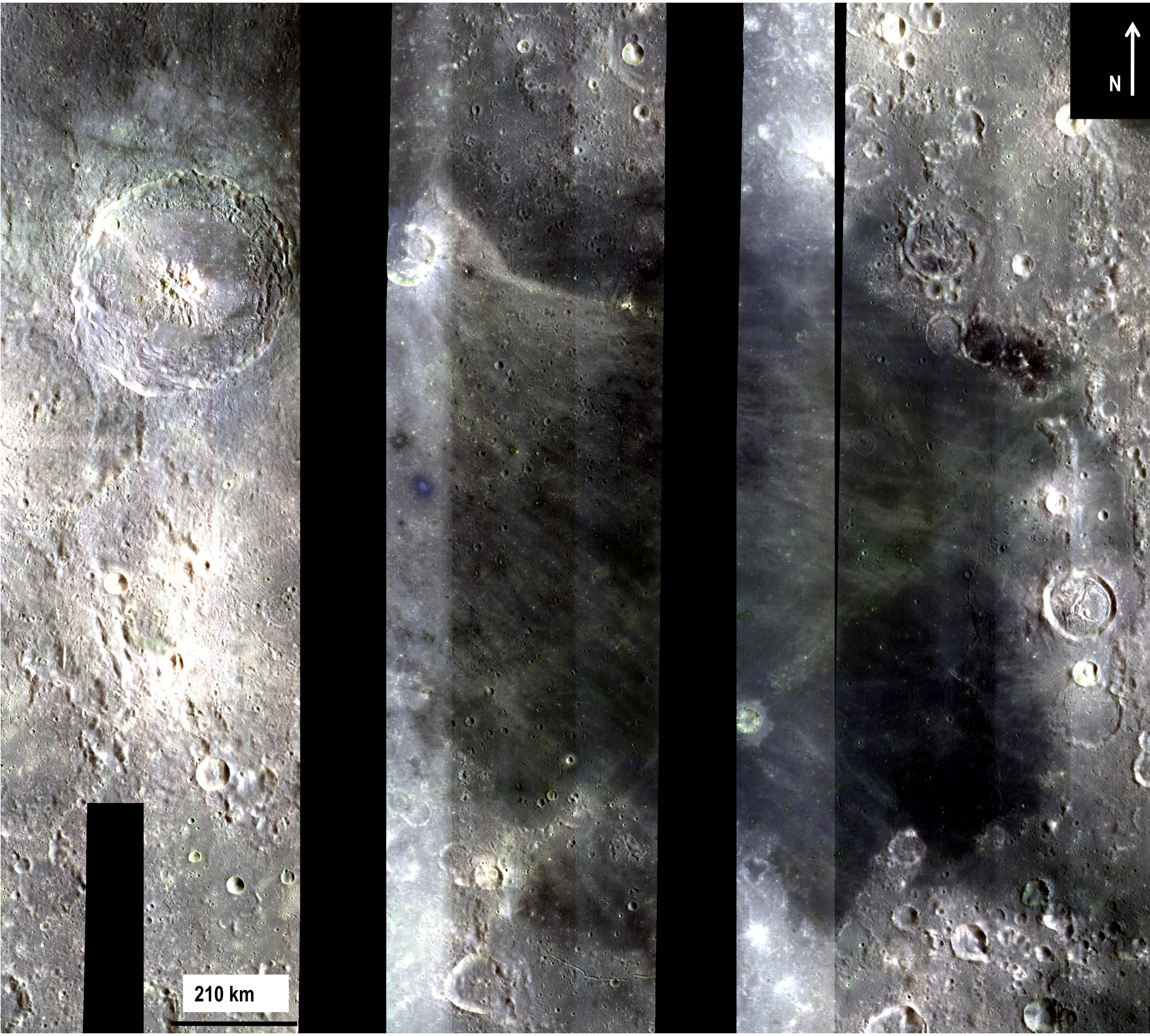
Mare Nectaris

Mare Nectaris is an multiring basin, centered at 16ºS, 34ºE which has been formed 3.92 billion years ago. The formation age of this basin defines the beginning of the Nectarian period of the Lunar Geological scale. This basin hosts a peculiar type of craters which has dark material or halo surrounds them and are called Dark-halo craters. One such prominent dark-halo crater is Beaumont-L crater displaying blue color in false color image due to presence of olivine rich material exhibiting strong absorption of light at 1000nm. The north western flank of the basin hosts large impact craters like Theophillus, Cyrillus and Madler the ejecta from these craters has formed a thin veneer covering the entire basin.

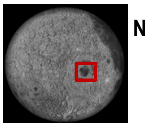




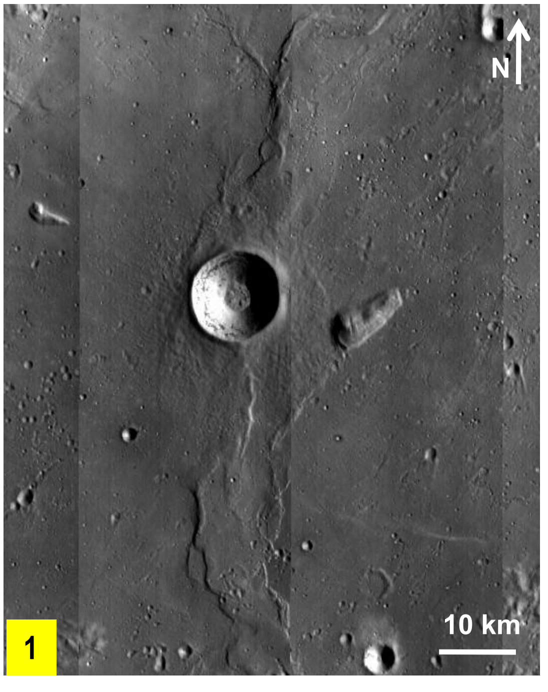
1. Color composite image (1009 ,1249 & 2000 nm bands) of Mare Nectaris as observed by Moon Mineralogy Mapper (M3) sensor.
2. View of some dark halo craters present in the Mare Nectaris.
3. A fresh crater with bright ejecta surrounding the crater. A cluster of secondary craters also present on the upper side of the image probably formed by the ejecta fragments of the near by crater. Green color is due to pyroxene rich fresh material exposed on the crater walls.

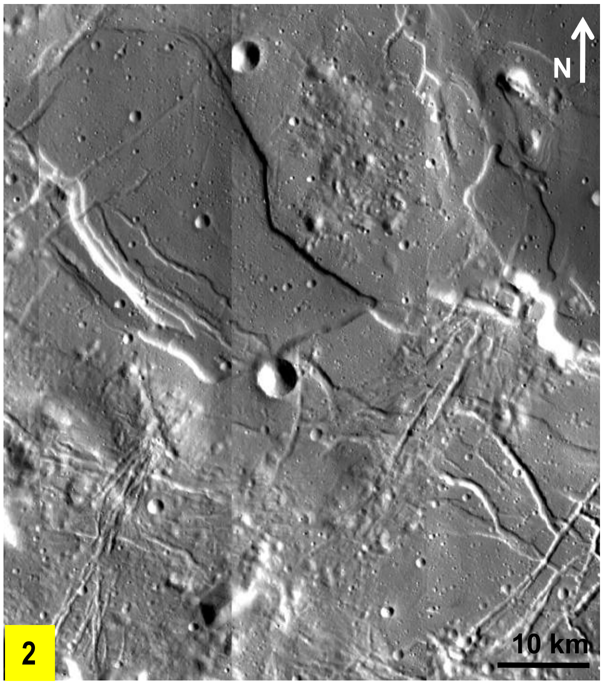

N
210 km

Mare Orientale: Multiring basin



The Orientale is a multi-ring young impact basin located on the western limb of the Moon (19°S and 93°W). Unlike most lunar basins, the interior of Orientale basin has not been completely filled with mare deposits making it particularly interesting. There are four main rings associated with Orientale Basin. The ~930 km Cordillera Mountain ring is an inward facing mountain scarp that defines the basin. The second largest ring, the Outer Rook ring, is an interconnected network of hills spanning ~ 620 km in diameter. The next innermost ring is the Inner Rook ring, ~480 km in diameter. The most interior ring is a central depression ~320 km in diameter that has been interpreted to have formed by ~3 km of thermal subsidence. The topography of the Orientale rings is well preserved which distinctly separate its various mare deposits from each other. The three large previously defined mare deposits in Orientale Basin include: Mare Orientale, Lacus Veris, and Lacus Autumni. In addition to the mare deposits located between the basin rings, there are four main deposits related to the underlying Orientale Basin: the Hevelius Formation, the Montes Rook Formation, the Maunder Formation and related plains material making this basin highly rich and diverse in morphological entities.

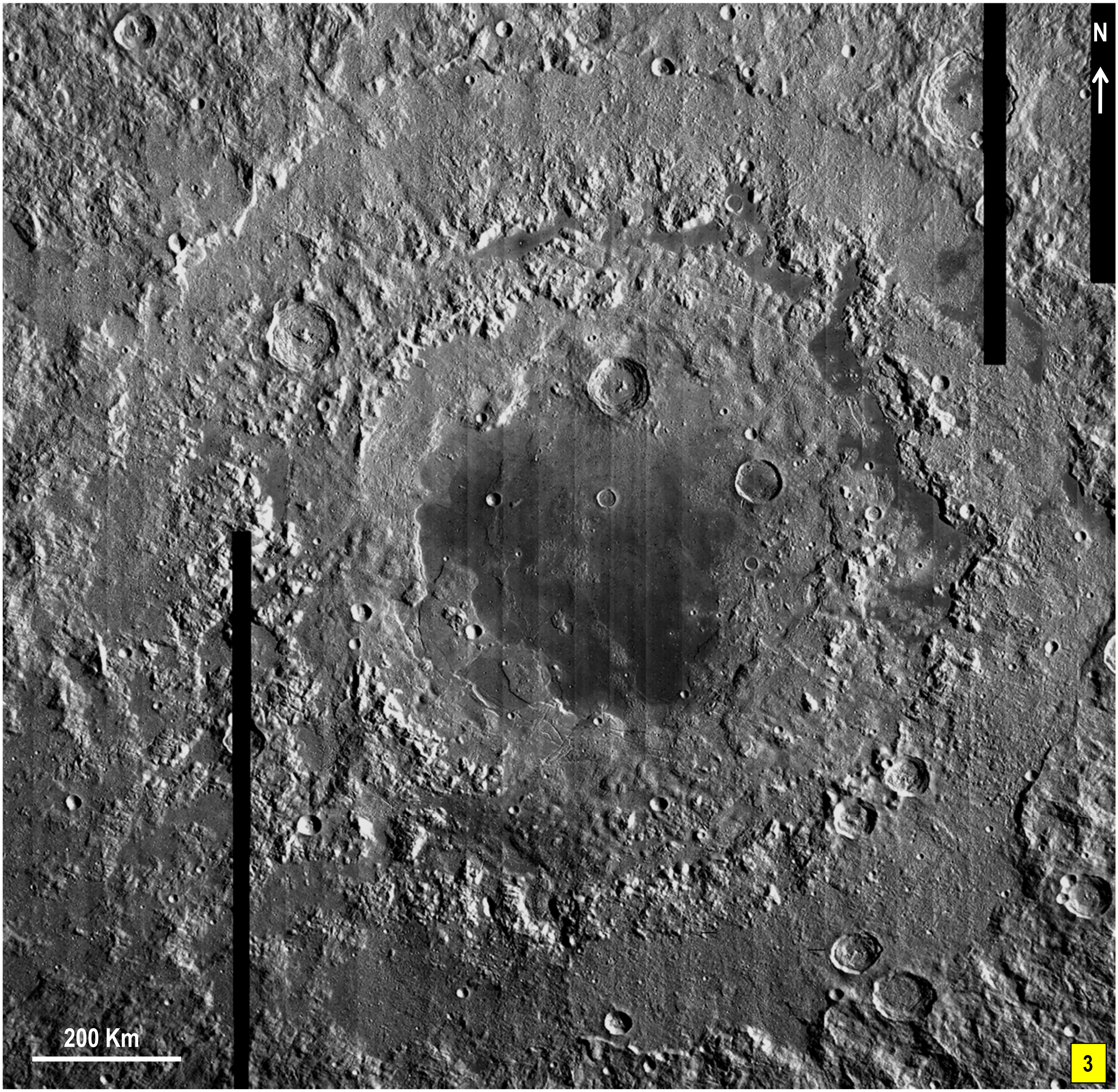




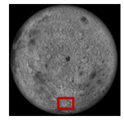
1. A ~13 km diameter crater Il'in, in northwest Mare Orientale flooded with mare and superposed on the wrinkle ridge. A small positive relief feature i.e. Kipukas (small island) protruding through the mare is also visible near the crater.

2. The polygonal mare deposit in the southwest is one of the volcanic units of Mare Orientale. Fractures or rilles indicate cooling or conduits for the melt flow are visible in this unit and adjoining areas.

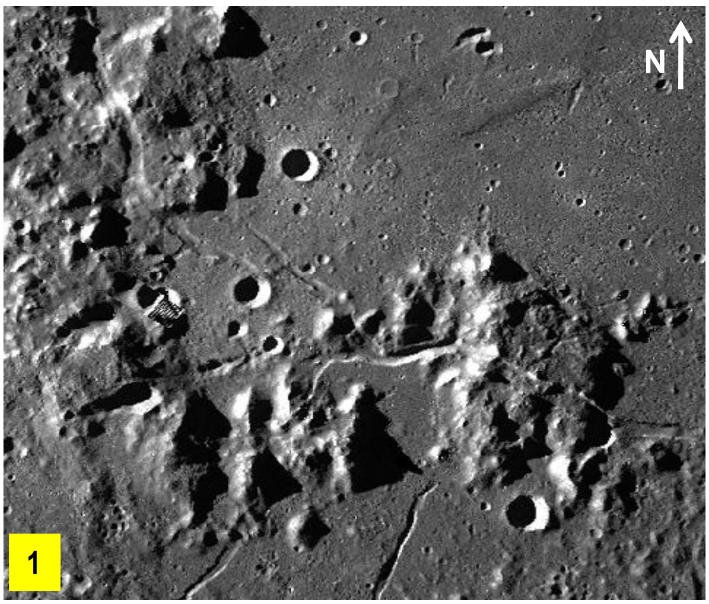
3. M3 mosaic of the Mare Orientale basin.

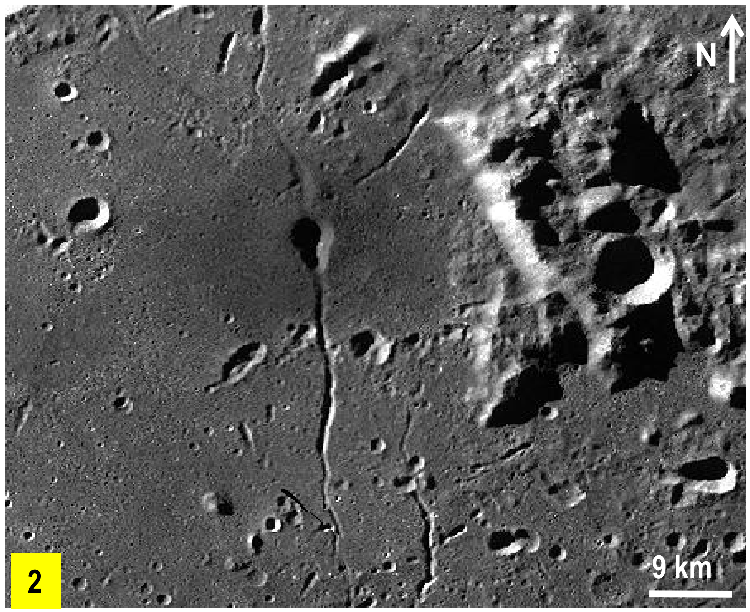

N
200 Km
3

Schrödinger Basin: Peak ring basin

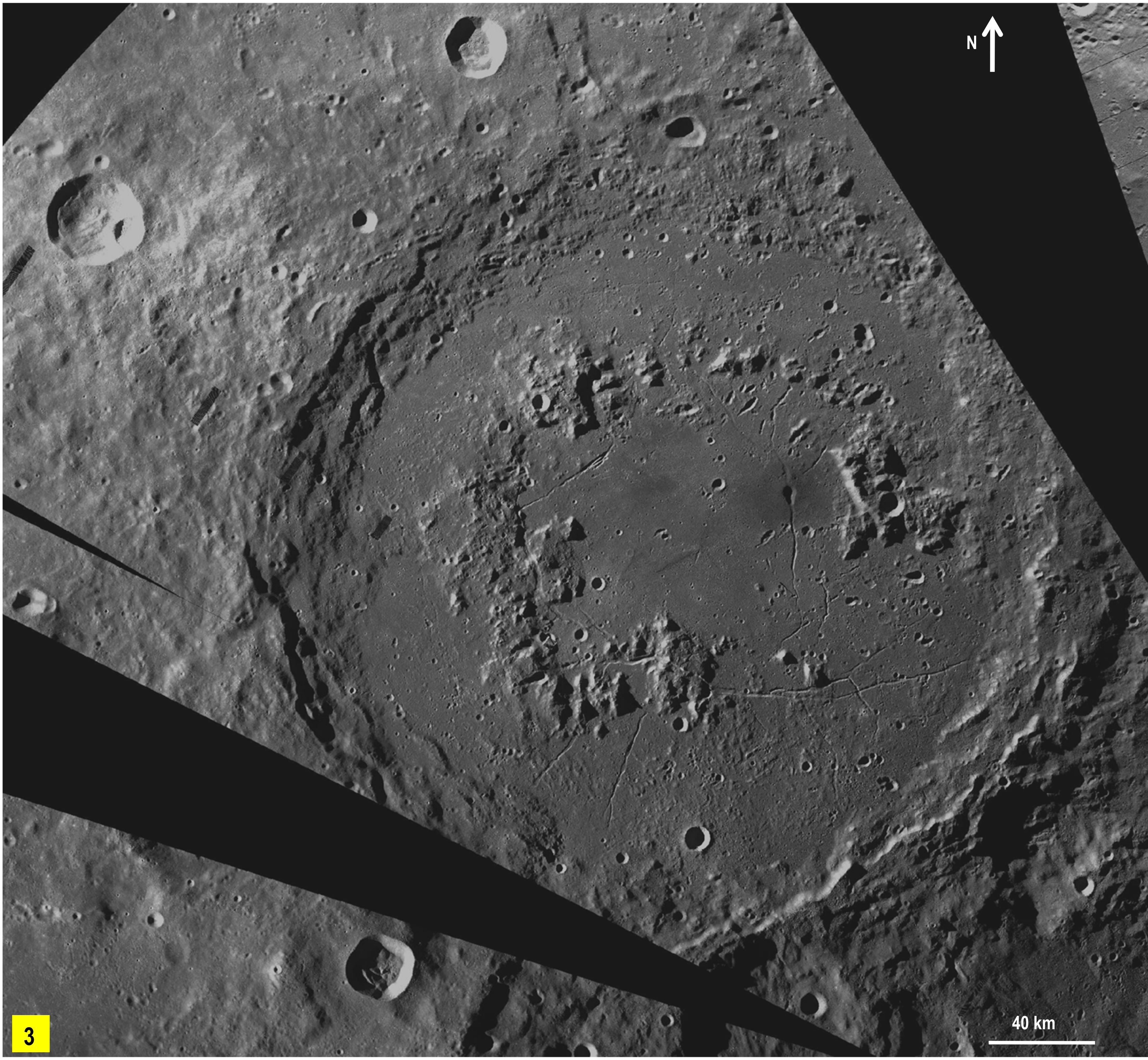


Schrödinger presents a well-preserved example of a peak-ring basin whose formation was heavily influenced by pre-existing topography and tectonic structures. Schrödinger is the multiring basin of about 320 km in diameter, located on the western rim of the oldest and largest lunar basin, South Pole-Aitkin Basin (SPA) near the south lunar pole. It is the second youngest large multiring basin. The outer rim of this basin has been slightly rounded due to subsequent impacts. The second ring lies in within the interior and is approximately half the diameter of the outer rim. A circular range of rugged mountains surrounds the center, with the exception of a wide gap in the south. The remainder of the floor has been resurfaced by subsequent lava flows, producing a relatively flat surface particularly within the inner ring. There is no central peak at the midpoint of the interior. Schrödinger hosts a series of fractures, a complex network of rilles, which exhibit complex cross-cutting relationships with each other and with the basin floor materials.





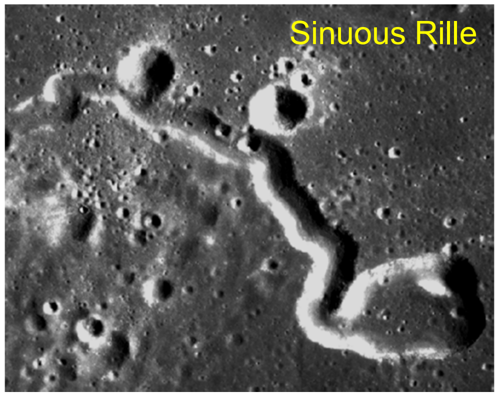
1. Image showing a large wide fracture trending east-west, geologically called Graben along with a set of fractures, cutting across the uplifted peak ring of rugged mountains.
2. TMC image showing a prominent, dark cone shaped feature known as Schrödinger cone, which is one of the largest single-vent deposits observed on the lunar surface. This cone is believed to be volcanic vent situated on a crater floor.
3. TMC mosaic of the Schrödinger basin.


N
40 km
3

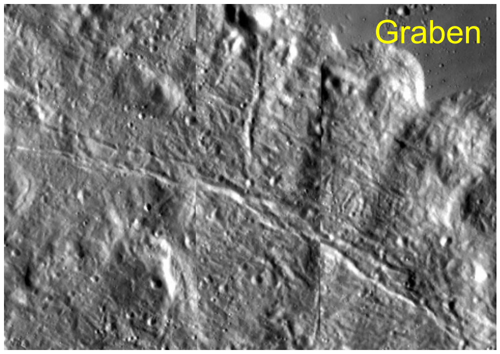
Lunar Geological Features

04 Lunar Geological Features

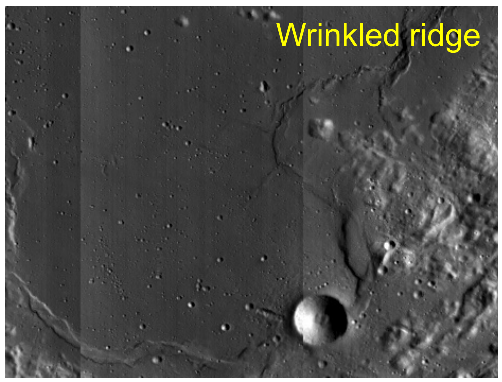
The present lunar surface has not been extensively reshaped by endogenic forces, as like the Earth. Most of the structures on the lunar surface are inside the basins, and many transect both the basins and the mare. The main lunar geological features associated with volcanism and tectonic activity are rilles, domes, scarps, graben. Some albedo features known as lunar swirls present on lunar surface are enigmatic features.



After impact cratering, volcanism is the next major geologic force that has modified the lunar surface. Radioactive elements like uranium, potassium, and thorium are the main source of the reheating of the lunar crust and upper mantle, but at very localized scale. Mare basins are the most preferential site for volcanism. The lunar lava generally erupted from fissures and poured and ponded in the geographically low plains. Sometimes when erupted on the inclined surface, the lava could flow downhill and create river like meandering channels called Sinous Rillles. Another interesting features present on the lunar surface are Collapsed Lava Tubes, which are formed when roofs of the lava tubes collapse. Domes are the geologic features formed by lunar volcanism at a very local scale. Lunar domes are smooth sided with low inclination and are result of more viscous silicic volcanism.

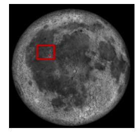


Tectonism refers to the forces that deform the lunar surface which can be endogenous such as 'thrust faults' and external such as 'creation of faults by impact process'. Two main type of tectonic forces generally act – extension and compression. Extension causes stretching and fracturing of the shallow lithosphere which result into the formation of the high-angle faults along which movement of blocks occurs and are usually long and straight. Rifts and grabens, fault-bounded valleys, are the common expressions of extension.

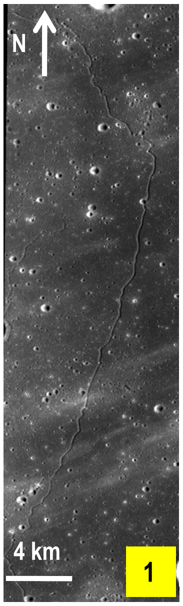


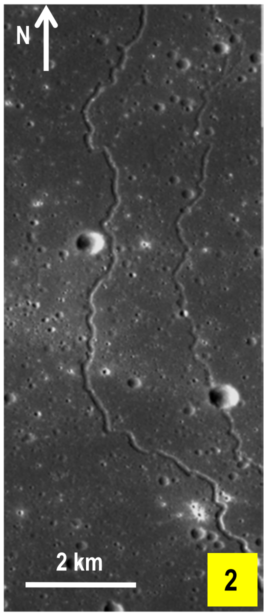
Compression generally refers to shortening due to which the lithosphere of a planet may buckle and fold, or break into thin sheets bounded by low-angle faults. These low-angle faults are named as thrust faults and they usually form sinuous, overlapping ridges that are quite different from grabens. The major features that may be attributed to crustal deformation are *linear rilles and wrinkle ridges.*

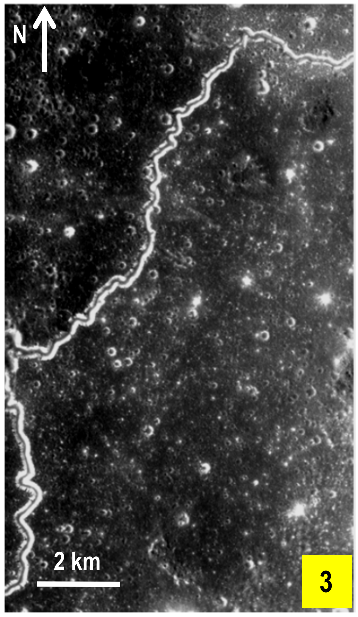
Sinuous Rilles: Meandering channels

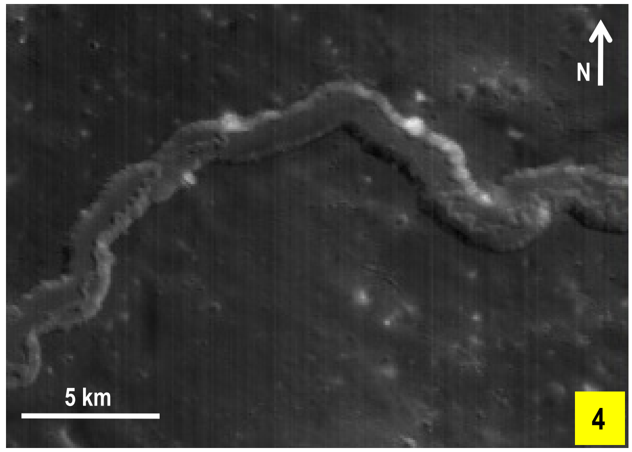


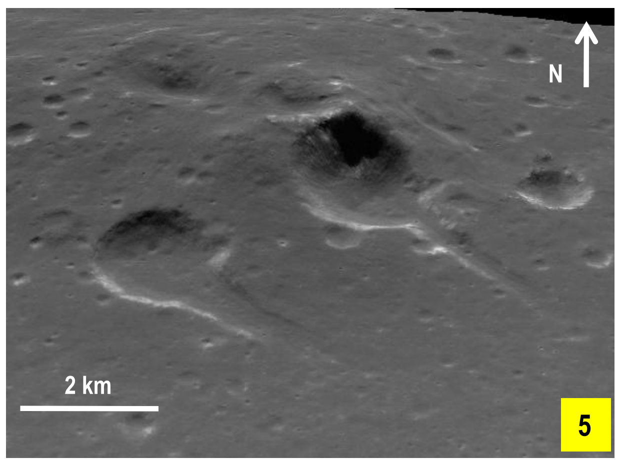
The lunar surface is marked with some narrow valleys called rilles, linear or curving features having appearance of channels or collapsed lava tubes. Rilles are the meandering or open channels created by the moving magma at the time of the mare basalts and commonly begin at crater or crater like landforms and end by fading downslope into the smooth mare surface. Rilles can be straight, arcuate or sinuous in shape. Rilles range in size from a few tens of meters to 3-4 km in width and from a few kilometers to ~300 km in length. The channels are U- or V-shaped, but the original cross-sections have been modified by fallen debris from channel walls or ejecta from nearby craters. The highest concentrations of sinuous rilles are in the Marius Hills (14°N, 50°W) and on the Aristarchus Plateau (27°N, 50°W).



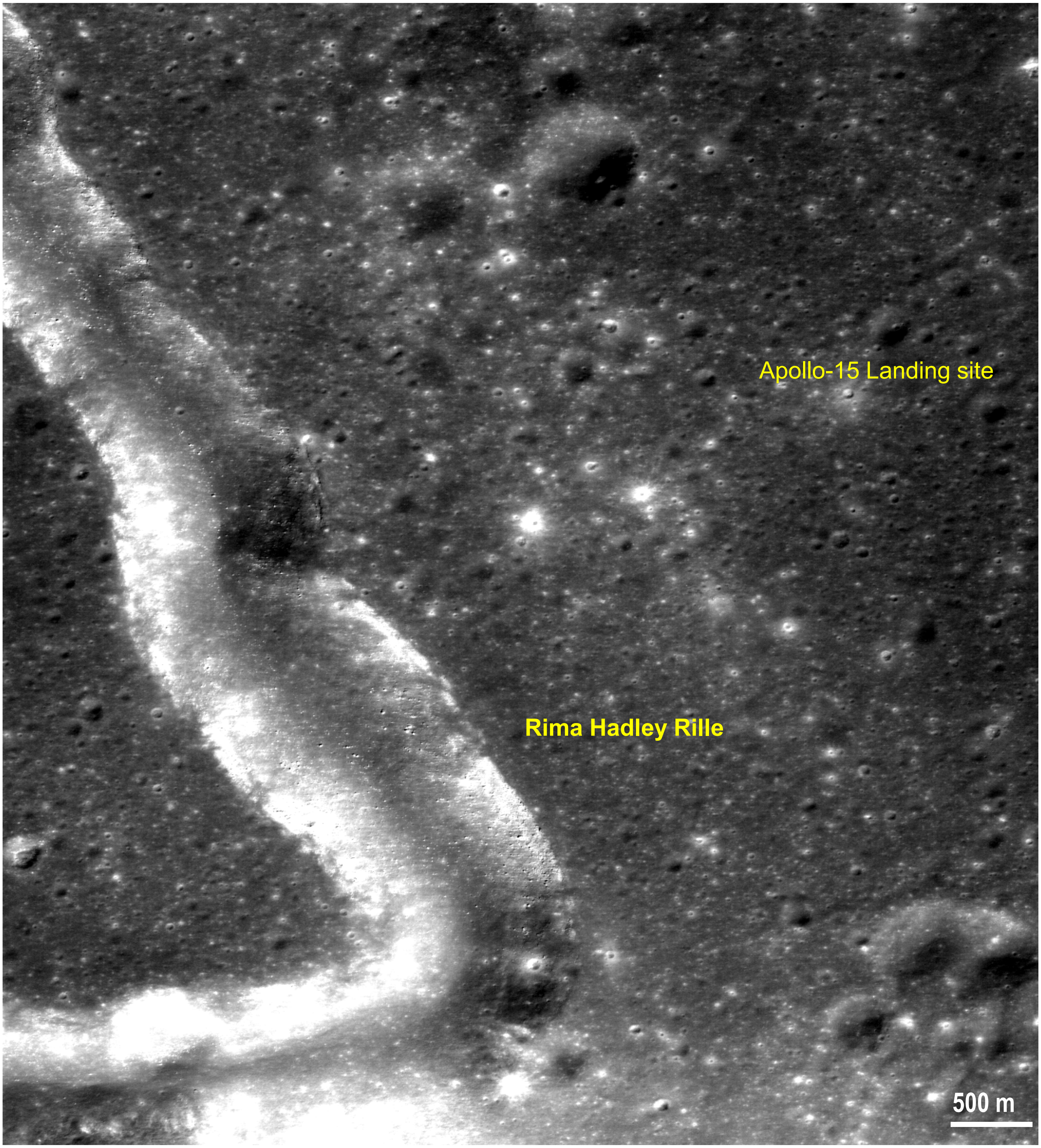


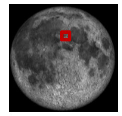






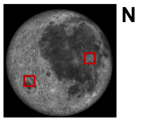
1. TMC image showing a long sinuous rille situated near the Kepler crater in Oceanus Procellarum.
2. TMC image showing a network of sinuous rilles situated in Oceanus Procellarum.
3. TMC image of Rima Gailei, a sinuous rille in Marius Hill region of Oceanus Procellarum.
4. M3 image of a highly winding sinuous rille contained within a broader valley.
5. Unique example of a dual rille system initiated after crater formation.



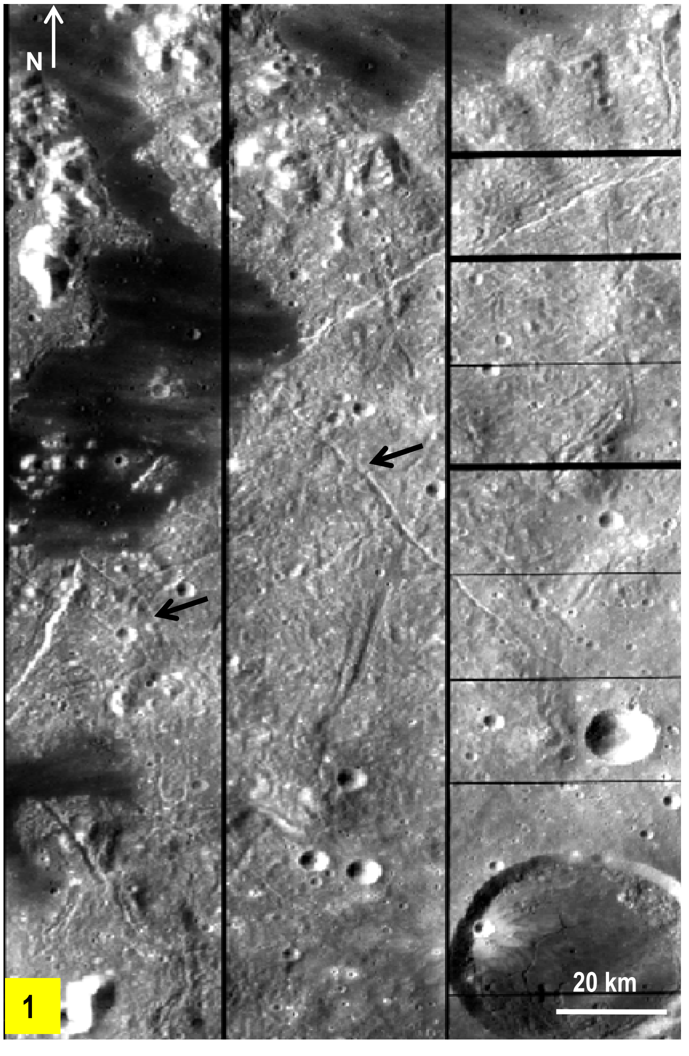


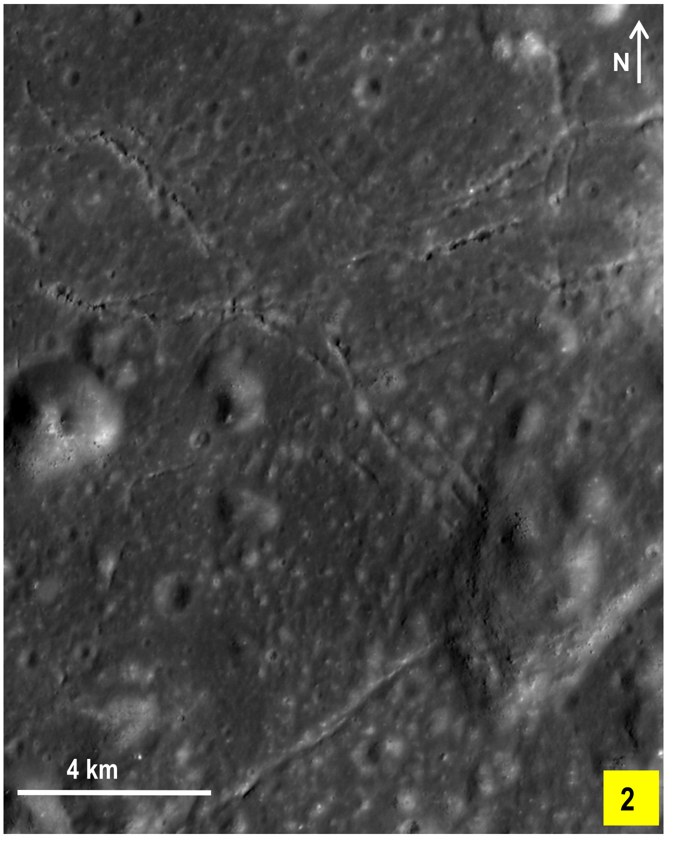
TMC image of the part of the Rima Hadley sinuous rille located south west of Apollo-15 landing site

Linear Rilles



Linear rilles are sharp, linear depressions, which generally take the form of flat-floored, steep-walled troughs ranging up to several kilometers in width and hundreds of kilometers in length. Linear rilles are parallel or arranged in an echelon pattern. Some intersect and others form zigzag patterns.

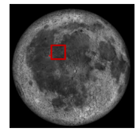




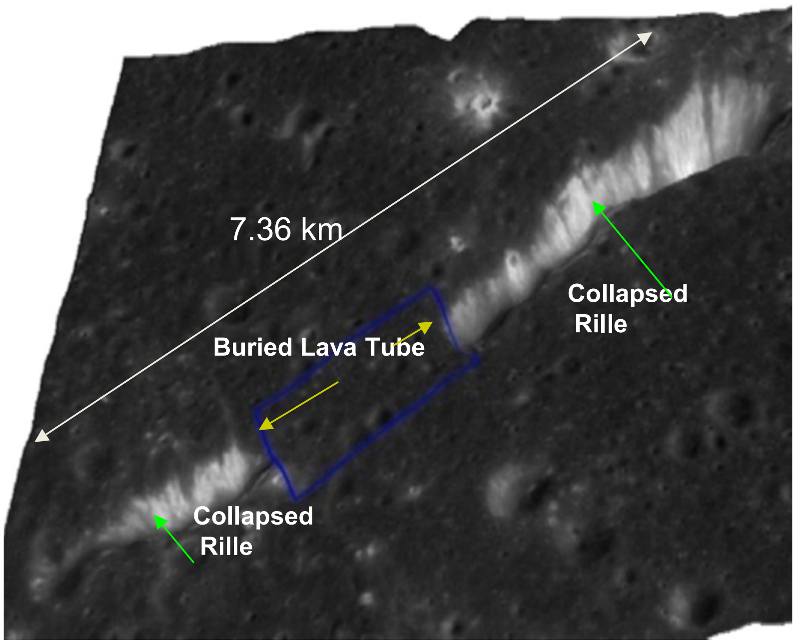
1. TMC image of the Orientale eastern portion shows the pattern of linear rilles cross cutting each other and forming zigzag pattern.

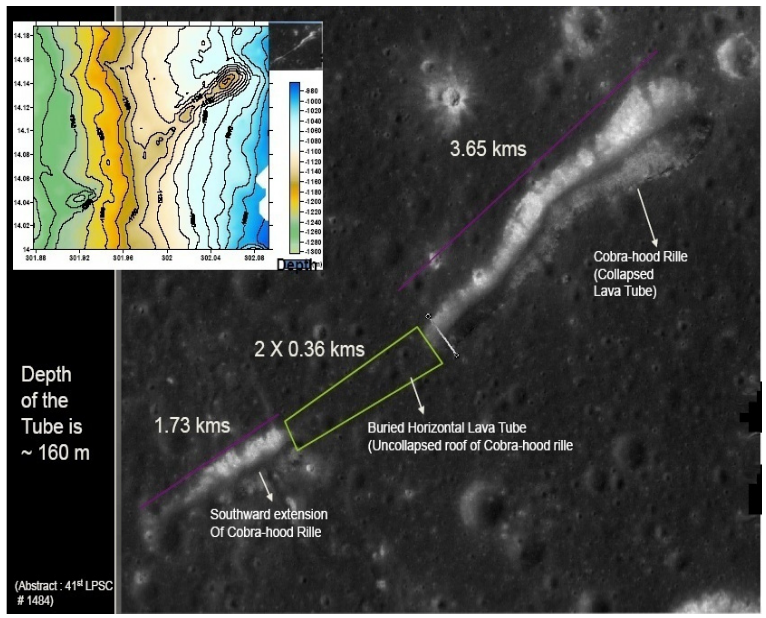
2. TMC image showing the linear rilles on the floor of the Copernicus crater.

Collapsed lava tube



Lava tubes are formed due to development of the thin crust over the liquid interior of a lava flow. Pipe-like zones of movement develop within the interior of the flow and may drain to form a long, hollow, cylindrical tube in the middle of the flow. The roofs of these lava tubes sometimes collapse, forming steep-sided troughs or chains of circular pits. One such collapsed lava tube of 7.36 km has been identified using TMC images in Oceanus Procellarum region of the Moon.

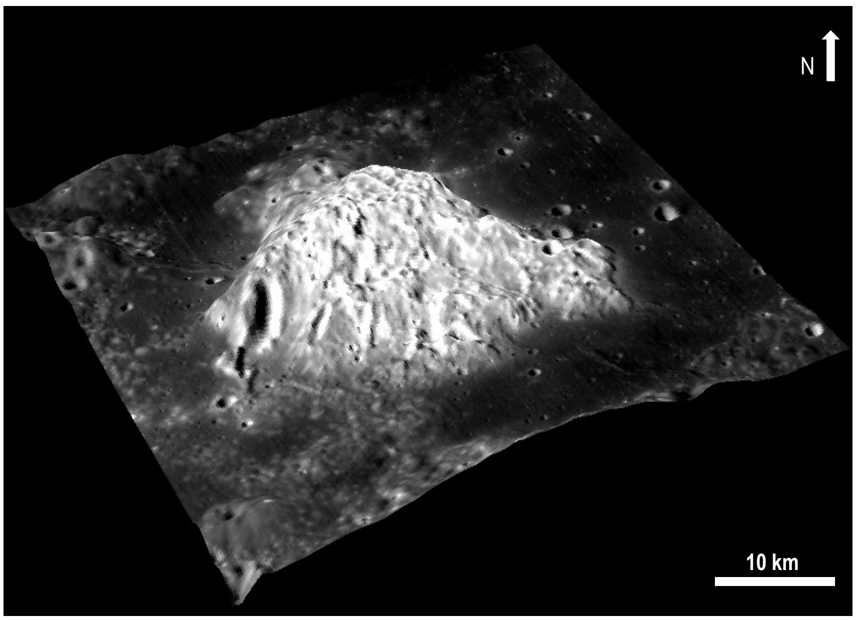




1. Three dimensional view of the collapsed lava tube of 7.4 km length in Oceanus Procellarum.
2. TMC image showing the same collapsed lava tube along with height contours derived from TMC data.

Lunar Domes: Hansteen Alpha

Lunar domes are the positive relief surface features associated with volcanism and cover only a small fraction of the lunar surface. Shields, cones and domes of around 3 to 17 km across and up to several hundred meters high were reported from various mare regions of lunar surface. Approximately 200 domes have been identified and subdivided into seven distinct morphological classes. Another type of domes are associated with highlands and maria regions and clearly distinct from the mare domes in terms of morphology and spectral properties. Domes of this type are characterized (1) by much steeper slopes, (2) by a high albedo similar to lunar highlands, and (3) by a strong absorption in the ultraviolet. Because of the strong absorption in UV region they appear spectrally red and therefore are known as red spots. Also, these domes were created by much more viscous lava similar to, e.g., terrestrial dacites, basaltic andesites, or rhyolites. Several red spots are abundant near the mare/highland boundary in Oceanus Procellarum, Mare Imbrium, Mare Humorum and Mare Cognitum. The Gruithuisen and Marian domes occur in northern Oceanus Procellarum. Wide expanses of low-silica basaltic mare lavas, were created large mare flows over several hundred millions of years in lunar history, volcanism producing lava with higher silica content were also active for much shorter time intervals resulted into the formation of some volcanic construct i.e. domes.

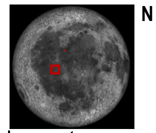


3D view of the Hansteen Alpha dome from M3 image

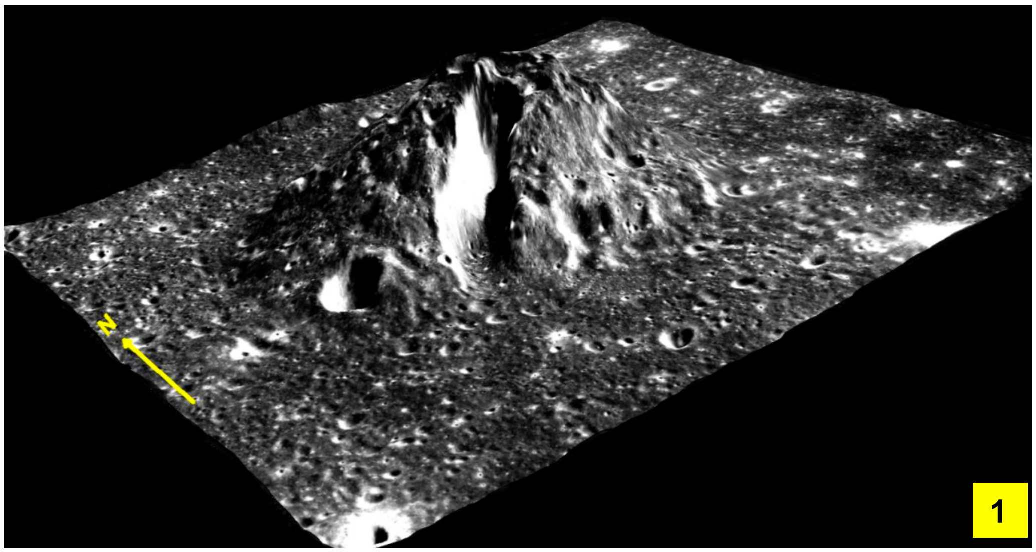
Hansteen Alpha Dome

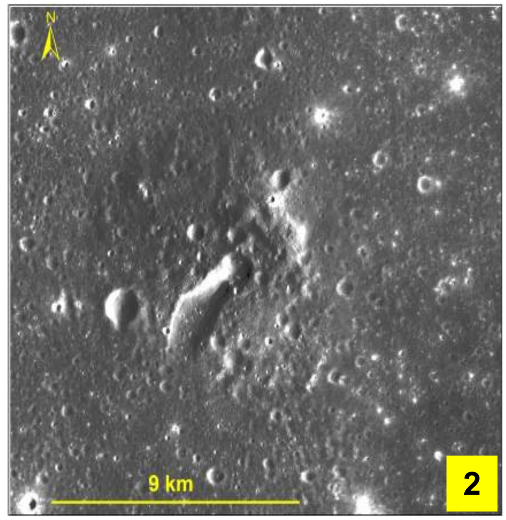
Hansteen Alpha is an arrowhead-shaped highlands feature located on the southern margin of Oceanus Procellarum approximately between latitude 0°S–20°S and longitude 30°W–60°W. It is a member of a class of lunar spectral anomalies (Red Spots) that are characterized by a relatively high albedo and a strong absorption in the UV region. This 25km rough textured triangular mound made up of steep-sided, bulbous, very bright dome materials exhibit hackly surfaces. It appeared distinctive in its surface texture, color and albedo from nearby highlands.

Lunar Domes: Marius Volcanic Hill Complex



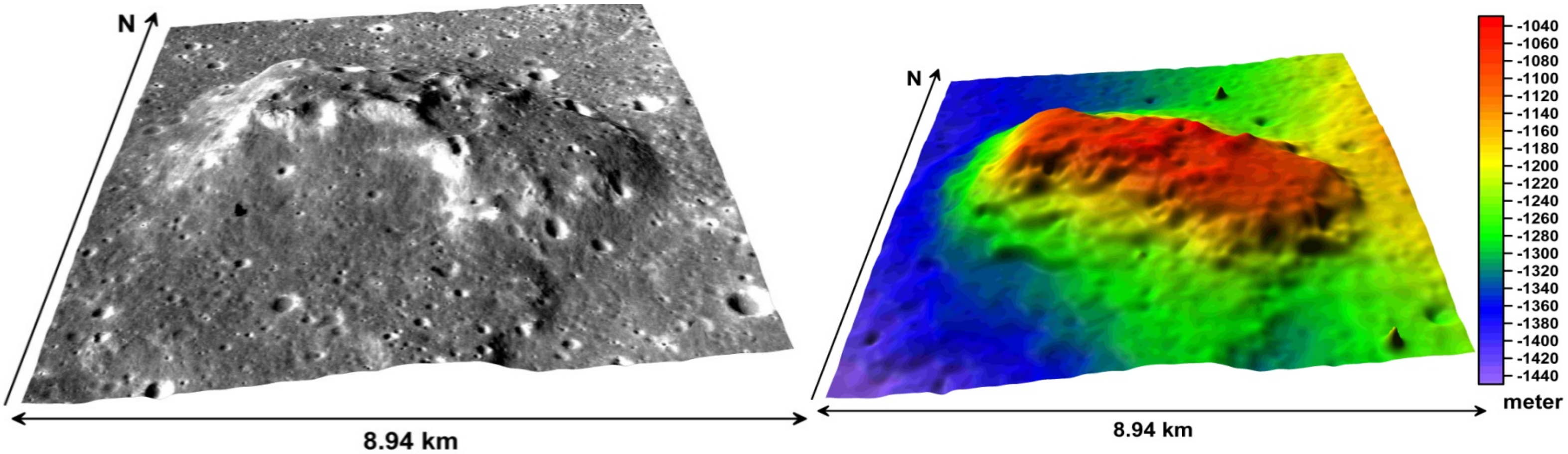
Marius Hills Complex (MHC) is one of the most important regions on the entire lunar surface, having a complex geological setting and largest distribution of volcanic constructs with an abundant number of volcanic features like domes, cones and rilles and lava flows. The MHC is a 35,000 km^2 plateau located in central Oceanus Procellarum at 13.3N/306.8E. Below is an example of an effusive dome located in MHC of Oceanus Procellarum to the south of Rima Galilaei rille on the near side of the Moon. Examples of some domes and cones 3D view from TMC data also is shown below.





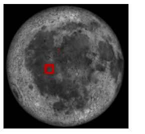
1. 3D perspective view of the dome in Ocean Procellarum region using TMC data.
2. HySI image of the dome and the surroundings

A flat topped dome



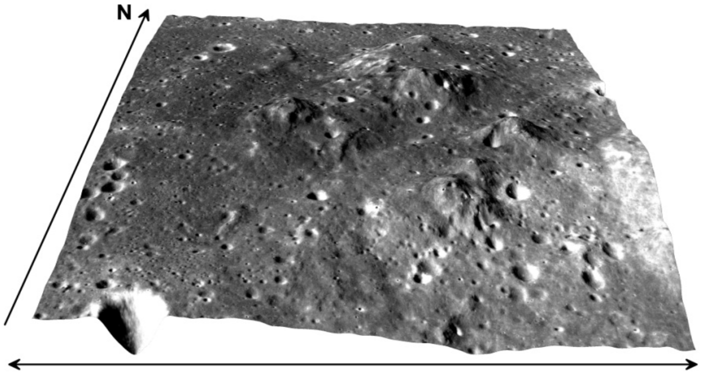
TMC Ortho image and 3D perspective view of a dome in MHC region

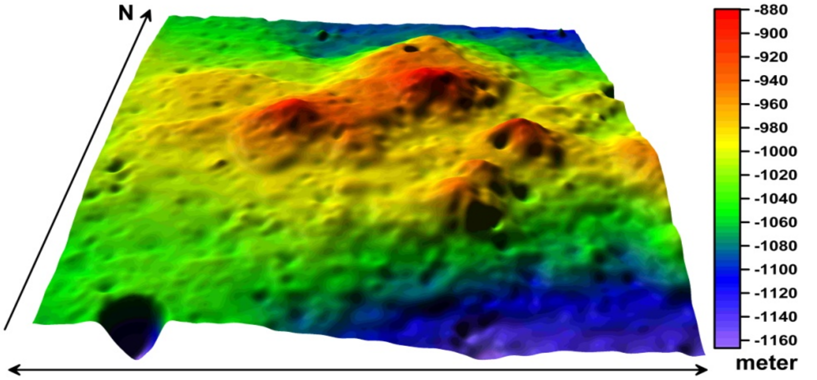
Domes of Marius Hill Volcanic complex



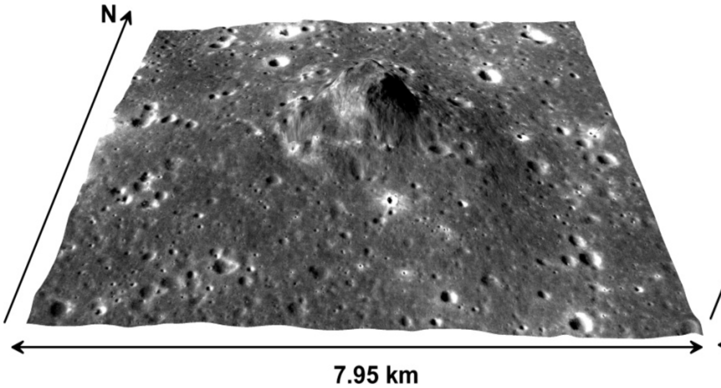
The Marius Hills volcanic complex (MHC) is one of the largest volcanic complexes on the Moon consists of a large number of geologic features like cones, domes, rilles, lava flows. The MHC is a 35,000 km^2 plateau located in central Oceanus Procellarum at 13.3N/306.8E and rising 100–200 m from the surrounding plains. Marius Hills domes are a unique class with irregular shapes, complex surface details, and a few summit craters or cones on top of some domes. Examples of some domes of different shapes and cones with their 3D view from TMC data is shown below.

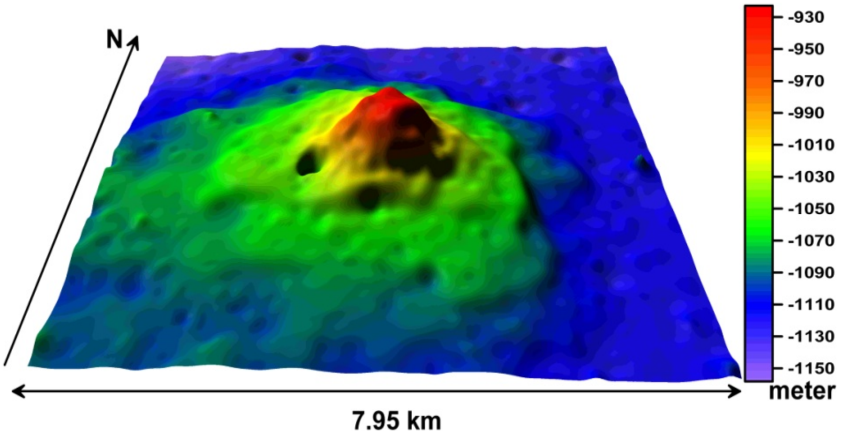
Cluster of domes/cones





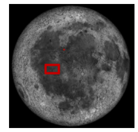
Cone



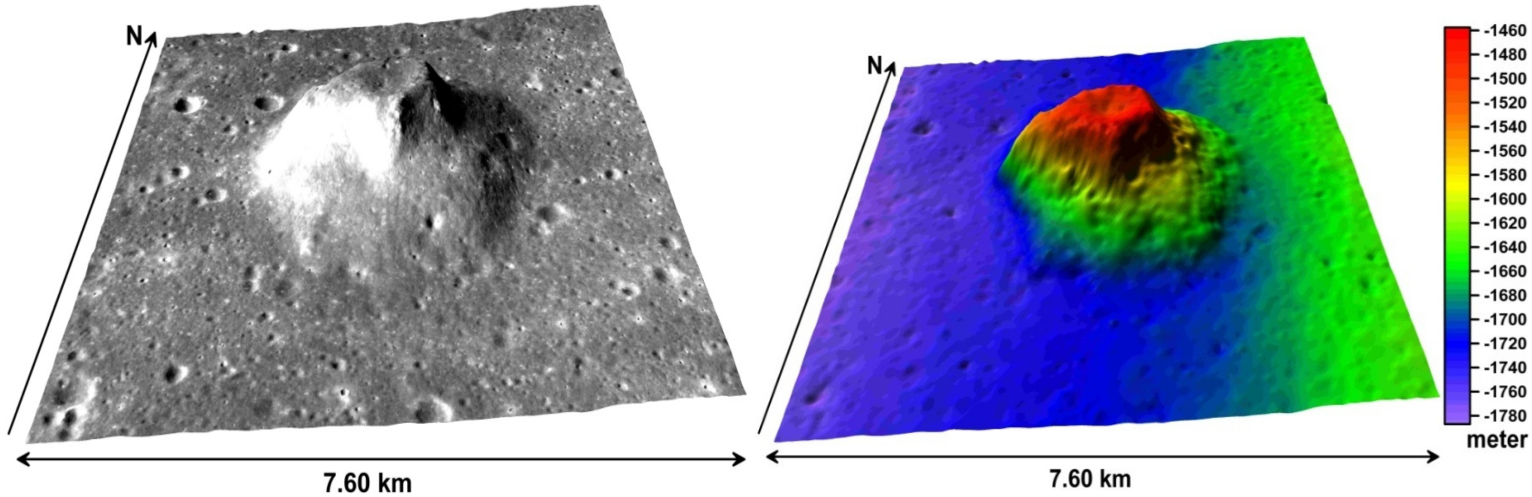


TMC Ortho image and 3D perspective view of a dome in MHC region

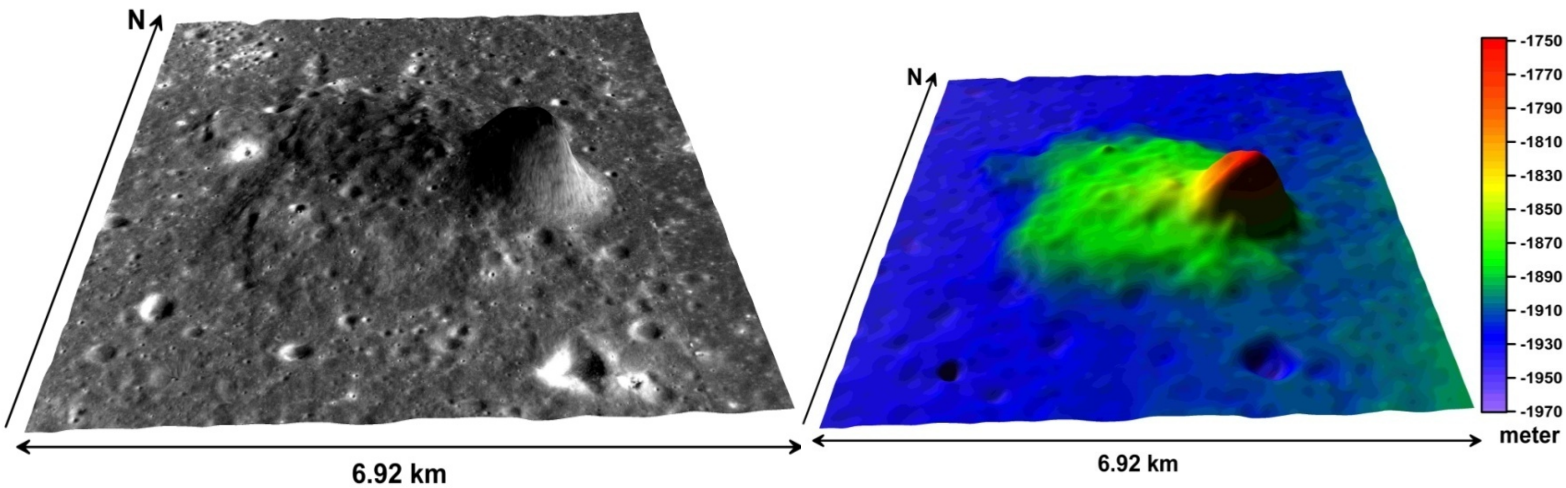
Domes of different morphologies of MHC region



Circular dome

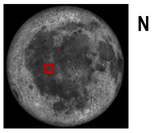


Cone

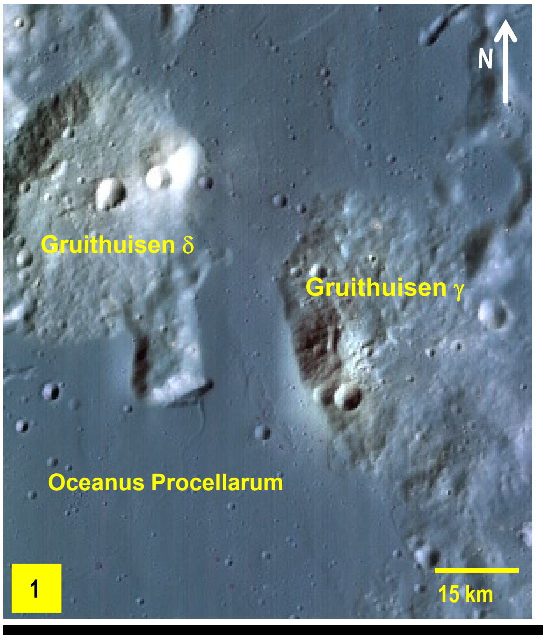


TMC Ortho images and 3D view of domes in MHC region

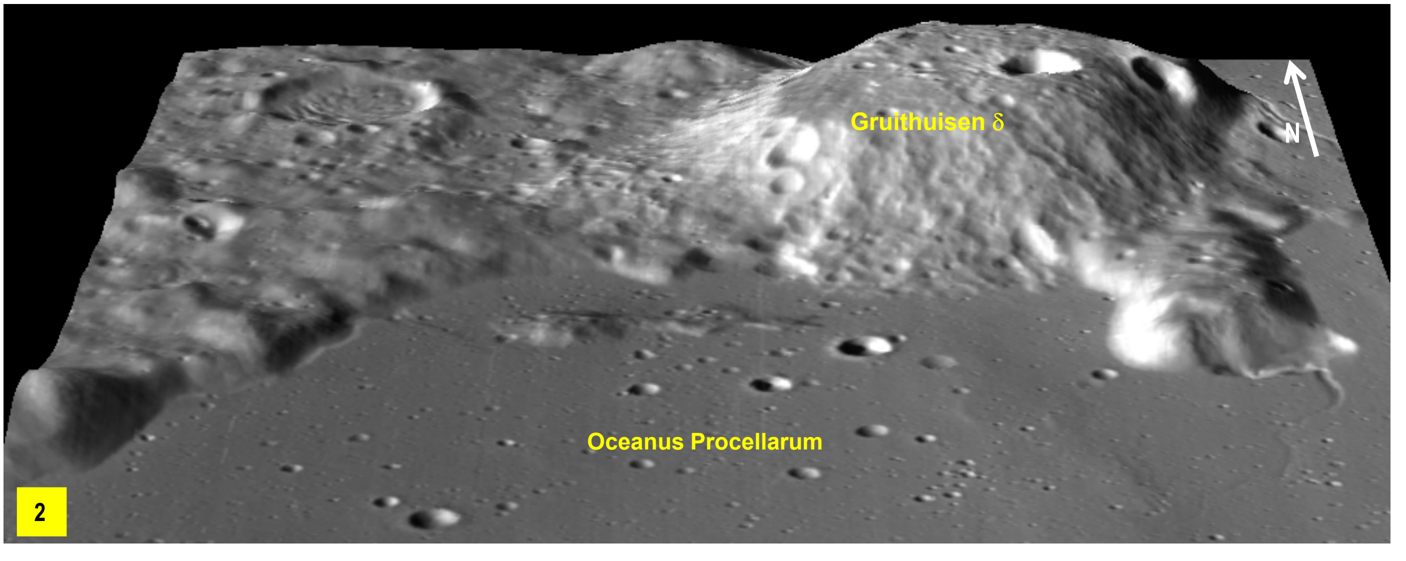
Gruithuisen Domes



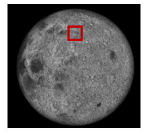
The Gruithuisen domes consist of two high-albedo features located near the western border of Mare Imbrium. Gruithuisen δ is a rectangular dome (33 km x 13.5 km) and has a height of 1600 m. Gruithuisen γ is a flat-topped feature, roughly elliptical in shape (24 km x18 km) that is of 1200 m high. Both domes are approximately 3.7 to 3.8 billion years old. Morphologic studies have indicated that the flows that produced these domes were highly viscous and that the domes themselves are similar in shape and texture to terrestrial dacite or rhyolite domes.



1. M^3 image of the Gruithuisen domes
2. Three dimensional view of the Gruithuisen δ dome

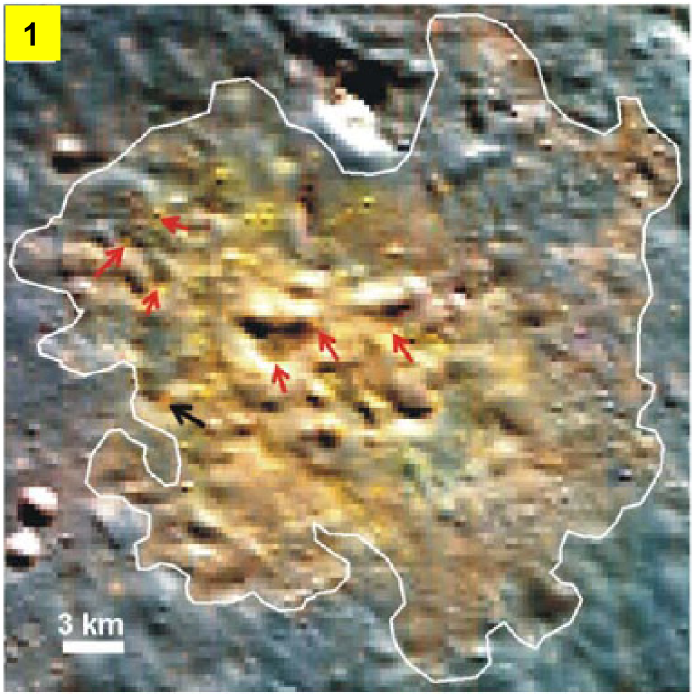


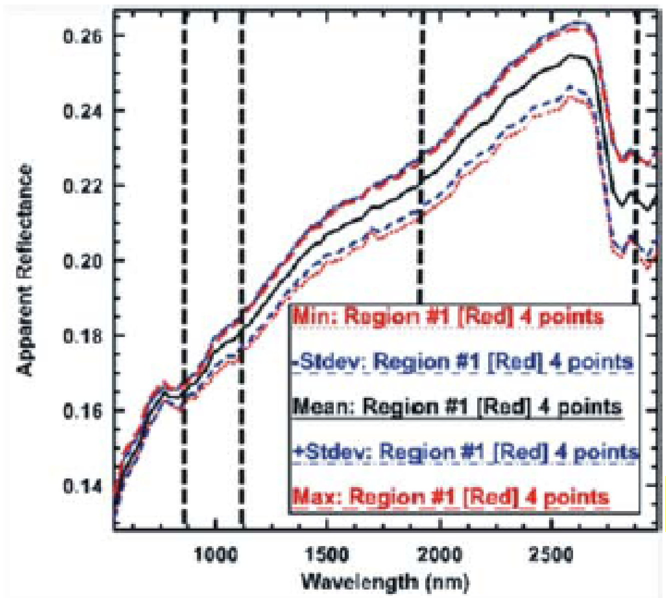
Water signature detected from lunar dome



The Compton Belkovich Volcanic Complex (CBVC) situated on the far side highlands centred at 61:1 N, 99:5 E is an isolated thorium `hotspot'. The CBTA has high, focused concentration of thorium (Th) and is isolated in an area of Th-poor terrain on the lunar farside. It is nestled between two ancient impact craters, Compton (162 km diameter) and Belkovich (214 km diameter).

Detection of OH/H_2O from the lunar surface was first time reported from M^3 observations which changed views regarding the borne-dry nature of the Moon. The strong 2800-nm OH/H_2O feature observed at the non-mare silicic CBVC could possibly indicate the presence of endogenic water associated with the late-stage silicic volcanism in the region

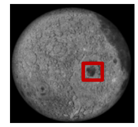




2

1. M^3 False colour composite image of Compton Belkovich Volcanic Complex (CBVC) (band assignments: R = 930-nm, G = 2018-nm and B = 2816-nm M^3 channels).
2. Reflectance spectra showing the enhanced water absorption around 2800 nm.

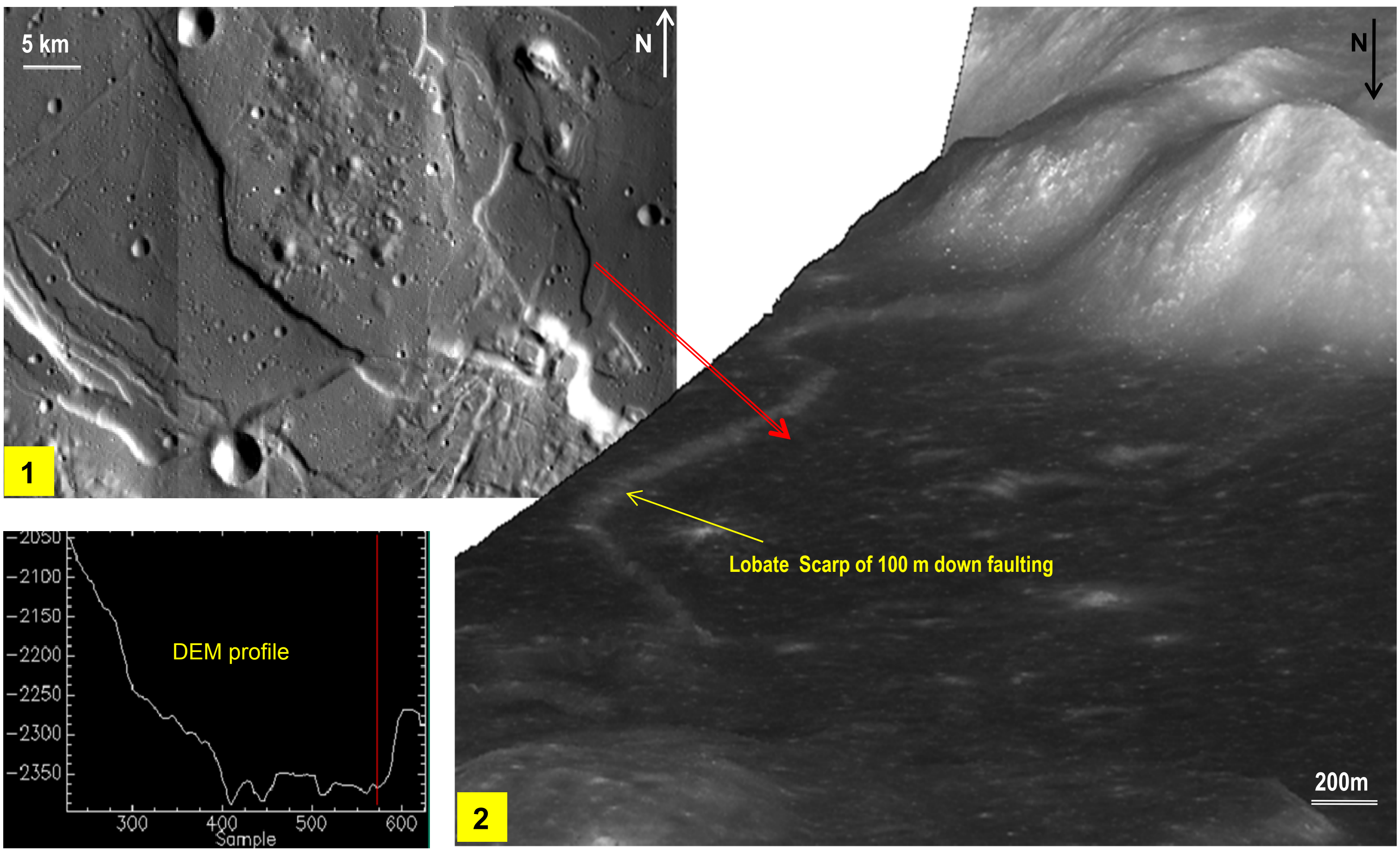
Lobate Scarp in Mare Orientale: Tectonic Feature



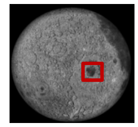
Scarps are interpreted as expressions of faulting of the Moon's surface layers. These are generally produced by tectonic extension, which may accompany the subsidence of a basin floor or global expansion. Relatively young and globally distributed thrust faults show recent contraction of the whole moon, likely due to cooling of the lunar interior. The image shown below is of the one of the mare unit situated in the southern part of the Mare Orientale basin.

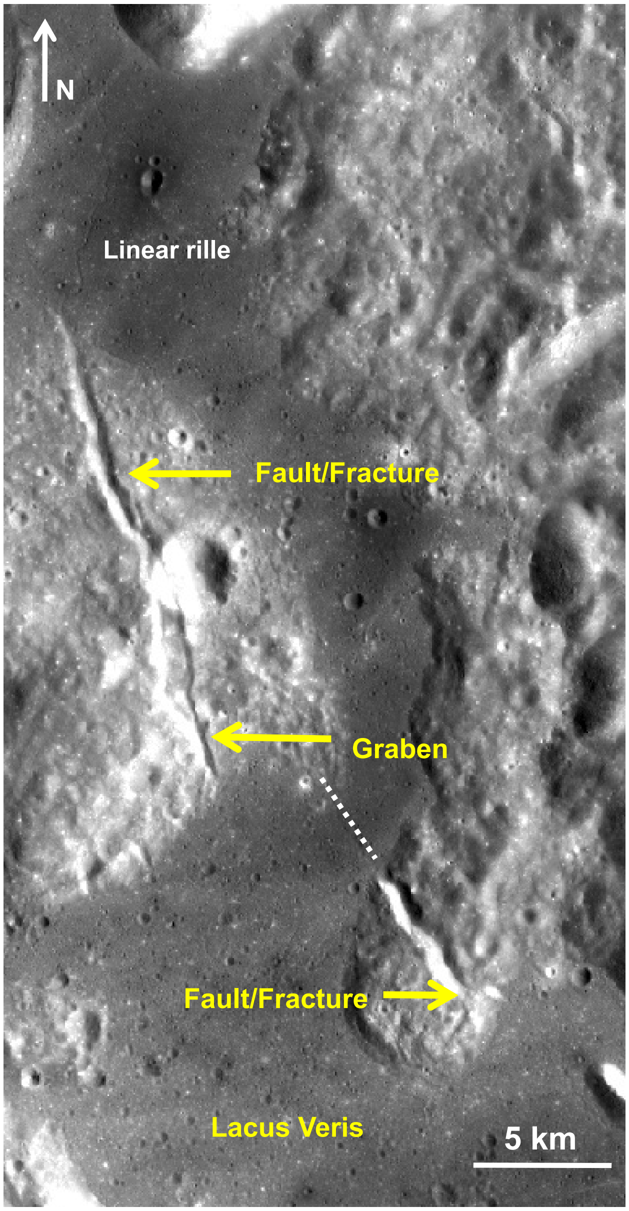
1. M3 image showing one of the mare unit situated in the south west of the Mare Orientale basin. The unit has been influenced by many fractures, mare flows or wrinkle ridges. The most striking feature is the scarp fault trending north-south which has caused ~100 m down-faulting.

2. 3D view of the scarp fault generated from TMC data.

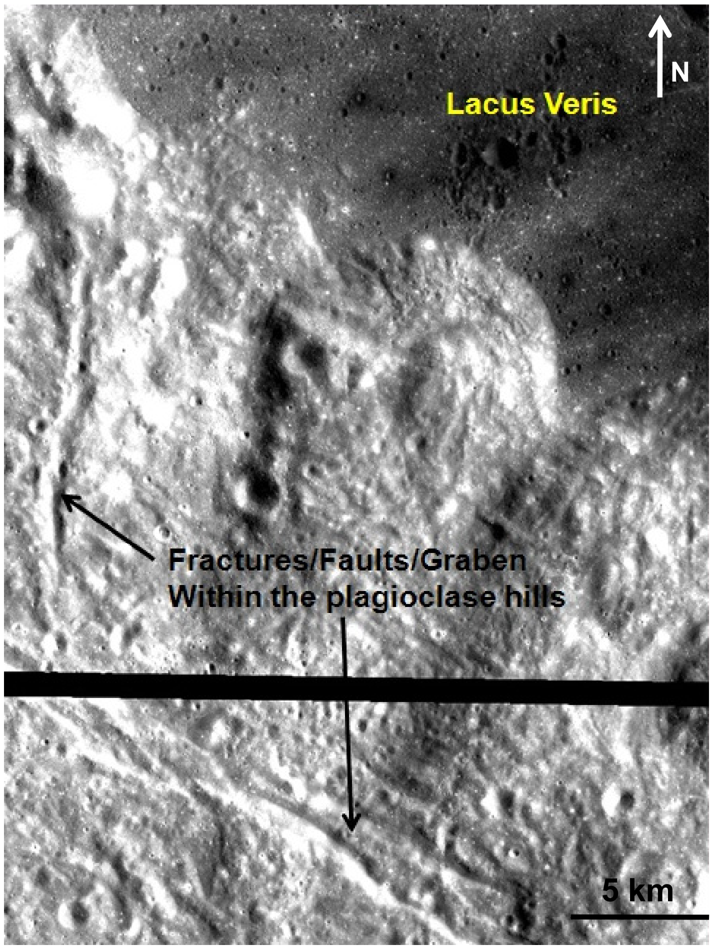


Graben in Mare Orientale: Example of Extensional regime

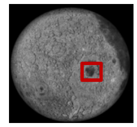




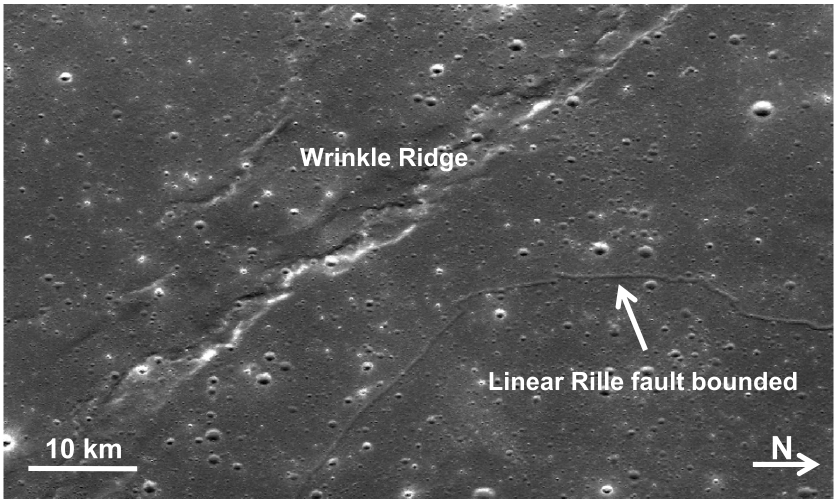
Tectonic features include faults and graben (fault bounded trenches). These are thought to be the result of tensional forces stretching the surface and are most common near the borders of circular maria. An example of such a graben located in Lacus Veris of Mare Orientale has been captured in TMC image. The below image shows fractures, trough or graben caused by sinking between the parallel faults.

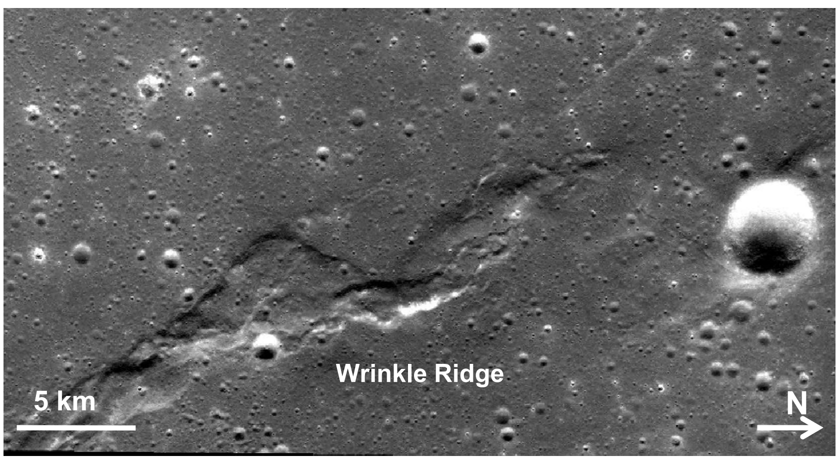


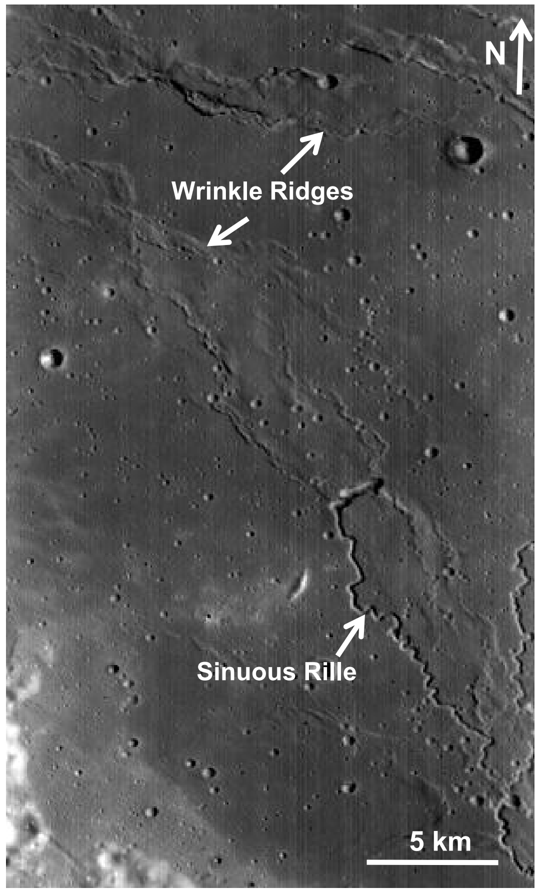
Wrinkle Ridges: Compressional Features



The major features attributed to crustal deformation are linear rilles and wrinkle ridges which are the most conspicuous structural features on the mare surface. These long narrow ridges typically, have sinuous outlines and extend discontinuously for great distances across the maria. In some places, they transect highland surfaces as well. Wrinkle ridges are believed to be caused by compressional forces as the dense lava filling a basin settles. These ridges are thought to be the result of thrust faulting produced by compressional forces exerted at the Moon's surface. The compression may be the result of global cooling and contraction superimposed on local adjustments to the load imposed by the mare basalts.

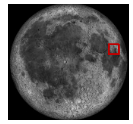


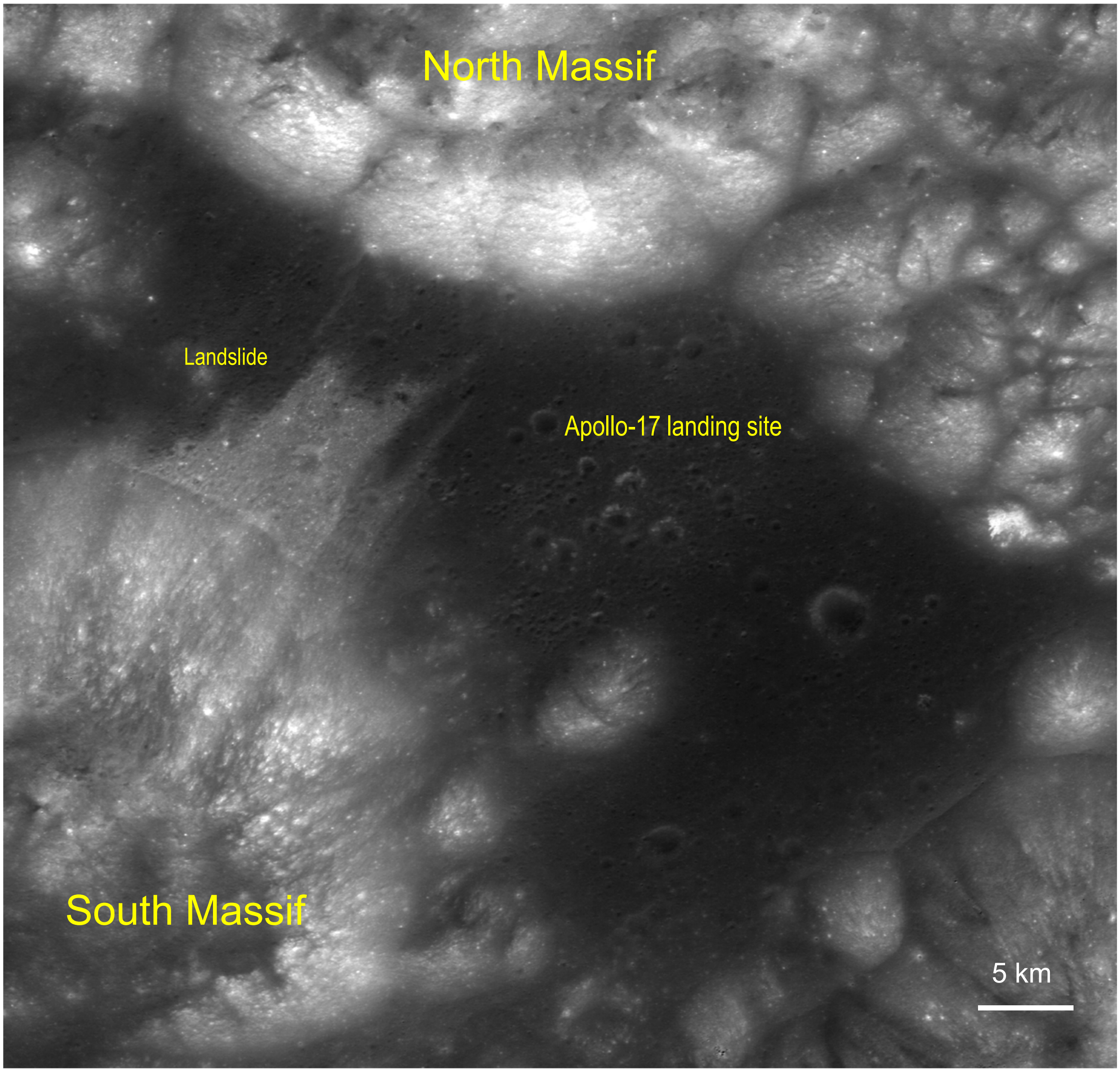




Wrinkle or mare ridges visible in this view are from the Oceanus Procellarum. Linear and sinuous rilles also running parallel with these ridges using TMC data

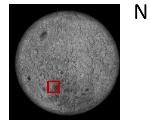
Landslides: Tarus Littrow Valley





TMC image of the Tarus Littrow valley, site of Apollo 17 landing showing landslide or the derbis flow from the south massif plagioclase hill

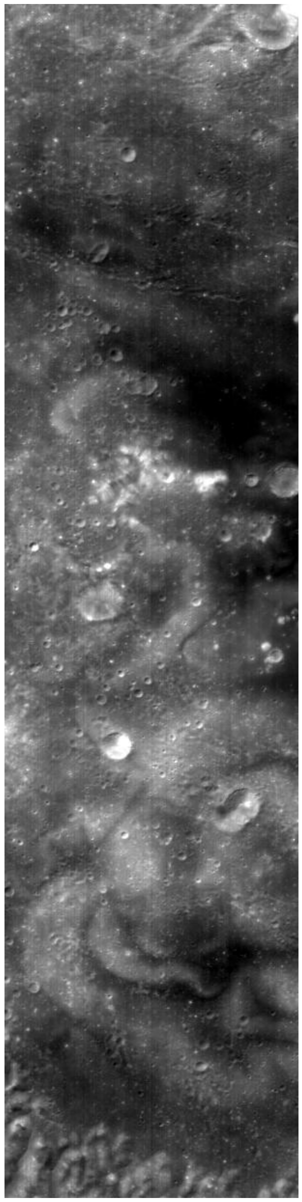
Lunar Swirls: Albedo paintings on the Moon

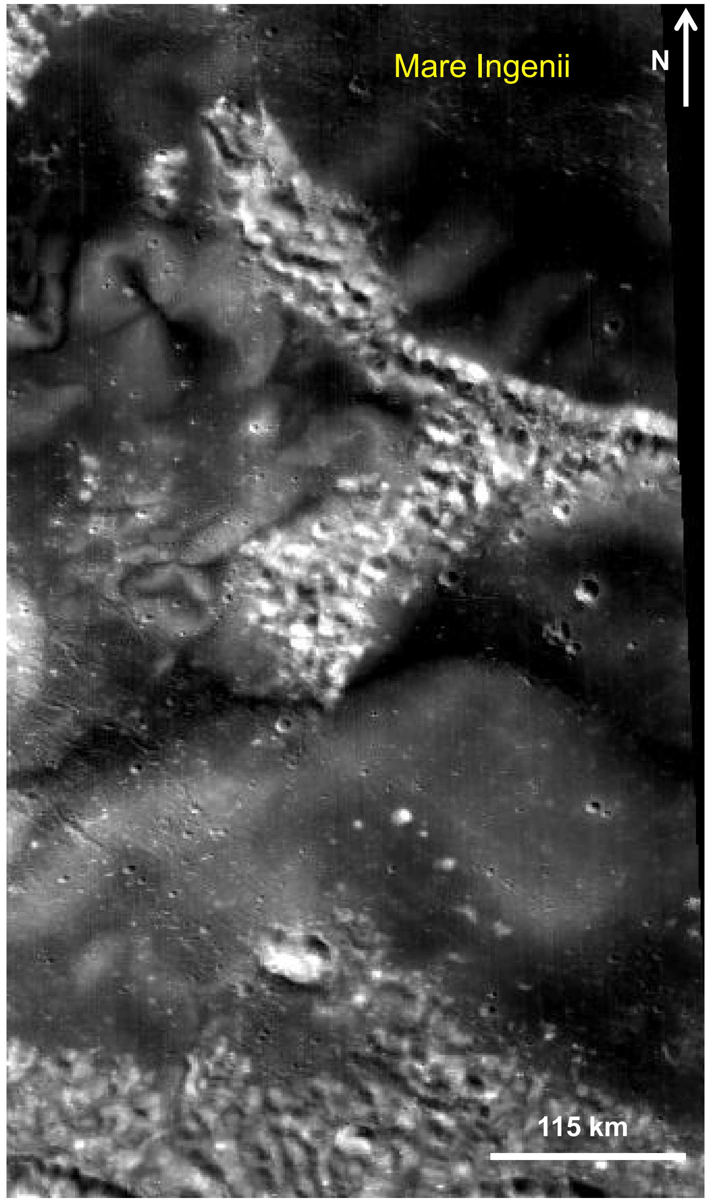


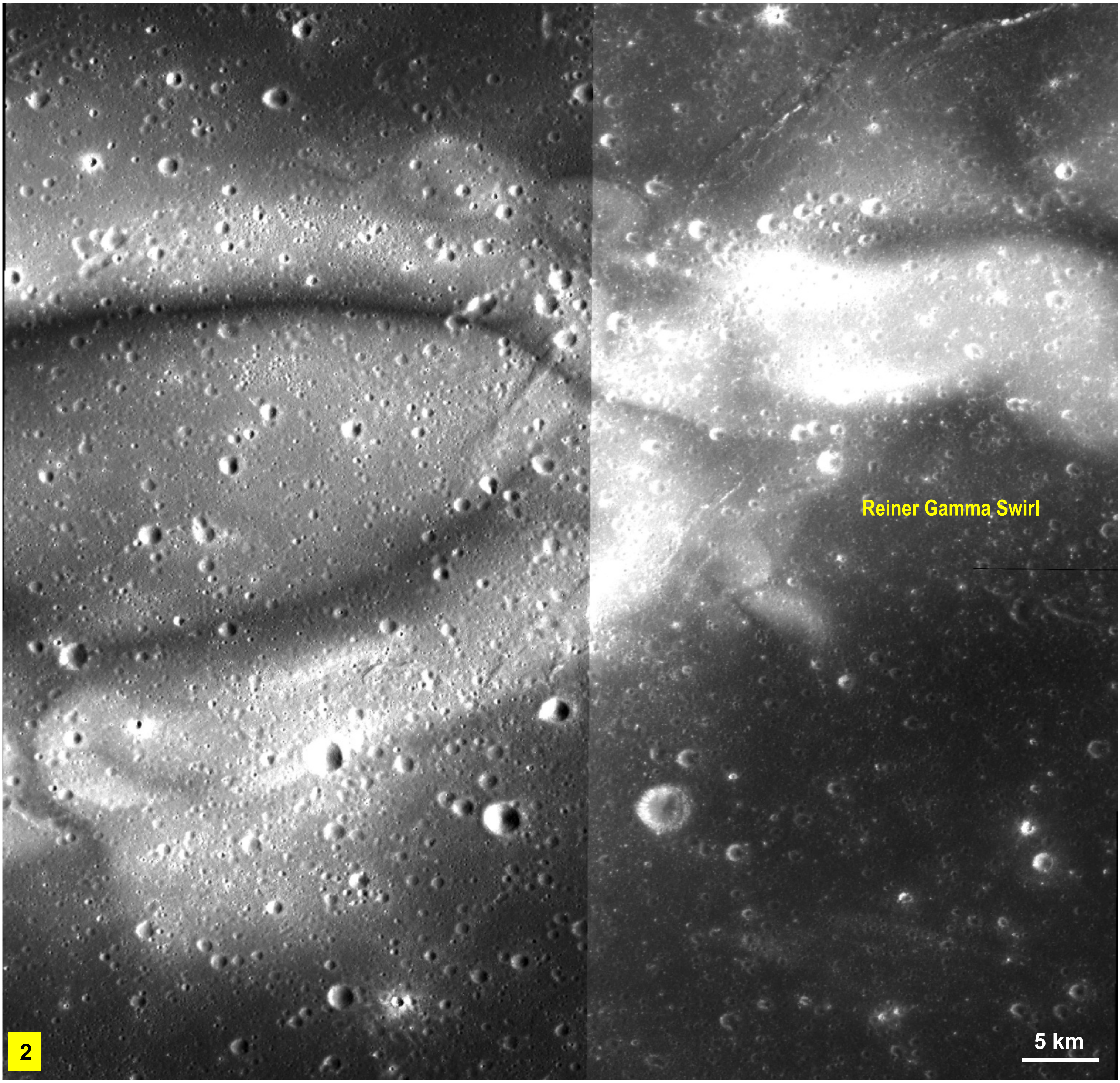
The term lunar swirls describes a unusual, sinuously shaped, high albedo features found across the Moon's surface. Swirls have been identified on the lunar maria and highlands due to the sharp contrast between the high-albedo material against their background and are coincident with regions of localized strong crustal magnetic fields. Swirls in the maria region are characterized by strong albedo contrasts and complex, sinuous morphology, whereas those present in highland terrain may be less prominent and exhibit simpler shapes such as single loops or diffuse bright spots. Their curvilinear shape is often emphasized by low albedo regions that wind between the bright swirls.

1. M3 image showing swirl in Mare Ingenii region which is one of the isolated basin in South-Pole Aitken basin located on the far side of the Moon.

2. High resolution TMC image of the eye shaped Reiner Gamma swirl on the Oceanus Procellarum region of the Moon. The extent of this swirl is about 41 Km on the lunar surface.

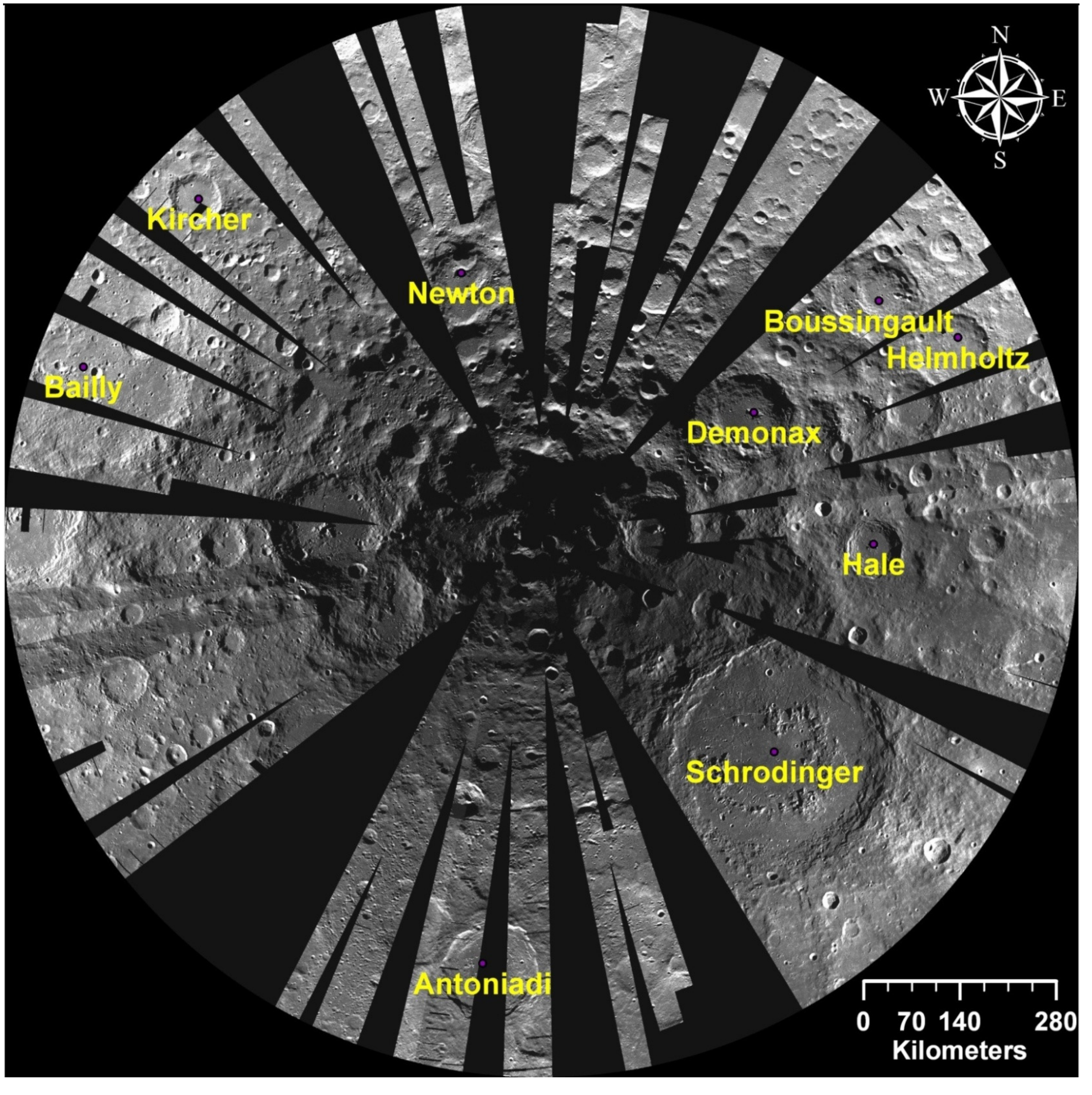





Reiner Gamma Swirl
2
5 km

Lunar Polar Science

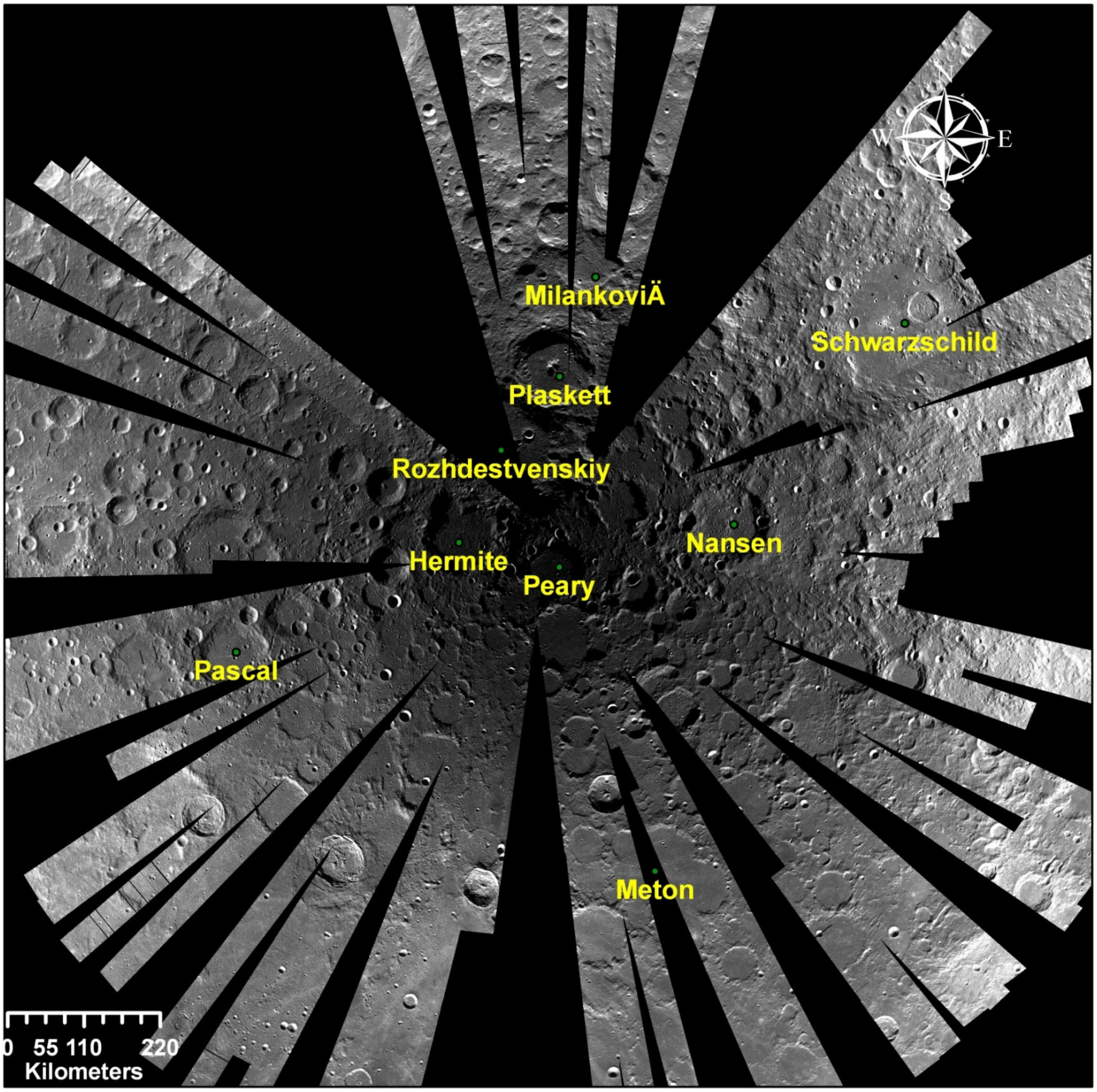
South pole of Moon from TMC



Lunar polar regions are the most unexplored areas of the Moon surface. The polar areas receives very less sunlight because of the very small tilt of the Moon's axis with respect to the sun. Therefore, some of the craters and depressions near the poles are permanently shaded from direct sunlight, as a consequence of which these surfaces are at extremely low temperature, well under 100^{0}K, for billion of years.

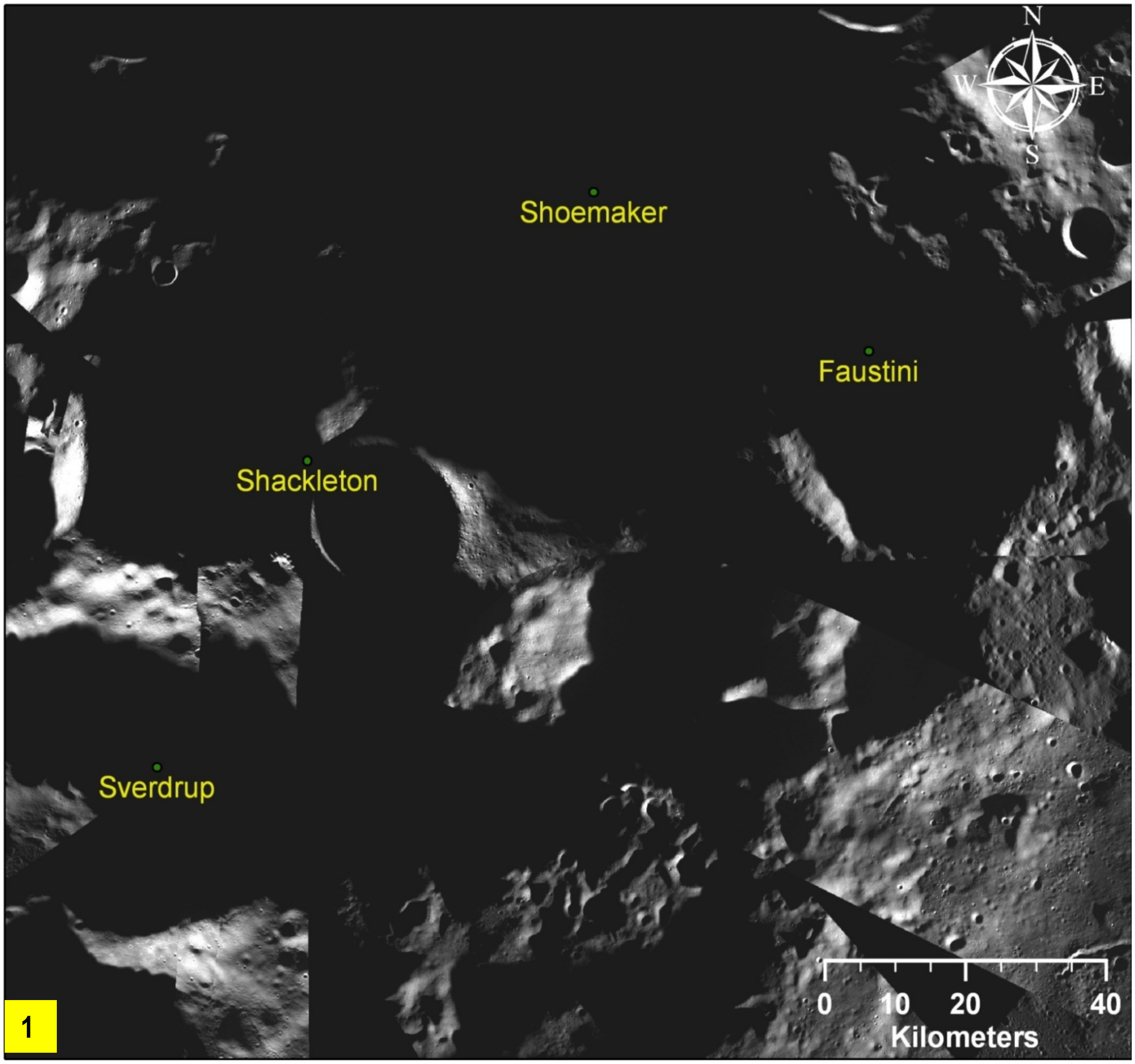
Mosaic of TMC images showing South pole of the Moon and some of the large impact craters.

North pole of Moon from TMC



Mosaic of TMC images showing north pole of the Moon

Permanently shadowed regions of the Moon

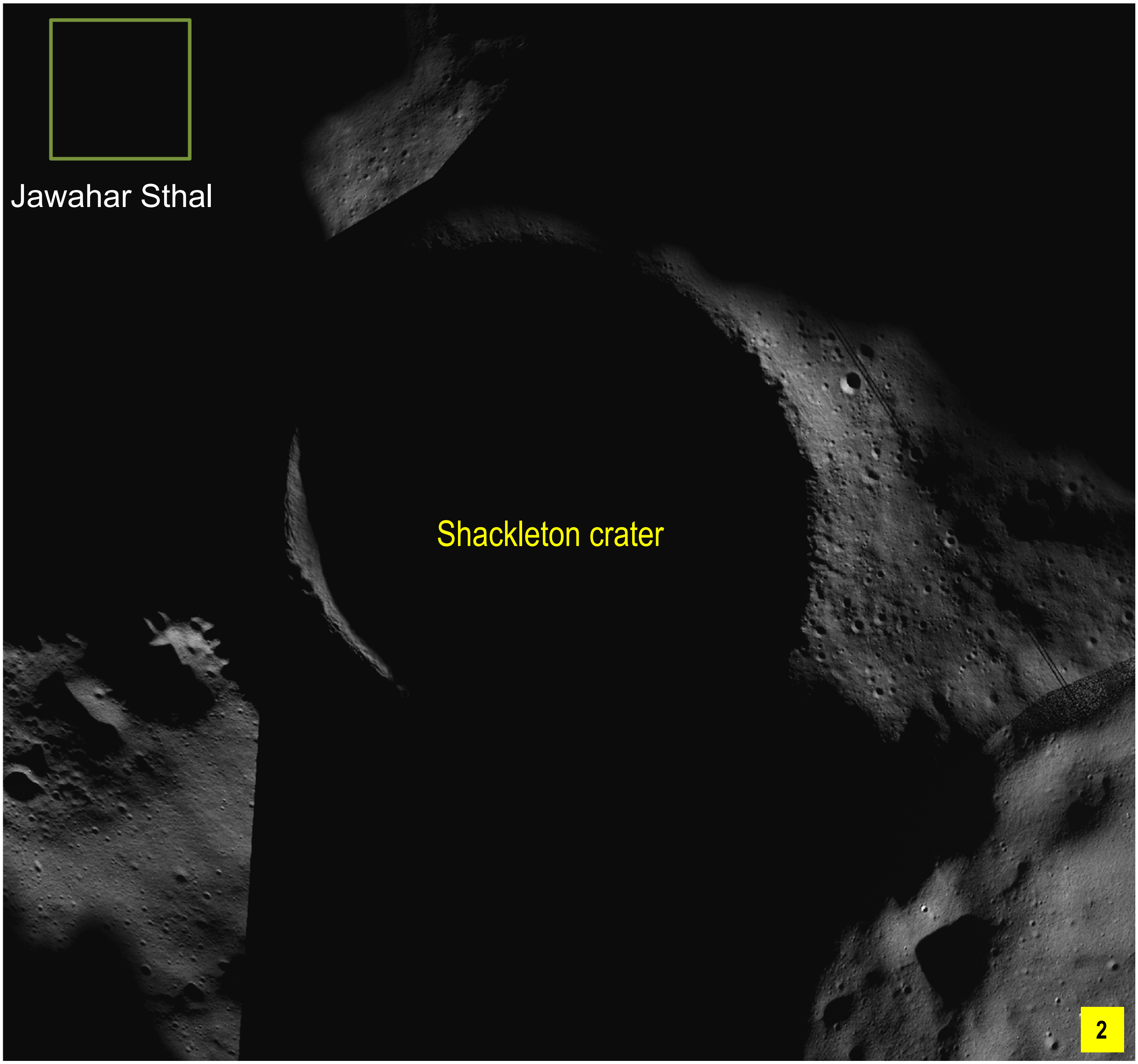


A permanent shadowed crater on the Moon is defined as an area on the surface of the Moon that never receives sunlight. This occurs at the poles since the Moon's axis of rotation is nearly perpendicular to the plane of its orbit around the Sun, so the Sun is always low, close to the horizon, casting long shadows off the crater rims or any other high point.

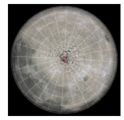
Temperatures in these regions never exceed about –230°C causing possible water in them is cold enough at all times that it cannot evaporate or even sublimate making them the high potential areas for water ice deposits.

The polar areas are also a hub of large amounts of vapor-mobilized elements, where permanently shaded crater floors can act as long-term cold traps or potential sites for volatile substances.

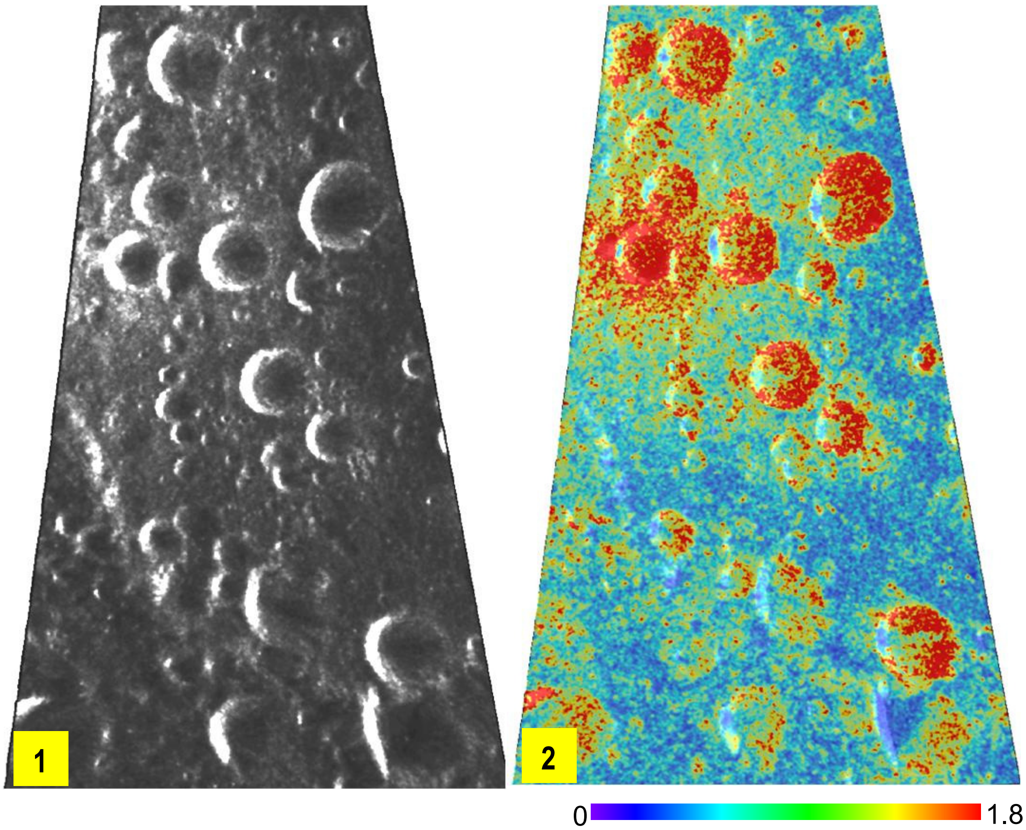
1. TMC mosaic showing permanently shadowed craters of the south pole of the Moon.
2. Close view of the Shackleton crater from TMC image also showing location of Jawahar Sthal, landing place of Moon Impact Probe.


Jawahar Sthal
Shackleton crater
2

Results from Mini SAR: Detection of water ice deposits



Lunar North Pole



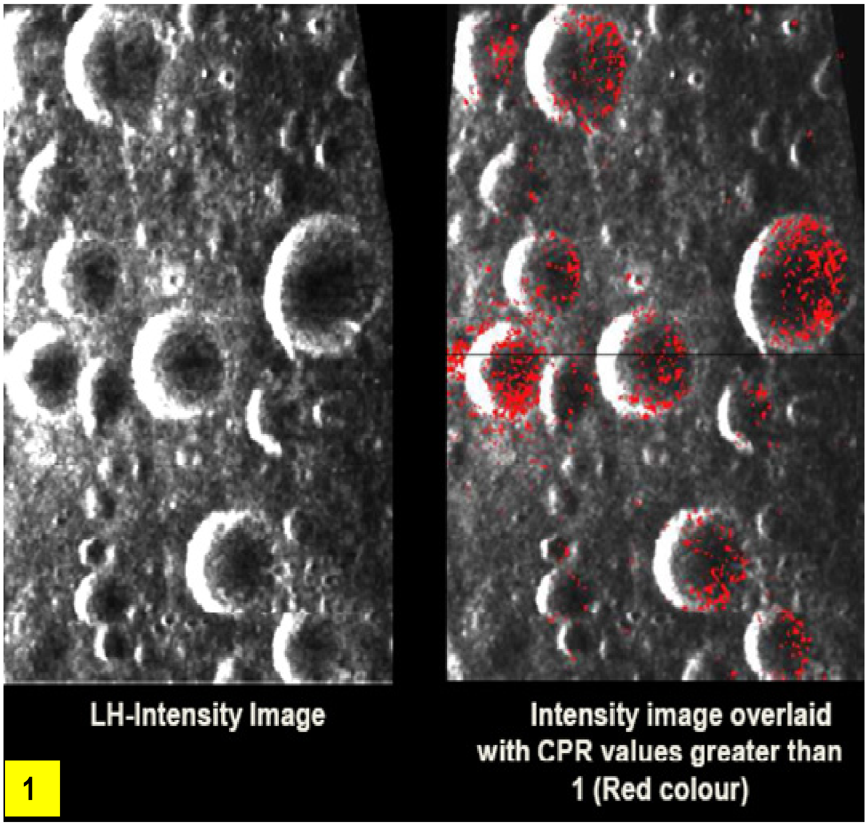
1. SAR backscatter intensity image of secondary craters on the floor of Peary crater in the lunar north polar region as observed by Mini-SAR.

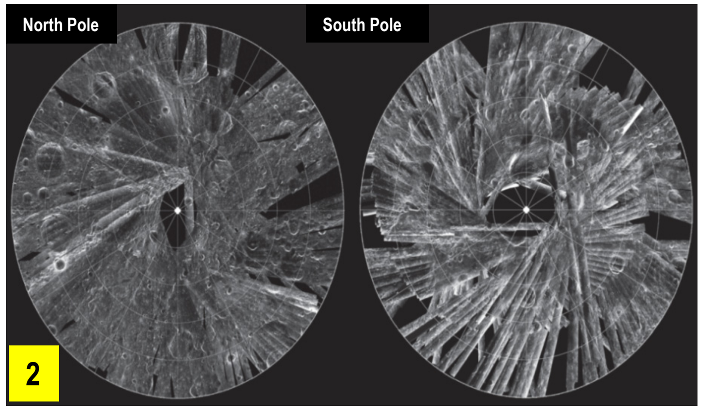
2. Corresponding color-coded circular polarization ratio image. The CPR values span the color spectrum from purple through red for values between 0 and 1.8. Higher values of CPR are assigned red color.

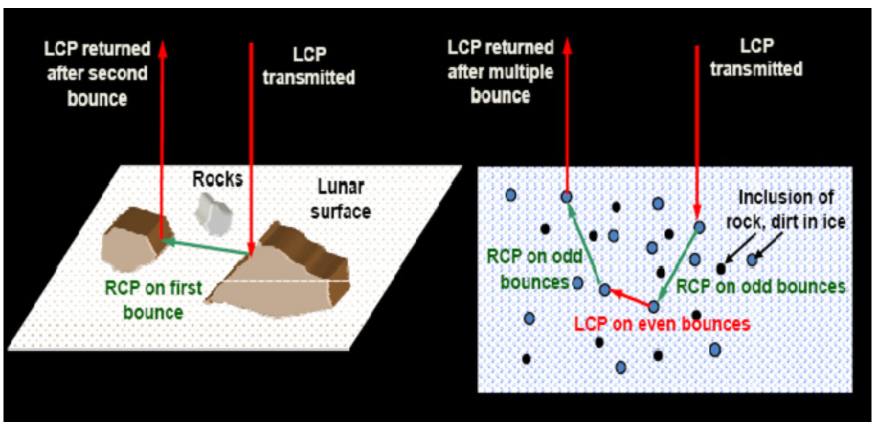
Secondary craters on the floor of Peary Crater

Secondary craters on the floor of Peary crater (88.6°N 33.0°E) near lunar north pole as observed by Mini-SAR sensor of Chandrayaan-1. The left picture shows SAR backscatter intensity image and the right picture shows corresponding color-coded image of circular polarization ratio (CPR). Higher CPR values corresponding to the scattering from water-ice bearing regolith are depicted in red color in the map. The secondary craters on the floor of Peary crater are among the most probable regions identified for the existence of water-ice in lunar polar regions. These smaller craters due to their proximity to the lunar north pole never receive sunlight and are believed to be in permanent darkness since millions of years accumulating substantial quantities of water molecules to form water-ice deposits. These craters along with some more polar craters were imaged for the first time by Chandrayaan-1 Mini-SAR sensor.

Polar water Ice deposits using Mini SAR





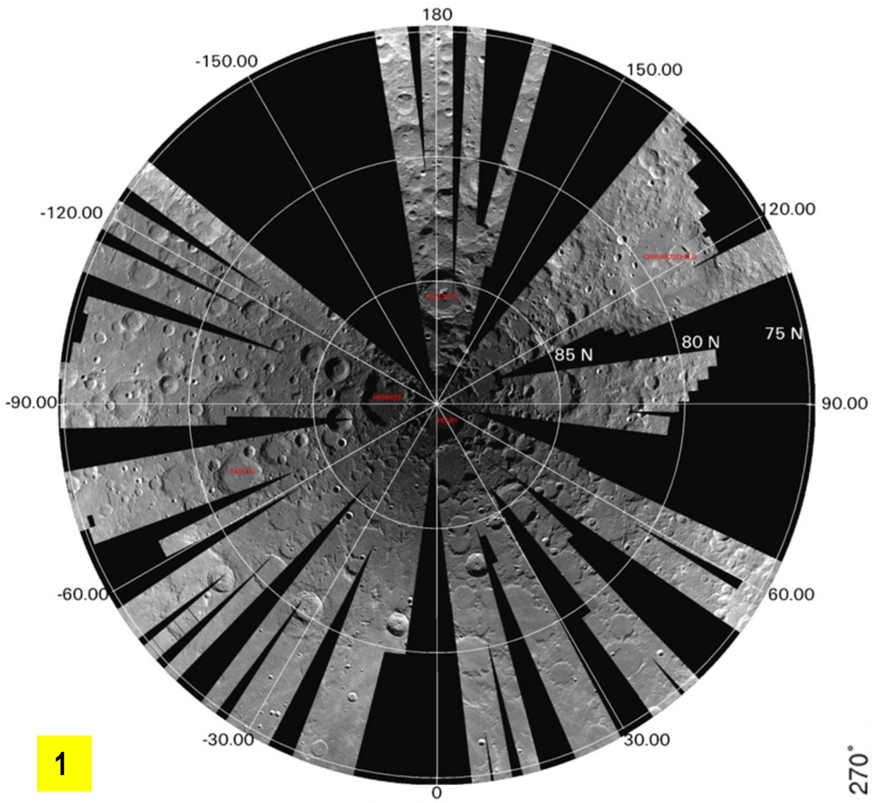


1. SAR backscattered L-H intensity image of Peary crater situated on north pole along with the intensity image overlaid with CPR greater than 1 (red color). Volumetric water-ice reflections are known to have CPR greater than unity while surface scattering from dry regolith has CPR less than unity.

2. Mosaic of polar regions showing Mini SAR data collected during its first imaging season. Mosaic cover within 10 latitude of each pole.

3. Image showing principle of Circular Polarization ratio for Ice detection.

Lunar Topography using Lunar Laser Ranging Instrument (LLRI)



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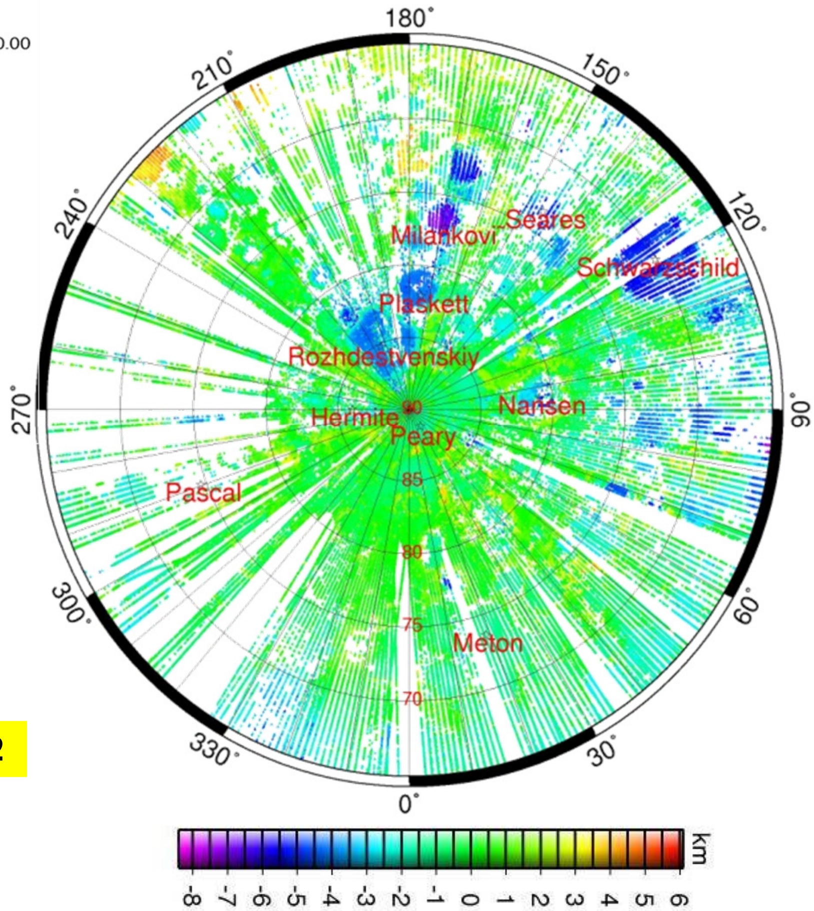
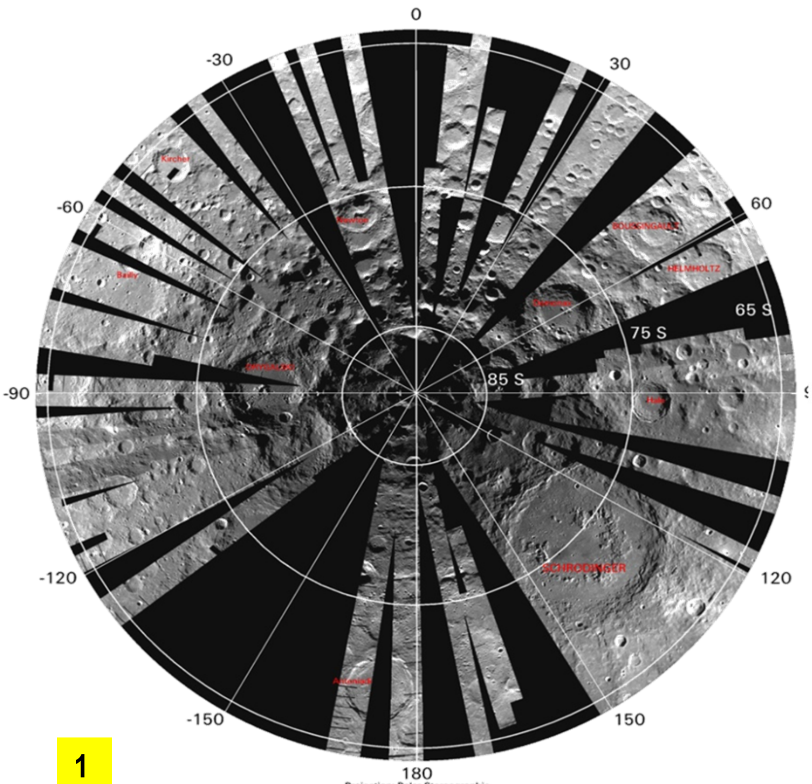


2

1. TMC mosaic of the north polar region of the Moon.

2. Mosaic of the LLRI derived topography of north polar region of the Moon.

Lunar Topography using Lunar Laser Ranging Instrument (LLRI)



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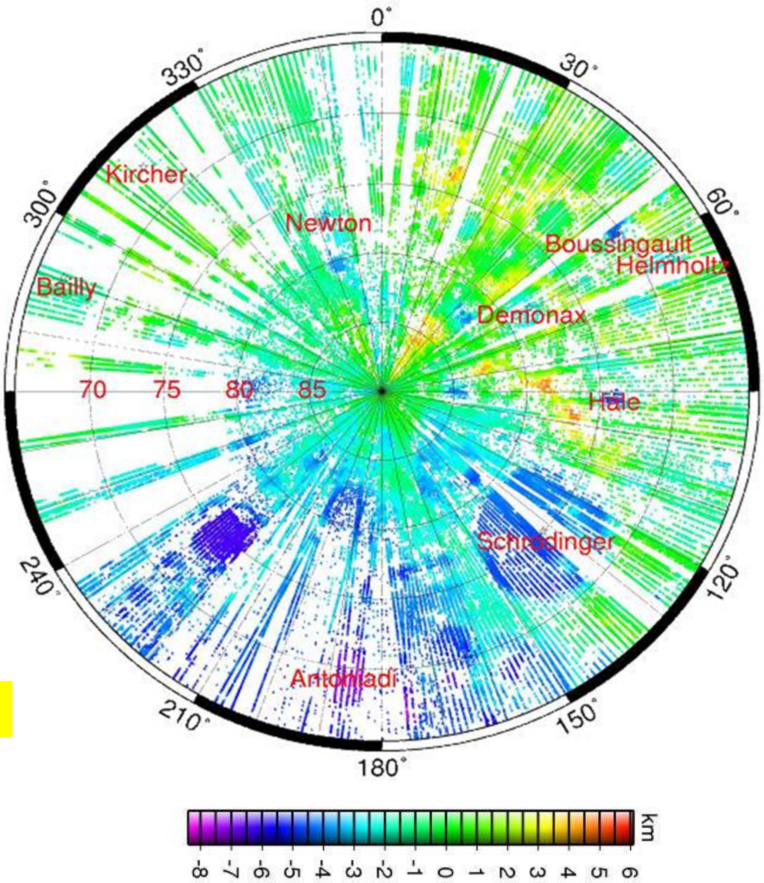
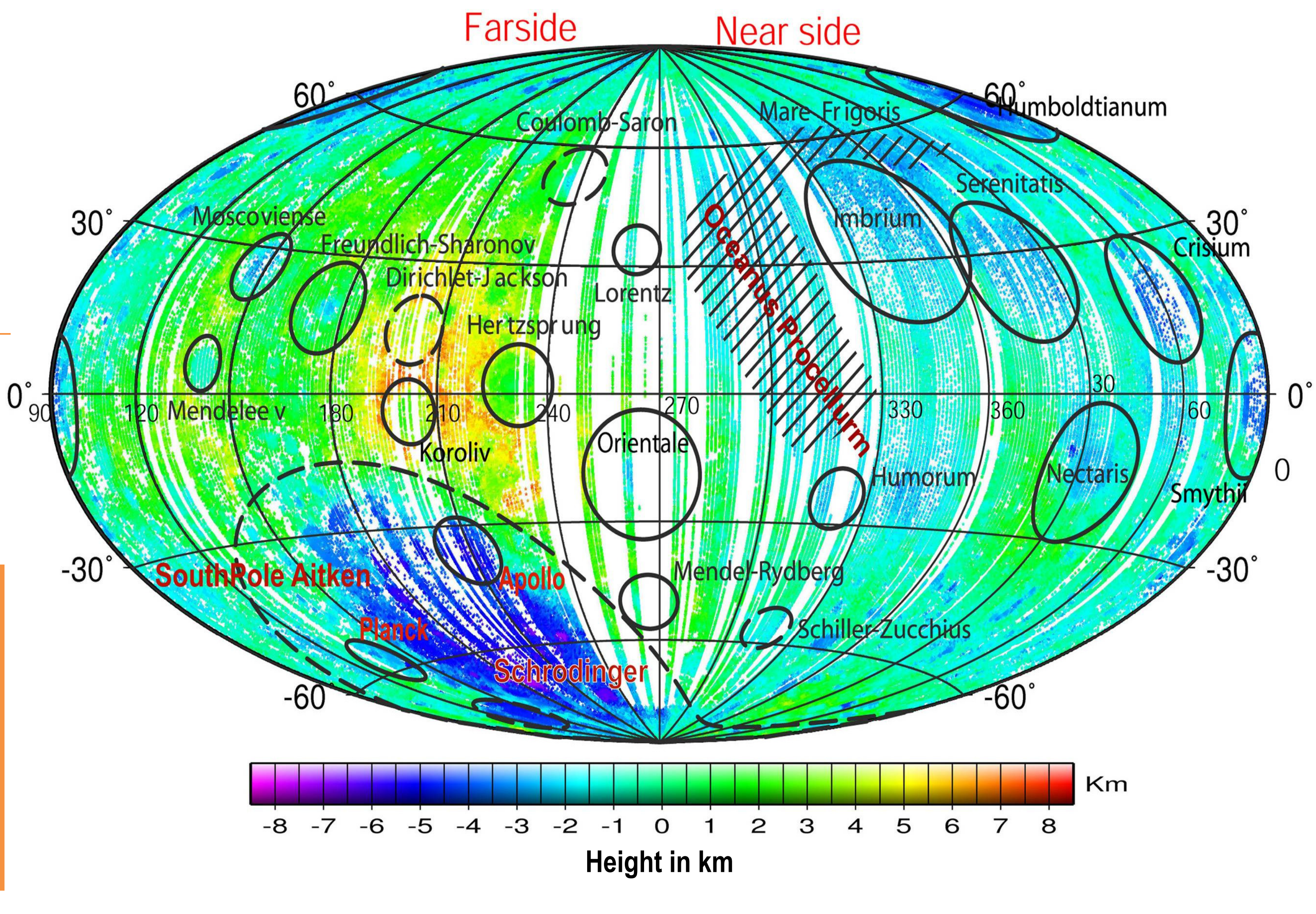


2

1. TMC mosaic of the south polar region of the Moon.
2. Mosaic of the LLRI derived topography of the south polar region of the Moon.

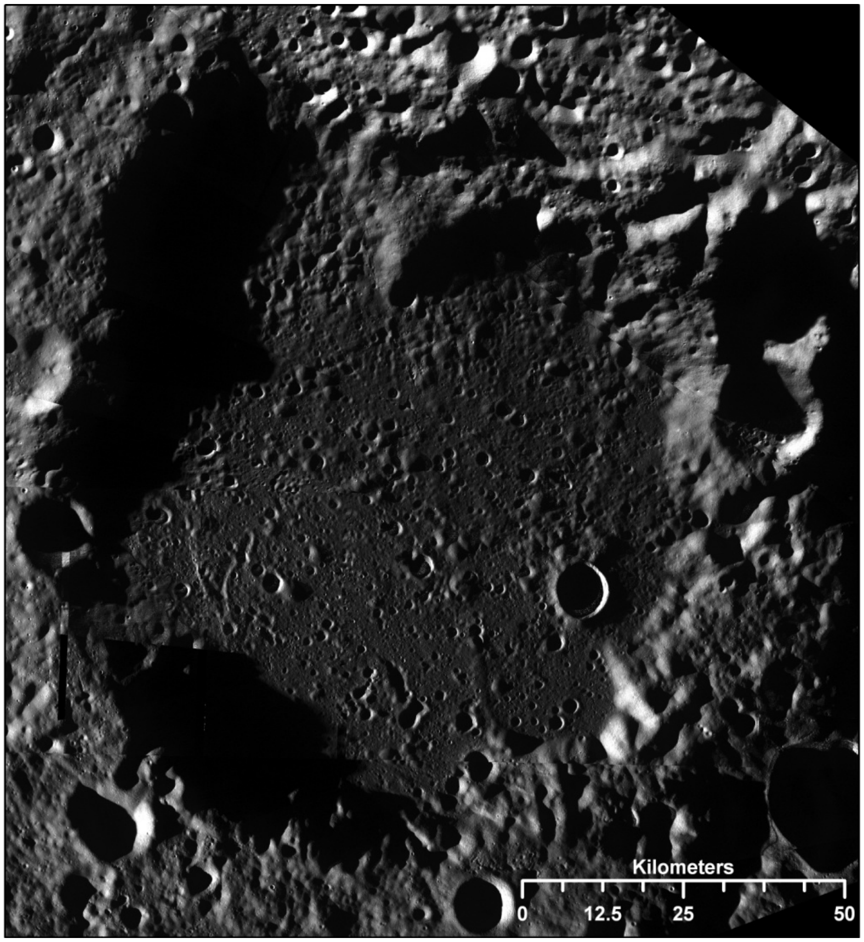
Lunar Topography using Lunar Laser Ranging Instrument (LLRI)

Global topography of the lunar surface derived from LLRI data showing the height variation between the various mare basins and highlands of the far and near side of the Moon. Deepest Lunar basin known as South Pole Aitken (SPA) Basin is seen on the bottom of this image.

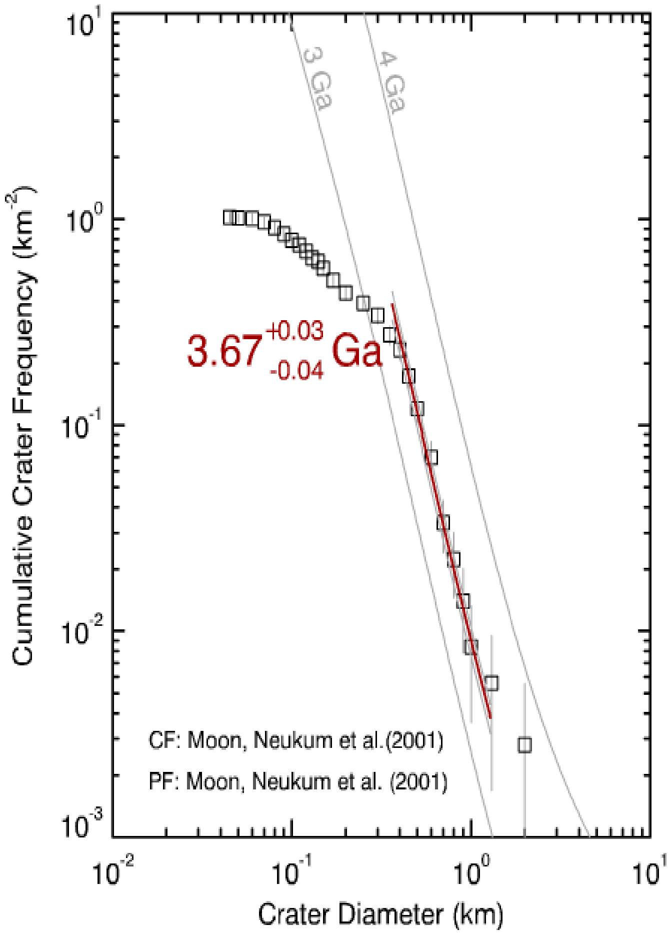


Lunar Surface Age Determination : Hermite Crater in Lunar North Pole

Hermite crater (~104 km, diameter) is an impact crater located close to the north pole of the Moon. Some of the portions of this crater are permanently shadowed including the coldest place -249^{0}C in the solar system. Age of the Hermite crater was determined by crater counting and using crater size frequency technique from high resolution TMC images, which is about 3.91 billion years (Ga).



TMC Image mosaic of Hermite crater

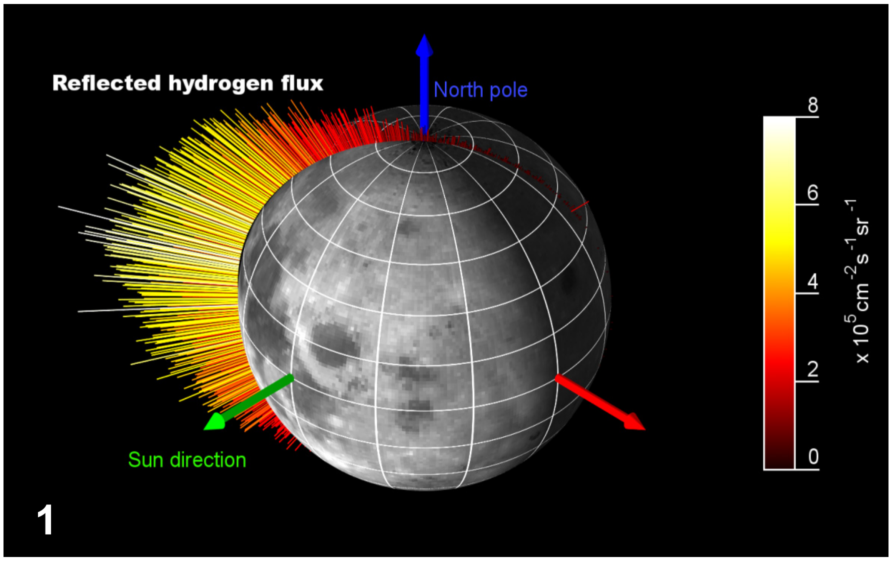


Surface age of Hermite crater determined using Cumulative crater size frequency technique

Miscellaneous Results

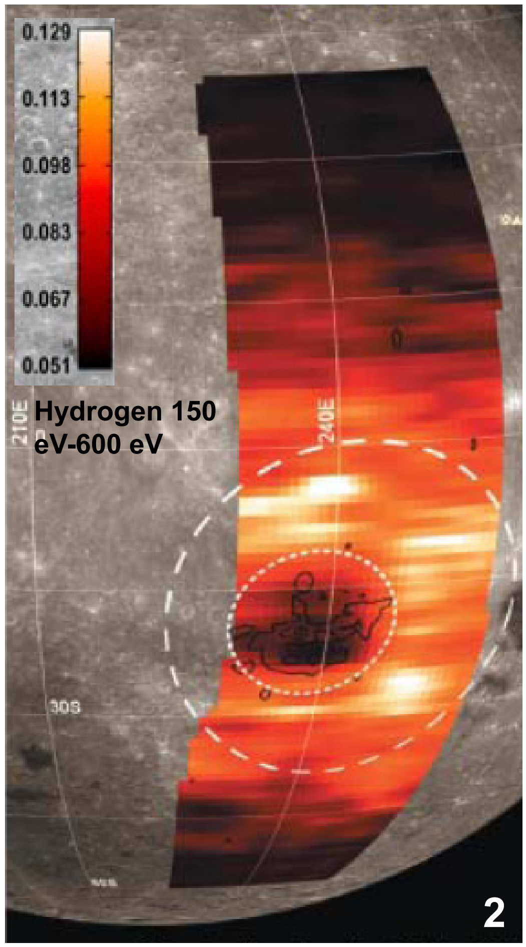
Solar wind interactions with Lunar Surface

The Sub-keV Atom Reflecting Analyzer (SARA) experiment had the objective to explore the physical processes happening during the interaction of solar wind with Moon. The objective was achieved by the measurement of particles energetic neutral atoms (ENA) and plasma which are produced in the interaction and carries the signature of the processes. SARA consisted of two sensors: CENA (Chandrayaan-1 Energetic Neutrals Analyzer), and SWIM (Solar Wind Monitor), and a digital processing Unit (DPU). Data obtained by SARA showed that up to 10% of the solar wind incident on the lunar surface is reflected back to the space. An completely unexpected result from the SARA experiment added a new dimension to solar wind-lunar surface interactions at sub-microscopic level.



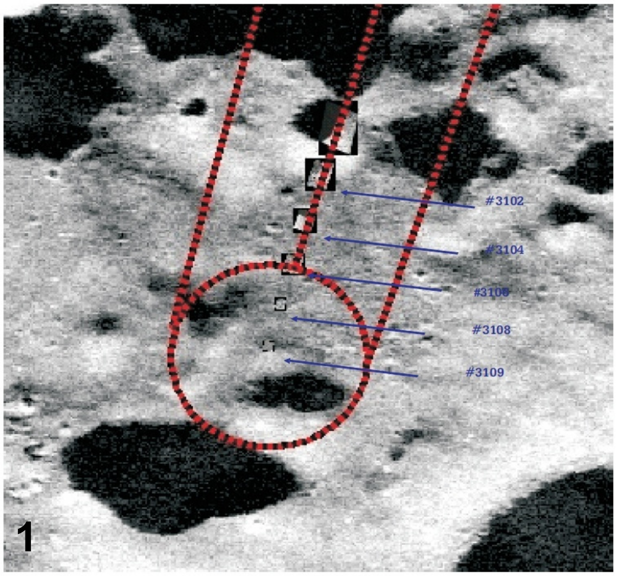
1. Map showing scattered energetic neutral hydrogen atoms observed by SARA on 6 February 2009. Green arrow indicates the direction of Sun. The color and length of the lines indicates the ENA flux.

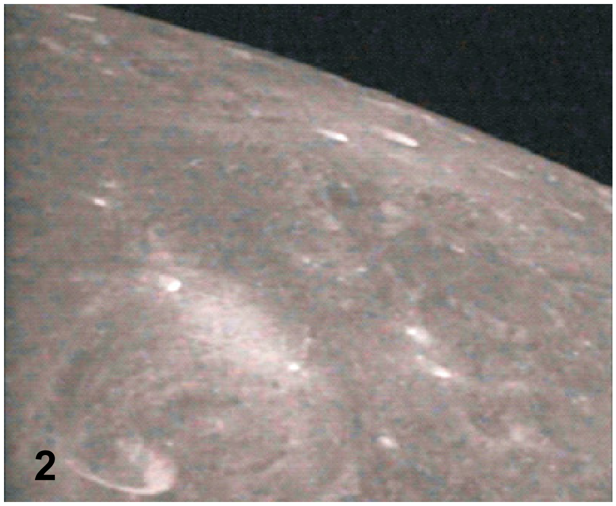
2. The energetic neutral hydrogen flux from the surface over the magnetic anomaly near 22^0S and 240^0E on the lunar far side based on the observation on 17 June 2009. The maps show a unit-less reflection coefficient: neutral hydrogen number flux integrated over the specified energy range divided by total solar wind number flux integrated over energy and cosine of lunar latitude in the energy ranges.

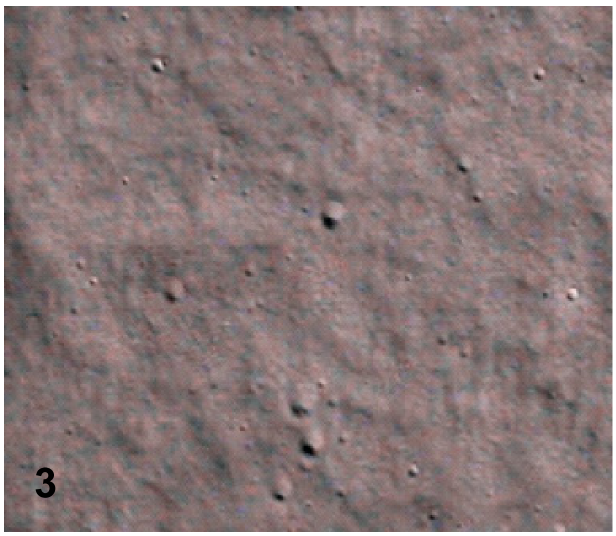


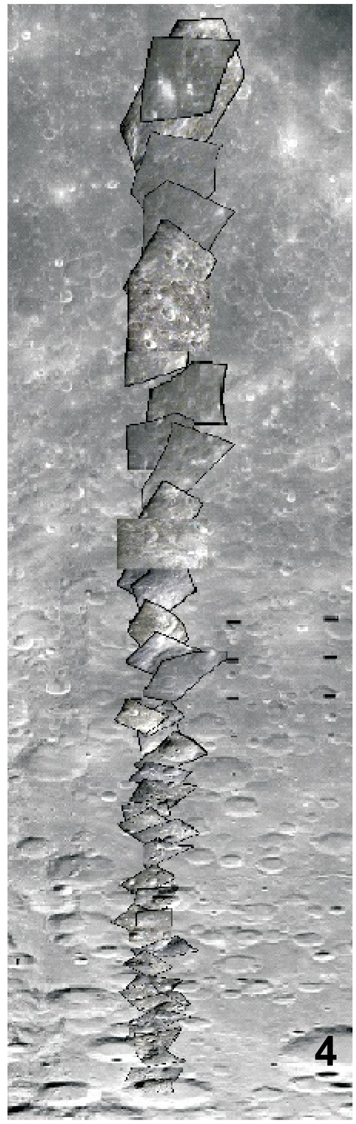
(Wieser M. et al. 2009)

Moon Impact Probe (MIP) experiment









MIP carried three instruments viz. Radar altimeter, Mass Spectrometer and Moon Imaging system (MIS) and operated during the descent to the Moon and imaged the lunar surface in a total of 3110 frames. Some of the example MIP frames are

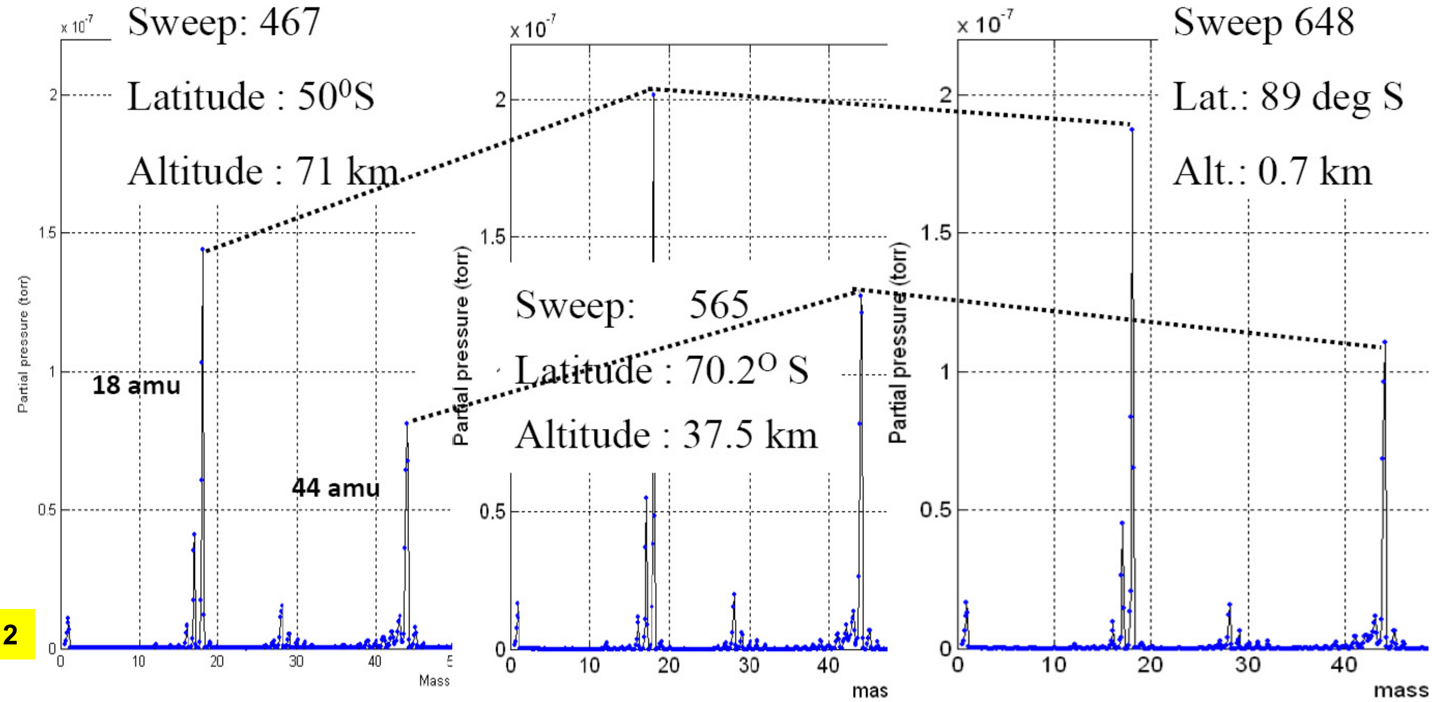
1. Image showing probable impact site of MIP. The frames 3102, 3104, 3106, 3108, 3109 overlaid on SAR data using calculation of distance traveled with speed and time of travelling.
2. Frame Number – 1455 of MIS camera
3. Frame Number – 3105 of MIS camera
4. MIS images overlaid on Clementine Equatorial mosaic image after the seleno-refrencing of selected frames of the MIS images.

Water Molecules and CO_2 in Lunar Exosphere

The mass spectrometer on board the MIP called Chandra's Altitudinal Composition Explorer (CHACE) has discovered CO_2 and water molecules in the tenuous atmosphere near to the surface of the Moon, during MIP descent. The results give an insight into a hydrological processes on the Moon and a hint towards the composition of the lunar atmosphere.

Figure 1 shows the picture of the CHACE instrument while figure 2 shows 18 amu (presence of water) and 44 amu (carbon dioxide) line at a distance of 71, 38, 0.7 km from the surface of the Moon, respectively.

1



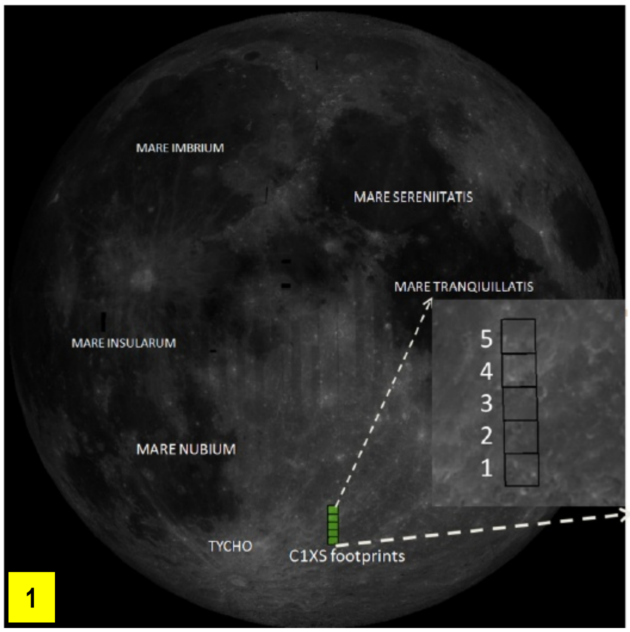
2

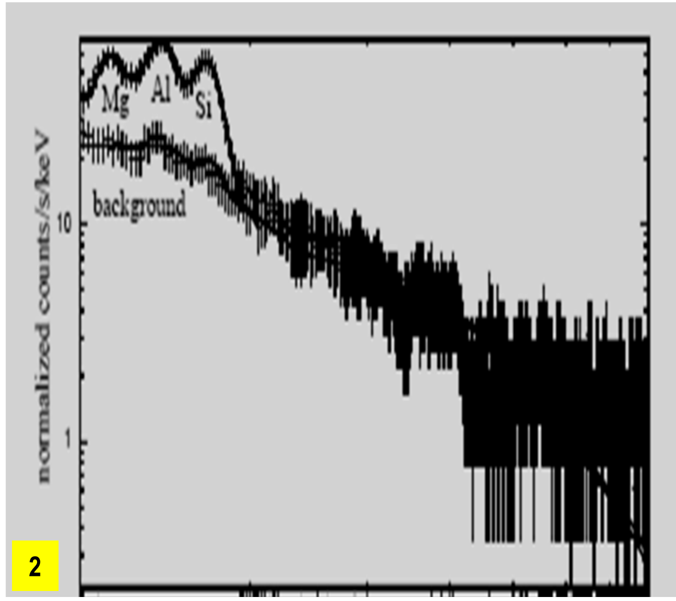
Sridharan et al. (2010)

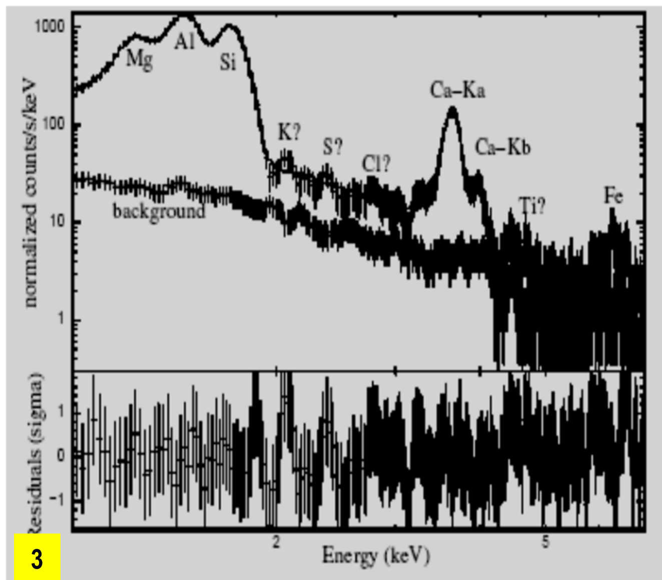
Lunar Elemental Abundance using C1XS

The Chandrayaan-1 X-ray Spectrometer (C1XS) on-board the Chandrayaan-1, measured X-ray fluorescence spectra during several episodes of solar flares. The accompanying X-ray Solar Monitor (XSM) provided simultaneous spectra of solar X-rays incident on the Moon which are essential to derive elemental chemistry.

Surface abundances of Mg, Al, Si, Ca and Fe, were derived from C1XS data for a highland region on the southern nearside of the Moon. New analysis techniques were developed in detail including absolute X-ray line flux derivation and conversion into elemental abundance. The results were found consistent with a composition rich in plagioclase with a slight mafic mineral enhancement and a Ca/Al ratio that is significantly lower than measured in lunar returned samples.







1. Location of the C1XS observation foot print
2. Lunar X-Ray fluorescence spectra during a moderate solar flare event
3. Lunar X-ray fluorescence spectra showing peak for Ca-Ka elements.

(Narendranath et al. 2011)

Publications on Chandrayaan-1 Results

Publications List

1. Bhattacharya, S., Chauhan, M. and Chauhan, P., **2015**. Remote detection of magmatic water in association with olivine of possible mantle origin. 46th Lunar and Planetary Science Conference, Abstract #1396.
2. Chauhan, M., Bhattacharya, S., Saran, S., Chauhan, P., Dagar, A., **2015**. Compton-Belkovich Volcanic Complex (CBVC): An ash flow caldera on the Moon. Icarus, http://dx.doi.org/http://dx.doi.org/10.1016/j.icarus.2015.02.024.
3. Chauhan, M., Bhattacharya, S., and Chauhan, P., **2015.** Understanding the nature of possible olivine-chromite exposures at craters Aristoteles using high-resolution remote sensing data. 46th Lunar and Planetary Science Conference, Abstract #1403.
4. Chauhan, M., Bhattacharya, S., and Chauhan, P., **2015.** Analysis of pryoxene mineralogy of basalts at Hansteen Billy, Moon through Chandrayaan-1 moon Mineralogy mapper (M^3). 46th Lunar and Planetary Science Conference, Abstract #1407.
5. Kaur, P., Chauhan, P. and Rajawat, A.S., **2015**. Mapping of olivine rich layer in Nectaris basalts using Moon Mineralogy Mapper (M^3) onboard Chandrayaan-1. 46th Lunar and Planetary Science Conference, Abstract #1973.
6. Kaur, P., Chauhan, P., Rajawat, A. S. and Kiran Kumar, A.S., **2015**. Study of olivine rich dark-haloed crater Beaumont L in Mare Nectaris using high resolution remote sensing data. Planet. Space Sci., 109,-110, 92-105.
7. Arya, A.S., Rajasekhar, R.P., Amitabh, Gopala Krishna, B., Ajai, Kiran Kumar, A.S. **2014**. Morphometric, rheological and compositional analysis of an effusive lunar dome using high resolution remote sensing data sets: A case study from Marius hills region. Advances in Space Research, Vol. 54,10, pp. 2073-2086.
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