Evidences of relatively new volcanic flows on the Moon

R. P. Gupta[1,*], N. Srivastava[2] and R. K. Tiwari[1]

[1]Department of Earth Sciences, Indian Institute of Technology-Roorkee, Roorkee 247 667, India
[2]Planetary Sciences and Exploration Programme, Physical Research Laboratory, Ahmedabad 380 009, India

It is generally believed that the Moon became internally dead ~1 b.y. from the present, and only old (□ 1 b.y.) volcanic flows forming largely the mare basins are known to occur. The old volcanic landforms stand largely obliterated and flows studded with impact craters. However, recent findings have indicated global presence of young thrust faults on the Moon, escape of gases from the interior and also predicted the presence of partially molten lower lunar mantle and core. Here, we have used high-resolution datasets from NASA's LRO, Kaguya of JAXA and ISRO's Chandrayan-1 missions to examine the characteristics and origin of multiple relatively fresh, coaxial, superposed viscous flows spotted inside the Lowell crater on the far side of the Moon. Various considerations apparently rule out the possibility of these melts being derived from nearby areas. An associated likely source crater and tectonic structures (a fault and a fracture) of two different ages but emanating from the same crater and affecting different flows have also been located – exhibiting tectono-volcanic relationship. These features provide evidences of likely volcanic activity in the region not too far in the past, are consistent with recent results that the Moon may not be internally dead, and thus have implications to the thermal history and present-day geologic nature of the Moon.

Keywords: Craters, Moon, tectonic features, volcanic flows.

GEOLOGIC state of the Moon has been debated for long among the lunar science community. Conventional wisdom suggests that the Moon became internally largely inactive around 3 b.y. ago due to global cooling and contraction[1–3]. Presence of relatively younger extrusive events, ~1–2.5 b.y., was reported only from the enigmatic Procellarum KREEP Terrain which is enriched in heat-producing radioactive elements U, Th and K (refs 2–5). However, observations from high-resolution global lunar missions, viz. Chandrayaan-1, Kaguya and Lunar Reconnaisance Orbiter (LRO) have revealed the occurrence of volcanic formations formed during the similar time-frame also at certain other sites across the Moon such as in the Moscoviense basin, Orientale basin and Compton–Belkovich region[6–9]. Thus, these recent observations have extended the areal extent of lunar volcanism (~1–2.5 b.y.) beyond the Oceanus Procellarum on the western near-side of the Moon. Still, this implies that on the Moon only old (□1 b.y.) volcanic flows occur that form largely the mare basins, and the related volcanic landforms stand largely obliterated and flows studded with impact craters.

In addition, several related researches during the past decade have yielded further insight into the geologic state of the Moon. Morphological and spectral reflectance study of the central peak of Tycho crater has revealed possibility of impact-induced volcanism ~100 Ma ago[10]. Studies of the conspicuous 'Ina' structure have pointed towards the likelihood of gas release from the Moon's interior within the last ~1–10 Ma (ref. 11). Besides, Transient Lunar Phenomenon (TLP) has been observed and it has been advocated that at least some of the TLP might be related to the escape of gases from the interior of the Moon[12–14].

Further, re-analysis of Apollo seismic data and experimental studies using lunar analogues and simulations has predicted partially molten lower lunar mantle and core[15,16]. Recent findings such as global presence of fresh thrust faults have indicated the possibility of tectonic-magmatic activity not too far in the past[17–19]. Recently, Srivastava *et al.*[20,21] have provided evidences favouring occurrence of possibly recent volcanic activity, ~2–10 Ma old, in a graben-like structure in the Lowell crater situated in the far-side segment of Orientale basin (Figure 1). Here, we present another case of a set of multiple coaxial small recent flows located within the graben-like structure described earlier[21] and provide evidences of their likely volcanic origin.

Methods

We have used datasets from the NASA's LRO, JAXA's Kaguya and ISRO's Chandrayan-1 missions (Table S1, see Supplementary Information online) to make a focused study of an area ~15 sq. km in extent centered at (–13.249°, –102.814°), as also an evaluation of regional setting. LROC–NAC (NASA)[22] images have been used for photo-geologic image interpretations. Topographic

---

*For correspondence. (e-mail: rpgesfes@iitr.ac.in)

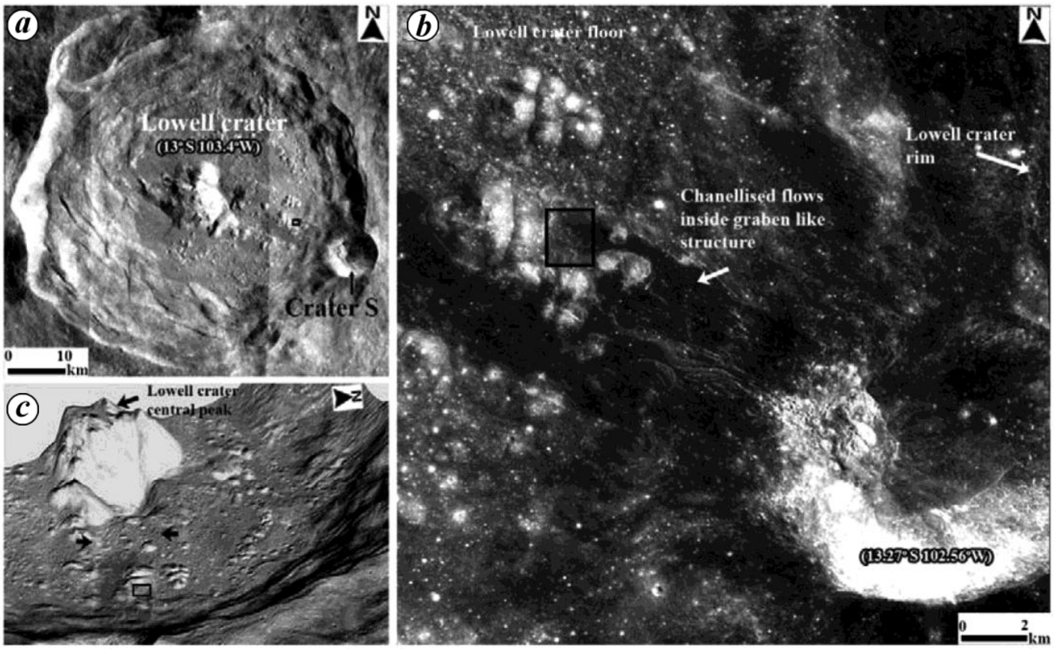

Figure 1. Synoptic view showing the regional setting. ***a***, The Lowell crater from Kaguya-TC image mosaic; several tectonic fractures and lineaments are seen; a crater *S* (~ 9 km dia) appears on the rim. ***b***, A larger view of the crater *S* and adjacent areas. Note the channelized flows from crater *S* are confined to a graben-like structure. ***c***, Perspective view of the valley-shaped interpreted graben, the site of the channelized flows. Location of the small flows specifically studied here is indicated by dark rectangle in all the three images. Figures ***b*** and ***c*** modified from Srivastava *et al.*[21].

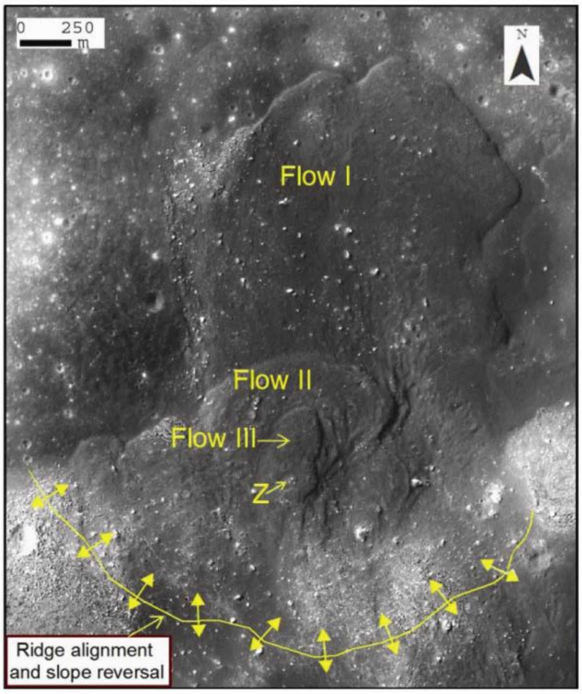

Figure 2. LROC–NAC subscene of the study area showing the presence of three flows (I, II and III) lying over one another such that flow-I is the oldest followed by flow-II and flow-III, successively (LROC–NAC image M184196652L); all the flows have flow towards north; absence of any identifiable primary impact crater (>5 m in diameter) on any flow suggests that these flows are relatively new; note the presence of crater *Z*, standing out centrally piercing through all the three flows on their up-gradient side. Regional topographic profiles (see Figure 3) indicate the presence of topographic ridge alignment causing slope reversal in the south.

profiles have been plotted using Digital Terrain Model (DTM) from Kaguya-Terrain Camera[23]. Due to non-availability of high-resolution DTM of the area, a relative DTM of a small area of interest has been generated using LROC–NAC images acquired during different orbits and the LPS software (see Appendix I in Supplementary Information online). Hyperspectral data from NASA's Moon Mineral Mapper (M^3)[24,25] onboard Chandrayaan-1 (ISRO) has been used to assess the surface composition.

Observations

In the area under investigation, three small flows (I–III; Figure 2), lying one over another, are distinctly observed. From their overlapping pattern, it is obvious that flow-I is the oldest in age, followed by flow-II and flow-III. These flows have a typical fan–lobate–lingulate shape, ropy surface, and appear to slope and spread out northward, the melt flow direction as indicated by surface textural features being northward. For a topographic assessment, profiles from Kaguya TC DTM data were generated and these profiles confirm that the local gradients in the flow area are from the south to north (Figure 3). Further, there is a topographic ridge (Figures 3 and 4) about 150–200 m high in the area south of the study area.

The areal extent of the three flows is estimated to be 2.3, 0.5 and 0.1 km^2 respectively. With the thickness of the three flows being ~50, ~40 and ~35 m, respectively (Figure S1, see Supplementary Information online), it is

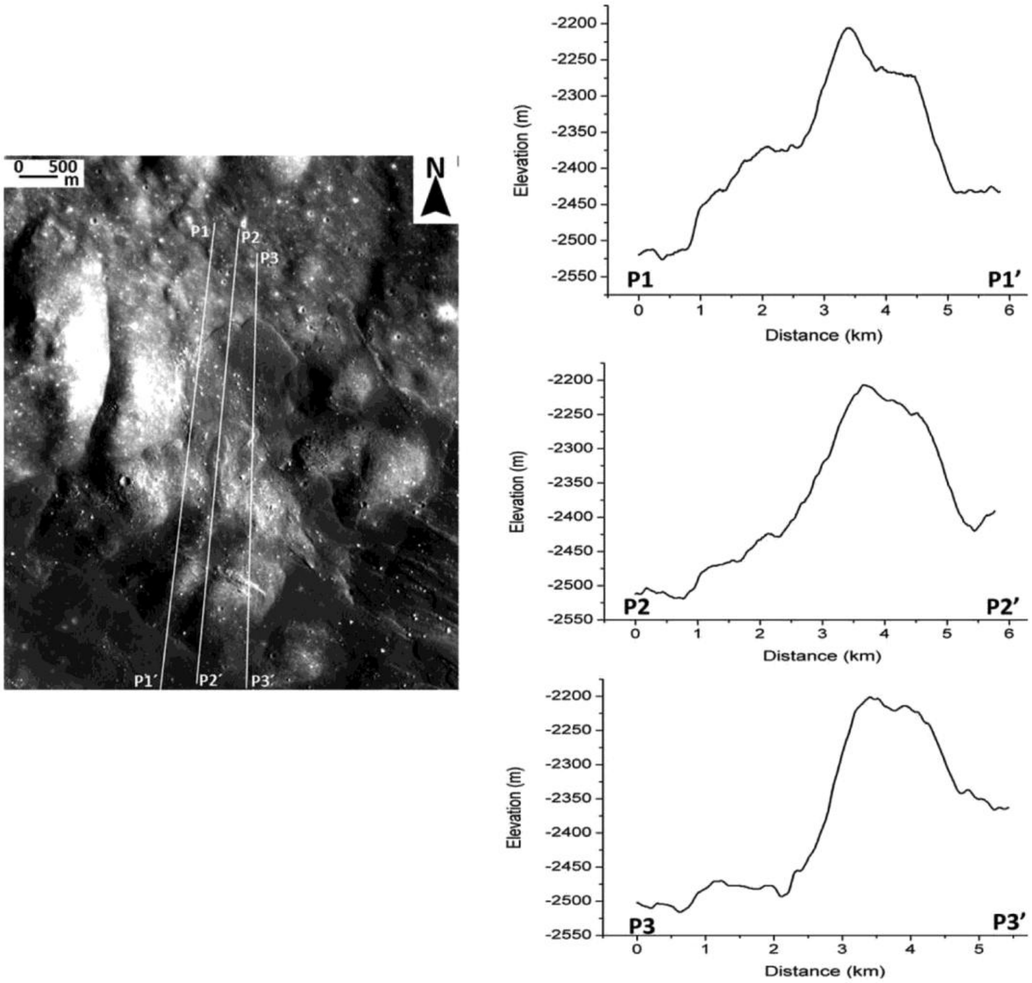

Figure 3. Topographic profiles generated from Kaguya TC data showing the presence of ridge alignment and slope reversal in the area south of the flows. The location of profile lines *P*1–*P*1′, *P*2–*P*2′ and *P*3–*P*3′ is shown in the accompanying LROC–NAC image. Note the presence of topographic depression (approx. 150–200 m deep) towards south of the ridge.

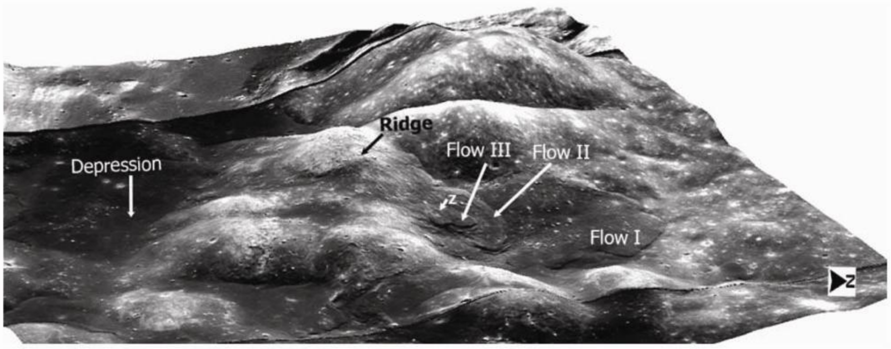

Figure 4. A perspective view generated from LROC–NAC image data draped over Kaguya TC DTM; note that to the south of the three small flows under study, there occurs a ridge followed by a topographic depression; location of crater *Z* is also marked.

estimated that they have volumes of approx. 0.115, 0.02 and 0.0035 km^3 respectively; cumulatively the viscous flow volume being ~0.1385 km^3.

A detailed examination of the LROC–NAC image (Figure 5) has revealed the presence of a small (65–70 m), but unique crater (*Z*; lat. –13.249, long. –102.814) situated within the flows on their up-gradient (south) side. Most of the flow lines appear to radiate from the crater *Z* (Figure 5 *b*). Further, there is a fault trace (*F*1 in Figure 5) on the youngest flow-III, which can be traced to

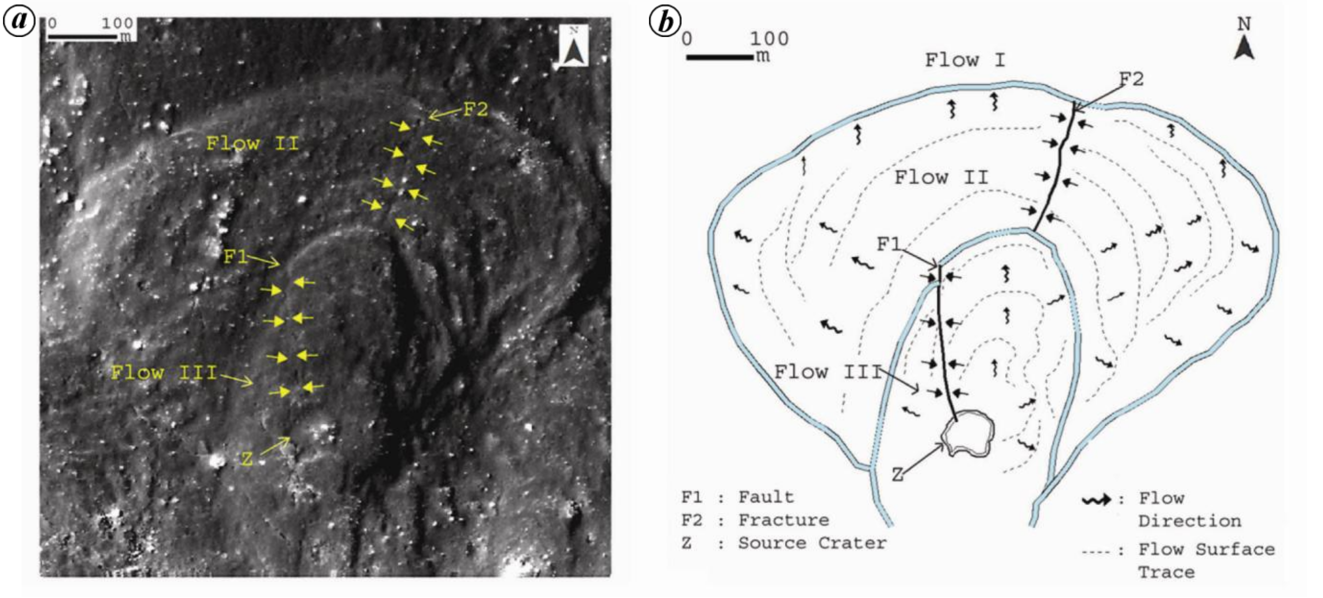

Figure 5. ***a***, Enlarged view of the area around crater *Z*. Note the presence of a fault (*F*1) in flow-III and fracture (*F*2) in flow-II, both oriented such that they can be traced to crater *Z*. Traces of *F*1 and *F*2 are indicated by short arrows on either side; LROC–NAC image M184196652L. ***b***, Interpretation map of the image in Figure 5 *a*.

inside the rim of the crater *Z*, as if it is a radial fault emanating from the crater. (Note: The fault displacement is even more clearly observed in the enlarged image; Figure 6 *a*.) Besides, one more prominent fracture-lineation (*F*2 in Figure 5) is also visible on the surface of the middle flow-II. It is partially concealed under the upper flow-III, and is also oriented such that it can be traced to the same crater *Z*. Thus, faults/fractures *F*1 and *F*2 of definitely two different ages are present and appear emanating from the same crater.

Discussion – origin of the flows

There could be only the following possibilities for the origin of the set of three viscous flows under consideration: (1) The flows are of impact origin from crater *Z*; (2) They are impact melts transported from a distant location; (3) They are endogenically produced, *Z* being the possible source crater.

The crater *Z* is a localized feature, is about 65–70 m wide, and stands out centrally piercing through all the three flows on their up-gradient (south) side (Figures 3–5). If this were an impact crater, with a diameter of about 70 m, depth of 14 m (assuming depth/diameter ratio of 0.2) and assuming semi-ellipsoid crater concavity, the amount of material removed would be approx. 0.00007 km^3, which is hardly a fraction of the melt volume of even the smallest and youngest flow (flow-III, volume = 0.0035 km^3) estimated above. Further, craters as small as these on the Moon are not known to be associated with impact melt sheets; the minimum sized impact crater known to exhibit melt deposits on the Moon is ~170 m in diameter[26]. Therefore, the possibility that these could be impact melts from crater *Z* is ruled out.

In the initial stages of lunar research, it was considered by some workers[27,28] that fresh viscous flows on the Moon could be of volcanic origin. However, subsequent workers[29–32] used various criteria (viz. vicinity of impact craters, viscous flow channel extension from impact craters, emplacement of melts in the impact direction, lack of source vent, etc.) to ascribe impact origin to fresh lunar viscous flows. It has been shown that lunar impact melts can be transported to long distances away from the impact site leaving only veneers and blocks in the path[31].

We have gone through the literature carefully particularly with a view to make a comparative study of such flows and features with those present in our study area. The most comparable case could be the flows of Giordano Bruno area, where multiple flows in a more or less coaxial-channel pattern occur and are interpreted to be the result of multiple and extended periods of melt remobilization[30,31]. However, a major difference is that the triplet of Giordano Bruno flows can be continuously and clearly traced up-gradient to a large source crater; in contrast, there is no continuity of the flows under consideration to any up-gradient likely impact source crater. It may be mentioned that a large impact crater is located in the SE ~9 km away from the study area (Figure 1). However, this is unlikely the possible source for the entire triplet of flows, since, except for flow-I, the eastern part of which could possibly contain a mixture of melt from the large impact crater mentioned above, the other two flows clearly lack any continuity towards south/southeast and appear to be just isolated.

Further, the regional topographic profiles generated from topographic data indicate the presence of a ridge (Figures 3 and 4) ~150–200 m high causing slope reversal (water divide in watershed terminology) in the area south of the study area; therefore, any viscous flow approaching from the south/southeast ought to have first filled up the local depression (~150–200 m deep) located to the south of the ridge. This point is particularly important as it is observed at several places on lunar images that even sub-metre-scale local topographic variations affect the viscous flow channel such that the flow is confined to the lowest elevation[29–31]. Therefore, in view of the presence of ridge and topographic depression further south, the possibility that these melt flows could have drained-in/flowed-in from an external source located further south/southeast is not tenable. It would be impossible to conceive that a viscous flow sheet as small as flow-III (35 m thick and 0.1 km^2 in area) presumably generated from an impact crater somewhere in the south could move northwards several kilometres, cross a ridge of 150–200 m height, and then sit on the top of the northern slope of the ridge, just where the crater *Z* occurs!

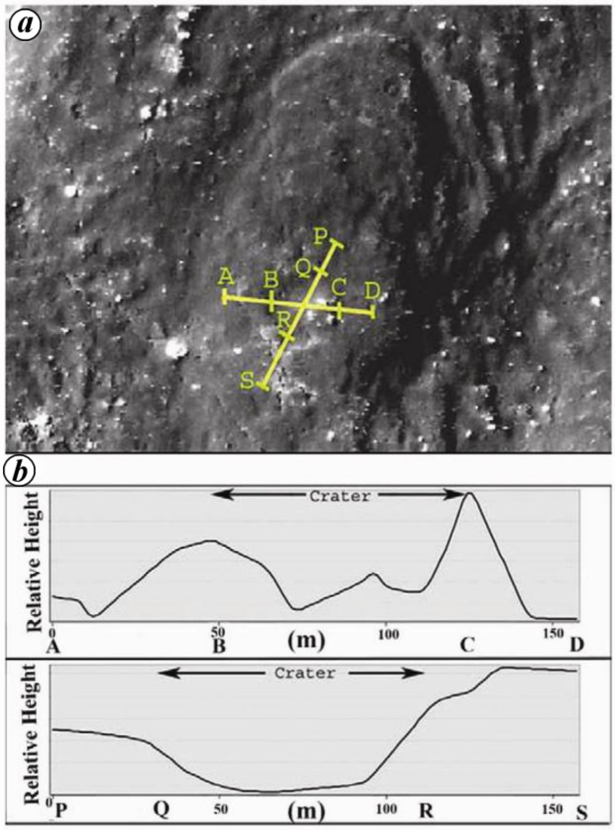

Figure 6. ***a***, Enlarged image of the area around crater Z. ***b***, Topographic profiles in and around the area crater *Z* generated from the relative DTM. Location of the two profile lines is shown in the image above. The sections show the presence of the outer crater rim and internal topographic depression inside the crater. (Note: *X*-axis gives distances in meters as in the image; due to lack of calibration in the relative DTM, *Y*-axis can be used only for relative local relief depiction).

If it is considered that the three impact melt ejecta sheets coming from distant source(s) could have taken aerial routes, then it is just unlikely that melt-sheet projectiles though different in volume and mass from different ejections, have repeatedly fallen at the same point (crater *Z*). Further, any transported melt model would not be able to explain the presence of associated tectonic structures (a fault and a fracture of two different ages).

Thus, the third scenario, i.e. the endogenic origin as the source of the present flows appears viable. The facts that the viscous melts exhibit flow direction from south to north and that there is a topographic ridge at the south followed by a steep (~150–200 m) depression to the south of the ridge – imply that the source crater ought to be located to the north of the topographic ridge. Therefore, it may not be a mere coincidence that the crater *Z* is associated with the flows and stands out centrally piercing through all the three flows on their up-gradient (south) side, but has a genetic significance for the flows.

In order to understand the local finer topographic variations in and around the crater area, several topographic profiles were drawn using the relative DTM. These sections show the presence of the outer crater rim and internal depression inside the crater (Figure 6).

Undoubtedly, the lunar surface is studded with innumerable impact craters. However, crater *Z* appears to be different in various characteristics from impact craters of comparable size found on the lunar surface. We consider crater *Z* to be of volcanic origin in view of the following:

(a) In case of impact craters, the rim is continuous, near-circular, relatively thin (approx. 2–3 m) and sharp, and slightly raised above the ground (Figure 7 *a*1–*a*5). In the case of crater *Z*, the rim is irregular, non-circular, jagged, and relatively thick (approx. 10–15 m) (Figure 7 *b*); all these characters could be related to the multiple eruptions and outpouring of lava and its partial accumulation on the upper edges of the crater rim.

(b) Impact craters of the comparable size do not possess fractures and broken rim (e.g. Figures 7 *a*1–*a*5). On the other hand, the rim of crater *Z* is fractured and discontinuous (Figure 7 *b*).

(c) Further, as mentioned earlier, there is a fault associated with the crater (Figure 5). If both crater *Z* and fault *F*1 were generated due to impact, then the fault trace ought to have been buried under the ensuing melt. Obviously, the fault *F*1 developed during the late-to-post stage of volcanic eruption.

The fault *F*1 and fracture-lineament *F*2 observed in the study area are tectonic in nature and different in morphology and pattern from the transverse cooling cracks that are typically irregular, zig-zag and recurring (Figure S2, see Supplementary Information online).

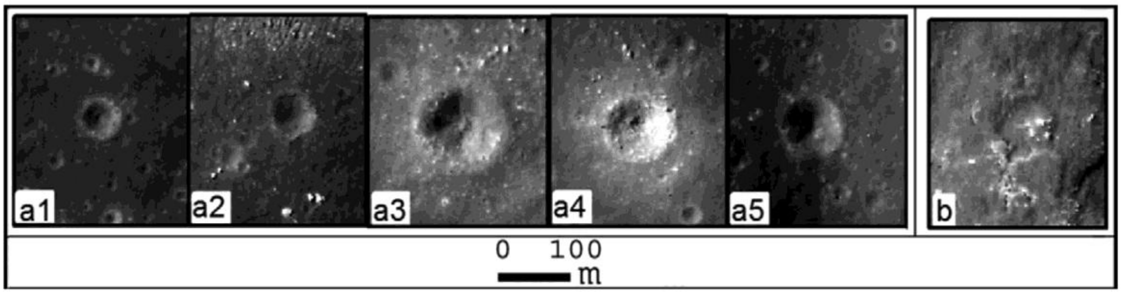

Figure 7. Comparison of morphology of craters. Craters of impact origin (Figure 7 *a*1–*a*5) possess continuous, unbroken, relatively thin, near-circular and sharp rim. In the case of volcanic crater (Figure 7 *b*), the rim is fractured, irregular, non-circular and jagged due to apparently successive outpouring of the lava and its partial accumulation in upper reaches of the rim (location co-ordinates of crater are given in Table S2, see Supplementary Information online) (LROC–NAC image sub-scenes).

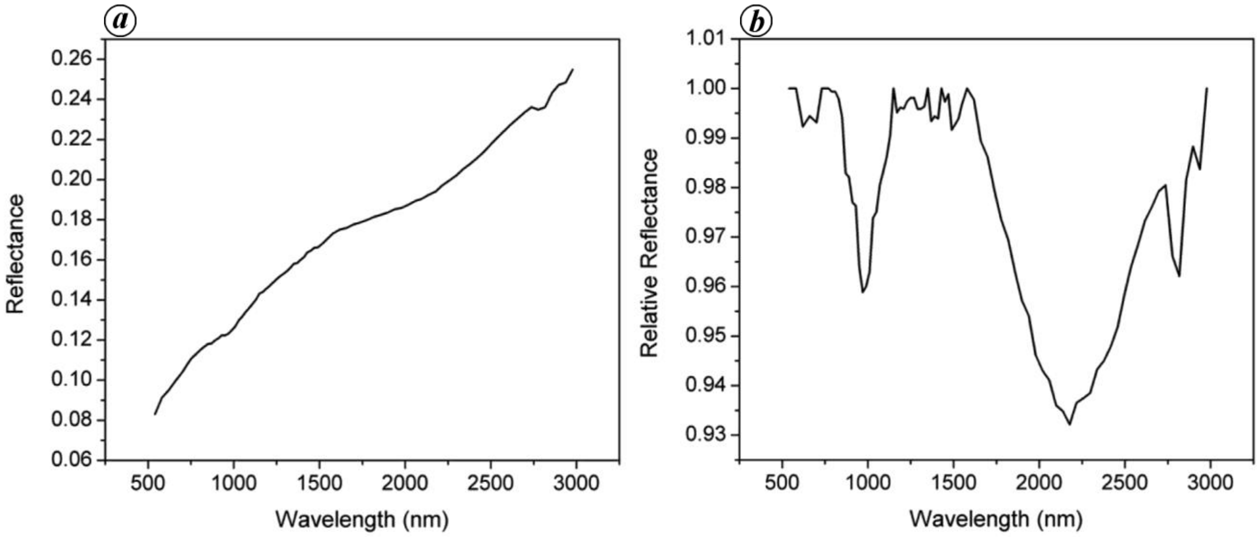

Figure 8. The average representative spectra (both normal and continuum removed) of the flows derived from global mode level-2 M3 data M3G20090213T115953. Note the distinct absorption features at ~0.97 μm and ~2.2 μm implying the presence of high-Ca pyroxenes, i.e. basaltic/gabbroic flows.

It may also be recalled here that these flows are located within the graben-like structure containing fresh flows of possibly volcanic origin described earlier[21] (Figure 1).

It is important to mention about the composition of these flows. The melts show presence of high-Ca pyroxene as indicated by absorptions centered at ~0.97 μm and ~2.2 μm in a representative spectrum of the flows (Figure 8); therefore, the flows are of basaltic/gabbroic composition. However, this character cannot be used to comment on the origin, since reflectance spectroscopy cannot unequivocally differentiate between fresh basalts and gabbroic melts.

Precise age of these flow-features could be a matter of conjecture and only radio-dating of samples can provide reliable age data. However, absence of any identifiable primary impact crater (>5 m in diameter) on any of the three flows suggests that undoubtedly these flows are much younger in comparison to the old impact-studded extensive mare flows.

Concluding remarks

This article describes the presence of three young viscous flows on the Moon. The morphological features and topographic constraints do not favour the possibility of an external source of melts, particularly for flow-II and flow-III. Associated with the flows is crater *Z* that is different in morphological characteristics than the ubiquitous impact craters, and stands out centrally piercing through all the three flows on their up-gradient (south) side. Besides, tectonic features, fault *F*1 and fracture *F*2 of two different ages, have affected the flows (II and III) and appear to emanate from the same crater (*Z*). Any ‘transported melt model’ is incompatible with the topographic features and would also not be able to explain the formation of tectonic features (viz. fault and fracture) that are associated with these flows. Based on all the above observations and arguments, it is logical to conclude that crater *Z* and the associated flows may not be impact-generated but are likely to be of volcanic origin.

As reviewed, the recently concluded other studies have yielded a wealth of new information on the Moon that indicate that the Moon may not have been completely dead. Our observations here provide evidence about the likelihood of localized volcanic activity not too far in the past. Samples from these flows in future could provide extremely valuable information on the age, geochemistry, thermal history and evolutionary state of the Moon.

1. Head, J. W., Lunar volcanism in space and time. *Rev. Geophys. Space Phys*., 1976, **14**, 265–300.
2. Schultz, P. H. and Spudis, P. D., The beginning and end of lunar mare volcanism. *Nature*, 1983, **302**, 233–236.
3. Head, J. W. and Wilson, L., Lunar mare volcanism: stratigraphy, eruption conditions, and the evolution of secondary crusts. *Geochim. Cosmochim. Acta*, 1992, **56**, 2155–2175.
4. Spudis, P. D., Volcanism on the Moon. In *Encyclopedia of Volcanoes* (eds Sigurdsson, H. *et al.*), Academic Press, New York, 2000, pp. 697–708.
5. Hiesinger, H., Head III, J. W., Wolf, U., Jaumann, R. and Neukum, G., Ages and stratigraphy of mare basalts in Oceanus Procellarum, Mare Nubium, Mare Cognitum, and Mare Insularum. *J. Geophys. Res.*, 2003, **108**, 5065.
6. Haruyama, J. *et al.*, Long-lived volcanism on the lunar farside revealed by SELENE Terrain Camera. *Science*, 2009, **323**, 905–908.
7. Whitten, J. *et al.*, Lunar mare deposits associated with the Orientale impact basin: new insights into mineralogy, history, mode of emplacement, and relation to Orientale Basin evolution from Moon Mineralogy Mapper (M3) data from Chandrayaan-1. *J. Geophys. Res. – Planets*, 2011, **116**, E00G09.
8. Cho, Y., Morota, T., Haruyama, J., Yasui, M., Hirata, N. and Sugita, S., Young mare volcanism in the Orientale region contemporary with the Procellarum KREEP Terrane (PKT) volcanism peak period 2 billion years ago. *Geophys. Res. Lett.*, 2012, **39**, L11203.
9. Jolliff, B. L. *et al.*, Non-mare silicic volcanism on the lunar far side at Compton Belkovich. *Nature Geosci*., 2011, **4**, 566–571.
10. Chauhan, P., Kaur, P., Srivastava, N., Bhattacharya, S., Ajai, Kiran Kumar, A. S. and Goswami, J. N., Compositional and morphological analysis of high resolution remote sensing data over central peak of Tycho crater on the Moon: implications for understanding lunar interior. *Curr. Sci.*, 2012, **102**(7), 1041–1046.
11. Schultz, P. H., Staid, M. I. and Pieters, C. M., Lunar activity from recent gas release. *Nature*, 2006, **444**, 184–186.
12. Buratti, B. J., McConnochie, T. H., Calkins, S. B., Hillier, J. K. and Herkenhoff, K. E., Lunar transient phenomena: what do the clementine images reveal? *Icarus*, 2000, **146**, 98–117.
13. Crotts, A. P. S. and Hummels, C., Lunar outgassing, transient phenomenon and the return to the Moon II. Predictions and test for outgassing/regolith interactions. *Astrophys. J.*, 2009, **707**, 1506–1523.
14. Crotts, A. P. S., Water on the Moon, III. Volatiles and activity. *Astron. Rev*., 2012, **7**, 53–94.
15. Weber, R. C., Lin, P., Garnero, E. J., Williams, Q. and Lognonné, P., Seismic detection of the lunar core. *Science*, 2011, **331**, 309–312.
16. Parker, M. V. K. *et al.*, Neutral buoyancy of titanium-rich melts in the deep lunar interior. *Nature Geosci*., 2012, **5**, 186–189.
17. Schultz, P. H., In *Moon Morphology*, University of Texas Press, Austin, 1976.
18. Binder, A. B., Post-imbrian global lunar tectonism: evidence for an initially totally molten Moon. *Moon Planets*, 1982, **26**, 117–133.
19. Watters, T. R. *et al.*, Evidence of recent thrust faulting on the Moon revealed by the Lunar Reconnaissance Orbiter Camera. *Science*, 2010, **20**, 936–940.
20. Srivastava, N., Kumar, D. and Gupta, R. P., Is Moon geologically active? In Proceedings of the Conference on Planetary Science and Exploration, PRL, Ahmedabad, Abstr., 2011, pp. 97–98.
21. Srivastava, N., Kumar, D. and Gupta, R. P., Young viscous flows in the Lowell crater of Orientale basin, Moon: Impact melts or volcanic eruptions? *Planet. Space Sci*., 2013, **87**, 37–45.
22. Robinson, M. S. *et al.*, Lunar Reconnaissance Orbiter Camera (LROC) instrument overview. *Space Sci. Rev*., 2010, **150**, 81–124.
23. Haruyama, J. *et al*., Global lunar-surface mapping experiment using the Lunar Imager/Spectrometer on SELENE. *Earth Planets Space*, 2008, **60**, 243–255.
24. Goswami, J. N. and Annadurai, M., Chandrayaan-1: India’s first planetary science mission to the Moon. *Curr. Sci*., 2009, **96**, 486–491.
25. Pieters, C. M. *et al.*, The Moon Mineralogy Mapper (M3) on Chandrayaan-1. *Curr. Sci*., 2009, **96**, 500–505.
26. Plescia, J. B. and Cintala, M. J., Impacts melt in small lunar highland craters. *J. Geophys. Res*., 2012, **117**, E00H12, doi:10.1029/2011JE003941.
27. Storm, R. G. and Fielder, G., Multiphase development of Lunar Crater Tycho. *Nature*, 1968, **217**, 611–615.
28. Strom, R. G. and Fielder, G., Multiphase eruptions associated with Tycho and Aristarchus. In *Communications of Lunar and Planetary Laboratory*, University of Arizona Press, Tuscon, 1970, vol. 8, pp. 235–288.
29. Howard, K. A. and Wilshire, H. G., Flows of impact melt at lunar craters. *J. Res. US Geol. Surv*., 1975, **3**, 237–251.
30. Bray, V. J. *et al.*, New insight into lunar impact melt mobility from the LRO camera. *Geophys. Res. Lett*., 2010, **37**, L21202.
31. Osinski, G. R., Tornabene, L. L. and Grieve, R. A. F., Impact ejecta emplacement on terrestrial planets. *Earth Planet. Sci. Lett.*, 2011, **310**, 167–181.
32. Denevi, B. W., Physical constraints on impact melt properties from Lunar Reconnaissance Orbiter Camera images. *Icarus*, 2012, **219**, 665–675.

ACKNOWLEDGEMENTS. LRO–LROC, LOLA, Kaguya – TC, MI and Chandrayaan-1 M^3 data teams are acknowledged for providing data through public access web-portals. Thanks are due to an unknown reviewer for useful comments leading improvements in the article.

Received 16 February 2014; revised accepted 10 June 2014