Vesta-HED Connection: A post Dawn View

It has been well established that Meteorites are broken fragments of asteroids (formed through impacts) that fall on Earth, when their orbits cross its gravity field. Connecting meteorites to their parent asteroids is the major goal of planetary scientists and hence of recent exploration activities. Moon and Mars have been identified as the parent bodies of small groups of basaltic achondrites. Of particular interest is to ascertain the earlier attributed link between the largest differentiated asteroid Vesta and the largest group of basaltic achondrites, HEDs (acrynom for Howardite, Eucrite and Diogenite meteorites), which is one of the principal objectives of the Dawn mission. In this article, we explain why HEDs are attributed to a single parent body and how this parent body has been identified as 4 Vesta (henceforth will be referred to as simply Vesta). The major findings of Dawn mission to Vesta will be discussed and then the Vesta-HED connection will be examined in light of these new findings.

HED Meteorites: These are the largest class of basaltic achondrites, numbering ~1200 in terrestrial collections. Eucrites are basalts or gabbros; and diogenites are orthopyroxenites and harzburgites, while howardites are breccias composed of eucrite and diogenite roughly in 2:1 proportion. Eucrites are believed to have crystallized as lavas on the asteroid's surface or within relatively shallow-level dikes and igneous bodies. Most eucrites are brecciated, and are dominated by pyroxenes and plagioclase, with lesser amounts of metal, troilite, chromite, ilmenite and silica. Diogenites are coarse-grained cumulates that are traditionally believed to have originated from an igneous body deep in the crust. Most diogenites are nearly mono mineralic, being composed almost entirely of orthopyroxene. Chromite and olivine generally occur in minor amounts (<10%). Out of ~368 diogenites in collection, only 11 show ≥ 40% olivine, making this mantle mineral conspicuously least abundant in HEDs. Impact mixing of eucritic and diogenitic lithologies has produced a range of polymict breccias, including the polymict eucrites and the howardites. Some of the howardites host solar-type noble gases that are concentrated on the surfaces of mineral grains, attesting to their implantation when the grains resided in the upper ~ 1 m of the regolith. The gas-rich howardites are also enriched in fragments of meteoritic impactors and of impact melts. Some of these impact clasts are similar to the hydrated, phylosilicate-bearing CM2 chondrites. Ni contents in polymict eucrites and howardites further support the presence of up to ~4% chondritic debris in them. Some HED meteorites which fell in India are depicted in Fig. 1. The petrologic and geochemical properties of the meteorites themselves argue for a large parent body. Depleted Na content and a unique Fe/Mn ratio serve as fingerprints for a differentiated solar system object, while lower siderophile element contents suggest a metallic core for this parent body. Identical oxygen isotopic composition of HEDs further strengthens their single parentage, as well as its homogenisation by a global magma ocean, though global magma ocean model has been recently contested, to prefer multiple, shallow magma chambers. Their ^{53}Cr anomaly places the location of their parent body after Mars (most likely Vesta) (see Fig. 2). The short lived radioactive isotope ^{26}Al has provided the heat pulse needed for early melting and differentiation within 5 Ma of solar system formation (Srinivasan et al., 1999); this duration has been further constrained to ~ 2 Ma by the ^{53}Mn-^{53}Cr isochron, while the core formation has been pegged at ~ 3 Ma by the ^{182}Hf-^{182}W isotope system. Imprints of thermal metamorphism have also been found in most HEDs. Thermal history

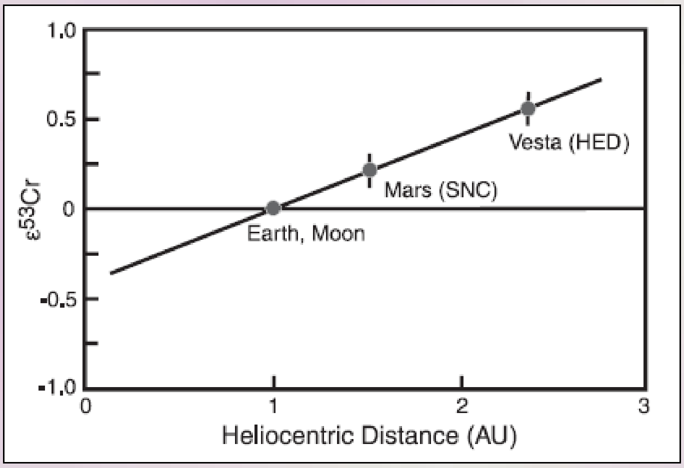

Figure 2: Lugmair and Shukolyukov (1998) noted that measured $\varepsilon^{53}Cr$ values for the Earth, Moon, Mars (SNC meteorites), and Vesta (HEDs) showed a linear increase with heliocentric distance. If this parameter is a true measure of body location, it provides further evidence linking the HEDs to Vesta.

Figure 1: Some HED meteorites that fell in India.

of HED parent body as recorded by Ar-Ar ages suggests initial cooling to Ar retention temperatures at 4.48 Ga, in addition to identifying major impact events between 4.1 to 3.5 Ga, probably corresponding to late heavy bombardment, as observed on Moon. Cosmic ray exposure ages of HEDs, which date the travel time of a meteorite from ejection from parent body by an impact till it falls on Earth, show two major (22, 36 Ma) and one minor (12 Ma) clusters, suggesting that these three recent impacts can explain most of the HEDs in our collections. These ejections could have occurred from Vestoids or directly from Vesta, as the 10–40 Ma cosmic-ray ages are consistent with orbital evolution from Vesta by the Yarkovsky effect.

Vesta-HED Connection: Asteroid Vesta was discovered by H.M.Wilhelm Olbers On March 29, 1807 and it was the 4th asteroid to be discovered and second largest in mass. A near perfect match between the reflectance spectrum of Vesta, obtained by ground telescope, with the laboratory spectrum of the eucrite Nuevo Laredo (from HED family) (McCord et al. 1970) has led to the suggestion that Vesta is the parent body of HEDs (Fig. 3). But the lack of a mechanism to deliver ejecta from Vesta (at 2.36 AU) to Earth posed a hurdle. The finding of a family of asteroids (named as Vestoids) with similar reflectance spectra as Vesta at 2.5 AU (3:1 resonance) which delivers ejecta to Earth has eased this problem, while Vestoids themselves have been suggested to be ejected from Vesta in a major impact event. Vesta has been described as the smallest terrestrial planet —the only known intact asteroid inferred to have a metallic core, an ultramafic mantle, and a basaltic crust. Absence of olivine in a majority of diogenites has led to the suggestion that crust of Vesta is thick and hence impacts could not expose the mantle as ejecta.

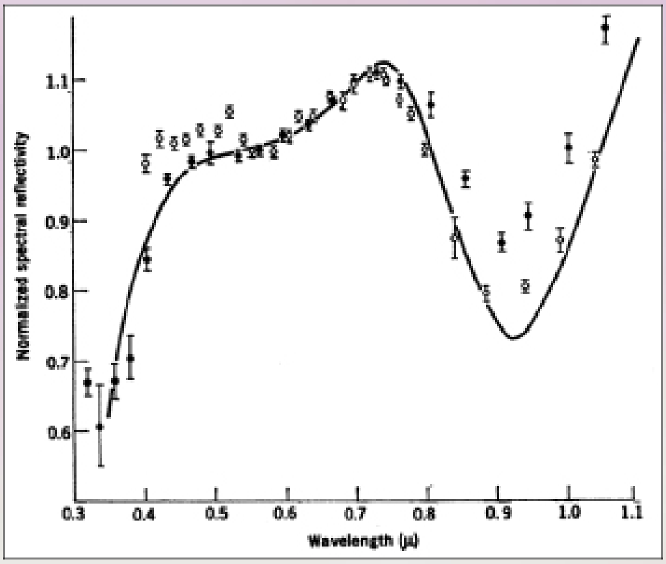

Figure 3: Laboratory measurements of the spectral reflectivity of the Nuevo Laredo meteorite shown with the telescope data points from Vesta. (Solid line) Nuevo Laredo basaltic achondrite; (open and solid circles) Vesta.

Though Vesta is the only intact differentiated asteroid with a basaltic crust, thus qualifying to be the parent of HEDs, there should have been a lot more basaltic crusted asteroids in the early solar system, as parent asteroids of magmatic iron meteorites. Magmatic iron meteorites have to come from the metallic cores of differentiated asteroids. To expose these metallic cores, these bodies have to be disrupted by collisions and hence the basaltic silicate parts either exist as broken asteroids or have been accreted to the terrestrial planets or the Sun. A minority view, due mainly to Wasson (2013) has argued, based on the 26 types of different magmatic iron meteorites in our collection, that there should have been at least those many asteroids (presently disrupted to expose the iron cores and hence facilitate ejection of iron meteorites and hence not intact) whose disrupted crusts could as well be the parents of HEDs. The match of oxygen isotopic composition of HEDs with that of the magmatic IIIAB irons (chromite inclusions), particularly makes this an equally possible parent.

Objectives of Dawn mission: Dawn, a mission by NASA was launched on Sep. 2007, to explore the asteroids Vesta (a ~530 km diameter differentiated asteroid) and Ceres (a ~950 km diameter undifferentiated asteroid). The chief objectives of the Dawn mission are 1) to determine shape, size, mass, composition, thermal history and size of the core of Vesta; 2) to understand the role of water in controlling asteroid evolution (pertains to Ceres and will not be further discussed in this article); 3) to test Vesta – HED meteorite connection. The payloads on Vesta to address these objectives are Framing Camera (FC); Visible and IR (VIR) Mapping Spectrometer and Gamma ray and Neutron Detector (GRaND), to map the surface morphology, mineralogy and chemical composition respectively. By comparing the results from Dawn instruments, with the laboratory data of HEDs, it is hoped to ascertain Vesta as the parent body of HEDs.

Results from Dawn on Vesta: Dawn has orbited Vesta for about 14 months and has provided some spectacular results on the geology, chemistry, mineralogy and internal structure of this differentiated and intact asteroid. Some physical characteristics obtained from Dawn are given in Table 1, and the composite image of Vesta, as obtained from framing camera images is given in Fig. 4. Dawn has provided three major results: (1) Two large and overlapping craters, named Rheasilvia (~500 km in diameter, ~1 Ga in age) and Venenia (~400 km, ~2 Ga age) of younger age, with a central peak of ~19 km (Fig. 5) have been revealed. The amount of material ejected from Rheasilvia is much more than the total mass of Vestoids and hence consistent with Vestoids ejection during this impact event. (2) It is expected that mantle minerals (olivine) dominate as ejecta from this giant impact, in and around Rheasilvia, as well as on the central peak, but olivine was particularly absent in these expected regions. The scant exposures of olivine detected on

Table 1: Physical parameters of Vesta as obtained by Dawn	
Diameter	530 km
Mass	2.67×10^{20} kg
Surface Temperature	-188° to -18° C
Albedo	0.4322
Rotation Period	5.342 hours
Orbital Period	3.63 Years
Eccentricity	0.0886
Aphelion	2.75 AU
Perihelion	2.15 AU
Closest Approach to Earth	1.14 AU

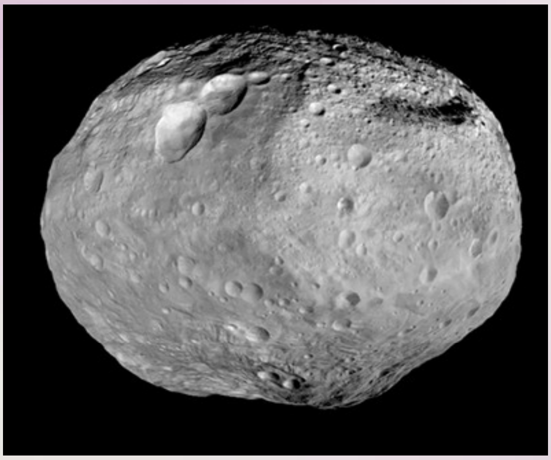

Figure 4: Overview mosaic of Vesta, made of Framing Camera images. The central mound of the Rheasilvia impact basin can be seen in the bottom right of the image. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

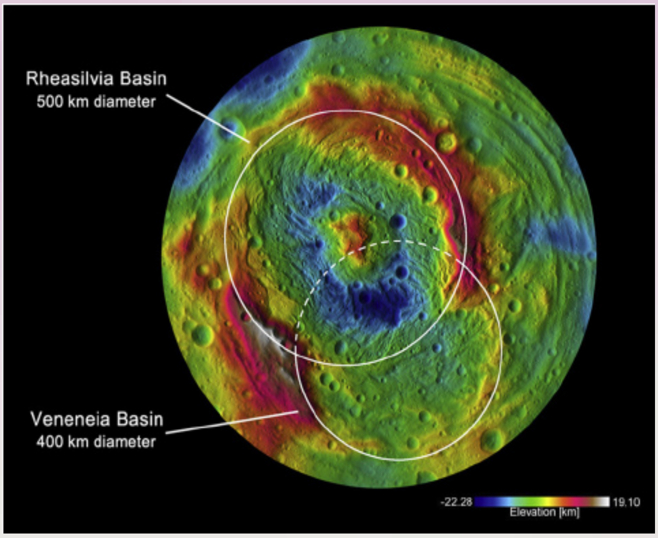

Figure 5: Two large craters, Rheasilvia (~1 Ga) Veneneia (~2 Ga), overlapping, with a central peak of height 19 km, is a major finding of DAWN mission. Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA. www.space.com

Vesta by VIR spectrometer are all far away from Rheasilvia. Additionally, the olivine spectra from Vesta do not match with the laboratory spectra of olivines from HEDs, but rather match those of chondritic impactors and hence are considered exogenous. 3) A large size of the dense metal-rich core is revealed by Dawn.

The topographic map of Vesta (Fig. 6) does not reveal any volcanic features. This would be expected if all such features are of very early origin (within ~100 Ma of formation of Vesta) and expected to be totally obliterated by subsequent impact events. This attests to the early thermal evolution of Vesta as also inferred from the chronology of HEDs. The near overlap of mineralogical lithology of Vesta (constructed as a plot of band centers of the absorption features around 1 and 2 μm, obtained by VIR) with those of HEDs affirms their parentage. Also, the global map of Fe/Si versus Fe/O as obtained by GRaND only matches with those of HEDs, but not with those of chondrites and other achondrite groups, further affirming the surface chemistry of Vesta to those of HEDs.

The results from Dawn mission have provided strict constraints on Vesta's overall density and the size of Vesta's core. The best fit ellipsoid of 286.3 by 278.6 by 223.2 km with an uncertainty of ±0.1 km, derived from Dawn data, coupled with a mass of 2.59076×10^{20} kg, yields a density of 3456 kg/m^3. This relatively high density of Vesta suggests that it contains considerably less macro porosity, than smaller asteroids, many of which are fragments formed by catastrophic fragmentations, and implies the presence of a core for this intact object. With these size and mass constraints and taking the precursors of Veata as 75% Na depleted H chondrite and 25% CM chondrite that satisfy both the chemistry as well as the oxygen isotopic composition, yield a core with a mass fraction of ~18% and radius of 114 km. The bulk density and core size put a strict limit on the density of the silicate portion of Vesta, to be near or just under 3000 kg/m^3. The lack of surface olivine also implies that any olivine within Vesta lies at a depth of at least 85 km, below the surface of Vesta. This is also consistent with a thick aluminum- rich howarditic crust. The surface composition of Vesta is remarkably uniform, being basaltic and pyroxene rich. Some (darker) hydrated material has been added through infall of exogenous meteorites, which were mixed into endogenic Vestan material by repeated impacts. Giant, basin-forming impacts in the south polar region have redistributed material globally, and beyond, and exposed material that should have been well below the crust of this differentiated body.

Our pre-DAWN view was that Vesta was a differentiated asteroid and the parent of the HED meteorites, representing the upper and lower layers of a relatively thin basaltic crust and diogenitic upper mantle and a large lower mantle dominated by olivine. The absence of large quantities of

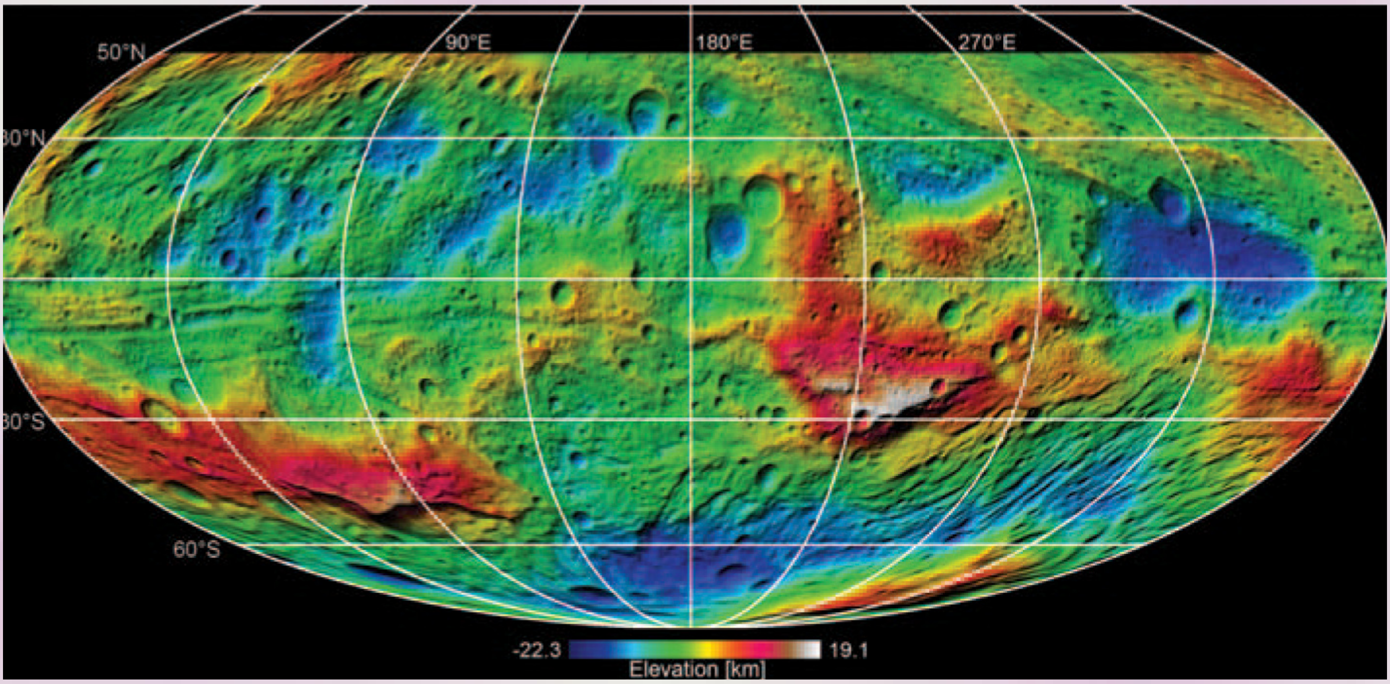

Figure 6: Global shape model of the surface of Vesta relative to a 285 x 285 x 229 km ellipsoid, produced by Gaskell. Source: www.space.com

olivine in the HEDs was consistent with the global survival of the vestan basaltic crust as indicated by spectral data from Dawn. The existence of the Vestoids fitted nicely in this picture, as it supported the idea that the giant impact basin Rheasilvia excavated mainly the basaltic surface of Vesta, and also provided a dynamical path for bringing the HEDs from Vesta to the Earth. The observations and finding of the Dawn mission confirmed the identification of the HEDs with the material composing the surface of Vesta. However, the Dawn mission revealed three facts as detailed in the section 'results from Dawn', that contradict some of these inferences.

While the puzzle of the large impact basins and the lack of olivine have been noted before, reconciling with the twin demands of a thick crust and a large core on the necessary density structure of Vesta have not been fully assessed. Fig. 7 represents the schematic view of the interior of Vesta, along with the dimensions of different layers as inferred from the results of Dawn. The mass and size of the core inferred by Dawn puts severe limits on the density and FeO content of the remaining rocky material making up Vesta's crust and mantle regions. All these new findings are seriously at odds with our pre-Dawn understanding of Vesta. There is too little olivine on Vesta's surface to be

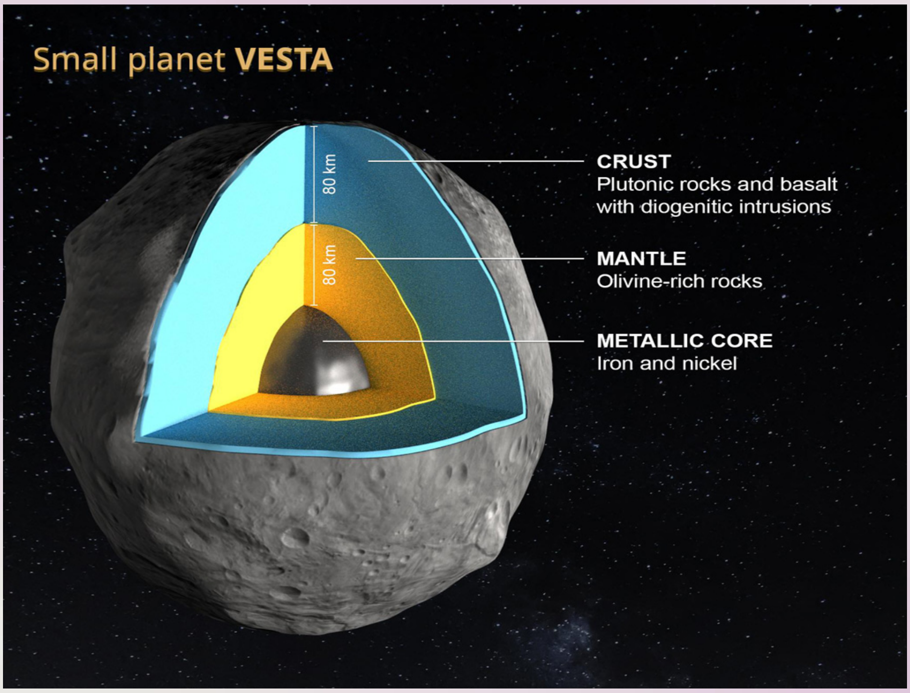

Figure 7: A schematic view of the interior of Vesta (Source- http//www. astronomy.com/news/2014/07)

consistent with the thin crust suggested by geochemical models based on the HEDs and the surface morphology and interior structure of the asteroid constrained by Dawn. At the same time, the existence of a thick crust and large core does not leave enough volume within Vesta to accommodate all of the olivine needed to explain the enrichment patterns of the HEDs based on our cosmochemical understanding of meteorites.

The mismatch between our pre- and post-Dawn understanding of Vesta might mean that either a) that Vesta formed from a non-chondritic source material or b) that the Vesta we see today is not the same as the Vesta where the HED meteorites formed; it must have been significantly altered in its global composition and interior structure. A future mission to Vesta with better capabilities of olivine detection and probably a sample return will certainly clear some of these ambiguities. A more refined laboratory study of HEDs should also be attempted to clarify on some chemical and isotopic data.

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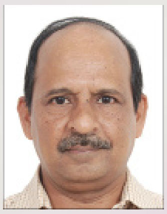

Silicic Caldera: A Phenomenon of rare explosive volcanism on the Moon

Planetary Volcanism:

Volcanism is a significant phenomenon that has been operational on several terrestrial planetary bodies and their satellites and is manifestation of a planet's internal dynamics (Wilson, 2009; Prockter et al., 2010). The complex interactions between the rising magma and the host rocks in the terrestrial crust are directly manifested by these volcanoes. The location and distribution of the various volcanic landforms provide significant information on mechanisms of heat transfer from the lithosphere, its chemical and thermal evolution, and links between volcanism, tectonism, and the state of stress in the lithosphere (Head and Wilson, 1986). On the other hand their characteristic morphology gives insight into style of eruption, chemistry and volatile content of the eruption products (Head and Wilson, 1986).

Lunar Volcanism:

Due to lack of plate tectonics on the Moon, the lunar surface has changed a little and preserved the evidence of its early volcanic history. In the Moon's geological history, after impact cratering, volcanism is the most dominant process that has modified its crust. Lunar volcanism is mainly dominated by basaltic lava flows occurring as dark, flat mare-units mostly confined to its near side (Head, 1975; Head and Wilson, 1992). Nearly all the lunar basalts are represented by vast lava flows that make up flat mare plains, with only a small fraction of the mare regions covered by positive topographic surface features, such as domes, cones, and shields of basaltic composition (Head and Gifford, 1980).

Rock samples belonging to highly evolved composition have been recorded on the Moon during the returned Apollo missions as clasts of granite, monzonite, felsites (e.g., Rutherford and Hess, 1975, 1978; Jolliff et al., 1999). But until early eighties no observations were made of silicic lavas on the Moon. Advances in remote sensing have enabled identification of silicic volcanic constructs on the Moon mostly in the form of a few non-mare domal features like Gruithuisen domes, Hansteen Alpha, Mairan T and Lassell Massif. They are termed as red spots and are characterized by steep slopes, high-albedo and strong absorption in the ultraviolet relative to the visible region of the electromagnetic spectrum (e.g. Malin, 1974; Wood and Head, 1975; Head and McCord, 1978; Chevrel et al., 1999; Hawke et al., 2003). Morphologically, these red spots show a much wider range commonly appearing as domes, smooth plains units, and rugged highland patches. They are surface manifestations of more viscous and highly evolved rocks such as terrestrial rhyolites and dacites (Bruno et al., 1991; Wilson and Head, 2003; Hawke et al.,