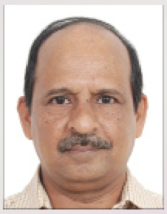
consistent with the thin crust suggested by geochemical models based on the HEDs and the surface morphology and interior structure of the asteroid constrained by Dawn. At the same time, the existence of a thick crust and large core does not leave enough volume within Vesta to accommodate all of the olivine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

Further Reading/References:

1. Binzel R. P. and Xu S. (1993) Science 260, 186–191.
2. Consolmagno C. J. et al. (2015) Icarus 254, 190-201.
3. Lugmair G. W. and Shukolyukov A. (1998) Geochim. Cosmochim. Acta 62:2863–2886.
4. McCord T. B., Adams J. B., and Johnson T. V. (1970) Science 168, 1445–1447.
5. McCord T. B. and Scully J. E. C. (2015) Icarus (In Press)
6. McCoy T. J. (2015) Chemie Der Erde (In Press)
7. McSween H. Y. et al. (2011) Space Science Reviews 163, 141–174.
8. McSween H. Y et al. (2013) Meteorit. Planet Sci. 48, 2090-2104.
9. Mittlefehdlt D. W. (2015) Chemie Der Erde (In Press)
10. Srinivasan G., Goswami J. N., and Bhandari N. (1999) Science 284, 1348–1350.
11. Wasson J. T. (2013) Earth Planet. Sci. Lett. 381, 138-146.

S. V. S. Murty
Physical Research Laboratory,
Ahmedabad
E-mail: murty@prl.res.in
Contact: +91-(0) 79-26314408



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., 2003; Glotch et al., 2010) and therefore represent evolved extrusive volcanic deposits. These are characterized by low FeO and TiO_2 and high concentrations of thorium being mostly confined to nearside of the Moon within the Procellarum KREEP Terrane (PKT) (Glotch et al., 2010).

Magma evolution and caldera formation:

Magma refers to masses of molten rocks and their dissolved fluid that are derived from the crust and upper mantle. These high temperature complex solutions are mostly comprised of silica, metallic oxides and variable amount of fluid substances. As silicon and oxygen are the most abundant element in the crust and mantle of the terrestrial planets, the principle oxide constituent SiO_2 is the basis for defining the broadest chemical classifications of magmatic rocks. It also determines the mantle's viscosity, density and its melting behavior, which in turn determines the type and volume of magma that erupt on to the surface. Magma with SiO_2 content ~38-53% are basaltic that changes to andesitic or intermediate composition with increase in silica and those with silica > 65 percent are considered to be silicic. During fractionation the increased silica concentration with decrease in melting temperature is accompanied by increase in melt viscosity due to the polymerization effect (Best, 2003). So, in less silicic or more mafic melts the degree of polymerization is less thus making these melts to be less viscous than highly silicic melts. The overall compositional diversity and the systematic compositional variation of magma therefore, reflect its primitive or evolved nature.

The volatile constituents (H_2O, CO_2, S, Cl) of magma also play an important role in the generation, evolution, and eruption of magma. Volatiles, particularly H_2O controls the melting behavior and crystallization temperatures of magma as well as the density and viscosity of the melts (e.g., Stopler, 1982). It is present as both molecular water as well as hydroxyl form being structurally bound with Si of silica tetrahedron in silicate melts (e.g., Stopler, 1982). In highly silicate melts it reacts with Si-O-Si bonding in silicate liquids and results in its depolymerisation thereby, reducing the melt viscosity (Hochella and Brown, 1984). Therefore, the high-silica melts at high strain rates due to high contents of suspended crystals or gas bubbles display non-Newtonian behavior while most magma at liquidus or higher temperatures and at low strain rates behave like Newtonian liquids as suggested by experimental studies (e.g., Shaw et at., 1968, Dingwell and Webb, 1989).

The viscosity of magma and its volatile content therefore determines the style of volcanic eruption and the morphology of resulting deposits. So, the basaltic magma being fluid are commonly extruded in quiet eruptions and produce succession of thin flows, small cinder cones and large and small shield volcanoes. In contrast, silicic magma due to its higher viscosity and lower mass diffusivity as well as relatively high pre-eruptive volatile contents produces a rich array of eruptive styles and rock types. It ranges from violent eruptions of fragmented magma in the form of coarse and fine pyroclasts to quiet effusion of dense lava in the form of domes (Eichelberger, 1995).

Calderas are large-scale collapse features generally formed late in a volcanic eruptive episode. These negative relief structures form when the denser solid strata above a shallow magma chamber subsides into the draining chamber. Their formation is associated with both decompression and overpressure in the magma chamber (e.g., Druitt and Sparks, 1984; Marti et al., 2000, Gudmundsson et al., 1997). Calderas and caldera complexes have been recognized in all volcanic environments in the Solar system and its planetary definition describe it as a multi-kilometer wide, quasi-circular non-impact depression formed in volcanic terrain by the collapse of the volcanic edifice into a partially drained magma chamber (Lipman, 2000). Patera found on Mars, Venus, and Io that is characterized by irregular volcanic crater-like structure with scalloped edges appears similar to the caldera (Sanchez and Shcherbakov 2012).

Calderas are surface manifestation of subsurface magma chamber and changing state of subsurface magma movement. Occurrence of collapse requires very specific stress and thermodynamic conditions and as such, caldera-forming eruptions are a rare phenomenon (e.g., Druitt and Sparks, 1984, Gudmundsson et al., 1997, Marti et al., 2000). They are formed only when enough eruption has occurred in events and resulted in constructing a large volcanic edifice. It will never form if the rate of magmatic replenishment to the chamber and rate of eruption are same. They thus, provide evidence of different conditions of crustal density and structure, variation in rates of volume of magma emplacement, and changing conditions associated with magmatic evolution (Head and Aubele, 1994).

Depending upon the composition of erupting magma at a caldera forming volcano, calderas can be basaltic or silicic and characterized by their effusive or explosive nature respectively. The effusive eruptions associated with basaltic calderas build the shield, erupt quietly from central vents or fissures and depletion of the magma reservoir causes collapse. Effusion is also associated with the silicic volcanoes, but does not usually lead to caldera formation. Small domes and lava flows often precede and follow the main caldera-forming event at rhyolitic calderas. They are associated with the large volume pyroclastic deposits and are usually huge collapse depressions. So, while basaltic calderas are characterized by moderate effusive activity silicic calderas are characterized by explosive eruptions triggering catastrophic events and associated ash-flow eruptions (Lipman, 1997).

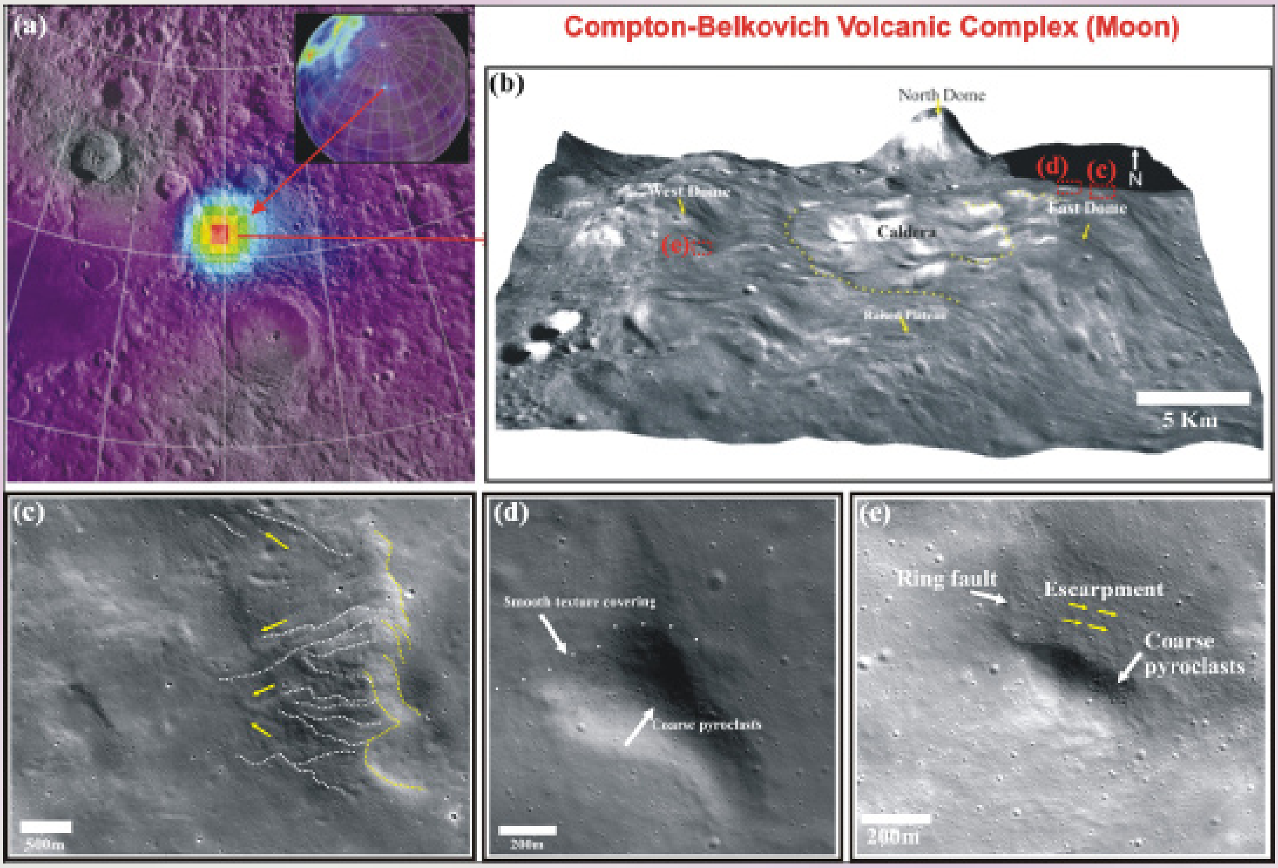


Figure1: (a) Location of CBVC in form of Thorium anomaly in northeast of Humboldtianum basin shown in deconvolved LP–GRS Th concentration map overlain over LROC-WAC (400m/px) base map (After Lawrence et al., 2007 and Jolliff et al., 2011) (b) 3-D surface view of CBVC derived from LROC-NAC image of the area draped over the LOLA Digital Elevation Model (DEM) with a vertical exaggeration of six showing the three prominent domes, the central caldera and slightly elevated plateau in the south. LROC-NAC image subsets (c) of peculiar depositional features of fine ash over the East dome (d) an effusive dome (the Bison dome) effected by late-course as well as fine-pyroclastic eruptions (e) a small effusive dome at the southern edge of the West caldera upper boundary along a ring fault. Source: Chauhan et al., (2015), Icarus

Compton Belkovich Volcanic Complex (CBVC): Analogous to a terrestrial Ash Flow Caldera on the Moon

Compton-Belkovich Volcanic Complex (CBVC) (98.5°-101.0° E longitude and 60.7° -61.6° N latitude) (Fig. 1a and b) is one such rare manifestation of evolved silicic magmatism on the far side of the Moon. Its uniqueness lies in its being located in the highland or non-mare region of the Moon on the lunar far side, isolated from the Procellarum KREEP Terrane (PKT) where the other red spots are located. It is situated between Belkovich and Compton craters to its northwest and southeast, respectively, and covers an area of ~25x30 kms. It has an elevated topography of ~500-600 m above the local elevation and about 3 km below the global mean surface elevation (Jolliff et al., 2011).

Earlier study of this area using Lunar Prospector Gamma ray spectrometer (LP-GRS) characterizes it with a high localized thorium concentration (40-55 ppm) (Lawrence et al. 2003). Spectral signatures from the LRO Diviner Lunar Radiometer of the CBVC indicate its highly polymerized mineralogy (Greenhagen, et al. 2010, Glotch, et al. 2010). Jolliff et al., 2011, 2012, describes this area as a manifestation of compositionally evolved volcanism and Bhattacharya et al., 2013 a and Petro et al., 2013 reported endogenic water of magmatic origin from CBVC with recorded band strength of ~10-17% relative to its surrounding for these enhanced hydroxyl absorption features (Bhattacharya et al., 2013b). Recent high-resolution observation of its varied morphological (e.g., Fig. 1(c-e)) and structural features is indicative of a series of deformation, eruptive and effusive events associated with its highly silicic lithology (Chauhan et al., 2015). It is a localized extrusive silicic volcanic area on the Moon that expresses complex episodes of volcanism through time. The area is filled by constructional extrusive volcanism and marked by the presence of three prominent Pre-caldera domes, in north, west and east side encircling a central caldera (Fig. 2). Post-caldera volcanic activity have also been observed at CBVC within the caldera and its boundary in form of fresh looking domes, flows, small effusive bulges and coarse and fine pyroclast eruptions. The presence of various observed domes, flows, volcanic features, with associated caldera suggests that the area has evolved through a series of eruptive and effusive events. Pyroclastic eruptions in form of coarse boulders and fine

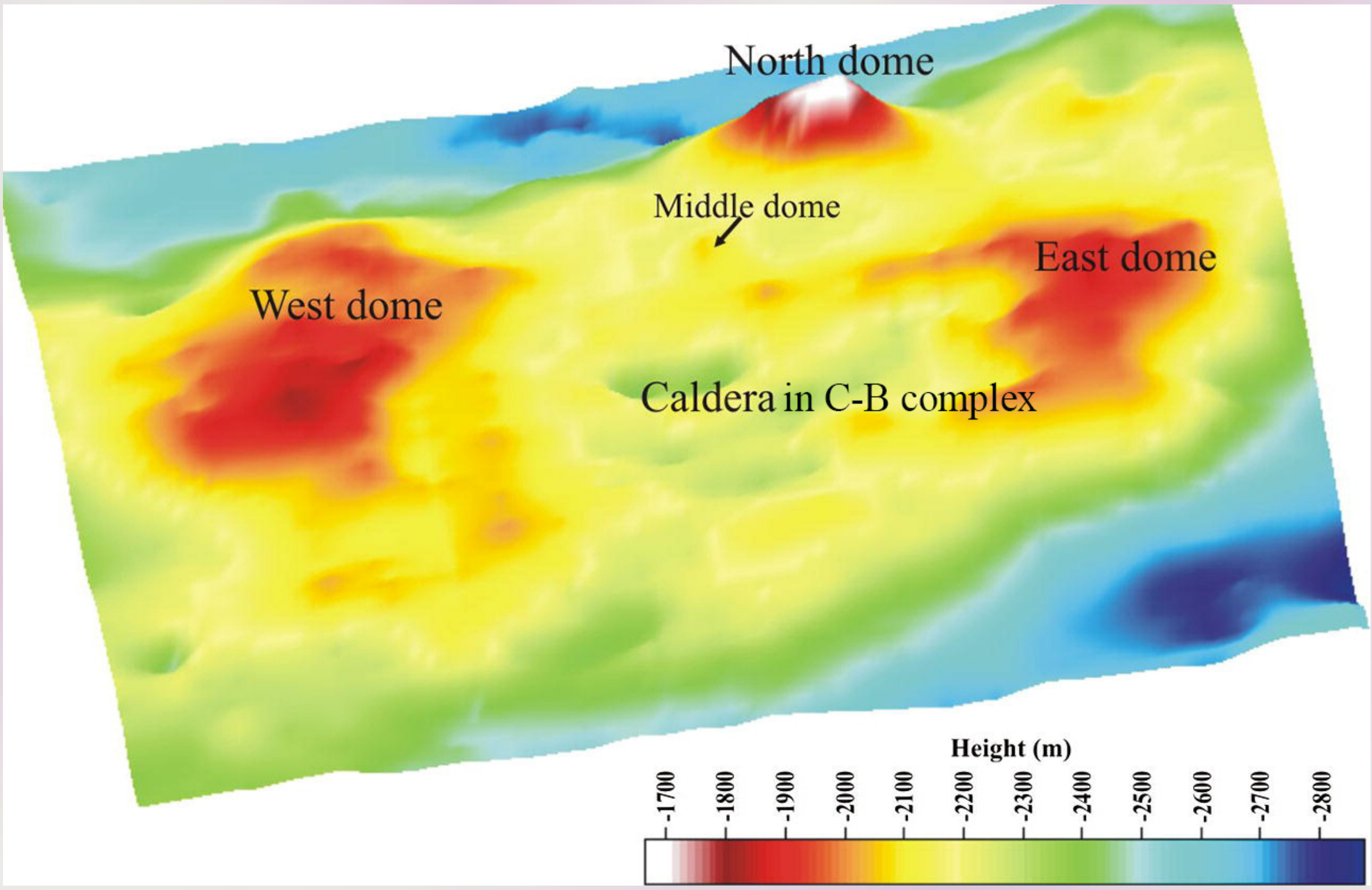


Figure 2: Colour coded LOLA DEM showing topographical variations at CBVC along with the central caldera. Source: Modified after Chauhan et al., (2015), Icarus

ash at CBVC are observed and related with the possible phenomenon of caldera collapse and different phases of eruptions and effusions. Radar observations of pyroclastic material along with high-resolution optical observations support and indicate that the CBVC is basically a localized ash flow caldera characterized by combination of dome complexes, caldera bounding faults and ash flows (Chauhan et al., 2015). The morphology, structure and highly siliceous nature of the CBVC are all consistent with the observed enhanced hydration feature in this region relative to its surroundings. CBVC, amongst all the highly evolved domes on the Moon, is the only silicic volcanic complex with a well developed central collapsed caldera structure analogues to terrestrial calderas. Presence of such features on the Moon indicates that though such features are rare but not totally absent on the Moon (Chauhan et al., 2015).

Further reading/References:

1. Best, M. G. 2003, Blackwell Pub. House, 729p.
2. Bhattacharya, S. et al. 2013a, 44th LPSC, Abs. 1382.
3. Bhattacharya, S. et al. 2013b, Curr. Sci., 105, 5, 685-691.
4. Bruno, B.C. et al.1991, Proc. 21st LPSC, 405-415.
5. Chauhan, et al., 2015, Icarus, 253, 115-129.
6. Chevrel, S. D. et al. 1999, JGR, 104, 16515-16529.
7. Dingwell, D. and Webb, S. 1989, Phys. Chem. Mineral., 16, 508-516.
8. Druitt, T. H. and Sparks, R. S. J. 1984, Nature, 310, 679-681.
9. Eichelberger, J.C. 1995, Annu. Rev. Earth Planet. Sci.,23, 41-63.
10. Glotch, et. al. 2010, Science, 17, 329, 5998, 1510-1513.
11. Greenhagen, et al. 2010, Science, 17, 329, 1507-1509.
12. Gudmundsson, A et al. 1997, GRL, 24, 1559-1562.
13. Hawke et al. 2003, JGR, 108, E7, 5069.
14. Head, J. W. and Aubele, J. C. 1994, 25th Lunar Planet. Sci. Conf., 305-306.
15. Head, J. W. and Gifford, A. 1980, The Moon and Planets, 22, 235-257.
16. Head J. W. and McCord. T. B. 1978, Science, 199, 1433-1436.
17. Head, J. W. and Wilson, L. 1986, JGR, 91, 9407-9446.
18. Head, J. W. III and Wilson L. 1992, Geochim. Cosmochim. Acta, 56, 2155-2175.
19. Head, J. W. 1975, Lunar Sci. Inst., Tex.,61-65.
20. Hochella, Jr. M. and Brown, J. G. 1984, Geochim. Cosmochim. Acta, 48, 2631-2640.
21. Jolliff et al. 1999, Am. Mineral. 84, 821-837.

22. Jolliff et al. 2011, Nature Geosci., doi:10.1038/ngeo1212.
23. Jolliff et al. 2012, 43rd LPSC, Abs. 2097.
24. Lipman, P.W. 1997, Bull. Volcanol., 59, 198-218.
25. Lipman, P.W. 2000b, Academic Press, San Francisco, 643-662.
26. Malin, M. 1974, EPSL,21, 331–341.
27. Martí, J. et al. 2009, Volcanology, Geol. Soc. Lond., 2, 249-266.
28. Petro, N. E. et al. 2013, LPSC, Abs. 2688.
29. Prockter, et al. 2010, Science, 329, 668–671.
30. Rutherford, M.J. and Hess P.C. 1975, Proc.6th LPSC, 696-698.
31. Rutherford, M.J. and Hess P.C. 1978, Proc. 9th LPSC, 987-989.
32. Sanchez, L. and R. Shcherbakov 2012, Nonlin. Proc. Geophys., 19, 585-593, doi:10.5194.
33. Shaw, H. 1968, Ann. Mtg. Geol. Soc. Amer., 274-275.
34. Stolper, E. 1982, Geochim. Cosmochim.Acta, 46, 2609-2620.
35. Wilson, L. and Head, J. W. 2003, JGR,108, 5012.
36. Wilson, L. 2009, Nature Geosci., 2, 388-396, doi:10.1038/ngeo529.
37. Wood, C.A. and Head, J. W. 1975, Lunar Sci. Inst., Houston, Tex, 234, 189-193.

Mamta Chauhan
E-mail: mamtageo@sac.isro.gov.in
Contact: +91-(0) 79-26914379

Sriram Saran
E-mail: saran@sac.isro.gov.in
Contact: +91-(0) 79-26914134

Satadru Bhattacharya
E-mail: satadru@sac.isro.gov.in
Contact: +91-(0) 79-26914361

Prakash Chauhan
E-mail: prakash@sac.isro.gov.in
Contact: +91-(0) 79-26914020

Space Applications Centre, ISRO
Ahmedabad

Cave Biosignatures on Earth: Implications for Extraterrestrial life

The key to understand past microbial life would be possible, if microbes left behind evidences of their activity, directly or indirectly. Microbes are known to often leave various evidences of their presence/activity and terrestrial cave ecosystems are reported to preserve biosignatures. Martian caves have renewed scientific excitement in the field of speleology as they are considered potential sites for future human habitation and astrobiology research. Basaltic volcanism is generally considered analogous between the Earth and Mars (e.g., Glaze et al., 2005) and volcanic caves are common on Mars. Occurring frequently in terrestrial basaltic volcanism, lava tubes are expected to be common in Mars's volcanic regions as well (e.g., Horz, 1985; Keszthelyi, 1995; Sakimoto et al., 1997). Cave entrances into Martian near-surface lava tubes, volcano-tectonic fracture systems, and pit craters are similar to terrestrial features such as tube-fed lava flows, volcano-tectonic fractures, and pit craters, that can produce caves (Cushing, 2012).

Because of the harsh Martian environment like dust storms, extreme temperature variations, high UV and cosmic rays (e.g., Mazur et al., 1978; De Angeles et al., 2002; Boston et al., 2004; Cushing et al., 2007), the organic materials cannot withstand such extreme environmental conditions. It is therefore assumed that Martian caves may be among the few human-accessible locations that preserve evidence of whether microbial life ever existed. To understand Martian sub-surface ecosystem, it is necessary to understand the Earth's subsurface ecosystem. The terrestrial caves due to unique biogeochemical conditions provide one of the best possible sites to look for the existence of life and their characteristic biosignatures. The term "Biosignatures" can include any one or combination of the following: microfossils, fossilized filaments, microfabrics, microbial mats/ biofilms, genetic data, biomineral formation, stable isotopic values consistent with microbial metabolism and unusual concentrations of certain elements.

Interestingly, carbonate minerals have now been identified in a wide range of localities on Mars as well as in several martian meteorites. The martian meteorites contain carbonates in low abundances (<1 vol %) and with a wide range of chemistries (Niles et al., 2012). The carbonate caves in earth are the dominant category. Speleothems are mineral deposits formed in caves, typically in karstified host rocks (Gunn, 2004). Caves are subsurface, nutrient-deficient ecosystems and usually dark due to lack of penetration of sunlight in deeper parts. Caves are reported to host diverse microbial communities. During the early Earth conditions, microbial life survived in an environment with limited nitrogen availability. Majority of the early earth microbes used minerals as their source of energy as the process of