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Craters of Volcanic Origin at the Ground Surface of Mars (Collapse Calderas and Volcanic Pipes)

Khaled Abdel-Kader Ouda* and Nadia Abdel-Fattah Sharara

Geology Department, Faculty of Science, Assiut University, Assiut 71516, Egypt

*Corresponding author: Khaled Abdel-Kader Ouda, Geology Department, Faculty of Science, Assiut University, Assiut 71516, Egypt

Abstract

A thorough examination of 300 craters on the Martian surface by satellite remote sensing (via Google Mars) has revealed that these craters which previously assumed to have been formed by meteorites are actually volcanic craters which were formed at the ground surface around a volcanic vent by lava flow or fragments of lava thrown out during eruption on Mars. The study clearly shows that all of these craters are volcanic in origin and represented by independent collapse calderas and volcanic pipes. These volcanic landforms are variable in size, morphology, topography, topographic elevation, relative age concept and history of volcanic eruption. They are occurring as independent landforms or as parasitic landforms on the flanks of shield and composite volcanoes or at the bottom floor of larger pre-existing calderas.

For means of graphical correlation between different types of volcanoes on Mars the topographic and morphologic characters of 150 independent volcanoes were subjected to a detailed statistical analysis using manual cross sections across the width of each volcano. The analysis reveals the recognition of six different types of volcanic calderas and two types of volcanic pipes. The topography, morphology and relative age of these types are given. The volcanic pipes are much distributed on Mars than on Earth, suggesting that Mars certainly has diamonds on its surface and very probably has much diamond than Earth does. The study contributes to improved understanding of the volcanic activity on Mars and confirms that the volcanic activity on the planet is not limited to shield volcanoes.

Keywords: Mars; remote sensing; volcanic craters; collapse caldera; volcanic pipes.

Introduction to Geology and Topography of Mars

Spacecraft exploration has revealed abundant evidence that volcanic activity, or volcanism, has played a significant role in the geologic evolution of Mars [1]. Scientists have known since the Mariner 9 mission in 1972 that Mars possesses some of the most dramatic volcanic landforms found anywhere within the solar system. These landforms include extensive lava plateau, vast lava plains, and the largest known shield volcanoes (both minor and major) in the Solar System [2,3]. Martian volcanic features range in age from Noachian (>3.7 billion years) to late Amazonian (< 500 million years), indicating that the planet has been volcanically active throughout its history [4], and some speculate it probably still is so today [5]. The volcanoes on Mars appear to be broadly similar in overall morphology (although, often quite different in scale) to volcanic features

on Earth, which suggests that Martian eruptive processes are not significantly different from the volcanic styles and processes on Earth [6].

The distribution of volcanoes on Mars is not uniform; there are several regions where central volcanic constructs are concentrated. The western hemisphere of Mars is dominated by a massive volcano-tectonic complex known as the Tharsis region or the Tharsis bulge. This immense, elevated structure is thousands of kilometers in diameter and covers up to 25% of the planet's surface [7]. It contains the highest elevations on the planet. Three enormous volcanoes, Ascraeus Mons, Pavonis Mons, and Arsia Mons (collectively known as the Tharsis Montes), sit aligned northeast-southwest along the crest of the bulge. The Tharsis bulge contains some of the youngest lava flows on Mars, but the bulge itself is believed to be very ancient

[8]. According to Hodges and Moore [9] a complex history of overlapping volcanic events over a long period of time characterizes the Tharsis volcanoes as deduced from their extraordinary larger or complex summit caldera. The extreme massiveness of Tharsis has placed tremendous stresses on the planet's lithosphere. As a result, immense extensional fractures (grabens and rift valleys) radiate outward from Tharsis, extending halfway around the planet [10].

The vast Alba Mons (formerly Alba Patera) occupies the northern part of the Tharsis bulge, whereas the huge shield volcano Olympus Mons lies off the main bulge, just off the western edge of the province. The Alba Mons is a unique volcanic structure, with no counterpart on Earth or elsewhere on Mars. The flanks of the volcano have extremely low slopes characterized by extensive lava flows which can be traced as far north as 61°N and as far south as 26°N, thus making it one of the widest extensive volcanic features in the Solar System [5,11,12]. The huge shield volcano Olympus Mons, the largest volcano on the planet, is located 1200 km northwest of the Tharsis Montes. It was built up by many thousands of individual flows of highly fluid lava

In addition to the large shield volcanoes, Tharsis contains a number of smaller volcanoes called tholi. The tholi are dome-shaped edifices with flanks that are much steeper than the larger Tharsis shields. Ceraunius Tholus, Uranius Tholus, and Uranius Mons and Uranius Mons follow a northeast-southwest trend which is the same trend of all three Tharsis Montes. A smaller volcanic center lies several thousand kilometers west of Tharsis in Elysium. The Elysium volcanic complex is about 2,000 kilometers in diameter and consists of three main volcanoes, Elysium Mons, Hecates Tholus, and Albor Tholus. Elysium Mons is the largest volcanic edifice in the province. It is thought to be somewhat different from the Tharsis Montes, in that development of the former involved both lavas and pyroclastics [11].

The main difference between Martian shield volcanoes and those on Earth is in size. For example, the tallest volcano on Mars, Olympus Mons, is nearly 100 times greater in volume than Mauna Loa in Hawaii, the largest shield volcano on Earth. Geologists think one of the reasons volcanoes on Mars were able to grow so large is that Mars has fewer tectonic boundaries in comparison to Earth [13]. Lava from a stationary hot spot was able to accumulate at one location on the surface for many hundreds of millions of years.

Topographically, the northern and southern

hemispheres of Mars are strikingly different from each other. This hemispheric dichotomy is a fundamental global geologic feature of the planet. The northern part of the planet is an enormous flat topographic depression with few craters and lies below the conventional 'zero elevation' level. About one-third of the planet's surface (mostly in the northern hemisphere) lies 3–6 km lower in elevation than the southern two-thirds. The other two-thirds of the Martian surface are the southern hemisphere which is mountains and highlands, with dense craters and mostly well above zero elevation. This dichotomy is also expressed in two other ways: as a difference in volcanic crater density and crustal thickness between the two hemispheres [5]. Concerning the crustal thickness, topographic and geophysical gravity data indicate that the crust in the southern highlands has a maximum thickness of about 58 km, whereas crust in the northern lowlands "peaks" at around 32 km in thickness [14,15].

The origin and age of the hemispheric dichotomy are still debated. Hypotheses of origin generally fall into two categories: one, the dichotomy was produced by a mega-impact event or several large impacts early in the planet's history [16-18] or two, the dichotomy was produced by crustal thinning in the northern hemisphere by mantle convection, overturning, or other chemical and thermal processes in the planet's interior [19,20]. The Martian dichotomy appears to be extremely old whatever its origin. Crater counting studies of QCDs suggest that the underlying surface in the northern hemisphere is at least as old as the oldest exposed crust in the southern highlands [21]. The northern lowlands were also urged as may have contained a large standing body of water in earlier Mars history [22-24].

Straddling the dichotomy boundary in Mars's western hemisphere is the massive volcano-tectonic province of the Tharsis bulge. Near the equator in the western hemisphere lies an immense system of deep, interconnected canyons and troughs collectively known as the Valles Marineris. The canyon system extends eastward from Tharsis for a length of over 4,000 km, nearly a quarter of the planet's circumference [25].

Scientists have never recorded an active volcano eruption on the surface of Mars [26]. However, the European Space Agency's Mars Express orbiter photographed lava flows interpreted in 2004 to have occurred within the past two million years, suggesting a relatively recent geologic activity [27]. An updated study in 2011 estimated that the youngest lava flows occurred in the last few tens of millions of years [28]. The latter authors consider this age makes it

possible that Mars is not yet volcanically extinct.

Because Mars has no oceans and hence no "sea level", a zero-elevation surface had to be selected as a reference level; this is called the areoid [29,30] of Mars, analogous to the terrestrial geoid. In 2001, Mars Orbiter Laser Altimeter data led to a new convention of zero elevation defined as the equipotential surface (gravitational plus rotational) whose average value at the equator is equal to the mean radius of the planet [31]. In practice, today this surface is defined directly from satellite gravity measurements.

Much works have been done on the volcanoes and volcanic activity on the surface of Mars. However, the vast majority of these works focused on the shield volcanoes, the giant impact basins, the big channels and the impact craters, but never really been able to look at the smaller volcanoes on Mars except of few works [4,32, 33].

The present investigation is concerned with the study of smaller volcanoes and volcanic landforms which are formed at or near the ground surface around a volcanic vent by lava flow or fragments of lava thrown out during eruption on the surface of Mars. The study has contributed immensely to the interpretation of different generations of independent collapse calderas and volcanic pipes, and thus confirms that the volcanic activity in the planet Mars is not limited to several shield volcanoes, but includes many volcanic craters that have long been identified as "impact craters" formed by collision of meteorites with the planet.

Previous Related Work

Mars has the greatest diversity of craters of any planet in the Solar System [34]. The craters have been described for a long time as belonging to the "impact crater types" [34-37]. Those which are below about 7 km in diameter were called simple craters; they are bowl-shaped with sharp raised rims and have depth/diameter ratios of about 1/5 [35]. According to this author the simple craters change to more complex types at diameters of roughly 5 to 8 km. Complex craters have central peaks (or peak complexes), relatively flat floors, and terracing or slumping along the inner walls. Complex craters are shallower than simple craters in proportion to their widths, with depth/diameter ratios ranging from 1/5 at the simple-to-complex transition diameter (~7 km) to about 1/30 for a 100-km diameter crater. Another transition occurs at crater diameters of around 130 km as central peaks turn into concentric rings of hills to form multi-ring basins [5].

Over 42,000 of "impact craters" greater than 5 km in diameter have been catalogued on Mars [36] while the

number of smaller craters is innumerable. The density of craters on Mars is highest in the southern hemisphere, south of the dichotomy boundary. A new study by SPACE.com Staff [38] recorded more than 635,000 "impact craters" at least 0.6 miles (1 kilometer) wide on Mars [37]. However, only about one thousands of these craters have names which are assigned by the International Astronomical Union [39].

However, several craters on Mars, thought to be created by impacts from space, have later been found by some scientists to be caused by explosive volcanic eruptions. Their assessment is based on images and topographic data from NASA's Mars Odyssey, Mars Global Surveyor and Mars Reconnaissance Orbiter spacecraft, as well as the European Space Agency's Mars Express orbiter.

In Search of Martian Craters by Schmidt [40], the author highlighted the valuable remarks by the scientists Ramsey and Crown. Ramsey who is part of a research team developing techniques to accurately identify and analyze small features on the Martian surface in satellite images said. "In the past, we've focused on the large volcanoes, the giant impact basins, and the big channels," "but we've never really been able to look at the small things on Mars". The "small things" that Ramsey and his team hope to shed light on are craters - bowl-shaped depressions on a planetary surface that are typically caused by one of two processes. Impact craters form when a meteoroid, asteroid, or comet collides with a planet. Volcanic craters delineate vent areas at the summit of a volcano. David Crown, senior scientist at the Planetary Science Institute in Tucson, Ariz., and a co-investigator on the project also said [40] that "When you get down to small sizes, it's hard to tell the difference between a volcanic crater and an impact crater". Schmidt commented that the researchers hope to come up with criteria that will enable them to distinguish between impact craters and maar craters solely by looking at satellite data. Because the presence of maar craters is a strong indication of water beneath the surface, the ability to identify them on Mars has important implications for understanding the planet's geologic history. "We're interested in craters that are potentially water-driven features, because that means there could be liquid water beneath the surface, which is a big deal for Mars exploration," said Ramsey. In the past, most scientists believed that Mars' volcanic activity was most intense in its early time (its first billion years), and that the last three billion years have been relatively quiet," Ramsey said, but the ability to now see smaller things on the Martian surface may change existing beliefs about the planet's geologic history.

Wilson and Head [41] maintained that explosive volcanic eruptions, potentially involving large amounts of magmatic and entrained water, are thought to have been very important in the Noachian and Hesperian periods earlier in Mars history. Evidence for ancient explosive volcanism within Arabia Terra, Mars has been recently given by Scientists from NASA and the Planetary Science Institute in Tucson, Ariz. [4,32]. These scientists have identified several irregularly shaped craters located within Arabia Terra, Mars, representing a new type of highland volcanic construct and together constitute a previously unrecognized Martian igneous province. Similar to terrestrial supervolcanoes, these low-relief paterae possess a range of geomorphic features related to structural collapse, effusive volcanism and explosive eruptions. Extruded lavas contributed to the formation of enigmatic highland ridged plains in Arabia Terra.

Michalski and Bleacher [32] paid attention to the fact that a series of Martian craters assumed to have been formed by meteorites may actually be extinct volcanoes so massive that, when they were active billions of years ago, they could have buried Mars in ash. They recorded several irregularly shaped craters located within Arabia Terra a geologically ancient region of northern Mars, representing a new type of highland volcanic construct and together constitute a previously unrecognized Martian igneous province. The craters appear as several huge circular pits that resemble Earth's calderas, in which magma beneath a volcano drains after a volcanic eruption, causing the ground above the magma chamber to collapse. The best example on Mars is a feature called Eden patera, a depression about 85 kilometers long, 55 kilometers wide and 1.8 kilometers deep. Michalski and his colleague Bleacher in a report in Nature today¹, describe three separate calderas within the depression, along with possible signs of a lake of solidified lava and a volcanic vent where lava could have oozed out.

Michalski et al. [4] interpreted Eden Patera as a complex caldera formed through structural collapse associated with withdrawal or migration of magma at depth, and explosive eruptions. Some of reasons for suspecting that Eden Patera is a collapsed caldera not an impact crater are its irregular shape, an apparent lack of a raised rim or central peak, and lack of impact ejecta. Other features recorded by [4] in northern Arabia Terra that contain evidence for collapse associated with volcanic activity include Siloe Patera, Euphrates Patera and Semeykin Crater. According to the same authors these features constitute a new category of Martian volcano that can be described as plains style caldera complexes, of which Eden Patera is the type-example.

The discovery of a new type of volcanic construct in the Arabia volcanic province [32] fundamentally changes the picture of ancient volcanism and climate evolution on Mars. Other eroded topographic basins in the ancient Martian highlands that have been dismissed as degraded impact craters should be reconsidered as possible volcanic constructs formed in an early phase of widespread, disseminated magmatism on Mars [4].

Emran et al. [33] interpreted surficial geology, including possible geologic history, of Siloe Patera by combining analysis of spectral analysis from TIR data of THEMIS, mineralogical phases (e.g. olivine, phyllosilicate, and hydrated silicates) from NIR data of CRISM, and local morphology from HiRISE and CTX. They came to the conclusion that the presence of faulting consistent with collapsed features and related lava-flow features confirm that Siloe Patera is a collapsed caldera of Late Noachian to Early Hesperian [1], which was modified by subsequent water-related processes.

The present investigation concerns with the topography, topographic elevation, morphology and relative age concept of different types of volcanic calderas and volcanic pipes. 300 volcanoes of the highest resolution on the surface of Mars were chosen for detailed study, of which 150 volcanoes were subjected to a detailed statistical analysis for means of graphical correlation of the morphological and topographical properties of these volcanoes. The study reveals the recognition of six different types of volcanic calderas and two types of volcanic pipes. The relative age of these types of volcanic landforms on the Martian surface is assigned on basis of stratigraphic relationships of different volcanoes.

Methods of Study

This study has been made possible by the use of Google Mars which is a program that allows exploring Mars through official satellite images gathered by different spacecraft orbiting the planet. The program is an application within Google Earth Pro which is currently the standard version of the Google Earth desktop application as of version 7.3.2.5776 (64-bit), Build Date Tuesday, March 5, 2019 12:43:51 AM UTC7.3. The program of Google Mars allows viewers to zoom around the Red Planet in much higher resolution than the simpler browser version and will even render certain locations in 3-D. It includes extremely high-resolution images from the Mars Reconnaissance Orbiter's HiRISE camera on the NASA Mars Reconnaissance Orbiter spacecraft, the Context Camera (CTX) on NASA's Mars Reconnaissance Orbiter which offers great details with around 20 feet per pixel, the Narrow Angle Mars Orbiter Camera (MOC) on the NASA Mars Global Surveyor spacecraft,

the High Resolution Stereo Camera (HRSC) instrument on the European Space Agency Mars Express spacecraft, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the NASA Mars Reconnaissance Orbiter spacecraft. Finally, there are many high-resolution panoramic images from various Mars landers, such as the Mars Exploration Rovers, Spirit and Opportunity, that can be viewed in a similar way to Google Street View.

300 satellite images (Visible imagery of Google Mars) of craters on the surface of Mars were carefully examined for resolution, distribution, unique morphology and evidence of volcanic activity. The images include volcanic craters at the ground surface with variable depths, sizes, outer rims and showing good evidence of eruption of volcanic lava and signs of formation of volcanic calderas around clear volcanic vents through the collapse of the volcano's roof and the withdrawal of the lava to the drained magma chamber, as well as craters with a second post caldera re-eruption of lava after re-filling of the magma chamber. They include also the small craters formed by violent, supersonic eruption of deep-origin volcanoes leading to the formation of pipe-like structures that penetrate the surrounding rock and create bowl-shaped, craterlike depression which does not form a large above-ground elevation as typical volcanoes do.

For means of graphical correlation between different types of volcanoes the morphological parameters of 150 volcanoes among the fore-mentioned 300 volcanoes have been subjected to detailed statistical analyses. To make the graphic comparison possible between different types of volcanoes, the electronic profile is rejected and a manual cross section has been made for each volcano across its width, where selected points of elevation were chosen along the width of the volcano in the range of 15 or 16 points which are more or less symmetrically spaced (side symmetry around the center of volcano) across the width of volcano. The results were subjected to the Microsoft Excel 2010 program where a cross-section is drawn representing the topography and topographic elevation of sides/flanks of volcano, the maximum depth of volcanic crater (caldera/volcanic pipe) below the ground surface, the height of the outer rims above the ground, the maximum height of the mountain volcano above ground surface (above surroundings). The width and diameter of the craters are given for each volcano according to the measurements of the ruler of Google Mars. Due to the great variability in thickness of the outer rim of the volcanic crater, so the value given for the height of the outer rim is the average of this height around the crater. Graphic representation of all these topographic and morphologic features in different

types of volcanoes has been given.

Correlation of different parameters in different types of volcanoes is made using bimodal and three-dimensional diagrams. The parasitic post-calderas composite volcanoes or cinder cones which are formed by re-filling of the magma chamber and re-eruption of lava at the bottom surface of some pre-existing large calderas are also described and measured for width and height using the electronic profile.

Results and Discussion

Evidence of Volcanic Origin of the Studied Craters on Mars

Volcanic craters produced by collapse of surface rock into an empty magma chamber after massive volcanic eruptions are called calderas. Craters produced by the collision of a meteorite with the surface of Mars (or another planet or moon) are called impact craters. Evidence of the first case includes presence of lava flows and/or water vapor and hematite near or around the crater, or successive collapse of the roof of the magmatic chamber instead of one stage of collapse, or re-filling of the magma chamber and re-eruption of post caldera volcanic landforms from the same vent at the bottom surface of the pre-existing caldera, or the presence of younger generations of different morphologies and different ages of volcanic eruption inside the same caldera. In the impact craters there is usually a large, rayed (star-shaped) distribution of ejecta blanket (enormous amounts of shattered material resulted from the pulverization of the rock immediately after the strike) around the rim of the resultant crater.

The detailed study of 300 craters in both northern and southern hemispheres of Mars revealed that these craters are volcanic in origin and represented by collapse calderas and volcanic pipes. These volcanic landforms are variable in size, subsurface depth below ground surface, height of outer rim above ground surface, topography of the bottom surface of depression and topographic levels with respect to the conventional 0 datum. They are occurring either independently as free landforms on surface of plains, valleys and plateaus or as parasitic landforms along the flanks of shield volcanoes or at the bottom floor of larger calderas.

The criteria of volcanic origin of the studied craters can be summarized as below:

1. The collapse calderas represent the most spectacular and abundant volcanic landform among the studied craters. They possess a bowl-shaped depression formed when the volcano collapse into the void left when its magma chamber is emptied to form a large crater. Magma

is stored beneath a volcano in a magma chamber. When a massive volcanic eruption occurs which empties the magma chamber, the unsupported rock that forms the roof of the magma chamber then collapses to form a large depression or bowl-shaped feature on the surface with steep walls and within which occurs a vent. Crater Lake National Park and many other calderas on Earth are thought to have formed by this process.

2. There is no surface material from outside the crater are occurring around or inside the caldera crater, but a strong evidence of lava flows or pyroclastic materials usually occurs either along the outer rim and sides of the crater depression (Plate 1, Figures A-J, Plate 2, Figures A-J), around the central vent beside the walls of the crater depression (Plate 3, Figures A-J) at a central-peripheral vent (Plate 4, Figures A-J) at a peripheral vent in the bottom floor of the collapsed caldera (Plate 5, Figures A-J) or around the parasitic volcanic landforms which may re-erupt at the bottom floor of the pre-existing caldera (Plate 3, Figures G-J). No water is found in the depression of the craters but the sides or outer rim of many depressions are covered by fine dust arranged in streaks formed by water vapor and hematite which accompanied the eruption of lava.

3. Many calderas on Mars exhibit a lava tube (open cave) which is a natural conduit formed by flowing lava which moves beneath the collapsed roof of the caldera. (Plate 6, Figures A-E). Draining of the liquid lava from these tubes will leave open caves.

4. A younger steam explosion (water vapor and hematite) took place after complete cessation of volcanic activity through a natural conduit (a vent or lava tube) on the collapsed roof of the lava tube of different calderas on Mars (Plate 7, Figures A-J). Very probably this steam explosion continued in calderas for a long time.

5. Many calderas belonging to different types have a zonal structure (Plate 8, Figures A-J) resulting from a series of gradual collapse of the roof of magmatic chamber rather than a single event (Plate 9, Figures A-J).

6. The so called "complex crater" which exhibits "central peak" uplift in the center of the crater and which is usually used to identify the impact craters is simply a large caldera crater with a younger post-caldera phase of lava re-eruption leading to the formation of cinder cone (Wizard Island), composite volcano or volcanic domes over the central vent at the bottom floor of the pre-existing caldera (Plate 10, Figures A-J). This type of caldera is commonly of a large to huge size. In few cases the central elevated mass at

the bottom floor of small-sized caldera results from upheaval of the caldera floor due to compression of the remaining magma beneath the collapsed roof of the chamber, not refilling of the magma chamber and re-eruption of new lava flow on the bottom floor of the collapsed caldera (see later). This phenomenon is almost confined to calderas which are lying near or at the southern ice-cap pole.

7. The calderas on Mars are not uniform in age, general morphology of the crater depression (flat with steep walls, broadly rounded, strongly concave), diameter of crater (from 7.7 km to 162 km), total width of volcano (from 11.2 km to 243 km), subsurface depth of the depression below ground surface (from 626 m to 2900 m), height of outer rim above ground surface (from 12.5 m to 1038 m), topographic level, geographic location, presence or absence of parasitic landforms (cinder cones, composite volcanoes, volcanic domes) formed by refilling of the underlying magma chamber and re-eruption of lava at the bottom floor type of the pre-existing caldera. All these morphologic variations suggest that these craters were formed by volcano caldera collapsing, rather than from an impact. In craters of equal size caused by a meteorite collision, it is assumed that these craters represent meteorites of the same size, same weight, same speed, same vertical collision force, and accordingly the depressions arising from these craters become consequently of equal depth and equal degree of slope since the surface rock is lithologically uniform. But the reality on Mars is that many of the caldera craters of equal sizes are different in the depth of depression, in the degree of its slope below the surface and in the surface topography of the bottom surface despite their adjacent occurrence in the same place (Plate 11, Figures A-F). There are also large caldera craters of little depth, while there are quite next to them smaller

8. Beside the calderas there are an innumerable number of volcanic pipes varying in diameter from less than 1 km to 10.25 km and reaching up 22.5 in width. These pipes are subterranean geological structures formed by the violent, supersonic eruption of deep-origin volcanoes. They rise onto surface of Mars through a series of deep fissures in the crust where magma rises through the crust by exploiting a vertical or inclined path of weakness on the surface ground where they penetrate the surrounding rock and create a bowl-shaped, craterlike depression. Unlike other kinds of volcanic eruption, the magma which eject as volcanic pipes does not collect in a subsurface reservoir prior to the eruption. The volcanic pipes are structurally controlled; those which are inclined on the surface possess a carrot-shaped profile and showing different trends, following the

Plate 1: Collapse calderas showing evidence of eruption of lava flows or pyroclastic materials along the side walls of the large bowl-shaped crater depression in the lowlands of the northern hemispheres of Mars. From now and going on, the geographic north lies to the north of the image unless it is shown on the image. The coordinates of the crater and the scale of the image as provided by Google Mars are given in each image. The names of named craters as provided by the IAU are given in the image when available, while other craters that are not named are left without a name.

Plate 2: Collapse calderas showing evidence of eruption of lava flows or pyroclastic materials along the side walls of the large bowl-shaped crater depressions in the highlands of the southern hemispheres of Mars.

Plate 3: Collapse calderas showing evidence of eruption of lava flows or pyroclastic materials around the central vent beside the side walls of the large bowl-shaped crater depressions in both lowlands in the northern hemisphere (B-E and G-I) and highlands in the southern hemisphere (A, F and J) of Mars.

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Plate 4: Collapse calderas showing evidence of eruption of lava flows or pyroclastic materials around the central vent or a central-peripheral vent at the bottom floor of the large bowl-shaped crater depressions in both lowlands in the northern hemisphere (B-E and G) and highlands in the southern hemisphere (A, F and H-J) of Mars.

Plate 5: Collapse calderas showing evidence of eruption of lava flows or pyroclastic materials around a peripheral vent along the side walls of the depression of the large bowl-shaped crater depressions in both lowlands in the northern hemisphere (B-C, E and G-H) and highlands in the southern hemisphere (A, D, F and I-J) of Mars.

Plate 6: Collapse calderas on Mars showing a lava tube (open cave) which is a natural conduit formed by moving of flowing lava beneath the collapsed roof of the caldera in lowlands of the northern hemisphere of Mars. Draining of the liquid lava from these tubes will leave open caves.

Plate 7: Collapse calderas showing a younger steam explosion (water vapor and hematite) which took place after complete cessation of volcanic activity through a natural conduit (a vent or lava tube) on the collapsed roof of the pre-existing caldera in lowlands of the northern hemisphere of Mars .

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Plate 8: Collapse calderas showing a zonal structure resulting from a series of gradual collapse of the roof of magmatic chamber rather than a single event in both lowlands of the northern hemisphere (B, E, F, H and I) and highlands of the southern hemisphere (A, C, D, G and J) of Mars.

Plate 9: Side walls of the depression of different collapse calderas showing a series of gradual collapse of the roof of magmatic chamber rather than a single event in both lowlands of the northern hemisphere (A-C, E and G-I) and highlands of the southern hemisphere (D, F and J) of Mars.

Plate 10: Collapse calderas of complex craters showing a younger post-caldera phase of lava re-eruption after re-filling of the magma chamber leading to the formation of cinder cones or composite volcanoes over the central vent at the bottom floor of the pre-existing caldera in both lowlands of the northern hemisphere (A, C, I and J) and highlands of the southern hemisphere (B, D and E-H) of Mars.

Plate 11: Electronic profiles showing adjacent caldera craters on Mars of equal sizes but with unequal subsurface depths below ground surface, and with different surface topography of the bottom surface of the calderas (A-F). There are also large caldera craters of little depth, while there are quite next to them smaller caldera craters of greater depth (G-J). These indications contradict the meteorite collision theory as the only source of formation of craters on Mars.

Plate 12: Structurally controlled volcanic pipes which are inclined on the surface of Mars and possess a carrot-shaped profile. The pipes show different trends, following the trends of surface fractures in the northern lowlands of Mars. Note the volcanic breccia and volcanic domes which accompany the violent eruption of volcanic pipes in Figs. G and I. Note also the intense steam explosion (water vapor and hematite) associated with the massive eruption of oriented volcanic pipes in J.

Plate 13: Volcanic pipes erupted perpendicular to the surface of Mars and are characterized by having a much deeper bottom surface than the inclines pipes and in possessing a vertical funnel-shaped profile. The pipes are represented in both lowlands of the northern hemisphere (A-D, E, G-H and J) and highlands of the southern hemisphere (F and I) of Mars

Plate 14: Bowl-shaped, crater-like shallow depressions of the inclined volcanic pipes which possess a carrot-shaped profile and are covered by fine dust arranged in streaks formed by water vapor and iron oxides which accompanied the eruption of magma in both lowlands of the northern hemisphere (A-C) and highlands of the southern hemisphere (D-F) of Mars.

Plate 15: Bowl-shaped, craterlike deep depressions of the vertical volcanic pipes which possess a funnel-shaped profile and are covered by fine dust arranged in streaks formed by water vapor which accompanied the eruption of magma in the lowlands of the northern hemisphere (A-E) of Mars.

Plate 16: Large collapse calderas on Mars showing three generations of different ages of volcanic eruption during the history of the same caldera. The first generation is the eruption of lava flows and collapse of the magma roof leading to the caldera formation; the second generation is the re-eruption of post caldera lava flows from the central vent of the pre-existing caldera leading to formation of parasitic composite volcanoes or cinder cones covering the bottom surface of the caldera; the third generation is the eruption of several volcanic pipes from different vents on the bottom floor of the caldera. The calderas are from both lowlands in the northern hemisphere (D-F and H-I) and highlands in the southern hemisphere (A-C, G and J) of Mars.

Plate 17: continuation of Plate 16: Large collapse calderas on Mars showing two or three generations of different ages of volcanic eruption during the history of the same caldera. The calderas are usually simple calderas which have no parasitic volcanic landforms over the central vent whereas the bottom surface of the caldera is randomly intruded by one or more younger generation of cinder cones and/or volcanic pipes. The calderas are from both lowlands in the northern hemisphere (M, Q and S) and highlands in the southern hemisphere (K, L, N-P, R and T) of Mars.

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Plate 18: Large collapse calderas on Mars showing extensive sand-sized dark dunes overlying the bottom surface of the caldera. The shape of the dune deposits inside the craters may be transverse (A and D) or barchanoid (B); sometimes they assume a linear shape or attain a wide network formed by intersection of linear and transverse dunes (C and E). The dune deposits are not blown into the craters as previously assumed, but they are volcanoclastic sediments produced from the volcanic ash erupted from a vent at the bottom surface of the caldera.

Plate 19: Representatives of impact craters (A-D) in the northern lowlands of Mars. They are very small in size as compared to volcanic calderas, circular in shape, with little subsurface depth below ground surface (89-133m) and bounded by a star-shaped distribution of amounts of shattered material around the rim of the crater. The crater A is surrounded by clusters of small simple cinder cones with a cone height varying from 24 m to 121m as indicated by the electronic profiles in F-J

Plate 20: Electronic profiles across some huge collapse calderas on Mars which were previously identified as impact craters and have recently been proposed to be volcanic caldera by Michalski & Bleacher (2013). The Eden Patera (A-A), is a complex calderas marked by a post-caldera eruption of lava from the central vent leading to the formation of parasitic composite volcano at the bottom surface of the pre-existing caldera. Siloe Patera (B-B) and Euphrates Patera (C-C), on the other hand, are large simple calderas with steep walls and deep smooth bottom surface below ground surface. For dimensions and subsurface depths of calderas see the text.

trends of surface fractures (Plate 12, Figures A-J; Plate 13, Figures A-B) The volcanic pipes which are perpendicular to the surface are deeper and expose a vertical funnel-shaped profile (Plate 13, Figures C-J). The outer rims and the sides of depressions of both inclined and vertical types of volcanic pipes are covered by fine dust arranged in streaks formed by water vapor which accompanied the eruption of magma (Plate 14, Figures A-E; Plate 15, Figures A-E), sometimes showing intense steam explosion (water vapor and hematite) associated with massive eruption (Plate 12, Figure J). It is thus apparent that the volcanic pipes have encountered rock layers containing groundwater during the ascent of the magma through a series of fissures. The water is vaporized together with other volatile materials (carbon dioxide) producing an explosive event at the surface. The impact craters which caused by perpendicular collision of meteorites are never occurring inclined to the ground surface and never becoming structurally controlled (i.e. following fissures or fault planes) in the crust as the volcanic pipes do on the surface of Mars.

9. The bottom floors of calderas are commonly intruded by younger generations of volcanic pipes of different types and sizes as well as cinder cones of small sizes. Sometimes, the volcanic pipes erupt on the flanks of the parasitic composite volcanoes which occur on the bottom floor of the large caldera. Some small calderas are also erupting at the expenses of large calderas. Thus, two or three generations of different ages of volcanic eruption could be recorded during the history of the same caldera. The first generation is the eruption of lava flows and collapse of the magma roof leading to the caldera formation; the second generation is the re-eruption of post caldera lava flows from the central vent of the pre-existing caldera leading to formation of parasitic composite volcanoes or cinder cones covering the bottom surface of the caldera; the third generation (second generation in case of presence of two generations) is the eruption of several volcanic pipes from different vents on the bottom floor of the caldera and often along the flanks of the parasitic volcanoes which re-erupt on the bottom floor of pre-existing caldera (Plate 16, Figures A-J). In simple calderas where no parasitic volcanic landforms cover the central vent, the calderas show a younger generation of volcanic eruption of small cinder cones and /or volcanic pipes from different peripheral vents at the bottom surface of the pre-existing calderas (Plate 17, Figures K-T). The detection of different generations of volcanic eruption at the bottom floor of the same crater as well as the flanks of the post caldera parasitic volcanoes which may re-erupt at the center of the bottom floor of many calderas calls for dropping the theory of meteorites that hit the surface of

Mars as the only reason for the formation of all craters on it. It is inconceivable that meteorites have a selective policy that hits the same site (same point of same altitude) three times over three different ages extending throughout the geologic history of Mars from the Noachian era (3.8 Ga) to the present with different strength, different shape and different size each time.

10. In many large caldera craters particularly those which occur in the southern highland hemisphere to the south of Latitude 43 there are extensive sand-sized dark dunes overlying the bottom surface of the caldera. For example are the dune deposits inside Proctor, Rabe, Russell and Liu Hsin as well as many unnamed craters near the southern ice-cape. Comparable deposits are found in some larger craters in the northern low lands such as Moreux and Radau. The dark color is due to the enrichment of pyroxene and olivine pointing to the basaltic origin (ancient volcanic ash) of the dune sand-sized grains [42,43]. The dune deposits are not blown into the craters as previously assumed, but they are volcanoclastic sediments produced from the volcanic ash erupted from a vent at

the bottom surface of the caldera or formed by erosion of lava flows and other lithified volcanic material which erupts inside caldera [43,44]. The shape of the dune deposits inside the craters may be transverse (Proctor, Rabe, Matara and others in the southern hemisphere; Radau in the northern hemisphere, Plate 18, Figs. A, B and E) or barchanoid (e.g. Moreux in the northern lowland hemisphere; Russell and Liu Hsin in the southern highland hemisphere, Plate 18, Fig. C). Sometimes they assume a linear shape or attains a wide network formed by intersection of linear and transverse dunes (several unnamed craters near the southern polar ice-cap) (Plate 18, Figure D-F).

The present authors noticed that dark dune volcanoclastic material inside the larger craters on Mars occurs around the parasitic post-caldera landforms which re-erupt after the re-filling of the underlying magma chamber from the central vent at the bottom surface of some large calderas (Plate 3, Figures G-J; Plate 10, Figures C, D, I and J). This confirms that the volcanoclastic material originates from the re-eruption of basaltic magma from a vent at the bottom surface of pre-existing caldera.

The volcanoclastic material inside the craters might occur during the main activity phases of the global volcanism of the early to middle Noachian period, before significant fluvial processes have taken place on Mars [45]. Other hypotheses which propose that dark fine-grained material (in this case, impact melts and glasses) might have

been produced by numerous meteorite impacts (Schultz and Mustard 2004) are not confirmed. However, recent studies prove the volcanic ash theory and strengthen the hypothesis of local material sources by multiple spectral correlations and image evidence from many regions on Mars [43,46,47].

11. Beside the above-mentioned volcanic indications, none of the studied craters which vary in diameter from 2 km to 162 km is surrounded by a star-shaped distribution of ejecta which characterizes the impact craters, except of two small craters lying in the northern low lands at altitudes 61°16'02.52" N 124°54'17.77" E and 44°13'14.43" N 23°24'07.46" E (Plate 19, Figures A & C). Both craters are circular in shape and bounded by a star-shaped distribution of amounts of shattered material around the rim of the crater probably as a result of collision of a meteorite with the Martian surface. The diameter of these craters is 3.3 km and 1 km while the width of the star-shaped ejecta around the crater is 7.6 km and 5 km respectively. The subsurface depth of depression of crater below ground surface is 133 m and 89 m respectively (Plate 19, Figures B & D). The larger crater (northern one) is surrounded by clusters of small simple cinder cones with a cone height above ground surface varying from 24 m to 121 m (Plate 19, Figures E-J).

A fresh Martian impact crater has also been detected in a stunning new image taken by NASA's Mars Reconnaissance Orbiter. Using its High-Resolution Imaging Science Experiment (HiRISE), the spacecraft photographed the new feature on April 17, 2019 [48]. The crater is located at 3.7 degrees north latitude, 53.4 degrees east longitude on Mars near the equator, and it formed at some point between September 2016 and February 2019. The crater spans approximately 100 feet (30 meters) in diameter and is surrounded by a large, rayed (star-shaped) distribution of rejecta. The explosion that excavated this crater threw ejecta as far as 9.3 miles (15 kilometers).

In impact craters it is supposed that the ejecta blanket that surrounds the rims of the crater is a generally symmetrical apron of material ejected from the crater during its formation and which is typically arranged in a star-shaped distribution around the crater rim. However, beside the definite absence of the star-shaped distribution of rock debris, the outer rim of the caldera craters on Mars is almost asymmetrical (having unequal height) around the crater as a result of building up of materials of volcanic flows higher on the downwind side of the vent before collapse of the roof of magma chamber.

12. The present study confirms the viewpoint of

Michalski and Bleacher [32] concerning the caldera concept for the origin of Eden Patera, Siloe Patera and Euphrates Patera. A thorough examination of the satellite images of these landforms indicates that they are distinctly huge volcanic calderas. Eden Patera belongs to the large and deep complex caldera which is identified here as Caldera No. 5 (Plate 20, Figures A-A). This type of caldera is formed by strong explosive eruption of lava which was accompanied by successive collapse of the summit crater into the partially drained magma chamber, then followed by an addition of a post-caldera eruption of lava from the central vent leading to the formation of composite volcano on the bottom floor of the original caldera. The central vent became entirely closed by the uprising volcanic material accompanying the post caldera eruption, but steam explosion took place through another vent on the flanks of the uprising younger volcanoes. Zonal structure is prominent in this type of Caldera as a result of successive collapse before the re-eruption of composite volcano. The Siloe Patera and Euphrates Patera are calderas of the type 4 as defined in the present work (Plate 20, Figures B-B & C-C). This type of caldera No.4 is generally large in size, with a much deep but smooth bottom surface and showing a well-developed zonal structure due to successive collapse. No additional post caldera eruption occurs on the bottom floor of this type of caldera.

Types Of Volcanic Craters

The Calderas

Previous Subdivisions of Calderas on Earth and Mars

Although various classifications schemes distinguish up to 12 caldera types on Earth based on morphology and eruption mechanism [49,50], only three general morphological classes of calderas are proposed by Wood [51]. These are calderas in basaltic shield volcanoes, (shield calderas), calderas that behead stratovolcanoes (stratocone calderas), and large calderas associated with broad ash flow sheets (ash flow calderas).

The shield calderas are best known from examples in Hawaii, where tumescent summits subside along near vertical ring fractures following partial drainage of magma from near surface chambers into rift zones. Macdonald [52] and Williams and McBirney [53] believed that calderas form only after the shields grow almost to their full height, but the discovery of a caldera on Loihi [54], a submerged shield in an early stage of growth just south of Hawaii, led Wood [51] to suggests that calderas probably exist throughout the growth of basaltic shields. According to Wood [51] the shield caldera formation is due principally to drainage

of magma rather than explosive removal of it, although evidence exists for both drainage and explosive emptying of shield magma chambers.

The stratocone calderas are the "Krakatoa"-type calderas of previous classifications. Williams'[55] classic review of calderas concluded that these calderas result from collapse following copious eruption of ash and pumice, generally from the summit vent of a pre-existing stratovolcano.

The Ash flow calderas are the Valles types of Williams and McBirney [53]. They result from collapse following the eruption of extremely large volumes of dacitic to rhyolitic ash flows. Besides Valles [56], examples are calderas in the San Juan volcano field of Colorado, Yellowstone in Wyoming, and Aso and Aira in Japan. According to Wood [51] ash flow calderas are the largest on Earth, and most were not formed on existing massive volcanoes. Many ash flow calderas larger than about 20 km diameter have resurgent centers, apparently updomed during or by the refilling of the underlying magma chamber [56].

Three Main Divisions of volcanic Caldera on earth were proposed by the Geological Sciences, San Diego State University [57] as follow:

a. Crater-lake type calderas associated with the collapse of stratovolcanoes [51]. This caldera type is generated after the main phase of a Plinian eruption, during collapse of a stratovolcano into the void of the underlying, depleted magma chamber. The caldera walls rise above the lake level an additional 600 m. This large depression formed from the violent eruption and collapse of the ancestral stratovolcano Mt. Mazama about 6850 years ago. The caldera has since been the site of several small eruptions which have covered parts of the caldera floor with andesitic to rhyolitic lava. The most voluminous of these post-caldera eruptions have built a volcanic cinder cone which forms an island (Wizard Island) at the west end of Crater Lake in Crater Lake National Park, Oregon

b. Basaltic shield volcano calderas associated with the summit collapse of shield volcanoes [51]. The summit regions of many active shield volcanoes are marked by calderas. Hawaiian examples include the Mokuaweoweo caldera on Mauna Loa and the Kilauea caldera on Kilauea. Most basaltic shield volcano calderas on earth are 1-5 km in diameter. Those observed on Mars, however, are extraordinarily large, the largest being the Olympus Mons caldera, with a diameter of more than 60 km!

c. Resurgent calderas. These are the largest volcanic structures on earth. They are associated with massive

eruptions of voluminous pyroclastic sheet flows [51]. They are similar to Crater-Lake type calderas in that they are also generated by crustal collapse above shallow magma chambers. Resurgent calderas, however, are too large to have been associated with a Crater-Lake type central volcano. Apart from their large size, the definitive feature of resurgent calderas is a broad topographic depression with a central elevated mass resulting from post-collapse upheaval of the caldera floor. There are three resurgent calderas in the United States less than 1.5 million years old -- the Valles Caldera in New Mexico, the Long Valley Caldera in California, and the Yellowstone Caldera in Wyoming.

Not much attention has been paid to the Martian collapse calderas which erupt at or near the ground surface. The only calderas that have been thoroughly described by several authors on the surface of Mars are the summit calderas [51,57] which occur at the top of large and relatively young shield volcanoes as well as on the older highland patera-type volcanoes. The terms Alba Patera, Uranius Patera and Ulysses Patera have been redefined by the international Astronomical Union (IAU) to refer only to the central calderas of these volcanoes.

Wood [51] maintained that although Mars has only 20-25 calderas (i.e. summit calderas at the top of major and minor shield volcanoes) a multitude of morphological varieties has been discerned. According to him Alba Patera, the shields, and the domes are all basically similar, representing variants of the shield class of caldera. Highland paterae are clearly different from the shields and constitute an additional class. Other caldera classes may exist but cannot be identified with certainty. Crumpler et al. [58] identified two fundamental types of summit calderas on Mars (the Olympus type and the Arsia type) that may represent end member variations in the size and depth of magma chambers. Both types occur on the large and relatively young shield volcanoes as well as on the older highland patera-type volcanoes.

The Olympus-type caldera: This type includes the calderas of most of the smaller Tharsis and the Elysium shield volcanoes. Calderas of this type are characterized by distinct fault-related boundary walls, and often occur in nested and overlapping sets of individual collapse craters, each of generally circular plan shape. The Olympus-type calderas on many volcanoes are contemporaneous with flows which erupted after formation of the main shield. Four sub-types of the Olympus-type caldera may be defined on the basis of the cluster patterns and the overlapping shape of the calderas contributing to the complex:

i. Overlapping,

- ii. Nested,
- iii. Irregular, and
- iv. Circular

The summit caldera complex of Ascræus Mons is an example of the 'overlapping' type, in which one or more of the smaller calderas lies on the margin of the largest caldera in the sequence. The summit caldera complex of Hecates Tholus is the clearest example of the 'nested' type, in which several smaller calderas all occur within a single much larger summit caldera or depression. The calderas of Uranius Patera and Uranus Tholus, and to some extent Tyrrhena Patera and Apollinaris Patera, may be defined as nested in this sense. The summit caldera of Olympus Mons consists of both nested and overlapping morphologies. The 'irregular' type is defined on the basis of scalloped and irregular margins. The calderas of Uranus Patera, Jovus Tholus, and Tharsis Tholus are irregular.

The 'circular' sub-type is often a single caldera or a caldera complex with one or more very small calderas associated with a much larger caldera of extremely circular planform. This sub-type includes Albor Tholus, Ulysses Patera, Elysium Mons, Hadriaca Patera and Ceraunius Tholus. The summit caldera of Elysium Mons is the best example of this type and ranks as one of the most circular compared with the typical shape of small calderas

The Arsia-type of caldera: This type is exemplified by the broadly concave depression on the summit of Arsia Mons. The Arsia-type has gently sloping (sag-like) margins rather than the abrupt bounding escarpments characteristic of the Olympus type, occurs characteristically as a single caldera, is generally more circular, and is larger in diameter than the simple Olympus-type calderas. The broad summit depressions of Pavonis Mons, Alba Patera, and some highland paterae may be included in this category.

Present Subdivisions of Calderas on Mars

Before presenting the characteristics of different types of the volcanic calderas on Mars we would like to point out that the common saying that the bottom of the impact crater is below the surrounding terrain, while the bottom of the volcanic crater (calderas) is above the surrounding terrain is not always true and is contrary to practical evidence. This is only true in case of the summit calderas of the shield volcanoes which form at the top of volcano as a result of either an enormous lava explosion which blasts away large volumes of rock to form the caldera, or due to emptying of shield magma chambers and continued collapse and subsidence of the overlying crust [51,58]. This

type of caldera which is known as shield caldera occurs at the top of major and minor shield volcanoes as well as the so-called Patera-type volcanoes on Mars (Sketch 1- A).

However, in case of collapse calderas which erupt at or very near the ground surface, the bottom floor of these caldera lies completely below ground surface as a result of collapse of the roof of the magma chamber into the partially or completely emptied magma chamber. These volcanic calderas are marked by two main successive events during its history, the first event is the eruption of lava on surface from a vent connecting the magma chamber with the caldera, and as more magma was erupted, cracks opened up around the summit, then the summit began in the second event to collapse below ground surface into the partially or completely drained magma chamber leaving an outer rim above the ground surface (Sketch 1-B). Thus, the height and shape of the outer rim above ground surface reflects two parameters; 1) the intensity of eruption of lava from down upward (first event), and 2) the rate of withdrew of lava from up downward, suddenly or gradually (second event). Thus the resultant volcanic caldera is a simple bowl-shaped crater with an outer rim of variable height above ground surface around the crater, while the sides of the crater become completely below ground surface. Calderas belonging to this type are known as simple calderas and they are widespread on Mars. This type of caldera is equivalent to the Stratocone Calderas of Wood [51] and partly equivalent to the simple Crater-Lake Type Calderas which have no wizard island at the bottom floor.

In some types of caldera the huge collapse caldera formed at the ground surface level by strong eruption of lava accompanied by successive collapse of the summit crater into the partially drained magma chamber, is followed by an addition of a post caldera re-eruption of lava flow as a result of refilling of the underlying magma chamber leading to the formation of parasitic volcanic landforms of different shapes and sizes (cinder cones, composite volcanoes or volcanic domes) on the bottom floor of the pre-existing caldera (third event). These types of caldera (Sketch 1-C) are known as complex calderas and they occur in common to abundant numbers on Mars. They are partly equivalent to the Ash Flow Calderas of Wood [51] and partly to the Crater-Lake Type Calderas on the western side of the Lake Oregon where post-caldera eruptions built a volcanic cone of Wizard Island at the bottom floor of the pre-existing caldera.

Calderas belonging to this type cannot be termed as resurgent calderas because in geology, a resurgent dome is a dome formed by swelling or rising of a caldera floor due to

Sketch 1-A: A shield caldera above ground surface level at the top of shield volcanoes and volcanic cones formed mostly as a result of either enormous explosion which blasts away large volumes of rock to form an explosive caldera, or due to emptying of shield magma chambers. This type of caldera is also known as summit caldera. It occurs at the top of major and minor shield volcanoes on the surface of Mars. It is very similar to the caldera complex at the summit of Earth's largest shield volcano - Mauna Loa Volcano on the island of Hawaii.

Sketch 1-B: A collapse caldera formed below the ground surface level when a large magma chamber is emptied by a volcanic eruption or by subsurface magma movement. The unsupported rock that forms the roof of the magma chamber becomes cracked as more magma was erupted, and the cracks opened up around the summit, then the summit begin to collapse suddenly or gradually below ground surface into the partially or completely drained magma chamber to form a large crater leaving an outer rim above the ground surface. The calderas belonging to this type are known as simple calderas and they are widespread on Mars.

Sketch 1-C: A huge collapse caldera formed at the ground surface level by strong eruption of lava accompanied by successive collapse of the summit crater into the partially drained magma chamber, then followed by an addition of a post caldera eruption of lava flow as a result of refilling of the underlying magma chamber leading to the formation of parasitic volcanic landforms of different shapes and sizes (cinder cones, composite volcanoes or volcanic domes) on the bottom floor of the pre-existing caldera. The calderas belonging to this type are known as complex calderas and they are also very common on Mars.

movement in the magma chamber beneath it. Unlike a lava dome, a resurgent dome is not formed by the extrusion of highly viscous lava onto the surface, but rather by the uplift and deformation of the surface itself by magma movement underground. The term Wizard Island [59] was generally used to denote the post-caldera parasitic cinder cone at the bottom floor of larger calderas, but here it extends to cover all post-caldera parasitic landforms including cinder cones, composite volcanoes and volcanic domes which re-erupt at the bottom floor of larger caldera as a result of re-filling of the magma chamber. The term resurgent caldera is here restricted only to calderas with a dome-like (upheaval) bottom floor formed by the uplift of surface due to magma movement underground.

On these grounds the volcanic calderas on Mars are subdivided in this work into three main groups as follow:

1. An independent (free) collapse caldera lying entirely below ground surface level (BGSL), and with an outer rim almost of varying height above ground surface level (AGSL). This group of caldera is formed by the collapse of the roof of magma into the void left when its magma chamber is emptied due to violent eruption, thus forming

a steep-walled bowl-shaped depression (Simple Caldera) on the surface. Sometimes these calderas show a younger post-caldera re-eruption of lava flow or ash leading to the formation of cinder cone, composite volcano or volcanic dome at the center or periphery of the bottom floor of the pre-existing caldera (Complex Caldera). Members belonging to this group of Caldera include the Ash-Flow Type and the Stratocone Type of Wood [51]; the Crater-Lake Type and the Resurgent Type of San Diego state university

This group of caldera includes 6 different types of calderas of variable morphologies and different relative ages:

- a. Caldera No.1 (Cal 1): It is a simple small-sized caldera with a shallow subsurface depth, flat bottom floor and faint outer rim or one-sided outer rim.
- b. Caldera No.2 (Cal 2): It is a simple moderately-sized caldera with a rounded moderately deep bottom floor and a well- developed symmetrical outer rim
- c. Caldera No.3 (Cal 3): It is moderate- to large-sized complex caldera with a deep funnel-like depression, an almost asymmetrical outer rims and an open deep central

vent. This type is characterized by the eruption of two different stages of volcanic lava from the same central vent; each of them is followed by successive collapsing into the void left when its magma chamber is emptied without leaving a post-caldera volcanic landform (Wizard Island) at the bottom floor. Zonal structure is evident due to gradual collapses rather than a single event

d. Caldera No.4 (Cal 4): It is a huge simple caldera with a large strongly concave and smooth bottom floor. It is also characterized by higher almost asymmetrical outer rim as a result of strong eruption. This type shows a well-developed zonal structure due to gradual collapse and has no wizard island at the bottom floor. The central vent is either open, or closed and buried by volcanic materials.

e. Caldera No. 5 (Cal 5): It is a complex caldera with a less strong younger post-caldera phase of eruption of volcanic materials from the same central vent giving rise to the formation of parasitic cinder cone, volcanic dome or very rarely composite volcano forming a Wizard Island of different shape and size at the center of the pre-existing caldera floor. A smaller variant of this type of caldera (Caldera 5') shows either a volcanic dome at the bottom floor or an up-domed floor formed by the uplift and deformation of the surface itself by magma movement underground

f. Caldera No. 6 (Cal 6): It is a huge complex caldera with a more strong younger phase of eruption of lava flow from the same central vent giving rise to the formation of post-caldera volcanic landform formed exclusively of parasitic composite volcanoes at the center of the pre-existing caldera floor. This type of caldera is much larger in size and deeper in bottom surface (below ground surface) than all other calderas. The height of the parasitic composite volcano at the bottom floor is often greater than the subsurface depth of the pre-existing caldera.

2. A Mountain (summit) Caldera lying above ground surface level, at the top of a shield volcano or composite volcano (= Shield Caldera of Wood 1984; Basaltic Caldera according to the classification of San Diego state University). This group of caldera (summit caldera) is marked by a large depression almost without outer rim at the top of shield or composite volcanoes. They are formed as a result of a series of tremendous explosion which rapidly drain in magma beneath the mountain and can no longer support the volcano top. In shield volcano the tops of volcanoes collapse when magma erupts as lava flows, emptying the magma chambers. The mountain caldera group includes the Olympus Mons Caldera type and the Arsia Mons Caldera type of Crumpler et al. [58]. Both types occur on

the large and relatively young shield volcanoes as well as on the older highland "patera"-type volcanoes. The caldera in both types is characterized by having a collapsed summit lying completely above ground surface and exhibiting a very shallow depth with respect to the height of shield volcano.

The mountain (summit) caldera group is outside of our scope. For detailed description of the summit caldera see Crumpler et al. 1996)

3. Parasitic Caldera. This group of caldera occurs on the flanks of shield and composite volcanoes. It is known as "flank crater" which forms at lower altitudes than summit craters (volcanic crater, National Geographic Society) It also occurs at the bottom floor of some larger calderas where it represents a relatively younger generation of eruption of lava flow with respect to the pre-existing volcano.

The description of parasitic calderas which occur at the bottom surface of some pre-existing large calderas is here included among the description of different types of independent calderas.

Caldera no. 1 (Cal 1) (Plates 21 - 23) (Text Figures 1 - 2)

This is the simplest type of caldera among the studied independent calderas. It is characterized by having a shallow subsurface depth (below ground surface), a more or less flat bottom floor, and the presence of a low, almost one-sided outer rim, as well as the absence of zonal structure inside the caldera. The shallow depth of this caldera and its faint outer rim supports that this caldera type was formed due to a shallow eruption of almost one phase of volcanic lava followed directly by one phase of collapse of the summit into the completely drained magma chamber. The lava is not always erupted in this type of caldera from a central vent but almost through a vent on the sides or peripheries of the bottom floor of caldera. No additional post-caldera eruption covering the caldera bottom floor, suggesting cessation of volcanic activity (Plate 21, Figures A-G; Plate 22, Figures H-N). However, steam explosions (water vapor and hematite) seem to have taken place sometime later through a peripheral vent on one side of the bottom surface of caldera (Plate 23, Figures A-D).

Caldera 1 occurs almost exclusively independently as an original landform both below and above 0 datum level. It occupies different topographic levels between elevation -5000 m below 0 datum level and elevation +7000 m above 0 datum level (Text Figure 1). The subsurface depth (below ground surface) of Cal 1 ranges between 768 m and 1522 m, with an average value of different studied series 1147 m, whereas the height of the outer rim (above ground surface)

Plate 21: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 1 (Cal 1) in both lowlands (below 0 datum) of the northern hemisphere (A-F) and highlands (above 0 datum) of the southern hemisphere (G) of Mars.

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Plate 22: continuation of Plate 21: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 1 (Cal 1) in highlands (above 0 datum) of the southern hemisphere (H-N) of Mars.

Plate 23: A- D - Electronic profiles (A-D) showing overlapping of caldera 1 (A), clusters of Cal 1 (B), parasitic Cal 1 erupts at the bottom floor of a huge Cal 4 (C), clusters of Cal 1 and Cal 2 in lowlands of the northern hemisphere (D) of Mars. E- Clusters of Cal 1 and Cal 2 in highlands of the southern hemisphere. F- Clusters of Cal 2. G- Electronic profile showing eruption of Cal 3 at the expense of Cal 1. H- Clusters of Cal 3 in the highlands of the southern hemisphere of Mars. I-J- Electronic profiles of parasitic Cal 2 along the upper flanks of Olympus Mons (I) and parasitic Cal 3 along the eastern flanks of Alba Mons (J).

Type of volcano: Caldera

Caldera No. 1 (Cal 1)

Data

Series of Caldera 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 1	2189	232	-1772	-1954	-1977	-604	3886	2055	2002	6409	2475	-1983	2337	-2240	1025
	2214	26	-1644	-1900	-1820	-518	3875	2000	2033	6495	2364	-1833	2019	-2147	1305
	1625	-569	-1612	-1850	-1790	-460	3865	1976	1800	6204	2164	-2528	1657	-2646	904
	1386	-980	-1731	-1786	-1723	-665	3603	1915	1400	5900	1921	-2990	1232	-3041	396
	1168	-1185	-2137	-2215	-2102	-1039	3455	1655	1074	5700	1865	-3073	1173	-3378	285
	1091	-1279	-2422	-2532	-2650	-1226	3311	1313	839	5657	1844	-3141	1111	-3556	172
	1073	-1258	-2715	-2719	-2816	-1331	3148	1134	852	5627	1842	-3184	1056	-3670	58
	1146	-1265	-2840	-2795	-2843	-1325	3108	882	1012	5587	1866	-3202	1059	-3702	49
	1124	-1263	-2882	-2815	-2891	-1357	3113	777	825	5567	1884	-3173	1048	-3744	53
	1194	-1235	-2800	-2787	-2928	-1372	3119	768	794	5505	1912	-3100	1077	-3762	66
	1218	-1218	-2700	-2709	-2808	-1221	3137	828	952	5494	1973	-2965	1124	-3695	108
	1268	-840	-2570	-2483	-2648	-924	3252	878	1184	5480	2124	-2636	1205	-3550	304
	1506	-527	-2312	-2253	-2350	-728	3580	1024	1430	5525	2456	-2304	1556	-3347	496
	2034	19	-1760	-1940	-2155	-485	4005	1477	1741	5691	2937	-2044	2015	-3016	685
	2326	210	-1680	-2000	-1975	-635	3907	1517	2087	6022	2831	-1843	2084	-2709	877
	2456	90	-1593	-2050			3788	1470	2218	6336	2736			-2422	683

Representation of Data

Text Figure 1: Topography and topographic location of different volcanic series of caldera No.1 (Cal 1) with respect to 0 datum on Mars. The measurements of elevation (1-16) are more or less symmetrically spaced across the width of each caldera, but the width of caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and average height of outer rim of each volcanic series of Cal 1 see Text Fig. 2.

Type of volcano: Caldera

Representation of Data

Caldera No. 1 (Cal 1)

Data

Caldera No. 1					
Series No.	Parameter	A	B	C	D
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)	Average height of outer rim (in meters)
series 1		58.3	61.6	1383	12.5
series 2		33.3	40.4	1497	60
series 3		35	51	1289	80
series 4		41.7	67	861	139
series 5		35	63	953	127
series 6		7.7	11.2	768	147
series 7		11.25	17.2	778	108.5
series 8		24.25	36	1278	23.5
series 9		35.5	40.9	1424	15.5
series 10		32	43.8	929	43
series 11		50	67	894	100
series 12		41.4	53.2	1359	75
series13		33.8	40.8	1289	0
series 14		39.5	45.9	1522	46.5
series 15		62	78.4	976	237

Text Figure 2: Morphologic features of Caldera No. 1 (Cal 1) on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

ranges between 12.5 m and 237 m, with most values lying between 43 m and 147 m and an average value of 81 m. These values are the least values among all other types of caldera on the Martian surface. The diameter of the crater of this caldera varies from 7.7 km to 62 km in different studied series with most values lying between 32 km and 41.7 km and an average value of 36 km, whereas the width of volcano varies from 11.2 km to 78.4 km, with most values lying between 40 km and 67 km and an average value of 47.8 km (Text Figure 2). Named craters belonging to this type of simple collapse caldera include Kolonga, Wukari, Russell, Proctor, Becquerel, Chinju, Jezero beside many other unnamed craters of the same type.

Overgrowth and occurrence in clusters is common in Cal 1 (Plate 23, Figures A-B, D-F). Association of independent Cal 1 and Cal 2 are also common. Parasitic Cal 1 is also found intruding the bottom floor of other larger caldera such as Cal 4 (Plate 23, Figures C). However, no parasitic Cal 1 is recorded along the flanks of shield volcanoes except of the Uranus Tholus where a deformed Cal 1 is recorded along its northern lower flanks. On the other hand, most members of this type of caldera are intruded by a younger phase of eruption of volcanic pipes around and on the caldera bottom floor. Caldera 1 is commonly found in the southern highland hemisphere where it shows a low relief due to intense erosion accompanied by deposition of transverse dune structure of volcanoclastic material particularly near the southern ice-cap pole (Plate 18, Figures A & D). Some of the craters of this caldera are covered by ice sheets leading to frozen caldera near the southern pole (Plate 21, Figure G, Plate 22, Figures I-J).

Caldera no. 2 (cal 2) (plates 24-25) (Text Figures 3-4)

This type of caldera is also a simple caldera type with no zonal structure on the bottom surface, suggesting one phase of eruption followed directly by collapse of summit into the completely drained magma chamber. It differs from Cal 1 by having a relatively deeper bottom surface below ground surface and in possessing a higher more or less symmetrical outer rim above ground surface, suggestive of a more violent eruption than Cal 1. It occupies different topographic levels in both low- and highlands between elevation -5000 m below 0 datum level and elevation +7000 m above 0 datum level (Text Figure 3).

The subsurface depth below ground surface varies in different studied series from 626 m to 1903 m, with an average value of 1286.5 m, whereas the outer rim above ground surface ranges between 157 m and 425 m, with an average value of 249 m (three times more than in Cal

1). The central vent is either closed and buried by volcanic materials or open and extended peripherally along the side walls of the caldera depression (Plate 24, Figures A-G; Plate 25, Figures H-N). In most members of this caldera there is a younger eruption of lava from a peripheral vent at the bottom surface of the caldera after complete cessation of volcanic activity from the central vent. Whenever the central vent is open there is younger steam explosion (water vapor and hematite) which probably continued through the vent for a long time (Plate 24, Figures E-F).

Caldera 2 differs also from Cal 1 by having a slightly less diameter of crater and less width of volcano. The diameter of crater ranges in different studied series between 12 km and 71 km, with an average value of 32.3 km, whereas the width of volcano varies from 18.25 km and 107 km, with an average value of 41.2 km (Text Figure 4). It seems to have occurred due to a strong and continuous eruption of volcanic lava which is not always ejected from a central vent, but also from a vent on the side of volcano as a side eruption. No additional post-caldera eruption occurred on the caldera bottom floor of this type. A younger phase of eruption of small-sized volcanic pipes is found in representatives of this type of caldera particularly those which have closed and buried central vents. However, representatives of Cal 2 which have open central vents do not show younger intrusion of volcanic pipes. This would suggest that calderas belonging to this type are not synchronous in age throughout. Named craters belonging to this type of simple collapse caldera include Pangboche, Voeykov beside many other unnamed craters of the same type.

Besides occurring as a common independent landform on the surface of Mars, Cal 2 is found as parasitic volcano in the bottom surface of large-sized Cal 4 and Cal 5 as well as along the flanks of several shield volcanoes including Olympus Mons (Plate 23, Figure I), Elysium Mons, Hecates Tholus, Uranus Tholus, Uranus Mons and the composite volcano Ulysses Tholus. This would indicate that the eruption of Cal 2 extended for a long time before and after the eruption of several shield volcanoes.

Caldera no. 3 (cal 3) (plates 26-29) (Text Figures 5-6)

This type of complex caldera is characterized by the eruption of two different stages of volcanic lava; each of them is followed by successive collapse of the summit crater into the same void left when its magma chamber is emptied. The first older stage was a large explosive eruption which partly emptied the magma chamber, then followed by a successive collapse of summit into the partially drained magma chamber forming a large bowl-shaped caldera with

Plate 24: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No.2 (Cal 2) in lowlands (below 0 datum) of the northern hemisphere (A-G) of Mars.

Plate 25: continuation of Plate 24: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No.2 (Cal 2) in the southern hemisphere both across 0 datum (H-J) and above 0 datum (K-N) of Mars

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Type of volcano: Caldera

Caldera No. 2 (Cal 2)

Data

Series of Caldera 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 2	-1246	-2067	-2712	504	-3483	-33	729	713	4989	4379	3954	6129	-1570	-2902	-2470
	-1223	-1956	-2694	711	-3443	30	882	925	5316	4654	4048	6412	-1484	-2779	-2406
	-1031	-2506	-2506	520	-3256	102	335	636	4914	4846	4324	5936	-1146	-3431	-2195
	-1303	-2827	-2881	127	-3101	232	41	386	4453	4562	4107	5433	-1707	-3850	-2584
	-1552	-3064	-3218	-251	-3662	-106	-261	38	3978	4210	3467	5093	-2381	-4189	-3020
	-1900	-3175	-3621	-536	-3891	-470	-466	-475	3663	4046	3052	4772	-2560	-4300	-3256
	-2100	-3275	-3677	-826	-3971	-818	-552	-559	3504	3979	2788	4477	-2674	-4377	-3366
	-2216	-3264	-3706	-1070	-4081	-955	-564	-592	3483	3968	2720	4295	-2762	-4440	-3467
	-2100	-3273	-3669	-962	-4092	-888	-556	-541	3508	4005	2840	4410	-2636	-4340	-3547
	-1854	-3150	-3583	-759	-4109	-777	-466	-401	3643	4031	3061	4484	-2585	-4238	-3378
	-1646	-3048	-3241	-449	-4036	-579	-351	179	3731	4168	3362	4689	-2462	-4000	-3062
	-1431	-2770	-2898	-71	-3690	-305	71	550	4117	4444	3659	4934	-2162	-3659	-2667
	-1187	-2273	-2518	360	-3075	0	510	834	4769	4751	3983	5316	-1499	-3351	-2273
	-977	-1814	-2676	816	-3431	245	1144	1032	5223	5030	4113	5867	-1353	-3008	-2450
	-1272	-1962	-2715	633	-3543	152	983	802	5730	5403	4016	5795	-1477	-2713	-2499
		-2135				0			5386	5028	3914			-2919	-2527

Representation of Data

Text Figure 3: Topography and topographic elevation of different volcanic series of Caldera No.2 (Cal 2) with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each Caldera, but the width of Caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each volcanic series of Caldera 2 see Text Fig. 4.

Type of volcano: Caldera

Caldera No. 2 (Cal 2)

Representation of Data

Data

Caldera No. 2				
Series No.	Parameter	A	B	C
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)
series 1		12	18.25	970
series 2		21	26.8	1208
series 3		12.7	19.3	994
series 4		34	47.2	1673
series 5		57	107	626
series 6		12.76	21.7	955
series 7		57	78.9	1547
series 8		63.5	83.6	1394
series 9		71	89.3	1903
series 10		18.2	25	1060
series 11		21	32.8	1244
series 12		33.5	47.2	1834
series 13		28.7	45	1275
series 14		25	32.6	1538
series 15		17.72	32.9	1077

Text Figure 4: Morphologic features of Caldera No. 2 (Cal 2) on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

a central open vent at the bottom floor leading from the emptied magma chamber to the bottom surface of the caldera. The second younger stage was ejected under less immense heat and pressure when the magma chamber was filled again and re-erupted from the same central open vent of the pre-existing caldera, then became collapsed again into the same vent without building any parasitic volcanic landform on the central vent (Plate 26, Figures A-G; Plate 27, Figures H-N; Plate 28, Figures A-E; Plate 29, Figures F-J).

This type of caldera is characterized by having a concentric ring pattern (Zonal structure), suggesting successive eruption of lava from a wide, open and deep central vent followed immediately or contemporaneously by successive gradual collapses rather than a single event into the void left below the vent when the magma chamber is emptied. The outer and inner (the central vent) rings are marked by steep walls with higher outer rims. Several representatives of this caldera are intimately associated to the oriented rows of volcanic pipes (VP1) and often intruded by a younger generations of volcanic pipes of different sizes. However, few representatives show an additional eruption from a peripheral vent beside the central vent

Calderas 1, 2 and 4 differs from Caldera 3 by having one stage of volcanic eruption followed directly by the collapse of the summit crater into the completely drained magma chamber and subjected later to closure of the central vent. Caldera 5 and 6, on the other hand, are characterized by the ejection of two stages of volcanic eruptions like Caldera 3 but differs from the later that the volcanic lava belonging to the second stage of eruption did not collapsed again into the emptied magma chamber but resulted in building up a large cone of parasitic volcanic materials (composite volcanoes, cinder cones, volcanic domes) around the central vent (see later).

Caldera 3 occupies wide topographic levels between elevation -5000 m below 0 datum level and elevation +7500 above 0 datum level (Text Figures 5). However, most representatives of this type are occurring in clusters in the high lands between elevation 0 and 7500 m above 0 datum level (Plate 23, Figure H) while occurring in individual sporadic craters in the low-lying lands across and below 0 datum level down to -5100 m.

Caldera 3 has wide deep sides extending symmetrically in the subsurface around a deep central funnel-shaped open vent. It differs from Cal 1 and Cal 2 by its greater size and by having a deep zoned bottom surface, a wide, deep and open central vent, and a more symmetrical outer wall. The subsurface depth of the crater below ground surface

ranges in different series between 1058 m to 2814 m, with an average value of 1860 m. The diameter of crater varies in different series between 17 km and 125 km, with an average value of 46 km. The width of volcano ranges between 20.7 km and 222 km, with an average value of 67.4 km. However, the outer rim of Cal 3 is more or less similar to those of Cal 2, but distinctly higher than in Cal 1. It varies between 0 m and 722 m, but most values range in different series between 116.5 and 349 m, with an average value of 220.5 m (Text Figure 6). Named craters belonging to this type of complex collapse caldera include Madler, Mazamba, Tugaske, Arima, Tibrikot beside many other unnamed craters of the same type.

Caldera 3 also occurs as parasitic landforms introducing on the flanks of some shield volcanoes such as Alba Mons, Elysium Mons, Hecates Tholus and Albor Tholus (Plate 23, Figure J). Taking into consideration the common presence of Cal 2 in Alba Mons, Elysium Mons and Hecates Tholus as parasitic landforms, it appears that the relative age of both calderas (Cal 2 & 3) is distinctly younger than these three shield volcanoes. On the other hand, the absence of all types of caldera on the flanks of the three Tharsis shield volcanoes (Arsia Mons, Pavonis Mons and Ascraeus Mons) indicates that these large shield volcanoes are relatively younger in age than all calderas and all other shield volcanoes.

It is worth of mention that Olympus Mons is not intruded by Cal 3, although Cal 2 and cinder cones occur as parasitic landforms on its flanks. This huge volcano was built up by many thousands of individual flows of highly fluid lava. So it is expected that the last flows in this volcano are younger in age than those forming Alba Mons, Elysium Mons, Hecates Tholus and Albor Tholus. This would substantiate the youngest age concept of Olympus Mons relative to these shield volcanoes, but not relative to the three major volcanoes of the Tharsis bulge which are representing the youngest volcanic eruption on the surface of Mars relative to calderas and other shield volcanoes.

Caldera 3 is characterized by having an open central vent in the bottom floor of the collapsed summit (Plate 28, Figures A-E; Plate 29, Figures F-J), thus indicating that this type of caldera did not suffered strong erosion or deposition of volcanic dusts as like other calderas. This would imply that caldera 3 is the youngest type of calderas on the surface of Mars, very probably synchronous with the eruption of the oriented volcanic pipes. Caldera 1 is older than Cal 3, but Cal 2 seems to be either simultaneous or closely related to Cal 3. Transitional forms between both types (Cal 2 and Cal 3) are not uncommon suggestive of their close genetic

Plate 26: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No.3 (Cal 3) in the highlands of both the southern hemisphere (A-F) and the northern hemisphere (G) of Mars.

Plate 27: continuation of Plate 26: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No.3 (Cal 3) in the highlands of the southern hemisphere (A) and the lowlands of both the northern (I, J, L-N) and southern (K) hemisphere of Mars.

Plate 28: Electronic profiles and three dimensional views of the open central vents at the bottom floor of different caldera No.3 (Cal 3) in highlands of the southern hemisphere of Mars. The caldera is characterized by the re-eruption of a second stage of lava flow of less immense heat and pressure from the same central vent of the pre-existing caldera after the re-filling of the magma chamber, then became collapsed again into the central vent without building any parasitic volcanic landform on the same vent.

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Plate 29: continuation of Plate 28: Electronic profiles and three dimensional views of the open central vent at the bottom floor of different caldera No.3 (Cal 3) in both lowlands (F and G) and highlands (H) of the northern hemisphere (F-H), and highlands of the southern hemisphere (I) of Mars. J- Parasitic Cal 3 along the eastern flanks of Alba shield volcano.

Type of volcano: Caldera

Caldera No. 3 (Cal 3)

Data

Series of Caldera 3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 3	4078	3586	3187	-396	-2778	1575	-525	-2769	3516	5664	-1505	6169	1040	2722	-3478
	4139	3856	3430	-244	-2594	1650	-392	-2635	3587	6047	-1721	6924	1242	2915	-3720
	3500	3552	2818	-616	-2797	1762	-542	-2944	3402	5523	-2214	7277	871	2390	-4155
	2710	2666	2364	-1291	-3113	1120	-1100	-3425	2990	4908	-3138	6068	565	1942	-4452
	2432	2070	1912	-1930	-3289	603	-1205	-3745	2505	4605	-3437	5634	236	1455	-4480
	2316	1886	1642	-1975	-3392	296	-1244	-3791	2384	4407	-3503	5527	-150	1278	-4432
	2440	1925	1535	-1949	-3415	114	-1208	-3734	2421	4225	-3608	5428	-200	1359	-4770
	1535	776	464	-2266	-3747	-468	-1189	-3917	2098	4004	-4055	5132	-400	1058	-4994
	2458	1845	1692	-1890	-3477	51	-1437	-3556	2331	4229	-3620	5422	-197	1374	-4700
	2526	1850	1803	-1945	-3492	-63	-1133	-3720	2288	4379	-3543	5540	-137	1302	-4670
	2828	2161	1915	-1839	-3455	17	-1054	-3693	2364	4501	-3457	5622	187	1450	-4614
	4172	2755	2150	-1497	-3334	417	-442	-3503	2653	4622	-2920	5865	497	2152	-4475
	3914	3324	2379	-810	-2976	940	-82	-3194	3251	4762	-2509	6011	821	2620	-3971
	3731	3668	2671	-470	-2426	1396	-200	-2800	3634	5551	-2071	6803	1136	2861	-3457
	3605	3523	2937	-195	-2475	1526	-284	-2968	3443	6316	-1629	6727	908	2765	-3621
	3535	3369	3278	-158		1364	-379		3187	6027	-1562	6575			-3742

Representation of Data

Text Figure 5: Topography and topographic location of different volcanic series of caldera No.3 with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each Caldera, but the width of Caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each volcanic series of Caldera 3 see Text Fig. 6.

Type of volcano: Caldera

Caldera No. 3 (Cal 3)

Representation of Data

Data

Caldera No. 3					
Series No.	Parameter	A Diameter of crater (in kilometers)	B Width of volcano (in kilometers)	C Subsurface depth (in meters)	D Average height of outer rim (in meters)
series 1		53	91	2543	349
series 2		51	77.6	2810	284.5
series 3		51.5	65	2814	121.5
series 4		57	71.7	2108	76
series 5		50.5	69	1272	116.5
series 6		48.3	75	2043	174.5
series 7		125	222	1058	215
series 8		17	20.7	1148	151.5
series 9		38.33	54.8	1418	259
series 10		25.92	30.7	2023	336
series 11		45	49	2550	0
series 12		31	56.3	1443	722
series13		23.5	31.6	1440	215
series 14		35.5	49.6	1707	144.5
series 15		36.5	47.4	1516	142.5

Text Figure 6: Morphologic features of Caldera No. 3 on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

relationship.

Large-sized representatives of Cal 3 which occur in lowland hemisphere below 0 datum level are commonly intruded by large volcanic pipes and cinder cones. However, those which occur at higher levels above 0 datum level either independently or as parasitic landforms on the flanks of some shield volcanoes are almost exclusively empty of any younger generations of volcanic pipes. This would suggest that members of Cal 3 are not synchronous in age; those which characterize the low-lying areas seem to have erupted sometime early than those which are situated in highlands

Caldera no. 4 (Cal 4) (Plates 30-32) (Text Figures 7-8)

This is a huge simple caldera formed by successive eruption followed directly by deep gradual collapse of the summit into the completely drained magma chamber. Caldera 4 is generally large in size, with a deep bottom surface and showing a well-developed zonal structure due to successive collapse. The central vent is either closed and buried by volcanic materials or open and extended peripherally. In case of closure of the central vent the caldera shows a peripheral eruption where lava pours from a vent on the side of the caldera wall (Plate 30, Figures A-G; Plate 31, Figures H-N).

Morphologically, this type of caldera differs from Cal 1, 2 and 3 in being much deeper below ground surface and in possessing much higher outer rims above the ground surface, thus suggesting a very strong explosion of volcanic lava followed by gradual collapse of the summit into the completely drained magma chamber. It also differs from Cal 3 by its larger size, by having rounded bottom surface that is much more convex downward, in lacking the deepest central vent which characterizes the bottom surface of Cal 3, and absence of evidence of second re-filling of the magma chamber and re-eruption of a younger phase of lava above the central vent.

Caldera 4 occurs usually in clusters below, above and across 0 datum level in both northern and southern hemisphere. Topographically, it occupies a more wide range of topographic levels than other calderas, between elevation of -6000 m below 0 datum level and elevation of +8000 m above 0 datum level. However, most studied representatives of this type of caldera are occurring either below or across 0 datum level between elevations -6000 m to +2000 m (Text Figure 7). Those which are recorded above and across 0 datum level in the highland are almost deformed and having asymmetrical sides and outer rims probably due to the effect of eruption of younger huge

shield volcanoes in this land. The negative representatives in the northern low lands (below 0 datum) belonging to this caldera are generally characterized by having a more or less symmetrical higher outer rims above the ground surface. Overgrowths of Caldera 4 of are not uncommon (Plate 32, Figure A).

The subsurface depth of Cal 4 below the ground surface level ranges from 1123 m to 2832 m, with an average depth of 1935 m. The crater of the caldera is larger, and the volcano has a great width as compared to Cal 1, 2 and 3. The diameter of crater ranges from 34 km to 104 km, with an average value of 70.7 km. The width of volcano ranges from 51 to 201 km, with an average of 115.6 km. The outer rim above the surface is much higher than in all caldera types, suggesting a more strong eruption than other calderas. It is varying between 115m to 1038.5 m, with most values lying between 266m and 822m, and an average value of 503.8 m (Text Figure 8). Named craters belonging to this type of simple collapse caldera include Siloe Patera, Euphrates Patera, Tikhov, Becquerel, Flammarion, Dawes, Kasimov, Pulawy, Dinorwic, Mie, Columbus, Niesten, Roddenberry, Darwin beside many more unnamed craters of the same type.

Caldera 4 is relatively older in age than Cal 1, Cal 2, Cal 3, Cinder cones and volcanic pipes as deduced from the stratigraphic relationships. Cal 1, Cal 2 and Cal 5 are commonly erupted as parasitic landforms on the sides of the bottom surface of some large-sized Cal 4. Caldera 5 is particularly found overlapping large-sized Cal 4 and Cal 6 where it sweeps a part of the older caldera (Plate 32, Figures C, G & H). Cinder cones, on the other hand are formed from younger generation of lava which pours from a peripheral vent on the sides of the bottom surface of some Cal 4 (Plate 32, Figure D). A younger generation of volcanic pipes of different sizes is also intruded in the bottom floor of many representatives of Cal 4. No Cal 4 is recorded as a parasitic landform along the flanks of both major and minor shield volcanoes.

Caldera no. 5 (cal 5) (plates 33-40) (Text Figures 9-12)

This is a complex caldera formed by strong eruption of lava which was accompanied by successive collapse of the summit crater into the partially drained magma chamber, then followed by a re-filling of the magma chamber and re-eruption of a post caldera volcanic phase, thus leading to the formation of parasitic volcanic landforms on the bottom floor of the pre-existing caldera. The parasitic volcanic landforms are cinder cones, volcanic domes or rarely composite volcanoes forming the so-called Wizard Island

Plate 30: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 4 (Cal 4) in lowlands (below 0 datum) of the northern hemisphere (A-G) of Mars.

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Plate 31: continuation of Plate 30: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 4 (Cal 4) in the northern hemisphere both below 0 datum (H) and across 0 datum (K), and in the southern hemisphere both above 0 datum (I, L and M) and across 0 datum (J and N) of Mars

Plate 32: A- Clusters and overgrowth of Cal 4 in the northern hemisphere of Mars. B and F- Clusters and overgrowth of Cal 5 in the southern hemisphere. C, G and H- Electronic profile and top views showing a younger Cal 5 or Cal 5' overlapping and sweeping part of large older Cal 4 in the southern hemisphere. D- Electronic profile showing parasitic cinder cones intruding on the peripheral side of bottom floor of huge Cal. 4 in the southern hemisphere. E- Clusters of Cal 5 showing swelling bottom floor near the southern ice cap pole. I- Association of Cal 4, Cal 5 and Cal 6 in the northern hemisphere. J- Electronic profile showing the difference in the subsurface depth and topography of the bottom floor of Cal 5 and Cal 5' in the southern hemisphere of Mars.

Type of volcano: Caldera

Caldera No. 4 (Cal 4)

Data

Series of Caldera 4	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 4	-2370	-1860	5052	-2331	-1331	-520	-244	3389	-3099	-3407	-4342	1744	1420	6424	-2080
	-2230	-1734	5388	-2157	-530	69	-49	3502	-3055	-3127	-4147	1847	1170	6613	-1867
	-1885	-1627	4978	-1972	-1440	733	156	3088	-2881	-2916	-3900	2356	374	6751	-1783
	-1636	-1834	4294	-2268	-2257	-370	-552	2236	-2801	-3783	-3391	1337	-320	7085	-1708
	-2375	-2343	3529	-3209	-2537	-1371	-941	1522	-3333	-4457	-4516	712	-1017	6623	-1904
	-3325	-2939	3046	-3775	-2599	-1507	-1300	1135	-3860	-4951	-5245	242	-1211	6003	-2636
	-3725	-3925	2984	-3960	-3402	-1403	-1447	1080	-4360	-5121	-5568	-96	-1277	5979	-3401
	-4050	-3992	2970	-4004	-3506	-1514	-1530	1031	-4540	-5321	-5736	-73	-1412	5974	-3791
	-4185	-3981	2984	-4020	-3400	-1636	-1373	1055	-4527	-5156	-5596	-104	-1400	5904	-3844
	-3945	-3964	2994	-3942	-2577	-1537	-1136	1076	-4062	-4655	-5231	-69	-1353	6023	-3801
	-3791	-3824	2997	-3537	-2527	-1365	-768	1200	-3726	-3786	-4785	-129	-1301	6071	-3692
	-3380	-3355	3291	-3060	-1904	-722	-169	1859	-3357	-3010	-4015	254	-902	6126	-3093
	-2305	-2246	3760	-2613	-546	311	534	2647	-2955	-3216	-3281	806	-420	6715	-2224
	-1612	-1611	4153	-2023	-774	-45	273	3090	-3000	-3320	-3678	2055	318	7901	-1530
	-2216	-1711	4503	-2160	-1071	-313	88	2666	-3044	-3442	-3851	1666	896	7840	-1604
	-2420	-1800	4077	-2196	-1332	-513	-255	2407	-3089		-3975	1255	630	7624	-1818

Representation of Data

Text Figure 7: Topography and topographic elevation of different volcanic series of Caldera No.4 with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each caldera, but the width of caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each volcanic series of Caldera 4 see Text Fig. 8

Type of volcano: Caldera

Caldera No. 4 (Cal 4)

Representation of Data

Data

Caldera No. 4				
Series No.	Parameter	A	B	C
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)
series 1		78.75	139	1815
series 2		87	130	2287
series 3		52	68.2	2082
series 4		35	51	1824
series 5		71	108	2175
series 6		85	158.7	1123
series 7		93	159.4	1785
series 8		80	108	2358
series 9		36.5	70	1451
series 10		34	57.4	1914
series 11		100.6	201	1761
series 12		104	162	1873
series13		66.75	78.7	2832
series 14		52.25	88	1720
series 15		85	155	2026

Text Figure 8: Morphologic features of Caldera No. 4 on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

of different sizes at the center of the original caldera floor. The central vent became entirely closed by the new uprising volcanic material accompanying the post caldera eruption, but steam explosion took place through another vent along the flanks of the uprising parasitic volcanoes. Zonal structure is prominent in this type of Caldera as a result of successive collapse before the re-eruption of parasitic volcanoes (Plate 33 Figures A-G, Plate 34, Figures H-N).

Caldera 5 differs from Cal 1, 2, 3 and 4 by the presence of a younger post-caldera phase of eruption of volcanic materials from the same central vent leading to the formation of a younger phase of new volcanic landforms at the center of the caldera bottom floor (Plate 35, Figures A-E; Plate 36, Figures F-J). This type of caldera is considerably variable in size so that it can be distinguished in two distinct varieties: the larger caldera variety is identified here as Cal 5, while its smaller one is named as Cal 5'.

The larger caldera (Cal 5) occupies a wider range of topographic levels than its variant Cal 5', from elevation of -6000 m below 0 datum level to elevation of +7000 m above 0 datum level, but the majority of volcanic series belonging to this type of caldera are occurring below and across 0 datum level (Text Figures 9). Those which occur across the 0 datum have asymmetrical sides whereas negative calderas (below 0 datum) are almost symmetrical. It is characterized by having a larger diameter of crater varying from 18.75 km to 122 km, with an average value of 61 km, a larger width of volcano varying from 26.2 km to 181 km with an average value of 91.2 km, a deeper bottom surface (below ground surface) varying between 959 m and 2508 m with an average value of 1565.5 m, a higher average height of outer rim (above ground surface) varying between 38.5 m and 708 m with an average value of 393 m (Text Figure 10), and a larger height of "Wizard Island" at the center of the caldera bottom floor varying between 392 m and 1648 m. This larger variety of Cal 5 is larger in diameter of crater, width of volcano and height of outer rim than Cal 1, Cal 2 and Cal 3, but distinctly smaller in all these parameters than Cal 4 and Cal 6.

The so-called wizard island is parasitic cinder cone, composite volcano, or volcanic dome (Plate 35, Figures A-E, Plate 36, Figures F-J). The cinder cones (e.g. series 3, 6, 12, 13, 14) are exclusively built of pyroclastics. They have a lower height ranging in the studied series between 368 m and 493 m, and a width ranging between 5.25 km and 16.8 km. The parasitic composite volcanoes (e.g. series 2, 5, 15) are built of layers of lava flow, pumice and ash. They have a higher height above the bottom floor of the collapsed crater

ranging in the studied series between 931 m and 1648 m and a width ranging between 6.6 km and 20.2 km. The lava domes (e.g. series 1, 7, 8, 9, 10) are steep sided ranging in height from 510 m to 1324 m and in width from 13 km to 24.6 km.

Named craters belonging to this type of complex collapse caldera include Eden Patera, Micoud, Bombala, Curie, Persbo, Barnard, Lockyer, Marth, Persbo, Holden, Ritchey, Playfair, South, Dromore, Quick beside many more of unnamed comparable volcanic craters.

The variant Cal. 5' occupies a smaller range of topographic levels than Cal 5, from elevation of -4500 m to elevation +3000 m (Text Figure 11). It has a smaller diameter of crater varying from 9.22 km to 59 km, with an average value of 25.5 km, a lesser width of volcano varying from 13.5 km to 84 km with an average value of 40.7 km, a shallower bottom surface (below ground surface) varying between 715 m and 2264 m with an average value of 1135.6 m, a lower average of height of outer rim (above ground surface) varying between 93 m and 464.5 m with an average value of 261.2 m (Text Figure 12).

In some representatives of Cal 5 particularly those which occur in clusters near or at the southern ice-cape pole no wizard islands are formed on the central vent and the caldera shows swelling bottom surface due to movement in the magma chamber beneath it (Plate 32, Figure E; Plate 36, Figures J-J). The swelling bottom surface is referred to by some workers as resurgent dome which unlike a lava dome. The latter is formed by the extrusion of highly viscous lava onto the surface, while resurgent dome is formed by the uplift and deformation of the surface itself by magma movement underground.

Caldera 5' has the smallest diameter of crater and width of volcano among all caldera types (Plate 37, Figures A-G, Plate 38, Figures H-N). However, it resembles the larger variety Cal 5 in possessing a higher average outer rim than calderas 1, 2 and 3. This is essentially attributed to the eruption of a second explosive phase of volcanic material from the same central vent at the bottom floor of the caldera. The "Wizard Island" in this variant is relatively smaller than in Cal 5 and made up of either parasitic cinder cone or lava dome (Plate 39, Figures A-E; Plate 40, Figures F-J). The width of the parasitic cinder cones ranges between 3.6 km and 12.5 km whereas the height of these cones varies between 211 m and 681 m with most values lying between 211 m and 465 m.

Zonal structure is evident in both varieties of Cal 5 but

it is much prominent in the large-sized variety. It reflects a gradual collapse of the summit into the partially drained magma chamber before this chamber became filled again by lava and re-erupt as a younger post caldera parasitic volcanic landform at the center of the bottom floor of the caldera. In the southern hemisphere near the southern ice-cape pole the craters of both Cal 5 and its variant 5' become of low relief due to strong erosion accompanied by appearance of extensive sand-sized dark dunes made up of volcanoclastic material overlying the bottom surface of the caldera. The dune structure is made essentially of transverse dunes in Cal 5, whereas in Cal 5' the

Caldera 5 and 5' occur both individually or in clusters (Plate 32, Figures B & E). Both varieties are commonly found overlapping Cal 1, Cal 4 and Cal 6, or occurring as parasitic landform at the bottom surface of large-sized Cal 4 (plate 32, Figs. C, G and H). Overgrowth of caldera 5 is not uncommon (Plate, 32, Figure F). No parasitic calderas belonging to Cal 5 are recorded on the flanks of shield volcanoes. However, the variant Cal 5' is recorded as parasitic landforms along the eastern flanks of the Alba Mons and the southern flanks of the composite volcano Ulysses Tholus. This would suggest that the eruption of the smaller and shallower variant of Cal 5 (i.e. Cal 5') continued younger for a long time after the cessation of eruption of the larger volcano of Cal 5.

Correlation of different morphologic parameters including diameter of crater (in km), width of volcano (in km), subsurface depth below ground surface (in meters) and average height of outer rim above ground surface between caldera 5 and its smaller and shallower variant Caldera 5' is given in Text Fig.12

Caldera no. 6 (cal 6) (plates 41-45) (Text Figures 13-14)

This is a huge complex caldera showing a younger huge post-caldera volcanic phase from the same central vent leading to the eruption of a large parasitic composite volcano at the center of the bottom floor of the pre-existing caldera. It differs from Caldera 5 by having a huge size, a much deep bottom surface (below ground surface) and a huge "Wizard Islands" which are made up exclusively of composite volcanoes (Plate 41, Figures A-G; Plate 42, Figures H-N).

Caldera 6 is generally rare relative to all other calderas. It occurs as individual landforms occupying limited topographic levels between elevation-5500 m and elevation +2750 m but the majority of the available series are recorded below and across 0 datum (Text Figures 13). Those which occur across the 0 datum level have asymmetrical sides like Caldera 5.

Caldera 6 is formed by a violent eruption of lava which is immediately followed or contemporaneously accompanied by a gradual collapse into the partially drained magma chamber before this chamber became filled again by lava and re-erupted strongly as a second post-caldera volcanic landform at the center of the bottom floor of the original caldera. This type of caldera is much larger in size and deeper in bottom surface (below ground surface) than all other calderas (Cal 1, 2, 3, 4 and 5). Its crater has a diameter varying in the studied series from 52 km to 162 km with an average value of 104.7 km, and a width varying from 82.3 km to 243 km with an average value of 145.7 km. The subsurface depth of the collapsed summit (below ground surface) is ranging between 1193 m and 2901 m with an average value of 2087.1 m. The average height of outer rim (above ground surface) is much more than that of Cal 1, 2, 3, and 5, but distinctly lower than that of Cal 4. It ranges between 145.5 m and 697.5 m, with an average value of 400.5 m (Text Figure 14).

The parasitic composite volcanoes which occur at the center of the collapsed caldera are built of alternating lava flow, ash and blocks of un-melted stone (Plate 43, Figures A-E; Plate 44, Figures F-J; Plate 45, Figures K-O). They form tall peaks ranging in height between 1638 m to 4502 m with most values ranging between 2210 m and 2806 m. The width of the parasitic composite volcano varies from 12 km to 114 km with most values ranging between 23 km and 94 km. Named craters belonging to this type of complex collapse caldera include Kinkora, Nicholson, Pettit, Moreux, Eddie, Reuyl, Schroeter, Boeddicker, Gale, Henry, Martz, Liu Hsin, Radau, Li Fan, Wright, beside other unnamed comparable craters.

Caldera 6 is commonly associated with Cal 4 and Cal 5 (Plate 32, Figure I). The latter caldera erupts onto the peripheral part of the collapsed bottom surface of Caldera 6, thus suggesting a relatively younger age of Caldera 5 than Caldera 6. As like Cal 1, Cal 5 and Cal 4, Caldera 6 is never recorded onto the flanks of the shield volcanoes, thus reemphasized the older age of these calderas relative to Cal 2, Cal 3, Cal 5' which are partly erupted as parasitic volcanoes on the flanks of some shield volcanoes. Younger phases of volcanic pipes of different sizes are also erupted onto the flat areas of the pre-existing Cal 6 around the parasitic composite volcanoes (e.g. series 1, 2, 6, 8, 10, 12, 13) and sometimes along the flanks of the parasitic composite volcanoes themselves (e.g. series 5, 6, 8).

In the northern hemisphere of Mars some representatives of Caldera 6 show fine barchans to barchanoid dunes of volcanoclastic material at the bottom

Plate 33: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 5 (Cal 5) in lowlands (below 0 datum) of both the northern hemisphere (A-B, D-E and G) and the southern hemisphere (C and F) of Mars.

Plate 34: continuation of Plate 33: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 5 (Cal 5) in the northern hemisphere below 0 datum (H-J) and in the southern hemisphere both above 0 datum (K and M) and across 0 datum (L and N) of Mars.

Plate 35: Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 5 after re-filling of the magma chamber. The volcanic landforms are made up of parasitic cinder cones (C and E), composite volcanoes (B and D) or volcanic domes (A) forming the so-called Wizard Island at the central vent of the pre-existing caldera in lowlands of northern hemisphere (B and C) and both lowlands (D and E) and highlands of southern hemispheres (A) of Mars

Plate 36: continuation of Plate 35: F-I- Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 5 after re-filling of the magma chamber and made up of parasitic cinder cones (H), composite volcanoes (I) or volcanic domes (F and G) at the bottom floor of the pre-existing caldera in lowlands of both northern (A and I) and southern hemispheres (G and H) of Mars. J- Caldera 5 shows swelling bottom surface due to movement in the magma chamber beneath at the southern ice cap pole of Mars.

Plate 37: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 5' (Cal 5') in lowlands (below 0 datum) of the northern hemisphere (A-G) of Mars.

Plate 38: continuation of Plate 37: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 5' (Cal 5') in the northern hemisphere both below 0 datum (H) and across 0 datum (I and N) and in the southern hemisphere both above 0 datum (J, and L) and across 0 datum (K and M) of Mars

Plate 39: A-D- Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 5' after re-filling of the magma chamber. The volcanic landforms are made up of parasitic cinder cones (A and D) or volcanic domes (B and C) forming the so-called Wizard Island at the bottom floor of the pre-existing caldera in both northern hemisphere (A, C and D) and southern hemisphere (B) of Mars. E- caldera 5' shows fine streaks along the sides of the depression formed by water vapor and iron oxides which accompanied the eruption of magma and a swelling bottom surface due to movement in the magma chamber beneath the pre-existing caldera.

Plate 40: continuation of Plate 39: Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 5' after re-filling of the magma chamber. The volcanic landforms are made up of parasitic cinder cones (F and I) or volcanic domes (G, H and J) forming the so-called Wizard Island at the central vent of the pre-existing caldera in both northern hemisphere (F, G and I) and southern hemisphere (H and J) of Mars.

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Type of volcano: Caldera

Caldera No. 5 (Cal 5)

Data

Series of Caldera 5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 5	1207	-2017	-1997	6578	880	-409	-3882	-1050	-579	-1222	3209	675	-1865	-3571	-4630
	1321	-1290	-1885	6730	1319	-82	-3665	-1709	293	-912	3586	907	-1778	-3514	-4391
	1744	-1677	-2204	6827	802	229	-4575	-1505	-560	-765	2926	1086	-1704	-3394	-4749
	866	-2488	-2760	6919	71	-762	-4946	-2327	-1053	-486	2407	1114	-1390	-3989	-5102
	140	-3335	-3170	6113	-427	-1431	-5025	-3073	-1484	-1246	1879	811	-2367	-4457	-5414
	255	-4525	-3215	5722	-720	-1905	-4979	-3444	-2050	-2360	1868	178	-3457	-4530	-5775
	648	-4500	-3054	5605	-1004	-1647	-4564	-3269	-2175	-2686	2314	-142	-3720	-4313	-5428
	873	-3052	-2850	5718	-155	-1309	-4357	-2875	-1120	-2275	1968	289	-3481	-4015	-5007
	655	-4380	-3214	5455	-657	-1696	-4408	-3064	-2168	-2611	2220	-131	-3884	-4472	-5517
	226	-4514	-3195	5326	-444	-2107	-5062	-3441	-2050	-2374	1925	-341	-3672	-4417	-5775
	310	-4068	-2940	5464	-135	-1801	-5111	-3234	-1720	-1824	1958	148	-3183	-4259	-5445
	622	-3506	-2504	5717	419	-1333	-4774	-2537	-1436	-1170	2512	643	-2667	-3853	-5094
	918	-2934	-1931	6040	1088	-736	-4488	-1919	-1005	-409	2952	1029	-1662	-3318	-4777
	1264	-2334	-1488	6459	1703	-157	-3475	-1387	-695	-830	3276	1109	-2123	-3366	-4354
	1732	-1720	-1572	6224	1363	-573	-3750	-1670	-478	-1055	3300	984	-2228	-3441	-4567
	1617	-2220		6089	887		-3880	-1720	-1023				-2390	-3597	-4648

Representation of Data

Text Figure 9: Topography and topographic elevation of different volcanic series of Caldera No.5 with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each caldera, but the width of caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each volcanic series of Caldera 5 see Text Fig. 10.

Type of volcano: Caldera

Representation of Data

Caldera No. 5					
Series No.	Parameter	A Diameter of crater (in kilometers)	B Width of volcano (in kilometers)	C Subsurface depth (in meters)	D Average height of outer rim (in meters)
series 1		36.5	49.9	1477	326
series 2		118.5	156	2508	613
series 3		63	85	1643	98
series 4		24.4	41.5	1252	38.5
series 5		122	181	1843	627.5
series 6		42	63	1698	527
series 7		50.5	65.5	1231	311
series 8		94.5	150	1724	389
series 9		90	115	1596	708
series 10		60	111.4	1631	691
series 11		60.25	72.7	1432	188.5
series 12		33.2	61.7	1325	282
series13		80	151	2019	601.5
series 14		22.74	37.9	959	228
series 15		18.75	26.2	1145	266.5

Text Figure 10: Morphologic features of Caldera No. 5 on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

Type of volcano: Caldera

Caldera No. 5' (Cal 5')

Data

Series of Caldera 5'	1'	2'	3'	4'	5'	6'	7'	8'	9'	10'	11'	12'	13'	14'	15'
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 5'	1362	-1596	-1500	851	2122	-3600	-2509	485	-55	-3106	-3636	1409	-3026	216	640
	1470	-1475	-1137	1091	2550	-3343	-2363	671	232	-3079	-3582	1527	-2977	315	678
	1572	-1924	-1030	1153	2197	-3113	-2036	462	91	-3025	-3519	1668	-2935	533	462
	1339	-2210	-1748	938	1927	-3603	-2455	220	-381	-2975	-3343	1316	-3088	1072	196
	1000	-2701	-2203	520	1570	-3852	-2783	0	-753	-3584	-3746	839	-3341	500	-81
	740	-3218	-2466	-207	1262	-4264	-3279	-229	-940	-3838	-4025	390	-3531	-458	-908
	594	-3418	-2590	-420	939	-4302	-3339	-474	-1037	-3621	-4312	234	-3683	-762	-435
	761	-3134	-2477	-235	1226	-4098	-3019	-700	-905	-3407	-4094	540	-3524	-783	-325
	908	-3569	-2608	-189	965	-4244	-3354	-587	-1034	-3708	-4334	760	-3674	-484	-417
	680	-3466	-2347	-353	1262	-4143	-3390	-772	-823	-3893	-4059	362	-3653	-616	-382
	735	-3009	-1700	-170	1532	-3884	-2850	-532	-510	-3777	-3672	800	-3382	-660	-237
	988	-2237	-1413	187	1871	-3570	-2469	-209	-286	-3186	-3404	1305	-3158	-6	-55
	1280	-1679	-1000	409	2167	-3133	-2032	134	-150	-3017	-3497	1590	-3025	658	159
	1595	-1577	-1380	1034	2470	-3348	-2371	349	-38	-3070	-3572	1682	-2996	1078	426
	1665	-1305	-1496	959	2286	-3498	-2488	560	-124	-3142	-3619	1532	-2986	550	655
	1734			893	2086	-3558		658	-205			1408		225	492

Representation of Data

Text Figure 11: Topography and topographic elevation of different volcanic series of Caldera No.5' (the smaller and shallower variant of Caldera 5) with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each caldera, but the width of caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and average height of outer rim of each volcanic series of Caldera 5' see Text Fig. 12.

Correlation of Caldera 5 and its variant 5'

Data

1- Diameter of crater (in km)			2- Width of volcano (in km)			3- Subsurface depth (in m)			4- Av. height of outer rim (in m)		
Caldera Variant	5'	5	Caldera Variant	5'	5	Caldera Variant	5'	5	Caldera Variant	5'	5
series 1	27	36.5	series 1	38.4	49.9	series 1	1140	1477	series 1	105	326
series 2	59	118.5	series 2	84	156	series 2	2264	2508	series 2	60.5	613
series 3	34	63	series 3	56	85	series 3	1112	1643	series 3	451.5	98
series 4	25	24.4	series 4	37	41.5	series 4	1313	1252	series 4	221.5	38.5
series 5	20	122	series 5	29.75	181	series 5	1183	1843	series 5	406	627.5
series 6	34	42	series 6	64.8	63	series 6	744	1698	series 6	456	527
series 7	24.2	50.5	series 7	39.8	65.5	series 7	902	1231	series 7	464.5	311
series 8	18.04	94.5	series 8	22	150	series 8	1430	1724	series 8	93	389
series 9	9.22	90	series 9	13.5	115	series 9	982	1596	series 9	227	708
series 10	17	60	series 10	31.4	111.4	series 10	787	1631	series 10	128	691
series 11	13.3	60.25	series 11	30.1	72.7	series 11	715	1432	series 11	254	188.5
series 12	25	33.2	series 12	41.6	61.7	series 12	1174	1325	series 12	268	282
series13	13.3	80	series13	23.6	151	series13	697	2019	series13	45.5	601.5
series 14	52	22.74	series 14	88	37.9	series 14	1008	959	series 14	854.5	228
series 15	16	18.75	series 15	19.1	26.2	series 15	1075	1145	series 15	100.5	266.5

Representation of Data

Text Figure 12: Correlation of 1-Diameter of crater, 2-Width of volcano, 3-Subsurface depth and 4-Average height of outer rim between Caldera No. 5 and its smaller and shallower variant Caldera No. 5' on Mars.

surface, almost associated with the re-eruption of a post-caldera parasitic composite volcano at the central vent of the pre-existing caldera (Plate 18, Figure B).

Correlation of data and graphic representation of data of the diameter of crater (in km), width of volcano (in km), subsurface depth below ground surface (in meters) and average height of outer rim above ground surface (in meters) of about 105 volcanic series belonging to six different types of caldera (Cal 1, 2, 3, 4, 5 and 6) is given in (Text Figures 15-18). The average values of these parameters in different types of calderas are illustrated in (Text Figure 19).

Relative Age Assignment of Calderas

Concerning the relative age of the different types of calderas with respect to themselves on one side, and to other volcanoes on the other side on the Martian surface, it can be concluded the following:

1. The morphological features of the different volcanic series belonging to calderas reveal the recognition of six types of calderas. The calderas are given numerical numbers, Cal 1, Cal 2, Cal 3, Cal 4, Cal 5 and Cal 6. Calderas 1, 2 and 4 are simple calderas which have no post-caldera re-eruption phase of parasitic volcano at the bottom surface of the pre-existing caldera. Calderas 3, 5 and 6, on the other hand, are complex calderas which show an additional post caldera phase of re-eruption of lava material from the same central vent as a result of re-filling of the magma chamber after the collapse of the roof of chamber of the original caldera. In calderas 5 and 6 the post caldera volcanic phase built up a parasitic volcanic landform which made up of cinder cone, composite volcano or volcanic dome on the central vent of the pre-existing caldera. However, in Cal 3 the re-eruption of the post caldera volcanic material is contemporaneously accompanied or directly followed by its collapse into the completely drained magma chamber. Thus, this type of caldera is characterized by having two successive phases of volcanic eruptions that are separated and ended by collapse of the volcanic material in the magma chamber without building up parasitic volcanoes on the central vent of the pre-existing caldera.

2. All studied representatives of volcanic series belonging to different caldera types are later invaded by younger generations of volcanic pipes (VP1 and /or VP2, see later) of different numbers and sizes. The huge calderas belonging to Cal 4 and Cal 6 are often intruded by a younger eruption of smaller parasitic caldera belonging to either Cal 1, Cal 2, Cal 5 (or Cal 5') and/or cinder cones (simple or modified cones; see later) from a peripheral vent at the

side of the bottom surface of the pre-existing larger caldera. Caldera 5 and its smaller variant Cal 5' could also be erupted at the expenses of pre-existing Cal 1, Cal 4 and Cal 6, thus sweeping part of the older caldera.

3. Concerning the relative age, Caldera 4 is the oldest simple caldera while Cal 6 is the oldest complex caldera on the surface of Mars. Both volcanoes are never recorded along the flanks of minor and major shield volcanoes, as well as the composite volcanoes, thus suggesting their relative older age than all other volcanoes (Plate 46). Caldera 6, the largest and least frequent caldera type on Mars and which includes huge post-caldera parasitic composite volcanoes on their central vent seems to represent the most absolute oldest caldera type on the surface of Mars.

On the other hand, Cal 2 is the youngest simple caldera while Cal 3 is the youngest complex caldera. Both volcanoes seem to be either simultaneous or closely related. Transitional forms between both types are not uncommon suggestive of their close genetic relationship. They are commonly occurring as parasitic landforms along the flanks of the shield volcanoes (Plate 46) except of the three major volcanoes of the Tharsis Montes which appear to be the youngest or at least including the youngest lava flows on Mars. Caldera 1 and Cal 5 are not recorded as parasitic volcanoes along the majority of the shield volcanoes although they occur as parasitic calderas among other larger calderas such as Cal 4 and Cal 6. This would indicate that Cal 1 and Cal 5 are distinctly younger than Cal 4 and Cal 6 and older than Cal 3 and Cal 2. In the southern hemisphere some of the large representatives of Cal 1 are partly overlapped by Cal 5 and /or Cal 2, suggestive of the relative younger age of Cal 5 and Cal 2 with respect to Cal 1. Also, the smaller and shallower variant of Cal 5 (Cal 5') seems to continued eruption younger than the larger and deeper Cal 5 up to the age of the flows of Alba Mons.

4. Summarizing the relative age of calderas with respect to shield volcanoes, two different groups of calderas could be recognized: a) an older group which was erupted and ceased eruption before the eruption of shield volcanoes including Cal 1, Cal 4, Cal 5 and Cal 6, and b) a younger group erupted and continued eruption for a long time after the eruption of shield volcanoes (except of the three major volcanoes of the Tharsis Montes) including Cal 2, Cal 3 and Cal 5' (the smaller and shallower variant of Cal 5).

Volcanic Pipes

Volcanic pipes are the smallest, widespread and youngest volcanic landforms on the surface of Mars. They are

subterranean geological structures formed by the violent, supersonic eruption of deep-origin volcanoes leading to the formation of pipe-like structures that penetrate the surrounding rock and create a bowl-shaped, craterlike depression. Unlike other kinds of eruptions, magma does not collect in a subsurface reservoir prior to the eruption. The eruption ejects a column of overlying material directly over the magma column, and does not form a large above-ground elevation as typical volcanoes do.

The volcanic pipes rise onto surface of Mars through a series of deep fissures in the crust where magma rises through the crust by exploiting a vertical or inclined path of weakness. These pipes are either vertical or inclined on the ground surface where they penetrate the surrounding rock (Plates 12-15).

Mechanism And Economic Value Of Volcanic Pipes On Earth

The definition, mechanism and economic value of the volcanic pipes on Earth's surface have been dealt with several workers (see the free Encyclopedia e.g. Wikipedia, Encyclopedia.com, Oregon State University, Encyclopedia Britannica).

As the volcanic pipes approach the surface, decreasing pressure above allows some of the volatile materials in the magma (such as water and carbon dioxide) to become gaseous, and these gases expand rapidly. Such expansion widens the pipes and produces an explosive event at the surface and creates a craterlike depression. When eroded, such a depression exposes a vertical funnel-shaped pipe that resembles a volcanic neck with the exception of the brecciated filling. If the eruption was explosive, these pipes, called diatremes, typically assume carrot-shaped profiles. In cases where the eruption is slower and corrodes the surrounding rock, diatremes may be bowl-shaped [60].

Onto surface of Earth the volcanic pipes are generally rare and considered to be a type of diatreme. They are composed of a deep, narrow cone of solidified magma (described as "carrot-shaped"), and are usually largely composed of one of two characteristic rock types: kimberlite or lamproite. These rocks reflect the composition of the volcanoes' deep magma sources, where the Earth is rich in magnesium. They are well known as the primary source of diamonds, and are mined for this purpose.

Kimberlite is a gas-rich, potassic ultramafic igneous rock that contains the minerals olivine, phlogopite, diopside, serpentine, calcite, and minor amounts of apatite, magnetite, chromite, garnet, diamond, and other upper

mantle minerals. Kimberlite magmas form "pipes" as they erupt. In the subsurface, a funnel-shaped body narrows to a depth of hundreds of meters. The pipe (also called a diatreme) is filled with kimberlite, with or without diamonds (only 1 in 5 of the pipes at Kimberley contain diamonds) [61]. During and after the eruption, the cone depression is often filled with breccia, a type of lithified sedimentary rock consisting of angular and subangular fragments rather than rounded clastics. Breccias that form during kimberlite eruptions are made up of rising kimberlite and the walls of the surrounding rock [60].

Lamproite pipes operate similarly to kimberlite pipes, except that the boiling water and volatile compounds contained in the magma act corrosively on the overlying rock, resulting in a broader cone of eviscerated rock. This broad cone is then filled with volcanic ash and materials. Finally, the degassed magma is pushed upward, filling the cone. The result is a funnel shaped deposit of volcanic material (both solidified magma, and ejecta) which appears mostly flat from the surface

Volcanic Pipes on Mars

On Mars there is no direct record to the presence of kimberlite or Lamproite. However the processes that brought these rocks to the surface on Earth (i.e. the volcanic pipes) are already existed on Mars on a large scale. The present investigation shows clearly that the volcanic pipes are widely distributed on the Martian surface where they represent the youngest volcanic craters on the surface of the planet. On the other hand, Mars has a similar planetary formation history as earth. So, Mars certainly has diamonds on its surface. Other indirect indications to the presence of these rocks and associated diamond on surface of Mars are the presence of higher amounts of potassium and a higher percentage of volatile elements than the Earth's crust do.

Martian meteorite analysis suggests that the planet's mantle is about twice as rich in iron as the Earth's mantle [62,63]. The planet's distinctive red color is due to iron oxides on its surface. Second, its core is richer in sulphur [64]. Third, the Martian mantle is richer in potassium and phosphorus than Earth's and fourth, the Martian crust contains a higher percentage of volatile elements such as sulphur and chlorine than the Earth's crust does. Many of these conclusions are supported by in situ analyses of rocks and soils on the Martian surface [65].

Based on these data sources, scientists think that the most abundant chemical elements in the Martian crust, besides silicon and oxygen, are iron, magnesium, aluminum, calcium, and potassium. These elements are

Plate 41: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 6 (Cal 6) in lowlands (below 0 datum) of both the northern hemisphere (A, C and D) and the southern hemisphere (B, E, F and G) of Mars.

Plate 42: continuation of Plate 41: Top view, side view, three dimensional view and morphologic features of volcanic craters belonging to Caldera No. 6 (Cal 6) in the northern hemisphere below 0 datum (H) and the southern hemisphere both above 0 datum (I-L) and across 0 datum (M and N) of Mars.

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Plate 43: Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 6 after re-filling of the magma chamber. The volcanic landforms are made up exclusively of parasitic composite volcanoes at the central vent of the pre-existing caldera in northern hemisphere of Mars.

Citation: Khaled Abdel-Kader Ouda* and Nadia Abdel-Fattah Sharara, Craters of Volcanic Origin at the Ground Surface of Mars (Collapse Calderas and Volcanic Pipes).Op Acc J Bio Sci & Res 7(3)-2021.

DOI: 10.46718/JBGSR.2021.07.000165

Plate 44: continuation of Plate 43: Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 6 after re-filling of the magma chamber. The volcanic landforms are made up exclusively of parasitic composite volcanoes at the central vent of the pre-existing caldera in both southern hemisphere (F-H and J) and northern hemisphere (I) of Mars. Note the volcanic pipes which intruded around and along the flanks of parasitic composite volcanoes in F, H and J.

Plate 45: continuation of Plate 44: Electronic profiles and three dimensional images of the post-caldera volcanic landforms which re-erupt on the bottom floor of Cal 6 after re-filling of the magma chamber. The volcanic landforms are made up exclusively of parasitic composite volcanoes at the central vent of the pre-existing caldera in both southern hemisphere (K-N) and northern hemisphere (O) of Mars.

Type of volcano: Caldera

Caldera No. 6 (Cal 6)

Data

Series of Caldera 6	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Caldera 6	-1541	-3060	-1338	-3121	-470	-2159	1433	1571	691	-596	-1482	2196	1966	1052	-1718
	-1367	-2562	-751	-2667	-171	-2030	1581	1657	940	-482	-1397	2383	2079	1407	-1617
	-763	-3185	-2254	-2322	80	-1789	1723	1164	-880	-1148	-2223	1434	1721	1171	-1883
	-1547	-4609	-3750	-3150	-541	-2218	1833	549	-1432	-2062	-3807	916	1034	429	-2520
	-2563	-5075	-4239	-4457	-1120	-3250	1559	-316	-1109	-2380	-4380	822	673	93	-3192
	-3240	-4095	-4048	-5054	-815	-3721	429	-581	-519	-2419	-2602	878	603	74	-3698
	-2466	-3070	-3540	-4674	-436	-2455	530	35	-42	-2427	-1143	1854	1253	356	-3046
	-1064	-1323	-1873	-2930	-84	-1509	2450	2225	652	-651	-13	2700	1034	2160	-2363
	-2570	-2555	-3537	-4501	-767	-2500	542	654	86	-2408	-1165	1800	2505	633	-2308
	-3034	-3642	-3879	-5222	-1502	-3060	240	-157	-468	-2529	-1828	932	860	331	-3721
	-2618	-4330	-3990	-4457	-1824	-3403	623	321	-1014	-2470	-2708	801	599	282	-3818
	-1574	-3973	-3740	-3649	-1543	-3034	1214	896	-1480	-2327	-3697	935	768	453	-3624
	-717	-2726	-2788	-2797	-204	-2092	1891	1419	-1142	-1203	-1052	1196	1202	707	-2796
	-1191	-2215	-1488	-3065	606	-1424	1604	1987	949	-424	-914	2193	1598	1544	-2061
	-1334	-2492	-1877	-3240	998	-1933	1477	2714	680	-570	-1704	2457	2221	2028	-1446
		-2715	-2114			-2088	1350	2406	343	-731	-2162	2144	2043	1846	-1657

Representation of Data

Text Figure 13: Topography and topographic elevation of different volcanic series of Caldera No. 6 with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each caldera, but the width of caldera is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each volcanic series of Caldera No. 6 see Text Fig. 14.

Type of volcano: Caldera

Representation of Data

Caldera No. 6					
Series No.	Parameter	A	B	C	D
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)	Average height of outer rim (in meters)
series 1		85	128.3	1906	697.5
series 2		106	149.4	2360	499
series 3		125	164	2901	606.5
series 4		96.5	172	2101	621
series 5		162	243	2822	275
series 6		76	117	1633	516
series 7		52	104	1193	470.5
series 8		110	135	2536	197
series 9		74.5	82.3	2123	427.5
series 10		101	133	1933	210.5
series 11		155	199	2898	666.5
series 12		95	119	1395	250
series13		71	115	1444	145.5
series 14		146.8	181	1772	268.5
series 15		115	144	2289	156

Text Figure 14: Morphologic features of Caldera No. 6 on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

Correlation of different types of caldera (1)

Data

		Diameter of Crater (In Km)					
		Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Number of volcanic series	series 1	58.3	12	36.5	53	78.75	85
	series 2	33.3	21	118.5	51	87	106
	series 3	35	12.7	63	51.5	52	125
	series 4	41.7	34	24.4	57	35	96.5
	series 5	35	57	122	50.5	71	162
	series 6	7.7	12.76	42	48.3	85	76
	series 7	11.25	57	50.5	125	93	52
	series 8	24.25	63.5	94.5	17	80	110
	series 9	35.5	71	90	38.33	36.5	74.5
	series 10	32	18.2	60	25.92	34	101
	series 11	50	21	60.25	45	100.6	155
	series 12	41.4	33.5	33.2	31	104	95
	series13	33.8	28.7	80	23.5	66.75	71
	series 14	39.5	25	22.74	35.5	52.25	146.8
	series 15	62	17.72	18.75	36.5	85	115

Representation of Data

Text Figure15: Correlation of diameter of crater (in km) of different volcanic series belonging to different types of caldera (Cal 1, 2, 3, 4, 5 and 6) on Mars.

Correlation of different types of caldera (2)

Data

		Width of Volcano (in km)					
		Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Number of volcanic series	series 1	61.6	18.25	49.9	91	139	128.3
	series 2	40.4	26.8	156	77.6	130	149.4
	series 3	51	19.3	85	65	68.2	164
	series 4	67	47.2	41.5	71.7	51	172
	series 5	63	107	181	69	108	243
	series 6	11.2	21.7	63	75	158.7	117
	series 7	17.2	78.9	65.5	222	159.4	104
	series 8	36	83.6	150	20.7	108	135
	series 9	40.9	89.3	115	54.8	70	82.3
	series 10	43.8	25	111.4	30.7	57.4	133
	series 11	67	32.8	72.7	49	201	199
	series 12	53.2	47.2	61.7	56.3	162	119
	series13	40.8	45	151	31.6	78.7	115
	series 14	45.9	32.6	37.9	49.6	88	181
	series 15	78.4	32.9	26.2	47.4	155	144

Representation of Data

Text Figure16: Correlation of width of volcano (in km) of different volcanic series belonging to different types of caldera Cal 1, 2, 3, 4, 5 and 6) on Mars.

Correlation of different types of caldera (3)

Data

Caldera Type		Subsurface Depth (in meters)					
		Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Number of volcanic series	series 1	1383	970	1477	2543	1815	1906
	series 2	1497	1208	2508	2810	2287	2360
	series 3	1389	994	1643	2814	2082	2901
	series 4	861	1673	1252	2108	1824	2101
	series 5	953	626	1843	1272	2175	2822
	series 6	768	955	1698	2043	1123	1633
	series 7	778	1547	1231	1058	1785	1193
	series 8	1278	1394	1724	1148	2358	2536
	series 9	1424	1903	1596	1418	1431	2123
	series 10	929	1060	1631	2023	1914	1933
	series 11	894	1244	1432	2550	1761	2898
	series 12	1359	1834	1325	1443	1873	1395
	series13	1289	1275	2019	1440	2832	1444
	series 14	1522	1538	959	1707	1720	1772
	series 15	976	1077	1145	1516	2026	2289

Representation of Data

Text Figure17: Correlation of subsurface depth below ground surface (in meters) of different volcanic series belonging to different types of Caldera (Cal 1, 2, 3, 4, 5 and 6) on Mars.

Correlation of different types of caldera (4)

Data

Caldera Type		Average Height of Outer Rim (in meters)					
		Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Number of volcanic series	series 1	12.5	255	326	349	771	697.5
	series 2	60	108	613	284.5	115	490
	series 3	80	201.5	98	121.5	381	606.5
	series 4	139	196	38.5	76	266	621
	series 5	127	425	627.5	116.5	793.5	275
	series 6	147	255	527	174.5	1038.5	516
	series 7	108.5	157	311	215	594.5	470.5
	series 8	23.5	221	389	151.5	398	197
	series 9	15.5	335.5	708	259	277	427.5
	series 10	43	421	691	336	461.5	210.5
	series 11	100	279.5	188.5	0	822.5	666.5
	series 12	75	177.5	282	722	706	250
	series 13	0	274	601.5	215	133	143.5
	series 14	46.5	164.5	228	144.5	460	268.5
	series 15	237	264.5	266.5	142.5	330	156

Representation of Data

Text Figure 18: Correlation of average height of outer rim above ground surface (in meters) of different volcanic series belonging to different types of caldera (Cal 1, 2, 3, 4, 5 and 6) on Mars.

Correlation of average data of different types of caldera

Caldera Type	Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Average Subsurface Depth (in m)	1147	1287	1566	1860	1935	2087

Caldera Type	Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Average Diameter of Crater (in km)	36	32	61	46	71	105

Caldera Type	Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Average Width of Caldera (in km)	48	41	91	67	116	146

Caldera Type	Cal 1	Cal 2	Cal 5	Cal 3	Cal 4	Cal 6
Average height of outer rim (in m)	81	249	393	221	504	400

Text Figure19: Correlation of 1- average subsurface depth (in meters), 2- average diameter of crater (in Km), 3-average width of volcano (in km), and 4- average height of outer rim (in m) of different types of calderas (Cal 1, 2, 3, 4, 5 & 6) on Mars.

major components of the minerals comprising igneous rocks [66]. The elements titanium, chromium, manganese, sulfur, phosphorus, sodium, and chlorine are less abundant [67,68], but are still important components of many accessory minerals in rocks and of secondary minerals (weathering products) in the dust and soils. Hydrogen is present as water (H₂O) ice and in hydrated minerals. Carbon occurs as carbon dioxide (CO₂) in the atmosphere and sometimes as dry ice at the poles. An unknown amount of carbon is also stored in carbonates.

Concerning the distribution of the volcanic pipes they cover large areas of the surface of Mars particularly between latitudes 45° N and 45° S. They do not exist individually but are found in clusters of different sizes where the density of each cluster ranges from tens to hundreds of pipes. Outside of this area they decrease gradually in abundance towards the northern and southern poles until they become entirely replaced by cinder cones north of Lat. 55° N. and south of Lat. 45° S. The pipes within each assemblage may be erupted perpendicular or inclined to the surface (Plates 12-13). The inclined pipes are found in a density greater than the density of vertical pipes and are characterized by being erupted in oriented way, a trend that reflects the direction of the system of superficial fissures through which magma emerges. More than one direction is exhibited by the inclined pipes. The most common trends are the eruption of pipes towards northeast, east-northeast and southeast arranged in order of abundance (Plate 12, Figures A-J).

The depressions caused by the eruption of the pipes are almost bowl-shaped and exposing substantial erosion during and after the eruption. Those pipes which are inclined on surface are relatively shallower in depth and having a broader craterlike depression of carrot-shaped profile suggestive of more corroded surrounding rocks (Plate 14, Figures A-E). The volcanic pipes which are perpendicular to the surface are deeper and expose a vertical funnel-shaped profile (Plate 15, Figures A-E).

Due to explosive eruption and strong corrosion of the surrounding rock the inclined pipes are often associated with breccia, consisting of angular and subangular fragments from the rising rock and the walls of the surrounding rock. Most of the breccia is concentrated around the crater of the pipes (Plate 14, Figures G & I).

Types of volcanic pipes on Mars (plates 47-52) (Text Figures 20-27)

The inclined pipes with a carrot-shaped profile are classified here as Volcanic Pipes No.1 (VP1) (Plate 47, Figures A-G; Plate 48, Figures H-N), whereas the vertical pipes with a

funnel-shaped profile are classified as Volcanic Pipes No.2 (VP2) (Plate 49, Figures A-G; Plate 50, Figures H-N). Several transitional pipes between VP1 and VP2 as well as smaller pipes with bowl-shaped craters of shallower depths are grouped here under the name VP1-VP2 (Plate 51, Figures A-G; Plate 52, Figures H-N).

The eruption of the independent volcanic pipes occurs both above and below 0 datum level, between elevation -6000 m and elevation +6000 m. Those belonging to VP1 occur between elevation -4000 m and elevation +6000, with the majority of pipes lying across 0 datum level between elevation -2000 m and +2000 m (Text Figures 20). The vertical pipes belonging to VP2 occupy the topographic interval between -6000 m and +5500 m, with the majority of the eruption occurs deep below 0 datum level between elevation -6000 m and -3000 m (Text Figure 21).

Both types of volcanic pipes are intruding in all volcanic volcanoes as parasitic landforms on the bottom floor of different calderas (Plates 16 & 17) and on the lower flanks of shield volcanoes and the composite volcanoes (Plate 46), suggestive of their youngest age than all other volcanic landforms on the surface of Mars. However, along the flanks of the major shield volcanoes (Olympus Mons, Tharsis Montes, Elysium Mons) the volcanic pipes are either missing or becoming sporadic, of minute size, and partly to completely deformed almost due to the influence of younger generations of flows of highly fluid lava which characterizes these volcanoes. The common occurrence of the volcanic pipes in the basaltic valleys and along fissure eruptions and cracks in the plateau basalts substantiates their younger age. The most common surface areas which are dominated by the eruption of a dense concentration of volcanic pipes include:

- a. South Syrtis Major Planum, positive pipes (above 0 datum), VP1, oriented east-northeastward
- b. Arena Dorsum, positive pipes (above 0 datum), VP1, oriented eastward
- c. North Arnis Vallis, positive and negative (below and above 0 datum), VP1, oriented southeastward
- d. South Adamas Labyrinthus and Hephaestus Rupes, negative pipes (below 0 datum), VP2, vertical
- e. East and southeast Albor tholus, negative pipes (below 0 datum), VP1, oriented northeastward
- f. South and southwest Elysium Mons, positive pipes (above 0 datum) VP2, vertical

Plate 46: Top views of representatives of minor shield volcanoes (A-H) and composite volcanoes (I-J) on Mars showing younger generations of parasitic calderas and/or volcanic pipes along the flanks of all of these volcanoes as well as in the summit caldera of some volcanoes (D, E, H and J). A- volcanic pipes along the flanks of Alba Mons. The relationship with intrusive parasitic calderas and volcanic pipes helps greatly in defining the relative ages of the different shield volcanoes as well as the composite volcanoes on Mars.

g. South Amazonis Planitia , negative pipes (below 0 datum), VP1, oriented northeastward

h. Acidalia Planitia , negative pipes (below 0 datum) VP2, vertical

i. Sacra fossae and Lunae Palus, negative pipes (below 0 datum), VP2, vertical

j. Southeast Syria Planum, positive pipes (above 0 datum,VP1),oriented northwestward

k. East Eumenides Dorsum, negative pipes (below 0 datum), VP2, vertical

l. North, and East of Chryse Planitia, negative pipes (below 0 datum), VP1, oriented north-northeastward

m. North and east of Oxia Colles, negative pipes (below 0 datum), VP1, oriented north-northeastward

n. Cerberus Fossae, negative pipes (below 0 datum), VP2, vertical

Comparing between VP1 and VP2,The former has a carrot-shaped profile extending below ground level for a depth ranging in the studied pipes between 496 m to 814 m with an average value of 627.5 m, and having a diameter of crater ranging between 2.4 km to 8.9 km with an average value of 5.9 km (Text Figures 22 A & 23). The VP2 has a funnel-shaped profile extending below ground level for a depth ranging in the studied pipes between 517 m and 1351 m with an average value of 802.5 m, and assuming a relatively larger crater ranging in diameter between 3.5 km to 10.25 km with an average value of 6.2 km (Text Figures 22 B & 24).

The transitional volcanic pipes (VP1-VP2) occupy a more restricted topographic interval between -4500 m and +3500 m, but differs in being commonly distributed in both northern lowlands (below and above 0 datum) and southern highlands above 0 datum (Text Figure 25) It is relatively shallower and smaller in size, having a diameter of crater ranging between 2.5 km and 5.7 km with an average value of 4 km and a depth below ground surface ranging between 292 m and 845 m with an average value of 483.7 m (Text Figure 26). Correlation of the morphologic parameters of different types of volcanic pipes is given in (Text Figure 27). These data show clearly that the volcanic pipes on Mars are much less than those of the different types of calderas whose average diameter of crater varies from 25.7 km to 104.7 km and average subsurface depth of the crater (below ground surface) varies from 1135.6 m to 2087 m (Text Figures 28).

Most of the surface areas affected by the eruption of volcanic pipes particularly the VP1 are rich in angular rock fragments formed due to intense explosion and substantial erosion of the pipes and the walls of the surrounding rocks during and after the eruption (Plate 12, Figures G & I). No water is found in the circular depressions of the volcanic pipes, but the outer rims and the sides of the steep-walled depressions of many volcanic pipes are covered by fine dust arranged in streaks formed by water vapor which accompanied the eruption of magma (Plates 14-15). A vast area southeast of Albor Tholus and north Athabasca Valles shows intense steam explosion (water vapor and hematite) associated with massive eruption of VP1 (Plate 12, Figure J). It is thus apparent that the volcanic pipes have encountered rock layers containing groundwater during the ascent of the magma through a series of fissures. The water is vaporized together with other volatile materials (carbon dioxide) producing an explosive event at the surface. It is, thus, concluded that the processes that brought diamond-bearing kimberlite and Lamproite volcanic pipes to the surface on Earth have existed on a large scale on Mars. So, Mars certainly has diamonds and very probably has much more diamond than Earth does.

The last kimberlite-bearing volcanic eruption on Earth is thought to have taken place more than 25 million years ago, and some scientists note that it most occurred during the Cretaceous Period (146 million to about 65.5 million years ago [60]. On Mars, the volcanic pipes (VP1 and VP2 as well as transitional VP1-2) occur in all provinces; northern and southern hemisphere, low lands below 0 level and high lands above 0 level, on the basalt plateaus, in the valleys, basins, and along cracks and fissures. They also intrude with varying degrees in size and number the bottom surface of all types of volcanic calderas, the flanks of the parasitic composite volcanoes which erupt at the bottom surface of large calderas nos. 5 and 6, and the flanks of shield volcanoes, thus it will be reasonable to attribute the volcanic pipes on Mars to the same time interval on Earth if not younger.

Correlation of data of the subsurface depth (below ground surface) of the volcanic crater (in meters) and diameter of crater (in km) of different types of Volcanic Pipes (VP1 and VP2) and Calderas (Cal 1, 2, 3, 4, 5 and 6) is graphically represented in (Text Figure 28).

Conclusions

1. Three hundred satellite images of craters on the surface of Mars were carefully investigated using Google Mars for resolution, distribution, unique morphology and

evidence of volcanic activity in both northern and southern hemispheres of Mars. The investigation has revealed that these craters which previously assumed to have been formed by meteorites are actually volcanic in origin and belonging to independent collapse calderas and volcanic pipes. These volcanic landforms are variable in size, morphology, topography, topographic elevation, relative age and history of volcanic eruption [69-78]. They are occurring as independent (free) landforms and as parasitic landforms inside larger pre-existing calderas or along the flanks of large mountain volcanoes (composite volcanoes and shield volcanoes).

The statistical analysis of 150 independent craters of the total examined craters has contributed immensely to the recognition of six different types of collapse calderas and two types of volcanic pipes, thus providing evidence that Mars possesses different generations of volcanic eruptions and resultant variable types of volcanoes other than the previously known major and minor shield volcanoes.

2. The independent collapse calderas are lying entirely below ground surface level, and showing an outer rim almost of varying height above ground surface level. This group of calderas represents the most spectacular and abundant volcanic landforms studied on the surface of Mars. It includes both simple caldera with a smooth bottom surface and complex caldera with a younger post-caldera re-eruption of lava flow or ash leading to the formation of parasitic cinder cone, composite volcano or volcanic dome at the center of the bottom floor of the pre-existing caldera.

3. The collapse calderas on Mars are not uniform in age, general morphology of the crater depression (flat with steep walls, broadly rounded, strongly concave), diameter of crater (from 7.7 km to 162 km), total width of volcano (from 11.2 km to 243 km), subsurface depth of the depression below ground surface (from 626 m to 2901 m), average height of outer rim above ground surface (from 12.5 m to 1038 m), topographic level, geographic location, presence or absence of parasitic landforms formed by refilling of the underlying magma chamber and re-eruption of lava from the central vent at the bottom floor type of the pre-existing caldera. All these morphologic variations suggest that these craters are volcanic craters formed by caldera collapsing, rather than from an impact.

4. No surface materials from outside the crater are occurring around or inside the caldera craters, but a strong evidence of lava flows or pyroclastic materials usually occurs along the sides of the crater depression, or ejected from a peripheral or the central vent at the bottom floor of the

collapsed summit as well as around the parasitic volcanic landforms which may re-erupt at the bottom floor of the pre-existing caldera. Many calderas exhibit a lava tube (open cave) which is a natural conduit formed by flowing lava which moves beneath the collapsed roof of the caldera. A younger steam explosion (water vapor and hematite) took place after complete cessation of volcanic activity through a natural conduit (a vent or lava tube) on the collapsed roof of different calderas on Mars. Very probably this steam explosion continued in calderas for a long time.

5. None of the studied caldera craters which vary in diameter from 7.7 km to 162 km is surrounded by a star-shaped distribution of ejecta which characterizes impact craters. The so called "complex crater" which exhibits "central peak" uplift in the center of the crater and which is usually used to identify the impact craters is simply a large caldera crater with a younger post-caldera phase of lava re-eruption after re-filling of the magma chamber leading to the formation of composite volcano, cinder cone or volcanic domes over the central vent at the bottom floor of the pre-existing caldera.

6. The different types of independent collapse calderas of variable morphologies and different relative ages are identified on Mars as follow:

a. Caldera No.1 (Cal 1): It is a simple caldera with a shallow subsurface depth below ground surface, flat bottom floor and faint outer rim above ground surface.

b. Caldera No.2 (Cal 2): It is a simple moderately-sized caldera with a rounded moderately deep bottom floor below ground surface and a well- developed symmetrical outer rim above ground surface.

c. Caldera No.3 (Cal 3): It is moderate- to large-sized complex caldera with a deep funnel-like depression below ground surface, an almost asymmetrical outer rim above ground surface and an open deep central vent. This type is characterized by the eruption of two different stages of volcanic lava from the same central vent; each of them is followed by successive collapsing into the void left when its magma chamber is emptied without leaving a post-caldera volcanic landform (Wizard Island) at the bottom floor. Zonal structure is evident due to gradual collapses rather than a single event.

d. Caldera No.4 (Cal 4): It is a huge simple caldera with a large strongly concave and smooth bottom floor below ground surface. This type shows a well-developed zonal structure due to gradual collapse and has no wizard island at the bottom floor. The central vent is either open,

or closed and buried by volcanic materials.

e. Caldera No. 5 (Cal 5): It is a complex caldera with a less strong younger post-caldera phase of eruption of volcanic materials from the same central vent giving rise to the formation of parasitic cinder cone, volcanic dome or very rarely composite volcano forming a Wizard Island of different shape and size at the center of the pre-existing caldera floor. A smaller and shallower variant of this type of caldera (Caldera 5') shows either a volcanic dome at the bottom floor or an up-domed floor formed by the uplift and deformation of the surface itself by magma movement underground

f. Caldera No. 6 (Cal 6): It is a huge complex caldera with a more strong younger phase of eruption of lava flow from the same central vent giving rise to the formation of post-caldera volcanic landform formed exclusively of parasitic composite volcanoes at the center of the pre-existing caldera floor. This type of caldera is much larger in size and deeper in bottom surface (below ground surface) than all other calderas. The height of the parasitic composite volcano at the bottom floor is often greater than the subsurface depth of the pre-existing caldera.

Beside the independent collapse calderas, there are two other caldera groups on the surface of Mars, The mountain (summit) caldera and the parasitic caldera. The mountain caldera (= Shield or Basaltic Caldera) is lying entirely above ground surface level, at the top of a shield volcano, composite volcano or cinder cones. This group of calderas is outside of our scope. The parasitic caldera group occurs along the flanks of large shield and composite volcanoes (=flank crater) as well as the bottom floor of some larger calderas where it represents a relatively younger generation of eruption of lava flow with respect to the pre-existing volcano. Representatives of the parasitic calderas are identified and described.

7. Two or three generations of different ages of volcanic eruption can be recognized during the history of the same crater of most calderas. The first generation is the eruption of lava flows and collapse of the magma roof leading to the caldera formation; the second generation is the re-eruption of post caldera lava flows from the central vent of the pre-existing caldera leading to formation of parasitic composite volcanoes, cinder cones or lava domes covering the central vent of the preexisting caldera; the third generation (second generation in case of presence of two generations) is the eruption of several volcanic pipes from different vents on the bottom floor of the caldera and sometimes along the flanks of the parasitic volcanoes which

re-erupt on the bottom floor of pre-existing caldera.

8. Summarizing the relative age of calderas with respect to shield volcanoes, two different groups of calderas could be recognized: a) an older group which was erupted and ceased eruption before the eruption of shield volcanoes including Cal 1, Cal 4, Cal 5 and Cal 6, and b) a younger group erupted and continued eruption for a long time after the eruption of shield volcanoes (except of the three major volcanoes of the Tharsis Montes) including Cal 2, Cal 3 and Cal 5'.

9. Beside the calderas there are an innumerable number of craters of volcanic pipes which are subterranean geological structures formed by the violent, supersonic eruption of deep-origin volcanoes leading to the formation of pipe-like structures that penetrate the surrounding rock and create a bowl-shaped, craterlike depression on the surface. The diameter of craters vary from less than 1 km to 10.25 km and reaching up 22.5 in width The volcanic pipes rise onto surface of Mars through a series of deep fractures and fissures in the crust where magma rises through the crust by exploiting a vertical or inclined path of weakness.

10. Two different types of volcanic pipes are recorded on the surface of Mars; carrot-shaped pipes (VP1) and vertical funnel-shaped pipes (VP2) equivalent to both Kimberlite and lamproite pipes on Earth. The pipes are structurally controlled; those which possess a carrot-shaped profile are almost inclined on the surface of Mars and showing different trends, following the trends of surface fractures. Both types of volcanic pipes (VP1 and VP2) as well as smaller and shallower transitional forms between both types (VP1-2) occur in all provinces; northern and southern hemisphere, lowlands below 0 level and highlands above 0 level, on the basalt plateaus, in the valleys, basins, and along cracks and fissures. They also intrude with varying degrees in size and number the bottom surface of all types of volcanic calderas, the flanks of the independent composite volcanoes, the flanks of the parasitic composite volcanoes which erupt at the bottom surface of large calderas nos. 5 and 6, and the flanks of shield volcanoes, thus suggesting a younger age of the volcanic pipes than all other volcanic landforms on the surface of Mars.

11. There is no direct record to the presence of kimberlite or Lamproite on Mars. However the processes that brought these rocks to the surface on Earth (i.e. the volcanic pipes) are already existed on Mars on a large scale. Other indirect indications to the presence of these rocks and associated diamond on surface of Mars are the presence of higher amounts of potassium and phosphorus

Plate 47: Top view, side view, three dimensional view and morphologic features of craters belonging to Volcanic Pipes No. 1 (VP 1) in the northern hemisphere below 0 datum (A, B, E, and F) and the southern hemisphere both above 0 datum (G) and below 0 datum (C and D) of Mars

Plate 48: continuation of Plate 47: Top view, side view, three dimensional view and morphologic features of craters belonging to Volcanic Pipes No. 1 (VP 1) in the northern hemisphere above 0 datum (I, K, M, and N) and the southern hemisphere above 0 datum (H, J and L) of Mars.

Plate 49: Top view, side view, three dimensional view and morphologic features of craters belonging to Volcanic Pipes No. 2 (VP 2) in the northern hemisphere below 0 datum (A-G) of Mars.

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Plate 50: continuation of Plate 49: Top view, side view, three dimensional view and morphologic features of craters belonging to Volcanic Pipes No. 2 (VP 2) in the northern hemisphere both below (H-J) and above (K and L) 0 datum, and the southern hemisphere above 0 datum (M and N) of Mars.

Plate 51: Top view, side view, three dimensional view and morphologic features of smaller volcanic pipes transitional between VP 1 and VP 2 (VP 1-2) in the northern hemisphere below 0 datum (A-G) of Mars.

Plate 52: continuation of Plate 51: Top view, side view, three dimensional view and morphologic features of smaller volcanic pipes transitional between VP 1 and VP 2 (VP 1-2) in the northern hemisphere above 0 datum (H, K , L, M and N) and the southern hemisphere above 0 datum (I and J) of Mars.

Type of volcano: Volcanic Pipe

Volcanic Pipe 1 (VP1)

Data

Series of Volcanic Pipe 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selected elevation points (in meters) relative to 0 datum across the width of Volcanic Pipe 1	450	-3310	-3164	-3256	-3050	-958	-143	1461	1832	4075	1377	5632	1678	1824	-2638
	520	-3277	-3055	-3204	-3030	-881	-82	1435	1888	4172	1410	5654	1790	1857	-2577
	568	-3250	-3018	-3185	-2906	-852	-40	1408	1946	4135	1428	5712	1820	1891	-2529
	587	-3233	-2970	-3233	-2951	-783	-26	1311	1834	4042	1503	5743	1776	1946	-2455
	301	-3205	-3004	-3327	-2879	-1044	-331	1122	1639	3900	1257	5516	1531	1746	-2652
	102	-3556	-3293	-3474	-3368	-1308	-576	926	1434	3729	1013	5305	1346	1400	-2933
	-101	-3825	-3565	-3650	-3592	-1652	-696	783	1284	3500	901	5199	1217	1252	-3128
	-180	-3925	-3730	-3752	-3710	-1772	-736	683	1263	3341	800	5098	1170	1186	-3245
	-102	-3814	-3551	-3652	-3566	-1602	-700	771	1285	3480	904	5198	1237	1305	-3132
	59	-3557	-3344	-3522	-3365	-1299	-578	925	1335	3658	1021	5290	1312	1500	-2930
	292	-3183	-3014	-3385	-3141	-955	-434	1168	1435	3883	1290	5398	1442	1760	-2741
	502	-3210	-2978	-3242	-3044	-820	-304	1481	1601	4102	1544	5586	1614	1972	-2455
	522	-3259	-3004	-3189	-2988	-777	-185	1437	1745	4149	1502	5798	1708	2013	-2500
	510	-3300	-3095	-3211	-3005	-860	-93	1378	1869	4102	1482	5711	1673	1955	-2606
	425	-3320	-3165	-3260	-3040	-974	-145	1347	1855	4069	1450	5644	1603	1874	-2691
									1836	4038		5625			

Representation of Data

Text Figure 20: Topography and topographic elevation of different series of Volcanic Pipes No.1 (VP1) with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each volcanic pipe, but the width of pipes is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each series of Volcanic Pipes No.1 see Text Fig. 23

Type of volcano: Volcanic Pipe

Volcanic Pipe 2 (VP2)

Data

Series of Volcanic Pipes 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
selected elevation points (in meters) relative to 0 datum across the width of Volcanic Pipe 2	1063	543	-4595	-4548	-3530	-4588	-4455	-4412	-3606	-3675	3894	-3678	-4115	-3378	4452
	1038	533	-4545	-4510	-3505	-4570	-4406	-4386	-3588	-3600	3915	-3700	-4058	-3364	4467
	954	479	-4502	-4480	-3560	-4493	-4381	-4325	-3593	-3552	3938	-3752	-4030	-3420	4474
	850	384	-4478	-4501	-3630	-4448	-4350	-4236	-3650	-3603	3875	-3797	-4006	-3524	4420
	725	293	-4423	-4585	-3704	-4358	-4313	-4385	-3800	-3730	3758	-3859	-4112	-3634	4325
	557	197	-4688	-4770	-3846	-4538	-4503	-4612	-4047	-3874	3637	-3941	-4302	-3748	4153
	405	70	-5290	-4956	-4015	-5038	-5255	-4912	-4247	-4080	3549	-4075	-4609	-3868	4003
	274	-143	-5635	-5150	-4157	-5777	-5848	-5283	-4532	-4381	3465	-4303	-4918	-3967	3852
	387	10	-5236	-4936	-4037	-5027	-5237	-4715	-4217	-4075	3597	-4160	-4720	-3869	3950
	491	120	-4751	-4739	-3905	-4635	-4456	-4430	-3938	-3830	3711	-4037	-4555	-3767	4037
	583	215	-4429	-4556	-3740	-4184	-4286	-4240	-3812	-3658	3830	-3940	-4400	-3669	4151
	698	320	-4474	-4403	-3604	-4360	-4348	-4273	-3675	-3600	3959	-3861	-4280	-3605	4280
	797	429	-4520	-4436	-3512	-4419	-4411	-4302	-3577	-3574	4054	-3781	-4210	-3526	4352
	870	522	-4545	-4460	-3544	-4483	-4447	-4348	-3549	-3607	4039	-3710	-4170	-3454	4415
	946	618	-4593	-4510	-3588	-4540	-4497	-4429	-3562	-3676	4020	-3676	-4140	-3411	4455
	980			-4590		-4565			-3609		3982		-4115		4467

Representation of Data

Text Figure 21: Topography and topographic elevation of different series of Volcanic Pipes No.2 (VP2) with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each volcanic pipe, but the width of pipes is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each series of Volcanic Pipes No.2 see Text Fig. 24.

Type of volcano: Volcanic Pipe

Topographic Details of VP1 & VP2

Text Figure 22: Cross sections of lowland volcanic pipes (below 0 datum) on Mars showing topographic details of VP1 (A) and VP2 (B). Notice the carrot-shaped profile of VP1 and the funnel-shaped profile of VP2 (Non-scaled horizontally). For elevation data of different series of different volcanic pipes see Text Figs. 20 & 21. To know the width of different series of different types of volcanic pipes see Text Figs. 23 & 24.

Type of volcano: Volcanic Pipe

Volcanic Pipe 1 (VP1)

Representation of Data

Data

Volcanic Pipes No. 1					
Series No.	Parameter	A	B	C	D
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)	Average height of outer rim (in meters)
series 1		5.4	9.35	630	68.5
series 2		8	22	615	118.5
series 3		7	19.5	605	190.5
series 4		2.4	4.2	496	35.5
series 5		5.6	13.6	670	135.5
series 6		8.9	22.5	814	186
series 7		5.75	9	593	84.5
series 8		6.64	11.8	778	67
series 9		4.88	7.49	573	73.5
series 10		6.9	11.5	734	104
series 11		5.5	12	650	110
series 12		6	11.4	534	142
series13		5.25	10.22	503	138
series 14		4.8	9.1	688	130.5
series 15		5.4	10.5	530	209.5

Text Figure 23: Morphologic features of Volcanic Pipes No. 1 (VP1) on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

Type of volcano: Volcanic Pipe

Representation of Data

Volcanic Pipes No.2					
Series No.	Parameter	A Diameter of crater (in kilometers)	B Width of volcano (in kilometers)	C Subsurface depth (in meters)	D Average height of outer rim (in meters)
series 1		9.33	11.8	789	0
series 2		8.8	11	761	0
series 3		7.5	23	1042	168
series 4		5.4	18.2	602	127.5
series 5		4.4	6.55	627	50.5
series 6		10.25	33	1212	305.5
series 7		7.8	26	1351	176.5
series 8		5.2	14.8	829	182.5
series 9		5	10.9	926	39
series 10		6.75	15.7	706	111.5
series 11		6.35	11.3	517	58
series 12		3.35	5.61	627	0
series13		5.2	12	803	54.5
series 14		3.5	4.9	589	7
series 15		4.5	8.65	615	11

Text Figure 24: Morphologic features of Volcanic Pipes No. 2 (VP2) on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

Type of volcano: Volcanic Pipe

Transitional volcanic pipes between VP1 & VP2 (VP1-2)

Data

Series of Volcanic Pipes	1'	2'	3'	4'	5'	6'	7'	8'	9'	10'	11'	12'	13'	14'	15'
selected elevation points (in meters) relative to 0 datum across the width of Volcanic Pipes transitional between VP1 and VP2	-1777	-1794	1161	3366	3270	645	-3520	-3410	-3331	940	565	795	-3248	-3670	-3415
	-1745	-1760	1210	3424	3238	708	-3510	-3377	-3319	895	534	818	-3280	-3672	-3385
	-1729	-1717	1237	3469	3206	762	-3500	-3345	-3368	815	465	839	-3341	-3720	-3328
	-1710	-1825	1168	3409	3167	841	-3494	-3351	-3420	750	357	792	-3420	-3780	-3270
	-1779	-2020	1080	3326	3131	694	-3580	-3365	-3545	679	243	672	-3515	-3833	-3488
	-1960	-2132	972	3218	3075	454	-3678	-3405	-3671	623	144	553	-3602	-3930	-3787
	-2057	-2215	925	3138	3031	269	-3738	-3572	-3801	560	19	442	-3701	-3999	-4079
	-2131	-2247	895	3129	2982	195	-3851	-3756	-4072	485	-37	341	-3785	-4092	-4260
	-2044	-2210	922	3131	2983	160	-3775	-3628	-3954	555	90	415	-3671	-3953	-4086
	-1942	-2132	971	3137	2985	253	-3715	-3529	-3750	621	212	493	-3550	-3813	-3880
	-1817	-2027	1060	3185	3040	425	-3625	-3446	-3590	680	319	570	-3416	-3715	-3748
	-1767	-1850	1123	3315	3112	680	-3585	-3386	-3496	757	398	633	-3315	-3675	-3670
	-1700	-1803	1224	3416	3202	790	-3550	-3360	-3394	833	438	684	-3235	-3656	-3577
	-1717	-1793	1275	3458	3334	764	-3530	-3330	-3363	907	476	725	-3250	-3636	-3517
	-1731	-1840	1298	3481	3297	758	-3515	-3390	-3317	935	506	760	-3267	-3632	-3480
					3274			-3455	-3338	953	521	797	-3666	-3423	

Representation of Data

Text Figure 25: Topography and topographic location of smaller and shallower volcanic pipes, transitional between volcanic pipes No.1 and No. 2 (VP 1-2) with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each volcanic pipe, but the width of pipes is not constant throughout. To know details of subsurface depth, diameter of crater, width and height of outer rim of each series of Volcanic Pipe 1-2 see Text Fig. 26.

Type of volcano: Volcanic Pipe

Transitional volcanic pipes between VP1 & VP2 (VP1-2)

Representation of Data

Data

Transitional Volcanic Pipes VP1-VP2				
Series No.	Parameter	A	B	C
		Diameter of crater (in kilometers)	Width of volcano (in kilometers)	Subsurface depth (in meters)
series 1		2.5	5.2	400
series 2		2.7	4.7	453
series 3		3.25	5.5	403
series 4		5	7.4	352
series 5		4.1	5.72	292
series 6		4.25	7	598
series 7		2.5	5	336
series 8		3.77	21	346
series 9		4.25	11.4	741
series 10		3.05	4.78	468
series 11		7.6	14.4	602
series 12		5.7	10.2	456
series13		3.6	7.7	537
series 14		4.5	10	426
series 15		4.7	10.8	845
				72.5

Text Figure 26: Morphologic features of smaller and shallower volcanic pipes, transitional between volcanic pipes No.1 and No. 2 (VP 1-2) on Mars: A- Diameter of crater (in km), B- Width of volcano (in km), C- Subsurface depth (below ground surface, in meters), and D- Average height of outer rim (above ground surface, in meters).

Text Fig. 27: Correlation of 1- Diameter of crater (in km), 2-Width of volcano (in km), 3- Subsurface depth below ground surface (in m) and 4- Average height of outer rim above ground surface (in m) in different series belonging to different volcanic pipes (VP 1, VP 2 and VP 1-2) on Mars.

Text Figure 28: Graphical representation showing correlation of subsurface depth (below ground surface) of the volcanic crater (in meters) and diameter of crater (in km) of different types of Volcanic Pipes (VP1 and VP2) and Calderas (Cal 1, 2, 3, 4, 5 and 6) on Mars. For data see Figs. 15, 17, 23 and 24.

as well as a higher percentage of volatile elements such as sulphur and chlorine than the Earth's crust do. Also, the majority of volcanic pipes are covered by fine dust arranged in streaks formed by water vapor which accompanied the eruption of magma. Intense steam explosion (water vapor and hematite) associated with massive eruption of oriented volcanic pipes is common in some areas. It is thus apparent that the volcanic pipes have encountered rock layers containing groundwater during the ascent of the magma through a series of fissures. The water is vaporized together with other volatile materials (carbon dioxide) producing an explosive event at the surface. It is, thus, concluded that the processes that brought diamond-bearing kimberlite and Lamproite volcanic pipes to the surface on Earth have existed on a large scale on Mars. So, Mars certainly has diamonds and very probably has much more diamond than Earth does.

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***Corresponding author:** Khaled Abdel-Kader Ouda, Email: khaledabdelkader_ouda@yahoo.com; kh.ouda@aun.edu.eg

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