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Composite Volcanoes on Mars: Topography, Morphology, Mode of Occurrence and Correlation with Shield Volcanoes

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Abstract

A thorough examination of composite volcanoes (stratovolcanoes) on the Martian surface by satellite remote sensing (via Google Mars) has revealed that these volcanoes are rarely occurring independently but frequently occurring as parasitic landforms which were re-erupted at the bottom floor of larger collapse calderas after re-filling of the magma chamber below. Fifteen independent composite volcanoes of which ten volcanoes are described for the first time, beside new twenty-one representatives of parasitic composite volcanoes are subjected to detailed statistical analyses for their topographic and morphologic characters. The data are discussed, correlated and represented graphically. In addition, the topography and morphology of fourteen volcanoes of the previously known major and minor shield volcanoes are statistically analyzed in order to homogenize method of study for means of correlation with the composite volcanoes. The study contributes to improved understanding of the volcanic activity, structures and deposits on Mars.

Keywords: Mars, composite volcanoes (stratovolcanoes), shield volcanoes, remote sensing, parasitic volcanoes

Introduction

Composite volcanoes are cone-shaped volcanoes built from many layers of lava, pumice, ash, and tephra. Because they are built of layers of viscous material, rather than fluid lava, composite volcanoes create steep slopes and tend to form tall peaks rather than rounded cones. Sometimes the summit crater collapses to form a caldera due to violent volcanoes. Composite volcanoes are some of the most dangerous volcanoes on the Earth. They tend to occur along oceanic-to-oceanic or oceanic-to-continental boundaries because of subduction zones. They tend to be made of felsic to intermediate rock and the viscosity of the lava means that eruptions tend to be explosive. The volcano is constructed layer by layer, as ash and lava solidify, one upon the other and are sometimes called stratovolcanoes or andesite volcanoes. Examples of composite volcanoes in modern times include Mount St. Helens, Mount Rainer, Mount Shasta, Mount Hood, and Mount Pinatubo. Two famous historical examples of composite volcanoes are Krakatoa in Indonesia, known for its catastrophic eruption in 1883, and Vesuvius in Italy, whose catastrophic eruption in AD 79 ruined the Roman

cities of Pompeii and Herculaneum. Both eruptions claimed thousands of lives.

Systematic morphometric studies of composite volcanoes and composite cone evolution on earth have been dealt with by several authors (Davidson and da Silva, Grosse, Karátson, Karátson [1-4]. Grosse [2] proposed a classification and evolutionary scheme for arc-related composite volcanoes, whereas Karátson [3] studied the regular stratovolcano shape using an advanced digital elevation model analysis. Note that there is no consensus on classification. According to Karátson [4] four subtypes of composite volcanoes could be recognized according to their morphology. However, there is little evidence whether there occurs a real trend in these volcanoes from simplicity to complexity

A- Concave, regular-shaped cone: this is the simplest "textbook" profile of composite volcanoes the regular-shaped composite volcano may retain its symmetrical cone shape for a long time. As it was demonstrated [3], there is a significant volumetric variation between regular-shaped volcanoes, implying a proportional growth of the

cone. Examples of Regular-Shaped Cones include Mayon, Philippines; Kliuchevskoi and Kronotsky, Kamchatka, Russia; Cotopaxi, Ecuador; Paríacota and Licancabur, Chile; Pavlof, Alaska, USA; Taranaki (Mt. Egmont), New Zealand; and Fuji, Japan.

B- Irregular cone: Regular symmetry becomes distorted when the volcano has a (much) longer lifetime or the eruptive vent is multiplied or shifted. Irregular composite volcanoes are grouped into “sub-cones” and “massifs” by Grosse, but there are a number of terms such as twin volcano, compound volcano, etc. Examples of Irregular Cones San Pedro–San Pablo, Chile; Tongariro, New Zealand; Pacaya, Guatemala; and Mt. Rainier, Washington, USA.

C- Truncated cone: Morphologically, the upper cone may be significantly lowered (e.g., from 2,950 to 2,550 m at Mt. St. Helens in 1980), and the resultant landform is a wide half-depression open toward the direction of the collapse. The dimensions of a half caldera can be typically 2–3km in diameter and several hundred meters in depth [5]. Examples of Truncated Cones include Mt. St. Helens, Washington, USA; Socompa, Chile-Argentina; and Bezymianny, Kamchatka, Russia.

D- Caldera volcano: Violent magmatic explosions cause a more significant and preferably symmetric collapse of the whole upper part of a composite volcano. This process results in the creation of a medium (6–8 km) or large (8–25 km) depression. Examples of Caldera Volcanoes include Crater Lake, Oregon, USA; Pinatubo, Philippines; Somma, Italy; Aniakchak, Alaska, USA; and Tejedá, Tenerife, Spain.

The vast majority of previous works focused on the shield volcanoes on Mars. However, the possible existence of composite volcanoes on other terrestrial bodies of the Solar System was not conclusively demonstrated [6]. The only record of composite volcano on Mars is the Zephyria Tholus which has been described by Stewart and Head. According to these authors this volcano is a truncated cone-type characterized by asymmetrical shape and a summit depression. The base of the volcano averages 30km wide and lies about 500-1000m elevation. The height is 2-2.5km. the flank slopes 14 degree near the summit and decrease with decreasing elevation, producing a concave-upward flank shape that is similar to Earth stratovolcanoes.

The present investigation records the occurrence of 35 composite volcanoes on Mars rather than Zephyria Tholus, fourteen of which are independent (free) composite volcanoes, whereas the remaining (twenty-one) are parasitic composite volcanoes. The latter volcanoes

were ejected under immense heat and pressure from underground conduit system of vents leading from the magma reservoir to the bottom surface of pre-existing huge caldera and resulting in building up of a large cone of composite volcanoes of alternating lava flow, ash and unmelted stone around the vent. The topography, topographic elevation and morphologic characters of all these volcanoes including updating of data on Zephyria Tholus are measured, discussed and represented graphically. Correlation with morphologic data obtained in this study for the different major and minor shield volcanoes on Mars is made both numerically and graphically. The study has contributed immensely to the interpretation of distribution, genesis and morphology of composite volcanoes on Mars.

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.

Fifty satellite images (Visible imagery of Google Mars) of composite (36 series) and shield (14 series) volcanoes on the surface of Mars were carefully examined for resolution, distribution, topography, morphology and mode of occurrence. The images include both independent (15 cones) and parasitic composite (21 cones) volcanoes which re-erupted at the bottom of pre-existing huge calderas after re-filling of the magma chamber, together with major and minor shield volcanoes for means of correlation. To make the graphic comparison possible between different

types of independent composite and shield 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 height above surroundings and the width (base diameter) of the volcanic cones. The morphologic features of the parasitic composite volcanoes are measured using the electronic profile. Graphic representations of all these topographic and morphologic features in different types of volcanoes are given and the data are correlated.

Results and Discussion

Composite Volcanoes on Mars

Independent Composite Volcanoes (ICV): Composite volcanoes are rarely occurring independently on Mars (15 volcanoes are only available in this study), but occur frequently as parasitic landforms at the bottom surface of huge calderas (21 representatives of parasitic volcano). When occurring separately (independently) the composite volcanoes show different morphologies which suggest the recognition of three types of Karatson's types (2014), a regular-shaped cone, a truncated cone and a caldera volcano. The caldera type (Plate 1, Figures A,B & D) is characterized by the presence of large caldera at the top of the cone as a result of collapse of summit into the drained magmatic chamber. It is represented in the northern hemisphere of Mars by the cones of Jovis Tholus (18°11'10.69" N 117°27'06.66" W), Ulysses Tholus (2°56'23.47" N 121°33'04.76" W) and the northern volcano of the Hibes Montes (4°21'08.62" N 170°51'05.30" E).

The truncated cone type (Plate 1, Figure F; Plate 2, Figures M & N) is represented only in the southern hemisphere by Zephyria Tholus (19°48'35.93" S 172°54'35.46" E), as well as two unnamed volcano at altitudes 23°40'29.61" S Lat. 58°40'16.00" E. and 45°28'38.22" S 55°06'11.70" E. The regular-shaped cones (Plate 1, Figures C,E & G, Plate 2, Figures H-L & O) are represented in the northern hemisphere by the southern volcano of the Hibes Montes (3°15'13.25" N 171°53'15.83" E) together with an unnamed volcano at 50°10'29.65" N 171°07'02.68" E, beside many unnamed volcanoes localized in the southern hemisphere at altitudes, 29°58'47.31" S 86°45'04.64" E, 31°05'32.70" S 53°40'22.74" E, 37°56'40.59" S 100°45'27.24" E, 38°52'06.44" S 95°46'21.94" E, 40°35'23.58" S 102°53'22.71" E,

54°31'09.64" S 93°28'28.22" E, and 68°52'55.40" S 5°10'12.67" E.

The independent representatives of this volcano occupy a wide topographic elevation between elevations -7300 m below 0 datum level and +5600 m above 0 datum level, but the majority of volcanoes are recorded in the highlands of the southern hemisphere. The deepest composite volcano is an unnamed regular-type cone (series 14) which occupies the elevations from -7261 m to -5217, whereas the highest one (series 2, Ulysses Tholus) which is caldera-type cone occupies the elevations from +3400 m to +5571 m (Text Figure 1). All the composite volcanoes are localized either in the lowlands of the northeastern hemisphere or both the highlands and lowlands of the southeastern hemispheres, except of Jovis Tholus and Ulysses Tholus which occur in the highlands of the northwestern hemisphere.

The composite volcanoes are rising up from 841 m to 6339m, with most height values ranging in different series between 1305 m and 4609 m and an average value of 2990m. The width of volcano varies from 27.3km to 116km, with most values lying between 30.7km and 73.4km and an average width value of 52.8 km (Text Fig. 2). The cone in these volcanoes has steep sides around its summit, with a maximum slope varying from 27.6 % to 55.8 %, with most values lying between 31.4 % and 47.8 % and an average maximum slope of 40.7 %. However, the slope becomes much lower toward the base of the volcanic cone as the lava flows for short distances before it solidifies. The average slope varies from 4.1 % to 26.15 %, with most values lying between 5.4 % and 20.45 % and a total average slope of 12.85 %, corresponding to a slope degree ranging in most series between 2.4° and 13.2° and attaining an average slope degree of 7.5°.

The summit caldera in the caldera-type composite volcanoes is wide and deeply collapsed in Jovis Tholus and Ulysses Tholus. It has a large diameter (30km and 58km) with respect to the width of volcano (68km and 116km respectively). It has also a considerably large depth with respect to height of volcano. The summit depth is 727m in Jovis Tholus, thus constituting about 86% of the height of cone (841m), and 757 m in the northern volcano of the Hibes Montes, thus constituting about 40 % of the height of cone (1886 m), whereas in Ulysses Tholus it measures 2171m thus exceeding the height of cone (1390m) by 781m which extend below ground surface. The Jovis Tholus and Ulysses Tholus were considered by Hodges and Moore [7] as minor shield volcanoes due to their least relief relative to other shields, although flank widths are narrow relative to caldera diameters in both volcanoes. However, the low

Plate 1: Top view, side view, three-dimensional view and morphologic features of independent composite volcanoes in the northern hemisphere, both above (A-B) and below 0 datum (C-D), and the southern hemisphere above (F) and across 0 datum (G) 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 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.

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Plate 2: Continuation of Figure 1: Top view, side view, three dimensional view and morphologic features of independent composite volcanoes in southern hemisphere above (H-J and L-M), below (N) and across 0 datum (K and O) of Mars.

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Topographic data of Independent Composite Volcanoes (ICV)

Series of Composite Volcano	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 Composite Volcanoes	1961	4206	-3931	-2956	-2992	316	-3129	-167	-560	1119	-2090	-784	-650	-7029	-3056
	1975	4258	-3864	-2695	-2620	479	-2819	-14	-223	1206	-1958	-473	-411	-6917	-2853
	2022	4461	-3808	-2483	-2238	709	-2544	160	190	1335	-1760	-155	-130	-6782	-2525
	2216	4741	-3717	-2127	-2140	1077	-2045	590	1146	1620	-1190	446	278	-6578	-2064
	2416	5143	-3551	-1725	-1696	1545	-1378	1168	2103	2125	-532	1547	1402	-6196	-1515
	2548	5571	-3344	-1070	-1333	2242	-267	1737	3134	2577	1168	2400	2280	-5846	-626
	2265	3733	-2970	-1555	-1028	2749	502	2228	4026	3061	2430	2820	2383	-5401	-67
	2035	3400	-2626	-1827	-893	2650	1480	2672	4616	3580	2930	3385	2336	-5217	295
	2040	3408	-2689	-1564	-1083	2649	1254	2447	3909	3437	3584	3095	2400	-5410	636
	2055	3409	-3014	-1227	-1464	2684	745	2086	3070	3162	4249	2566	2409	-6010	330
	2090	3470	-3310	-1149	-1884	2157	136	1673	2113	2827	3450	1587	2196	-6475	-280
	2908	3533	-3515	-2118	-1937	1680	-442	1038	1430	2156	2273	900	1696	-6692	-935
	2741	5278	-3674	-2748	-2059	1352	-1171	833	952	1771	1608	618	633	-6888	-1358
	2408	5015	-3781	-2850	-2623	1067	-1887	582	350	1552	-832	703	-17	-7021	-1655
	2137	4668	-3850	-2991	-2839	960	-2196	-135	-393	1294	-1638	139	-201	-7261	-2232
	2067	4357	-3925		-3024		-2370	-547	-627	1190	-1855	-203	-333		-2655

Representation of Data

Text Figure 1: Topography and topographic elevation of different Independent Composite Volcanoes (ICV) with respect to 0 datum on Mars. The measurements of elevation (from 1 to 16) are more or less symmetrically spaced across the width of each simple cinder cone, but the width of cones is not constant throughout. To know details of diameter of summit, width of cone, subsurface depth of the summit and height of cone of each series of ICV see Text Figure 2.

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Morphologic data of Independent Composite Volcanoes (ICV)

No. of volcanic series	Ser. 1	Ser. 2	Ser. 3	Ser. 4	Ser. 5	Ser. 6	Ser. 7	Ser. 8	Ser. 9	Ser. 10	Ser. 11	Ser. 12	Ser. 13	Ser. 14	Ser. 15
Width of volcano (km)	68.4	116	27.3	49.2	56	36.9	30.7	29.3	56.6	35.6	73.4	42.8	53.8	70.7	44.9
Height of volcano (m)	841	1365	1305	1886	2131	2433	4609	3219	5293	2461	6339	4169	3059	2044	3692
Average slope (%)	4.1	5.8	10.0	10.5	7.65	11.95	26.15	20.45	16.9	13.3	16.7	17.4	10.95	5.4	15.45
Maximum slope (%)	34.7	49.8	27.6	41.7	35.1	31.4	55.8	53.9	42.2	29.4	53.8	47.8	39.2	29.0	39.1

Representation of Data

Text Figure 2: Morphologic data of the Independent Composite Volcanoes (ICV) on Mars and graphic representation of data; A- maximum height of volcano above surroundings (in m); B- width of volcano (base diameter, in km); C- average slope of volcano (%); D- maximum slope (%) of volcano around its summit; E- height versus width of volcano; F- height versus average slope of volcanic cone.

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relief (low slope degree) is not always a matter of wide extension of lava flows for a long distance, but also a matter of intensive erosion of volcanic flanks whatever the type of volcanic cone (shield, composite, cinder). This could be deduced from the low height and width beside low slope of the volcanic flanks as well as the presence of channels along the flanks of both Jovis Tholus and Ulysses.

Tholus. Both volcanoes have a considerably low height above surroundings (841-1365 m) as compared to all major and minor shield volcanoes (2655-22925m). The width of cone is also narrow relative to the diameter of the summit caldera. The latter constitutes 44 % and 50 % of the width of volcanic cone in Jovis Tholus and Ulysses Tholus respectively, whereas in the shield volcanoes it constitutes 2.6-37.3% with the majority of values lying between 10 % and 24 % of the width of volcano. In addition, the maximum slope around the summit is markedly higher in all composite volcanoes (Av. 40.7 %) due to steep slopes including Jovis Tholus 34.7 % and Ulysses Tholus (49.8 %) whereas in shield volcanoes the maximum slope ranges from 1.95 % to 38.9 % with the majority of values lying between 6.75 % and 23.8 % and an average value of 20.6 %.

In the truncated-type of composite volcanoes the diameter of summit is much smaller than the caldera-type. It ranges from 6.7km to 10.5km, thus constituting 14 % -19.5 % of the total width of volcano (36.9 km-70.7 km). The depth of summit varies in this type from 54 m to 138 m, thus constituting 2.6% to 4.5 % of the total height of the volcano (2044m to 3059m). The regular-type of composite volcanoes is made up of a single, shallow vent at the top of volcano. No collapse of summit occurs in the volcanoes of this cone type and accordingly no caldera is formed at the top of cone. Thus, the depth of summit in all the investigated composite volcanoes lies above ground surface, except of Ulysses Tholus which shows a strong and continuous deep collapse of the summit caldera leading to the formation of a deep, steep-sided depression extending below the ground surface.

Parasitic Composite Volcanoes and their calderas hosts on Mars: Although the composite volcanoes are occurring rarely as independent landforms on Mars, they are intimately occurring as parasitic volcanoes at the bottom surface of huge calderas. They are ejected under immense heat and pressure from underground conduit system of vents leading from the magma reservoir to the bottom surface of pre-existing huge caldera and resulting in building up of a large cones of composite volcanoes of alternating lava flow, ash and un-melted stone around the vent (Plate 3, Figures A-J). Twenty-one parasitic composite volcanoes are

recorded in twenty-one huge calderas lying independently between elevations -5500 m and +3000 m in lowlands of the northern hemisphere and both highlands and lowlands of the southern hemisphere. However, the majority of these calderas are recorded below and across 0 datum level (Plate 4, Figures A-G, Plate 5, Figures H-N, Plate 6, Figures O-U).

The huge craters which enclose parasitic composite volcano are independent (free) collapse caldera lying entirely below ground surface level, and with an outer rim of variable height above ground surface level. These craters which are known on Earth as complex caldera have a huge size, a much deep bottom surface (below ground surface) and a huge "Wizard Islands" which are made up exclusively of composite volcanoes. They are formed by a massive volcanic 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 composite volcano at the center of the bottom floor of the pre-existing caldera. The volcanic origin of these huge calderas is emphasized by the presence of lava flows and/or water vapor and hematite near or around the crater (Plate 3, Figures A-J), 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.

The craters of the huge calderas which host parasitic composite volcanoes have a great diameter varying mostly from 52 km to 162 km (with an average value of 100 km), and a much great width varying mostly from 82 km to 243 km (with an average value of 140 km) (Text Figure 3A). The subsurface depth of the collapsed summit (below ground surface) is ranging between 1080 m and 2901 m with an average value of 1988 m. Beside the definite absence of the star-shaped distribution of rock debris around the crater, the outer rim of the hosting caldera craters on Mars is almost asymmetrical 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. The average height of outer rim (above ground surface) ranges between 145 m and 697 m, with an average value of 410 m. Named craters belonging to this huge caldera type and which host composite volcanoes include Kinkora, Nicholson, Pettit, Moreux, Eddie, Reuyl, Schroeter, Boeddicker, Gale, Henry, Martz, Liu Hsin, Radau, Li Fan, Wright, Curie, Barnard and Eden Patera, beside other unnamed comparable craters (Plates 4-6).

In the northern hemisphere of Mars some

Plate 3: A-J- Three-dimensional views of Parasitic Composite Volcanoes (PCV) erupted at the bottom surface of huge collapse caldera at the ground surface on Mars. The re-eruption of lava took place after re-filling of the magma chamber below the pre-existing caldera. They are ejected under immense heat and pressure accompanied by water vapor and iron oxides from underground conduit system of vents leading from the magma reservoir to the bottom surface of the pre-existing caldera and resulting in building up of large cones of alternating lava flow, ash and un-melted stone around the vent.

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Plate 4: A-G- Electronic profiles and three-dimensional images showing parasitic composite volcanoes covering the central vent at the bottom floor of huge complex collapse calderas as a result of re-filling of the magma chamber below the vent and re-eruption on the bottom floor of pre-existing caldera. The first left column is a cross section of the hosting caldera showing a younger phase of eruption of parasitic composite volcano over the central vent at the bottom of the collapsed caldera. The middle column is a cross section of the parasitic composite volcanoes. The right column is a three-dimensional view of the parasitic composite volcano at the bottom surface of caldera. A-E from the northern hemisphere; F and G from the southern hemisphere of Mars.

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Plate 5: Continuation of Plate 4: H-N- Electronic profiles and three dimensional images showing parasitic composite volcanoes covering the central vent at the bottom floor of huge complex collapse calderas as a result of re-filling of the magma chamber below the vent and re-eruption on the bottom floor of pre-existing caldera. For the definition of columns see Plate 4; H and J-N from the southern hemisphere; I from the northern hemisphere of Mars.

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Plate 6: Continuation of Plate 5: O-U- Electronic profiles and three-dimensional images showing parasitic composite volcanoes covering the central vent at the bottom floor of huge complex collapse calderas as a result of re-filling of the magma chamber below the vent and re-eruption on the bottom floor of pre-existing caldera. For the definition of columns see Plate 4; Q and S-T from the southern hemisphere; O-P, R and U from the northern hemisphere of Mars.

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representatives of the huge complex calderas which host composite volcanoes show fine barchans to barchanoid dunes of volcanoclastic material at the bottom surface, almost associated with the re-eruption of a post-caldera parasitic composite volcano at the central vent of the pre-existing caldera. For example, are the dune deposits inside Liu Hisn (Plate 5, Figure N) as well as many unnamed craters near the southern ice-cape pole. Comparable deposits of dark color are found in some larger craters in the northern low lands such as Moreux (Plate 3, Figure I; Plate 4, Figure C) and Radau (Plate 3, Figure G; Plate 6, Figure O). The dark color is due to the enrichment of pyroxene and olivine pointing to the basalt origin.

(ancient volcanic ash) of the dune sand-sized grain [8,9]. The 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 [10]. The parasitic composite volcanoes which occur at the bottom of these collapsed calderas are built of alternating lava flow, ash and blocks of un-melted stone (Plate 4, Figures A-G; Plate 5, Figures H-N; Plate 6, Figures O-U). They form tall peaks varying in height in the studied representatives from 931 m to 4502 m with most values ranging between 1638 m and 2806 m, and an average height value of 2153 m (Text Figure 3B-F). The height of the parasitic composite volcano at the bottom floor of caldera is often greater than the subsurface depth of the pre-existing caldera. The width of the parasitic composite volcano varies from 6.6 km to 114 km with most values ranging between 13 km and 61 km and an average value of 33.7 km. The maximum slope around the summit of these parasitic volcanoes varies mostly from 20.8 % to 48.5 % attaining an average value of 37.6 %. The average slope ranges in most parasitic series between 7 % and 26.3 % and attains a total average value of 16 %, corresponding to a slope degree ranging in most representatives between 4.9° and 16° with an average degree of 9.76° . Among the 21 series of parasitic composite volcanoes 10 series belong to the regular-shaped cone-type, 7 series belong to the irregular-shaped cone-type and 4 series belong to the truncated cone-type of Karatson's types. No caldera volcano type is found in the parasitic composite volcanoes. The regular-shaped cone-type is distributed in both the northern and southern hemispheres. The irregular-shaped cone type is preferentially distributed in the southern hemisphere while the truncate cone type is preferentially distributed in the northern hemisphere of Mars. In the northern hemisphere, the parasitic composite volcanoes occur either below or across 0 datum, whereas in

the southern hemisphere they occur both below and above 0 datum.

Correlation of independent and parasitic composite volcanoes (Text Figure 38) shows that the independent landforms are almost larger in height (Av. 2990 m) and width (Av. 52.8 km) than the parasitic ones (Av. 2195 m and 34.3 km respectively) (Text Figures 4A-B). The difference in width is attributed to the limited horizontal extension of the parasitic lava which is restricted by the host caldera walls. However, the average slope of the independent composite volcanoes is normally lower than the parasitic ones due to the relatively wider extension of the former than the latter. It ranges in most independent volcanoes between 5.4 % and 20.45 %, attaining a total average slope of 12.85%, whereas in most of the parasitic landforms the average slope ranges from 7.05 % to 26.75 % and attains a total average of 16.11 % (Text Figure 4C). The maximum slope around the summit of both independent and parasitic cones is more or less similar, ranging mostly between 25 % and 55 % and averaging between 37 % and 40 % (Text Figure 4D). Correlation of height versus width and height versus average slope of both types of composite volcanoes is graphically represented in Text Figure 4E-F).

Topography and morphology of shield volcanoes

The shield volcanoes represent the largest and most conspicuous volcanoes on the surface of Mars. They have been dealt with many scientists [11-18]. They are broad, gently sloping volcanic mountains built of low-viscosity basalt lava flows spreading out as thin layers in all directions from a central vent. The topography and morphology of these volcanoes are revised here in order to homogenize the method of study for means of correlation with the composite volcanoes. The data are given in Plates 7-10 and represented graphically in Text Figures 5-7. The shield volcanoes occupy vast areas in the higher lands above 0 datum level particularly in the western hemisphere (Plate 7, Figures A-G; Plate 8, Figures H-N). They are several thousand meters above the ground surface (from 2655 m to 22925 m above surroundings) and extending laterally for large distances varying from 70 km to 1305 km, forming gentle slopes that range from 0.53° to 6.74° . Topographically, they occupy the topographic levels between elevation -3000 m and elevation +21000 m (Text Figure 5). The flanks of few shield volcanoes extend slightly down below 0 datum but the majority of shield volcanoes stand up completely above 0 datum level.

A summit caldera is almost occurring at the top of the shield volcanoes formed due principally to drainage of magma

A- Morphologic data of volcanic craters which host parasitic composite volcanoes

No. of volcanic series	Ser. 1	Ser. 2	Ser. 3	Ser. 4	Ser. 5	Ser. 6	Ser. 7	Ser. 8	Ser. 9	Ser. 10	Ser. 11	Ser. 12	Ser. 13	Ser. 14	Ser. 15	Ser. 16	Ser. 17	Ser. 18	Ser. 19	Ser. 20	Ser. 21
Diameter of crater (km)	85	106	125	96.5	162	76	52	110	74.5	101	155	95	71	147	115	118.5	122	18.8	103	110	55
Width of volcano (km)	128	149	164	172	243	117	104	135	82	133	199	119	115	181	144	156	181	26	143	143	98
Subsurface depth (m)	1906	2360	2901	2101	2822	1633	1193	2536	2123	1933	2898	1395	1444	1772	2289	2508	1843	1145	1403	1080	1461
Av. Height of outer rim	697	499	608	621	275	516	470	197	427	210	666	250	145	268	156	613	627	266	297	315	495

B- Morphologic data of Parasitic Composite Volcanoes (PCV)

No. of volcanic series	Ser. 1	Ser. 2	Ser. 3	Ser. 4	Ser. 5	Ser. 6	Ser. 7	Ser. 8	Ser. 9	Ser. 10	Ser. 11	Ser. 12	Ser. 13	Ser. 14	Ser. 15	Ser. 16	Ser. 17	Ser. 18	Ser. 19	Ser. 20	Ser. 21
Width of volcano (km)	21.8	61	50	40	114	32	25	27	38	11.9	94	33.6	13	22.7	16	18.5	20.2	6.6	22.4	18.6	21.6
Height of volcano (m)	2222	3876	2366	2340	1740	2212	2210	2806	2493	1878	4502	1899	1906	2086	1638	1648	1008	931	2485	1663	1306
Average slope (%)	18.8	12.6	7.05	10.65	2.45	12.0	17.4	17.35	12.6	31.2	9.6	11.15	26.3	18.45	20.9	19.55	8.95	26.75	21.85	16.6	13.1
Maximum slope (%)	30.7	46.1	20.8	26.2	5.1	26.7	57.5	57.5	41.3	39.9	35.1	27.6	41.5	38.6	46.2	48.5	27.8	42.4	52.8	33.3	43.5

Representation of Data of PCV

Text Figure 3: A- Morphologic data of 21 huge volcanic craters which host parasitic composite volcanoes on Mars B- Morphologic data of 21 Parasitic Composite Volcanoes (PCV) re-erupted at the bottom surface of the pre-existing calderas after re-filling of the magma chamber below. C-F- Graphic representation of data of PCV; C- maximum height of volcano above surroundings (in m); D- width of volcano (base diameter, in km); E- average slope of volcano (%); F- maximum slope (%) of volcano around its summit.

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Text Figure 4: A-F- Graphic representations showing correlation between Independent (ICV) and Parasitic Composite Volcanoes (PCV) on Mars.; A- maximum height above surroundings (in m); B- width (basal diameter in km); C- average slope of cone (%); D- maximum slope of cone (%); E- height (m) versus width (km) of volcano; F- height (m) versus average slope (%) of volcanic cone. For data of the independent composite volcanoes see Text Figure 2, and for data of parasitic composite volcanoes see Text Figure 3.

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Plate 7: Top view, side view, three-dimensional view and morphologic features of different Shield Volcanoes in the northern hemisphere, both above (B, C and E-G) and across 0 datum (D), and the southern hemisphere across 0 datum (A) of Mars.

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Plate 8: Continuation of Plate 7: Top view, side view, three-dimensional view and morphologic features of different shield volcanoes rising above 0 datum in both the northern hemisphere (H-L and N) and the southern hemisphere (M) of Mars.

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rather than explosive removal of it (Plate 9, Figures A-J; Plate 10, Figures K-N). Eruption of these volcanoes (commonly called Hawaiian-type eruptions) is not generally explosive because the fluid lava loses its gases easily. According to Crumpler [19], two fundamental types of summit calderas of shield volcanoes 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 terms Alba Patera, Uranus Patera and Ulysses Patera have been redefined by the international Astronomical Union (IAU) to refer only to the central calderas of these volcanoes.

Major Shield Volcanoes of the Tharsis Bulge: At mid-latitude a huge upland called the Tharsis bulge is dotted by 4 volcanic peaks, one of these peaks is Olympus Mons which is the highest known mountain in the solar system. This immense, elevated structure is thousands of kilometers in diameter and covers up to 25% of the planet's surface. It contains the highest elevations on the planet. The huge shield volcano Olympus Mons lies at the western edge of the main Tharsis bulge which is dominated by a massive volcano-tectonic complex made up of three enormous shield volcanoes namely Ascraeus Mons, Pavonis Mons and Arsia Mons (collectively known as the Tharsis Montes). These volcanoes were built up by countless generations of lava flows and ash. So, the Tharsis bulge contains some of the youngest lava flows on Mars, but the bulge itself is believed to be very ancient [20]. 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 [21].

The three Tharsis shield volcanoes extend for about 2100 km across the equator in the western hemisphere. They are all several hundred kilometers (450-550 km) in width and range in height from 7613 m to 15376 m above surroundings. They have low profiles with shallow slopes ranging in different volcanoes from 2.28° to 5.54°. The southernmost member of the group (Arsia Mons) is 12295 m high above its surroundings (= 17350 m above 0 datum level) and 549 km wide (Plate 8, Figure M; Text Figure 6). Its summit caldera at the top of the volcano has a maximum diameter of 126.5 km and a depth of 1144 m (Plate 10, Fig. M). The middle member of the Tharsis Montes (Pavonis Mons) is the shortest volcano of this group, attaining a height of 7613 m above surroundings (= 13338 m above 0 datum level) and a width of 450 km (Plate 8, Figure K; Text Figure 6). Its summit caldera has a maximum diameter of 46 km, but its depth (4438 m) is more than those of the

northern and southern members of the Tharsis group (Plate 10, Figure K). The northern shield volcano of this group (Ascraeus Mons) is 15376 m high above surroundings (=17364 m above 0 datum level) and 491 km wide (Plate 8, Figure L; Text Figure 6). Its summit caldera has a maximum diameter of 57 km and a depth of 2920 m (Plate 10, Figure L).

Olympus Mons which is the tallest larger shield volcano has a height of 22925 m above its surroundings (20762 m above 0 datum and 2163 m below 0 datum level) and a width of 734 km (Plate 8, Figure N, Text Figure 6). The volcano has a summit caldera at its top made up of nested and overlapping calderas, thus constituting a complex depression (= Olympus-type summit caldera of Crumpler) with a maximum diameter of 74.2 km and a depth of 2626 m (Plate 10, Figure N). It has a low profile with shallow slopes ranging from 3.4° to 4.9°. Lava domes are very restricted and occurring sporadically along the southeastern flanks. Immense lava flow could also be seen extending into adjacent plains around the volcano particularly north of the volcano. Olympus Mons, like those of the Tharsis Montes, was built up by countless generations of highly fluid lava flow during the time interval from the Noachian (3.7 billion years) to late Amazonian (< 500 million years), thus indicating that the planet Mars has been volcanically active throughout its history [22].

Olympus Mons constitutes with Alba Mons a distinctive northeast-southwest alignment parallel to the main trend of the Tharsis Montes. 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 most widely extensive volcanic features in the Solar System. It attains a width of 1305 km, although its height does not exceed 6035 m above surroundings (= 6453 m above 0 datum level) (Plate 7, Figure G, Text Figure 6). The volcano has shallow slopes and very low profile ranging from 0.54° to 0.58°. Its summit caldera is made up of two nests attaining a maximum diameter of 120 km, but with a shallow depth of 753 m (Plate 9 Figure G). Most geological models suggest that Alba Mons is composed of basaltic lava flow, but some researchers have identified possible pyroclastic deposits on the flanks of the volcano [23].

Minor Shield Volcanoes: In addition to the above-mentioned large shield volcanoes, there are a number of smaller volcanoes called Uranus Tholus, Ceraunus Tholus and Uranus Mons, occurring together at the same trend of the Tharsis group to the northeast. The height of these

Morphologic data of Shield Volcanoes

Series of Shield Volcano	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selected elevation points (in meters) relative to 0 datum across the width of shield volcanoes	-2837	421	1342	-1722	2243	2000	556	1975	2210	1392	5906	1988	5055	-2074
	-2585	570	1430	82	3603	2608	1500	2370	2240	1875	6590	5329	6110	1944
	-1993	1403	1516	1178	5413	2938	2259	2598	2952	2417	8561	8500	8576	4608
	-436	2401	1614	2180	7022	3240	3424	2916	4140	4109	10396	12599	11530	7845
	1825	3159	1761	2769	8607	4173	4959	3157	4985	6130	12006	15501	13754	10769
	2529	3479	2787	3309	5680	4545	5412	3630	5680	8997	13338	16325	16395	12741
	3077	3742	3708	3837	3238	4614	5294	4321	6450	14091	12765	17364	16864	17173
	2443	1554	2286	4285	2500	4655	5797	5260	6845	13280	10014	17084	16300	19242
	1667	3222	2946	4237	3522	4445	6250	7160	6600	10575	9876	14577	16430	20762
	2235	2875	2664	3560	4930	4415	5895	5847	7279	8488	10370	16321	16301	18555
	2530	2322	1698	2535	4460	4088	5597	4549	8667	6166	12279	17307	17350	20551
	2413	1798	1595	1621	3065	3747	4325	2960	6763	4838	12255	16450	16900	18223
	1626	375	1425	485	2021	3207	3665	6531	4340	3216	11288	12337	15660	11187
	150	-661	1178	-672	1407	2166	1638	6063	2719	2022	9676	8914	13400	8775
	-703	-1009	873	-1461	1218	2054	742	5209	2396	1039	8222	6265	8025	4860
	-1998	-1066	607	-2286			429	4304	2210	317	5725	3500	6855	780

Representation of Data

Selected elevation points (1-16) across the width of different Shield volcanoes (series 1-14)
(Non-scaled horizontally)

Series1 : Apollinaris Mons
Series 4: Hecates Tholus
Series 7: Alba Mons
Series 10: Elysium Mons
Series 13: Arsia Mons

Series 2: Albor Tholus
Series 5 : Tharsis Tholus
Series 8: Biblis Tholus
Series 11: Pavonis Mons
Series 14: Olympus Mons

Series 3: Uranius Mons
Series 6: Uranius Tholus
Series 9: Ceraunius Tholus
Series 12: Ascaerus Mons

Text Figure 5: Topography and topographic location of different shield volcanoes with respect to 0 datum on Mars. The measurements of elevation are more or less symmetrically spaced across the width of each shield volcano, but the width of volcano is not constant throughout. To know the width, height, average slope and maximum slope of each series of shield volcano see Text Figure 6.

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Text Figure 6: A- Three-dimensional diagram showing surface topography and height (in meters) of different major and minor shield volcanoes relative to 0 Datum on Mars (non-scaled horizontally). B- Morphologic data of investigated shield volcanoes. C- Representation of width of different shield volcanoes (in km). C- Representation of maximum height of different shield volcanoes (in meters). of 13.4 km and 24.6 km respectively whereas the Uranus Mons has a considerably large summit caldera attaining 112.5 km in diameter. The slope of Uranus Mons is extremely low ranging between 0.53° and 0.54° degrees (corresponding to average slope percent 1.0%) whereas the other two Tholus volcanoes have slopes ranging from 3.44° to 5.75° (corresponding to average slope percent 7.45-9.15 %). The flanks of the three volcanoes have densely channeled flanks, suggesting that the flank surfaces are made up of easily erodible material rich in volatiles and ash on their flanks.

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Plate 9: Electronic profiles and morphologic features of the summit caldera of different shield volcanoes in the northern hemisphere above 0 datum (B-J) and the southern hemisphere above 0 datum (A) of Mars.

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Plate 10: Continuation of Plate 9: Electronic profiles and morphologic features of 1) summit caldera of different shield volcanoes in both northern (K, L and N) and southern hemisphere (M); 2) summit caldera of composite volcanoes in the northern hemisphere (O, P and Q); and 3) truncated summit of composite volcanoes (R, S and T) in the southern hemisphere of Mars.

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volcanoes is respectively 2655 m, 6457m and 2502 m above surroundings (= 4655 m, 8667 m, 3957 m above 0 level respectively). The width of the same volcanoes is 70 km, 127 km and 245 km respectively (Plate 7, Figures C and F; Plate 8, Figure I; Text Figure 6). The three volcanoes have a shallow compact summit caldera with asymmetrical sides at the top of the volcano and which vary in depth from 246 m to 2094 m (Plate 9, Figures C, I & F). The summit caldera of the Uranus Tholus and Ceraunus Tholus are relatively small and attaining a maximum diameter

Additional two high volcanoes occur along both sides of the Tholus bulge, one is aligned northeast of the bulge, and about 600 km south of the Uranus Mons, namely Tharsis Tholus, and the other is aligned west of the bulge, namely Biblis Tholus. The Tharsis Tholus (Plate 7, Figure E; Text Figure 6) is 143 km wide and 7389 m high above surroundings (= 8607 m above 0 level), whereas Biblis Tholus (Plate 8, Figure H; Text Figure 6) is 356 km wide and 5771 m high above surroundings (= 7074 m above 0 level). Both volcanoes have a large non-centered summit caldera at the top of the volcano. The summit caldera shows in both volcanoes a distinct zonal structure as a result of successive collapse of summit into the partially drained magma chamber. It has a more or less equal diameter (53-55 km) and a great depth reaching up 4129 m (=71.5 % of the height of volcano) in Biblis Tholus and 6550 m (= 87 % of the height of volcano) in Tharsis Tholus (Plate 9, Figures E and H). The slopes of both volcanoes are finely dissected in part with channels which may have been attributed to lava or ash flows, but not as heavily as in Ceraunus Tholus and Uranus Tholus. The flank slope ranges between 4.0° and 9.47° (corresponding to average slope percent of 13.55 %) in Tharsis Tholus whereas Biblis Tholus has a lower slope degree ranging between 1.23° and 5.07°.

Shield volcanoes of the Elysium Province: Another significant volcanic center which includes three main volcanoes lies several thousand kilometers west of Tharsis bulge in Elysium province. The Elysium volcanic complex consists of three main volcanoes, Elysium Mons, Hecates Tholus, and Albor Tholus, arranged from north to south. Elysium Mons is the largest volcanic edifice in this province. The Elysium group of volcanoes is thought to be somewhat different from the Tharsis Montes, in that development of the former involved both lavas and pyroclastics. The Elysium Mons is the third tallest shield volcano on the surface of Mars (after Olympus and Arsia Montes). It has a height of 14051 m above surroundings (= 14091 m above 0 datum level) and a width of 496 km (Plate 8, Figure J; Text Figure 6). Hecates Tholus lies across 0 datum with a total height of 6571 m of which 4285 m above 0 datum and 2286 m

below 0 datum level (Plate 7, Figure D). It has a width of 177 km. Both volcanoes have a low profile with shallow slopes ranging between 2.46 to 4.36 (corresponding to average slope percent between 5.75 % and 6.65 %). They differ from those of the Tharsis Montes and Olympus Mons by having a simple small and shallow summit crater at the top of the volcano, 639 and 310 m deep, and 14.3 km and 10.8 km long, for Elysium Mons and Hecates Tholus respectively (Plate 9, Figures D and J).

The Albor Tholus, the southernmost of the Elysium province is markedly different from Hecates Tholus and Elysium Mons. It is much similar to Tharsis Tholus and Biblis Tholus, being 4808 m high above surroundings, 3742 m of which lie above 0 datum level and 1066 m below 0 level at the eastern flanks (Plate 7, Figure B; Text Figure 6). Its width is 198 km and the volcano has a long and much deep summit caldera. The maximum diameter of its summit caldera is 32.4 km whereas its depth is 3082 m equivalent to 64% of the height of the volcano (Plate 9, Figure B), thus being correlative to the depth of the summit caldera of Tharsis Tholus and Biblis Tholus which constitutes 71.6-87% of the height of the volcanoes. The slopes of Albor Tholus are very low ranging from 2.89° to 5.77° (corresponding to average slope percent of 6.2 %). They are dissected with channels as other volcanoes in the Elysium province and which may have been attributed to lava or ash flows, but the channels are not as heavily as in the Uranus and Ceraunus Tholi.

The Apollinaris Mons lies individually at latitudes 8°45'58.80" S 174°10'02.53" E. it was historically known as Apollinaris "Patera". It is a shield volcano outcropping across the 0-datum level with a total height of 5914 m, of which 3077 m occur above 0 datum level and 2837m below 0 datum level. The width of the volcano is 225 km (Plate 7, Figure A, Text Figure 6). Its summit caldera at the top of volcano is considerably large attaining a maximum diameter of 54.5 km and a depth of 1572 m (Plate 9, Figure A). The slopes of the volcano are low, ranging from 3.3° to 5.5°. Apollinaris Mons, on the other hand, is characterized from all other shield volcanoes by having long channels and valleys forming a lava fan extending along the southern flanks from high lands at north to low lands at south. Gulick and Baker [24,25] concluded from their analyses of valley formation on Martian volcanoes that the valleys on Apollinaris Mons display features suggestive of mixed fluvial and lava origins, and that the stage of valley development indicates a Noachian age. However, Hodges and

Moore maintained that the relative ages suggest that Apollinaris is Hesperian, older than the Tharsis volcanoes and, probably, than Elysium Mons as well.

Summarizing the above discussion, the shield volcanoes have a height above surroundings varying from 2655 m and 22925 m, with Olympus Mons as the tallest volcano on Mars, and Uranus Tholus as the shortest volcano. The remaining volcanoes range in height between 3101 m and 15376 m. The average total height of all studied shield volcanoes is 8625 m. The width of these volcanoes varies between 70 km to 1305 km, with Alba Mons as the widest volcano and Uranus Tholus as the most limited (narrowest) one. The remaining volcanoes vary in width between 127 km and 734 km and the total volcanoes attain an average width value of 424 km. The average slope of shield volcanoes ranges between 1.0 % and 9.15 % with a total average value of 6.16 %, corresponding to a slope degree ranging between 0.53° and 5.75° and with a total average value of 3.7°, except of the Tharsis Tholus which assumes a relatively higher average slope of 13.55%. The least steep volcanoes are the Alba mons (1%) and the Uranus Mons (1.1 %). A Mountain Caldera is usually lying above ground surface level, at the top of a shield volcano (= Shield Caldera of Wood, 1984; Basaltic Caldera according to the classification of San Diego state University). This summit caldera is marked by a large depression varying in depth from 246 m (Uranus Tholus) to 6550 m (Tharsis Tholus) and in diameter from 10.8 km (Hecates Tholus) to 143.0 km (Alba Mons). Regarding the major volcanoes of the Tharsis bulge, the Pavonis Mons has the deepest summit (4438 m) and the least diameter (46.0 km), whereas the Arsia Mons has the shallowest summit (1144 m) and the greatest diameter (126.5 km). Representation of morphologic data of different major and minor shield volcanoes on the surface of Mars is given in Text Fig. 6C and 6D; Text Figure 7A and 7B.

Correlation of composite and shield volcanoes

A. Topographically, the shield volcanoes occupy the topographic levels between elevations -3000 m and +21000 m (Text Figure 5). The flanks of few shield volcanoes extends slightly down below 0 datum but the majorities of volcanoes stand up completely above 0 datum level. They are located in the northern hemisphere except of Apollinaris Mons and Arsia Mons which lie in the southern hemisphere, near the equator. The independent representatives of composite volcanoes occupy a wider topographic elevation between elevations -7300 m below 0 datum level and +5600 m above 0 datum level (Text Figure 1). They occur in both the lowlands and highlands of the northern and southern hemispheres, but the majorities of volcanoes are located in the highlands of the southern hemisphere.

B. The height of shield volcanoes is much greater than the height of composite volcanoes (Text Figure 7C).

It varies from 2655 m to 22925 m above surroundings and with an average height value of 8625 m, whereas the height of independent composite volcanoes varies from 841 m to 6339 m above surroundings, and with an average height value of 2990 m.

C. The width of shield volcanoes is much greater than the width of composite volcanoes (Text Figure 7D). It varies from 70 km to 1305 km, and attains an average width value of 424 km, whereas the composite volcanoes have a width varying from 27.3 km to 116 km, and attaining an average value of 52.77 km.

D. The greater width and height of the shield volcanoes relative to composite volcanoes is attributed to the fact that shield volcanoes are made up exclusively of basic lava, which is non-acidic and very runny. On the other hand, the composite volcanoes are made up of acidic lava, which is very viscous (sticky) so that cannot go far. The relation between height and width in both shield and composite volcanoes is graphically represented in Text Figure 7G.

E. Both the maximum slope (%) and the average slope (%) of the shield volcanoes is much lower than those of the composite volcanoes because of the gentle sides of the cone of volcano as the lava flows for long distances before it solidifies (Text Figures 7E and 7F). The individual average slope (%) ranges in different studied shield volcanoes between 1.0 % and 9.15 % corresponding to an average slope degree ranging between 0.53° and 5.75°, except of the Tharsis Tholus which assumes a relatively higher average slope of 13.55%. However, the total average slope value of all studied shield volcanoes is 6.16 %, corresponding to a total average degree of 3.7°. The maximum slope is varying in the same volcanoes from 1.95 % and 38.9 % with an average value of 20.6 %. The independent composite volcanoes, on the other hand, have an average slope ranging from 4.1 % to 26.15 % with the majority of values lying above 10% and with a total average slope value of 12.85 %, corresponding to a total degree of slope of 7.5°. They show a maximum slope varying from 29 % to 55.85 % with most values higher than 30 % and an average maximum slope of 40.7 %. The higher maximum slope values of the composite volcanoes is attributed to the fact that these volcanoes are steep sided near their summit, with high slope angles, but the slope decreases relatively toward the base of the volcanoes. The relation of height versus average slope in both shield and independent composite volcanoes is represented graphically in Text Figures 7H.

F. A mountain caldera is usually lying above ground surface level, at the top of a shield volcano. This summit caldera in these volcanoes is marked by a depression varying

Text Figure 7: A-F- Graphic representations showing correlation between independent composite volcanoes and shield volcanoes on Mars. A- Width (basal diameter) of volcano (in km). B- Maximum height of volcano above surroundings (in m). C- Average slope of volcanic cone (%). D- Maximum slope of volcanic flanks (%). E- Height of volcano (m) versus average slope (%). F- Height of volcano (m) versus width (km). For data of the composite volcanoes see Text Figure 2, and for data of the shield volcanoes see Text Figure 6.

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in depth from 246 m to 6550 m and in diameter from 10.8 km to 143.0 km. The depth of summit constitutes 0.2 % to 88.6 % of the height of volcano, whereas the diameter of summit constitutes 6.1 % to 37.3 % of the width of volcano. In the composite volcanoes, the caldera, if present, at the summit of volcano is characterized by having a deep depression ranging in depth from 727 m and 1983 m, thus constituting 40 % to 86.4 % of the volcanic height, except of Ulysses Tholus which has a much deeper summit caldera with steep-walled sides straddling the ground surface. However, the majorities of composite volcanoes examined on Mars have no calderas at the top of their volcanic cone. They are either belonging to the truncated cone type or mostly to the regular-shaped cone type. In the truncated-type of composite volcanoes the diameter of summit constitutes 14 % to 19.5 % of the cone width, whereas the depth of summit constitutes 2.65 % to 4.5 % of the cone height. The regular-type is made up of a single, shallow vent at the top of volcano. Thus, the summit in all investigated composite volcanoes lies above ground surface, at the top of mountain (like all shield volcanoes), except of Ulysses Tholus where the summit caldera extends below the ground surface by 618 m.

G. According to Hodges and Moore the stratigraphic age of the four major Montes Arsia Mons, Pavonis Mons, Ascraeus Mons and Olympus Mons is Amazonian, with Olympus Mons as the youngest one. These volcanoes show a complex history of overlapping volcanic events over a long period of time as deduced from their extraordinary larger (Arsia Mons) or complex (Pavonis Mons, Ascraeus Mons, Olympus Mons) summit caldera. Although there are somewhat differences between scientists concerning the relative age of minor shield volcanoes, they all agree that all these volcanoes are older than the surface flows of the four major Tharsis volcanoes. This relation has been demonstrated by both superposition and crater-count data. Neukum and Hiller [26] suggested a long history for Alba Mons, and this large, low shield was generally included in the older volcano group. The volcanoes Alba Mons,

Text Figure 7: A-F- Graphic representations showing correlation between independent composite volcanoes and shield volcanoes on Mars. A- Width (basal diameter) of volcano (in km). B- Maximum height of volcano above surroundings (in m). C- Average slope of volcanic cone (%). D- Maximum slope of volcanic flanks (%). E- Height of volcano (m) versus average slope (%). F- Height of volcano (m) versus width (km). For data of the composite volcanoes see Text Figure 2, and for data of the shield volcanoes see Text Figure 6. Elysium Mons and Apollinaris Mons were assigned to Amazonian-Hesperian by Hodges and Moore. The Hecates

Tholus was considered as Noachian by Gulick and Baker [24,25] and Hesperian by Greeley and Guest [27]. The Albor Tholus was assigned to be Noachian, possibly early Hesperian, but not Amazonian by Hodges and Moore.

H. The composite volcanoes are also not synchronous throughout Mars. Those of Series 1, 2, 3, 4, 5 and 14 which have a lower height (841-2131 m) and a lower average slope (4.1 % -10.5 %) appear to have subjected to erosion more than Series 7-9, 11,12 and 15 which have a higher height (3219-6339 m), and a higher average slope 15.45 % -26.15 %. This would suggest that the former volcanic series are stratigraphically older than the volcanoes of the latter series. The volcanoes of Jovis Tholus (Series 1) and Ulysses Tholus (Series 2) as well as the unnamed volcano of Series 14 are intensively eroded as deduced from their low height, very low average slope (4.1 %-5.8 %) and presence of channels along the flanks of these volcanoes. They appear to be as old as several minor shield volcanoes (e.g. Biblis Tholus, Albor Tholus, Ceraunius Tholus, Uranius Mons, Uranius Tholus, Hecates Tholus, Tharsis Tholus). Parasitic composite volcanoes are distinctly younger than their hosting huge calderas; and since these calderas are never recorded along the flanks of shield volcanoes it would be reasonable to state that the parasitic composite volcanoes are older than the independent composite volcanoes and hence older than all shield volcanoes.

Conclusion

1- Composite volcanoes are rarely occurring independently on Mars, but occurring frequently as parasitic landforms at the bottom surface of huge calderas. When occurring independently (15 volcanoes are available), the composite volcanoes show different morphologies which suggest the recognition of three types, a regular-shaped cone, a truncated cone and a caldera volcano. They occupy a wide topographic elevation between elevations -7300 m below 0 datum level and +5600 m above 0 datum level, but the majorities of volcanoes are recorded in the highlands of the southern hemisphere. The volcanic cones are rising up from 841 m to 6339 m, with an average height value of 2990 m. Their width (basal diameter) varies from 27.3 km to 116 km, with an average width value of 52.8 km. The cone in these volcanoes has steep sides around its summit, with a maximum slope varying from 27.6 % to 55.8 %, with an average maximum slope of 40.7 %. However, the slope becomes much lower toward the base of the volcanic cone as the lava flows for short distances before it solidifies, attaining an average slope between 5.4 % and 20.45 % with a total average slope of 12.85 %.

2- The summit caldera in the caldera-type composite

volcano is wide and deeply collapsed. Its diameter constitutes 18.3 % -50 % of the width (basal diameter) of cone, whereas the depth of the collapsed caldera is either constituting 40 % (Hibes Montes N) to 86 % (Jovis Tholus) of the height of cone or exceeding the height of cone and, thus, extending below ground surface (Ulysses Tholus). In the truncated-type of composite volcanoes the diameter of summit is much smaller and constituting 14 % to 19.5 % of the width of cone, whereas the depth of summit constitutes 2.65 % to 4.5 % of the total height of cone. However, most of the independent composite volcanoes belong to the regular-type with no summit caldera.

3- The parasitic composite volcanoes are ejected under immense heat and pressure at the bottom surface of some pre-existing huge caldera and resulting in building up of a large cone of alternating lava flow, ash and un-melted stone around the vent. Twenty-one representatives of parasitic composite volcanoes are recorded in twenty-one huge calderas lying independently between elevation -5500 m and elevation +2750 m in the lowlands of the northern hemisphere and in both highlands and lowlands of the southern hemisphere. The huge craters which enclose parasitic composite volcano are independent (free) collapse calderas lying entirely below ground surface level, and with an outer rim of varying height above ground surface level. These calderas which are known on Earth as complex caldera have a great width varying from 82.3 km to 243 km (Av. 145.7 km), and a large crater varying in diameter between 52 km and 162 km (Av. 104.7 km). They have also a much deep bottom surface (below ground surface) ranging between 1193 m and 2901 m (Av. 2087 m) and with an outer rim varying in height (above ground surface) between 145 m and 697 m (Av. 410 m).

4- The parasitic composite volcanoes which occur at the bottom of the collapsed calderas form tall peaks which often rise greater than the subsurface depth of the hosting caldera. They are varying in height in the studied representatives from 931 m to 4502 m (Av. 2153 m) and in width (basal diameter) from 6.6 km to 114 km (Av. 33.7 km), and thus being relatively smaller in height and width than the independent composite volcanoes (Av. Height 2990 m and Av. Width 52.8 km). This difference is attributed to the limited horizontal and vertical extension of the parasitic lava which is restricted by the host caldera walls. The maximum slope around the summit is considerably large in both independent (Av. 40.7 %) and parasitic cones (37.6 %). However, the average slope of the parasitic composite volcanoes is notably higher (Total Av. 16 %) than the independent ones (Total Av. 12.85 %) due to the limited width of the former cones than the latter ones. No caldera

volcano type is found at the top of parasitic composite volcanoes. Among the 21 series of parasitic composite volcanoes 10 series belong to the regular-shaped cone-type, 7 series belong to the irregular-shaped cone-type and 4 series belong to the truncated cone-type.

5- Correlation of composite and shield volcanoes reveals that the latter volcanoes are much greater in height and width, but much lesser in maximum slope and average slope than the composite volcanoes. A mountain caldera is usually lying above ground surface level, at the top of shield volcanoes while the majorities of composite volcanoes have no calderas at the top of their volcanic cone. They are either belonging to the truncated cone type or mostly to the regular-shaped cone type. Only three composite volcanoes have a summit caldera at the top of volcano; they are characterized by having a deep depression which constitutes 40 % to 86.4 % of the volcanic height, except of Ulysses Tholus which shows a strong and continuous deep collapse of the summit caldera leading to the formation of a deep, steep-sided depression extending below the ground surface.

6- The composite volcanoes, like shield volcanoes, are not synchronous throughout. The parasitic composite volcanoes are older than the independent ones. The latter volcanoes show variable rates of erosion as deduced from the differences in height and average slope of the different cones, thus being stratigraphically of different ages. The volcanoes of Jovis Tholus and Ulysses Tholus as well as the unnamed volcano of Series 14 are intensively eroded as deduced from their low height, very low average slope and presence of channels along their flanks, thus appearing as old as several minor shield volcanoes.

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