Height Concordance of Martian Volcanoes Over Time

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Abstract

An update to Carr's 1976 paper is provided by using modern public-release Mars Global Surveyor and Mars Observer measurements from the past five years. Specifically, the heights for 21 of the largest volcanoes on Mars were compiled using MOLA elevation data. This was then combined with crater counts obtained from THEMIS visual images of the volcano flanks and calderas to yield relative ages assuming a constant crater flux. The new data confirms that there is a decrease in both summit elevation and volcanic edifice height with increasing age, Elysium Mons being a notable exception. However, while all features appear to have the same relative ages, the absolute age, assuming a -1.8 power law, is higher by an order of magnitude at smaller crater diameters compared to the 1976 data.

1. Introduction

Since before the Viking missions it has been known that the tallest volcano on Mars, Olympus Mons, is also among the youngest surfaces present on the planet. It was this observation, in particular, which prompted Carr to speculate that there might be a relationship on Mars between the height of a volcano and its relative age[1]. To this end, a survey of 2km or greater sized craters on 11 prominent volcanic-type features was conducted using the resources available. This survey showed a clearly decreasing trend of height with age despite the large errors involved with the count [Figure 1 – On first page of Appendix].

What could be the cause of such a pattern? The most obvious explanation - at least if considering the earth as an analogue - is that the older features are being weathered and destroyed over time. This does not appear to be the case for Mars. Given the current atmosphere and lack of surface water it seems unlikely that erosion is the cause of this trend. This supposition is further reinforced by the fact that on all the features to be studied, summit craters are still visible and have not been destroyed as we would expect for an erosion-type process.

Thus there are two possibilities: either the features are isostatically relaxing over time or the volcanic processes on mars have simply been building taller volcanoes later on in the history of the planet.

Both of these ideas require some sort of a concordance of the height of the volcanoes produced. If the effect is purely due to the former, we would expect that the height of the volcanoes produced is constant over time and we are simply watching the viscous relaxation of volcanoes into the subsurface. However, if the trend is due purely to the latter effect, we require a mechanism to increase the height of a volcano with time such that there is a concordance of maximum volcanic height at any particular time in the history of the planet.

The latter case has some interesting implications. It has often been observed on earth that the summit elevation of a mature volcano is consistent with the so-called 'stand-pipe theory' in which the hydraulic head at the base of the lithosphere pushes up liquid magma until equilibrium is reached[6,7]. As such, a change in the height of volcanoes produced over time might be indicative of a thickening lithosphere (i.e. a lowering zone of melting) such as we would expect from a cooling planet[1]. This will be discussed more in-depth in the discussion section.

However, the research conducted in this paper seeks only to determine if there is in fact a relationship between the age of a volcano on mars and its height and if so what that relationship is. That is to test the findings of Carr and extend his research by considering both a greater number of large volcanic type features on mars and to examine if the trend remains evident at lower-sizes of craters. Furthermore, since a good geoid is now available we may examine whether summit elevation or volcanic edifice height is most important.

2. Theory

The theory required to conduct this exercise is simple. Heights accurate to 0.3m vertically may be acquired easily from Mars Observer Laser Altimeter (MOLA) passes[3], although the chance of a particular pass (often separated by up to several 10s of km in parts of the public release) passing over the precise highest point of a feature is small. Thus the uncertainty is likely on the order of a few 10s to 100s of meters. Features which do not have MOLA passes sufficiently close to the apparent summit (from the visual data) must be discarded.

Since several bins were used to average out the dataset a means of comparing craters of different sizes is required (Carr did not require this step since only one size of crater was considered). We know that if we assume a constant cratering flux – probably a good approximation as long as the total span of the data is not longer then several hundred million to a billion years[5] – we may relate the number density of all craters with diameters greater than D_0 on a surface of area A and age t as:

$$N(D>D_0) = ktAD^{-1.8} \qquad [1]$$

Where k depends upon the incident flux, which while often assumed is unknown for the orbit of Mars. As such, we may absorb the time elapsed into a variable which only depends upon time. Rearranging yields:

$$(N/A)\, D^{1.8} = \tau \qquad [2]$$

Thus if we know the number of craters of any number of sizes on a number of surfaces we may determine the relative ages of the surfaces without having to know their absolute ages[5,6].

3. Methodology and Procedure

The first step towards compiling a listing of large (i.e. diameters greater then 20km) volcanoes of mars is to examine the listings provided in the Gazetter of Planetary Nomenclature from the USGS[2]. From this list approximately 100 named features were selected for further study, principally Mons, Patera and Tholus. Note: since this list does not include unnamed features it should not be considered exhaustive.

This list was then reduced down by locating the features on the MOLA public-access map. Those features which clearly did not appear to be volcanic in origin (such as mountain ranges) and features without a near-summit MOLA pass were then eliminated. This resulted in 21 features which are listed in the appendix and displayed visually in figure 2.

Finally the public-access THEMIS visual data[4] was consulted and appropriate passes were obtained over the flanks and summit craters of all but one of the features. Where possible multiple passes were obtained - a sample of three was considered representative as the coverage of any one map was on the order of 1000 square km.

THEMIS Visual images were chosen over Mars Observer Camera (MOC) captures for two reasons. Firstly, the coverage of any one image is greater which allows a smaller number of images to be used. Secondly, it is well known that there is significant dust deposition in certain parts of the planet and as such it was important to choose a mid-range size for the crater distribution binning on the order of a few hundred meters to attempt to avoid degradation issues.

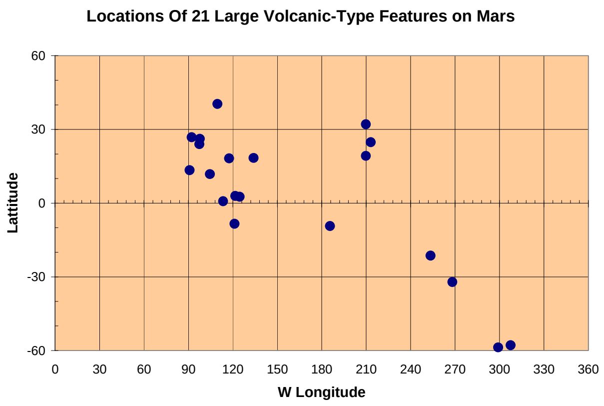


Figure 2: locations of 21 most prominent volcanic-type features on Mars expressed in W longitude (reverse of typical maps) [Reference 2]

In total, 37 images were selected for review using Paint Shop Pro 3 and NIH Image 1.62 and are logged in the appendix. After the images were reviewed, bin sizes of 200m, 400m and 575m were chosen to give a good spread (due to some confusion over image resolution before counting began some images also feature 200m and 290m bins). This gave satisfactory numbers for each area ranging from as few as 13 craters on an image of Olympus Mons to 481 on an image of Hecates Tholus. Only two images, both of Peneus Patera failed to show any cratering whatsoever, however, this could be the result of a bad sun angle, or out of focus capture. As such, this is not necessarily indicative of the age of the surface and thus this feature and its images were excluded.

4. Results and Analysis

Using equation 2 and averaging equally over all distributions for a particular feature, average time constants were derived for the 19 remaining features. These are expressed in arbitrary units due to the unknown flux constant and are summarized in the appendix.

These were then plotted against the MOLA summit elevation and edifice height values. Figure 3 contains the age data plotted against summit elevation whereas Figure 4 contains the age data plotted against Volcanic Edifice Height. For comparison, figure 5 contains the 1976 data regridded using equation 2 to express the age axis in terms of the time constant instead of crater number.

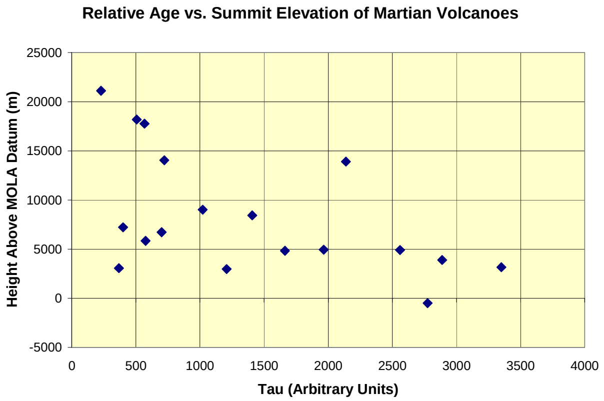


Figure 3: Relative Age vs. Summit Elevation of Martian Volcanoes. Features to the right are relatively old while features to the left are young. Tau of zero corresponds to the present day.

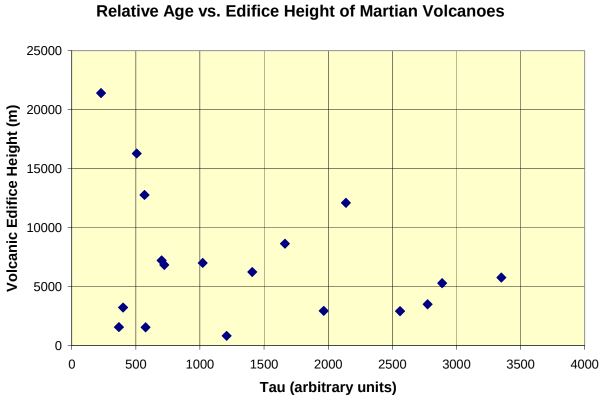


Figure 4: Relative Age vs. Edifice Height of Martian Volcanoes. Features to the right are relatively old while features to the left are young. Tau of zero corresponds to the present day.

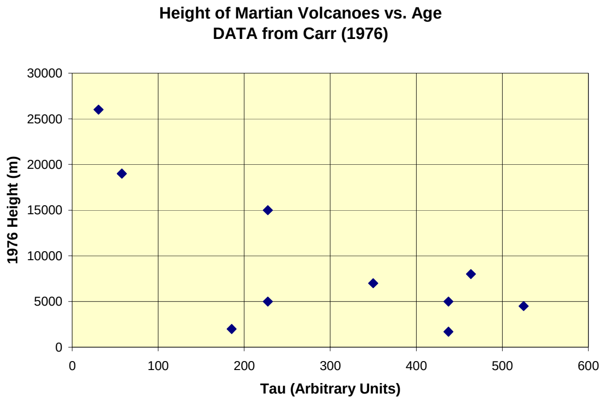


Figure 5: Regridded Relative Age vs. Height of Martian Volcanoes from image analysis of Viking data. Features to the right are relatively old while features to the left are young. Tau of zero corresponds to the present day. While features remain relative to one another, the tau scale is comparable to Figures 3 and 4.

Several things are immediately apparent from these plots. First, both summit elevation and edifice height decrease with increasing relative age. If we ignore the apparent outlier, Elysium Mons (the point with tau between 2000 and 2500) we see a gradual decrease of the highest values underlain by additional datapoints. This is the expected trend as it is likely that not all volcanic centers will achieve the maximum elevation before they become extinct.

It also appears that the trend for the Edifice Height is less smooth and steeper then the trend for Summit Elevation.

Comparing the old and the new data there is a peculiar observation. While the relative ages within each dataset are somewhat consistent – for instance in the 1976 dataset Elysium is 7.5 times as old as Olympus whereas in the new set it is 9.3 times as old – the two sets are different from one another by an order of magnitude.

5. Discussion

5.1 Error Considerations

A good place to begin is with error. One of the major focuses of this research was to improve the accuracy and precision of the 1976 data. In some values there has been a great deal of success, for instance the summit elevations, originally known only to within several km are now known to within a few tens to hundreds of meters at worst and then only because we cannot be certain that a MOLA pass has crossed the absolute summit.

Additionally, the crater counting has become more significant. By adding additional bins over which to average, and considering smaller crater sizes a better picture has emerged of the relative ages of various features described. However, there is still a great deal of spread in the data, for instance if we consider Elysium Mons depending upon which size bin one considers, a tau can be calculated anywhere from 917 for the largest bin to 3976 for the smallest. In fact it was generally observed that there was a dependence of tau upon the size of the craters being examined which is troubling but which might explain the differences observed in tau between the old and new datasets.

This difficulty was compounded by the format of the THEMIS visual datasets. Unlike the Infrared datasets, the THEMIS visual data had been map-projected and it was therefore unclear as to whether the geometrical information accompanying each image referred to the map-projected version or to the raw data. For the purposes of this report and without any indication to the contrary the published THEMIS resolutions are assumed to correspond to the map-projected images.

5.2 Elysium Mons: Outlier?

Even considering this we must still address an important question about the dataset – the apparent outlier Elysium Mons. What is perhaps most confusing about this problem is that even though Elysium Mons appears to be an outlier, its two sister Volcanoes, Albor and Hecates Tholus follow the general trend observed. The answer could lie in the concept of secondary cratering flux. Nowhere else were so many secondary streaks of crater chains observed, as such, perhaps Elysium simply happens to be a statistical fluke in which this flux is more important then the extramartian flux.

5.3 Elysium Mons: Evidence?

There is another peculiarity between the three peaks of Elysium: neither of the two sister peaks were formed at the same time as Elysium Mons. This seems odd for three volcanoes so close together on the same volcanic center. A possible solution however, lies in the sequence of the three. The oldest is Albor at 2888 followed by Elysium at 2137 and finally Hecates at 1662 (in arbitrary tau units). Also, Albor is the furthest South, Elysium next and Hecates in the North. Since the spatial and temporal sequences are the same, this suggests that the three might have formed over a hotspot migrating North with respect to the surface.

This situation is analogous to that of many ocean chains such as the Hawaiian islands in which a plate is in motion over an assumed steady hotspot. Is this then evidence for plate tectonics on Mars? It cannot be determined – it could be that the hotspot moved under a stationary crust or that the entire crust of the planet moved as a unit over a stationary hotspot – the truth is likely somewhere in the middle.

This observation does, however, warrant asking whether there are other observed trends in other volcano chains on Mars. The most obvious potential is the three in a row sequence of the Tharsis rise: Arsia, Pavonis and Ascraeus Mons from the southwest to northeast. Here we find that the first to form, according to the crater counts derived, was Pavonis, the middle feature at 721 followed by Ascraeus and Arsia at roughly the same time (567 and 506 respectively). As such, this does not appear to support the hypothesis of a single mobile hotspot, however, the creation of this volcanic chain occurred at only a third to a fourth as long ago as Elysium according to the derived crater counts.

5.4 A Changing Lithosphere?

This leads to the most fundamental question posed by the data: why should it have the form of decreasing height with time at all?

The explanation favored by Carr was that as the planet cooled, the lithosphere became thicker[1] – thus the hydraulic head available to drive magma to the surface increased with time. This line of reasoning is supported by evidence from Venus where Keddie and Head[8] have found evidence from Magellan Data that the largest volcanoes (edifice height) are built upon the highest terrain and thus the thickest elastic lithosphere (neglecting dynamic means of support). There is also strong support for the hydraulic hypothesis in the shape of the volcanic edifice above the magma chamber[9] and in terrestrial subduction zone volcanoes which exhibit interesting height concordance properties in their own right[7].

A secondary effect of a changing lithospheric thickness is an increase in the effective elastic thickness. As such, it is also possible to build a taller structure which will take longer to relax where the lithosphere is thicker.

6. Future Work

As mentioned in the discussion section, there are several avenues open for future research on this topic. First, a more complete crater count could be conducted by examining the entire area of each feature instead of simply taking a representative sample. Additionally, the crater binning could be extended in both directions to larger and smaller sizes using MOC regional and high resolution captures – this would be especially useful in resolving the dispute between the two counts as to the absolute age of the features being examined.

As such, a determination of the flux constant k would also be beneficial, however, this is unlikely to occur until in-situ measurements are made on the Martian surface either by sample return or by robotic analysis.

An extended and improved dataset of this kind could then be compared to volcano summit elevations on earth and the corresponding depth of melting, that is, the effective lithospheric thickness at the volcanic centre. This could be used to determine a paleothickness of the Martian Lithosphere to determine if and when plate tectonics might have been active on the body. Furthermore the current elastic thickness of the lithosphere from free-air gravity anomalies could be compared to similar measurements for the earth.

7. Conclusions

By using recent MOLA and THEMIS data it was possible to update and extend the work of Carr and calculate ages and heights for Volcanoes on Mars. It was found from this analysis that the older a martian volcano the less elevated is its summit and the shorter is its volcanic edifice with the exception of Elysium Mons. However, the absolute age appears to have changed from the 1976 data by an order of magnitude and may in fact be model dependant. The data for any one feature show a great deal of skatter which must be addressed before any definitive conclusions may be reached. However, the data suggest that the planet's lithosphere may have thickened in the past, potentially as the result of planetary cooling. As well, a potential instance of relative motion between the crust and the mantle was discovered at the Elysium rise.

8. References

[1] M. Carr (1976) "Change in Height of Martian Volcanoes With Time." *Geologica Romana* v.15 pp.421-422.

[2] United States Geological Survey (2003) *Gazetteer of Planetary Nomenclature*. Available online at: http://planetarynames.wr.usgs.gov/mars/marsTOC.html.

[3] Mars Orbiter Laser Altimeter *public release data* (2003) Available online at: http://marsoweb.nas.nasa.gov/MOLA/index.html.

[4] Mars 2001 Odyssey Thermal Emission Imaging System *Visual Archive public release data* (2003) Available online at: http://themis-data.asu.edu

[5] D. Kring (2003) *PTYS 511 Course Notes.* University of Arizona Press.

[6] H.J. Melosh (2003) *PTYS 554 Course Notes.* As transcribed by the Author.

[7] Z. Ben-Avraham and A. Nur (1980) "The Elevation of Volcanoes and Their Edifice Heights at Subduction Zones." *JGR* v.85 no B8 pp. 4325-4335.

[8] S.T. Keddie and J.W. Head (1994) "Height and Altitude Distribution of Large Volcanoes on Venus." *Planetary Space Sciences* vol 42 no 6 pp. 455-462.

[9] A Lacey et al (1981) "On the Geometrical Form of Volcanoes." *Earth and Planetary Science Letters* vol 54 pp. 139-143.

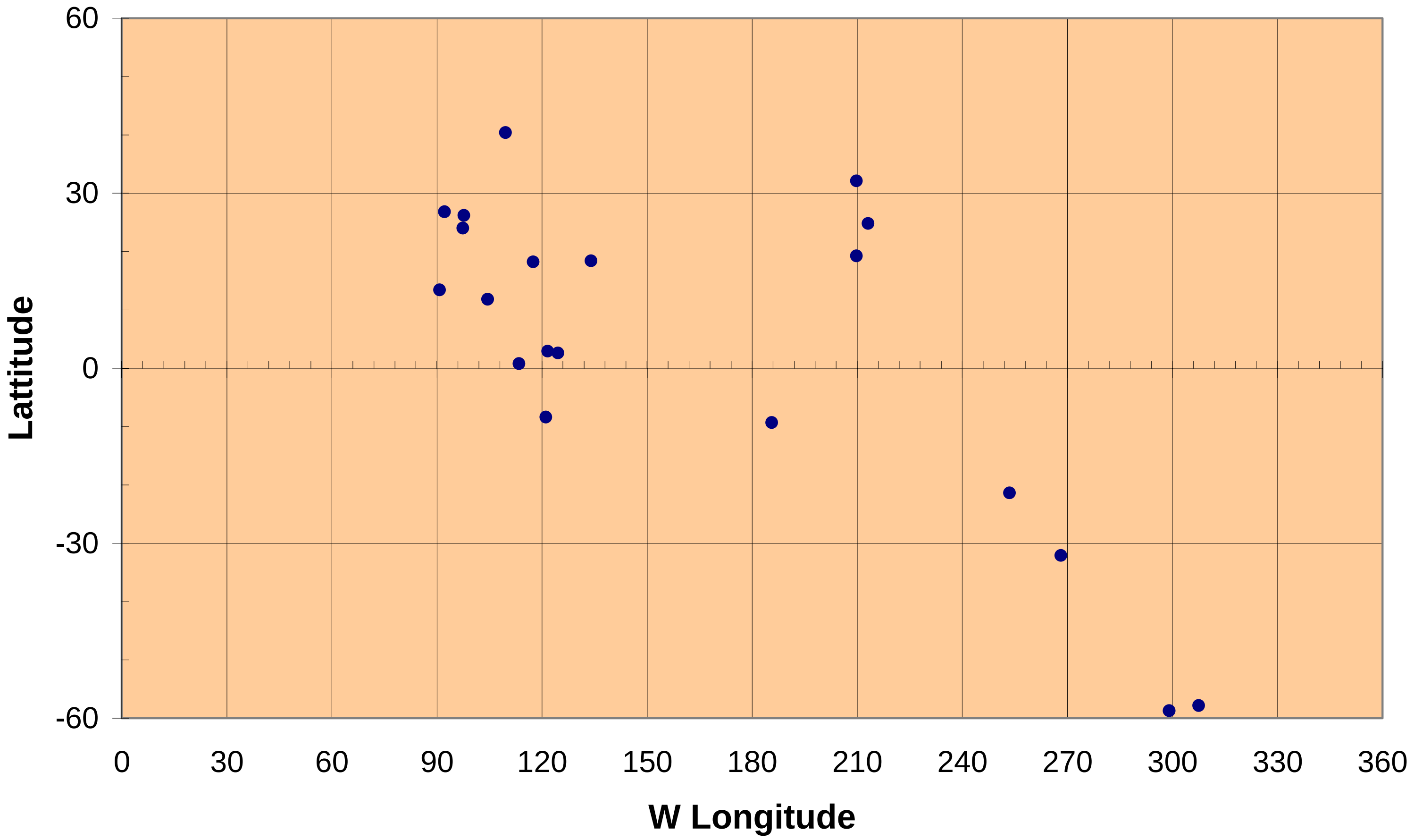
APPENDIX A

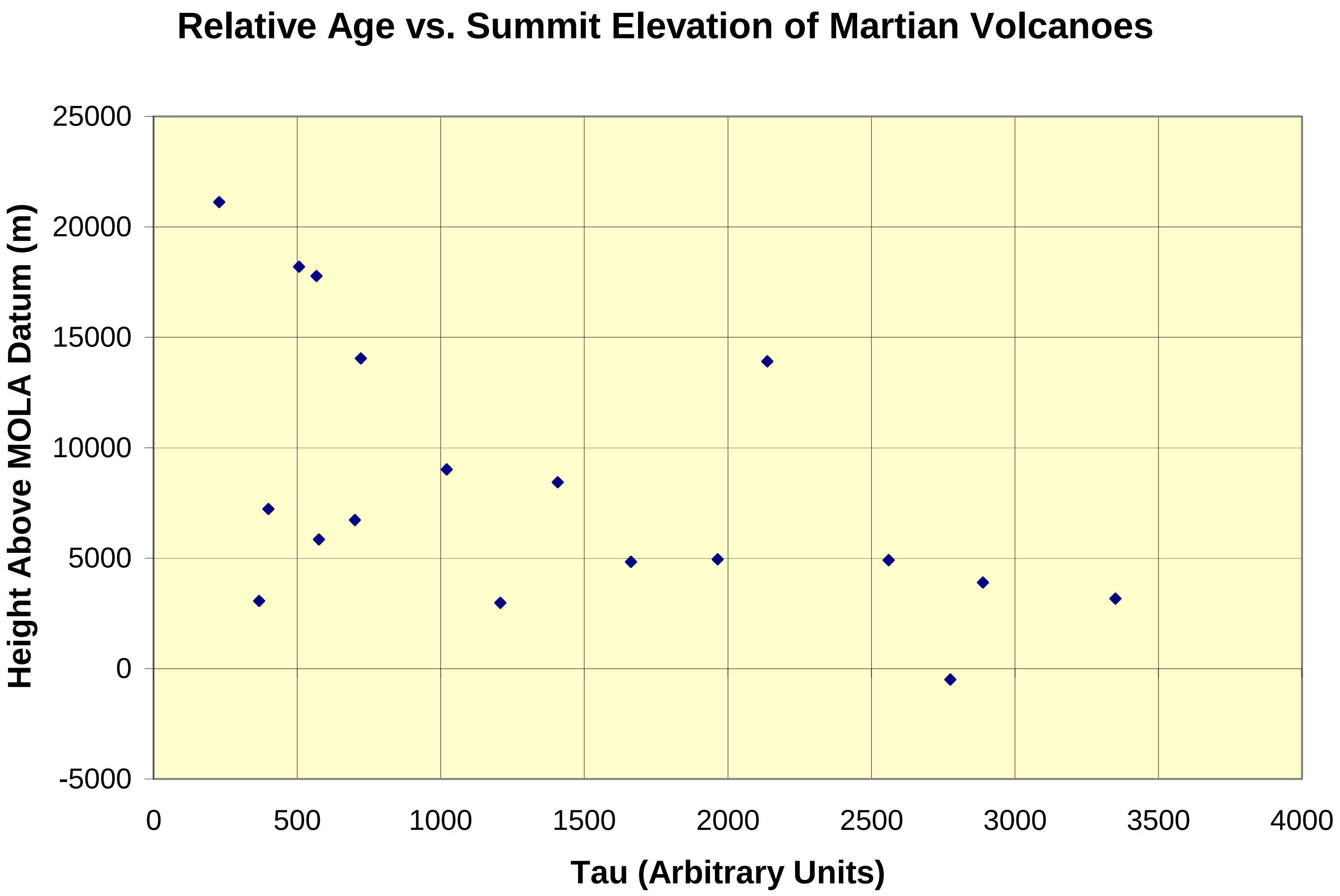
Contents: Graphical

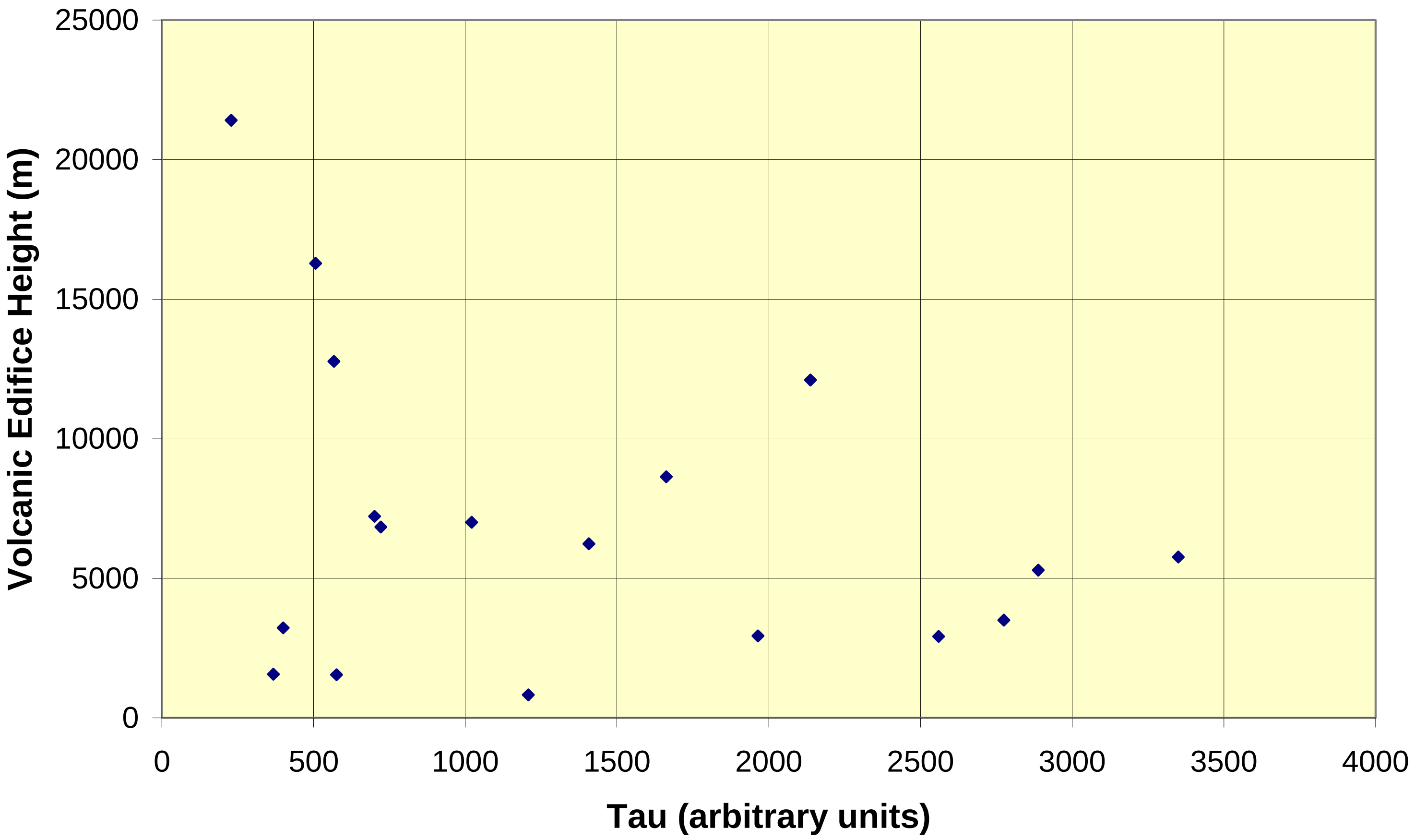
APPENDIX B

Contents: Tabular

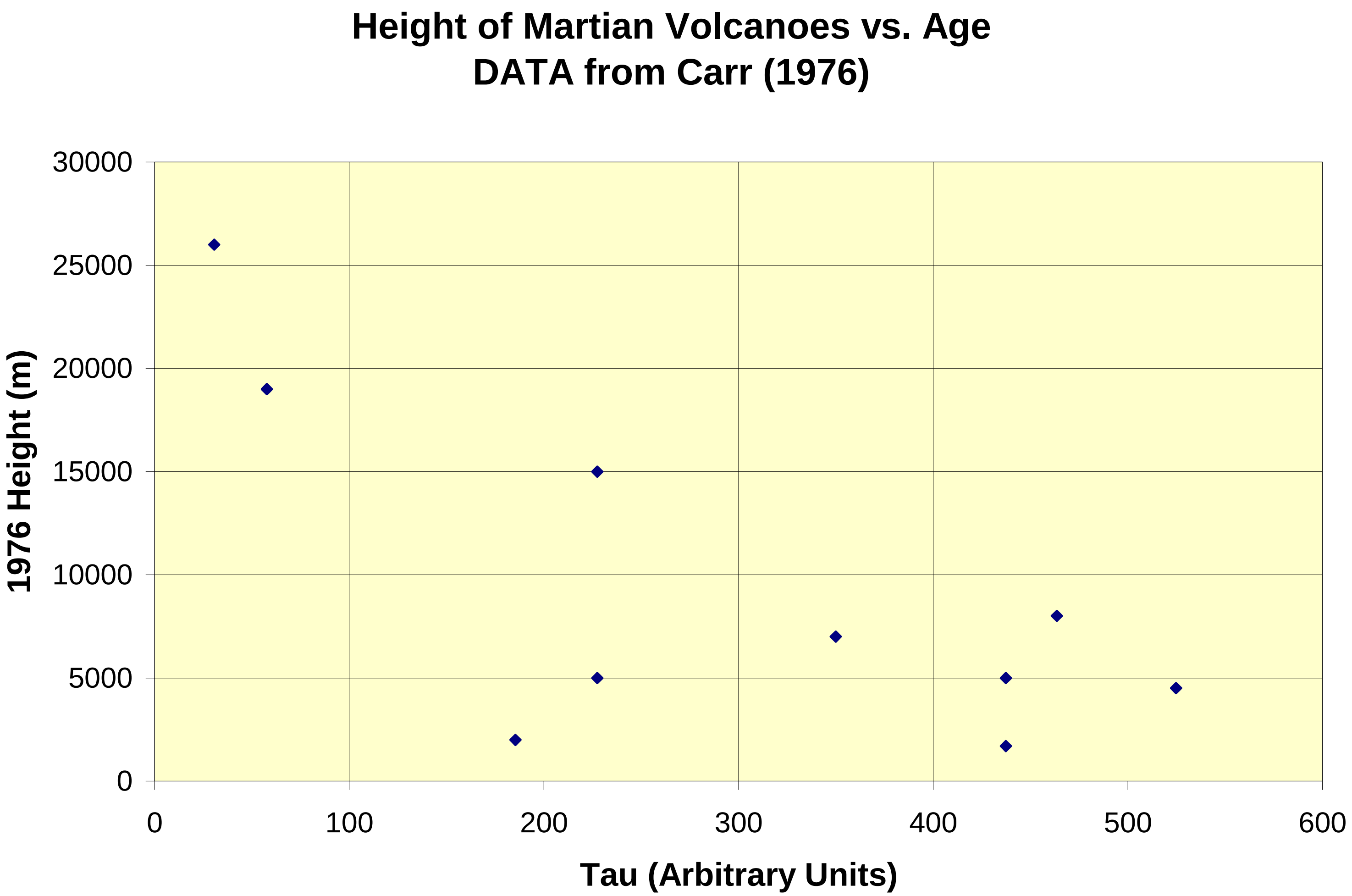
Locations Of 21 Large Volcanic-Type Features on Mars




Relative Age vs. Summit Elevation of Martian Volcanoes
Height Above MOLA Datum (m)
25000
20000
15000
10000
5000
0
-5000
0
500
1000
1500
2000
2500
3000
3500
4000
Tau (Arbitrary Units)



Relative Age vs. Edifice Height of Martian Volcanoes


Height of Martian Volcanoes vs. Age
DATA from Carr (1976)
1976 Height (m)
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
Tau (Arbitrary Units)