EPISODICITY IN THE GEOLOGICAL EVOLUTION OF MARS: RESURFACING EVENTS AND AGES FROM CRATERING ANALYSIS OF IMAGE DATA AND CORRELATION WITH RADIOMETRIC AGES OF MARTIAN METEORITES.

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Introduction: In early attempts of understanding the time-stratigraphic relationships on the martian surface by crater counting techniques and principles of stratigraphic superposition, most of the geological units and constructs came out as being rather old, in the range of billions of years; a notable exeption was the Tharsis province, whose volcanoes were believed to be, at least partly, relatively young (hundreds of millions of years) [1-10]. On the other hand, most of the ages of the martian meteorites cluster at relatively young values of around 175 m.y., 300-600 m.y. and ~ 1.3 Ga, whereas very few old ages >3 Ga had been found [20,21].

Although there was no a priori contradiction in terms of total age range measured through either method, crater counting on Mars imagery and isotopic dating of martian meteorites, there appeared to be an inconsistency with respect to frequency of occurrence of ages: If most of the martian surface is old as deduced from remote sensing cratering data, then most martian meteorites should show old ages; the surface area of Tharsis was not sufficient to make an appreciable difference towards a substantially higher frequency of young meterorite ages.

The early cratering age data were based on post-Viking image data analysis. With the new data from MGS (MOC) [11], MEX (HRSC) [12,13], and Mars Odyssey (THEMIS) [14], it has become clear by now that the apparent discrepancy between the two age sets and the predominance of old ages was a selection effect due to the limited Viking resolution showing predominantly large, old features. Ages as young as a few 100s, a few tens or even a few million years have been determined since on the basis of the new high-res imagery with spatial resolutions in the meter to tens-of-meters range [15-19]. It has become clear therefore by now, that there is no basic discrepancy with respect to the age ranges and occurrence of age groups per se. Neukum et al. [18] could even show that there exists at least one cratering-age group (~ 180 m.y.) frequently found on Tharsis which

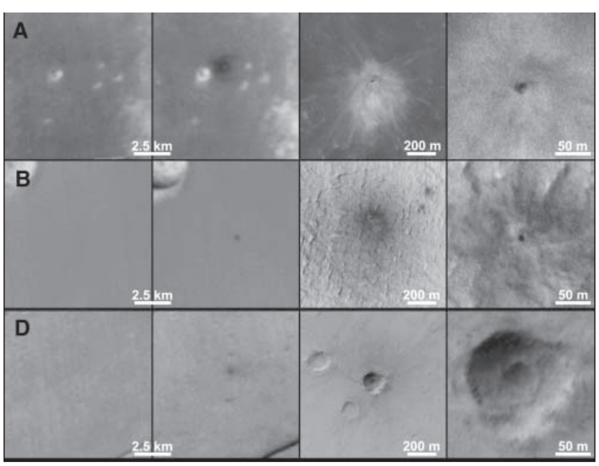

Fig. 1a: Examples of recent impacts on Mars (from: Malin et al. 2006): First Column: Before impact, Second Column: after impact (Both: MOC WA), Third Column: MOC NA Image, Fourth Column: Close-up image of impact site.

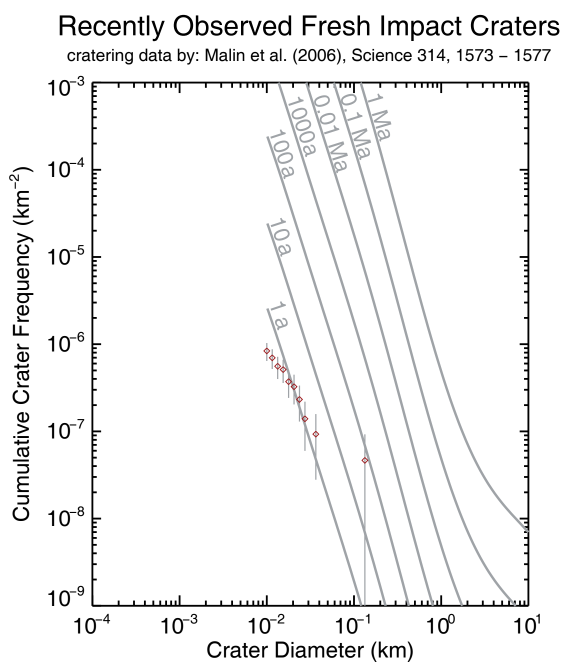

Fig. 1b: Isochrons according to Hartmann and Neukum (2001), Martian size-frequency distribution by Ivanov (2001).

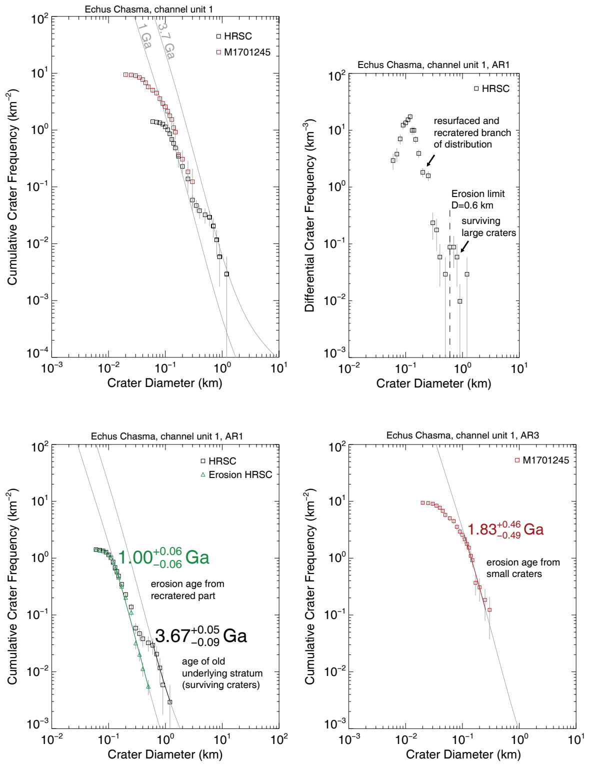

Fig. 2: Examples of measurements showing characteristic resurfacing effects.

directly corresponds to an equivalent age group found in the martian meteorites. Nevertheless, although all ages found in the martian meteorite age groups [20,21] are also found even in the new high resolution imaging data as individual cratering ages in terms of values scattered across the martian surface [19], a strong peaking (apart from the 180 m.y. peak) in direct relation to the ages of the martian meteorites was not found (with the exception of the ancient volcanic activity around 3.5 Ga ago [19]). On the other hand, it appears very unlikely to find strong peaks in martian meteorite ages if such processes leaving their age marks were not very widespread on the martian surface over large areas.

The ages have been determined by way of applying the Hartmann & Neukum cratering chronology model [17]. McEwen et al. [28] maintained based on their secondary cratering hypothesis that the Hartmann & Neukum chronology model is wrong by up to 3 orders of magnitude. As shown by Neukum [6] and more recently in great detail by Werner [19], the small craters are predominantly primary impact craters and not secondaries from large primaries. This has been confirmed by Malin et al. [9] by way of direct measurements on MOC imagery of the numbers and impact rates of craters in the 25m-100m size range over a < 7 year age period. These data are displayed in Fig. 1 and show remarkably

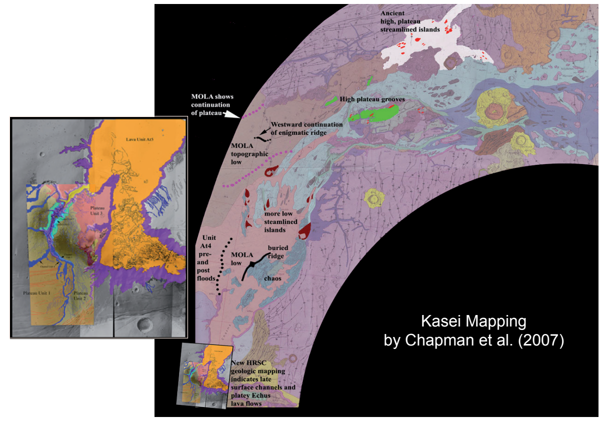

Fig. 3: Geological Maps of Echus Chasma and Kasei Valles from Chapman et al. [23].

good agreement with isochron values as obtained from the Hartmann & Neukum cratering chronology thus confirming its correctness and validity.

Areas investigated, measurements: We reported on first preliminary results from investigation of a combination of HRSC and MOC imagery previously [22] where we believed to have seen peaks of activity temporally coinciding with martian meteorite age groups. We have now been able to investigate a much higher number of areas and have in particular mapped out and analyzed for their geologic evolution and cratering ages two large outflow channel areas, Echus Chasma/Kasei Valles [23] and Mangala Valles [24]. In both areas we have found multistage geological histories with mixed volcanic, fluvial, glacial, and hydrothermal activity. The new data in combination with the previous data have been analyzed by way of a refined method of cratering age extraction also giving fine details of periods of resurfacing from the characteristics of the measured crater size-frequency distributions as they deviate from the production size-frequency distributions due to resurfacing effects. This method was in a rudimentary form already applied by [5], refined by [19], and again refined in the course of the work presented here. In Fig. 2, examples of measurements showing such characteristic resurfacing effects and the way of extracting resurfacing ages is shown. As here, most martian crater size-frequency distributions do not follow the relatively steep production distributions at smaller crater sizes but show kinks and flatter distribution characteristics due to resurfacing and recratering events. There are only very few notable exceptions where the production function can be measured directly. This particular issue with the reconstruction of the function in pieces and for the few direct measurements of the undisturbed function over a larger size range has been treated by [19] and the function put forward by Neukum and Ivanov [e.g.

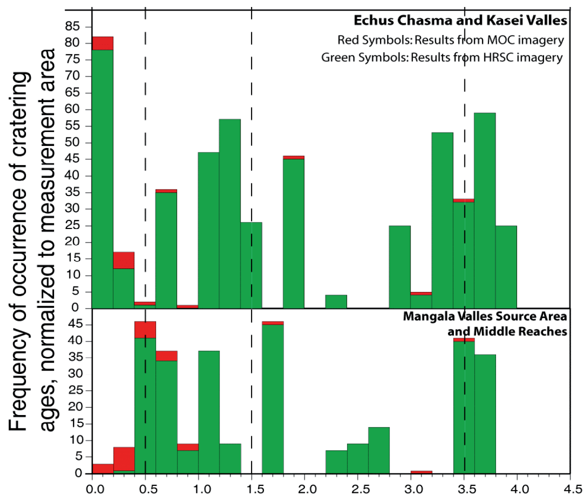

Fig. 4: Histogram of ages extracted from measurements on HRSC (green) and MOC (red) imagery in the Echus Chasma/ Kasei Valles and Mangala Valles. HRSC-related values normalized to size of counting area.

6,17,18,25-27] has been confirmed in all aspects. This function is used in Figs. 1 and 2 in the way of isochrons for individual surface ages based on the Hartmann and Neukum [17] chronology.

Episodicity in the geologic evolution of the martian surface: In order to arrive at a clear-cut unambiguous result, it is absolutely necessary to map out geologic units with clear boundaries. The Echus Chasma/ Kasei Valles geologic map as one of the two contiguous type areas treated here is given in Fig. 3. Measuring across boundaries of geologic units may lead to ambiguities in the age determination due to mixed-area crater frequency contributions at different crater sizes or erroneous areal normalization. We are confident to have avoided major blunders, but also are aware of some residual effects washing out the age signatures in terms of 100-200 m.y. uncertainty. In Fig. 4 we have compiled all our results of detailed age extraction in two large contiguous areas, Echus/ Kasei and Mangala. The Mangala area was particularly critical, and the time resolution for the younger ages therefore is a bit inferior to the Echus/Kasei results.

The cratering age measurements show, despite all possible imperfections of the geologic mapping process and resurfacing age extractions that practically all surface units looked at have experienced multiple events of resurfacing throughout martian history, partly until very recently. This is in agreement with our former findings in more limited areas on Tharsis [18].

In Fig. 5 the dating results for Echus/Kasei and Mangala substantiated with a number of additional measurements on geologic constructs from all over the martian surface are compiled. All the ages from cratering measurements are compared with the radiometric ages of the martian meteorites [21]. There is a striking appearance of peaking of the geological activity or episodicity of resurfacing at certain times: ~3.5 Ga, 1 to 1.5 Ga, 300 to 600 m.y., ~200 m.y. ago, respectively. Even more striking is that within relatively narrow limits, the cratering ages of the different age groups fall together with the age groups of martian meteorites. The martian meteorite ages reflect both igneous events and aqueous alteration events. So do the cratering ages. There is a remarkable paucity of age occurrences in the 2-3 Ga age range in the cratering data. This corresponds to a paucity of meteorite ages in the same, even somewhat more extended age range. This appears to be a hint to either lower geologic activity in this time frame, or, more likely, the covering up of more ancient activity by subsequent events <2 Ga ago, with the exception of the residues from the time >3 Ga ago (the peak at ~ 3.5 Ga) when the martian surface was thoroughly shaped at a very high level of activity by gigantic volcanic, fluvial, and glacial events which could not be completely erased by later events but most always show up in the cratering data in terms of the large-crater survivors of the tail end

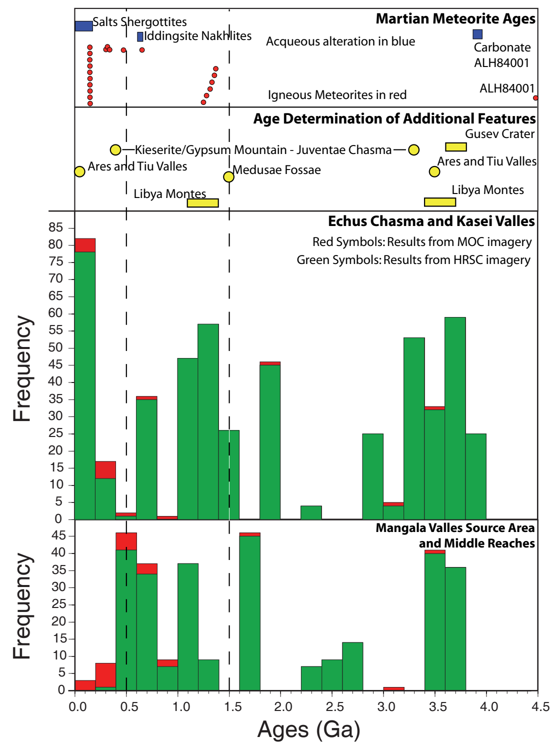

Fig. 5: Histogram of ages extracted from measurements on HRSC and MOC imagery in the Echus Chasma/Kasei Valles and Mangala Valles combined with cratering age measurements on additional features in comparison with known radiometric ages of martian meteorites (from [21]).

of the distributions.

Conclusion: We can demonstrate, that there has been geologic activity on the martian surface in terms of volcanic, fluvial, glacial, hydrothermal activity at all times from >4 Ga ago until today. This activity must have declined in magnitude through time. This activity was not continual but episodic. The episodes we find on the martian surface in the crater frequency analyses are remarkably well coincident with the age groups of the martian meteorites found from radiometric dating. A very consistent picture of the evolution of the martian surface is shaping up in the comparison of two data sets of very different origin, telling us that Mars was geologically utterly active until 3-3.5 Ga ago but later has been resurfaced at a lesser and lesser rate making possible to identify different episodes of activity in many areas. The former apparent discrepancy between the apparent "youthfulness" of martian meteorite ages and the old-appearing surface of Mars was an artifact from insufficient spatial resolution of the Viking imagery.

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