Why Mars may have a higher ratio of intrusive to extrusive magmatism than Earth. B.A. Black[1] and M. Manga[2], [1]Department of Earth and Atmospheric Science, City College, City University of New York, New York, NY 10031 (bblack@ccny.cuny.edu), [2]Department of Earth and Planetary Science, University of Calfiornia, Berkeley, CA 94720 (manga@seismo.berkeley.edu).

Overview: Magnetic and geologic data indicate that the ratio of intrusive to extrusive magmatism (the I/E ratio) is higher in the Tharsis and Syrtis Major volcanic provinces on Mars relative to most volcanic centers on Earth. The fraction of magmas that erupt helps to determine the effects of magmatism on crustal structure and the flux of magmatic gases to the atmosphere, and also influences estimates of melt production inferred from the history of surface volcanism [e.g., 1-3].

We consider several possible controls on the prevalence of intrusive magmatism at Tharsis and Syrtis Major, including melt production rates, lithospheric properties, regional stresses and strain rates, and magmatic volatile budgets. To erupt, overpressure (and the accompanying stresses around the magma chamber) or buoyancy must be sufficient to promote failure of the surrounding rocks and permit dikes to propagate to the surface. In the limit that viscous relaxation quickly alleviates lithospheric stresses from changes in magma volume, loading and regional tectonics, buoyancy from volatile exsolution during decompression or second boiling controls eruptibility [e.g., 4-6].

We develop a one-dimensional model for the development of overpressure and buoyancy that accounts for recharge, cooling, crystallization, volatile exsolution, bubble coalescence and rise, fluid egress, and compaction of country rock. Under these conditions, we find that initial water and CO_2 contents typically <1.5 wt % can explain the observed range of intrusive/extrusive ratios. Our results support the hypothesis that warm crust and a relatively sparse volatile budget encouraged the development of major intrusive complexes beneath Tharsis and Syrtis Major.

Intrusive/Extrusive ratios: Even on Earth, calculation of I/E ratios carries substantial uncertainties [7-8]. Nevertheless, some generalizations are robust: a ratio of 5:1 is a fair approximation for most magmatic systems [8]. On Mars, crustal remanent magnetism provides one of the best records of intrusive activeity [e.g., 9]. Analysis of Tharsis suggests ratios of 10-20 [10] and possibly much larger [11]; at Syrtis, values between 10-100 have been inferred from demagnetization [9].

Model: We use a one dimensional model to study the thermal and buoyancy evolution of intrusions in the crust. The model solves for vertical transport of heat, including the effects of latent heat; crystallinity and density are computed with MELTS [12]. We account for the exsolution of gas and the ascent and loss of gas through permeable roof rocks. Details and equations are provided in [13-14].

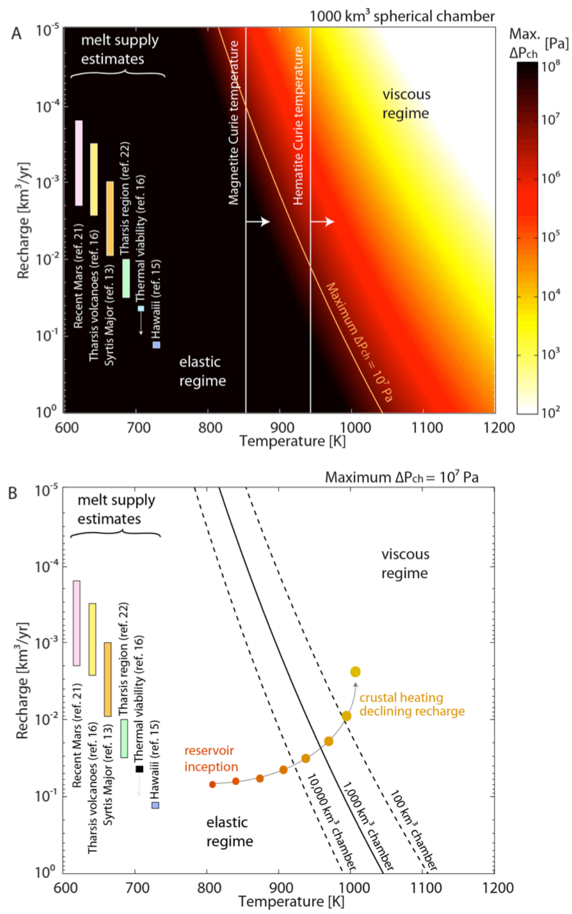

Figure 1: Controls on the maximum chamber overpressure for a spherical chamber, and estimates of melt production on Mars (from long-term averages, recharge rates required to build individual Tharsis volcanoes, and minimum recharge required for magma chamber viability). A) Recharge and wall rock temperature control the transition between elastic and viscous regimes in a 1000 km³ magma body. Curie temperatures give a mineralogy-dependent lower limit on crustal temperatures attained during magmatism. B) For a given recharge and wall-rock rheology, chamber volume determines whether the maximum overpressure will be sufficient to cause eruption. Colored circles represent a conceptual trajectory for the evolution of a magmatic episode. Adapted from [13].

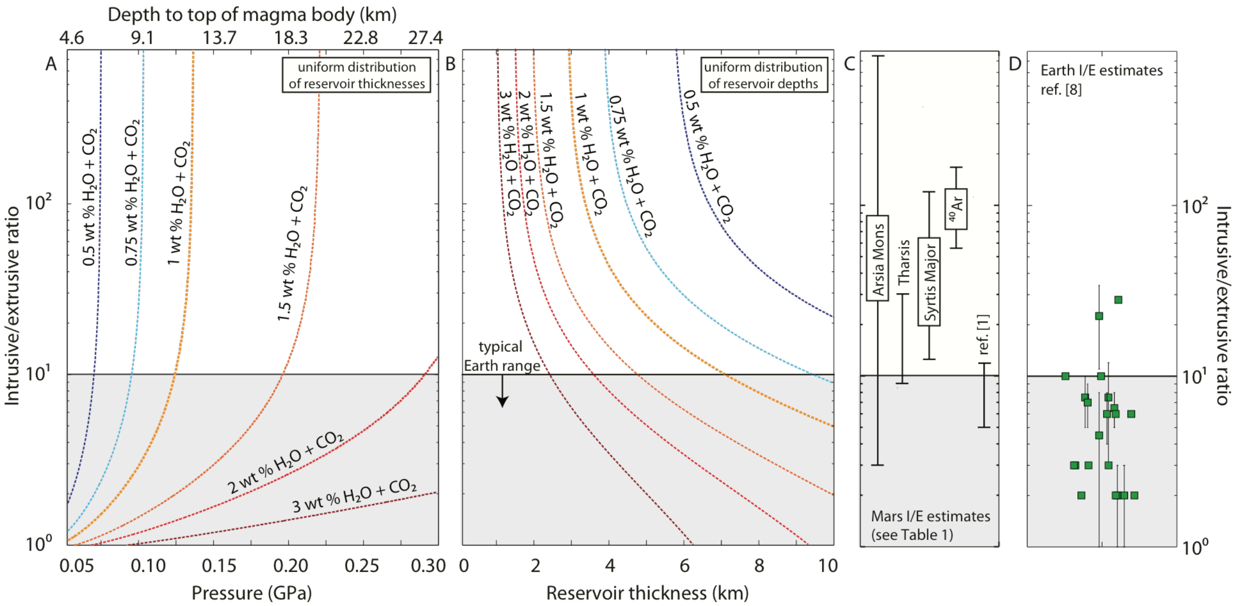

Figure 2: Intrusive/extrusive ratios on Mars as a function of initial volatile contents. A) for a given volatile content and chamber depth, assuming a uniform distribution of chamber thicknesses (between 0.1 and 10 km); B) for a given volatile content and chamber thickness, assuming a uniform distribution of chamber depths (between 0.05 and 0.30 GPa, which on Mars correspond to depths of approximately 5 and 27 km respectively). C) Intrusive/extrusive ratios on Mars from published estimates (see Table 1 for details and references). D) Intrusive/extrusive ratios on Earth, from [8]. In panels C and D the I/E ratios are spread along the horizontal axis to increase legibility. Adapted from [13].

Why buoyancy overpressure dominates: Magma bodies develop overpressure from exsolution and as fresh magma recharges the magmatic system. These overpressures decay at a rate controlled by wall rock viscosity [15]. Figure 1 shows that large magma bodies and Martian recharge rates (lower than those on Earth) lead to magma bodies being in the viscous regime in which elastic overpressures have relaxed – eruption then requires buoyancy overpressure [4,6].

Buoyancy in magma chambers in a mafic crust will be dominated by volatile exsolution and when exsolution outpaces permeable escape of exsolved volatiles: thicker magma bodies and greater volatile contents thus favor eruptibility (and hence lower I/E ratios). Figure 2 shows model predictions for the limit that all volatiles rise to the top of the chamber and do not escape – this provides a lower bound on the implied I/E ratio – assuming that the entire chamber erupts when buoyancy overpressure exceeds 10 MPa (the approximate tensile strength of rock).

Conclusions: We conclude that the thick lithosphere, crustal heating, and limited quantities of magmatic water and CO_2 [17-19] are among the most important factors in the suppressed eruptibility of Tharsis and Syrtis Major magmas. A limited water and CO_2 budget in most Martian magmas implies that SO_2 or other greenhouse gases are required to link volcanism to clement surface temperatures on early Mars [18,20].

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