CONTROLS ON MAGMATIC EXTRUSIVE:INTRUSIVE RATIO ON EARTH AND MARS. W. Degruyter[1], C. Huber[2], J. W. Head[2], and O. Bachmann[3], [1]Cardiff University (Main Building, Park Place, Cardiff, CF103AT, UK, degruyterw@cardiff.ac.uk), [2]Brown University (324 Brook street, Providence, RI 02912, USA; christian_huber@brown.edu and james_head@brown.edu), [3]ETH Zurich (Clausiusstrasse 25, 8092 Zurich, Switzerland; olivier.bachmann@erdw.ethz.ch).

Introduction: Magmatic processes are playing an important role in chemical differentiation and volatile delivery to planetary surfaces. On Earth, tectonics controls, to a large extent, the fraction of magmas that reach the surface above the solidus (extrusive) versus the fraction of intrusive rocks that outgas at depth. For instance, at mid ocean ridges the extrusive to intrusive ratio approaches 1:3, whereas in continental arcs it is believed to be often smaller than 1:10 [1-3]. On Mars, it is suggested to be even smaller down to 1:100 [4-6]. Although volcanic and plutonic series both outgas efficiently, the processes, rates and composition of the associated volatile flux differ depending on the pressure at which outgassing takes place. Determining the fraction of the magma that accumulates in the crust and later erupts to the surface is therefore key to assess how tectonics impact the production and composition of volatiles released from deeper planetary reservoirs to the surface.

The extrusive:intrusive ratio remains poorly constrained on Earth and Mars, because of the lack of accurate constraints on melt production and delivery from the mantle to the crust. For these reasons, published estimates [1-6] are plagued with large errorbars and we have limited understanding of the factors (geothermal gradient, magma composition, volatile solubility, regional stress conditions…) that influence it.

Contrasting Earth to Mars, we expect widely different extrusive:intrusive rock ratios because of the differences in tectonic regime and gravitational acceleration. First, tectonics influences the primary magma composition as well as thermal gradients in the crust which impacts the rheological response of magma reservoirs to magma recharges. Second, the difference in gravitational acceleration influences the pressure-depth relationship and by extension the thermal environment around the reservoir as well as the buoyancy of magmas. The question we focus on is: how do the different conditions on Earth and Mars [7,8] influence the overall probability of melts produced at depth to rise to the surface?

Methods and Results: A quantitative attempt to address this question requires a model of magma reservoirs that includes (1) magma recharge events, (2) viscoelastic coupling with the surrounding crust, (3) cooling to the surrounding crust which induces crystallization, possibly volatile exsolution and volatile outgassing and (4) mass withdrawal due to diking/eruptions. We have developed a model that involves all these feedbacks and that was applied to arc magmatism on Earth [9,10]. We found that eruption frequency, which indirectly controls the extrusive:intrusive magma ratio, is governed by the competition between the time required for cooling the reservoir below the solidus, the viscoelastic response of the crust (depends on the temperature around the reservoir) and the rate of magma recharge (see Figure 1). Our model highlights that mechanical feedbacks have a large influence on the rate and volume erupted, factors that would be discarded from thermal models [6].

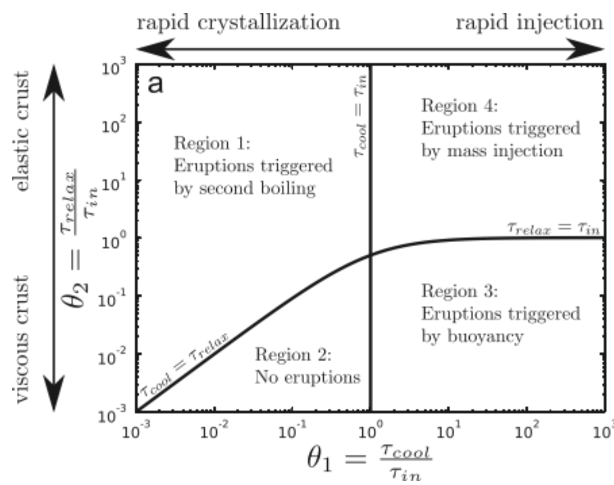

Figure 1: Regime diagram for eruption trigger at a fixed recharge rate. Modified from [9].

We expanded on the model to now compute the fraction of magmas that are able to reach the surface before solidifying during diking events propagating out of the reservoir. We estimate the mass erupted by considering only the mass extruded from the chamber while the excess pressure in the reservoir is great enough to drive magma to the surface before solidification. This allows us to compute extrusive:intrusive ratios and to quantify the influence of various factors such as the magma composition, recharge rate, crustal thermal gradients, regional stress conditions and gravitational acceleration.

We ran simulations to compute the extrusive to intrusive ratio for conditions typical of Earth for a reservoir at 200 MPa (~7.5 km depth) over a range of recharge rates (see blue trend in Figure 2). All simulations shown in Figure 2 display the extrusive:intrusive ratio before the reservoir reaches a critical crystal volume fraction of 0.5 (rheological locking point), above which the magma becomes too stiff to erupt. The simulations on Earth are compared to two cases relevant to Mars, one at the same depth (7.5 km) in yellow and one at the same pressure of 200 MPa (22 km depth) in orange. Because of the lower average thermal gradients on Mars, the 7.5 km reservoir is surrounded by a colder and less compliant crust (favors more eruption), while the 200 MPa simulation is deep and hosted in a hotter more viscous crust. The extrusive:intrusive ratio values plotted in Figure 2 are upper bounds, as they discard the mass balance beyond 0.5 crystal volume fraction, where eruptions are less likely.

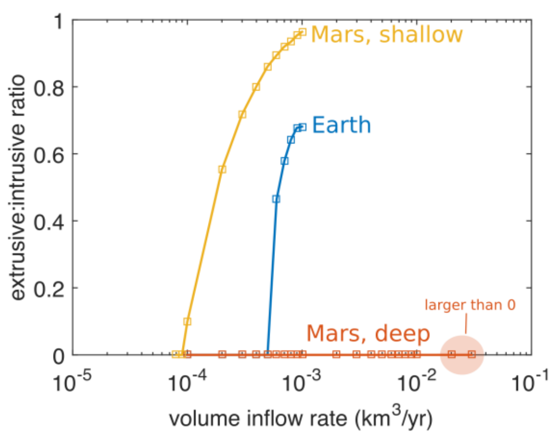

Figure 2: Extrusive:intrusive ratio calculated for various volume inflow rates. The ratios are computed up to the locking point where the reservoir reaches 50% vol. of crystals. The conditions are 200 MPa, 7.5 km depth, 0 ºC at the surface and a geothermal gradient of 30 ºC/km for Earth. The shallow Mars system is at 7.5 km depth and 75 MPa, the deep Mars system is at 22 km depth and 200 MPa. In both cases surface temperature is -40 ºC and the geothermal gradient is 15 ºC/km.

Conclusions: The typical depth of the upper crustal magma reservoirs on Earth is often controlled by the pressure at which water exsolves from magmas. Therefore, the thermal environment at 200 MPa exerts a strong control over the extrusive:intrusive ratio on Earth. On Mars, we consider two endmember cases where the reservoirs feeding eruptions is located at depths comparable to Earth (between 7 and 10 km) or at a pressure comparable to Earth (more than 20 km deep). These two scenarios yield a significantly different response with respect to extrusive:intrusive ratios. The shallow depth case (7.5 km) leads to an erupted fraction similar to arcs on Earth, while the second case (200 MPa) results in a minute fraction of magmas reaching the surface unless much greater magmatic fluxes are considered.

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