ASSIMILATION-FRACTIONAL CRYSTALLIZATION ON MARS AS A FORMATION PROCESS FOR FELSIC ROCKS.

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Introduction: The crust of Mars was long thought to mostly be composed of tholeiitic basalt, but recent findings in Gale Crater have shown that the crust is compositionally diverse [1,2]. Felsic (> 55 wt.% SiO_2) Gale Crater targets are likely the product of intraplate magmatic fractional crystallization [2–5]. Gale crater alkaline rocks, such as the igneous component for Jake_M (a sedimentary rock), are thought to be the product of high degrees of fractional crystallization from a metasomatized source at high pressures [3,4].

Although recent studies [2] showed that felsic rocks at Gale Crater could be formed through fractional crystallization, some discrepancies exist in these results, as some observed Gale Crater felsic rocks could only occur under high degrees of fractionation (>60%), when melt is difficult to remove from accumulated solids. Assimilation is a very common magmatic process on Earth to form evolved rocks. However, assimilation and fractional crystallization (AFC) processes involving the assimilation of the martian crust have never been investigated for martian magmas. Here we assess the potential role of assimilation in the formation of felsic rocks and, more broadly, martian magmatic evolution with the goal of constraining what processes contributed to crustal diversity on Mars.

Methods: Magma Chamber Simulator (MCS) conducts AFC models through interactions of distinct reservoirs: a magmatic body, a cumulate pile, and wallrock [6]. In MCS AFC models, magma intrudes cold wallrock, and the exothermic process of fractional crystallization (forming the chemically distinct cumulate pile) heats the wallrock until it reaches its solidus and contributes partial melt to the magma (Fig. 1) [6]. Assimilation models end when the wallrock and magma reach thermal equilibrium [6]. All MCS models utilize the MELTS algorithm. We selected Rhyolite-MELTS v.1.0 to best approximate hydrous, silica-enriched magma in low pressure environments [7].

Model parameters and starting compositions. We calculated isobaric models at varying pressures (1, 2, 4, and 6 kbar) to represent depths of the shallow subsurface to the base of the average thickness of the Mars crust [2,8]. The fO_2 in each model was constrained at the Fayalite-Magnetite-Quartz (FMQ) buffer. We used the near-primary magmatic composition of Fastball (observed in Gusev Crater) as the initial magmatic composition, to which we added varying initial water contents (0.07, 0.5, and 1.0 wt.% H_2O) [9,10]. We used the bulk composition of the regolith breccia meteorite Northwest Africa (NWA) 7034 as the wallrock subsystem, because it is our best approximation for the bulk Noachian crust [11]. Wallrock starting temperatures were selected by estimating the temperature at a given depth along an estimated late Noachian-early Hesperian geothermal gradient at Gale Crater of 15 K/km, assuming a surface temperature of 0°C [12].

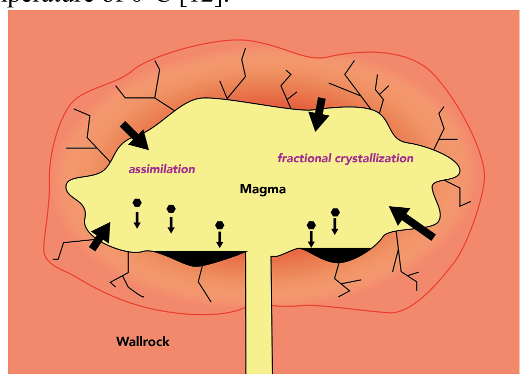

Fig. 1: Schematic of assimilation and fractional crystallization model in the Magma Chamber Simulator.

Model Results: Models at 1 kbar pressure (corresponding to a depth of 8.3 km and wallrock temperature of 125°C) did not begin assimilating wallrock until late in the crystallization sequence when the magma subsystem contains ~ 60% cumulates (Fig. 2). Assimilation in 1 kbar pressures, regardless of the initial water content of the magma, began at cool magma temperatures (~1000°C) and for a short duration prior to thermal equilibrium between the magma and wallrock subsystems, occurring for a span ~50°C. Models at pressures of 2 kbar (17 km, wallrock temperature of 249°C) began assimilation earlier in the evolutionary sequence than in low pressure models at ~30% crystallinity for a duration of ~90°C. Magmas with 0.07 wt.% and 0.5 wt.% H_2O at 4 kbar reached the trachyandesite field at 55% crystallinity. Magmas under pressures of 6 kbar (50 km, 747°C wallrock) resulted in high degrees of assimilation and compositions significantly enriched in alkali elements (Fig. 2). The 6 kbar models began assimilation nearly immediately at ~1500°C, in total occurring over a span of 320°C.

At a pressure of 4 kbar, a 0.07 wt.% H_2O magma reached the Gale Crater target Jake_M [3] at 42% crystallinity, where the magma was within ~1 wt.% of every major oxide (e.g., SiO_2, Al_2O_3, CaO) except FeO, which was estimated ~6 wt.% higher by the model than as observed. At 6 kbar, a 0.07 wt.% H_2O initial magma approached Gale felsic target Harrison 1 [5] composition with 54% solids in the magma. The 6 kbar model, when compared to Harrison 1, underestimated Al_2O_3 by ~7 wt.%, and contained ~4 wt.% more FeO, but is otherwise compositionally similar. At 2 kbar, a magma with an initial 0.50 wt.% H_2O reached a Harrison 2 [5] composition at 54% crystallinity (Fig. 2). The model composition again contained more Al_2O_3 than the target (~4 wt.%) and less FeO (~2 wt.%), but is otherwise similar.

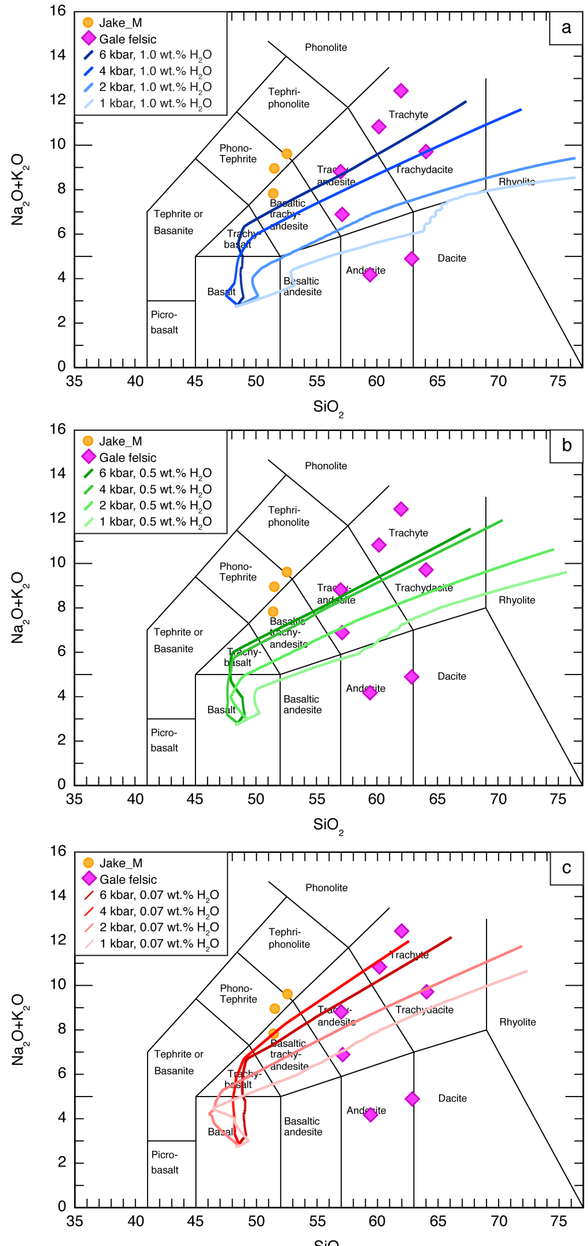

Figure 2 (a): Total alkali versus silica (TAS) diagram of 1.0 wt.% H_2O initial Fastball magma compositions at 1-6 kbar. (b) TAS diagram of 0.5 wt.% H_2O magma compositions at 1-6 kbar. (c) TAS diagram of 0.07 wt.% H_2O magma compositions at 1-6 kbar. Gale felsic compositions [5]; Jake_M compositions [15].

Models at 1 kbar did not begin assimilation until reaching the critical crystallinity of 55% solids, after which point eruption or separation of the liquid is rare and additional evolution is localized [2,4]. An initial magma containing 1.0 wt.% H_2O at 1 kbar approached the observed Gale andesitic compositions only after 60% crystallinity and at the onset of assimilation. The compositional difference between liquid lines of descent of wet, moderately wet, and dry magmas was also more pronounced at 1 kbar.

Discussion: Higher pressures correspond to higher temperatures of wallrock, which when closer to its solidus, melts more readily and assimilates for a longer duration. Thus, the factor that most limits the contribution of crustal assimilation in intraplate magmatism is the initial temperature of the wallrock. Estimates for the martian geothermal gradient range from 6 K/km to 21 K/km, and the martian crust was likely hotter in the Noachian than today [13,14]. Assimilation may have been a prevalent process in the Noachian, contributing to the observed diversity at Gale Crater beginning at crustal depths of 2 kbars (17 km depth) or higher, including rocks like Harrison and the protolith of Jake_M. Lower pressures (1 kbar or below) result in assimilation that occurs only after crystallinity is too high to isolate the residual melt. Thus, subalkaline felsic compositions at Gale Crater may be the result of high degrees of fractionation with limited contribution from assimilation. Alternatively, lesser degrees of assimilated material contributing to the magma subsystem throughout, or using different initial compositions, may reproduce the subalkaline felsic rocks observed at Gale Crater. Beyond the Noachian, as Mars cooled and the crust thickened, assimilation may be limited to magmatic processes occurring at depth, possibly reducing magmatic diversity over time.

Future work will include models using different compositions for the wallrock and magma subsystems. Additional models will account for different starting compositions and initial temperatures for the wallrock in order to adjust for the geothermal gradient.

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