Lithos 254–255 (2016) 36–52

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited review article

Magmatic complexity on early Mars as seen through a combination of orbital, in-situ and meteorite data

Violaine Sautter [a,*], Michael J. Toplis [b], Pierre Beck [c], Nicolas Mangold [d], Roger Wiens [e], Patrick Pinet [b], Agnes Cousin [b], Sylvestre Maurice [b], Laetitia LeDeit [d], Roger Hewins [a], Olivier Gasnault [b], Cathy Quantin [f], Olivier Forni [b], Horton Newsom [g], Pierre-Yves Meslin [b], James Wray [h], Nathan Bridges [i], Valérie Payré [j], William Rapin [b], Stéphane Le Mouélic [d]

[a] IMPMC, Muséum d'Histoire Naturelle de Paris, France
[b] IRAP, Toulouse, France
[c] Institut de Planétologie et d'Astrophysique, Grenoble, France
[d] LPG Nantes, France
[e] Los Alamos National Laboratory, Los Alamos, NM, USA
[f] Laboratoire de Géologie, Université Lyon 1, ENS Lyon, Villeurbanne, France
[g] Institute of Meteoritics, Albuquerque, NM, USA
[h] Georgia Institute of Technology, Atlanta, GA, USA
[i] Applied Physics Laboratory, Laurel, MD, USA
[j] G2R, Nancy, France

ARTICLE INFO

Article history:
Received 4 August 2015
Accepted 26 February 2016
Available online 5 March 2016

Keywords:
Mars
Crust
Alkaline suite
Orbital spectroscopy
Martian meteorites
Rover observations

ABSTRACT

Until recently, Mars was considered a basalt-covered world, but this vision is evolving thanks to new orbital, in situ and meteorite observations, in particular of rocks of the ancient Noachian period. In this contribution we summarise newly recognised compositional and mineralogical differences between older and more recent rocks, and explore the geodynamic implications of these new findings. For example the MSL rover has discovered abundant felsic rocks close to the landing site coming from the wall of Gale crater ranging from alkali basalt to trachyte. In addition, the recently discovered Martian regolith breccia NWA 7034 (and paired samples) contain many coarse-grained noritic-monzonitic clasts demonstrably Noachian in age, and even some clasts that plot in the mugearite field. Olivine is also conspicuously lacking in these ancient samples, in contrast to later Hesperian rocks. The alkali-suite requires low-degree melting of the Martian mantle at low pressure, whereas the later Hesperian magmatism would appear to be produced by higher mantle temperatures. Various scenarios are proposed to explain these observations, including different styles of magmatic activity (i.e. passive upwelling vs. hotspots). A second petrological suite of increasing interest involves quartzo-feldspathic materials that were first inferred from orbit, in local patches in the southern highlands and in the lower units of Valles Marineris. However, identification of felsic rocks from orbit is limited by the low detectability of feldspar in the near infrared. On the other hand, the MSL rover has described the texture, mineralogy and composition of felsic rocks in Gale crater that are granodiorite-like samples akin to terrestrial TTG (Tonalite–Trondhjemite–Granodiorite suites). These observations, and the low average density of the highlands crust, suggest the early formation of 'continental' crust on Mars, although the details of the geodynamic scenario and the importance of volatiles in their generation are aspects that require further work.

Contents

1. Introduction . . . 37
2. Composition and mineralogy of the southern hemisphere as constrained from orbit . . . 37
3. In-situ data . . . 39
4. Meteorite data . . . 43

* Corresponding author at: IMPMC, 61 rue Buffon, 75005 Paris, France.
E-mail address: vsautter@mnhn.fr (V. Sautter).

http://dx.doi.org/10.1016/j.lithos.2016.02.023
0024-4937/

5. Discussion . . . 44
5.1. Mineralogy and petrology of Noachian rocks . . . 44
5.1.1. Mineralogy . . . 44
5.1.2. Petrology . . . 46
5.2. Petrogenesis and some geodynamic implications . . . 46
5.2.1. The alkaline suite . . . 46
5.2.2. Sub-alkaline andesite and granodiorite-like lithologies . . . 47
5.2.3. Chronology of early magmatism on Mars and comparison with the Earth . . . 48
6. Conclusion . . . 48
Acknowledgements . . . 49
References . . . 49

1. Introduction

The chemistry and mineralogy of the Martian surface are increasingly well constrained thanks to a combination of orbital spectroscopy (e.g. Mars Odyssey, Mars Reconnaissance Orbiter, Mars Express), in-situ analyses (landers and rovers such as Pathfinder, Spirit, Opportunity, Phoenix and Curiosity) and study of the Shergottite–Nahklite–Chassignite (SNC) family of meteorites. All of these lines of evidence point to a primary magmatic crust that is globally basaltic, consistent with liquids produced by partial melting of the mantle and transport of those magmatic liquids towards the surface (McSween et al., 2003). Indeed, variations in the composition of Hesperian and Amazonian volcanic terrains as constrained by the Gamma Ray Spectrometer (GRS) instrument onboard Mars Odyssey (Taylor et al., 2006), have been shown to be consistent with liquids produced by partial melting of a mantle that was cooling over time under a lithosphere that was increasingly thick, a set of observations that have been successfully interpreted as the result of global cooling beneath a stagnant lithospheric lid (Baratoux et al., 2011). However, application of this approach to older Noachian terrains is restricted by the fact that there are no unambiguous volcanic provinces of this age that are large enough for study using GRS data (>100 km in size, Grott et al., 2013). Furthermore, early-formed rocks may have been buried under subsequent surface material such as later lavas and alteration products (e.g. Murchie et al., 2009; Mustard et al., 2009). Quantifying the chemical nature of the earliest magmatic crust is thus a significant challenge, in turn complicating the reconstruction of the earliest geological history of the planet, in particular the thermal history of its mantle during the critical period following accretion.

The aim of this contribution is to consider and discuss data obtained over the past ten years, bringing together geochemical and geophysical constraints. In particular, we will concentrate on what is known about the mineralogy and chemistry of the Noachian crust at a variety of spatial scales, from that sampled by the footprint of the GRS spectrometer, down to the hand specimen scale. These data will be discussed with the aim of providing a self-consistent and unified view of the formation of Mars' oldest crust, highlighting novel parallels with what is known about crust-building processes on Earth.

2. Composition and mineralogy of the southern hemisphere as constrained from orbit

Over the last 40 years, orbiting spacecraft have studied the Martian surface at a number of different spatial scales using a variety of remote sensing techniques, each of which provides different but complementary information. Morphologically Mars is characterised by a prominent dichotomy where the heavily cratered southern highlands contrast with a younger low-lying northern hemisphere. In terms of age, the southern highlands are Noachian to early Hesperian whereas the northern lowlands are Hesperian to Amazonian, covering a Noachian basement (Wyatt et al., 2004). In detail, the geologic map of Mars (Fig. 1) shows that the majority of the southern highlands is dominated by terrains that are mid-Noachian in age with a few scattered patchy areas of early Noachian age, while Hesperian terrains are characterised by many large volcanic provinces (e.g. *Hesperia* Planum, Syrtis Major Planum).

In this context the Mars Odyssey Gamma Ray Spectrometer has quantified the concentrations of Si, Fe, Th, K, Cl, and H over a broad equatorial band (±60°) (Boynton et al., 2007), and more recently Ca (Newsom et al., 2007a), Al (Karunatillake et al., 2009), and S (Karunatillake et al., 2014). The depth probed by this technique is typically a few tens of centimetres, having the advantage of avoiding the influence of surface coatings but not eolian deposits. As such, GRS is able to measure regional variations in composition that include a strong contribution from the bedrock (Newsom et al., 2007b). However this method has low spatial resolution (~400–500 km) and thus gives its best results only for large regions that are more or less constant in composition, precluding application to outcrops that are of limited spatial extent. For example, individual craters such as Gale or Gusev that have been the sites of landed missions are sub-pixel features for the GRS instrument. Having said that, it is of note that all provinces identified by GRS are in the range of basaltic rocks and no large unit with evolved lithologies (SiO_2 > 52 wt.%) has been detected (Gasnault et al., 2010; Taylor et al., 2010). A few Th and K 'hotspots' have been observed in regions such as Terra Cimera and Terra Sirenum (Fig. 2), but in the light of the poor spatial resolution, it is difficult to ascertain if this is the result of spatial averaging of complex sedimentary processes or if it is related to regional exposure of igneous bedrock.

There is thus a clear need for study at small spatial scales. In this respect, optical and infrared spectroscopy (i.e. Visible and Near Infrared (VNIR): OMEGA and CRISM, Bibring et al., 2005; Murchie et al., 2007; Thermal IR (TIR): TES and THEMIS; Christensen et al., 2001, 2004) are better suited as these techniques can constrain mineralogy at high spatial resolution (up to 300 m/pixel for OMEGA, 18 m/pixel for CRISM, and 100 m/pixel for THEMIS, 3 km/pixel for TES). However, the principal drawback of these methods is the fact that penetration depth is small (typically tens of microns for VNIR, several cm for TIR) making them sensitive to secondary coatings or dust cover that potentially obscure the signature of the primary bedrock. Furthermore, the major igneous mineral plagioclase is spectrally neutral in the VNIR and cannot be generally detected using this technique unless the rock contains <5% of the mafic minerals olivine and pyroxene (Carter and Poulet, 2013). The situation is slightly better in the thermal infrared as plagioclase shows absorption features in this spectral range (e.g. Donaldson Hanna et al., 2012, 2014), although even in this case there are many potential ambiguities in the deconvolution and interpretation of surface emissivity spectra (e.g. Ruff et al., 2014 and references therein) in addition to the fact that the spatial resolution of TIR instruments is smaller than more recent VNIR studies. Despite these limitations, the mineralogy of the southern hemisphere is typically considered to be dominated by mafic rocks (Hamilton et al., 2001; Christensen et al., 2005, with a pronounced contribution of low-calcium pyroxene (LCP) at a level similar to or higher than that of high-calcium pyroxene (HCP) (Mustard et al., 2005; Poulet et al., 2009). This situation contrasts with younger terrains, where LCP is almost absent