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The split fate of the early Earth, Mars, Venus, and Moon

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Abstract

Plate tectonics shaped the Earth, whereas the Moon is a dry and inactive desert, Mars probably came to rest within the first billion years of its history, and Venus, although internally very active, has a dry inferno for its surface. Here we review the parameters that determined the fates of each of these planets and their geochemical expressions. The strong gravity field of a large planet allows for an enormous amount of gravitational energy to be released, causing the outer part of the planetary body to melt (magma ocean), helps retain water on the planet, and increases the pressure gradient. The weak gravity field and anhydrous conditions prevailing on the Moon stabilized, on top of its magma ocean, a thick buoyant plagioclase lithosphere, which insulated the molten interior. On Earth, the buoyant hydrous phases (serpentines) produced by reactions between the terrestrial magma ocean and the wet impactors received from the outer solar system isolated the magma and kept it molten for some few tens of million years. The planets from the inner solar system accreted dry: foundering of wet surface material softened the terrestrial mantle and set the scene for the onset of plate tectonics. This very same process also may have removed all the water from the surface of Venus and added enough water to its mantle to make its internal dynamics very strong and keep the surface very young. Because of a radius smaller than that of the Earth, not enough water could be drawn into the Martian mantle before it was lost to space and Martian plate tectonics never began. The radius of a planet is therefore the key parameter controlling most of its evolutional features. ***To cite this article: F. Albarède, J. Blichert-Toft, C. R. Geoscience 339 (2007).***

Résumé

La Terre, Mars, Venus et la Lune et leurs divers destins. La tectonique des plaques a donné ses formes à la Terre, alors que la Lune est devenue un désert sec et pétrifié, que l'évolution interne de Mars s'est probablement arrêtée au bout d'un milliard d'années et que la surface de Vénus, à l'activité interne très active, ressemble à un enfer sec. Dans cet article, nous passons en revue les différents paramètres qui ont déterminé le devenir de chacune de ces planètes et leurs spécificités géochimiques. L'existence d'un champ de gravité fort sur une planète résulte en la dissipation d'une quantité énorme d'énergie gravitationnelle, entraînant la fusion du sommet du manteau de la planète (océan magmatique). Il aide ainsi à retenir l'eau et crée un fort gradient de pression interne. La faible gravité et l'absence d'eau à la surface de la Lune ont entraîné la stabilisation et la flottation, à la surface de son océan magmatique, d'une lithosphère isolante épaisse, formée de plagioclase. Dans le cas de la Terre, l'océan magmatique a été isolé par une croûte hydratée et a pu ainsi rester fondu pendant quelques dizaines de millions d'années. Les minéraux hydratés légers (serpentines) sont produits par l'interaction de l'eau apportée par des impacteurs riches en glace avec l'océan magmatique. Alors

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que l'eau est en grande partie perdue lors de l'accrétion des planètes du système solaire interne, l'accumulation de matériel hydraté à la surface de la Terre a changé la rhéologie de son manteau et mis en place les conditions favorables à l'apparition de la tectonique des plaques. Toute l'eau présente à la surface de Vénus a sans doute été perdue et transférée dans le manteau par le même processus, donnant ainsi une planète avec une forte activité interne et une surface continuellement renouvelée. De par son rayon plus petit que la Terre, Mars n'a pas pu accumuler dans son manteau autant d'eau avant qu'elle ne s'échappe vers l'espace, de sorte que la tectonique des plaques n'a jamais pu commencer. Le rayon d'une planète est donc le paramètre clé qui détermine pour l'essentiel son devenir. ***Pour citer cet article : F. Albarède, J. Blichert-Toft, C. R. Geoscience 339 (2007).***

Keywords: Planetary differentiation; Gravity; Early hydrosphere; Earth; Mars; Venus; Moon; Plagioclase; Early atmosphere; Magma ocean; Early life

Mots clés : Différenciation planétaire ; Gravité ; Hydrosphère primitive ; Terre ; Mars ; Venus ; Plagioclase ; Atmosphère première ; Océan magmatique ; Origine de la vie

1. Introduction

The rocky planets (Mercury, Venus, Earth, and Mars), their satellites, and the large bodies from the asteroid belt each have distinct mineralogical and geophysical identities. They differ by the presence, or not, and volume of a core, their mineralogical nature, the thicknesses of their crust and mantle, the existence, or not, of a liquid ocean and of an atmosphere, not to mention the existence of life. One of the most striking contrasts is between the Earth, with its liquid ocean and granitic continental crust, on the one hand, and the bone dry Moon, with a lithosphere enriched in plagioclase, on the other hand. With respect to the overwhelming homogeneity of the Solar System, which harbours the elemental and isotopic composition of chondrites (the material dominating the asteroid belt), in particular for the less volatile elements, such a prominent variability of the most visible features of the rocky planets calls for a strong first-order explanation. There is very little geochemical information on Mercury and Venus. The information on the composition of Mars as obtained from Martian meteorites is fragmentary and controversial, notably for the lack of a useful chronological perspective, while the spectrometric data obtained from the orbiters are imprecise.

This paper will focus on the identification of a common thread that can account for the geochemical, mineralogical, and chronological evolution of differentiated rocky planets with emphasis on the Earth, Moon, Mars, and the parent body of eucrites, for all of which samples are available. It will be shown that most of the modern mineralogical and dynamical features of these planets are related to the size of each planet and therefore to its capability of retaining light elements, notably water, and to the distance of each planet from the Sun. We will demonstrate that much of the early history of each planetary body, in particular the existence of a magma ocean stage, and its dynamic regime, such as plate tectonics on Earth, can be explained successfully in this way.

After first reviewing the effect of gravity and water content on the nature of minerals crystallizing from liquid silicates, we will address the relationships between the size of an accreting planet, its gravity, and its thermal evolution. Gravity and water content affect the early thermal stages, especially the presence and evolution of a magma ocean.

2. The effect of gravity and water content on magmatic differentiation

In a medium of density ρ in hydrostatic equilibrium, pressure P and acceleration of gravity g at depth z are related by the simple relationship:

$$\mathrm{d}P = \rho\, g\, \mathrm{d}z$$

Pressure affects the stability field of compressible mineral phases and, by far, its most important effect is on plagioclase, a Ca–Na feldspar present in many basaltic rocks and which has a very large compressibility. Fig. 1 uses experimental data to outline the stability fields of the major minerals of anhydrous basalt and emphasizes a crucial point of planetary differentiation, which is the cross-over between plagioclase and pyroxene at $\sim$0.5 GPa [43,48]. A cooling anhydrous basaltic magma will first experience saturation of olivine regardless of pressure. At pressures below $\sim$0.5 GPa, olivine will be followed by plagioclase, which saturates before pyroxene, whereas at pressures $>$0.5 GPa, pyroxene will saturate before plagioclase, which appears only much later during magma solidification.

The density and bulk modulus of the relevant mineral phases [6] are shown in Table 1. Two key features