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Convective outgassing efficiency in Earth and planetary magma oceans: insights from numerical fluid dynamics modeling

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Earth and planetary atmospheres are commonly thought to result from the efficient outgassing of cooling magma oceans. During this stage, vigorous convective motions are believed to transport the dissolved volatiles to shallow depths where they exsolve and burst at the surface. This assumption of efficient degassing has important implications for the study of planetary atmosphere formation, but has never been tested against fluid dynamics considerations. Yet, during a convective cycle, only a finite fraction of the magma ocean can reach the shallow depths where exsolution can occur, and a large-scale circulation can exist for vigorously convecting fluids in the presence of inertial effects. This can prevent a substantial fraction of the magma ocean volume from rapidly reaching the planetary surface. Therefore, we conducted computational fluid dynamics experiments of vigorous 2D Rayleigh-Bénard convection at Prandtl number of unity to characterize the ability of the convecting fluid to reach shallow depths at which volatiles are exsolved and extracted to the atmosphere. From these experiments, we derive simple expressions to predict the time evolution of the volatiles outgassed as a function of the magma ocean governing parameters.

We applied these expressions to show that for plausible cases, the time required to exsolve all oversaturated volatiles can exceed the magma ocean lifetime in a given dynamic regime, leading to incomplete or even negligible outgassing, accounting for different initial magma ocean water content. The latter strongly affects the magma ocean degassing efficiency, possibly leading to divergent planetary evolution paths and resulting surface conditions.

In the light of these results, we will therefore discuss the consequences on planetary evolution paths, and in particular on the resulting surface conditions that can affect the subsequent thermal evolution of the Earth and other terrestrial planets, along with their habitability.