PETROLOGICAL EXPERIMENTS ON ROCKY EXOPLANET COMPOSITIONS REVEAL CLUES TO HABITABILITY.

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Introduction: Key questions driving the study of extra-solar planets have focused on their habitability, and therefore require an understanding of what minerals and rock types are available for surface geochemical reactions that could potentially support life. Soon we will be able to characterize exoplanet atmospheres (e.g., [1, 2, 3]) but observations of surface chemistries (i.e., crusts) remain forthcoming. Investigations of exoplanets have primarily utilized methods from the fields of astronomy and geophysics. However, answering questions about exoplanets' compositions, interior structures, and near surface conditions with regards to their suitability for life necessitates applying methods from a broad range of Earth and planetary science disciplines.

For exoplanets likely to be rocky, knowledge of geologic characteristics such as composition and mineralogy, surface recycling mechanisms, and volcanic behavior are key to determining their suitability to host life. This study uses established methods from the field of experimental petrology to produce the compositions of likely exoplanet partial mantle melts, which are the building blocks for a planet's crust. Experimentally determined petrologic characteristics such as the solidus and mantle mineral modes are used to explore implications for the habitability of these hypothetical exoplanets.

Methods: High temperature and pressure experiments were conducted to produce upper mantle and partial melt compositions for two hypothetical rocky silicate exoplanets. The experimental starting compositions were selected to establish relevant calibration points for future models. A host star's composition can be used as a first order proxy to an exoplanet's composition, as established by the correlation between the compositions of condensed planetary material (i.e., carbonaceous chondrites) and the solar photosphere [5, 6]. Stellar compositions may vary significantly relative to the Sun, particularly in Mg, Fe, Al, Ca, and Si, elements critical in rock-forming minerals [4]. The selected hypothetical rocky exoplanet bulk silicate compositions are outside the compositional space of the Sun and solar system and were not intended to directly simulate observed exoplanets.

The first hypothetical exoplanet starting composition (HEX1) was created by adjusting the undepleted Earth mantle composition to produce a molar Mg/Si ratio of 1.23 and represents exoplanet compositions with Mg/Si ratios greater than Earth's undepleted mantle (Mg/Si = 1.06 [7]). The second hypothetical exoplanet starting composition (HEX2) has a lower Mg/Si than that of Earth (0.82 vs. 1.06), but a higher molar Ca/Al ratio (1.58 vs. 1.07 [7]).

All experiments and analyses were conducted at the Experimental Petrology and Igneous processes Center (EPIC) and the Eyring Materials Center at Arizona State University (ASU). The nominally anhydrous experiments were performed in an end-loaded, solid-medium, Boyd & England-style piston-cylinder apparatus [8] using a ½" assembly, $BaCO_3$ pressure cell, and $Au_{80}Pd_{20}$ capsule. Experimental products were analyzed using energy-dispersive X-ray spectroscopy (EDS) and wavelength-dispersive X-ray spectroscopy (WDS) on a JXA-8530F EPMA. Time-dependent intensity (TDI) corrections were applied to melt analyses to mitigate migration of light elements away from the electron beam.

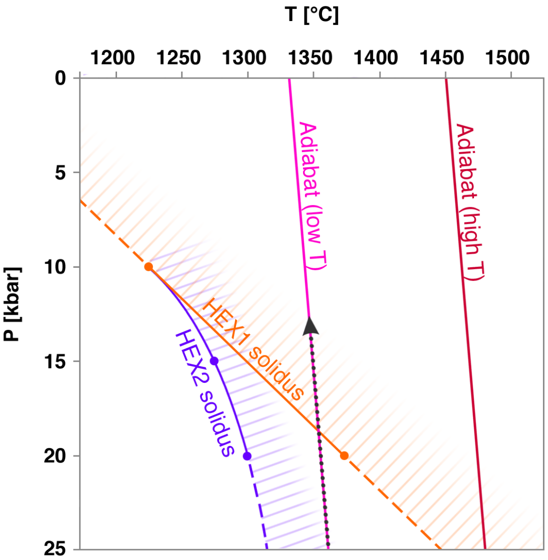

Figure 1: *P-T diagram showing the locations of the HEX1 and HEX2 solidi. Earth's anhydrous undepleted mantle solidus [9] is not distinguishable from that of HEX1. The side of the solidus where melt can exist is shaded. Modern-day Earth adiabats are shown pinned to bracketing mantle* T_{pot} *estimates (1330–1450°C [10]). The gray arrow indicates a sample decompression melting path that crosses the HEX1 solidus but may not cross the HEX2 solidus.*

Depth of initial melting and possibility of a surficial magma ocean: Adiabatic decompression melting does not require Earth-style plate tectonics and is the simplest mantle melting scenario to which our results may be applied. Decompression melting occurs when solid mantle rises towards the planet's surface via convection along an adiabat (for Earth: ~1.2°C/kbar or ~0.3°C/km) (e.g., [11, 12, 13]). Eventually a rising packet of mantle will cross the mantle's solidus and begin to melt (Fig. 1, gray arrow). A hypothetical exoplanet with the same approximate size and core-mass fraction as Earth (~0.323) and a silicate mantle composition similar to the HEX1 or HEX2 bulk compositions is expected to have an adiabatic gradient similar to Earth [14]. For HEX1, the location of the nominally anhydrous solidus is the same as Earth's nominally anhydrous peridotite solidus [9] at the resolution of the experimental spacing in pressure-temperature (P-T) space (Fig. 1). However, for HEX2, the location and slope of the solidus differs from Earth's; the slope of the HEX2 solidus is ~10°C/kbar relative to ~15°C/kbar for Earth (Fig. 1).

For an exoplanet with an Earth-like mantle potential temperature (T_{pot}) of 1330°C [10] and a bulk silicate composition similar to HEX1, adiabatically ascending mantle will cross this solidus and begin to melt by ~18 kbar (Fig. 1). If we assume the same scenario for a HEX2-composition exoplanet mantle and extrapolate the experimentally determined solidus to greater pressures, then melting begins at ~90 kbar. This implied > 4-fold increase in initial depth of melting for HEX2 could result in a much greater total extent of melting than is produced by modern decompression melting on Earth.

The location of the HEX2 solidus also implies that exoplanet's with higher bulk mantle Ca/Al ratios than that of Earth's undepleted mantle could be prone to surficial magma oceans. Assuming an Earth-like adiabat, there is only a narrow range of $T_{pot} < 1330°C$ that would allow decompression melting on such a planet without the entire upper mantle remaining above or below the solidus. Furthermore, T_{pot} may have been higher (1500–1600°C) throughout much of Earth's history [15], and so it is reasonable that an exoplanet could have $T_{pot} \geq 1600°C$ as well, thereby increasing the likelihood of a magma ocean for high Ca/Al exoplanets.

In lieu of a surficial magma ocean, the possibility of no volcanic activity: If an exoplanet with a bulk-silicate composition similar to HEX2 has a T_{pot} that does not lead to the formation of a magma ocean, it is possible that generated melt may fail to erupt on the exoplanet's surface. Melt migration depends on many factors, but in a highly simplified scenario, only the density contrast between the melt and its residuum is used to approximate the melt's relative velocity as compared to Earth MORB [16]. Using DensityX [17], the anhydrous density of melt produced by HEX2 at near-solidus conditions was calculated to be 2.90 g/cm^3, which is at the high end of natural Earth nominally anhydrous magma densities [17]. A residuum density of 3.27 g/cm^3 was determined using HEX2's mantle modes and the average densities of the appropriate minerals (mindat.org). When comparing these densities to the same calculations for average MORB [18] and undepleted Earth mantle modes [7], we find that for the same porosity, viscosity, g, and melt fraction extracted, HEX2's melt migration velocity could be ~50% slower than that of Earth MORB [16]. This slower migration rate indicates that melts from silicate mantles higher in Ca/Al than Earth's mantle could be more likely to stall and crystallize as igneous intrusions, or that generated melt may fail to coalesce into an eruptible melt altogether.

Impact on habitability: These results indicate that an exoplanet will not exhibit broadly different petrological characteristics from those of Earth if its bulk silicate composition differs from Earth only in having a higher Mg/Si ratio. However, increasing the Ca/Al ratio has the potential to produce an exoplanet with either a molten surface or a surface devoid of volcanic activity. In the former scenario, it is unlikely that life as we know it would develop. In the latter scenario—although life may arise—it may be difficult for it to persist in an environment that lacks a means of cycling elements necessary for life back to the surface where they can be utilized.

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