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Decoding exoplanetary mantle melting with experimentally constrained phase diagrams and thermodynamic simulations

VILLE J. VIRTANEN[1], FABRICE GAILLARD[1], STEPHEN J. MOJZSIS[2,3], MALCOLM MASSUYEAU[4], NICOLAS RIEL[5], HUGH ST.C O'NEILL[6] AND ROB SPAARGAREN[7]

[1]ISTO - CNRS
[2]Bavarian Geoinstitute (BGI), University of Bayreuth
[3]HUN-REN Research Centre for Astronomy and Earth Sciences, MTA Centre of Excellence
[4]BRGM
[5]Johannes-Gutenberg University
[6]Monash University
[7]Kapteyn Astronomical Institute, Rijksuniversiteit Groningen

Thousands of plausible mantle compositions modeled for rocky exoplanets point to the strong likelihood for substantial departures from Solar System analogs. This likely compositional diversity translates to styles of exoplanetary mantle melting, composition of the produced melts, and their capacity to form planetary crusts and to convey volatile elements from the planetary interior to the atmosphere that depart from conventional Earth-centric processes. To navigate this vast compositional space, we rely on high-pressure (P)-temperature (T) experimental data and thermodynamic phase equilibrium modelling. We compiled a dataset of melting experiments conducted with compositions relevant for upper mantles of Earth, Moon, Mars, Mercury, and hypothetical exoplanets. The dataset encompasses melts in equilibrium with a range of (nominally) dry mantle assemblages: ± olivine ± orthopyroxene ± clinopyroxene ± spinel ± garnet ± plagioclase (± alkali feldspar ± rutile). We use these data to (i) construct phase diagrams that provide first-order constraints on the range of melt compositions produced through mantle melting of rocky planets and (ii) identify P-T–composition (X) regions, which are relevant for exoplanetary mantles but where experimental data remain sparse. Our exercise shows that SiO_2-Al_2O_3-CaO-(MgO+FeO) phase diagrams are sufficient for approximating the overall melting behavior of complex multicomponent mantles even with wildly variable compositions. We benchmark the performance of commonly used thermodynamic modeling tools, *MAGEMin* (same thermodynamic databases as in *Thermocalc* and *PerpleX*) and *pMELTS*, against the experimental dataset to assess the reliability of current simulations within the relevant P-T-X space. Our results offer practical guidelines and theoretical principles for estimating melt compositions and melt productivity under non-Earth-centric conditions prevailing for exoplanets. This petrological framework helps us to parameterize endmember cases for the physics and chemistry of fluid envelopes draping rocky exoplanets in our galactic neighborhood.