The compositional range of terrestrial exoplanets in the Solar neighborhood.

R.J. Spaargaren[1], H.S. Wang[2], M.D. Ballmer[3], S.J. Mojzsis[4] and P.J. Tackley[1], [1]Dept. of Earth Sciences, ETH, Sonnegstrasse 5, 8092 Zürich, CH (rob.spaargaren@erdw.ethz.ch), [2] Dept. of Physics, ETH, Wolfgang-Pauli-Strasse 27, 8093 Zürich, CH, [3]Dept. of Earth Sciences, UCL, 5 Gower Place, London WC1E 6BS, UK, [4]Dept. of Earth Sciences, University of Colorado, UCB 399, Boulder, CO 80309, USA.

Summary: With more observations of terrestrial exoplanets becoming available every year, the importance of geodynamical studies focusing on exoplanets is increasing. We know from observations that stellar chemical abundances vary in the Solar neighborhood, which is likely to result in terrestrial exoplanets with a similar chemical diversity. Bulk planet composition affects many properties of the interior directly (e.g., core size, mantle viscosity) or indirectly (e.g., thermal evolution, layering). This may extend to atmospheric properties, since terrestrial planet atmospheres form and evolve under continuous interaction with the interior. In order to better understand the variability of interior properties among terrestrial exoplanets, here we attempt to constrain the range of bulk compositions of terrestrial exoplanets in the Solar neighborhood. We subsequently study the effects of this compositional spread on the planet interior properties by determining mantle mineralogical profiles.

Introduction: Terrestrial exoplanets have interior properties that may diverge from Earth's, and therefore may follow different evolutionary pathways as a result. It has been studied how interior properties, such as mantle viscosity, melting behavior, core size, and planet radius, affect interior evolution, dynamical behavior of the lithosphere, and evolution of the atmosphere. However, bulk planet composition has only been considered for simple compositional models (e.g., [1]). We know from observations that stellar chemical abundances vary in the Solar neighborhood, and this is likely to result in terrestrial exoplanets with a similar chemical diversity, and can affect results of these models.

In our previous work [2], we established that interior composition affects the evolution of both the interior and the atmosphere of a planet. Bulk planet composition affects many properties of the interior directly (e.g., core size, mantle viscosity) or indirectly (e.g., thermal evolution, layering). This extends to atmospheric properties, since terrestrial planet atmospheres form and evolve under continuous interaction with the interior. Here, we aim to incorporate a more complex compositional model, where we constrain the range of possible bulk terrestrial exoplanet compositions with observations of stellar abundances. Additionally, we aim to investigate the effects of this range on interior evolution, by first constraining using a geodynamical model.

Constraining bulk compositions: Since a planet forms from the same material as its host star, we can use stellar abundances to constrain bulk compositions of exoplanets. We use abundance data from the Hypatia catalog [3], which records elemental abundances of stars in the Solar neighborhood (within 200 pc). To determine planetary compositions, we utilize the compositional trend between Earth and the Sun. This trend shows a growing depletion of elements in Earth with decreasing condensation temperature of the element. We apply this devolatilization trend from [4] to the stellar abundance data from the Hypatia catalog, to simulate compositions of hypothetical exoplanets with the same formational history as the Earth. We consider the elements Si, Fe, Mg, O, Al, Ca, Na, K, Ni, and S.

For this set of simulated bulk planet compositions, we simulate core-mantle differentiation by assuming a similar distribution of oxygen between core and mantle as Earth (i.e., the same bulk planet Fe/FeO as Earth). We include partitioning of light elements into the core, by including 6 wt\% Si and 2 wt\% O in the core [5]. Additionally, we assume that all S ends in the core of the planet.

From the obtained range of bulk terrestrial exoplanet compositions, we identify 20 end-member bulk planet compositions, which are representative for the full range. We study these end-member compositions in more detail, and we recommend these end-member compositions for use in modelling of terrestrial exoplanet interiors. Since these compositions span the range found for planets in the Solar neighborhood, they represent the full extent of planetary diversity in terms of bulk composition. Therefore, studying these compositions will show the range of compositional effects that can be expected in the Solar neighborhood, and therefore for most terrestrial planets that we can realistically observe in more detail in the next few decades.

Mantle modelling: To investigate the interior properties and evolution of these planets, we first translate the obtained bulk silicate compositions to mineralogical mantle profiles. We determine mantle mineralogy and physical properties by using a Gibbs energy minimization algorithm, Perple_X [6], with a thermodynamic database which is valid for most of the pressure-temperature conditions found in the mantle [7]. This allows us to study the physical properties of our 20 end-member compositions, including density, viscosity, and the presence and effects of phase transitions. Here, we assume that all planets are of 1 Earth mass.

Finally, we explore the effect of this variability in bulk composition on long-term evolution of the planetary interior using a 2D parametrized convection model [8]. By implementing the physical properties and phase transitions obtained with Perple_X, we can model the interior evolution of planets with these 20 end-member compositions. We will expand on this in the future by studying mantle melting behavior for each of our compositions, and implementing the melting curve and the melting product and residue in the convection model.

References: [1] Noack L. and Lasbleis M. (2020), A&A, 638, A129 [2] Spaargaren R.J. et al. (2020), A&A, 643, A44. [3] Hinkel N. et al. (2014), AJ, 148(3), 33 pp. [4] Wang H.S. et al. (2018), MNRAS, 482(2), 2222-2233. [5] Javoy M. et al. (2010), EPSL, 293(3-4), 259-268. [6] Connoly J.A. (2005), EPSL, 236(1-2), 524-541. [7] Stixrude L. and Lithgow-Bertelloni C. (2011), Geophys. J. Int., 184(3), 1180-1213. [8] Tackley P.J. (2008), Phys. Earth Planet. Int., 171(1-4), 7-18.