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Key Points:

- Mineral abundances affect the time-scale for the formation of mylonites, a key element of Earth-like plate tectonics
- Planets composed of two or more minerals will form plate boundaries more readily than planets that are effectively monomineralic
- The search for habitable worlds should prioritize targets with compositions that favor the development of Earth-like plate tectonics

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The Effect of Composition on Shear Localization in Planetary Lithospheres

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Abstract Earth's particular style of plate-tectonics—characterized by localized deformation along dynamic plate boundaries and long-lived stable plate interiors—appears to be unique among rocky objects in the solar system. However, it is entirely unknown how common plate tectonics and related lithospheric phenomena are among the vast population of exoplanets discovered astronomically or assumed to exist throughout the Universe. In this study, we explore the effect of planetary composition on mylonitization—a set of microphysical processes that is commonly associated with shear localization and plate boundary deformation on Earth. A model for planet compositions, based on stellar spectroscopy, is used to define a plausible range of theoretical mineral abundances in the mantles of rocky Earth-sized exoplanets. These mineral abundances, along with experimental rock rheology, are used to model microphysical evolution with two-phase mixing. The model is then used to determine the effect of composition on the time-scales for shear zone formation. We demonstrate that lithospheres composed of sub-equal proportions of two mineral phases will form shear zones over relatively short time-scales, a more favorable condition for forming Earth-like plate boundaries. In contrast, lithospheres that are nearly monomineralic may require unrealistically long time-scales to form plate boundary shear zones. Using this approach, we identify specific nearby stars with the optimal range of compositions to be targeted by future astronomical missions, including the Habitable Worlds Observatory.

Plain Language Summary Plate tectonics is foundational to virtually all geologic phenomena on Earth and is widely considered to be an important factor promoting Earth's habitability. However, Earth is the only known planet that currently exhibits plate tectonics, and it is unknown how common plate tectonics should be among the vast number of exoplanets in the Universe. This study explores how the chemical composition of exoplanets influences the time scales over which plate tectonics may arise. We show that many exoplanets have mantles composed of sub-equal proportions of two or more minerals, a necessary (albeit insufficient) condition for developing plate tectonics. We use this model to identify specific targets for future astronomical investigations.

1. Introduction

Mantle convection, volcanism, and tectonics govern mass transfer, heat flux, and geochemical cycling between a planet's interior and surface. In the most general sense, a planet's style of tectonics is controlled by its size, heat budget, and the mechanical properties of its crust and mantle (Bercovici et al., 2015; Schubert et al., 2001; Solomatov & Moresi, 1997). More specifically, Earth-like plate tectonics requires the lithosphere—the rigid upper thermal boundary layer in the convecting system—to form plate boundary shear zones that are narrow relative to the plates that they separate (Bercovici, 2003; Montési & Zuber, 2002). Yet, plate tectonics is notably complex, and its emergence on Earth and its apparent absence on other terrestrial planets is still difficult to reconcile with data from experimental rock physics (Bercovici & Ricard, 2014; Regenauer-Lieb et al., 2001; Tackley, 1998; Toth & Gurnis, 1998). For planets to develop plates, rather than a Mars-like stagnant lid, a minimum criterion is that the rocks that make up the lithosphere must be able to localize deformation (Figure 1).

While many questions about the origins and dynamics of plate tectonics remain, it is also important to consider the vast number of exoplanets discovered or assumed to exist (Hill et al., 2023), and factors that might promote or inhibit plate tectonics elsewhere in the universe (Foley et al., 2012; Korenaga, 2010; O'Neill & Lenardic, 2007; Valencia et al., 2007; Van Heck & Tackley, 2011). Here, we explore a critical piece of the plate tectonic puzzle by

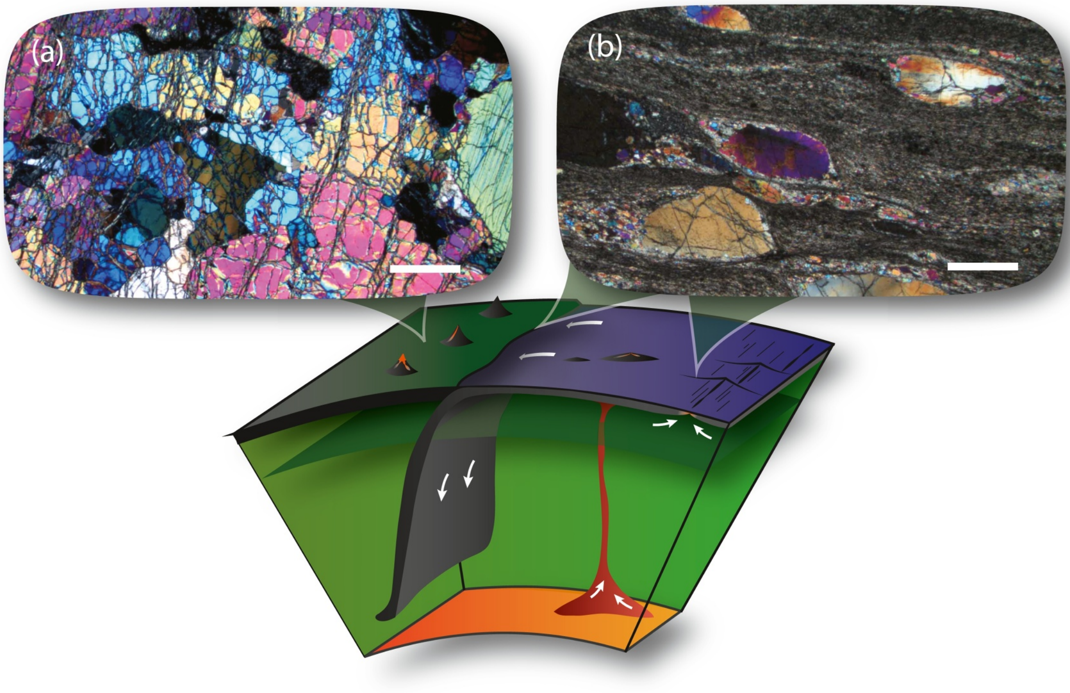

Figure 1. Feedbacks between deformation and microstructure affect the dynamics of planetary lithospheres. The inset photomicrographs in cross-polarized light (scale bar = 1 mm) show examples of microstructures from deformed mantle peridotites (after Linckens et al., 2015). (a) Earth's plate interiors and presumably the stagnant lids of other planets experience low rates of deformation and exhibit relatively large, unrecrystallized mineral domains that deform by the dislocation creep mechanism. (b) In contrast, plate boundaries on Earth are frequently characterized by mylonitic shear zones where grain-size is reduced, mineral phases are intermixed, and the dominant deformation mechanisms are grain-size sensitive.

investigating the connection between mineralogy and the microphysics that controls the formation of plate boundary shear zones.

Localized deformation along faults and ductile shear zones are both essential features of plate boundary deformation (Fossen & Cavalcante, 2017; Vauchez et al., 2012). The mechanical properties of a planet's lithosphere, and hence its propensity to exhibit plate-like behavior, are controlled by the brittle strength of the uppermost crust and mantle and the viscous strength of rocks below the brittle-ductile transition (Brace & Kohlstedt, 1980). The viscosity of rocks below the brittle-ductile transition is affected by several factors, including temperature, melt-fraction, convective stress, grain-size, and mineral composition (e.g., Kohlstedt & Hansen, 2015). However, some of the most important weakening processes involve feedbacks between deformation and microstructure (Skemer et al., 2010, 2013). For example, when solid rocks are deformed at high stresses in a dislocation creep regime, grain-size may be reduced by dynamic recrystallization (Urai et al., 1986). This grain size reduction is often accompanied by a change in the deformation mechanism, from dislocation to diffusion creep. Due to the grain-size sensitivity of diffusion creep, these microphysical transitions also yield a reduction in the effective viscosity (Etheridge & Wilkie, 1979; Rutter & Brodie, 1988; Warren & Hirth, 2006). In a polymineralic rock, continued deformation may cause recrystallized grains of different minerals to become interspersed. This phenomenon, known as "phase mixing," suppresses syn- and post-deformation grain-growth through the Zener-pinning mechanism (Evans et al., 2001; Herwegh et al., 2011), allowing mechanical weakness to persist through multiple tectonic cycles (Bercovici & Ricard, 2014). In the geologic record, these fine-grained, well-mixed, mechanically weak rocks are classified as "mylonites" and are widely interpreted as the product of viscous shear localization (Bell & Etheridge, 1973; Etheridge & Wilkie, 1979; White et al., 1980). The ubiquitous presence of mylonites along plate boundaries or zones of localized deformation is considered important evidence for (and is arguably an essential ingredient of) plate tectonics (Bercovici & Ricard, 2012; Fossen & Cavalcante, 2017).

Estimates of exoplanet mineralogy, based on stellar spectroscopy (Putirka & Rarick, 2019), now allow us to apply principles of rock rheology to evaluate how readily plate tectonics might emerge outside the Solar system.

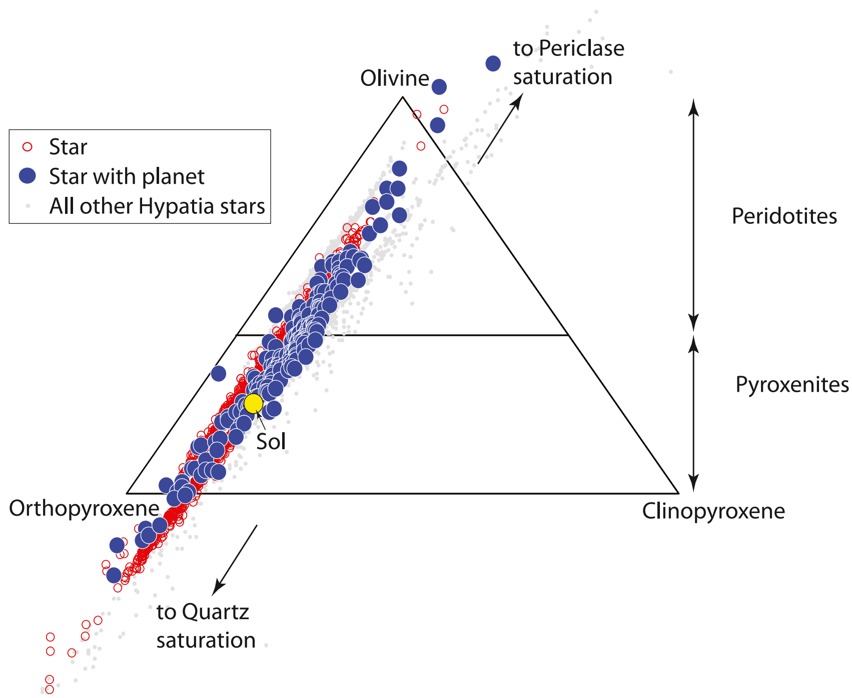

Figure 2. Mineral compositions of fictive exoplanets orbiting stars from the Hypatia catalog, calculated following the method of Putirka and Rarick (2019). The projection is from the aluminous phases (not shown), with the peridotite/pyroxenite ternary diagram included for reference. Red symbols denote the subset of the Hypatia catalog that meets the selection criteria for our model (n = 1,747). Blue symbols denote those entries that meet the selection criteria and also have astronomically detected exoplanets of any size, mass, or composition (n = 228). All other entries from the Hypatia catalog are shown in small gray dots (n = 5,938). Symbols that fall outside of the ternary diagram are quartz- or periclase-normative.

Previous authors (Putirka et al., 2021; Putirka & Rarick, 2019) have shown that most rocky planets should have sufficient oxygen to form silicates, and most are bi- or polymineralic (i.e., 79% have at least 30 vol% secondary phases). Indeed, most planetary mantles are effectively composed of one of three pairs of mineral phases: (a) quartz and orthopyroxene, (b) orthopyroxene and olivine, or (c) olivine and periclase (Figure 2). The relative abundance of these minerals depends on the FmO/SiO_2 ratio (where FmO = MgO + FeO). At $FmO/SiO_2 = 1.02$, Earth falls in the middle of this range, with an upper mantle predominantly composed of the minerals orthopyroxene, olivine, and their high pressure polymorphs.

In this study, we examine a subset of 7,686 stars in the Hypatia Catalog (Hinkel et al., 2014), of which 1,398 are known to have at least one exoplanet. (Note that in subsequent text we use the word "planet" to denote a modeled, fictive rocky planet, not an astronomically detected exoplanet, except when explicitly stated.) Our approach is to merge a model of mineral abundances for planets, with a deformation model that is based on empirically determined flow laws, relationships between stress and recrystallized grain-size, and a theory for phase mixing, to identify exoplanet systems with compositions that are most favorable for the formation of Earth-like lithospheric shear zones.

2. Methods

2.1. Compositional Model

Spectroscopic data for several thousand stars within 150 parsecs of the Sun are compiled in the Hypatia Catalog (Hinkel et al., 2014). From these spectra, Putirka and co-authors model bulk composition and the stable mineral phases within the mantles of fictive rocky Earth-sized planets orbiting these stars (Putirka, 2024; Putirka et al., 2021; Putirka & Rarick, 2019).

The first step in the compositional model is to calculate the core mass fraction, which is determined from the Fe-Si mass balance. Even when total oxygen and fO_2 are unknown, and considering uncertainties in the partitioning of silicon into the core, previous work has shown that estimates of the core mass fraction are accurate to within ±3 wt. % (Putirka, 2024). With the core composition removed from the bulk planetary composition, mineral abundances within the remaining silicate mantle are modeled using a "CIPW-like" norm, a cation accounting system similar to the method introduced by Cross et al. (1902). An important feature of the model is that it provides positive values of mineral abundance spanning planets with normative SiO_2 to those with normative FmO. The model is limited to include only the most volumetrically abundant minerals that might conceivably impact composite rheology: olivine, orthopyroxene, clinopyroxene, quartz, periclase, and garnet. For a detailed accounting of the algorithm, we refer the reader to Putirka (2024, p. 227).

Using this approach, planetary compositions are subdivided into three groups: Planets with mantles that contain (a) quartz and orthopyroxene, when $FmO/SiO_2 < 0.62$ (b) orthopyroxene and olivine, when $0.62 < FmO/SiO_2 < 1.8$; and (c) olivine and periclase, when $FmO/SiO_2 > 1.8$. For each group, we only consider planets that are nearly bimineralic by excluding those for which the sum of the two most abundant phases is less than 80% by volume. After applying this filter, we are left with 31 planets with normative quartz and orthopyroxene, 1,554 with normative orthopyroxene and olivine, and 162 with normative olivine and periclase (Figure 2). A final normalization step yields planets with only two nominal mineral phases.

2.2. Two-Phase Deformation Model

Recent progress has shown that phase mixing depends primarily on the strain-magnitude, as geometric stretching of mineral domains, accompanied by chemical diffusion and grain-boundary sliding, increases the spatial density of phase boundaries (Bercovici & Skemer, 2017; Bercovici et al., 2023; Billings & Skemer, 2024; Cross & Skemer, 2017; Tasaka, Zimmerman, & Kohlstedt, 2017; Tasaka, Zimmerman, Kohlstedt, Stünitz, & Heilbronner, 2017; Wiesman et al., 2018).

The deformation model used here is adapted from the experimentally validated geometric phase-mixing model of Cross and Skemer (2017). In this previous study, it was shown that mylonitic textures form when individual mineral domains are stretched until the domain thickness is reduced to the dimension of one recrystallized grain, which is described using the term "monolayer" (Figure 3). In this monolayer configuration, each grain in a bimineralic assemblage is effectively pinned by grains of the opposite phase and microstructural recovery is strongly inhibited. We predict that when mineral phase domains are initially larger, either due to the primary nature of the microstructure or the relative sparseness of the intervening secondary phase, more strain is required to achieve a steady-state microstructural configuration.

In the present model, phase mixing is only strain-dependent. We do not consider other superimposed mixing mechanisms such as those that are diffusion limited and/or require cavitation or metamorphic reactions. The critical shear strain for mixing is approximated as

$$\gamma_{\text{crit}} \approx \frac{w}{d_{\text{rxl}}} \tag{1}$$

where γ_{crit} is the critical shear strain for a well-mixed phase, w is the initial width of the mineral domain, and d_{rxl} is the recrystallized grain-size. The criterion is applied to the two phases independently since both phases must be mutually intermixed in order to generate a canonical (ultra)mylonitic microstructure (e.g., Passchier & Trouw, 1998, p. 104).

The initial width of a mineral domain is assumed to be a function of the initial grain-size and the mineral volume fraction. For a volumetrically unequal mixture of two minerals, the more abundant phase is expected to have larger domains (e.g., Figure 3a). The minimum domain size is assumed to be the initial grain-size. Grain-sizes in Earth's interior are not well-constrained, although studies of global seismic anisotropy and direct observations of mantle xenoliths suggest values in the mm to cm range (Karato et al., 2008). Grain-sizes in the interiors of other planets are completely unknown. Therefore, we employ for most calculations an initial grain size of 10 mm. The domain size for the ith mineral phase (w_i) is defined as:

$$w_i = \max\left(d_o, d_o\left(\frac{1}{(1-\phi_i)} - 1\right)\right) \tag{2}$$

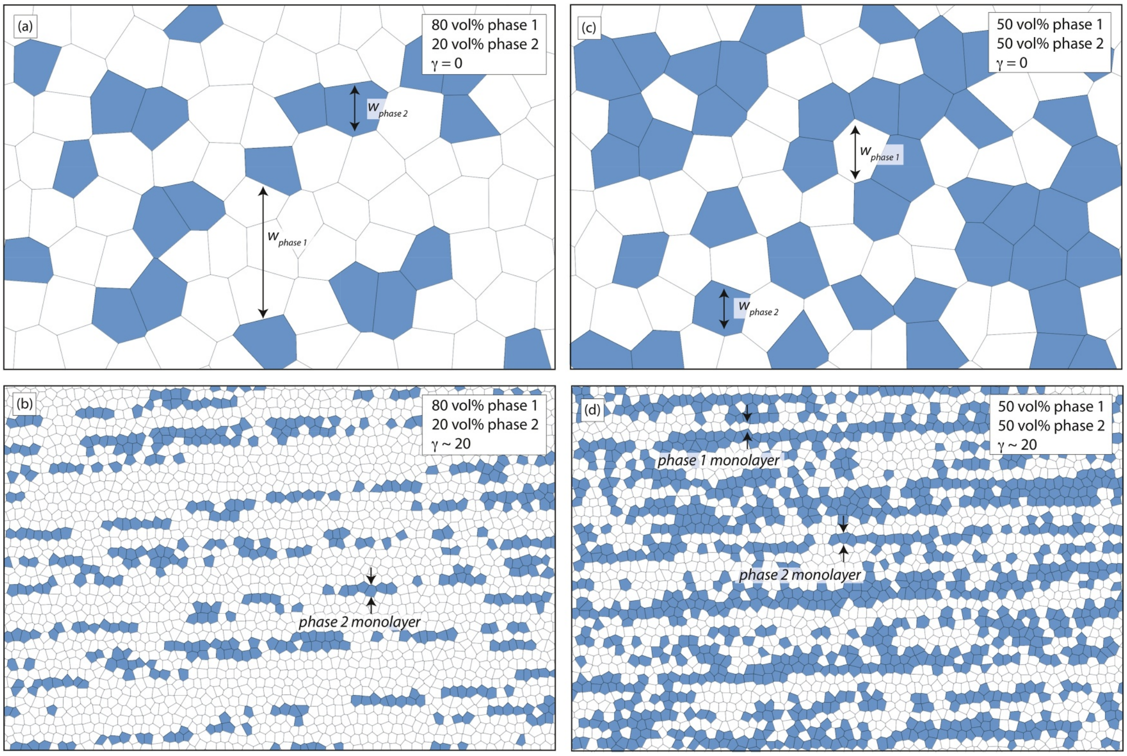

Figure 3. Phase mixing experiments show that a terminal microstructural state is achieved when individual mineral domains are thinned and stretched to the width of a single recrystallized grain (Cross et al., 2020; Cross & Skemer, 2017). Cartoons (a) and (c) illustrate undeformed two-phase composites with an initially coarse-grained and randomly interspersed microstructure for two different mineral proportions. For mineral phases with volume fraction ≤50%, the domain width, w, is the same as the initial grain-size in the model; phases with volume fractions >50% will have larger domains. Panels (b) and (d) show these same mineral proportions with grain size reduced at a shear strain of $\gamma \sim 20$. Monolayers do not readily form in the more abundant Phase 1 in Panels (b) because the strain is insufficient. However, monolayers form in both phases when the mineral proportions are equal (d).

where d_o is the assumed initial grain-size and ϕ_i is the volume fraction of phase i.

The recrystallized grain-size is assumed to quickly reach a steady-state (Cross & Skemer, 2019) that depends only on stress (Twiss, 1977). For the primary model result shown in Figure 4, we assume a flow stress of 100 MPa. This is a typical estimate for a lithospheric stress (e.g., Richards et al., 2001) and is of the same order as peak flow stresses inferred from some deep crustal and upper mantle xenoliths (Behr & Platt, 2011; Lallemant et al., 1980; Mercier, 1980). Grain-size piezometers—the relationship between recrystallized grain-size (d_{rxl}) and stress (σ)—have an inverse power-law relationship:

$$d_{\text{rxl}} = B\sigma^{-p} \tag{3}$$

B and p are empirical constants for quartz (Cross et al., 2017), orthopyroxene (Linckens et al., 2014), olivine (Van der Wal et al., 1993), and periclase (Huther & Reppich, 1973). p is typically of the order 1. γ_{crit} is calculated for a continuous range of possible mineral fractions for all three mineral pairs, from the quartz to the periclase end-members, using Equations 1–3.

Strain-rates for each mineral phase are calculated following a standard temperature-dependent power-law formulation (e.g., Frost & Ashby, 1982):

$$\dot{\gamma} = A\sigma^n \exp\left(-\frac{Q^*}{\text{RT}}\right) \tag{4}$$

where $\dot{\gamma}$ is the shear strain-rate, A is a pre-exponential factor, σ is stress, n is the stress exponent, Q^* is the effective activation enthalpy for deformation, R is the gas constant, and T is temperature. A standard pressure (2 GPa) and a

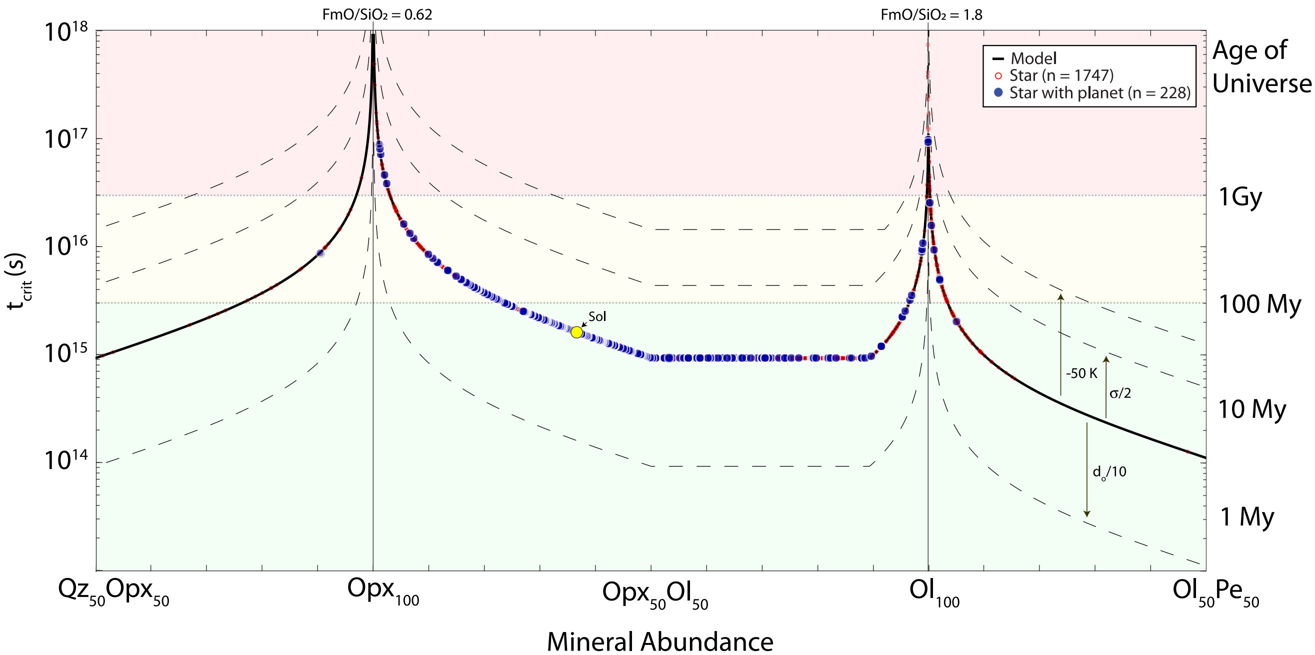

Figure 4. The critical time-scale for steady state mylonite formation (t_{crit}) as a function of mineral abundance. Qz = quartz; Opx = orthopyroxene; Ol = olivine; Pe = periclase. The full model range is not shown here because there are few stars that yield exoplanet compositions with >50 vol% Qz or Pe. The thick black line shows model results for selected values of stress (σ = 100 MPa), initial grain-size (d_o = 10 mm), and temperature (T = 1173 K). Dashed lines illustrate the sensitivity of the model to selected changes in these variables. Specific stars in the Hypatia catalog that meet the selection criteria are shown in red. The subset of these stars with astronomically detected exoplanets of any mass, size, or composition is shown in blue (the vast majority of these are not Earth-sized or rocky). Shorter time scales are more favorable for the formation of mylonites, lithospheric shear zones, and plate tectonics; longer time scales are less favorable. Compositions for which t_{crit} > 100 My includes ~26% of the stars in the catalog.

range of temperatures (1073–1623 K) are used for all calculations. 1173 K, the temperature selected for the primary model shown in Figure 4, is a typical temperature for 100 million year old oceanic lithosphere at a depth of 70 km, which is below the brittle-plastic transition (McKenzie et al., 2005). Mineral specific constants A, n, and Q^* are taken from laboratory derived flow laws for quartz (Gleason & Tullis, 1995), orthopyroxene (Bystricky et al., 2016), olivine (Hirth & Kohlstedt, 2003), periclase (Mei et al., 2008). All flow laws used here describe deformation in a dislocation creep regime with a stress exponent of n = 3–3.5, under conditions that are melt-free and nominally dry.

The critical time scale (t_{crit}) over which phase mixing is achieved is calculated from Equations 1–4 assuming steady-state rheology under constant stress and temperature conditions:

$$t_{crit} = \frac{\gamma_{crit}}{\dot{\gamma}(T, \sigma)} \tag{5}$$

where γ_{crit} and $\dot{\gamma}$ are defined in Equations 1 and 4 respectively. t_{crit} is calculated for both minerals in the two-phase system, with the greater of the two values considered to be the rate-limiting time-scale required for complete intermixing of both mineral phases.

3. Results

Calculations were performed for a continuous range of compositions from 100 vol% quartz to 100 vol% periclase. Figure 4 summarizes these results, with t_{crit} plotted against composition. Specific compositions corresponding to entries in the Hypatia Catalog that meet the selection criteria are plotted as red points; blue points highlight the subset of catalog entries that meet the selection criteria and also have astronomically detected exoplanets.

Compositions are monomineralic at the end-members and for compositions where the FmO:SiO_2 molar ratio is exactly 1:1 (orthopyroxene) and 2:1 (olivine). As compositions approach these monomineralic limits t_{crit}

increases by orders of magnitude as the secondary phases are too sparse to be readily mixed. Local minima in t_{crit} occur where mixtures of phases are sub-equal. Flat regions in the curve result from the assumption of a minimum initial domain size that is equal to the grain-size ($w = d_o$) for the less abundant phase. The primary model, selected for illustrative purposes and shown as the thicker black curve, assumes $T = 1173$ K, an initial grain size of 10 mm, and a constant flow stress of 100 MPa. For these assumed model conditions, time scales for mylonite formation range from ∼30 million years to over 10 billion years, depending on the composition. For Earth, the time scale for convection (i.e., the duration of a stable lithospheric drip or the impingement of a mantle plume) is on the order of 100 million years. Over longer time scales (yellow and red regions of Figure 4), convective stresses to the lithosphere are not applied consistently—either spatially or temporally—and this criterion for generating a new zone of localized deformation may not be achieved.

Appropriate model parameters for rocky exoplanets are both variable and highly uncertain. Therefore, we explored the sensitivity of our model to a range of values. Results of models with different parameters are shown as secondary curves marked with dashed lines in Figure 4. Decreasing the initial grain-size by one order of magnitude reduces t_{crit} by the same order because the critical strain (γ_{crit}) scales linearly with the spacing of different mineral domains (see Equations 1 and 2). Decreasing stress by a factor of two increases t_{crit} by approximately a factor of four, due to the power-law dependence of strain-rate on stress, and the inverse power-law dependence of recrystallized grain-size on stress (from Equations 3 and 4, $t_{\mathrm{crit}} \propto \sigma^{p-n}$). Temperature has the largest sensitivity due to its exponential effect on strain-rate (i.e., effective viscosity). Decreasing temperature by 50 K increases t_{crit} by approximately an order of magnitude although the exact sensitivity depends on the activation energy for creep of the rate-limiting mineral phase. For 50-50 mixtures of olivine and orthopyroxene, $\frac{dt_{\mathrm{crit}}}{dT} \approx -1.5 \times 10^6$ years/K. Notably, while minimum values for t_{crit} may increase or decrease depending on the assumed stress, initial grain-size, and temperature, the shapes of these curves are largely insensitive to the choice of model parameters. In all cases t_{crit} is orders of magnitude greater for effectively monomineralic compositions than it is for compositions with sub-equal proportions of the two constituent mineral phases.

4. Discussion

Decades of geological field studies have shown that plate boundary deformation manifests as frictional faults at shallow depths and mylonitic viscous shear zones below the brittle-ductile transition, with individual strands as narrow as 10–100s of meters (Fossen & Cavalcante, 2017; Sibson, 1977). The physical mechanisms that produce mylonites from a primary lithosphere are of considerable interest since it is presumably impossible to create or sustain Earth-like plate tectonics without them (Bercovici, 2003; Bercovici & Ricard, 2014).

Experiments and modeling confirm that dynamic recrystallization and phase mixing can generate mylonitic microstructures over geologic time-scales, provided all other necessary conditions are met. In this study, we apply the geometric phase mixing model first introduced by Cross and Skemer (2017). However, it is important to acknowledge that phase mixing in the Earth may occur by more than one mechanism. Our model explicitly neglects the role of diffusion-enhanced phase mixing (Bercovici & Skemer, 2017; Tasaka, Zimmerman, & Kohlstedt, 2017; Tasaka, Zimmerman, Kohlstedt, Stünitz, & Heilbronner, 2017), metamorphic or melt-rock reactions (Dijkstra et al., 2002; Newman et al., 1999), or cavitation creep (Fusseis et al., 2009; Gilgannon et al., 2017). Each of these additional phase-mixing mechanisms occurs when appropriate chemical potentials are present, and is especially relevant under fluid-rich conditions that promote dissolution and reprecipitation. All of these mechanisms may work in parallel with geometric phase mixing, effectively reducing the time required for mylonitization to occur. As such, it is appropriate to consider the t_{crit} calculated in this study to be an upper limit.

Our present model seeks to isolate the effect of mineral abundance on geometric phase mixing. To do so, we have made a number of simplifying assumptions. The selection of mineral flow laws (nominally dry, melt-free, and in dislocation creep) imposes some inherent constraints on the model. Dislocation creep flow laws were selected because the Earth's upper mantle deforms predominantly by dislocation creep, as is evidenced by the olivine crystallographic preferred orientation (CPO) found in exhumed rocks and the mantle's pervasive seismic anisotropy (Karato et al., 2008; Long & Becker, 2010). Furthermore, a dislocation-enabled deformation mechanism is necessary to induce dynamic recrystallization with a predictable piezometric relationship between stress and grain-size (e.g., Twiss, 1977), which is an essential feature of our model. More rigorous approaches to modeling shear localization would account for additional chemical, microphysical, and deformation processes, but would greatly expand the parameter space. Other assumptions, constrained only through analogy with Earth, include the initial grain-size, deformation temperature, and constant stress state. These assumed values may not be appropriate for exoplanets of different sizes, ages, orbital characteristics, or formation histories. Clearly, our understanding of exoplanetary interiors is still extremely limited. Future studies, with fully dynamic treatments of stress-state, grain-size evolution, and composite rheologies, are needed to confirm and expand upon the present results.

Figure 4 demonstrates that the conditions necessary for the formation of Earth-like ductile shear zones are not uniformly probable across the universe. Even with the significant uncertainty in the true grain-size, stress, and temperature of these fictive planets, a highly robust aspect of our model is that t_{crit} is always orders of magnitude greater for compositions that are effectively monomineralic. While the true values for t_{crit} are only approximated by our model, systematic trends emerge: exoplanets orbiting stars with compositions that yield polymineralic planetary interiors are more likely to generate the microstructures associated with shear localization and plate tectonics on Earth. Exoplanets that are effectively monomineralic may never be Earth-like in their dynamic behavior.

Earth is the only planet in the inner solar system that conclusively exhibits active plate tectonics, and so stellar composition cannot be the sole determinant of the style of tectonism in an associated planetary system. There are numerous factors that promote or inhibit plate-like behavior and the model described here represents only one piece among many in the plate tectonic puzzle. Indeed, our model provides no obvious explanation for the first order differences in tectonic style between Earth and Venus, since both planets presumably have similar mantle compositions (Turcotte, 1996). However, we suggest that the presence of multiple mineral phases may be a necessary (albeit insufficient) criterion for shear localization and Earth-like plate tectonics.

5. Conclusions

While Earth represents only a single data point, exoplanets form with a range of sizes and compositions that reflect the properties and metallicity of the stars that they orbit and the condensation of the molecular cloud that formed the stellar system. At present, the vast majority of astronomically detected exoplanets are not Earth-sized due to the challenge of measuring the size and density of smaller bodies orbiting bright stars. However, as techniques improve and the discovery of other worlds becomes increasingly routine, spectroscopy of rocky exoplanets stripped of their atmospheres offers the enticing possibility of directly determining surface compositions. Indeed, recent data hint at exoplanets surfaced with basalt (Kreidberg et al., 2019; Zieba et al., 2023), implying crusts formed by partial melting of an Earth-like ultramafic mantle (Green & Ringwood, 1967). As more data become available, it is reasonable to expect that more varied surface compositions will be detected.

While our results do not imply that plate tectonics will be found on all or even most rocky exoplanets, the criterion of multiple mineral phases is met by a large percentage of the fictive planets in our study. Indeed, very few are effectively monomineralic (<5% contain more than 80 vol% of any single mineral phase). On the other hand, 29% have no mineral phase that exceeds 50% by volume (i.e., secondary and tertiary phases are relatively abundant); all other factors being equal, these planets with abundant secondary phases should provide the best opportunity to generate ductile shear zones over relatively short time-scales. In the search for Earth-like worlds, stellar systems predicted to have sub-equal bimineralic or polymineralic exoplanets should be a priority for current missions and future mission concepts, such as the Habitable Worlds Observatory.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Matlab code for the model and a data table containing model results are archived by WashU Research Data, and has been assigned the DOI: https://doi.org/10.7936/6RXS-108297 (Skemer, 2025).

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References

Behr, W. M., & Platt, J. P. (2011). A naturally constrained stress profile through the middle crust in an extensional terrane. *Earth and Planetary Science Letters*, *303*(3–4), 181–192. https://doi.org/10.1016/j.epsl.2010.11.044

Bell, T. H., & Etheridge, M. A. (1973). Microstructure of mylonites and their descriptive terminology. *Lithos*, *6*(4), 337–348. https://doi.org/10.1016/0024-4937(73)90052-2

Bercovici, D. (2003). The generation of plate tectonics from mantle convection. *Earth and Planetary Science Letters*, *205*(3–4), 107–121. https://doi.org/10.1016/S0012-821X(02)01009-9
Bercovici, D., Mulyukova, E., Girard, J., & Skemer, P. (2023). A coupled model for phase mixing, grain damage and shear localization in the lithosphere: Comparison to lab experiments. *Geophysical Journal International*, *232*(3), 2205–2230. https://doi.org/10.1093/gji/ggac428
Bercovici, D., & Ricard, Y. (2012). Mechanisms for the generation of plate tectonics by two-phase grain-damage and pinning. *Physics of the Earth and Planetary Interiors*, *202–203*, 27–55. https://doi.org/10.1016/j.pepi.2012.05.003
Bercovici, D., & Ricard, Y. (2014). Plate tectonics, damage and inheritance. *Nature*, *508*(7497), 513–516. https://doi.org/10.1038/nature13072
Bercovici, D., & Skemer, P. (2017). Grain damage, phase mixing and plate-boundary formation. *Journal of Geodynamics*, *108*, 40–55. https://doi.org/10.1016/j.jog.2017.05.002
Bercovici, D., Tackley, P. J., & Ricard, Y. (2015). The generation of plate tectonics from mantle dynamics. In *Treatise on geophysics* (2nd ed., pp. 271–318). Elsevier Inc. https://doi.org/10.1016/B978-0-444-53802-4.00135-4
Billings, K., & Skemer, P. (2024). Evolving microstructure during experimental deformation of Maryland diabase. *Earth and Planetary Science Letters*, *627*(November 2023), 118564. https://doi.org/10.1016/j.epsl.2023.118564
Brace, W. F., & Kohlstedt, D. L. (1980). Limits on lithospheric stress imposed by laboratory experiments. *Journal of Geophysical Research*, *85*(B11), 6248–6252. https://doi.org/10.1029/JB085iB11p06248
Bystricky, M., Lawlis, J., Mackwell, S., Heidelbach, F., & Raterron, P. (2016). High-temperature deformation of enstatite aggregates. *Journal of Geophysical Research: Solid Earth*, *121*(9), 6384–6400. https://doi.org/10.1002/2016JB013011
Cross, A. J., Olree, E., Couvy, H., & Skemer, P. (2020). How does viscosity contrast influence phase mixing and strain localization? *Journal of Geophysical Research: Solid Earth*, *125*(8), 1–20. https://doi.org/10.1029/2020JB020323
Cross, A. J., Prior, D. J., Stipp, M., & Kidder, S. (2017). The recrystallized grain size piezometer for quartz: An EBSD-based calibration. *Geophysical Research Letters*, *44*(13), 6667–6674. https://doi.org/10.1002/2017GL073836
Cross, A. J., & Skemer, P. (2017). Ultramylonite generation via phase mixing in high-strain experiments. *Journal of Geophysical Research: Solid Earth*, *122*(3), 1744–1759. https://doi.org/10.1002/2016JB013801
Cross, A. J. J., & Skemer, P. (2019). Rates of dynamic recrystallization in geologic materials. *Journal of Geophysical Research: Solid Earth*, *124*(2), 1324–1342. https://doi.org/10.1029/2018JB016201
Cross, W., Iddings, J. P., Pirsson, L. V., & Washington, H. S. (1902). A quantitative chemico-mineralogical classification and nomenclature of igneous rocks. *The Journal of Geology*, *10*(6), 555–690. https://doi.org/10.1086/621030
Dijkstra, A. H., Drury, M. R., Vissers, R. L. M., & Newman, J. (2002). On the role of melt-rock reaction in mantle shear zone formation in the Othris Peridotite Massif (Greece). *Journal of Structural Geology*, *24*(9), 1431–1450. https://doi.org/10.1016/s0191-8141(01)00142-0
Etheridge, M. A., & Wilkie, J. C. (1979). Grainsize reduction, grain boundary sliding and the flow strength of mylonites. *Tectonophysics*, *58*(1–2), 159–178. https://doi.org/10.1016/0040-1951(79)90327-5
Evans, B., Renner, J., & Hirth, G. (2001). A few remarks on the kinetics of static grain growth in rocks. *International Journal of Earth Sciences*, *90*(1), 88–103. https://doi.org/10.1007/s005310000150
Foley, B. J., Bercovici, D., & Landuyt, W. (2012). The conditions for plate tectonics on super-Earths: Inferences from convection models with damage. *Earth and Planetary Science Letters*, *331*, 281–290. https://doi.org/10.1016/j.epsl.2012.03.028
Fossen, H., & Cavalcante, G. C. G. (2017). Shear zones – A review. *Earth-Science Reviews*, *171*, 434–455. https://doi.org/10.1016/j.earscirev.2017.05.002
Frost, H. J., & Ashby, M. F. (1982). *Deformation-mechanism maps: The plasticity and creep of metals and ceramics* (1st ed.). Pergamon Press.
Fusseis, F., Regenauer-Lieb, K., Liu, J., Hough, R. M., & De Carlo, F. (2009). Creep cavitation can establish a dynamic granular fluid pump in ductile shear zones. *Nature*, *459*(7249), 974–977. https://doi.org/10.1038/nature08051
Gilgannon, J., Fusseis, F., Menegon, L., Regenauer-Lieb, K., & Buckman, J. (2017). Hierarchical creep cavity formation in an ultramylonite and implications for phase mixing. *Solid Earth*, *8*(6), 1193–1209. https://doi.org/10.5194/se-8-1193-2017
Gleason, G. C., & Tullis, J. (1995). A flow law for dislocation creep of quartz aggregates determined with the molten salt cell. *Tectonophysics*, *247*(1–4), 1–23. https://doi.org/10.1016/0040-1951(95)00011-b
Green, D. H., & Ringwood, A. E. (1967). The genesis of basaltic magmas. *Contributions to Mineralogy and Petrology*, *15*(2), 103–190. https://doi.org/10.1007/bf00372052
Herwegh, M., Linckens, J., Ebert, A., Berger, A., & Brodhag, S. H. (2011). The role of second phases for controlling microstructural evolution in polymineralic rocks: A review. *Journal of Structural Geology*, *33*(12), 1728–1750. https://doi.org/10.1016/j.jsg.2011.08.011
Hill, M. L., Bott, K., Dalba, P. A., Fetherolf, T., Kane, S. R., Kopparapu, R., et al. (2023). A catalog of habitable zone exoplanets. *The Astronomical Journal*, *165*(2), 34. https://doi.org/10.3847/1538-3881/aca1c0
Hinkel, N. R., Timmes, F. X., Young, P. A., Pagano, M. D., & Turnbull, M. C. (2014). Stellar abundances in the solar neighborhood: The hypatia catalog. *Astronomical Journal*, *148*(3), 54. https://doi.org/10.1088/0004-6256/148/3/54
Hirth, G., & Kohlstedt, D. L. (2003). Rheology of the upper mantle and the mantle wedge: A view from the experimentalists. In *Inside the subduction factory*. In *Geophysical monograph series* (Vol. 138, pp. 83–105). American Geophysical Union. https://doi.org/10.1029/138gm06
Huther, W., & Reppich, B. (1973). Dislocation structure during creep of MgO single crystals. *Philosophical Magazine*, *28*(2), 363–371. https://doi.org/10.1080/14786437308217459
Karato, S. I., Jung, H., Katayama, I., & Skemer, P. (2008). Geodynamic significance of seismic anisotropy of the upper mantle: New insights from laboratory studies. *Annual Review of Earth and Planetary Sciences*, *36*(November), 59–95. https://doi.org/10.1146/annurev.earth.36.031207.124120
Kohlstedt, D. L., & Hansen, L. N. (2015). Constitutive equations, rheological behavior, and viscosity of rocks. In *Treatise on geophysics* (2nd ed.). Elsevier B.V. https://doi.org/10.1016/B978-0-444-53802-4.00042-7
Korenaga, J. (2010). On the likelihood of plate tectonics on super-Earths: Does size matter? *The Astrophysical Journal Letters*, *725*(1 PART 2), L43–L46. https://doi.org/10.1088/2041-8205/725/1/L43
Kreidberg, L., Koll, D. D. B., Morley, C., Hu, R., Schaefer, L., Deming, D., et al. (2019). Absence of a thick atmosphere on the terrestrial exoplanet LHS 3844b. *Nature*, *573*(7772), 87–90. https://doi.org/10.1038/s41586-019-1497-4
Lallemant, H. G. A., Mercier, J.-C. C., Carter, N. L., & Ross, J. V. (1980). Rheology of the upper mantle: Inferences from peridotite xenoliths. *Tectonophysics*, *70*(1–2), 85–113. https://doi.org/10.1016/0040-1951(80)90022-0
Linckens, J., Bruijn, R. H. C., & Skemer, P. (2014). Dynamic recrystallization and phase mixing in experimentally deformed peridotite. *Earth and Planetary Science Letters*, *388*, 134–142. https://doi.org/10.1016/j.epsl.2013.11.037
Linckens, J., Herwegh, M., & Müntener, O. (2015). Small quantity but large effect - How minor phases control strain localization in upper mantle shear zones. *Tectonophysics*, *643*, 26–43. https://doi.org/10.1016/j.tecto.2014.12.008

Long, M. D., & Becker, T. W. (2010). Mantle dynamics and seismic anisotropy. *Earth and Planetary Science Letters*, *297*(3), 341–354. https://doi.org/10.1016/j.epsl.2010.06.036

McKenzie, D., Jackson, J., & Priestley, K. (2005). Thermal structure of oceanic and continental lithosphere. *Earth and Planetary Science Letters*, *233*(3–4), 337–349. https://doi.org/10.1016/j.epsl.2005.02.005

Mei, S., Kohlstedt, D. L., Durham, W. B., & Wang, L. (2008). Experimental investigation of the creep behavior of MgO at high pressures. *Physics of the Earth and Planetary Interiors*, *170*(3–4), 170–175. https://doi.org/10.1016/j.pepi.2008.06.030

Mercier, J. C. (1980). Magnitude of the continental lithospheric stresses inferred from rheomorphic petrology. *Journal of Geophysical Research*, *85*(B11), 6293–6303. https://doi.org/10.1029/JB085iB11p06293

Montési, L. G. J., & Zuber, M. T. (2002). A unified description of localization for application to large-scale tectonics. *Journal of Geophysical Research*, *107*(B3), 2045. https://doi.org/10.1029/2001JB000465

Newman, J., Lamb, W. M., Drury, M. R., & Vissers, R. L. M. (1999). Deformation processes in a peridotite shear zone: Reaction-softening by an H2O-deficient, continuous net transfer reaction. *Tectonophysics*, *303*(1–4), 193–222. https://doi.org/10.1016/s0040-1951(98)00259-5

O'Neill, C., & Lenardic, A. (2007). Geological consequences of super-sized Earths. *Geophysical Research Letters*, *34*(19). https://doi.org/10.1029/2007GL030598

Passchier, C. W., & Trouw, R. A. J. (1998). *Microtectonics*. Springer-Verlag.

Putirka, K. D. (2024). Exoplanet mineralogy. *Reviews in Mineralogy and Geochemistry*, *90*(1), 199–257. https://doi.org/10.2138/rmg.2024.90.07

Putirka, K. D., Dorn, C., Hinkel, N. R., & Unterborn, C. T. (2021). Compositional diversity of rocky exoplanets. *Elements*, *17*(4), 235–240. https://doi.org/10.2138/GSELEMENTS.17.4.235

Putirka, K. D., & Rarick, J. C. (2019). The composition and mineralogy of rocky exoplanets: A survey of >4000 stars from the Hypatia Catalog. *American Mineralogist*, *104*(6), 817–829. https://doi.org/10.2138/am-2019-6787

Regenauer-Lieb, K., Yuen, D. A., & Branlund, J. (2001). The initiation of subduction: Criticality by addition of water? *Science (New York, N.Y.)*, *294*(5542), 578–580. https://doi.org/10.1126/science.1063891

Richards, M. A., Yang, W., Baumgardner, J. R., & Bunge, H. (2001). Role of a low-viscosity zone in stabilizing plate tectonics: Implications for comparative terrestrial planetology. *Geochemistry, Geophysics, Geosystems*, *2*(8). https://doi.org/10.1029/2000gc000115

Rutter, E. H., & Brodie, K. H. (1988). The role of tectonic grain size reduction in the rheological stratification of the lithosphere. In H. Zankl, J. Belliere, & A. Prashnowsky (Eds.), *Detachment and shear* (Vol. 77(1) pp. 295–308). Springer International. https://doi.org/10.1007/bf01848691

Schubert, G., Turcotte, D. L., & Olson, P. (2001). *Mantle convection in the Earth and planets*. University of Cambridge.

Sibson, R. H. (1977). Fault rocks and fault mechanisms. *Journal of the Geological Society of London*, *133*(3), 191–213. https://doi.org/10.1144/gsjgs.133.3.0191

Skemer, P. (2025). *The effect of composition on shear localization in planetary lithospheres [code]*. Washington University. https://doi.org/10.7936/6RXS-108297

Skemer, P., Warren, J. M., Hansen, L. N., Hirth, G., & Kelemen, P. B. (2013). The influence of water and LPO on the initiation and evolution of mantle shear zones. *Earth and Planetary Science Letters*, *375*, 222–233. https://doi.org/10.1016/j.epsl.2013.05.034

Skemer, P., Warren, J. M., Kelemen, P. B., & Hirth, G. (2010). Microstructural and rheological evolution of a mantle shear zone. *Journal of Petrology*, *51*(1–2), 43–53. https://doi.org/10.1093/petrology/egp057

Solomatov, V. S., & Moresi, L. (1997). Three regimes of mantle convection with non-Newtonian viscosity and stagnant lid convection on the terrestrial planets. *Geophysical Research Letters*, *24*(15), 1907–1910. https://doi.org/10.1029/97gl01682

Tackley, P. J. (1998). Self-consistent generation of tectonic plates in three-dimensional mantle convection. *Earth and Planetary Science Letters*, *157*(1–2), 9–22. https://doi.org/10.1016/s0012-821x(98)00029-6

Tasaka, M., Zimmerman, M. E., & Kohlstedt, D. L. (2017). Rheological weakening of olivine + Orthopyroxene aggregates due to phase mixing: 1. Mechanical behavior. *Journal of Geophysical Research: Solid Earth*, *122*(10), 7584–7596. https://doi.org/10.1002/2017JB014333

Tasaka, M., Zimmerman, M. E., Kohlstedt, D. L., Stünitz, H., & Heilbronner, R. (2017). Rheological weakening of olivine+ orthopyroxene aggregates due to phase mixing: Part 2. Microstructural development. *Journal of Geophysical Research: Solid Earth*, *122*(10), 7597–7612. https://doi.org/10.1002/2017jb014311

Toth, J., & Gurnis, M. (1998). Dynamics of subduction initiation at preexisting fault zones. *Journal of Geophysical Research*, *103*(B8), 18053–18067. https://doi.org/10.1029/98jb01076

Turcotte, D. L. (1996). Magellan and comparative planetology. *Journal of Geophysical Research*, *101*(E2), 4765–4773. https://doi.org/10.1029/95JE02295

Twiss, R. J. (1977). Theory and applicability of a recrystallized grain size paleopiezometer. *Pure and Applied Geophysics*, *115*(1–2), 227–244. https://doi.org/10.1007/bf01637105

Urai, J. L., Means, W. D., & Lister, G. S. (1986). Dynamic recrystallization of minerals. In B. E. Hobbs & H. C. Heard (Eds.), *Mineral and rock deformation; laboratory studies; the Paterson*, *Geophysical monograph series* (Vol. 36, pp. 161–199). American Geophysical Union. https://doi.org/10.1029/gm036p0161

Valencia, D., O'connell, R. J., & Sasselov, D. D. (2007). Inevitability of plate tectonics on super-Earths. *The Astrophysical Journal*, *670*(1), L45–L48. https://doi.org/10.1086/524012

Van der Wal, D., Chopra, P., Drury, M., & Gerald, J. F. (1993). Relationships between dynamically recrystallized grain size and deformation conditions in experimentally deformed olivine rocks. *Geophysical Research Letters*, *20*(14), 1479–1482. https://doi.org/10.1029/93gl01382

Van Heck, H. J., & Tackley, P. J. (2011). Plate tectonics on super-Earths: Equally or more likely than on Earth. *Earth and Planetary Science Letters*, *310*(3–4), 252–261. https://doi.org/10.1016/j.epsl.2011.07.029

Vauchez, A., Tommasi, A., & Mainprice, D. (2012). Faults (shear zones) in the Earth's mantle. *Tectonophysics*, *558–559*, 1–27. https://doi.org/10.1016/j.tecto.2012.06.006

Warren, J. M., & Hirth, G. (2006). Grain size sensitive deformation mechanisms in naturally deformed peridotites. *Earth and Planetary Science Letters*, *248*(1), 438–450. https://doi.org/10.1016/j.epsl.2006.06.006

White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D., & Humphreys, F. J. (1980). On mylonites in ductile shear zones. In J. Carreras, P. R. Cobbold, J. G. Ramsay, & S. H. White (Eds.), *Shear zones in rocks* (Vol. 2(1–2), pp. 175–187). Pergamon. https://doi.org/10.1016/0191-8141(80)90048-6

Wiesman, H. S., Zimmerman, M. E., & Kohlstedt, D. L. (2018). Laboratory investigation of mechanisms for phase mixing in olivine+ ferropericlase aggregates. *Philosophical Transactions of the Royal Society A*, *376*(2132), 20170417. https://doi.org/10.1098/rsta.2017.0417

Zieba, S., Kreidberg, L., Ducrot, E., Gillon, M., Morley, C., Schaefer, L., et al. (2023). No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c. *Nature*, *620*(7975), 746–749. https://doi.org/10.1038/s41586-023-06232-z