Comment on "If Not Brittle: Ductile, Plastic, or Viscous?" by Kelin Wang

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Abstract

In continuum mechanics, viscous materials are those that lack rigidity and elastic response under shear stress. We argue that using the term *viscous* to refer to the aseismic lithosphere is thus a misnomer because it denies the propagation of *S* waves through the lithosphere in total contradiction to decades of seismic surveys. Similarly, *viscous* materials lack yield stress, which is another feature expected in most situations within the aseismic lithosphere but is more difficult to assess. Aiming to reconcile the definitions of rheological terms between material and Earth and mineral sciences, we propose a decision tree chart for the use of the terms *viscous*, *viscoelastic*, *plastic*, and *viscoplastic*, all widely used terms in the materials and Earth sciences communities for describing fundamental macroscopic behavior of rocks under shear stresses.

The terms *viscous* and *frictional-viscous* transition are gaining traction lately to refer to the aseismic part of the lithosphere or the transition toward it as opposed to the term *plastic* or *brittle–plastic* transition used in seminal studies dealing with the rheology of crustal or lithospheric-scale faults (Rutter, 1986; Sibson, 1986; Scholz, 1988; Kohlstedt *et al.*, 1995). Most rock rheology and mechanics textbooks avoid the term *viscous* to refer to the permanent deformation of rocks without fracturing, using instead terms such as *plasticity*, *viscoelasticity*, or *viscoplasticity* (e.g., Jaeger *et al.*, 2007; Karato, 2008). The same applies to textbooks that deal with the rheology of all types of solids (e.g., Courtney, 2000; Malkin and Isayev, 2017). In a recent contribution, Wang (2021) discusses, among other things, which term to use to refer to the macroscopic behavior of the aseismic lithosphere, raising important points on the problem of establishing a consistent terminology in Earth sciences. Unfortunately, Wang (2021) favors the term *viscous* over others to refer to the overall rheology of the middle and lower crust through lithospheric-scale shear zones. This choice, yet again, leaves the rheology terminology inconsistent between continuum mechanics (followed in material science) and geophysics, in particular the meaning of the term *viscous*.

Problem Statement and Constraints

In continuum mechanics, *viscous* materials are those that lack elasticity (i.e., a null shear and Young's modulus) as opposed to terms such as *viscoelastic*, *viscoplastic*, or *plastic*, which all imply an initial elastic response (Fig. 1). Consequently, using the term *viscous* to refer to the lower crust and upper mantle would mean assuming a lack of elastic response in such parts of the lithosphere, in total contradiction to decades of seismic studies indicating that *S* waves propagate through the aseismic lithosphere. We think much of the confusion stems from the use of the parameter *viscosity*, widely used in rheological models of the lithosphere as a synonym for macroscopic *viscous* behavior. Additional problems in establishing a clear terminology in this respect, somewhat already pointed out in Wang (2021) are: (1) the definition of a *plastic* behavior does not present a consistent definition across or even within the same (e.g., Earth sciences) scientific branch and (2) the introduction of the term *yield stress* in brittle deformation (Coulomb plasticity model).

The aim of this contribution is twofold:

1. Propose guidelines to refer to the fundamental macroscopic behavior of rocks under shear stresses within the aseismic part of the lithosphere.
2. Keep the meaning of the terms consistent across different branches of science.

Because the topic of material behavior can be approached from different points of view, it is necessary to specify what we mean here with macroscopic material behavior. In the past, most terminology to refer to the lithosphere was based on two different concepts (e.g., Rutter, 1986; Blenkinsop, 2000): (1) how strain distributes, that is, the degree of homogeneity of strain on a macroscopic scale or (2) deformation mechanisms at the microscopic scale. The former uses terms such as *ductile* or *brittle deformation*, whereas the latter uses terms such as *intracrystalline plasticity*, *cataclasis*, or *mass transfer*. The problem with terminology based on the degree of homogeneity was already addressed by Rutter (1986) and covered by Wang (2021), and thus will not be considered again here. Terminology based on deformation mechanisms refers primarily to phenomena occurring at the nano- and microscale, and scaling these phenomena

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to the macroscale is complex, first, because different deformation mechanisms may coexist during deformation, and second, because different deformation mechanisms or combinations between them can result in a rather similar (macroscopic) rheological behavior.

For the sake of simplicity, we will limit to basic terms such as *elastic*, *plastic*, *viscous*, and their combinations, which are all well entrenched in the material and Earth sciences communities and serve to describe the fundamental macroscopic rock behavior under shear stresses.

Viscous versus Plastic Definition and Their Combinations

The basis for understanding *viscous* behavior is:

1. Viscous materials resist no shear stress and thus flow under any shear stress. Accordingly, the degree of permanent deformation depends on how much time has passed, and a material undergoing viscous flow is said to be *time dependent*.
2. For fixed stress (or applied force), the strain rate primarily depends on temperature. Therefore, material undergoing viscous flow is said to be strongly *temperature dependent*.

When the strain rate is linearly proportional to the applied stress, the behavior is said to be Newtonian or linear; otherwise it is said to be non-Newtonian or nonlinear. In the basic mathematical expression representing a linear viscous behavior,

$$\tau = \mu\dot{\gamma}, \tag{1}$$

in which the τ is the shear stress, $\dot{\gamma}$ is the shear-strain rate, and μ is the viscosity that accounts for the resistance of the material to flow (μ = shear-stress ÷ shear-strain rate). In particular, the shear-strain rate accounts for the time dependency of the flow ($d\gamma/dt$), whereas the viscosity for the temperature dependency commonly through an Arrhenius-type equation of the type $\mu = \mu_0 \exp(Q/RT)$, with Q being the activation energy, R the gas constant, and T the absolute temperature. The concept of stiffness (or strength) has no meaning in viscous materials because their rigidity (shear) modulus is by definition zero, and any shear stress will cause permanent deformation, that is, they behave like fluids, and indeed, this is the definition of *fluid* in continuum mechanics. Because of the time dependence of the deformation, it is not possible to derive the magnitude of the stress from the attained strain because any stress can result in any strain given sufficient time. Stress is thus related to strain rate via *viscosity*.

The core idea behind *plastic* deformation is that the material needs to reach a threshold shear stress value, called *yield stress*, to deform permanently. Below this threshold, the material undergoes recoverable (i.e., elastic) deformation under shear stresses; we ignore on purpose here the *rigid-plastic* model (e.g., Jaeger *et al.*, 2007) for which no elastic response exists before reaching permanent deformation because it is unrealistic in materials. As anticipated, *plastic* behavior is not as consistently defined as *viscous* or *elastic* across earth science textbooks. For example, some use a restrictive definition in which the plastic behavior requires constant stress for the material to deform at a constant strain rate above the yield stress (e.g., Stüwe, 2007). Most material science and structural geology textbooks, however, refer to this behavior as *perfectly plastic* and present the term *plastic* (or *general plastic*) as less restrictive by allowing the material to harden or soften during the inelastic stage and thus varying the strain rate over time (Poirier, 1985; Jaeger *et al.*, 2007; Twiss and Moores, 2007; Karato, 2008).

The value of yield stress in the stress–strain space, which defines the elastic-to-plastic transition, depends on temperature (e.g., Paterson, 1958; Frost and Ashby, 1982), and thus plastic behavior is by definition strongly temperature dependent. Because there is a threshold shear stress for producing permanent deformation, plastic behavior is said to be *time independent*; which means that if the shear stress is below the yield stress, no permanent deformation occurs irrespective of the time that has passed. However, it should be noted that the amount of permanent deformation produced at shear stresses above the yield stress is only a matter of time, and deformation becomes time dependent (Courtney, 2000), blurring the difference between *viscous* and *plastic* behavior, especially for materials exhibiting very small yield stresses. However, it is possible to distinguish the time dependence in both cases by conducting an unloading exercise (e.g., Cooper *et al.*, 2016).

Viscoelastic refers to materials that display both elastic and viscous properties depending on the time scale of the deformation. On short-time scales (e.g., seismic waves), viscoelastic materials behave elastically, whereas at large-time scales, they behave viscously (e.g., mantle convection) (Fig. 1). Viscoelasticity is therefore a time- and temperature-dependent material behavior.

Viscoplastic (or *elastoviscoplastic or viscoelastoplastic*) refers to materials that display elastic behavior below the yield stress and linear (steady state) viscous behavior above the yield stress. The difference with a *viscoelastic* material is that it requires exceeding the yield stress to undergo permanent deformation. Another way of looking at this is that the viscosity of the material below the yield stress tends to infinity but above it has a defined and constant value (at given P, T, and composition). Thus, under constant shear stress, viscoplasticity implies a temperature-dependent deformation of the material and a time-independent or time-dependent deformation below and above the yield stress, respectively.

A Flow Decision Chart for Aseismic Lithosphere Rheology

To ensure consistent terminology between geosciences and materials sciences, the term *viscous* should be reserved only for the behavior of melts in the lithosphere (Dingwell, 2006). This should not be confused with the use of the parameter

LACK OF ELASTICITY	ELASTIC RESPONSE	
	NO YIELD STRESS	HAS YIELD STRENGTH
VISCOUS	VISCOELASTIC	VISCOPLASTIC / PLASTIC
FLUIDS		SOLIDS
Time-dependent deformation		Time-independent deformation*

*At shear stresses above the yield strength plastic-like deformation is time-dependent (e.g., Courtney 2000)

Figure 1. Key features of the terms *viscous*, *viscoelastic*, *viscoplastic*, and *plastic* as defined in continuum mechanics and material sciences. The color version of this figure is available only in the electronic edition.

viscosity for modeling solid rock macroscopic response to shear stress, which is perfectly valid and indeed used in viscoplastic and viscoelastic numerical models. This point will be discussed further in the Subtleties and Final Remarks section. By the same logic, the use of the term *frictional-viscous* to refer to crustal or lithospheric-scale faults (Schmid and Handy, 1991; Imber *et al.*, 2001; Handy *et al.*, 2007) should be avoided. Interestingly, in the synoptic fault model that likely causes the spreading of this term in the geophysics community (figure 6.7 in Handy *et al.*, 2007), it is stated that the rocks outside the *viscous* shear zone fall “below the rock yield stress,” conflicting with the definition of the term *viscous* in continuum mechanics and materials sciences (Fig. 1).

To refer to the fundamental macroscopic behavior of rocks in the aseismic lithosphere, we propose a decision flowchart mainly built around two different concepts: the presence or lack of elasticity and yield strength (both related to the time dependency of deformation; Fig. 2). The ultimate goal is to standardize the meaning of these terms to send a clear message of what is meant when the terms are used. Similarly, we need to emphasize that it should always be specified when rocks under study (1) possess elasticity and a certain degree of rigidity (i.e., yield stress or a positive stiffness modulus), (2) possess elasticity and rigidity but can be ignored in the model, or (3) lack any strength at the time scale of observation (i.e., only have rigidity at short—seismic—time scales). The terminology proposed refers to the macroscopic behavior and is independent of deformation mechanisms and strain distribution.

Subtleties and Final Remarks

Most of these terminology issues in the realm of rheology primarily exist because fluids and solids are idealized. As such, the boundary between the two blurs under certain circumstances, with real materials exhibiting a mixture of liquid- and solid-like properties (e.g., partially molten rocks with low-melt fractions). Another subtler but very important rheological concept for the Earth sciences is the characteristic time scale under stress measured by the Deborah number (Poirier, 1985; Twiss and Moores, 2007; Malkin and Isayev, 2017). Thus, depending on the time scale of observation, a material can be treated as solid or fluid. For example, a rock that behaves like a solid in a deformation experiment might flow macroscopically like a fluid under very small stresses and over very long periods as shown in a few long-term (several years) creep tests in granite and gabbro bars (Kumagai and Itô, 1968; Itô, 1979). In other words, the same rock may exhibit elasticity at high stresses (and then short-time scales) but also exhibit yield strength (solid-like behavior), for which value decreases with decreasing applied stress until it becomes negligible at very low-differential stresses and thus start to behave like an extremely flow-resistant fluid (e.g., Deborah’s number). As noted earlier, the general propagation of *S* waves through the lithosphere indicates that rocks do possess rigidity at short time scales. The only question then is whether the rocks in the aseismic lithosphere behave as *viscoelastic* or as *plastic* or *viscoplastic* materials or, to put it another way, whether they exhibit yield stress at deformation rates typical of lithospheric shear zones (Figs. 1 and 2). The presence or lack of yield stress in the aseismic lithosphere is, however, a tougher issue and should be primarily confronted with evidence in nature because in the laboratory, it is impossible to reach strain rates typical of plate tectonics, within the range of 10^{-13} to 10^{-15} s^{-1} (Pfiffner and Ramsay, 1982).

Another source of misunderstanding is that deformation models are often placed in the same category of describing the macroscopic material response to shear stress in terms of forces, stresses, strain rates, and/or strain. We think they are essentially different. The aim of establishing a rheological terminology is to provide a framework for understanding or conveying how a material deforms macroscopically under certain conditions in a qualitative manner. In contrast, models are mathematical idealizations of material behavior, and as such, their drive is to produce accurate enough predictions in a particular context at the cost of ignoring certain variables to simplify or just being mathematically tractable (compare to Ben-Zion, 2017), for example, ignoring the elastic response or the yield stress. An illustrative example of this would be the successful use of a viscous framework to predict the behavior of rocks under coseismic fault lubrication observed in laboratory experiments (Pozzi *et al.*, 2021). In this case, the viscous model provides useful predictions of the process, but no one would argue that the suite of rocks tested (carbonates, sulphates, halides, and silicates) lacks elastic properties at upper crustal

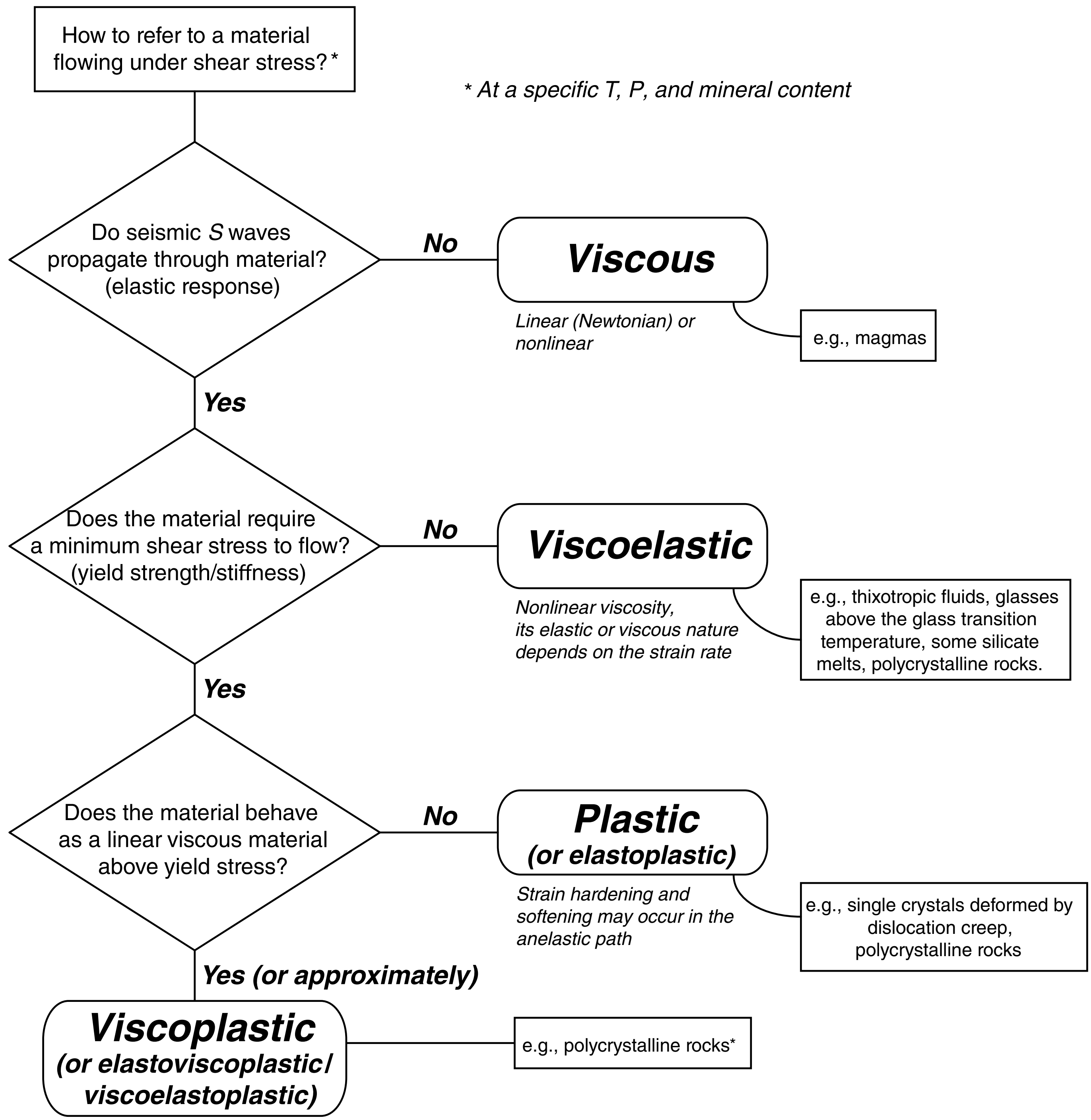

Figure 2. Decision flowchart on which rheological term to use to refer to the aseismic flow of rocks based on the macroscopic behavior under shear stress.

conditions. It is the lubrication process that shows viscous-like behavior, not the material itself. It is also important to recall that using the parameter *viscosity* to model the material response does not necessarily mean that the material has a *viscous* or perfect fluid-like behavior. The viscosity parameter is used indistinctly in *viscous*, *viscoelastic*, and *viscoplastic* models, for example, in the *Bingham*, *Casson*, and *Hershel–Bulkley* rheology models, all of which include a parameter defining the yield stress (Malkin and Isayev, 2017).

Finally, Wang (2021) raised another potential source of misunderstanding in the geophysics community, which is the use of the concept *yield stress* or yield *strength* within the brittle domain, that is, the Coulomb plasticity model.

The use of the term *yield stress* in such a way conflicts with material sciences and metallurgy, in which some materials fracture before *yielding*, and *yielding* can be favored by imposing a higher hydrostatic stress field limiting or suppressing the development of porosity and dilatancy caused by the fracturing process (e.g., Malkin and Isayev, 2017; Courtney, 2000). That is, they separate brittle failure (elastic to fracture transition) from *yielding* (elastic-to-plastic or -viscous transition), which strictly speaking would lead to a permanent deformation with a strong temperature dependency and no volume (or negligible) increase (Paterson, 1967). A similar distinction was made for rocks by Paterson and Wong (2005). In Earth sciences, the coefficient of internal friction in Coulomb's law is usually presented as almost independent of temperature and resulting in pressure dependence due to dilatancy (Paterson and Wong, 2005). Yet again, the aim here is to propose unambiguous terminology, not to question the utility of Coulomb's plastic model. For clarity, we suggest that if the terms *yield stress* or yield *strength* are used in this sense in Earth sciences, it should always be paired with the adjective *brittle* or, preferably, referred to as *Coulomb yield stress*.

In essence, the two provided figures capture the core message of the article. The ultimate goal is that when an Earth scientist uses one of these rheology terms, it sends an unambiguous message about its meaning that is in line with other branches of rheology.

Data and Resources

No data were used in this article.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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