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# Sediment control on subduction plate speeds

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ABSTRACT

Tectonic plate velocities predominantly result from a balance between the potential energy change of the subducting slab and viscous dissipation in the mantle, bending lithosphere, and slab–upper plate interface. A range of observations suggest that slabs may be weak, implying a more prominent role for plate interface dissipation than previously thought. The shallow thrust interface is commonly assumed to be weak due to an abundance of fluids and near-lithostatic pore fluid pressures, but little attention has been paid to the influence of the deeper, viscous interface. Here we show that the deep interface viscosity in subduction zones is strongly affected by the relative proportions of sedimentary to mafic rocks that are subducted to depth. Where sediments on the down-going plate are sparse, the deep interface is dominated by mafic lithologies that metamorphose to eclogites, which exhibit viscosities 1–2 orders of magnitude higher than the asthenospheric mantle, and reduce subduction plate speeds. In contrast, where sediments are abundant and subducted to depth, the deep interface viscosity is 1–2 orders of magnitude lower than the asthenospheric mantle, thus allowing significantly faster plate velocities. This correlation between subduction plate speed and deep sediment subduction may help explain dramatic accelerations (or decelerations) in convergence rates, such as the acceleration documented for India–Asia convergence during the mid-Cenozoic.

## 1. Introduction

Sediment subduction at convergent plate boundaries has long been recognized to play an important role in the dynamics of our planet. Sediments occupying the shallow (seismogenic) subduction interface, for example, appear to influence seismic coupling and the frequency of megathrust earthquakes (e.g. Moore and Saffer, 2001; Heuret et al., 2012), as well as the mechanics and morphologies of accretionary prisms and forearc basins that occupy subduction fronts (e.g. von Huene and Scholl, 1991; Melnick and Echtler, 2006; Simpson, 2010). Sediments subducted to greater depth are essential in the generation of melt, the growth of continental crust, and the cycling of volatiles from Earth's crust and atmosphere to its deep interior (e.g. Hawkesworth et al., 1997; Plank and Langmuir, 1998). Furthermore, because sedimentation patterns are controlled by the distributions of landmasses and their topography, and surface processes such as weathering, erosion, and biologic productivity (themselves sensitive to climate), sediment subduction represents one of several systems that can exhibit feedbacks between plate tectonics, climate, and life.

Sediment subduction has been suggested to play a particularly important role in weakening or lubrication along the shallow frictional megathrust in modern subduction zones. A range of geophysical, geological and experimental observations suggest that subducted sediments are frictionally weak and/or exhibit high pore fluid pressures (e.g. Kopf and Brown, 2003; Bangs et al., 2009; Tobin and Saffer, 2009). Through their effects on interface shear strength, sediments may control the transmission of stress between the down-going slab and the overriding plate, thus affecting the trench state (advance or retreat), and the upper plate topography and strain regime (von Huene and Scholl, 1991; Clift and Vannucchi, 2004; Beaumont et al., 1999). This sets up interesting potential feedbacks between upper plate uplift patterns and the processes that control sediment supply to the subduction trench. Lamb and Davis (2003), for example, suggested that changes from a sediment-rich to sediment-starved subduction regime during Cenozoic climatic cooling may have been responsible for the rise of the Andean mountain belt. Shorter timescale variations in trench-forearc interactions in the Andes have also been correlated to climate-driven denudation of upper plate topography (Melnick and Echtler, 2006).

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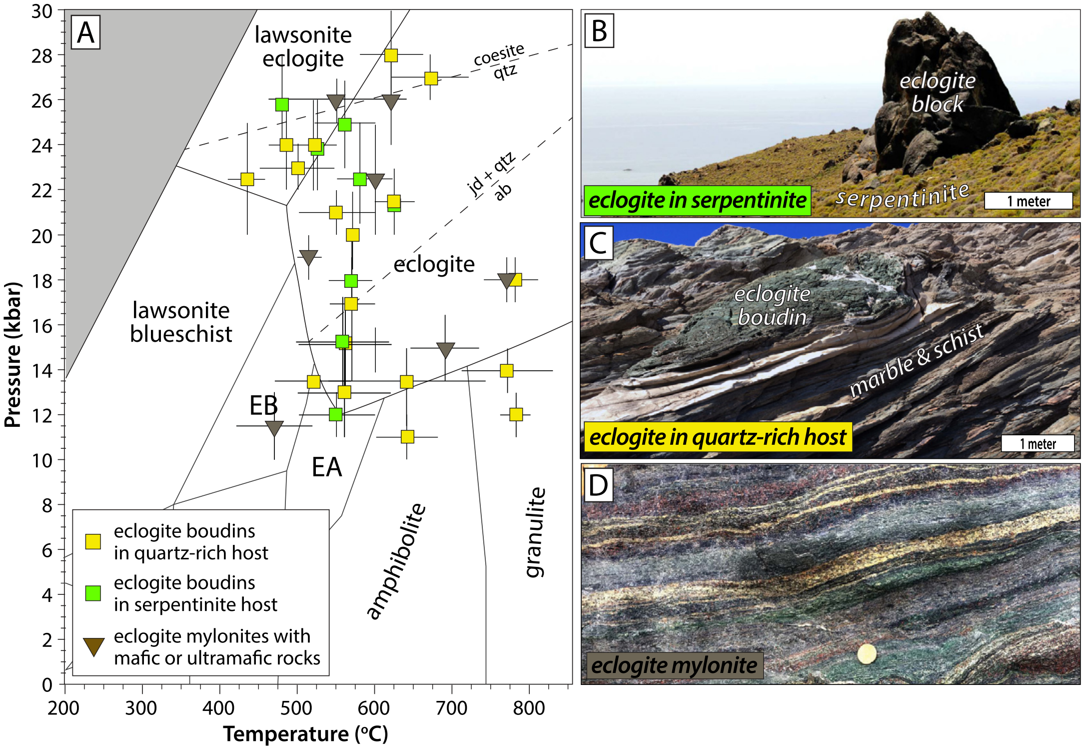

**Fig. 1.** [A] Compilation from the literature of the range of $P$–$T$ conditions at which metabasic rocks metamorphosed to eclogite occur in exhumed subduction complexes, color-coded by context/host rock. [B–D] Field photographs of eclogites in the same range of contexts from the Cycladic Blueschist Unit on Syros Island, Greece. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

A corollary of the role of sediments in lubricating the plate interface is that they should also promote faster subduction speeds. Subducting plate velocities predominantly result from a balance between the potential energy change of the subducting slab, and viscous dissipation in the mantle, bending lithosphere, and slab–upper plate interface. Efforts over the past two decades have focused on quantifying dissipation due to slab bending, originally considered to be one of the largest dissipation sources (e.g. Conrad and Hager, 1999; Becker et al., 1999; Capitanio and Morra, 2012; Garel et al., 2014). By contrast, plate interface dissipation has largely been assumed negligible, partly because of the inference of strong slabs and partly because of the low shear stresses inferred for sediments along the shallow interface (Conrad and Hager, 1999; Duarte et al., 2015). Here we suggest, however, that a reconsideration of the role of the plate interface in controlling plate speeds is warranted for two reasons. Firstly, several recent observations suggest that slabs may in fact be weaker than previously recognized (e.g. Čižková et al., 2002; Wu et al., 2008; Buffett and Becker, 2012; Holt et al., 2015), implying a more prominent role for the plate interface. Secondly, in all subduction zones, the slab–upper plate interface must transition downdip at some depth to a viscous shear zone where rock strength is more sensitive to factors that influence viscosity, such as protolith rock type, temperature, strain rate, water fugacity, and deformation mechanism. This means that even in regions where the shallow frictional interface is weak, resistance to subduction may still be imparted down-dip below the frictional–viscous transition.

In this paper we explore the role of the viscous slab–upper plate interface (herein referred to as the 'deep plate interface') in influencing subduction plate speeds. We first use compiled field observations and experimental data to demonstrate that the deep interface viscosity in subduction zones should be strongly affected by the relative proportions of sedimentary to mafic rocks that are subducted to depth. We then evaluate the effects of different interface viscosities on subduction plate speeds for a range of subduction parameters, including upper plate thickness, and slab strength, age, length, and viscosity. We discuss the implications for modern subduction zones, explore potential feedback mechanisms between sediment subduction and other subduction parameters, and suggest the possibility that subduction of equatorial sediments may have driven the well-documented mid-Cenozoic acceleration of India.

## 2. Viscosity contrast as a function of subducted protolith

Observations from drilling, seismic imaging, and exhumed rocks indicate that the subduction interface can be occupied by a range of rock types derived from mafic oceanic crust, pelagic sedimentary cover, siliciclastic trench fill, and hydrated ultramafic rocks. The most common sedimentary protoliths that occupy the top of subducting slabs in modern subduction zones are argillites and greywackes, silicious oozes and cherts, and pelagic carbonates (e.g. Clift, 2017). With progressive subduction, these protoliths metamorphose to produce schists with variable quartz-mica ratios, meta-cherts, and marbles, respectively. Subducted igneous protoliths derived from the oceanic crust, on the other hand, commonly consist of basalts and gabbros, which metamorphose to form metabasites. In particular, at depths where pressure ($P$) and temperature ($T$) conditions approach $> 450\,^\circ\mathrm{C}$ and $> 12$ kbars, the metabasites dehydrate to form eclogites, which are exceptionally dense rocks composed primarily of omphacitic pyroxene and garnet (Fig. 1). In instances where ultramafic material has been incorporated into the interface shear zone, it is very commonly hydrated to produce serpentinite minerals.

Field observations suggest that these variations in subducted protolith and their metamorphic equivalents result in viscosity variations along the deep subduction interface. Viscosity contrasts between mixed heterogeneous materials can be recognized in outcrop by examining fold wavelengths and boudinage (e.g. Smith, 1977): materials with high viscosity contrast relative to their sur-