Dehydration-induced rheological heterogeneity and the deep tremor source in warm subduction zones

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ABSTRACT
We present observations from an exhumed subduction complex that resembles the environment of modern deep episodic tremor and slow slip (ETS). We focus on the Cycladic Blueschist Unit on Syros Island in Greece. Syros metabasites consist of blueschists and eclogites that record prograde deformation, with peak metamorphism of 1200–1600 MPa and 450–550 °C. Field observations reveal that coexistence of blueschist and eclogite sets up an important rheological contrast: blueschists show distributed viscous dislocation creep, whereas eclogites dispersed within the blueschist matrix show brittle shear fractures and veins. These observations are consistent with the inferred prominent role of high fluid pressures from geophysical studies, but are inconsistent with models of deep ETS that invoke changes in rate-and-state friction parameters along a narrow fault. Instead, we suggest deep ETS may be controlled by coupled brittle-viscous deformation in partially eclogitized oceanic crust embedded within high-fluid-pressure patches along the plate interface.

INTRODUCTION
Episodic tremor and slow slip (ETS) is observed in several subduction zones down-dip of the locked megathrust, and may provide clues for preparatory processes before megathrust rupture. ETS consists of geodetically detected, slow slip that is accompanied by swarms of low-frequency earthquakes that lack distinct impulsive phases, known as tectonic tremor (Peng and Gomberg, 2010; Thomas et al., 2016). These events are most commonly observed in warm subduction zones where they occur periodically, and where they occupy a significant depth interval around the mantle wedge corner (Hyndman et al., 2015). A wide range of mechanisms have been proposed to explain ETS, including changes in frictional properties from velocity-weakening to strengthening (Shibazaki, 2003; Rubin, 2008; Segall et al., 2010), fluid migration/pulsing (Brown et al., 2005), silica enrichment and mineralization in veins (Audet and Burgmann, 2014), metamorphic reactions (Burlini et al., 2009; Brantut et al., 2011), and fracture and viscous flow within mixed-mode shear zones (Hayman and Lavier, 2014). All of these mechanisms invoke rheological heterogeneity, but there are more proposed mechanisms for ETS than observations to distinguish among them. Here we present data from an exhumed subduction shear zone that closely resembles the geologic environment of modern ETS, and discuss implications for the rock behavior that controls ETS.

GEOLOGIC SETTING
The Mediterranean Island of Syros, Greece, consists of a series of tectonic slices associated with Eocene-Oligocene oceanic and continental subduction, and Miocene-to-present backarc extension along the Hellenic subduction zone (Fig. 1) (Papanikolaou, 2013). The rocks on Syros belong to the Cycladic Blueschist Unit (CBU) and include metabasites, metasediments, and metaserpentinites, most of which are deformed and tectonically stacked into northwest-striking nappes. The CBU on Syros has been metamorphosed to blueschist and eclogite facies, with selective blueschist and greenschist facies overprinting during exhumation (Keiter et al., 2004; Schumacher et al., 2008). Previous work suggests that Syros records (1) prograde deformation to high strain during subduction, (2) early syn-subduction exhumation within a subduction channel, and (3) exhumation during regional detachment faulting (Rosenbaum et al., 2002; Parra et al., 2002; Jolivet et al., 2003; Keiter et al., 2004; Laurent et al., 2016). Although top-to-the-east/northeast kinematics associated with exhumation are most prominent in the CBU, prograde deformation fabrics are preserved in several localities on Syros, as evidenced by (1) pristine preservation of eclogite paragenesis, (2) preservation of high-pressure pseudomorphs (lawsonite, aragonite) that are post-kinematic or only weakly strained, and (3) north-south lineations consistent with subduction kinematics (Keiter et al., 2004). We focus on one such locality comprising metamafic rocks from the western side of the island near the town of Kini.

FIELD AND MICROSTRUCTURAL OBSERVATIONS
The Kini exposure is an ~1 km² lens of blueschist and eclogite-facies metabasites bounded on the south and east-northeast by retrogressed metasediments. The outcrops occur along a 400 m stretch of wavecut slopes up to 10 m in height. The Kini rocks are dominantly blueschists that exhibit a penetrative, moderately south-dipping foliation (S₁) and south-plunging lineation (L₁) defined by aligned glaucophane, epidote,
and phengite. Tight to isoclinal folds with axial planes subparallel to the Sfoliation, and hinges parallel to the Ll lineation, are common. Locally, the Sfoliation is overgrown by undeformed, blocky lawsonite pseudomorphs (Fig. DR1c in the GSA Data Repository). In some places, the Sfoliation is broadly warped into upright folds with steeply dipping, northeast-striking axial planes and a weak crenulation cleavage (Ss) (Fig. DR1b).

Omphacite-garnet–rich lenses and pods (we refer to these as eclogites), with varying concentrations of glaucophane, epidote, and phengite, decorate the primary foliation. In some areas, eclogite is intercalated with blueschist at the centimeter scale, forming knobby porphyroclasts extended and winged parallel to the foliation. In other places, they form discrete boudins up to 50 cm in diameter (Fig. 2A). Eclogite blocks are also observed as float, ranging in diameter from 1 to 2 m. In contrast to the matrix blueschists, the eclogites are coarser-grained and massive, and exhibit dilational and shear fractures oriented at low to intermediate angles to the foliation (Figs. 2A–2C). This brittle deformation is accompanied by ductile flow in the surrounding blueschist, and is associated with veins filled with quartz, white mica, glaucophane, and/or chlorite (Figs. 2A and 2B).

In thin section, the blueschists consist of alternating layers of aligned epidote and glaucophane (with minor garnet, quartz, and rutile) with grain sizes in the range of 50–300 µm. Two blueschists were analyzed using electron backscatter diffraction (EBSD) to quantify intracrystalline strain and lattice preferred orientations (LPO). Both glaucophane and zoisite show evidence for intracrystalline plasticity, including undulose extinction, bulging grain boundaries, subgrain formation, new strain-free grains, and LPOs (Figs. 2D, 2F, and 2G). Eclogites consist primarily of garnet and omphacite, with grain sizes in the range of 300–1000 µm and minor quartz, chlorite, and/or phengite precipitated in veins. Some veins exhibit evidence for incremental growth under changing fluid compositions (Fig. 2E). Omphacites show brittle fracture, undulose extinction, and some marginal recrystallization. Garnets are undeformed or exhibit intracrystalline fractures. The contacts between blueschists and eclogites are gradational and do not show evidence for disequilibrium.

**DEFORMATION CONDITIONS**

Previous estimates of peak metamorphic conditions on Syros show good agreement in temperature (T = 450–550 °C), but span more than 1000 MPa in pressure (P) (Trolet et al., 2001; Schumacher et al., 2008). To precisely constrain peak P for rocks at Kini, we used quartz-in-garnet inclusion barometry (Kohn, 2014; Ashley et al., 2016). This technique is based on quantification of residual pressures of inclusions using laser Raman spectroscopy. Residual pressures are correlated with entrainment pressure through knowledge of the P-T dependence of molar volumes in the inclusion (quartz) and host phase (garnet) and the shear modulus of the host phase. Two blueschists and two eclogites from Kini were measured (see Data Repository); results overlap within error and span 1250–1550 MPa. The overlap in P between samples suggest the assemblages were in equilibrium, consistent with the lack of evidence for textural disequilibrium. The variation in facies likely represents slight differences in bulk composition (Fig. DR3), as well as incomplete dehydration due to overlap in P-T space near the blueschist-eclogite transition (Fig. 3). Silica concentrations in phengite are also consistent with the S fabric and coeval brittle structures in eclogites forming at high-P conditions. Phengites in blueschists, massive eclogite pods, and dilational veins cutting eclogite overlap each other in the range of 3.35–3.50 Si atoms per formula unit (Fig. DR4), values consistent with many other high-P terranes globally.

**INTERPRETATION**

Figure 3 shows the P-T conditions of the Kini rocks superimposed on P-T paths for the Cascadia and Mexico (North America) subduction zones. The estimated conditions overlap the modeled geotherm and depth range of ETS for both regions. Additionally, the co-stability of blueschist and eclogite at Kini is consistent with interpretations of the seismic low-velocity layer (LVL) observed along the plate interface in many subduction zones, and that commonly coincides with the tremor source region (Song et al., 2009). Several studies suggest the LVL represents partially hydrated metabasalts like those observed at Kini (Abers, 2005; Hansen et al., 2012). Furthermore, the abundant evidence at Kini for high fluid
content and near-lithostatic pore fluid pressures, in the form of dilational fractures, is consistent with high $V_p/V_s$ ratios associated with the LVL and commonly also inferred for tremorgenic regions (Kodaira et al., 2004; Shelly et al., 2006). These consistencies in $P$-$T$-fluid pressure conditions, the overlap in depth, and the penetrative high strain lead us to interpret the Kini exposure as a ‘geological snapshot’ of a subduction shear zone formed in the deep tremor source region. As such, we can use our observations to place constraints on (1) the constitutive laws that may govern subduction shear zone strain in oceanic crustal rocks at this depth, and (2) the types of rheological heterogeneities that may contribute to ETS mechanisms.

**Bulk Rheology of Subducted Oceanic Rocks**

The behavior of the subduction interface in the ETS source region is most commonly parameterized as frictional slip on a planar fault. ETS-like behavior has been produced within a rate- and state-friction framework for a variety of constitutive laws that describe, for example, velocity-weakening friction, dilational faults that are sensitive to slip speed, or rate-dependent transitions from velocity weakening to strengthening (Shibazaki and Shimamoto, 2007; Beeler, 2009; Hawthorne and Rubin, 2013). The Kini data suggest, however, that oceanic crustal rocks at conditions similar to the deep tremor source deform via distributed shear in a ductile shear zone. Furthermore, the observation of intracrystalline plasticity and LPOs in the Kini blueschists (Fig. 2) suggests the bulk deformation mechanism was viscous dislocation creep. Flow law parameters for dislocation creep in amphibole and epidote are not constrained, highlighting a significant gap in our knowledge of subduction rheology. However, lab and theoretical studies on all other crustal and mantle minerals indicate that dislocation creep is stress-dependent, with stress exponents ranging from 3 to 5 (Poirier, 1985), thus suggesting that the bulk plate interface in the tremor source may be dominated by power-law viscous creep. The distinction between power-law creep and rate- and state friction becomes important to understanding ETS, as it is likely to affect rates/spatial distribution of stress loading, rates/mechanisms of healing, and rates/pathways of fluid diffusion. It also raises a potential role for anisotropy associated with viscous fabric development in affecting ETS behavior.

**Rheological Heterogeneities in the Subduction Shear Zone**

Although the fabrics preserved at Kini suggest deformation occurs in bulk by viscous creep, our observations also indicate that partial dehydration to eclogite sets up an important source of rheological heterogeneity. First, dehydration to form eclogite causes viscous hardening relative to the surrounding blueschists; and second, high fluid pressures resulting from dehydration lower the brittle yield strength of the eclogite relative to its viscous strength. The dehydration process from blueschist to eclogite is thus a form of ‘reaction hardening’ in which metamorphism modifies the mechanics of the deforming system (cf. Hobbs et al., 2010).

The role of coupled frictional-viscous deformation in affecting seismic style has been discussed in several recent observational and modeling studies (Hayman and Lavier, 2014; Fagereng et al., 2014; Fagereng and den Hartog, 2017). Hayman and Lavier (2014), for example, demonstrated that plastic failure of rigid inclusions within a viscous matrix could generate periodic strain transients that closely resemble slow slip. Block-and-matrix-style deformation similar to what we describe here is very common in shallow interface mélanges, including those formed under conditions analogous to zones of modern shallow slow slip (Fagereng et al., 2014). This deformational style has also been described for other settings involving varying subducted rock types and eclogitization (Angiboust et al., 2011). The observations from Syros substantiate the suggestion that brittle-viscous flow is an important component of ETS behavior. However, the development of coupled brittle-viscous flow does not necessarily require substantial lithological variations in the subducted protolith—the Syros case demonstrates that these heterogeneities can arise spontaneously in a single oceanic protolith during the dehydration process.

**Scaling Up to Modern Geophysical Observations**

Seismological observations from modern subduction zones suggest that the source areas of low-frequency earthquakes that compose tremor are on the order of hundreds of meters (Bostock et al., 2012; Thomas et al., 2016). Although the eclogite pods at Kini are 1–2 orders of magnitude smaller, there are two ways in which these heterogeneities could scale up to produce larger seismic signals. First, the data from Kini suggest a wide distribution of pod sizes, with the maximum limited by the 5–6 m of structural thickness exposed. Other metamafic lenses on Syros, however, while significantly retrogressed, are structurally thicker, extend for greater distances along strike (Fig. 1), and exhibit proportionally larger relict eclogite domains (up to 30 m in diameter). In principle, the extreme upper limit to the size of mafic eclogite domains will be the thickness of the oceanic crust on the downgoing slab (5–10 km). Preservation of very large eclogite domains in the rock record may be uncommon, however, because of biases in what is underplated and exhumed back to the surface. The second possibility takes into account that the tremor signal does not have to be sourced from a single eclogite pod. Brittle shear slip events as described at Kini have the potential to communicate and migrate along- and across-strike, either via stress concentrations and viscoelastic response, or through generation of porosity waves within the viscous matrix (e.g., Skarbek and Rempel, 2016; Webber et al., 2018). Thus, even where eclogite lenses are small, slip from several pods rupturing in close proximity may accumulate to produce tremor sequences and/or patches of combined tremor and slow slip. In this case, the length scales of ETS events would be controlled by upper plate permeability (which in turn controls fluid pressures along the interface), and distributions and effective contiguity (controlled in part by matrix rheology) of individual eclogite lenses.

**CONCLUSIONS**

Our observations from an exhumed subduction complex provide insight into the geologic environment of ETS in warm subduction zones. Syros rocks demonstrate that the bulk rheology of metabasic rocks within the interface shear zone at tremor source depths can be governed by power-law viscous flow, and that dehydration of blueschist to form eclogite sets up a source of rheological heterogeneity that can lead to combined brittle-viscous shear, potentially resembling episodic tremor and slow slip.

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*Figure 3. Pressure-temperature conditions of Kini (Syros, Greece) samples superimposed on modeled geothermal gradients for Cascadia and Mexico (North America; Syracuse et al., 2010) and the observed depth range of episodic tremor and slow slip (ETS) for both regions (Audet and Kim, 2016). EB—epidote blueschist; EA—epidote amphibolite; GS—greenschist.*
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