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Punctuated energetics of dehydration contributes to slow earthquake phenomena

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ABSTRACT

The prograde breakdown of hydrous minerals like lawsonite is energy-intensive and releases fluids at depths coincident with extensive slow earthquake phenomena for many subduction geotherms. However, there remains inconsistency between the spatial occurrence and inferred temporal rates of these dehydration reactions relative to the episodic character of slow earthquakes. The example of lawsonite breakdown shows that dehydration reactions will dictate heat consumption, thus buffering the rate of temperature increase for a rock undergoing intervals of metamorphism (<30 °C) and delaying each small increment (~1 °C) of fluid release. A nonlinear behavior is predicted involving periods of fast fluid release paused by periods of slower heat absorption. Such stepped reaction progress is consistent with natural rock textures of lawsonite breakdown indicating intermittent fluid-present crack propagation and associated step changes in mineral growth. Pulsed fluid flow into rocks of heterogeneous permeability may result in stress build-up enabling crack propagation and slip at different scales. Energetics of punctuated dehydration and resultant fluid flow match temporal and spatial characteristics of slow slip behavior. Consequently, episodic dehydration is suggested as a viable trigger for slow slip.

INTRODUCTION

Slow slip earthquake phenomena are multiscale in dimension, time, and energy emission. Slow earthquake processes operate over longer durations (seconds to years) and at lower seismic moments than regular earthquake rupture (Gombert and Hawthorne, 2023). Fast tremor events and slow-slip earthquakes are known to re-occur episodically at the same spatial location in modern subduction zones and propagate over large spatial areas (1–100 km^3), interspersed by irregular periods of inactivity (Obara et al., 2004).

A range of processes underpinning the observed geophysical phenomena of slow-slip earthquakes has been proposed, but these remain controversial (Platt et al., 2024). Cycles of slow slip failure at low imposed stresses have been linked to circumstances with high proportions of pore fluid and low rock permeability (Peacock, 2009; Frank et al., 2015; Gombert and Hawthorne, 2023). Metamorphic dehydration through the destabilization of hydrous minerals has been correlated with intervals of tremor and slow earthquakes (Delph et al., 2018; Condit et al., 2020). It remains unclear how slip cyclicity is induced at the same spatial location as rock dehydrate.

Predictions for the duration of subduction metamorphism span a large empirical range. Dehydration reactions are expected to be protracted due to their greater heat-consumption (Schorn et al., 2018). The growth of parts or entire grains of garnet have been estimated to take ~200 k.y. to 1 m.y. (Dragovic et al., 2012; Viete et al., 2018). Conversely, fluid advection in blueschist can reflect pulses of just months to years (Taetz et al., 2018; Hoover et al., 2022). The disparity in time scale between fast advection relative to slower dehydration reaction needs to be resolved if fluid release during metamorphism is to be responsible for the episodicity of slow earthquake phenomena. Lawsonite breakdown is identified in experimental studies to directly induce stress perturbations (Incel et al., 2017). Here, we assess a thermal energy model of lawsonite dehydration and compare it with the lawsonite blueschist terrane from New Caledonia. The blueschists are predicted to react and deform at distinct but repetitious rates due to energy and strain requirements. Similar behavior is predicted for the breakdown of other hydrous phases.

LAWSONITE BLUESCHIST IN NEW CALEDONIA

The ~6000 km^2 (ca. 37–44 Ma; Vitale Brovarone and Agard, 2013) high-pressure belt of NE New Caledonia extends from unmetamorphosed Eocene–Jurassic sedimentary and volcanic rocks through to their metamorphosed blueschist and eclogite facies equivalents. It includes one of the few field examples of the lawsonite- to epidote-blueschist transition (pressure [P] = 1–1.5 GPa, temperature [T] = 440–520 °C) in a 3–4-km-thick zone with a nearly 200 km strike length (Figs. 1A and 1B; Clarke et al., 2006). The transition is telescoped by faulting but overlaps with the initial growth of garnet and consumption of chlorite (Chapman and Clarke, 2021).

Over the entirety of the exposed lawsonite–epidote transition, multiple generations of syn-metamorphic epidote, glaucophane, and omphacite veins develop with jigsaw fit and stockwork textures in metabasaltic blueschist; early veins are folded or sheared (Figs. 1C–1E). Mineral zoning patterns, crystallization sequences, and crack-seal textures are consistent with multiple episodes of rock failure and slip (Fig. 1C). Metapelitic blueschist records greater penetrative strain with abundant folded and deformed quartz veins (Fig. 1E). Thus, the rock sequence records transient periods of brittle failure and slip associated with fluid release during ongoing background ductile creep.

Microstructure in the lawsonite–epidote transition indicates varied but commonly dis-

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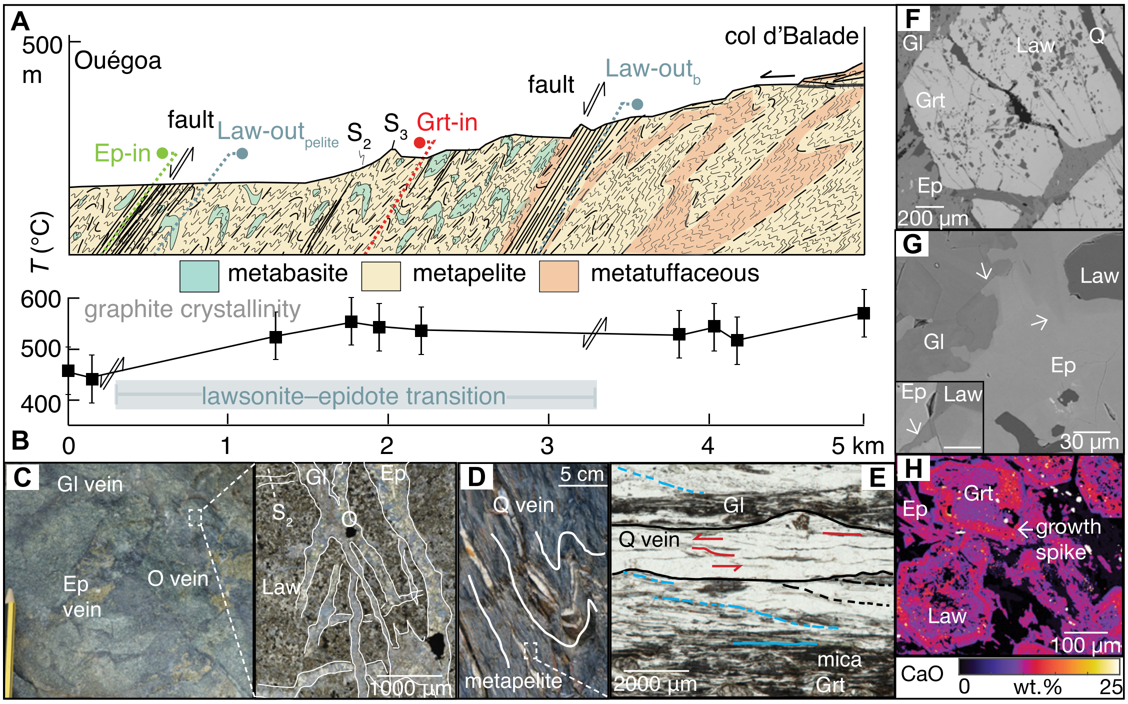

Figure 1. New Caledonian blueschists. (A) Cross section of the lawsonite–epidote transition. (B) Temperature (*T*) progression (2σ error; after Vitale Brovarone and Agard, 2013). (C) Stockwork of epidote (Ep), glaucophane (Gl), and omphacite (O) veins. (D) Quartz (Q) veins in metapelitic schist that are folded, (E) parallel or at an angle to the foliation (black lines), truncated mica-planes with small displacements (blue), sheared and displaced mica fibers (red). (F, G) Backscattered electron image of fractured garnet (Grt) with lawsonite inclusions and irregular truncated epidote zoning (white arrows). Inset of delicate lawsonite growth form (white arrow). (H) Ca-growth spike in fractured garnet.

rupted mineral growth cycles. Early garnet has progressive and irregular Ca-growth zoning and spikes coinciding with mineral inclusion patterns associated with lawsonite breakdown (Fig. 1G). Late garnet growth has compositions distinct to the early formed grains (Fig. S1 in the Supplemental Material[1]). Garnet also hosts fractures partially healed by ongoing metamorphism (Fig. 1F). Epidote is coarse grained (up to 2 mm) and inclusion-rich but can record resorption features (Fig. 1G). Similarly, lawsonite has irregular crystal habit involving delicate growth formed along a grain-boundary network (inset, Fig. 1G). The mineral growth features support the interpretation of intermittent reaction progress in the metabasalt, involving periods of pulsed lawsonite destabilization. Metapelitic blueschist is dominated by successively transposed S-C planes (Fig. 1E). Quartz veins are parallel and at an angle to the main foliation and have laminated crack-seal features and aligned mica fibers consistent with their repeated formation during shear (Fig. 1E). Asymmetric and truncated mica folia, both within and at the edges of the veins, involve small (µm–mm-scale) displacements (Fig. 1E).

MODELING OF FLUID PRODUCTION REACTIONS

Phase equilibria modeling determines the amount of structurally bound fluid released by mineral breakdown in metabasaltic and metapelitic rocks (Fig. 2; Supplemental Methods). The geotherm for the New Caledonian belt (8.3 °C/km; Chapman and Clarke, 2021) is comparable within uncertainty to modern global subduction geotherms such as in Guerrero, Mexico (~8.5 °C/km), that produces slow earthquakes (Fagereng and Diener, 2011; Condit et al., 2020). The high Ca-Fe-Mg content of metabasaltic protoliths facilitates the growth and retention of higher proportions of hydrous minerals relative to that in quartz-rich metapelitic schist (Fig. 2A). In particular, the multivariant lawsonite–epidote transition in metabasalt facilitates the cumulative release of 2–3 wt% of H_2O from the rock over a temperature interval of 28 °C (zone i in Fig. 2B). The equivalent transition in a metapelitic rock only produces 0.55 wt% of H_2O over a 19 °C interval due to lower lawsonite mode (zone ii in Fig. 2B). The breakdown of chlorite releases 1.8–2 wt% H_2O in both metabasaltic and metapelitic rocks over multiple *T* intervals (zones iii and iv in Fig. 2B).

ENERGY REQUIREMENTS FOR REACTION PROGRESSION

Modeling results allow quantification of the energy budget associated with reaction progress. Prograde lawsonite breakdown is one of the largest fluid-producing and most energy intensive (5.8 kJ mol^{-1}) reactions experienced by subducted oceanic crust (Fig. 2C). At constant heat flow, any heat consumed by lawsonite breakdown will buffer the rate at which rock temperature increases (Schorn et al., 2018). A rock at equilibrium cannot exceed the temperature of a reaction increment before the processes of mass (fluid) transfer, mineral nucleation, and growth enable reaction progress (Walther and Wood, 1984). Only if sufficient heat is available will reaction progress. The projected heating path during subduction involves mostly linear increases in temperature with enthalpy, except for inflections at key fluid-producing reactions (Fig. 2C).

Based on these constraints, the rate of reaction across a defined *T* interval (d*T*) can be calculated. The rate accounts for dependencies on thermal requirements (heat capacity [d*H*/d*T*]) and the availability of heat (Connolly and Thompson, 1989). During subduction, the physical descent of the slab into the mantle will continue regardless of the state of any given reaction. Based on the geochronology record of the New Caledonia high-*P* belt (Penniston-Dorland et al., 2025), modeled heat capacities, and an inferred descent rate (0.6 cm/yr), a simple prediction of the temperature–time progression during subduction with a dip of 30° can be made (Figs. 3A and 3B). A similar prediction is made for modern subduction beneath Mexico (Fig. 3D). Thermal buffering at major dehydration intervals delays the progression in d*T*/d*t* by timeframes upward of 20% and smear the lawsonite–epidote transition across a 40% larger depth range (Figs. 3A and 3E).

Delayed reaction progress is consistent with mineralogical change observed within blueschist now exhumed in New Caledonia. The coexistence of lawsonite and epidote in metabasaltic blueschist occurs over an apparent minimum thickness of 3.5 km and only 0.5 km in metapelitic schist. This corresponds to a 16%–40% thicker interval than predicted without thermal buffering (Fig. 3A). A subdued temperature inflection is recorded by graphite crystallinity in

[1]Supplemental Material. Field relations, microstructural features, detailed methods, and phase diagrams. Please visit https://doi.org/10.1130/GEOL.S.32537271 to access the supplemental material; contact editing@geosociety.org with any questions.

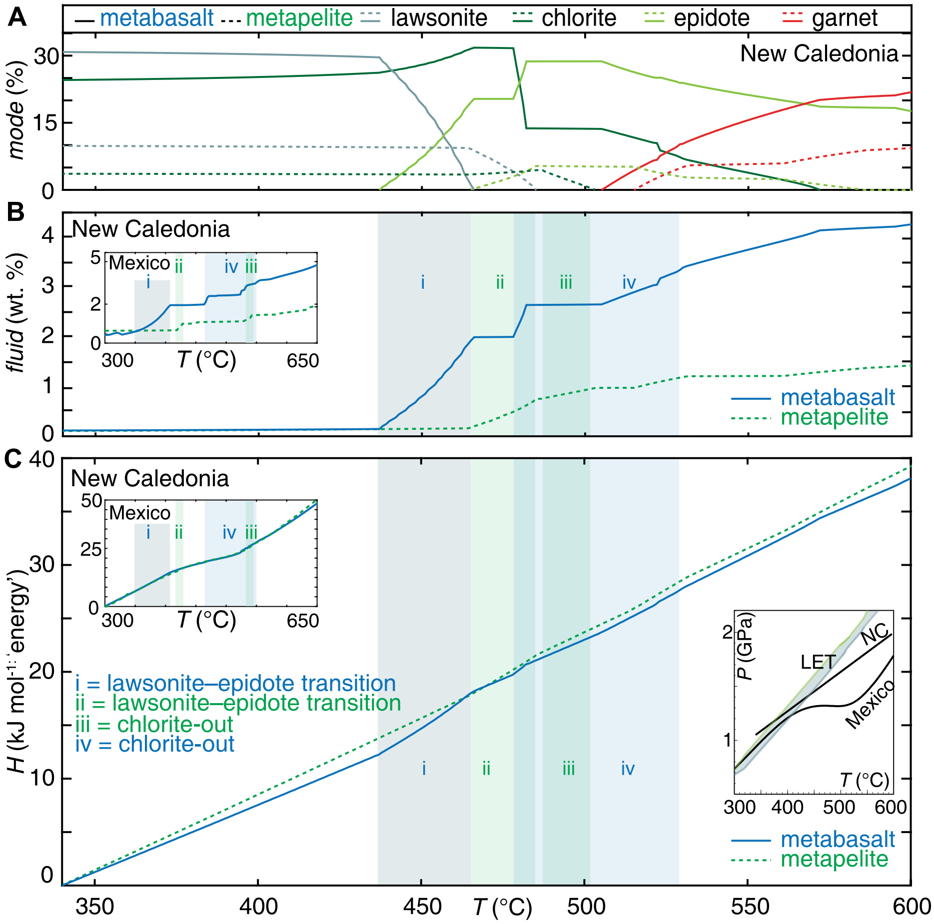

Figure 2. Phase equilibria. (A) Mode changes; (B) temperature (*T*)–fluid egress; (C) enthalpy–*T*. Inset of Mexico subduction geotherm and pressure-temperature (*P-T*) diagram. LET—lawsonite–epidote transition; NC—New Caledonia.

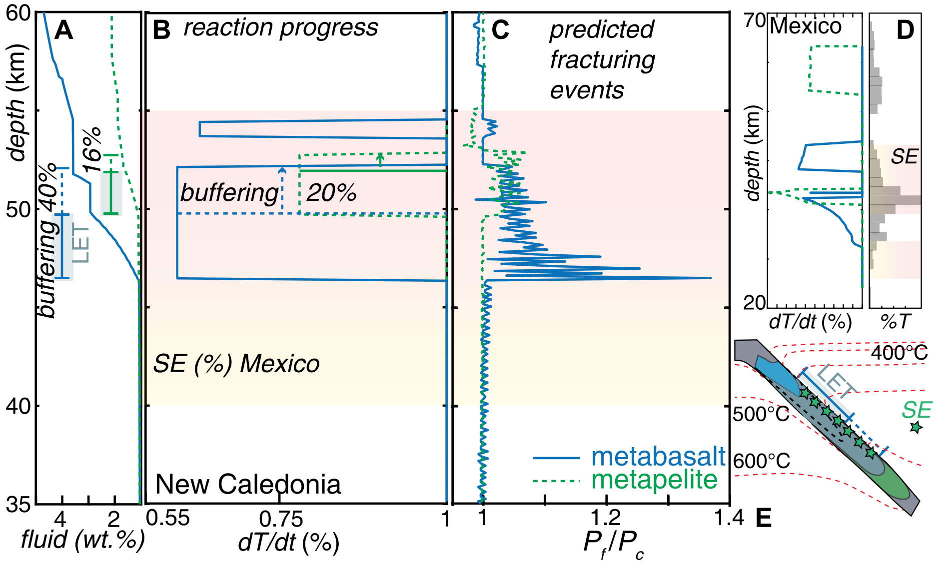

Figure 3. Reaction buffering (A) fluid release vs. depth, with expansion of buffered lawsonite stability. (B) Depth vs. d*T*/d*t* (%) with delayed reaction. (C) Pore fluid factor (*Pf/Pc*); spikes are fracturing events. (D) Mexico depth vs. d*T*/d*t*, with slow earthquakes distribution (%temperature [*T*] and slow earthquakes [SE] after Condit et al., 2020). (E) Schematic of expanded lawsonite (law) breakdown. LET—lawsonite–epidote transition; ep—epidote.

metapelitic blueschist of the lawsonite-epidote transition relative to the rest of the New Caledonian field array (Fig. 1B; Vitale Brovarone and Agard, 2013). This feature cannot easily be accounted for by differences in the structural repetition (Chapman and Clarke, 2021).

MECHANICAL RESPONSES TO PUNCTUATED FLUID PRODUCTION

Deformation is controlled by the interplay between Mohr–Coulomb yield strength, viscous flow, and the effective stress. Externally imposed differential stress and pore fluid pressure magnitude control brittle failure in tension or shear (Etheridge et al., 2021; Hobbs and Ord, 2022). Shear failure triggered by higher pore fluid pressure may also involve slip along preexisting structures (Rutter and Hackston, 2017). In multilayered sequences, slip surfaces are localized at the lower boundary of the less permeable rock, where efficient slip and slip plane propagation is enabled by elevated pore fluid pressure (Mourgues and Cobbold, 2006).

Predictions for the force exerted by free fluid (P_f) in the lawsonite-epidote transition in metabasalt are consistent with even small (1 °C) increments of reaction progress inducing fluid proportions in excess of porosity (<2%–4%; Peacock et al., 2011) and rock strength (>P_c = confining pressure; Fig. 3C; Etheridge, 1983). Fracturing, with failure episodes, is predicted to repeat incrementally during heating over the entire reaction interval (Fig. 3C). The events may trigger tremor or slip depending on the state of differential stress and failure mode (Incel et al., 2017; Chapman et al., 2022).

Embrittlement in metabasalt from the lawsonite–epidote transition is predicted to be orders of magnitude faster than mineral reaction kinetics. Discontinuities generated by failure are likely to be multiscale, initiating at the grain-scale as cracks, and coalescing into larger mm- to cm-scale tensional, shear, or interface parallel fractures that eventually form veins in the geological record (Okamoto and Shimizu, 2015; Koehn and Passchier, 2000). Fractures will only remain open with sufficiently high fluid pressure; otherwise, the system relaxes back to one of low permeability in a near-lithostatic stress state.

Lower fluid production rates in the metapelitic rocks means internal pore fluid will mostly remain below critical values and contribute to lower permeability (Fig. 3C). Accumulated pore fluid at permeability discontinuities such as layer interfaces with metabasalt, previously formed capped veins, or mica-planes may transiently enable shear rupture along these low cohesion interfaces via frictional sliding or granular flow (Reber et al., 2015; Giuntoli and Viola, 2022). Elevated pore fluid pressure along these planes may enhance total slip, slip velocity, and shear stress drop (French et al., 2016).

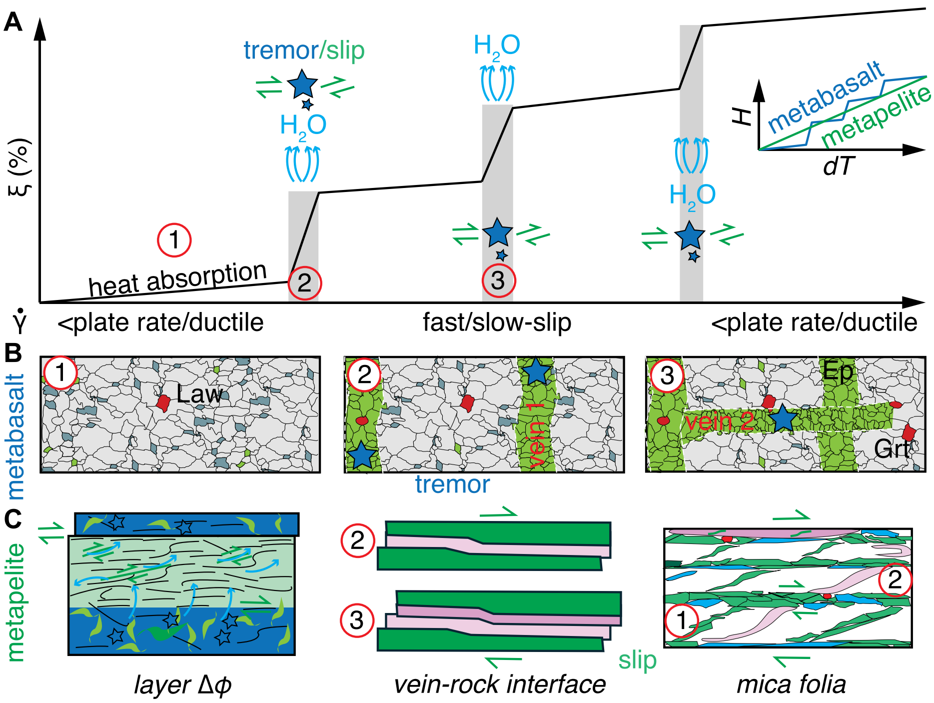

Figure 4. Nonlinear dehydration (A) reaction progress (ξ) vs. strain rate ($\dot{\gamma}$); fast tremor and slow slip episodes punctuated by slow–ductile response. Inset of differential *H* vs. d*T* response. (B) Failure during increasing pore fluid pressure (numbered) in metabasalt relative to ductile creep. (C) Pulsed slow slip in metapelite due to layer permeability (Δϕ) contrasts, formation of interface veins, and folia displacements. Ep—epidote; Law—lawsonite.

PUNCTUATED FLUID RELEASE MATCHES EPISODIC SLOW EARTHQUAKES

During lawsonite breakdown, mechanisms switch between fast, brittle events with fluid-enhanced slip and slower ductile flow. The dynamic interplay generates multiple veins, mineral fractures, and slip along interfaces punctuated by periods of episodic grain resorption and growth during penetrative foliation formation (Figs. 1C–1H). Bursting events are consistent with heat absorption driving small (∼1 °C) increments of lawsonite reaction that liberate enough fluid suitable to induce tensile fracturing and sliding along preexisting discontinuities. A local reaction–porosity runaway episode can be generated as more mineral surfaces become available for efficient reaction progress (e.g., Miller et al., 2003; Okamoto and Shimizu, 2015). However, once fluid flow is hindered by mineral precipitation, reaction kinetics will be stalled, and a slower-ductile response will be resumed (Miller et al., 2003). The nonlinear process could repeat with additional heat absorption and further reaction progress involving the breakdown of additional lawsonite. For metamorphic conditions above lawsonite stability, the prograde breakdown of other hydrous minerals such as chlorite and epidote will likely induce pulsed reaction progress.

Repeated cycles of lawsonite breakdown may be directly linked to slow earthquake cycles involving bursts of reaction-generating tremor that cascade into slow slip activity (Fig. 4). Rates of the transient fluid pulses modeled for the New Caledonian blueschists match predictions for the duration and periodicity of slow earthquake phenomena (days to years; Beroza and Ide, 2011). Variability in the rates of fluid production between intercalated metabasalt and metapelite reinforce permeability discontinuities and localize weakness during pulsed fluid flow. Fracturing and slip episodes are predicted to migrate along broader meter-scale fluid flow pathways controlled by the less reactive and cohesive metapelitic blueschist (Giuntoli and Viola, 2022; Platt et al., 2024). The formation of slip surfaces along layer interfaces, vein-rock interfaces, and mica rich folia are consistent with fluid pressure-induced slip at different scales (Figs. 1E, 4B, and 4C).

Fluid replenishment and slip events that repeat over a larger depth interval (40%) than commonly predicted during subduction can therefore account for the episodicity, spreading habit, and scale of observed slow earthquake phenomena. The nature of the reaction energy budget means the periodicity of the events is likely to be semi-regular and will match slow-earthquake swarms and their pattern of energy and fluid dissipation during migration (Obara et al., 2004; Gombert and Hawthorne, 2023). The migration of fluid flow and slip through metabasaltic and metapelitic blueschist may also induce dissipative feedback to contribute to additional lawsonite breakdown. Estimates of energy dissipation from elastic and inelastic stress relaxation are generally of a magnitude (1–335 J mol^{-1}; Plümper et al., 2017) that may be suitable for contributions to small reaction increments (211 J mol^{-1} per °C) but that are less than that required for the entire consumption of lawsonite (5.8 kJ mol^{-1}; Fig. 2C). A small input of energy into intermixed rock types may be suitable to overcome reaction or strain activation barriers and enable reaction migration up dip or along strike. Additional energy in the form of work or shear heating may contribute to a positive feedback loop over small increments of reaction on larger slip planes (Poulet et al., 2014). The patchy distribution of lawsonite and slip features observed in New Caledonia could reflect these interactions. The true uniformity of slow-slip activity will depend on the distribution of permeability and reactive capacity of blueschists across their kilometer-scale operation.

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