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Hikurangi megathrust slip behavior influenced by lateral variability in sediment subduction

Andrew C. Gase[1]*, Nathan L. Bangs[1], Harm J.A. Van Avendonk[1], Dan Bassett[2] and Stuart A. Henrys[2]
[1]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas 78758, USA
[2]GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand

ABSTRACT

Subduction megathrusts exhibit a range of slip behaviors spanning from large earthquakes to aseismic creep, yet what controls spatial variations in the dominant slip mechanism remains unresolved. We present multichannel seismic images that reveal a correlation between the lithologic homogeneity of the megathrust and its slip behavior at a subduction zone that is world renowned for its lateral slip behavior transition, the Hikurangi margin. Where the megathrust exhibits shallow slow-slip in the central Hikurangi margin, the protolith of the megathrust changes ~10 km downdip of the deformation front, transitioning from pelagic carbonates to compositionally heterogeneous volcaniclastics. At the locked southern Hikurangi segment, the megathrust forms consistently within pelagic carbonates above thickened nonvolcanic siliciclastic sediments (unit MES), which subduct beyond 75 km horizontally. The presence of the MES layer plays a key role in smoothing over rough volcanic topography and establishing a uniform spatial distribution of lithologies and frictional properties that may enable large earthquake ruptures.

INTRODUCTION

Great earthquakes occur where large areas of subduction megathrusts accumulate substantial elastic strain. While slip deficit is difficult to constrain, observations of interseismic coupling and transient aseismic slip (i.e., slow-slip) indicate that the processes by which elastic strain accumulates and releases can vary spatially and influence earthquake dynamics (Avouac, 2015). For example, megathrust zones prone to slow-slip can hinder propagation of large earthquakes (Rolandone et al., 2018). Such observations have major implications for how we infer earthquake and tsunami hazards at subduction margins (Dixon et al., 2014), especially where strong lateral variability in slip behavior is observed. Yet, the causes for along-strike variations in megathrust slip behavior are not well understood.

The Hikurangi subduction margin (HM), where the Hikurangi Plateau subducts beneath North Island, New Zealand, has an exceptional record of geodetic monitoring (Wallace, 2020). Geodetic slip inversions reveal a lateral transition in the prevalence of shallow slow-slip along the megathrust (Wallace, 2020) (Fig. 1). The offshore HM north of Cape Turnagain (e.g., slow-slip zone) undergoes short-duration (<1 mo), quasi-periodic (~12–18 mo recurrence) shallow slow-slip events between ~2 and 15 km below the seafloor that have accommodated much of the cumulative plate motion since the year 2002 CE (Wallace, 2020). South of Cape Turnagain (i.e., locked zone), the megathrust is locked to ~27 km depth. The aim of this study is to examine the cause of persistent lateral variability in slip behavior at the Hikurangi margin. We use deep penetrating seismic reflection data to show that the thickness and homogeneity of subducting sediments vary in concert with along-strike changes in slip behavior.

STRUCTURE OF THE SHALLOW SLOW-SLIP TRANSITION

During the Seismogenesis at Hikurangi Integrated Research Experiment (SHIRE) conducted in 2017, the R/V *Marcus G. Langseth* acquired 4004 line km of two-dimensional multichannel seismic data with a 12.8-km-long receiver array and 6600 in^3 air-gun source. We present four dip-oriented seismic images that reveal structural contrasts across the transition from shallow slow-slip to locking and combine the SHIRE data with legacy seismic images (see the Supplemental Material[1]) to determine regional variations in subducting sediment thickness. We interpret four lithologies within the incoming sediments and crust (Davy et al., 2008; Bland et al., 2015; Barnes et al., 2019, 2020). In order of decreasing age these are (1) volcaniclastics of the subducting Cretaceous Hikurangi Plateau (unit HKB), (2) Late Cretaceous siliciclastic sediments (unit MES), (3) Paleocene through middle to lower Pleistocene calcareous pelagic sediments that grade upward from chalks to marls (unit CL), and (4) middle to lower Pleistocene to present hemipelagic turbidites (unit TF).

Time-migrated seismic images reveal structures within the incoming plate, megathrust, and overthrusting plate in both the slow-slip and locked zones (Fig. 2). Common features observed in both zones include frontal accretion of sedimentary unit TF and the upper part of unit CL into an accretionary wedge with predominantly seaward-verging thrusts. Proto-thrusts seaward of the deformation front indicate horizontal tectonic compression and may contribute to sediment dewatering and compaction prior to accretion. The décollement (i.e., megathrust) forms within the lower strata of unit CL, commonly referred to as sequence Y and/or reflector 7 (Barnes et al., 2010).

Though the deformation front characteristics are common to both the slow-slip and locked zones of the HM, we observe sharp along-strike variations in sediment subduction and the resulting interaction of subducting volcanics with the décollement. In the transitional and locked zones, unit MES subducts completely and can be traced uniformly to at least 30 km landward of the deformation front (Figs. 2B and 2C).

*E-mail: agase@utexas.edu

[1]Supplemental Material. Uninterpreted seismic images and legacy seismic data. Please visit https://doi.org/10.1130/GEOL.S.20076257 to access the supplemental material, and contact editing@geosociety.org with any questions. Processed seismic images presented in this article are available upon request to A. Gase, and data from R/V *Langseth* cruise MGL1708 are archived at the Academic Seismic Portal (http://www.marine-geo.org/collections/).

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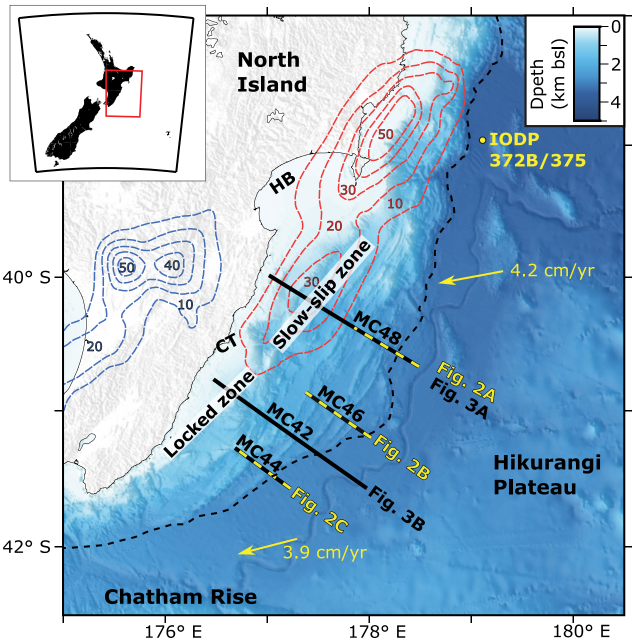

Figure 1. Map of the Hikurangi margin with select seismic lines displayed (black and yellow). Cumulative slow-slip (in cm) (Wallace, 2020) between the years 2002 and 2014 CE is plotted in red (shallow) and blue (deep) contours. Yellow arrows indicate relative motion between the Pacific and Australian plates. CT—Cape Turnagain; HB—Hawke Bay; IODP—International Ocean Discovery Program Expedition; bsl—below sea level. Bathymetric data are from New Zealand National Institute of Water and Atmospheric Research (https://niwa.co.nz/).

Here, unit MES is sufficiently thick to insulate the megathrust from minor volcanic topography (e.g., volcanic cone at 25 km in Fig. 2B), resulting in a smooth and lithologically homogeneous megathrust. Unit CL is uniformly accreted into the outer wedge along the profiles (Figs. 2B and 2C), reflecting a structurally stable décollement uninfluenced by subducting topography.

By contrast, in the slow-slip zone, unit MES is thinner and pinches out against the small volcanic structures of the Hikurangi Plateau 5 km landward of the deformation front such that the megathrust forms along unit HKB (Fig. 2A). In the prism, the accreted layer of unit CL is >~0.8 km thick >15 km landward of the deformation front and thins to <~0.25 km toward the deformation front. We suggest that unit CL onlapped and locally thinned over the volcanic topography. This thinned zone of unit CL has since accreted to the upper plate and the volcanic relief has subducted to 15–25 km beyond the deformation front. In contrast with the locked zone, here unit CL is not accreted consistently.

Pre-stack depth-migrated images (Fig. 3) of seismic lines MC48 and MC42 provide new insights on megathrust structure to depths of ~10–13 km and traverse the primary rupture zones of shallow slow-slip events and large earthquakes, respectively (Clark et al., 2019; Wallace, 2020). In the slow-slip zone (Fig. 3A), Mesozoic sediments pinch out against subducting Hikurangi Plateau volcanics. Deeper along the megathrust, a 2–3-km-thick reflective zone dips 5°–7.5° landward. We do not observe a singular décollement reflector nor any topography that could indicate a large subducting seamount

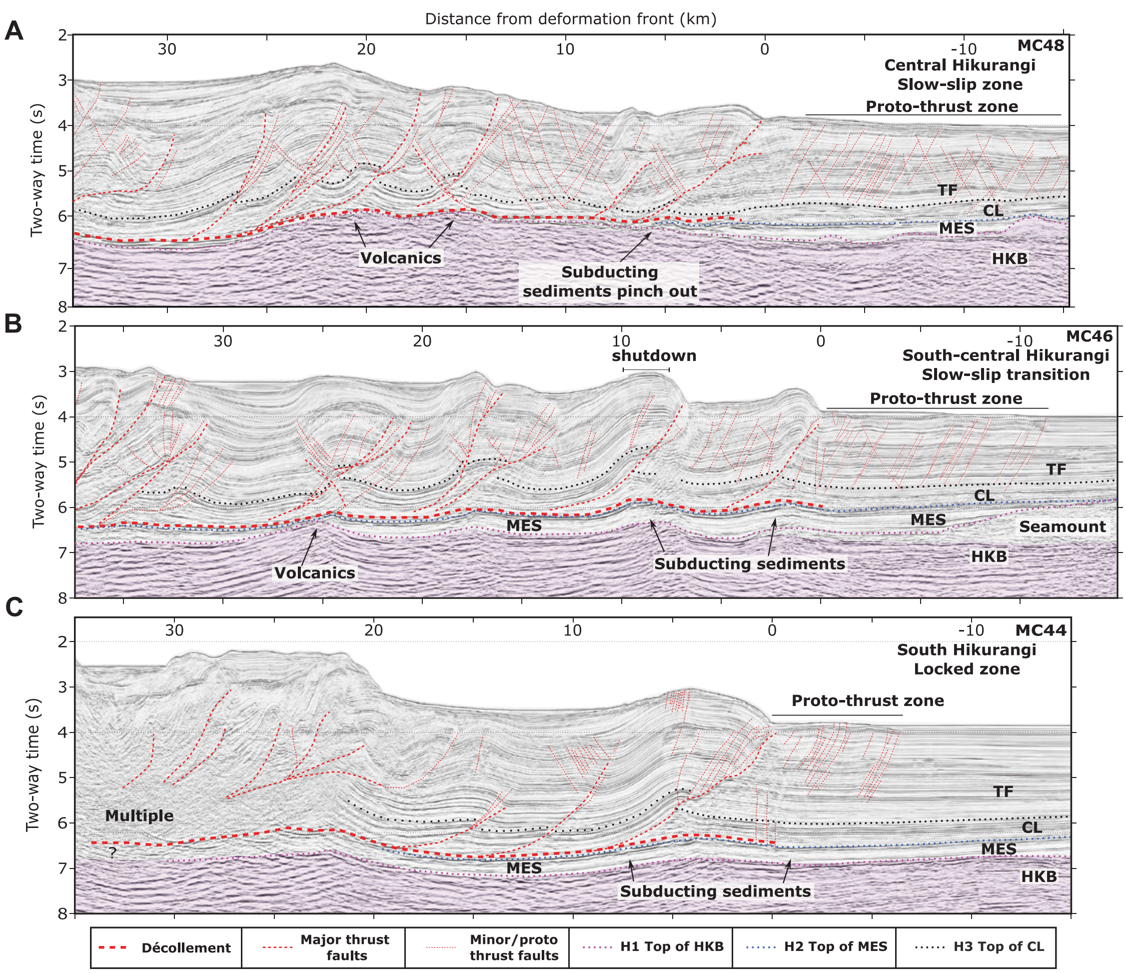

Figure 2. Time-migrated reflection images of frontal prism zone of seismic lines MC48 (A), MC46 (B), and MC44 (C) (see Fig. 1 for location). Geologic units include trench-fill sediments (TF), calcareous sediments (CL), Mesozoic clastic sediments (MES), and Hikurangi Plateau volcanics (HKB).

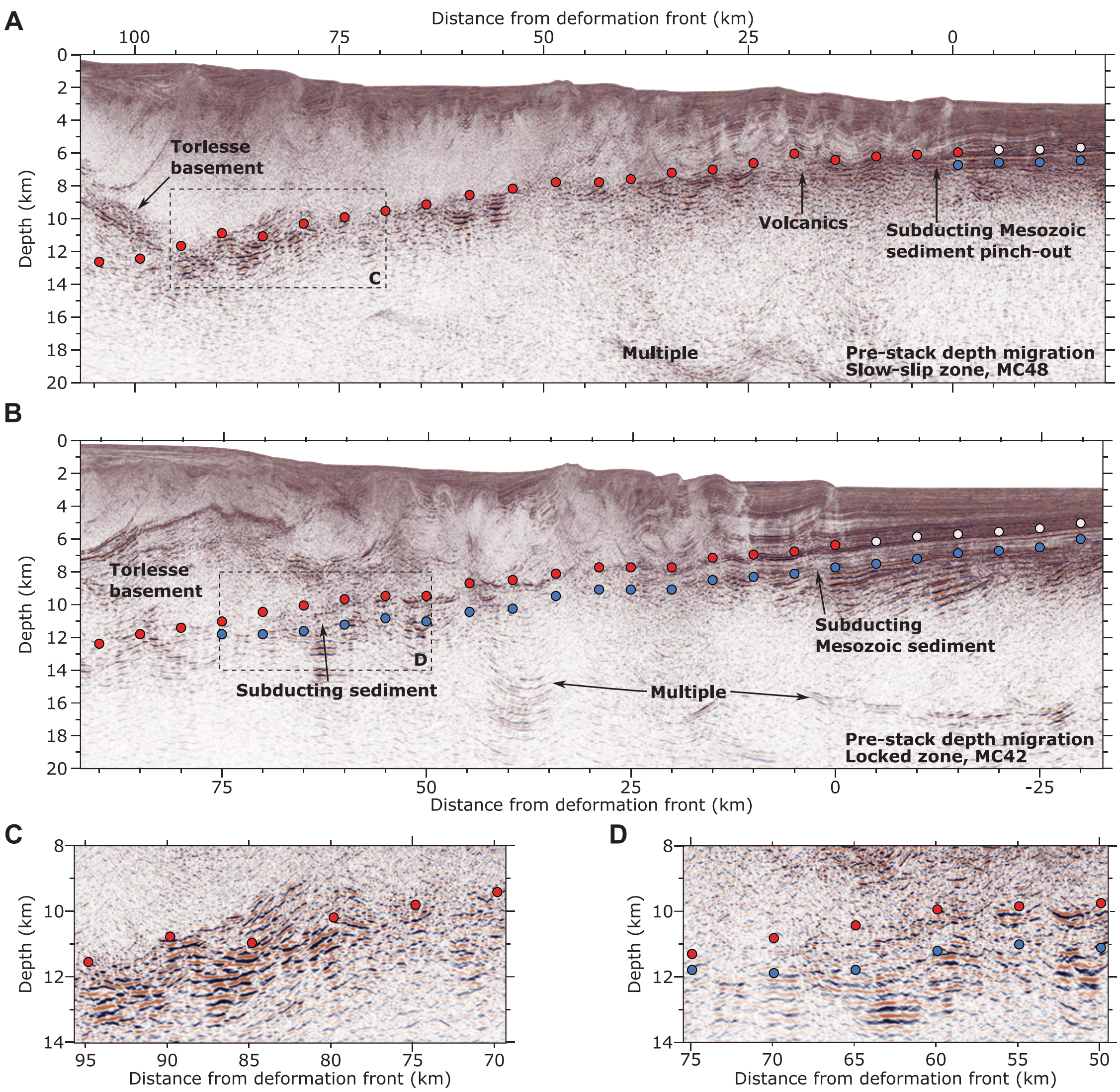

Figure 3. (A,B) Pre-stack depth-migrated reflection images of seismic lines MC48 (A) and MC42 (B) (see Fig. 1 for location). Proto-décollement, décollement, and the base of subducting Mesozoic sediments (unit MES) are indicted by white, red, and blue circles, respectively. (C,D) Magnified images reveal contrasting structures along the megathrust. High upper-plate reflectivity is interpreted as Early Cretaceous basement rocks of the Torlesse composite terrane (Barker et al., 2009).

(Figs. 3A and 3C). In contrast, along the locked zone (Figs. 3B and 3D), a décollement reflector can be traced continuously to >75 km landward of the deformation front to depths of ~11 km, dipping 6°–7° landward. Beneath the décollement, we observe a band of low reflection strength that is contiguous with unit MES at the deformation front. We interpret a zone of elevated reflection amplitude underlying unit MES as the top of unit HKB (Fig. 3D). We suggest that the megathrust is hosted within subducting units CL and MES sediments in the locked zone, whereas in the slow-slip zone, the megathrust forms within Hikurangi Plateau volcanics and interspersed unit CL lenses.

We use legacy and SHIRE seismic data on the Hikurangi Plateau to reveal variations in incoming and subducting stratigraphy between the locked and slow-slip zones (Fig. 4). We find that unit MES is consistently ~0.8 km thick in the locked zone and that unit MES thickens to >2 km further south at the slope of the Chatham Rise (Fig. 4). In contrast, within the slow-slip zone, unit MES reaches local thicknesses of ~0.5 km within ~20-km-wide basins and pinches out completely against volcanic relief. The thickness of unit MES is anticorrelated with the presence of large Cretaceous-age seamounts, implying that Mesozoic sediments were routed to the intervening basins between seamounts during deposition. Areas with substantial thickness of unit MES isolate the megathrust from subducting

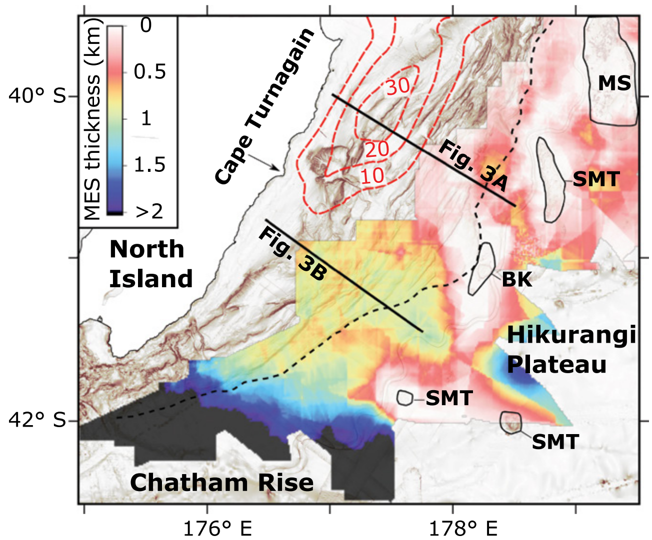

Figure 4. Apparent thickness of Mesozoic sediment (unit MES) on the incoming and subducting Hikurangi Plateau overlain on bathymetric relief. Red contours indicate cumulative shallow slow-slip (in cm) between 2002 and 2014 CE (Wallace, 2020). Black-line polygons are bathymetric perimeters of seamounts: BK—Bennett Knoll seamount; MS—Māhia seamount; SMT—unnamed seamounts.

volcaniclastic sediments, resulting in a more geometrically smooth and lithologically homogeneous fault than in adjacent seamount regions.

INFLUENCE OF SEDIMENT SUBDUCTION ON SLIP BEHAVIOR

We show that the lateral transition in HM slip behavior coincides with a distinct change in the protolith at the megathrust. Within the slow-slip zone, unit MES is thin or absent and the megathrust protolith varies between unit HKB and unit CL (Figs. 2A and 3A). Seismic profiles in areas of recurring shallow slow-slip north of the presented profiles represent a more extreme example of the slow-slip zone examined here with the absence of unit MES and larger seamount interactions along the megathrust (e.g., Barnes et al., 2020; Gase et al., 2021). In contrast, the megathrust of the locked zone consistently forms within unit CL and is shielded from volcanics by ~0.5–1.5 km of unit MES down to at least 11 km depth where we lose resolution, but likely beyond (Fig. 3B).

Proposed causes of persistent lateral differences in slip behavior involve a combination of compositional, thermal, stress, and structural characteristics that influence rate-and-state friction and rheology (e.g., Fagereng and Ellis, 2009; Saffer and Wallace, 2015). Our observations raise the question: Is the variation in the presence of unit MES the subducting plate's primary influence on slip and seismogenesis, or is seamount-controlled roughness the more dominant process? To address this question, we assess (1) interactions between the subducting volcanic relief and the megathrust, and (2) how friction may vary with the observed transition in megathrust protolith.

The thinned unit MES and increased volcanic roughness in the slow-slip zone could promote differences in stress distribution controlled by volcanic roughness and seamounts. Correlations between seafloor roughness and interseismic creep have led some to suggest that subducting seamounts promote broad spectrums of slip at the megathrust by forming complex fracture networks, creating inhomogeneities along the megathrust, and delocalizing slip (Wang and Bilek, 2014). Seamount collisions produce zones of enhanced downdip effective stress and trailing stress shadows that could lead to locally variable frictional stability (Sun et al., 2020). The edges of seamounts could result in zones of enhanced material mixing and heterogeneity (Barnes et al., 2020). A seamount collision model is appropriate for the northern HM, where numerous collisions of large seamounts are inferred (Gase et al., 2021), but this is less appropriate for areas characterized by slow slip and low-relief subducting volcanics (Figs. 2A and 3A). At the slow-slip zone presented here (Fig. 2A), minor volcanic relief both imparts excess roughness to the megathrust and promotes material heterogeneity by controlling the location of the décollement during frontal accretion (Morgan and Bangs, 2017), but the lack of clear subducting seamounts suggests that basement roughness along the megathrust may be too small to cause major stress heterogeneities.

A stratigraphically variable and rough décollement requires that plate convergence is accommodated by immature faults that may form anastomosing shear zones with heterogeneous distributions of materials capable of supporting both earthquakes and slow-slip (Fagereng, 2011). In addition, the volcanically roughened megathrust within the slow-slip zone may be segmented into smaller frictional asperities that slip independently (Romanet et al., 2018; van Rijsingen et al., 2019). Thus, seismogenic cycles in the slow-slip zone could be segmented such that large ruptures are less likely to nucleate but large adjacent ruptures may propagate through rate-strengthening barriers (Kaneko et al., 2010). In the locked zone, where the offshore megathrust is hosted predominantly in unit CL and above a thick subducting unit MES layer, we suggest a uniform, smooth fault model (Ruff, 1989; Scholl et al., 2015) in which stress and material uniformity allow for broad rate-weakening frictional asperities that are uninterrupted by topographic or rate-strengthening barriers. Seamount-influenced volcanic roughness could control seismogenesis and slip behavior within the slow-slip zone, however megathrust protolith is more clearly correlated with slip behavior along this margin.

The megathrust interacts with units CL and HKB at the slow-slip zone, and units CL and MES in the locked zone. This presents the possibility that the frictional properties of the megathrust vary widely due to compositional variations in the protolith, in particular the amount of smectite, calcite, and quartz. Subducting oceanic crust is seldom considered an important source of smectite; however, the Hikurangi Plateau is covered with ~1–3 km (Gase et al., 2021) of volcaniclastic sediments that form the megathrust protolith in ~5–20-km-wide patches north of the slip-behavior transition (Figs. 2 and 4). Cores recovered from a nearby seamount and the upper Hikurangi Plateau volcaniclastics included a heterogeneous assortment of smectite-rich volcaniclastics with vesicular basalt, carbonate, and diagenetic products (Barnes et al., 2020; Allen et al., 2021). In contrast, the pelagic chalks that form the proto-décollement within unit CL are commonly >60% calcite by volume (Boulton et al., 2019; Barnes et al., 2020). The composition of unit MES remains unknown, but the unit has been interpreted as a deep-water turbidite with quartzofeldspathic sandstones and siltstones (Bland et al., 2015).

Unstable rate-weakening friction is a necessary condition for earthquake nucleation that depends on velocity, temperature (T), lithology, and effective stress (e.g., den Hartog et al., 2012). Shallow slow-slip may occur where low effective stresses are paired with a geometrically complex interface and clay-dominated fault rocks (Saffer and Wallace, 2015). At the depths where shallow slow-slip primarily occurs along the central and northern HM (~7–15 km), temperatures are thought to range between ~50 and 200 °C (McCaffrey et al., 2008). Smectite-rich marine sediments have unfavorable conditions for earthquake nucleation due to their velocity-neutral to velocity-strengthening frictional properties at $T > 90$ °C, irrespective of effective stress (Mizutani et al., 2017). Experiments confirm that the clay-rich Hikurangi Plateau volcaniclastics have low coefficients of friction and mixed rate-strengthening and rate-weakening properties (Shreedharan et al., 2022). Moreover, the lithologic heterogeneity of the volcaniclastics provides a mixture of mechanical strengths and frictional behaviors that promotes conditional stability and slow-slip (Skarbek et al., 2012). In contrast, pelagic chalks are strong and conditionally stable at low temperature and pressure (Shreedharan et al., 2022) but become slip weakening at $T > 80$ °C (Kurzawski et al., 2016; Boulton et al., 2019). The frictional properties of unit MES are unknown, but seismic tomography indicates the unit is well drained upon subduction (Crutchley et al., 2020). Unstable quartz-illite-rich lithologies within unit MES could contribute to unstable slip nucleation within the deeper locked zone at $T > 150$ °C (den Hartog et al., 2012). Therefore, at appropriate temperature and pressure conditions, a megathrust within pelagic carbonates and Mesozoic sediments offshore southern Hikurangi may provide the necessary conditions for seismogenic slip: a rate-weakening, drained megathrust.

Although the Hikurangi Plateau is unique for its substantial variations in sediment composition and thick volcaniclastic unit, other subduction zones with along-strike variations in thickness of subducting sediment also correlate with transitions in slip behavior (Li et al., 2018). The structural characteristics of the locked zone, most notably a smooth megathrust hosted above deeply subducting clastic sediment, are likely to be a major contributing factor in large earthquake ruptures, as is observed at other subduction margins that produce great earthquakes (e.g., Bangs et al., 2020). Recent evidence of paleo-tsunamis from great earthquakes within the Cook Strait indicate that the locked zone of the HM may represent a persistent segment prone to large earthquakes (Pizer et al., 2021) and a potential source for margin-wide ruptures (Clark et al., 2019).

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