Seafloor Overthrusting Causes Ductile Fault Deformation and Fault Sealing Along the Northern Hikurangi Margin

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Abstract

IODP Site U1518, drilled during IODP Expeditions 372 and 375, penetrated a large-offset (~6 km) thrust, the Pāpaku fault, rising from a megathrust that hosts recurring slow slip events along the Hikurangi margin. Although drilling intersected the fault zone at only ~300 m below the seafloor within porous silty mudstone, it exhibits intense tectonic ductile deformation, including finely banded mudstones contorted into decimeter-scale folds; elongate mudstone clasts with grain tail complexes; stacked and truncated silt beds in distorted mudstones; and soft sediment injections. Locally, these ductile features are overprinted by brittle deformation, including normal faults, fracture arrays, and breccias. The more consolidated hanging wall is dominated by brittle structures, whereas the footwall exhibits ductile and brittle deformation that decreases in intensity with depth. The intense tectonic ductile deformation and asymmetric distribution of structures across the fault zone at Site U1518 can be explained by seafloor overthrusting. The emplacement of the hanging wall upon the footwall flat overrode high-porosity, undeformed, and previously unburied sediments, localizing shear deformation within these weak sediments. In contrast, the overconsolidated hanging wall preferentially experienced brittle deformation during folding and displacement. Interstitial pore water geochemical profiles at Site U1518 show a repetition of near-seafloor diagenetic sequences below the fault, consistent with overthrusting of previously unburied strata. The preserved diagenetic profiles in the footwall suggest that overthrusting occurred within the last 50-100 kyr, and indicate little along- or across-fault fluid flow at the location of Site U1518. Thus the Pāpaku fault appears to define a low-permeability seal that restricts footwall consolidation, maintaining locally high pore fluid pressures and low fault strength. If similar low permeability structures occur elsewhere along the margin, they could support regionally high pore pressure conditions favorable to the occurrence of SSEs on the Hikurangi megathrust fault.

Keywords: Forearc deformation, overthrusting, ductile sediment deformation, fault processes, fluid flow

1. Introduction

Accretionary prisms preserve a record of deformation processes at convergent margins. A fundamental question in such settings is how and why strain is partitioned within and beneath the prism, and how such partitioning affects fault slip behavior and associated hazards (e.g., Park et al., 2002; Martin et al., 2010; Greve et al., 2020). Some faults exhibit significantly greater displacements than others, posing the possibility that slip on these faults correlates with higher risk of earthquakes or tsunamigenesis (e.g., Lay et al., 2005; Moore et al., 2007). Furthermore, the distribution and mode of deformation may strongly influence the distribution of pore fluid pressures and fluid flow within and across the margin (e.g., Tobin et al., 2001; Saffer and Tobin, 2011; Kastner et al., 2014; Fagereng et al., 2018), with implications for the types of fault slip behavior that may occur (Saffer and Wallace, 2015).

Drilling at the northern Hikurangi Margin during International Ocean Discovery Program Expeditions 372 and 375 (Wallace et al., 2019) provided an unprecedented opportunity to study these topics in a setting known to host both repeating slow slip events (SSEs; Wallace and Beavan, 2010; Wallace et al., 2016) and tsunami earthquakes along the shallow megathrust (Doser and Webb, 2003). In particular, coring and logging-while-drilling (LWD) at Site U1518 penetrated the ~6 km offset Pāpaku thrust fault at a depth of ~300 m below the seafloor (mbsf). The fault is characterized by a zone of ductilely deformed fine-grained hemipelagic sediments, with modest brittle overprint (Fagereng et al., 2019; Saffer et al., 2019; Cook et al., 2020). As the Pāpaku thrust soles into the megathrust near the interpreted source area of some SSEs (Wallace et al., 2016; Barker et al., 2018; Barnes et al., 2020), these observations suggest that the combination of ductile and brittle deformation within the fault zone reflects variable slip behaviors (e.g., Fagereng et al., 2019). There also may be unique conditions that favor ductile sediment deformation in this shallow fault setting, which we explore further through combined analysis of core data and interpretations of a co-located seismic reflection profile.

Here, we use core observations and porosity measurements collected on Expeditions 372 and 375 to examine the distribution of deformation across the Pāpaku fault. Based on seismic interpretations of the frontal wedge, we propose a simplified kinematic evolution, concluding that the hanging wall of the Pāpaku fault overthrust the seafloor producing a classic “ramp-on-flat” hanging wall – footwall configuration (Boyer and Elliott, 1982; Suppe, 1983). The process of consolidated hanging wall overthrusting a poorly consolidated, porous footwall can explain the intense ductile shearing observed within the fault zone, the contrasting deformation histories of the hanging wall and footwall, and other distinctive characteristics of this system. Pore fluid geochemical profiles across the fault zone support this explanation, suggest that overthrusting occurred within the last 50-100 kyr, and that presently, the Pāpaku fault is a barrier to fluid flow.

2. Geological Setting

Expeditions 372 and 375 drilled a transect of sites across the Northern Hikurangi Margin (Figures 1) where the Hikurangi Plateau, a Cretaceous large igneous province, is subducting westward beneath the North Island of New Zealand at ~5 cm/yr (Wallace et al., 2004). Although the northern part of the margin is primarily non-accretionary (Collot et al., 2001), a ~1-2 km thick Cenozoic to Mesozoic sedimentary sequence is partially accreted in the vicinity of Site U1518 (Figure 1). Megathrust slip is accommodated primarily by shallow repeating SSEs that occur every 18–24 months in this location (Wallace and Beavan, 2010). Recent seafloor geodesy suggests slow slip may reach within ≤2 km of the trench along the Expedition 375 drilling transect (Wallace et al., 2016), although the exact structures that accommodate slip are not known. Constraining the causes and consequences of such SSEs was a primary motivation for these Expeditions.

A portion of the time-migrated, depth-converted seismic profile 05CM-04 is shown in Figure 1c, with interpretations from Barnes et al. (2020) and Davy et al. (2021). The Pāpaku fault is characterized by a steeply dipping landward fault segment that transitions into a gentler dipping (~10°) seaward segment. A prominent fault-bend fold has developed in the hanging wall of the fault. In contrast, footwall reflections are oriented approximately parallel to the seaward fault segment. Offset stratigraphic reflections, including horizon BSU4, provide a first-order estimate of apparent displacement on the Pāpaku fault of ~6 km (Barnes et al., 2020). Site U1518 penetrated the seaward extent of the Pāpaku fault, about 0.5 km from where the fault emerges at the seafloor along a steep slope marked by truncated reflections, indicating removal of strata by landslides (Saffer et al., 2019) (Figure 1c). Two seaward thrust faults exhibit lower fault offsets and smaller hanging wall folds. Small offset faults are interpreted in the hanging wall of the Pāpaku fault near the fault kink (Figure 1c) and additional splay faults have been identified using full-waveform inversion reflection images of the 2018 NZ3D data (Davy et al. 2021).

3. Site U1518 Overview

As detailed in Saffer et al. (2019), LWD data from Hole U1518B, drilled to a depth of 600 m below seafloor (mbsf) during Expedition 372 suggest the primary fault zone lies between 315 and 348 mbsf (Cook et al, 2020). Two boreholes (U1518E and F) about 50 m to the south were cored during Expedition 375 (Figure 2a). Hole U1518E sampled the hanging wall down to ~200 mbsf, but severe drilling disturbance prevented identification of primary structures. Hole U1518F provided reasonable core recovery (43%) to a depth of 492.3 mbsf, sampling the lower hanging wall, the soft-sediment Pāpaku fault zone, and the footwall. The hanging wall (lithological Unit I) is composed of silty to clayey, normally graded turbidites and hemipelagic sediment, and intermittent tephra layers (Figure 2b). The uppermost footwall (lithological Unit II) has a similar composition but with fewer silt beds, and the deepest footwall (Unit III) exhibits dispersed contorted beds suggestive of syn-depositional soft-sediment deformation. Based on shipboard observations of recovered cores, the main strand of the Pāpaku fault was identified at 304.5-322.4 mbsf and a subsidiary fault at 351.2-361.7 mbsf (Figure 2). Biostratigraphy reveals an age inversion across the main fault; the base of the hanging wall is dated at 0.67 ma, whereas the top of the footwall is estimated at ~0.31 ma (Crundwell and Woodhouse, 2022). A second age inversion at ~185 mbsf hints at a shallow splay fault within the hanging wall (Davy et al., 2021) that was not detected in drill cores.

Porosities measured on discrete shipboard samples generally decrease with depth through Holes U1518E and F (Figure 2c), but exhibit significant variation due to lithologic and structural changes. In the shallowest hanging wall, mean porosities are ~55%, decreasing to ~41% just above the main fault zone. Mean porosities step up to ~46% within the fault zone, remain at ~44-45%, between the two faults, then decrease slightly within the subsidiary fault. Mean porosities increase to ~50% at the base of the subsidiary fault zone, and decrease unsteadily across the footwall, reaching 40-45% at the base of the hole. Thus, both the top and base of the interval containing the fault zones are marked by steps up in porosity of up to 5% and 7%, respectively. The trends in shipboard sample porosities are in general agreement with Neutron porosities measured in the LWD data from Hole U1518B (Cook et al, 2020), but the absolute values of the discrete samples are a few percent lower shallower than ~200 mbsf (Figure 2c), likely due to intense drilling disturbance throughout Hole U1518E. LWD porosities are noticeably higher in the shallow footwall, from 370-450 mbsf, possibly due to porosity variations between the holes or overestimated LWD porosities due to enlarged borehole diameter.

Structural domains identified in the core coincide closely with the lithostratigraphic units determined shipboard (Figures 2d and e). The hanging wall is characterized by variable bedding dips, with zones of inclined bedding dipping up to ~60° and locally overturned, indicative of broad folding. More consistent bedding dips of ~30° or less occur within the fault zones and footwall, with dips generally decreasing with depth. Fractures and faults occur throughout the core, but are most abundant and variably oriented within the hanging wall (Savage et al., 2021). Locally, zones of intense brecciation occur, particularly within the two fault zones.

4. Characteristics of the Pāpaku Fault Zone and Adjacent Domains

The distinct physical properties and structural characteristics of the hanging wall and footwall (Figure 2) point to contrasting deformation histories of these two domains, structurally separated by the Pāpaku fault. Figure 3 presents a generalized interpretation of Cores 375-U1518F-13R through the upper part of -15R, covering the interval identified as the main fault zone and revealing downhole distributions of deformation. Representative close-up core photos in Figure 4 highlight some of the key features discussed below.

4.1. Hanging Wall

The hanging wall is preserved at the top of Core 375-U1518F-13R (Figure 3) and displays characteristics consistent with shallower cores from Hole U1518F (Saffer et al., 2019). This domain is composed of cohesive sediment cut by abundant healed fractures and faults (blue lines, Figure 3). Cross-cutting structures of different types and orientations demonstrate multiple phases of brittle deformation. Minor faults exhibit mm- to cm-scale apparent offsets, typically with normal displacements (Figure 4a). Several intensely brecciated zones occur with fracture networks defined by mm-scale fracture spacing, often with no obvious shear displacement (Figures 3 and 4a). The density of fractures within the hanging wall generally increases with depth, with zones of locally higher fracture density occurring ~10-20 m above the fault zone (Fagereng et al., 2019; Savage et al., 2021).

4.2. Primary Fault Zone

The main fault zone is characterized by a mixture of ductile and brittle deformation (Figure 3). The types of observed structures are described in detail in Fagereng et al. (2019) and only briefly summarized here. The ductile deformation features fall into several categories, with characteristics that distinguish them as products of intense tectonic shearing rather than syn-depositional soft-sediment deformation. The predominant ductile structures are classified as "flow-banding", which includes parallel layers of sediments ranging in scale from sub-mm laminations up to ~5 mm thick color bands (green lines in Figure 3), dismembered sedimentary layers, in particular silt beds (gray bands in Figure 3), elongate sedimentary clasts, and apparent grain tail complexes. These ductile deformation features are interpreted to result largely from bedding-parallel ductile shear flow accommodated by sediment disaggregation, comminution, and particulate flow, and are well developed throughout the main fault zone (green lines in Figure 3). Locally, brittle structures such as fractures, faults, and brecciation, disrupt layering and overprint the ductile features, demonstrating multiple phases of tectonic deformation. As the drilling process can also cause brittle deformation, we distinguish tectonic brittle structures as those that are now sealed, or fractures and faults that span the core with offsets or slip indicators that cannot be caused by drilling.

In this study, the top of the main fault zone is re-interpreted at 375-U1518R-13R-1, 100 cm, at a sharp downhole transition from fractured hanging wall to a zone with variably oriented color banding that lacks overprinting fractures (Figure 4c). This transition marks the first clear-cut occurrence of flow-banding at a depth of 304.20 mbsf, 30 cm shallower than previously interpreted (Saffer et al., 2019; Fagereng et al., 2019). This judgement is based on the lack of such flow-banding above this point. The occurrence of very finely laminated flow-banded mudstone is the most distinctive characteristic of the main fault zone (green lines, Figure 3). Locally, these flow-banded zones also exhibit mm-scale asymmetric clasts with tails (e.g., Figure 4e), and may be further contorted into decimeter-scale folds (e.g., Figure 4e), indicating local non-planar shear deformation.

Tectonic brittle deformation occurs throughout the primary fault zone. Examples include small-offset normal faults that cross-cut coarse planar flow-banding (Figure 4h), as well as distorted and truncated stacks of mudstones and silt layers cross-cut by fine filled fractures near the top of the faulted interval (Figure 4g). Zones of intense sediment brecciation (red x in Figure 3), possibly caused or enhanced by drilling disturbance, locally preserve the underlying flow-banding (Figure 4d), confirming an earlier history of ductile shearing.

Several features within the main fault zone suggest fluidization of soft sediments (pink bands in Figure 3). These include divergent sediment stringers sandwiched between zones of planar flow-banding (Figure 4d), disaggregated sediment injected into adjacent cohesive sediment (Figure 4f), and local occurrences of homogenized gray material, e.g., within a flow-banded unit, now cross-cut by small-offset normal faults (Figure 4h).

Notably, the discrete silt beds (gray bands) observed within the hanging wall are generally absent throughout the fault zone, with the exception of a package of stacked and contorted muds and silts (Interval U1518R-14R-1A, 109-150 cm, Figure 4g). The few silt beds that occur within the fault zone are highly distorted, dismembered and offset along small faults.

Based on the occurrence of well-developed flow-banding, the primary fault zone is interpreted to extend to the base of Core 375-U1518R-14 (322.4 mbsf), encompassing a domain up to ~18 m thick. However, due to incomplete core recovery (Figure 2) significant material is missing and the exact thickness of the fault zone is unknown. This compares with an interpreted fault zone thickness of ~33 m (315-~348 mbsf) interpreted in the LWD data in Hole U1518B, 50 m to the north, based on boundaries of bedding orientation domains (Cook et al., 2020).

4.3. Footwall

Below the main fault zone, at the top of Core 375-U1518F-15R, the character of the sediment changes and deformation decreases in intensity (Figure 3). Coarse flow-banding is still evident, but the domains of mm scale laminations are absent. Distinct ductile deformation features of various types persist, including convolute layering, sharp bedding truncations, and rare injection features, but they are not well developed. These features generally occur within otherwise coherent strata, indicating that they are not due to drilling disturbance. The density of fractures within this domain is reduced relative to the lower hanging wall and the primary fault zone (Figure 2 and Savage et al., 2021), although small-offset normal faults occur. Irregular zones of homogeneous gray material lacking internal fabric occur, with boundaries that truncate sedimentary horizons. In at least one example, the gray material was injected into the surrounding sediment in the plane of split core (Figure 4i). These features may reflect fluidization of soft sediments, likely remobilized during shearing along the fault. The sharply bounded, homogenized sediment in Figure 4i is also cross-cut by a planar black band and small-offset normal faults, demonstrating brittle overprinting. Thin silt beds appear again, locally dismembered (Figure 4j) or distorted into small recumbent folds (Figure 4k).

Between 351.2 and 361.7 mbsf, deformation intensity increases again, defining a subsidiary fault that cuts through the footwall with no obvious lithologic or age change (Fagereng et al., 2019). This feature may correlate with a possible subsidiary fault zone interpreted in LWD at

~369 mbsf in Hole U1518B (Cook et al., 2020). Flow-banding is less intense than in the main fault, although several mud clasts exhibit elongate asymmetric tails that suggest non-coaxial shear deformation (Figure 4l). Locally, discrete faults juxtapose convolute beds or banding of different orientations. The subsidiary fault zone boundaries are poorly defined, instead deformation intensity gradually decreases with distance. Deeper occurrences of flow-banding, contorted bedding, and fractures are rare, and may relate to additional subsidiary faults (Cook et al., 2020) or syn-depositional soft-sediment deformation (Saffer et al., 2019).

5. Origin of Ductile Fault Deformation and Kinematics of the Pāpaku Fault System

The distinct contrasts in structural styles between the hanging wall and footwall of the Pāpaku fault system, and prevalence of intense tectonically-induced ductile sediment deformation are atypical in most shallow fault zones previously drilled at subduction forearcs (e.g., Lundberg and Moore, 1986; Taira et al., 1992; Kirkpatrick et al., 2014). One exception is the frontal décollement zone along the Costa Rica margin drilled during Leg 170 (Tobin et al., 2001), where the more consolidated lower slope wedge overrode less consolidated, higher porosity trench sediments. Similar to the Pāpaku fault, the upper plate at Costa Rica is characterized by brittle fractures, faults, and deformation bands, whereas the uppermost underthrust section experienced ductile shearing (Vannucchi and Tobin, 2000). The example of the cohesive Costa Rica wedge superposed upon less consolidated trench sediments offers helpful perspectives about accretionary processes along the northern Hikurangi margin.

Structural and stratigraphic geometries exhibited in seismic profile 05CM-04 (Figure 1c) clarify the evolution of the Pāpaku fault system. Displacement along the Pāpaku fault is estimated at ~6 km, much greater than the initial thickness of the incoming sedimentary section (Barker et al., 2018; Barnes et al, 2020). Thus, the hanging wall ramped through the entire incoming section, and overthrust the seafloor. Presently, the hanging wall ramp defines the base of the hanging wall fault-bend fold, and is superimposed upon a footwall flat parallel to the underlying strata (Figure 1c). This geometry defines a classic ramp-on-flat configuration of an overthrust fault (Boyer and Elliott, 1982; Suppe, 1983). To first order, the hanging wall ramp overrode the undeformed seafloor a distance of at least 3 km.

Figure 5a presents a simplified kinematic evolution of the frontal prism that broadly reproduces this configuration. Progressive displacement of the landward edge of a package of sediments (Stage 1) activated the Pāpaku fault, which ramped through the incoming strata (Stage 2), eventually emerging onto and sliding along the seafloor (Stage 3), undergoing folding above the ramp-flat kink in the fault. At that point, the seafloor became the thrust fault, accommodating continued displacement of the hanging wall. Continued convergence activated two more seaward thrust faults, which exhibit less displacement (Stage 4). This schematic model explains the evolution of the fault system to first order and highlights several interesting features. As the hanging wall of the Pāpaku fault slid over the footwall flat, fault length increased progressively as new seafloor was incorporated into the fault zone. Thus, both the magnitude of slip along the footwall flat and age of the fault decrease in the seaward direction; they are highest at the ramp-flat kink and reach zero where the fault intersected the original seafloor. Furthermore, at Site U1518, the hanging wall has been displaced significantly farther than the footwall, and thus experienced a longer history of tectonic deformation.

Site U1518 (vertical black bar in Stage 4) penetrated the shallowest reaches of this fault, ~0.5 km from where it now intersects the seafloor. Truncation of shallow horizons in the seismic profile (Figure 1c) suggests landslide removal of some of the hanging wall. Depending on when landsliding occurred and amount of material removed, the original tip of the fault may have been seaward of the current seafloor intersection by as much as ~1.5 km. Thus fault displacement at Site U1518 could range from ~0.5-1.5 km.

The schematic kinematic evolution in Figure 5a clarifies why the hanging wall and footwall at Site U1518 experienced such contrasting deformation histories, and provides insights into the origin of the intense ductile deformation along the Pāpaku Fault. Two small rectangles track representative positions of the hanging wall (dashed) and footwall (solid gray), until they become superimposed in Stage 4. A plausible evolution of these representative domains at each kinematic stage of deformation is shown in Figure 5b.

Prior to Stage 1 and onset of tectonic loading, the deepest hanging wall strata at Site U1518 were buried to a depth of more than 300 m. At Stage 1, thrust faulting initiated under tectonic loading, accompanied by brittle deformation and distributed wall rock damage typical along faults within cohesive lithologies (e.g., Meneghini and Moore, 2007; Savage and Brodsky, 2011). Stage 2 captures uplift of the hanging wall and onset of time-transgressive folding as it passed through fault-bend kinks linked to the footwall ramp-to-flat transition (Suppe, 1983). This folding and unfolding caused additional local fracturing (Cosgrove, 2015).

By Stage 3, the shallowest hanging wall had overthrust poorly consolidated seafloor sediments. The superposition of the hanging wall upon these previously undeformed porous strata, shifted shear deformation into the weaker footwall unit. Footwall sediments may have experienced further consolidation due to burial beneath the hanging wall. Given the initially high porosities and low effective stresses in the shallowest footwall sediments, ductile deformation would have been favored in the footwall (Muir Wood, 1991). This contrasts with the brittle deformation and off-fault damage commonly associated with forearc thrust faults, as now preserved in the hanging wall of the Pāpaku fault (Savage et al., 2021). Rapid loading of porous footwall sediments may have generated excess pore pressures capable of causing local sediment fluidization, injection, and fracturing, schematically shown in Stages 3-4 in Figure 5b. Although the underthrust sediments are expected to dewater over time, pore fluid dissipation depends on the loading rate and sediment permeability, neither of which is well constrained. However, steps up in porosities within and across the Pāpaku fault in shipboard and LWD data (Figures 2), and interpreted from geophysical data (Gray et al, 2019; Cook et al., 2020), suggest that the footwall is underconsolidated relative to the hanging wall, and likely still supports excess pore fluids (French and Morgan, 2020).

Emplacement and displacement of the hanging wall along the Pāpaku fault were likely associated with ongoing slope failure, as in other accretionary settings (Strasser et al., 2011; Moore et al., 2019). Removal of shallow sediments reduced the vertical stress within the hanging wall and fault, enabling brittle deformation (Muir Wood, 1991) that enhanced fracturing of the hanging wall, and overprinted earlier ductile deformation in the fault zone. Sediments sloughed off the slopes were entrained into the fault zone as the hanging wall overrode the seafloor, resulting in sediment mixing and complex deformation (Stages 3-4 in Figure 5b). The translation of a cohesive hanging wall across porous seafloor also may have offscraped shallow footwall strata.

6. Pore Water Geochemical Profiles

Pore water geochemical profiles collected shipboard at Site U1518 (Saffer et al., 2019; Solomon et al., 2018) provide further support for seafloor overthrusting. Near-seafloor redox reactions (Mn- and Fe-reduction, SO_4-reduction, methanogenesis, anaerobic oxidation of methane, i.e., AOM) are largely dependent on reactive organic matter concentrations and are the dominant control on pore water solute profiles in the upper ~50-100 m in continental margin sediments worldwide. Thus, duplication of seafloor sections, even those originating in different places, should produce a repetition of pore water profiles of metabolic products associated with this early diagenesis of organic matter (e.g. NH_4, PO_4, alkalinity) across the fault.

The rates of ammonium (NH_4) and phosphate (PO_4) production will be the highest in the upper ~50 m of the sediment column due to the reactivity of organic matter (e.g. Middelburg, 1989; Wallmann et al., 2006). NH_4 and PO_4 concentrations typically decrease with depth below this zone, due to decrease in organic matter degradation rates, solute diffusion, authigenic mineral precipitation, ongoing microbial activity, and adsorption. These patterns are observed in the hanging wall at Site U1518; pore water NH_4 and PO_4 concentration profiles (Figure 6) clearly reflect characteristic organic matter degradation near the present seafloor. Ammonium concentrations increase with depth to a hanging wall maximum at 71 mbsf, then decrease towards the base of the hanging wall. Phosphate concentrations also increase from seawater value near the seafloor to a peak at 21 mbsf, then decrease sharply to 58 mbsf, and remain relatively constant to the top of the Pāpaku fault. Within the footwall, ammonium and phosphate concentration profiles show similar trends as observed in the upper hanging wall; concentrations increase with depth beneath the fault zone, and then decrease to the base of the hole. The sharp increases in NH_4 and PO_4 concentrations below the fault zone are consistent with recent underthrusting of the seafloor.

The solute profiles across the Pāpaku fault are similar to those across Sites 1040 and 1043 along the Costa Rica margin drilled during ODP Leg 170, where complete underthrusting of the incoming seafloor sediments beneath the lower slope wedge preserved near-seafloor signatures of NH_4 and PO_4 below the deollement (e.g., Kimura et al., 1997; Tobin et al., 2001). If the Pāpaku hanging wall was emplaced directly on top of the seafloor, then NH_4 and PO_4 concentrations also should preserve bottom water values (close to zero) immediately below the fault zone, and sulfate should be enriched in the upper ~10 m of the footwall (Saffer et al., 2019). Instead, we see that SO_4 is depleted and NH_4 and PO_4 concentrations are well above their seawater values. This disparity in concentrations at the seafloor and top of footwall may indicate that the shallowest footwall sediments were scraped off during hanging wall overthrusting, although alternative explanations exist.

The downhole trends in Cl and Li concentrations further confirm overthrusting, and provide preliminary estimates of the timing of hanging wall emplacement. Both Cl and Li concentrations should increase with depth below the seafloor at Site U1518 due to shallow sediment diagenesis. Immediately below the fault zone, Li concentrations step down to approximately half the concentration at the base of the hanging wall, and then increase with depth, mimicking the profile at the top of the hanging wall. Cl concentrations, however, exhibit a more complicated pattern. Relatively high Cl concentrations occur at the base of the hanging wall due to authigenic hydrous aluminosilicate formation (Saffer et al., 2019). Concentrations then decrease linearly to near-seawater values just below the subsidiary fault zone. The peak in Cl concentrations seen in the hanging wall at ~75 mbsf, however, is missing in the footwall trend. Its absence could be due to the removal of the shallowest footwall sediments during overthrusting, or to partial removal of the shallow hanging wall. More importantly, the persistence of the decreasing linear gradient in

Cl concentrations across the fault zone indicates relatively recent superposition of the hanging wall onto the footwall along the Pāpaku fault at Site U1518. Although dependent on poorly constrained boundary conditions, preliminary advection-diffusion modeling of the Cl profile indicates that underthrusting of Site U1518 occurred within the last 100 kyr, possibly as recent as 50 kyr (Solomon et al., 2018). Again, this scenario is similar to that interpreted near the deformation front of the Costa Rica margin, where the steep diffusional gradient in chloride across the plate boundary at ODP Site 1040, 1.6 km from the deformation front, is attributed to seafloor overthrusting ~17 kyr ago (e.g. Kimura et al., 1997; Saffer and Screaton, 2003; Solomon and Kastner, 2012).

In contrast to many other fault zones that have been drilled at subduction zones, no chemical anomalies occur within the Pāpaku fault zone that indicate advection of deeper-sourced fluids along the fault at Site U1518. The Pāpaku fault is interpreted to connect with the plate boundary landward of Site U1518, and thermal models show that subducted sediments at the interpreted depths are within the temperature range for mineral dehydration reactions (Antriasian et al., 2019). However, we do not observe the low Cl concentrations and elevated Li and B concentrations that are characteristic of fluid-rock reactions at these temperatures, as at other subduction zones (Kastner et al., 1991, 2006; You et al., 1995; Spivack et al., 2002; Hensen et al., 2004). These reactions may be occurring at depth, and advecting along deeper reaches of the Pāpaku fault, but lack a pathway to the seafloor along the shallow fault zone. Furthermore, the preservation of a diffusional gradient for Cl within the shallow footwall below the Pāpaku fault suggests little to no upward drainage of footwall fluids into the fault zone at Site U1518 (Solomon et al., 2018; Saffer et al., 2019). Thus, we interpret that the Pāpaku fault is a low permeability zone that prevents drainage of the footwall, consistent with interpretations based on seismic velocities and LWD data (Gray et al., 2019; Cook et al., 2020).

7. Discussion

7.1 What Causes Seafloor Overthrusting at Subduction Margins?

At Site U1518, the primary strand of the Pāpaku fault zone defines a distinct structural boundary and stratigraphic age inversion, juxtaposing comparatively cohesive but highly fractured hanging wall rocks upon a more porous footwall section, separated by a zone of intense ductilely deformed sediments. Overthrusting of the cohesive hanging wall onto pre-existing porous seafloor explains the contrasting properties and structural histories of the two domains (Figure 5). Pore water chemical profiles confirm this interpretation (Figure 6), suggest that overthrusting was relatively recent, and record little to no signal of fluid flow along or across the fault zone.

This is only the second example of seafloor overthrusting at subduction zones documented by ocean drilling, and compares with the Costa Rica margin where the frontal wedge rides out over incoming soft sediments (Tobin et al., 2001). The two examples of seafloor overthrusting provide interesting similarities and differences. In both settings, overthrusting of more cohesive hanging wall onto and over weak porous seafloor resulted in intensely ductilely deformed sediments, although at Costa Rica the fault rocks derived from the hanging wall (Vannucchi and Tobin, 2000), rather than from the footwall as along the Pāpaku fault. Interestingly, along the Costa Rica margin, the overthrusting horizon lies along the basal décollement, which defines a planar horizon separating the overriding plate from the incoming sediments (Tobin et al., 2001).

In contrast, the locus of deformation at the Hikurangi margin is a splay fault that diverged from the megathrust and ramped through and onto the trench sediments. Thus, an essential question is why displacement along the Pāpaku fault was so large that it ramped through the entire sedimentary section and caused the hanging wall to override seafloor an additional ~3 km?

Seismic profile 05CM-04 offers little insight into the origin of the Pāpaku fault, which is interpreted to splay downdip as it approaches the megathrust fault (Figure 1c). Such large offset faults may result from variations in mechanical properties or stress conditions (e.g., Gutscher et al., 1996), but also from incoming seafloor topography. For example, seamounts and subducting plate roughness have been shown to interact with subduction forearcs in other settings (Bangs et al., 2006; Dominguez et al., 2007), and appear to influence fault locations, offsets, and longevity by deflecting deformation away from the decollement horizon. Importantly, previous studies of the northern Hikurangi margin suggest the presence of subducted seamounts beneath the forearc, recognizable from pronounced magnetic anomalies (e.g., Barker et al., 2018) and high reflectivity zones in seismic profiles attributed to porous sediments flanking buried seamounts (Bell et al., 2010). Thus we explore the potential of seamount interactions to impact the Pāpaku fault.

Numerical simulations by Morgan and Bangs (2017) clarify the consequences of seamount-forearc interactions along accretionary margins with relatively thick incoming sedimentary sections. These models demonstrate that splay faults initiate along the leading flank of a subducting seamount and propagate into the overlying sediments. Depending on the height of the seamount and the internal strength of the sedimentary section, the splay fault may ramp through the entire section to glide along the seafloor as interpreted at Hikurangi, or it can occupy an internal weak horizon to create a secondary décollement as interpreted for the Nankai margin

(Moore et al., 2009). If the Pāpaku fault formed in association with a seamount not visible in our seismic profile, these models suggest that the seamount height is similar to the trench fill thickness. Significantly, seamount-guided splay faults can accommodate disproportionately high displacements (Morgan and Bangs, 2017) consistent with our interpretations for the Pāpaku fault, which potentially served as the active plate boundary for a period of time.

7.2. Mechanical and Hydraulic Consequences of Seafloor Overthrusting

The intense ductile deformation documented within the Pāpaku fault at Site U1518 appears to correlate with restricted advective flow from the footwall. Along the Costa Rica margin, across-fault fluid flow also is significantly reduced (Tobin et al., 2001). In both settings, a potential control on across-fault flow is the presence of an extensive ductilely deformed layer within the fault zone. Typically fault zones cored at subduction zones are characterized by abundant brittle faults, brecciation, and occasionally scaly fabrics in clay-rich materials (e.g., Lundberg and Moore, 1986; Moore et al., 2001; Kirkpatrick et al., 2014). Pervasive fracturing within and adjacent to such fault zones creates important fluid conduits, recorded by geochemical pore fluid anomalies that indicate the passage of deeply sourced fluids (Kastner et al., 1991, 2006, 2014; You et al., 1995; Spivack et al., 2002; Hensen et al., 2004). However, there is little evidence for such flow at Site U1518. The absence of active fluid flow in the Pāpaku fault could be due to the lack of significant fracture permeability adjacent to the fault, which may be incompatible with ongoing ductile shearing. Even pre-existing fractures in the hanging wall, inherited from earlier stages of evolution of the Pāpaku fault system, are predominantly filled or sealed (Savage et al., 2021), further restricting present-day fluid flow.

Ductile deformation has been shown to restrict fluid flow in fault zones elsewhere. “Clay smear” is mechanically generated clay gouge that develops along normal faults in layered sedimentary sequences, creating a fault seal in petroleum reservoirs (e.g., Vrolijik et al., 2016 and references therein). The most effective fault seals are characterized by tabular, well-mixed clay-rich lithologies that deformed by porous granular flow, commonly exhibiting planar flow-banding and local injection features, similar to the Pāpaku fault. Importantly, to serve as seals, these domains must be laterally continuous and not breached, e.g., by fracturing. The character and extent of clay smear depends on the abundance of clay in the strata, the thicknesses of the involved lithologies, and mechanical conditions (Vrolijk et al., 2016). Although clay content within the Pāpaku fault sediments only approaches ~50% by weight of total bulk sediment (Underwood, 2021), the thickness and continuity of the ductilely deformed zone within the main fault zone appears capable of restricting across-fault fluid flow, with significant implications for the mechanical conditions along the Pāpaku fault.

Figure 7 shows a hypothetical evolution of fault strength with displacement for the Pāpaku fault zone, mapped to the deformation stages shown in Figure 5. During fault initiation (Stage 1) and displacement along the thrust ramp (Stage 2), deformation was concentrated within the consolidated incoming sediments, with off-fault damage symmetrically distributed in both hanging wall and footwall (Figure 5b). Fault strength would have evolved due to strain localization and off-fault deformation, with peak strength and post-failure sliding strength defined by mechanical properties and pore fluid pressures (e.g., Moore and Byrne, 1987). However, emplacement of stronger consolidated and deformed hanging wall upon a more porous footwall flat (Stage 3 and beyond) caused fault-related deformation to migrate from the strong hanging wall into the weaker footwall. Thus, from the point of emergence onto the seafloor flat, the hanging wall became a largely passive element of the system, gliding along a weaker fault zone that coincided with the former seafloor. From this point on, fault strength was defined by the effective shear strength of the more porous seafloor sediments, primarily governed by sediment porosity and pore fluid pressures (Muir Wood, 1991). The shear stress acting on the hanging wall decreased below its critical failure stress, reducing the likelihood of further fault-related brittle deformation as the hanging wall slid passively on the seafloor fault, although brittle structures inherited during fault initiation and folding would have been preserved.

The footwall at the location of Site U1518 experienced a very different mechanical evolution (Figure 7). The earliest stages were characterized by burial and vertical consolidation prior to incorporation into the fault zone. This is indicated by the progressive increase in shear stress (Stages 1-2) that tracks decreasing porosity in the absence of shear strain (Muir Wood, 1991). As the hanging wall approached (Stage 3), the footwall may have felt its effects, and then the superposition of the hanging wall upon the local footwall in Stage 4 fully mobilized the top of the footwall in shear. Fault slip was transferred away from the hanging wall onto the top of the footwall. For simplicity, effective shear stress is shown as constant with increasing shear strain (black arrow), although it likely fluctuated in response to pore pressure changes or additional tectonic loading. Alternatively, further consolidation of the fault zone could strengthen the fault over time (gray arrow), possibly causing the locus of shear strain to migrate deeper into the footwall.

The steps up in porosities across the main and subsidiary faults preserved at Site U1518 (Figure 2) suggest that the footwall has not fully consolidated under the additional load of the overthrust hanging wall, and thus may still support excess pore pressures (e.g., Gray et al, 2019; Cook et al., 2020). This is further supported by the lack of evidence for fluid advection at the drill site in the solute profiles (Figure 6), and deformation experiments on representative footwall sediments (French and Morgan, 2020) that suggest pore pressure ratios as high as 0.5-0.9 of lithostatic within the fault zone. Sheared clay-rich sediments tend to have significantly lower permeabilities than their unsheared analogs (Takahashi, 2003; Cuisiat and Skurtveit, 2010), decreasing with shear strain (Ikari and Saffer, 2012). Furthermore, the intensity of ductile deformation within the Pāpaku fault zone, apparent lateral continuity of the planar flow fabric, and the comparatively minor overprint of sealed fractures and faults (Savage et al., 2021), suggest that the in-situ Pāpaku fault zone does not host abundant open fractures, at least where penetrated at Site U1518. LWD evidence for conductive fractures and macroscale deformation within the fault zone at Site U1518 are similarly sparse, except near the top of the primary fault strand (Cook et al., 2020). Thus, the comparative coherence of the fault zone and the thick continuous package of intensely sheared clay-rich sediments may define a laterally extensive fault seal that resists significant fault-normal fluid flow, at least since overthrusting occurred. This configuration has preserved excess pore pressures within the footwall and fault zone, resulting in low fault strengths along the Pāpaku fault that enable large displacements and enduring activity. Although it is still unclear how local overpressures in this setting may impact conditions along the megathrust fault, if similar low permeability structures occur elsewhere along the margin, they could enable regionally high pore fluid pressures that favor the occurrence of SSEs on the Hikurangi megathrust fault.

8. Conclusions

Predominantly ductile deformation within the large-offset Pāpaku fault at Hikurangi subduction margin Site U1518 resulted from overthrusting of a consolidated hanging wall upon a footwall composed of high porosity, previously unburied sediments at the seafloor. Overthrusting may have been associated with a subducting seamount located down-dip of the fault. The juxtaposition of the strong hanging wall upon a weak footwall caused fault-related deformation to migrate from the hanging wall onto the weaker seafloor interface below, resulting in locally intense ductile deformation, accompanied by sediment fluidization and injection. Duplication of downhole trends in pore water solute profiles across the Pāpaku fault at Site U1518 confirm the seafloor overthrusting model. The preservation of typical near-seafloor, early diagenetic profiles below the fault indicate relatively recent overthrusting, possibly ~50-100 kya (Saffer et al., 2019; Solomon et al., 2018), and demonstrate little to no advective fluid flow either along or across the fault. The intense ductile deformation along the fault zone is interpreted to have produced a thick continuous layer of low permeability fault rocks resistant to fluid flow, which preserves high pore pressures within the underthrust sediments and fault zone (French and Morgan, 2020; Gray et al., 2019; Cook et al., 2020). In combination, the extensive ductile deformation, apparently low fracture permeability, and enhanced pore pressures along the fault, likely define a fault seal that prevents fluid flow in this location. This distinctive structural, mechanical, and hydraulic configuration defines a significant tectonic feature along the frontal Northern Hikurangi Margin. If similar low permeability structures occur elsewhere along the margin, they may preserve high pore fluid pressures that enable SSEs on the Hikurangi megathrust fault.

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Figure Captions

Figure 1. (a) Tectonic setting of the northern Hikurangi margin (bathymetry from GeoMapApp); black box shows approximate location of survey area shown in (b). (b) Bathymetry of study area showing locations of seismic line 05CM-04 (black line) and Expedition 375 drill sites (red dots). Blue box shows location of seismic profile. (c) Depth converted pre-stack time migrated seismic profile 05CM-04 (after Barker et al., 2018), showing location of Site U1518, with stratigraphic and structural interpretations modified from Barnes et al. (2020) and Davy et al. (2021). Further details of the interpretation of the Papaku fault hanging wall stratigraphy are shown in Davy et al. (2021). Seismic units (SU) are defined at IODP Site U1520 (Barnes et al., 2019).

Figure 2. Summary of core observations with depth from Site U1518. (a) Core recovery from Holes U1518E and U1518F. (b) Graphic lithology, showing lithologic units and age; key at bottom of figure. (c) Discrete sample porosity measurements (small open circles), core average values (large filled circles), and LWD neutron porosities (gray lines). (d) Bedding dips. (e) Fracture (solid squares) and fault dips (open squares). Modified after Saffer et al., (2019).

Figure 3. Synthesis of core and section observations across the main strand of the Pāpaku fault and immediately adjacent wall rocks. Key shows symbols used here. Missing core denoted by large X and unrecovered core is symbolized at the based of each core. Interpreted hanging wall (HW), main fault zone (FZ), and footwall (FW) are labeled and uniquely shaded. Locations of core photos in Figure 4 are denoted.

Figure 4. Representative core samples with locations noted on Figure 3. All intervals are from Hole 375-U1518F. Hanging wall: (a) normal fault offsets silt bed and terminates in brecciated zones (13R-1W, 46-53 cm), (b) abundant fractures cross-cut distorted sedimentary layers (13R-1A, 88-94 cm). Main fault zone: (c) variably oriented color banding at top of fault zone (13R-1A, 112-117 cm), (d) brecciated rock with discordant flow-banding (13R-2A, 28-33 cm), (e) finely laminated flow-banded mudstone with elongated clasts (13R-3W, 11-33 cm), (f) disaggregated sediment injected into adjacent cohesive rock (13R-3W, 82-88 cm), (g) distorted and truncated stacks of mudstones and silt layers cross-cut by fractures (14R-1A, 126-140 cm), (h) flow-banded unit with homogenized gray material cross-cut by normal faults (14R-2A, 34-42 cm). Footwall: (i) small injection feature (15R-1A, 18-22 cm), (j) dismembered silt beds (15R-2A, 1-7 cm), (k) silt beds distorted into recumbent fold (15R-3A, 109-112 cm), (l) mud clast with asymmetric tails in coarse flow-banding (18R-1A, 77-81 cm).

Figure 5. (a) Hypothetical kinematic reconstruction of the frontal Hikurangi margin, showing stages of evolution of the Pāpaku fault (T_2), from the initiation of Papaku fault (Stage 1), initial uplift and folding the hanging wall (Stage 2), hanging wall overthrusting and slumping (Stage 3), and juxtaposition of hanging wall and footwall at Site U1518 (Stage 4). Dotted and gray boxes show the trajectory of the hanging wall and position of the footwall, respectively. (b) and (c) Schematic deformation paths of materials within the dotted and gray boxes in (a) at each stage for the hanging wall and footwall, respectively, as they undergo contrasting deformation histories and eventually converge at Site U1518. See text for details.

Figure 6. Concentration profiles of (a) NH_4, (b) PO_4, (c) SO_4, (d) Cl, and (e) Li. Blue and red circles represent data for hanging wall and footwall samples, respectively. Open circles represent phosphate and sulfate concentrations measured by spectrophotometry and ion chromatography, respectively and closed circles measured by ICP-AES (Saffer et al., 2019). Horizontal dashed lines mark lithological unit boundaries, shaded bars locate the main and subsidiary fault zones. Vertical dotted lines indicate seawater values.

Figure 7. Hypothetical stress-strain histories of the hanging wall (no shading), and shared history of the footwall and fault zone (shaded), with Stages 1 through 4 from Figure 5 denoted for both settings. The stress and shear strain magnitudes are only representative, showing hypothesized relative magnitudes. See text for discussion.

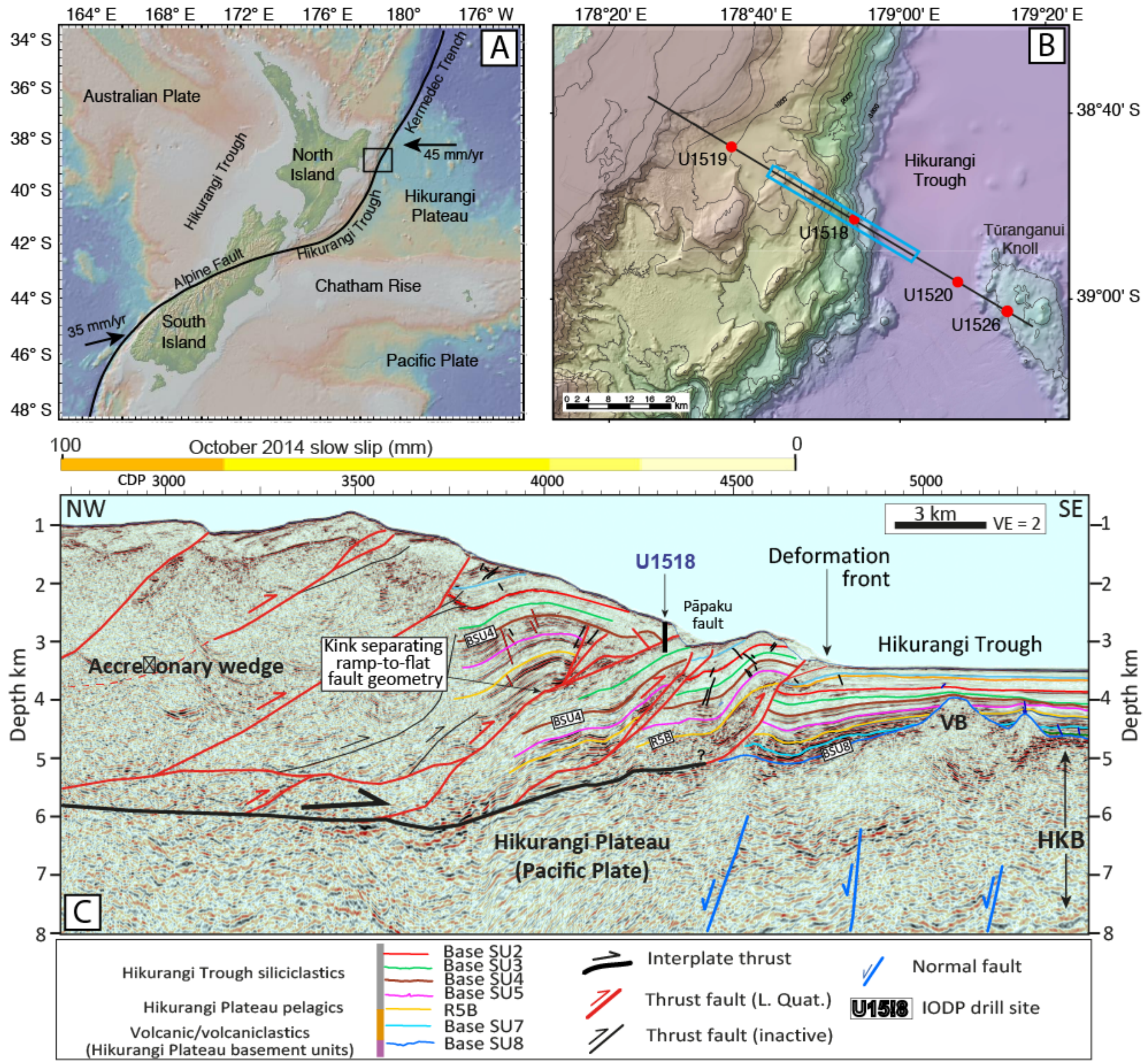

164° E
168° E
172° E
176° E
180°
176° W
34° S
36° S
38° S
40° S
42° S
44° S
46° S
48° S
A
Australian Plate
Hikurangi Trough
North Island
Kermadec Trench
45 mm/yr
Hikurangi Trough
Hikurangi Plateau
Alpine Fault
Chatham Rise
35 mm/yr
South Island
Pacific Plate
178°20' E
178°40' E
179°00' E
179°20' E
B
38°40' S
39°00' S
U1519
Hikurangi Trough
U1518
Tūranganui Knoll
U1520
U1526
100
October 2014 slow slip (mm)
0
CDP 3000
3500
4000
4500
5000
NW
SE
3 km
VE = 2
U1518
Deformation front
Pāpaku fault
Hikurangi Trough
Kink separating ramp-to-flat fault geometry
BSU4
Accretionary wedge
Depth km
BSU4
R5B
BSU8
VB
Hikurangi Plateau (Pacific Plate)
HKB
C
Hikurangi Trough siliciclastics
Hikurangi Plateau pelagics
Volcanic/volcaniclastics (Hikurangi Plateau basement units)
Base SU2
Base SU3
Base SU4
Base SU5
R5B
Base SU7
Base SU8
Interplate thrust
Thrust fault (L. Quat.)
Thrust fault (inactive)
Normal fault
U1518
IODP drill site

Figure 1

839
840

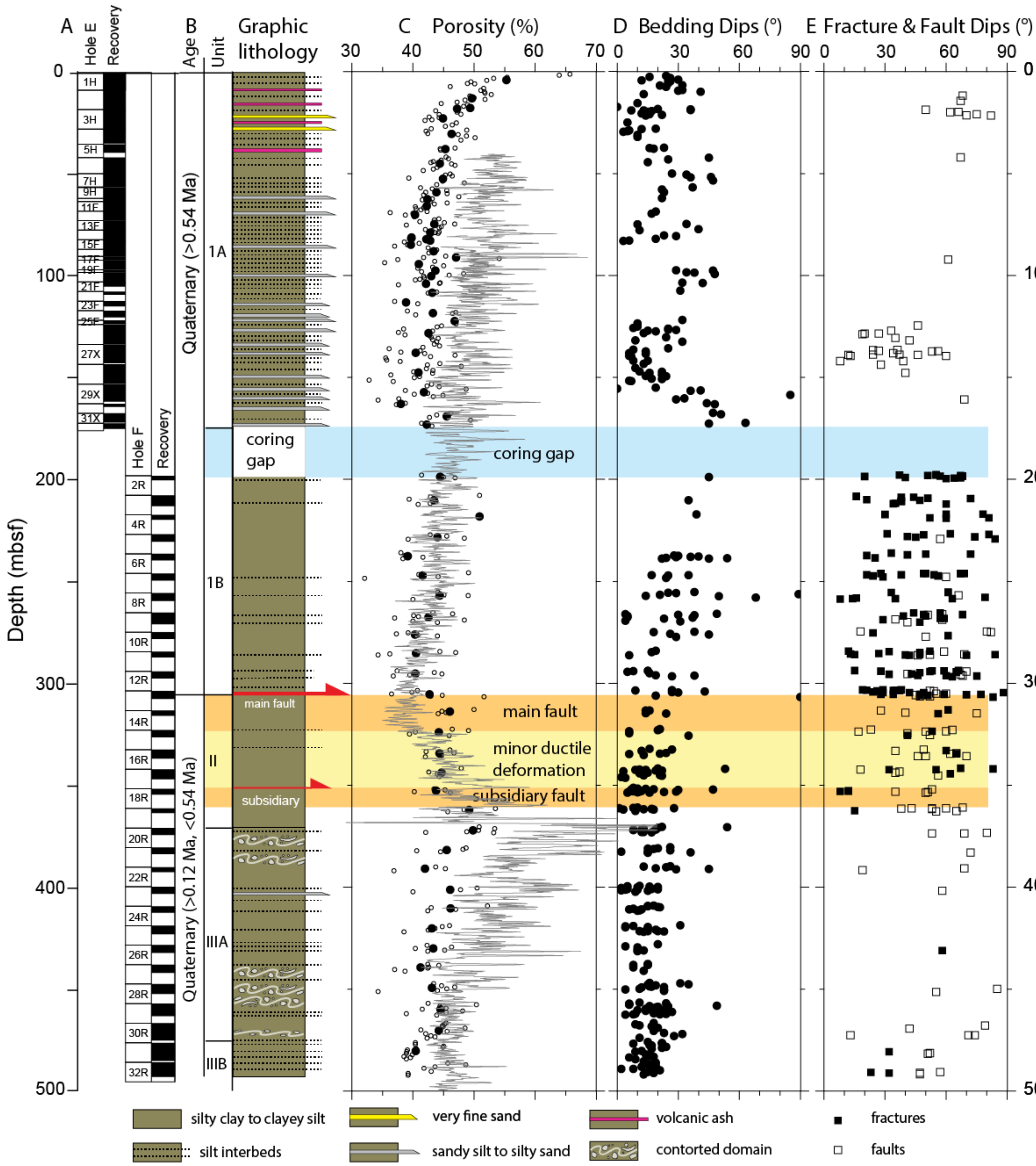


Figure 2

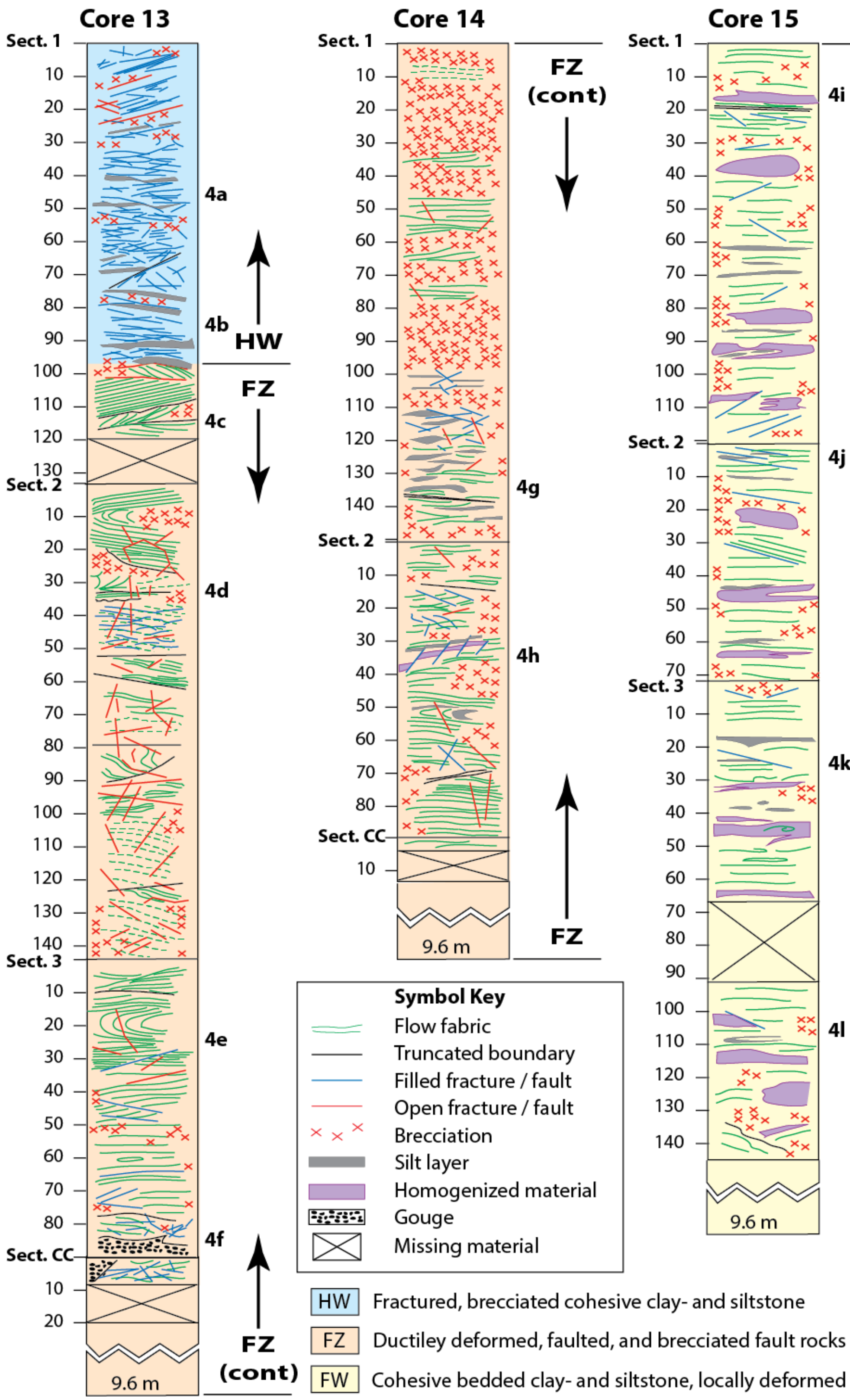

Core 13
Core 14
Core 15
Sect. 1
Sect. 2
Sect. 3
Sect. CC
4a
4b
4c
4d
4e
4f
4g
4h
4i
4j
4k
4l
HW
FZ
FZ (cont)
Grada- tional FW
9.6 m
Symbol Key
Flow fabric
Truncated boundary
Filled fracture / fault
Open fracture / fault
Brecciation
Silt layer
Homogenized material
Gouge
Missing material
HW Fractured, brecciated cohesive clay- and siltstone
FZ Ductiley deformed, faulted, and brecciated fault rocks
FW Cohesive bedded clay- and siltstone, locally deformed

Figure 3

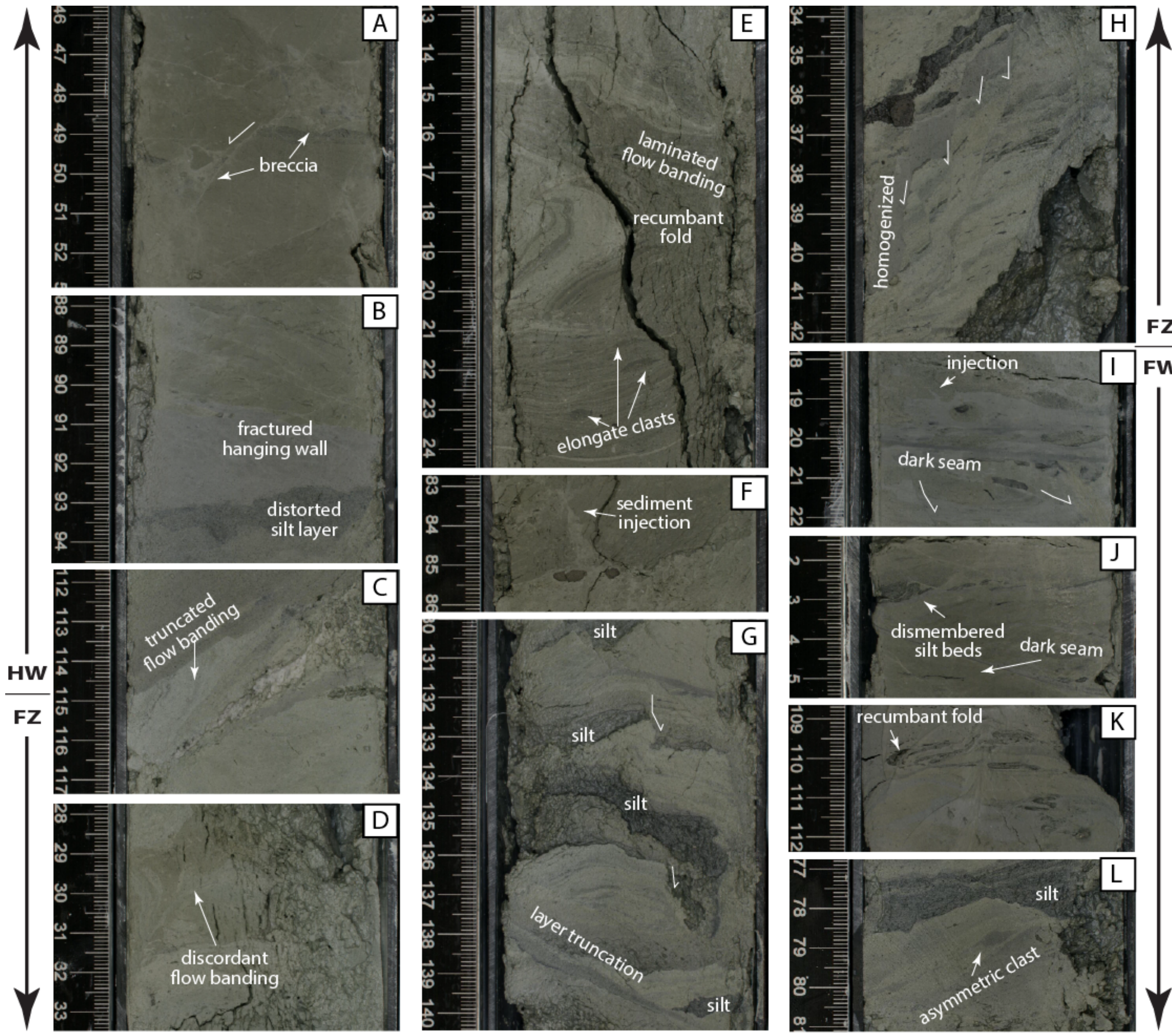


Figure 4. Representative core intervals, with locations noted on Figure 3. All intervals are from Hole 375-U1518F. Hanging wall: (a) normal fault offsets silt bed and terminates in brecciated zones (13R-1W, 46-53 cm), (b) abundant fractures cross-cut distorted sedimentary layers (13R-1A, 88-94 cm). Main fault zone: (c) variably oriented color banding at top of fault zone (13R-1A, 112-117 cm), (d) brecciated rock with discordant flow banding (13R-2A, 28-33 cm), (e) finely laminated flow banded mudstone with elongated clasts (13R-3W, 11-33 cm), (f) disaggregated sediment injected into adjacent cohesive rock (13R-3W, 82-88 cm), (g) distorted and truncated stacks of mudstones and silt layers cross-cut by fractures (14R-1A, 126-140 cm), (h) flow-banded unit with homogenized gray material cross-cut by normal faults (14R-2A, 34-42 cm). Foot wall: (i) small injection feature (15R-1A, 18-22 cm), (j) dismembered silt beds (15R-2A, 1-7 cm), (k) silt beds distorted into recumabnt fold (15R-3A, 109-112 cm), (l) mud clast with asymmetric tails in coarse flow banding (18R-1A, 77-81 cm).

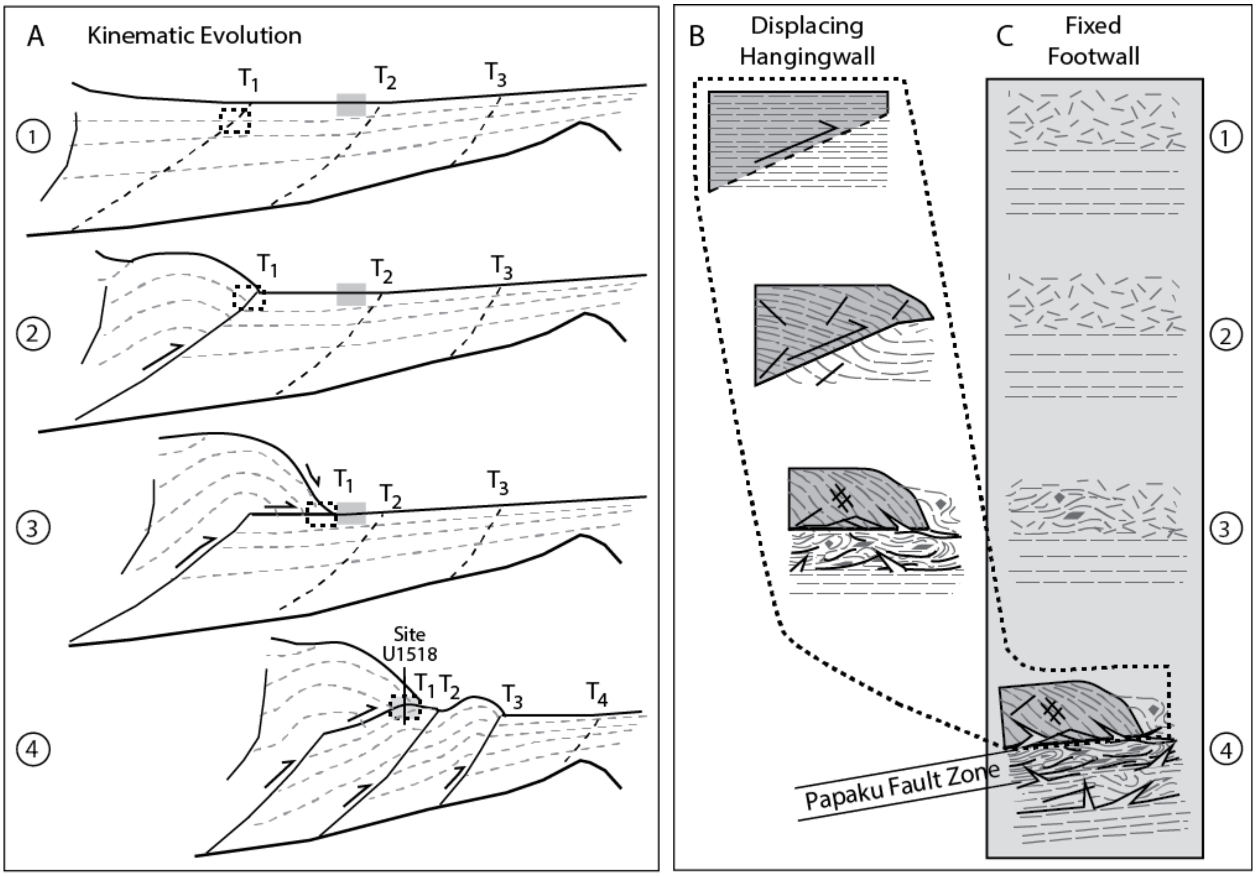


Figure 5

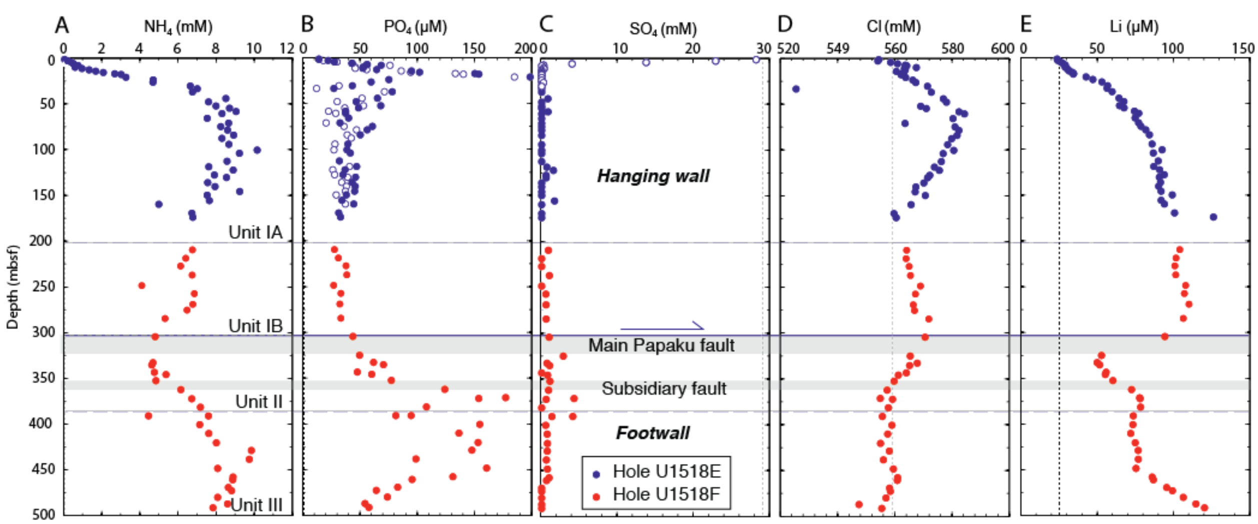
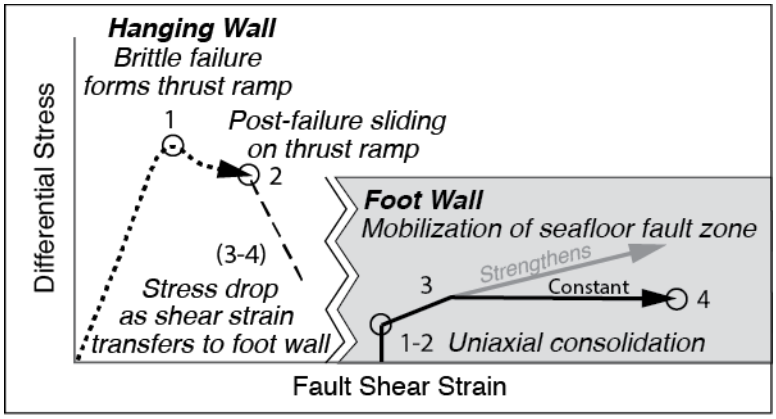


Figure 6

849



Hanging Wall
Brittle failure
forms thrust ramp
1
Post-failure sliding
on thrust ramp
2
(3-4)
Stress drop
as shear strain
transfers to foot wall
Foot Wall
Mobilization of seafloor fault zone
Strengthens
3
Constant
4
1-2
Uniaxial consolidation
Differential Stress
Fault Shear Strain

Figure 7