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Physical properties and gas hydrate at a near-seafloor thrust fault, Hikurangi Margin, New Zealand

Ann Elizabeth Cook[1], Matteo Paganoni[2], Michael Benedict Clennell[3], David Daniel McNamara[4], Michael Nole[5], Xiujuan Wang[6], Shuoshuo Han[7], Rebecca Bell[8], Evan A Solomon[9], Demian M Saffer[10], Philip Barnes[11], Ingo Pecher[12], Laura Wallace[13], Leah J. LeVay[14], and Katerina Petronotis[15]

[1]Ohio State University
[2]Shell International Global Solutions B.V.
[3]CSRIO
[4]University of Liverpool
[5]Sandia National Lab
[6]Institute of Oceanology,Chinese Academy of Sciences;Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology
[7]University of Texas Institute for Geophysics
[8]Imperial College London
[9]University of Washington
[10]University of Texas at Austin
[11]National Institute of Water & Atmospheric Research
[12]University of Auckland
[13]GNS Science
[14]International Ocean Discovery Program, Texas A&M University
[15]Texas A&M University

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Abstract

The Pāpaku fault zone, drilled at IODP Site U1518, is an active splay fault in the frontal accretionary wedge of the Hikurangi Margin. In logging-while-drilling data, the 33 m-thick fault zone exhibits mixed modes of deformation associated with a trend of downward decreasing density, P-wave velocity and resistivity. Methane hydrate are observed from ~30-585 mbsf, including within and surrounding the fault zone. Hydrate accumulations are vertically discontinuous and occur throughout the entire logged section at low to moderate saturation in silty and sandy cm-thick layers. We argue that the hydrate distribution implies that the methane is not sourced from fluid flow along the fault but instead by local diffusion. This, combined with geophysical observations and geochemical measurements from Site U1518, suggests that the fault is not a focused migration pathway for deeply-sourced fluids and that the near-seafloor Pāpaku fault zone has little to no active fluid flow.

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Ann E. Cook[1], Matteo Paganoni[2], M. Ben Clennell[3], David D. McNamara[4], Michael Nole[5], Xiujuan Wang[6], Shuoshuo Han[7], Rebecca E. Bell[8], Evan A. Solomon[9], Demian M. Saffer[7], Philip M. Barnes[10], Ingo A. Pecher[11], Laura M. Wallace[12], Leah J. LeVay[13] & Katerina E. Petronotis[13]

[1]School of Earth Sciences, The Ohio State University, Columbus, Ohio, USA; Corresponding author: cook.1129@osu.edu

[2]Department of Earth Sciences, University of Oxford, Oxford, UK & Shell International Global Solutions, Rijswijk, The Netherlands

[3]CSIRO, Kensington, Western Australia, Australia

[4]Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, UK

[5]Center for Energy and Earth Systems, Sandia National Laboratories, Albuquerque, New Mexico, USA

[6]Institute of Oceanography, Chinese Academy of Sciences, Quidao, China

[7]Institute for Geophysics, University of Texas-Austin, Austin, Texas, USA

[8]Basins Research Group, Imperial College London, Kensington, UK.

[9]School of Oceanography, University of Washington, Seattle, Washington, USA

[10]National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand

[11]School of Environmental and Marine Sciences, University of Auckland, Auckland, New Zealand

[12]GNS Science, Lower Hutt, New Zealand

[13]International Ocean Discovery Program, Texas A&M University, College Station, Texas, USA

Key Points

The Pāpaku fault zone is a 33-m thick near-seafloor splay fault drilled at Site U1518 on the Hikurangi Margin

Multiple lines of observational, geophysical and geochemical evidence suggest that there is little to no fluid flow along the Pāpaku fault

Abstract

The Pāpaku fault zone, drilled at IODP Site U1518, is an active splay fault in the frontal accretionary wedge of the Hikurangi Margin. In logging-while-drilling data, the 33 m-thick fault zone exhibits mixed modes of deformation associated with a trend of downward decreasing density, P-wave velocity and resistivity. Methane hydrate are observed from ~30-585 mbsf, including within and surrounding the fault zone. Hydrate accumulations are vertically discontinuous and occur throughout the entire logged section at low to moderate saturation in silty and sandy cm-thick layers. We argue that the hydrate distribution implies that the methane is not sourced from fluid flow along the fault but instead by local diffusion. This, combined with geophysical observations and geochemical measurements from Site U1518, suggests that the fault is not a focused migration pathway for deeply-sourced fluids and that the near-seafloor Pāpaku fault zone has little to no active fluid flow.

Plain Language Summary

Faults are boundaries in the Earth where two different blocks of sediment or rock slide past each other. Offshore New Zealand, the Pāpaku Fault is very shallow and intersects the seafloor but connects to deeper faults kilometers below the seafloor where large earthquakes can occur. An ice-like form of methane called hydrate also occurs within and surrounding the fault. We use scientific drilling data to understand the physical properties of the fault. Hydrate can affect fault properties and how fluid flows; however, based on the pattern of hydrate distribution and other geochemical and geophysical measurements we suggest that the Pāpaku fault does not have active fluid flow.

Keywords: Hikurangi Margin, fault, gas hydrate, accretionary wedge

1. Introduction

The physical and hydrological properties of subduction zone thrust faults are of great interest because of their relationship with large earthquakes. Movement along these faults span a range of behaviors from large earthquakes, to slow and low frequency earthquakes, to aseismic creep behavior [*Hyndman et al.*, 1997; *Rogers and Dragert*, 2003]. A number of variables influence this spectrum of slip behavior, such as temperature, frictional properties, effective stress and pore pressure [*Beroza and Ide*, 2011; *Saffer and Wallace*, 2015; *Bürgmann*, 2018]. In addition, fault slip behavior near the trench of subduction zones is critical to understand as these areas can generate large tsunamis [*Ide et al.*, 2011]. The fluid flow and drainage patterns of active faults play an important role in mediating the distribution of fluid pressure and effective stress. These flow patterns are also a first-order control on seepage, dewatering processes, and volatile fluxes in subduction forearcs [e.g. *Moore and Vrolijk*, 1992; *Carson and Screaton*, 1998; *Saffer and Tobin*, 2011].

At the Hikurangi Margin along the eastern North Island of New Zealand, the Pacific plate subducts westward beneath the Australian plate at a rate of ~35-55 mm/year. A range of fault slip styles have been observed or inferred along the Hikurangi Margin including short-term and long-term slow-slip events (SSE), earthquakes, and tsunami earthquakes [*Doser and Webb*, 2003; *Wallace et al.*, 2009, 2012]. Moreover, SSEs at the northern Hikurangi Margin have been observed within 2 km of the seafloor, and these are among the shallowest SSE observations on Earth [*Wallace et al.*, 2016]. The variety of slip styles on the Hikurangi Margin, opportunities for near-field monitoring of SSEs near the trench, and the accessibility of the SSE source to scientific ocean drilling and seismic imaging, makes the area an excellent location to study fault structure, fault properties and fluid flow.

The Pāpaku fault (Figure 1), drilled at International Ocean Discovery Program (IODP) Site U1518, intersects the seafloor in a highly active part of the outer margin. The fault is part of a splay system in the accretionary wedge that connects to the deep décollement 10-25 km landward of the drill site, and 2-3 km deeper [*Barker et al.*, 2018]. While the Pāpaku fault zone has been penetrated at very shallow depths at the drilling location (~315 meters below seafloor, mbsf) it may slip and may exhibit pore pressure and fluid flow changes as a result of SSEs.

An extensive suite of *in situ* measurements were collected across the Pāpaku fault in Hole U1518B using logging-while-drilling (LWD) tools during IODP Expedition 372 (Figure 1) [*Saffer et al.*, 2019b]. About 50 m to the south, the Pāpaku fault was cored at Hole U1518F during Expedition 375 (Figure 1). There was 43% core recovery over a ~300 m interval surrounding the fault [*Saffer et al.*, 2019b] and 33% recovery in the fault zone [*Fagereng* et al., 2019]. While this core recovery is comparable to other fault zones, coring alone leaves significant gaps in the characterization of the Pāpaku fault zone and surrounding sedimentary system that can be resolved with continuous LWD measurements.

Methane hydrate, a solid clathrate of methane and H_2O [*Sloan and Koh*, 2007] was observed in core at Site U1518 at several different intervals from 33-391 mbsf using infrared scanning and pore water chlorinity measurements [*Saffer et al.*, 2019b]. Methane hydrate is stable throughout Site U1518; the top of methane hydrate stability occurs at ~600 m below sea level and the base of the methane hydrate stability occurs at ~585 mbsf, using the CSMHyd software [*Sloan and Koh*, 2007] which incorporates measured temperature, background pore water salinity, and estimated pressure [*Saffer et al.*, 2019b]. Hydrate can affect fluid flow patterns by influencing sediment permeability and pore pressure [*Nimblett and Ruppel*, 2003; *Xu and Germanovich*, 2006; *Sultan*, 2007; *Daigle et al.*, 2015] as well as alter the sediment physical properties such as increasing stiffness, cohesion and shear strength [*Pearson et al.*, 1983; *Yun et al.*, 2005; *Waite et al.*, 2009; *Yoneda et al.*, 2017].

The Pāpaku fault now hosts a borehole observatory installed in Hole U1518H (only a few meters from Hole U1518B) that is monitoring pore fluid pressure, fluid flow rates and temperature, as well as sampling fluids for geochemical analyses [*Saffer et al.*, 2019b]. Therefore, the logging and coring datasets collected at Site U1518 yield insight into the properties of the Pāpaku fault, surrounding sediment, hydrate distribution, and the fluid flow system that provides valuable context for the interpretation of fault slip processes and the observatory data [e.g. *Sawyer et al.*, 2008; *Kinoshita et al.*, 2018].

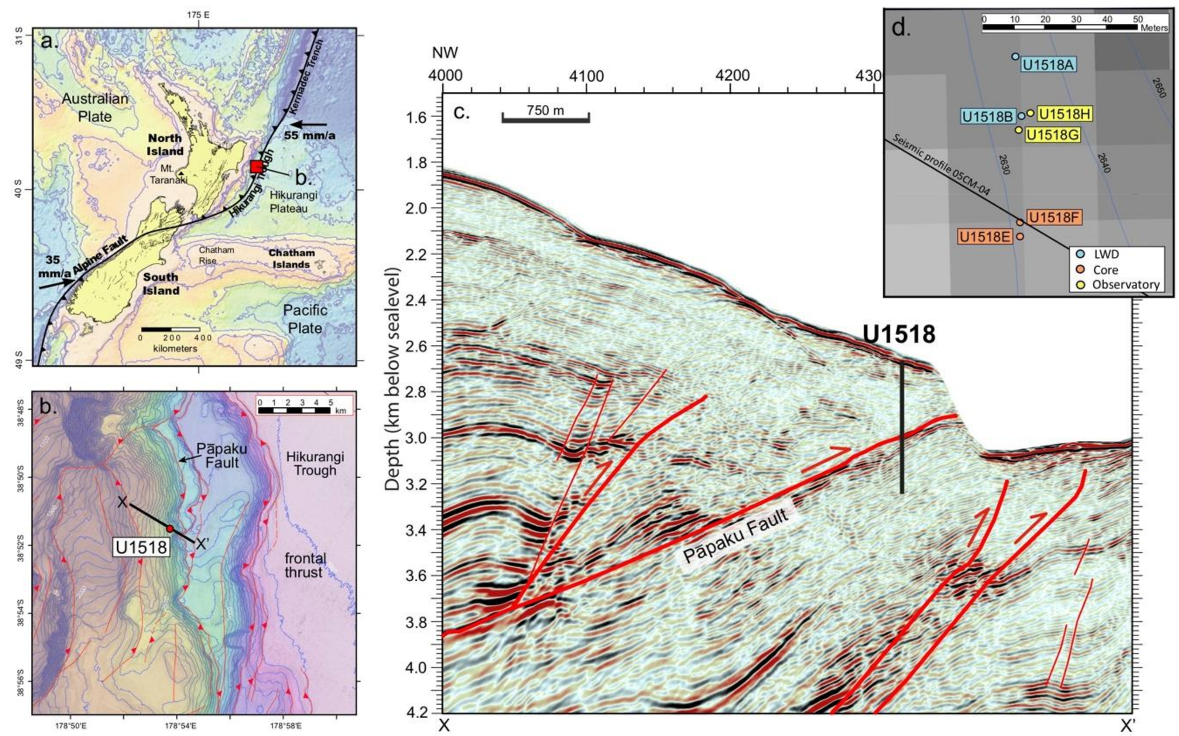

Figure 1. a) Location of Site U1518 offshore the North Island of New Zealand on the Hikurangi Margin. b) Zoomed in bathymetry near the Pāpaku Fault. c) Seismic cross section over the area, with ancillary faults and the Pāpaku Fault identified with red lines. Seismic line location shown in b (black line). d) The placement of six holes at Site U1518. All images are modified from *Saffer et al.*, [2019a; 2019b]. LWD = logging while drilling.

2. Methods

A comprehensive set of *in situ* LWD measurements were collected across the Pāpaku fault in Hole U1518B, which included natural gamma ray, ultrasonic caliper, neutron porosity, source-less neutron density, button, ring and propagation resistivity measurements, resistivity imaging, P-wave and S-wave velocity, nuclear magnetic resonance (NMR) porosity and NMR T_2

relaxation time distribution [*Wallace et al.*, 2019]. Figure 2 depicts selected measurements across the fault zone from Hole 1518B.

We used Schlumberger's petrophysical analysis software, Techlog, to orient and interpret statically and dynamically normalized resistivity images to identify bedding, fault and fractures orientations [e.g. *Wallace et al.*, 2019]. We also interpreted deformation features in the image, which we define as either non-throughgoing sinusoids likely fragmented due to deformation, or throughgoing features that change orientation on the image (for example, features appear squeezed and a traditional sinusoid cannot be fit to the feature), which indicate possible soft-sediment deformation.

We calculate hydrate saturation, S_h, using Archie's equation [*Archie*, 1942; *Goldberg et al.*, 2010] with the measured RING resistivity, R_{RING}, an estimated background resistivity, R_o:

$$S_h = 1 - \left(\frac{R_o}{R_{RING}}\right)^{1/n} \qquad \text{Equation 1}$$

We estimate R_o by carefully considering the background trends in resistivity, P-wave velocity, neutron porosity and NMR porosity; we also conservatively overestimated R_o in intervals with borehole washout. R_{RING} is used in saturation calculations because it is the most sensitive resistivity measurement for hydrate in cm-thick layers due to the high vertical resolution (5-8 cm) for depth of penetration [*Cook et al.*, 2012]. For the saturation exponent, n, we apply n = 2 & n =3 to show the probable range of hydrate saturations [*Cook and Waite*, 2018]. We also calculated R_o from neutron porosity for comparison, but we chose not to use the neutron porosity-derived background because the neutron porosity has a much lower vertical resolution than the RING resistivity and neutron porosity can be inaccurate in high-porosity (> 0.3) clay-rich sediments [*Ellis and Singer*, 2007].

Other than hydrate, sediment overcompaction or cementation could cause spikes in resistivity, but 1) cements are not observed in the core at Site U1518 [*Saffer et al.*, 2019b] and 2) there is no decrease in neutron porosity or NMR porosity indicating cementation or overcompaction at the locations of any of the thicker resistivity spikes; thus hydrate the most likely cause of resistivity exceeding R_o throughout Site U1518.

3. The Pāpaku fault zone & surrounding system

In the LWD data, we observe significant changes in the physical properties and bedding orientation above, below and within the Pāpaku fault zone (Figure 2), which are described in the following section. Overall, more deformation features are identified in the hanging wall (Figure 2), which may explain the acoustic transparent nature in the hanging wall relative to the footwall on seismic data (Figure 1c).

On the LWD data, we observe hydrate filling the pore space of thin (on the order of cm to 10's of cm) coarse-grained layers above, below and within the Pāpaku fault zone (Figure 2). Herein, we define coarse-grained as sand or coarse-silt that does not have a significant clay fraction. While there is variation in hydrate concentrations with depth, there is not a large difference in the concentration of hydrate filled layers in the hangingwall, fault zone and footwall (Figure 2); some of the variation may be due to the occurrence of coarse-grained layers. The fault zone itself does have lower hydrate saturations (<0.1) than the immediate surrounding hanging wall and footwall, however, other sections such as 235-263 mbsf in the hanging wall and 455-485 mbsf in the footwall also have similar low hydrate saturations (<0.1).

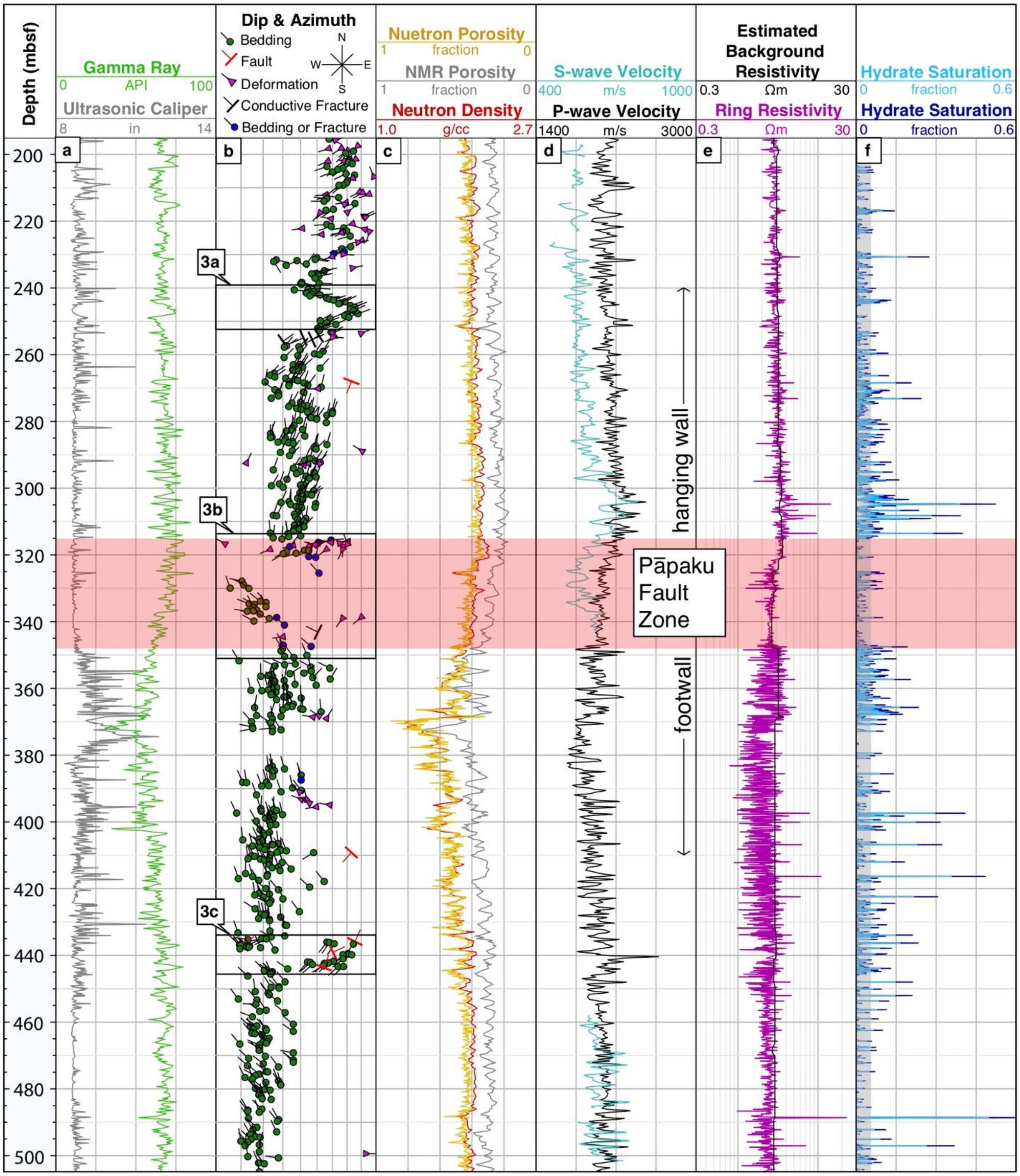

Figure 2. a. Logging-while-drilling (LWD) well log measurements (Tracks a, c, d & e), image interpretation (Track b), estimated background resistivity (Track e) and calculated hydrate saturation (Track f) at Hole U1518B. Note that the neutron porosity and neutron density may not

provide accurate measurements in this high porosity, clay rich environment, and NMR porosity measurements are affected by the presence of gas hydrate. When resistivity is low and close to the background, calculated hydrate saturations (Track f) have lower confidence; we grayed these lower confidence saturations. At low resistivity, intervals without hydrate could be identified with low saturation and intervals could be incorrectly identified as water-saturated.

3.1 Hanging wall and fault zone

In core from Hole U1518F, the Pāpaku fault zone was identified from 304-361 mbsf, which includes an ~18 m-thick fault zone underlain by ~30 m of less deformed material, followed by a ~10 m-thick subsidiary fault zone [*Fagereng et al.*, 2019]. The Pāpaku fault zone depths are different in LWD Hole U1518B ~50 m to the north, where we interpret the base of the hanging wall and the top of the Pāpaku fault zone to begin 11 meters deeper, at 315 mbsf, where there is an abrupt change from 25-45° north-dipping beds to a chaotically oriented and deformed interval (Figure 3b) [*Fagereng et al.*, 2019; *Saffer et al.*, 2019].

The base of the hanging wall (300-315 mbsf) is marked by elevated P-wave and S-wave velocity and low neutron porosity. Increased compaction and shear strengthening from fault movement compared to the adjacent intervals may explain such trends. However, this interval also hosts hydrate (Figure 2b), which contributes to the increase in P-wave and S-wave velocity by increasing the cohesive and mechanical strength. The hydrate is occurring at saturations up to 0.5 in 10's of cm-thick layers that are generally coarser-grained (as indicated by lower gamma ray).

The bedding orientation from the hanging wall (dipping 25-45° north) is truncated against chaotically dipping features which are a combination of deformation, fractures and bedding (Figure 3b). The interval between 315-318.5 mbsf is the densest interval in the hole, likely related to increased compaction caused by fault movement, though the P-wave and S-wave velocity are lower than the interval just above that contains hydrate (Figure 2).

Most of the fault zone in Hole U1518B is marked by a gradual decrease in P-wave velocity, resistivity and neutron density with depth. These LWD measurements are of high quality in the fault zone as the borehole diameter is close to the bit size, however, bedding and fracture orientation is often difficult to distinguish within the fault zone as the image appears mottled (Figures 2 & 3). A variety of deformation features were observed in the core, including breccia, flow banding, breccia clasts, dismembered beds, small faults and fractures [*Fagereng* et al., 2019]. The mottled appearance observed on the image logs over several large sections in the fault zone (Figure 3b) are likely caused by discontinuous deformation features below the horizontal (~1 cm) and vertical resolution (~5-8 cm) of the resistivity images [*Schlumberger*, 2007]. Bright white mottled features on the image log (Figure 3b) may also be hydrate forming in nodules or in deformed coarser-grained packages within the fault zone. Intervals in the fault zone with identified bedding may be a relatively intact section within the fault zone or could be deformed beds or flow banding.

Below ~335 mbsf, the gamma ray (Figure 2) and NMR T2 distribution (shown in [*Saffer et al.*, 2019b]) indicate sediment gradually grades into a thick, coarse-grained unit of silts and sands with cm-thick mud interbeds. Below 348 mbsf, bedding orientation is visible and the bedding in this zone dips between 15-55° and generally north to northwest. With the continuing transition to coarser-grained sediment, the borehole washes out resulting in enlarged hole size and erroneously high porosity measurements approaching 0.8 at some depths (Figure 2). While the average resistivity in this unit is lower due to the borehole washout, it is also much more variable. The local highs or spikes in the RING resistivity within the coarser unit are most likely caused by thin, pore-filling hydrate layers providing some sediment strength and transient borehole stability.

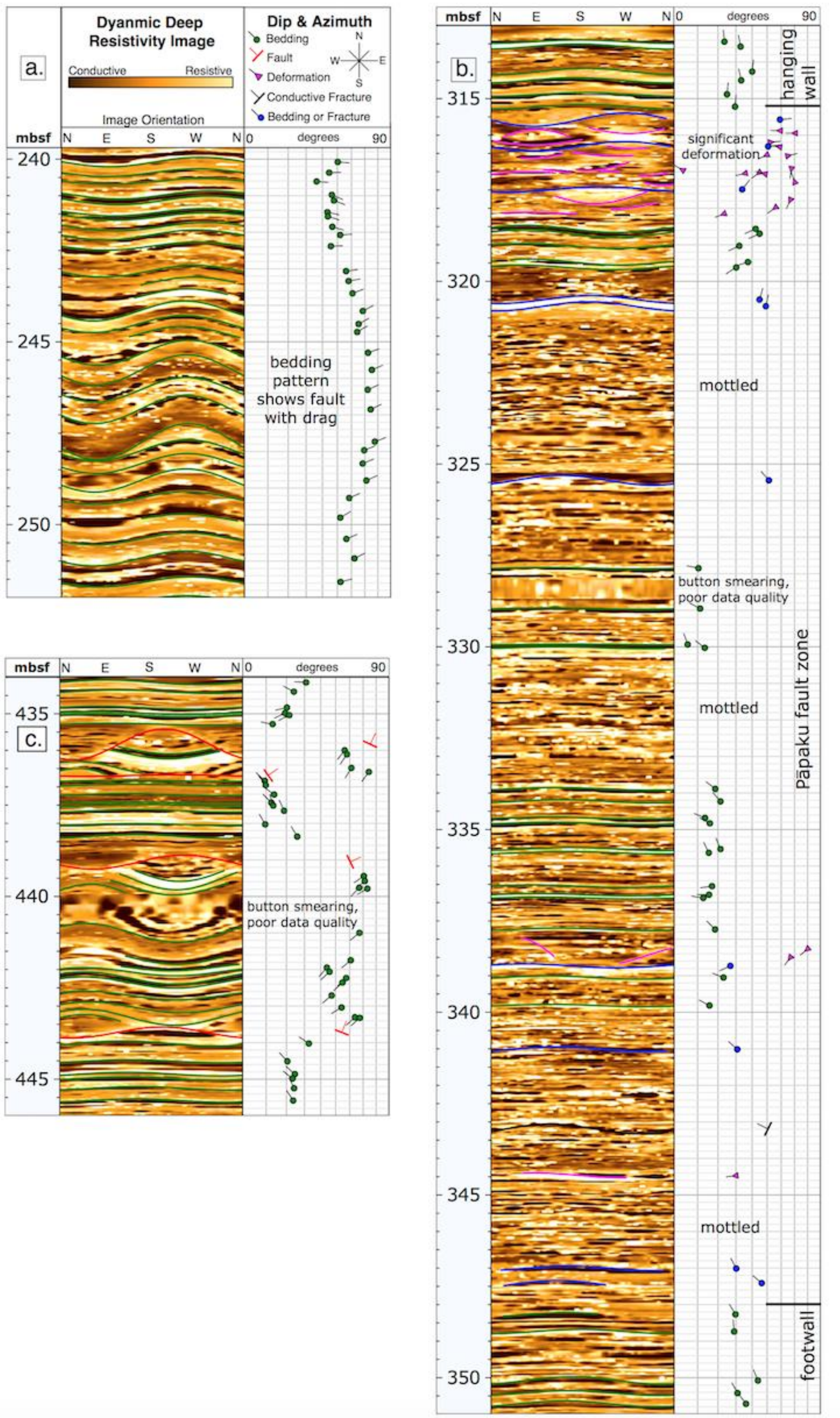

Figure 3. Selected resistivity image log intervals and interpretation from Hole U1518B. a) Bedding patterns indicating a thrust fault propagation fold, b) the Pāpaku fault zone and c) a section of faults and offset beds in the footwall.

3.2 Footwall

The base of the Pāpaku fault zone and the transition to the footwall is not as clear as the hanging wall transition on LWD data. Part of this ambiguity is due to the lithology, as grading into coarser sediments is indicated by the gamma ray beginning at ~335 mbsf, making it difficult to distinguish between physical property changes from coarsening sediment versus changes produced by deformation processes within the fault zone. Core observations note silts and hemipelagic mud at the bottom the fault zone and the top of the footwall, however, core recovery was low in the footwall (<36%) which may indicate loss of coarser-grained sands and slits [*Saffer et al.*, 2019b].

We argue the most likely depth for the base of the Pāpaku fault zone on LWD data is 340-348 mbsf. At this depth, there are only a few features identified on the image logs (Figure 3), but based on the gamma ray in the interval (Figure 2) the sediment should be composed of alternating finer and coarser grained beds, with the concentration of coarser-grained beds increasing towards 348 mbsf. Alternating beds of this type are typically easily identifiable on good quality images, so the lack of bedding suggests the interval is still affected by fault-related deformation. The contrasting bedding orientations above 340 and below 348 mbsf further suggests there is deformation occurring in this interval. Below 348 mbsf, most identified beds have a similar orientation to beds significantly below the fault zone (i.e. from ~450-500 mbsf) indicating that this is the footwall.

3.3 Subsidiary faults

There are several subsidiary faults and fault-related features visible on the LWD resistivity images. Six faults identified at 272, 409, 436, 437, 439, and 444 mbsf are dipping between 12-75° (Figure 2). Figure 3c shows four of these faults, which occur between 435-445 mbsf and are associated with sharp changes in bedding orientation above and below the fault sinusoid. We cannot identify the relative movement of these faults because beds cannot be correlated above and below the fault plane sinusoid. This also means that the throw is more than the amplitude of the sinusoid in the borehole (between 10-100 cm).

A major fault zone was interpreted at 351-361 mbsf in coring Hole U1518F [*Fagereng et al.*, 2019] and at 369 mbsf in LWD Hole U1518B [*Saffer et al.*, 2019b]. LWD evidence for a fault near 369 mbsf includes changing bedding orientations from 368-370 mbsf with some deformation features; however, there is no clear fault plane like other subsidiary faults observed in the resistivity images (Figure 3c). In addition, there are several depths (e.g. 226, 234, and 355 mbsf) where bedding orientation changes suddenly which could also be evidence for additional faults.

Another fault-related feature is the orientation of beds from 242-250 mbsf (Figure 3a), which increase in dip from 242 mbsf and reach the highest angle dip of almost 80° at ~247 mbsf and then decreases. This pattern of increasing and decreasing dip is consistent with a thrust fault-propagation fold as well as the stress regime in the hanging wall.

4 Discussion

On LWD data from Hole U1518B, we interpret an apparent 33 m-thick Pāpaku fault zone from 315-348 mbsf. From core in Hole U1518F, *Fagereng* et al. [2019] interpreted the fault zone over an apparent 58 m-thick interval from 304-361 mbsf. The 11 m difference between the top of the fault is supported by the presence of a low porosity zone at the base of the hanging wall and at the top of the fault zone observed in both LWD and core data [*Saffer et al.*, 2019a]. The difference in the Pāpaku fault zone thickness (58 m fault from core and 33 m from LWD) and the top of the fault zone may be the result of a variety of different factors [*Saffer et al.*, 2019b]. Most likely, there is a change in fault geometry and thickness over the 50 m distance between holes due to splays or imbricate structure; in addition, core recovery and borehole deviation could cause small differences in the fault zone thickness between holes.

4.1 Fluid flow and gas hydrate

Hydrate is observed in thin, cm- to 10's of cm-thick coarse-grained sediments throughout Site U1518, from near-seafloor to total depth (Figure 2). Such a frequent occurrence of hydrate implies that the dissolved pore water methane concentration is very close to solubility throughout the site, yet hydrate appears to preferentially form in coarse-grained sediments with little or no hydrate in marine muds.

This pattern of hydrate-bearing coarse-grained layers interbedded within water-saturated or low-hydrate saturation marine muds has been observed in several locations, such as the Gulf of Mexico, offshore India, and the Cascadia Margin accretionary prism [*Malinverno*, 2010; *Cook and Malinverno*, 2013; *Malinverno and Goldberg*, 2015]. The pattern can be explained by a diffusion-dominated methane migration, which is driven by the difference in methane solubility between coarse-grained sands (or silts) and marine muds [*Malinverno*, 2010; *Nole et al.*, 2017]. The solubility threshold is higher in muds due the high curvature of the pore surface in small pores [*Clennell et al.*, 1999; *Rempel*, 2011]. In marine muds near the seafloor, methane can be generated through a series of microbial reactions, and it is dissolved in the pore water. This methane diffuses into adjacent sand layers over time, and when the solubility threshold is reached, hydrate forms in the sands first. Because methane solubility is lower in the sands, this allows for a constant diffusive flux of methane rich pore water from marine muds both above and below the coarse-grained sand layers. Eventually, this leads to significant hydrate saturation in thin sands surrounded by water-saturated marine muds. Because the methane generated in the muds only diffuses a few centimeters to meters to fill the thin sands, the mechanism is referred to as short-migration [*Malinverno*, 2010].

Yet, in accretionary wedge environments advective methane fluxes along faults are observed at many locations worldwide [*Moore and Vrolijk*, 1992; *Kastner et al.*, 1998, 2014; *Geersen et al.*, 2016] as well as observed and inferred along the Hikurangi Margin [*Crutchley et al.*, 2011; *Plaza-Faverola et al.*, 2012; *Kroeger et al.*, 2015; *Watson et al.*, 2019]. Additionally, the Pāpaku fault zone does have relatively high porosity (>0.4) in deformed and fractured sediment which could facilitate fluid flow.

We argue, however, that there is combined observational, geochemical, geophysical and petrophysical evidence supporting little to no advection of deeply sourced, gas-bearing or geochemically distinct fluids along the Pāpaku fault zone. First, methane to ethane ratios in headspace gas samples are greater than 20,000, suggesting that a microbial origin for the methane is more likely than a deeply-sourced thermogenic origin [*Saffer et al.*, 2019b]. We recognize that thermogenic methane can be microbially altered and microbial methane can be generated rather deep in some systems and advected upward (for example, modeling suggests microbial generation peaks at 1600 mbsf in the Pegasus Basin in the southern Hikurangi Margin [*Kroeger et al.*, 2015]). Even so, an in-situ microbial origin for the methane forming hydrate appears more in line with the observed pattern of hydrate distribution. At Site U1518, hydrate is not concentrated along a specific stratigraphic interval (for example, in the thick coarse-grained unit from ~335-405 mbsf) as would be expected from hydrate originating from methane fluxes along a thrust fault, but is instead dispersed within thin coarse-grained layers throughout Site U1518. If methane or methane-rich fluid were shuttled through the fault zone, it is likely that hydrate would form at high-concentration in fractures or veins within the fault zone, as they commonly do in other focused flow settings [*Weinberger and Brown*, 2006; *Abegg et al.*, 2007; *Riedel et al.*, 2010; *Kim et al.*, 2013]; however, there is no evidence for veins or fractures of hydrate on images in the Pāpaku fault zone.

Moreover, there is no evidence for active fluid flow along the fault from pore water solute profiles, and the absence of diagenetic cements at Site U1518 further support the lack of fluid advection [*Saffer et al.*, 2019b]. In seismic data, high amplitude, reversed seafloor-polarity reflections from the decollement and other thrust faults on subduction margins have been linked to possible evidence of fluid flow and/or high pore pressure in both observations and in models [*Moore et al.*, 1995; *Bangs et al.*, 1999, 2015; *Saffer and Tobin*, 2011]. At the Pāpaku fault, the reverse-seafloor polarity reflection can be produced by the reduction in both P-wave velocity and density from the hanging wall into the fault zone (Figure 2), as shown by the synthetic seismogram in *Saffer et al.*, [2019b]. Therefore, fluid flow and high pore pressure are not required at Site U1518 to explain the negative impedance on seismic data. In addition, a 2D high-resolution full waveform inversion P-wave velocity model by *Gray et al.*, [2019] showed that some fault zones in the wedge are associated with velocity reductions of up to 500 m/s. The smaller velocity reduction of ~100 m/s in the Pāpaku fault zone in the *Gray et al.* [2019] model indicates that the fault may not be acting as a significant conduit for fluid flow in the same way as inferred for other faults.

Collectively, multiple lines of evidence suggest the shallow part of the Pāpaku fault zone currently has low or no fluid advection; however, we cannot rule out fluid flow at greater depths or brief pulses of fluids along the shallow fault zone in the past. If pulsing occurred in the past, the fluids are likely through-going and not interacting with the surrounding footwall and hanging wall system.

Although evidence for long distance migration of fluids is fairly common from drilling frontal thrust faults at subduction zones, another example of a location where there is limited evidence for fluid flow and methane flux is along the Kumano transect on the Nankai Trough [*Screaton et al.*, 2009]. Together, these two sites suggest that inactive or lower advection hydrologic systems along frontal thrusts could be a more common occurrence than previously thought. How shallow faults without advection may or may not relate to the deeper fault system is unknown. In the future, data and fluid samples recovered from the borehole observatory installed at Site U1518 will provide direct constraints on in situ near-seafloor fluid flow rates and fault zone hydrologic properties of the Pāpaku fault zone.

5 Conclusions

Understanding physical properties and fluid flow around subduction fault zones is essential for illuminating the role of fluids in fault mechanics and slip behavior. Herein, we argue that the Pāpaku fault zone does not have significant fluid flow in the near-seafloor system. The 33 m-thick fault zone does have high porosity and a trend of decreasing P-wave velocity from top to bottom of the fault. Despite high porosity measured within the fault zone and the occurrence of high-saturation methane hydrate in thin sands at Site U1518, we argue that advective fluid flow is likely not causing the unconnected but frequent occurrence of gas hydrate in thin sands from 30 to 585 mbsf on logging-while-drilling (LWD) data. Instead we argue that the hydrate distributed in coarse-grained sediments less than 1 m-thick is caused by local diffusion of microbially generated methane. This further supports evidence from geochemical analysis on pore water samples and modeling work on seismic data that the Pāpaku fault does not have significant, active deeply-sourced fluid flow.

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