ECORD IODP-Italia

Unlocking the secrets of slow slip events: the role of lithological and geometric heterogeneity of the subducting plate

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(and many others!)

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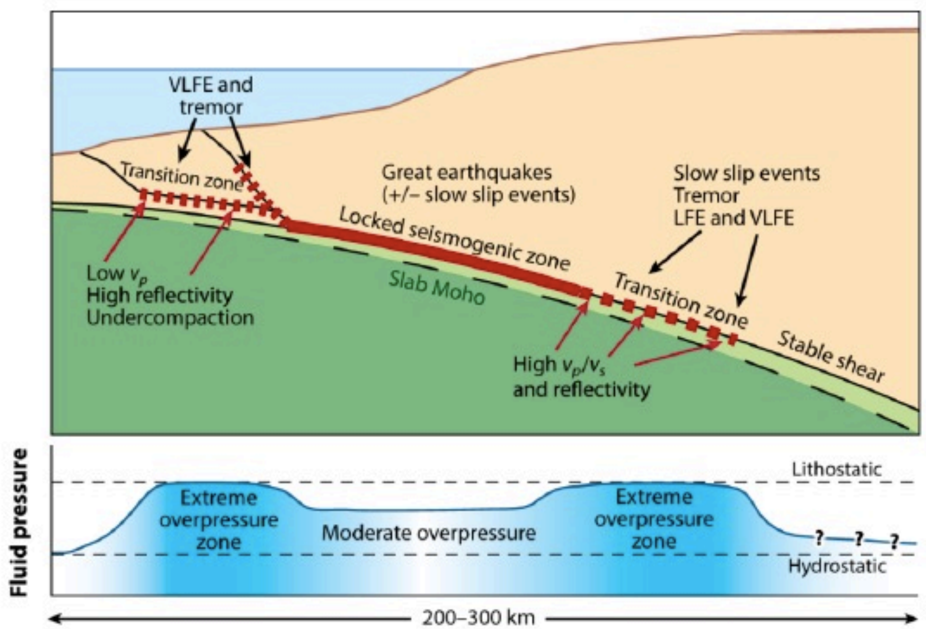
Crustal fault zones (comprising subduction thrusts) accommodate displacement in a variety of slip styles:

- steady creep at rate typical of plate motions (1-10 cm/y);
- coseismic slip at rate ca. 1 m/s: nearly all of Mw>8 earthquakes occur along the seismically active part of the subduction plate interface thrusts;
- everything in between falls in the category of ***slow earthquakes,*** a category of slip events with durations up to several orders of magnitude longer than regular earthquakes of comparable size (slow slip events (SSEs), tremor and low-frequency earthquakes) - *see Kirkpatrick et al., 2021*

WHAT ARE SSEs?

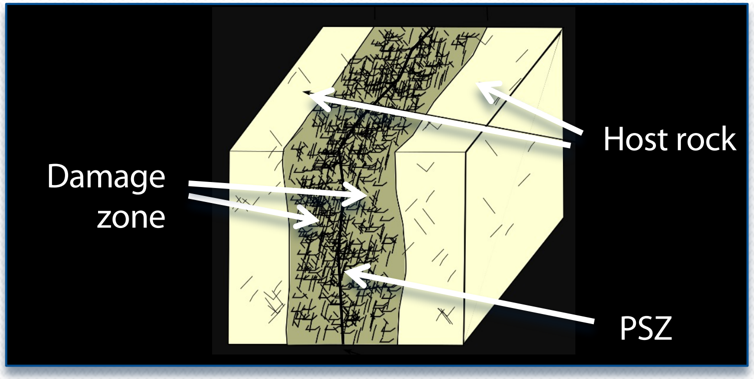
- transient aseismic slip on a fault lasting for days to years
- slip velocities too small to radiate seismic energy and cause ground shaking
- recorded both at the upper and lower transitions to aseismic slip along the place interface (associated with zones of high to fluid overpressure?),
- exhibit unclear spatio-temporal associations with large seismic events (causal relation between modes of slip at different slip rate?)



Saffer and Tobin, An Rev EPS 2011

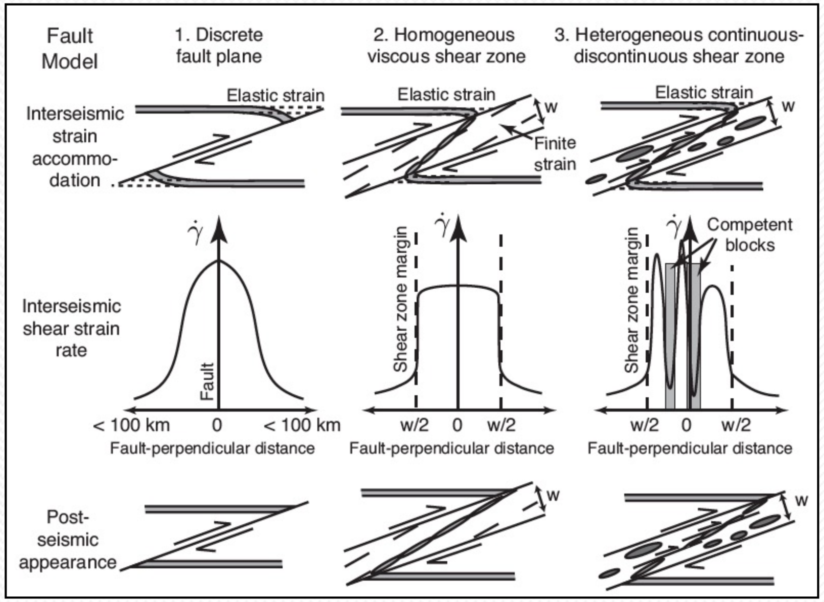
Fault styles in onland exhumed structures

1.



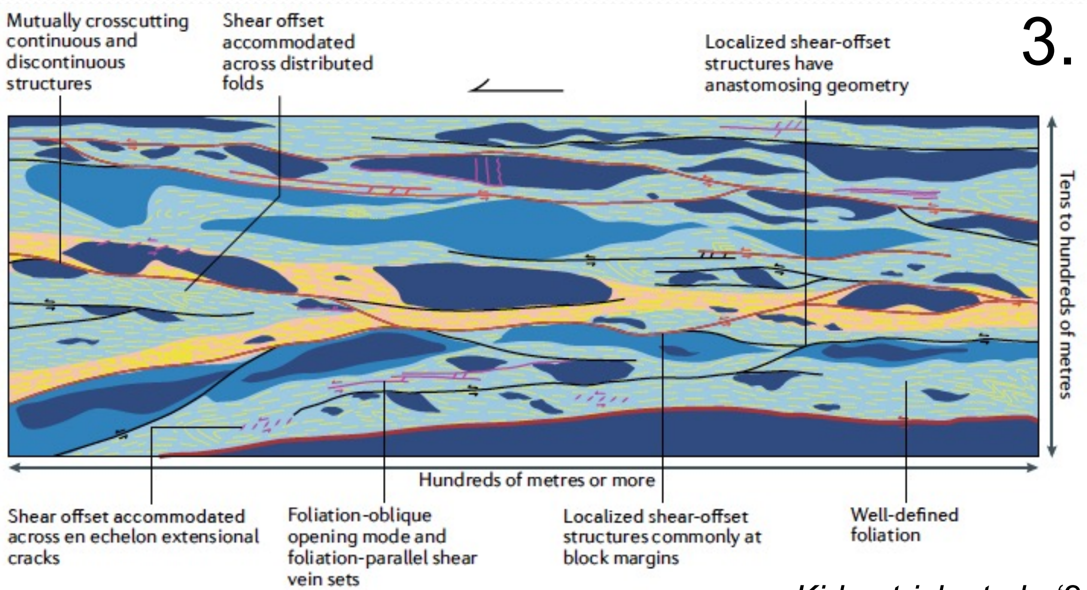
High-strain zones geometries/structures varies depending on rheology and degree of localization (e.g. Fagereng and Sibson, ’10):

1. localized faults with a discrete, narrow principal slip zones (PSZs) surrounded by damage zones (Chester and Logan ’86);
2. thick homogeneous layers of viscous material;
3. thick delocalized fault zones with mixture of heterogeneous materials and heterogeneous continuous-discontinuous deformation (Rowe et al., ’13, Kirkpatrick et al, ‘21),



Fagereng and Sibson, ‘10

3.



Kirkpatrick et al., ‘21

FAULT STYLE VS. SLIP BEHAVIOR

1. Discrete, localized faults store elastic strain and episodically accommodate irrecoverable strain by seismic failure.
2. Homogeneous viscous shear zone accommodate most displacement by continuous, aseismic deformation ("stable sliding");
3. Delocalized fault zones with heterogeneous distribution of deformation and materials with spatial variations in rheology (shear strength, viscosity, shear strain rate) and faulting style: elastic strain is released heterogenously in slip surfaces within the shear zone ("unstable sliding").

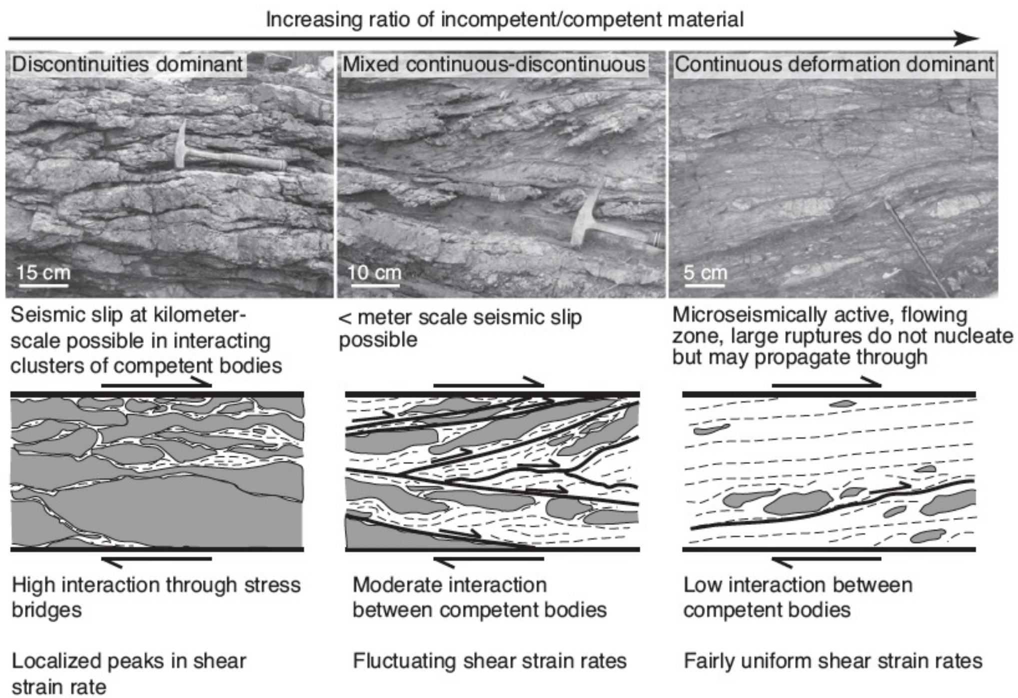
IN THE SPACE BETWEEN

A wide range of fault rocks and textures are recorded on land as falling between 1. and 2. :

- this variety is time-dependent, and may represent a progression in fault evolution;
- the "seismic character" of this variety can be modeled in terms of incompetent vs. competent ratio

(e.g. SSEs are widely thought to be a manifestation of transitional frictional stability)

Is the "space between" fault styles the record of "in between" slip behaviors?



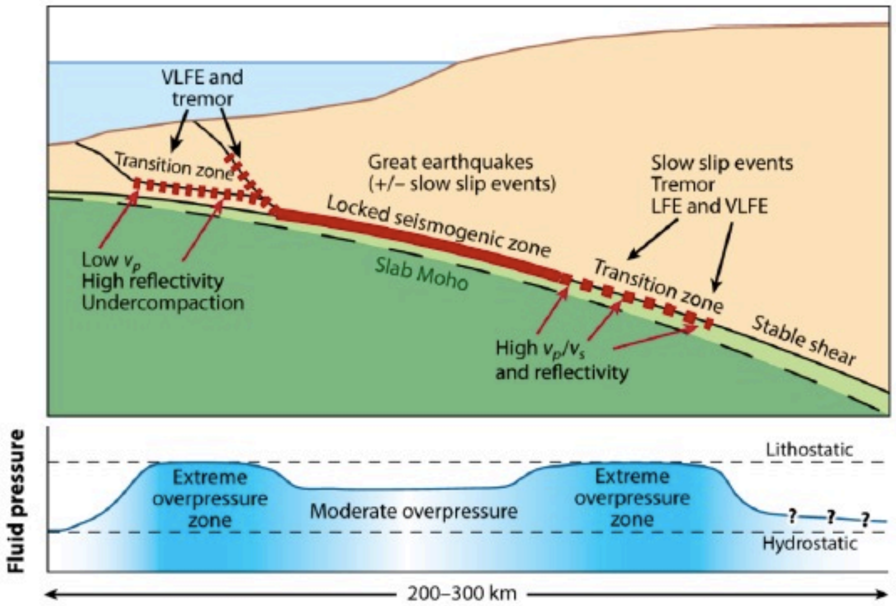
Fagereng and Sibson, '10

SUBDUCTION ZONE SLIP STYLES: OPEN QUESTIONS

Steady creep, coseismic slip, and the variety of «slow earthquakes» in between (LFE, SSEs, tremors etc.), all contribute to plate motion accommodation along subduction thrust faults during the seismic cycle.

However:

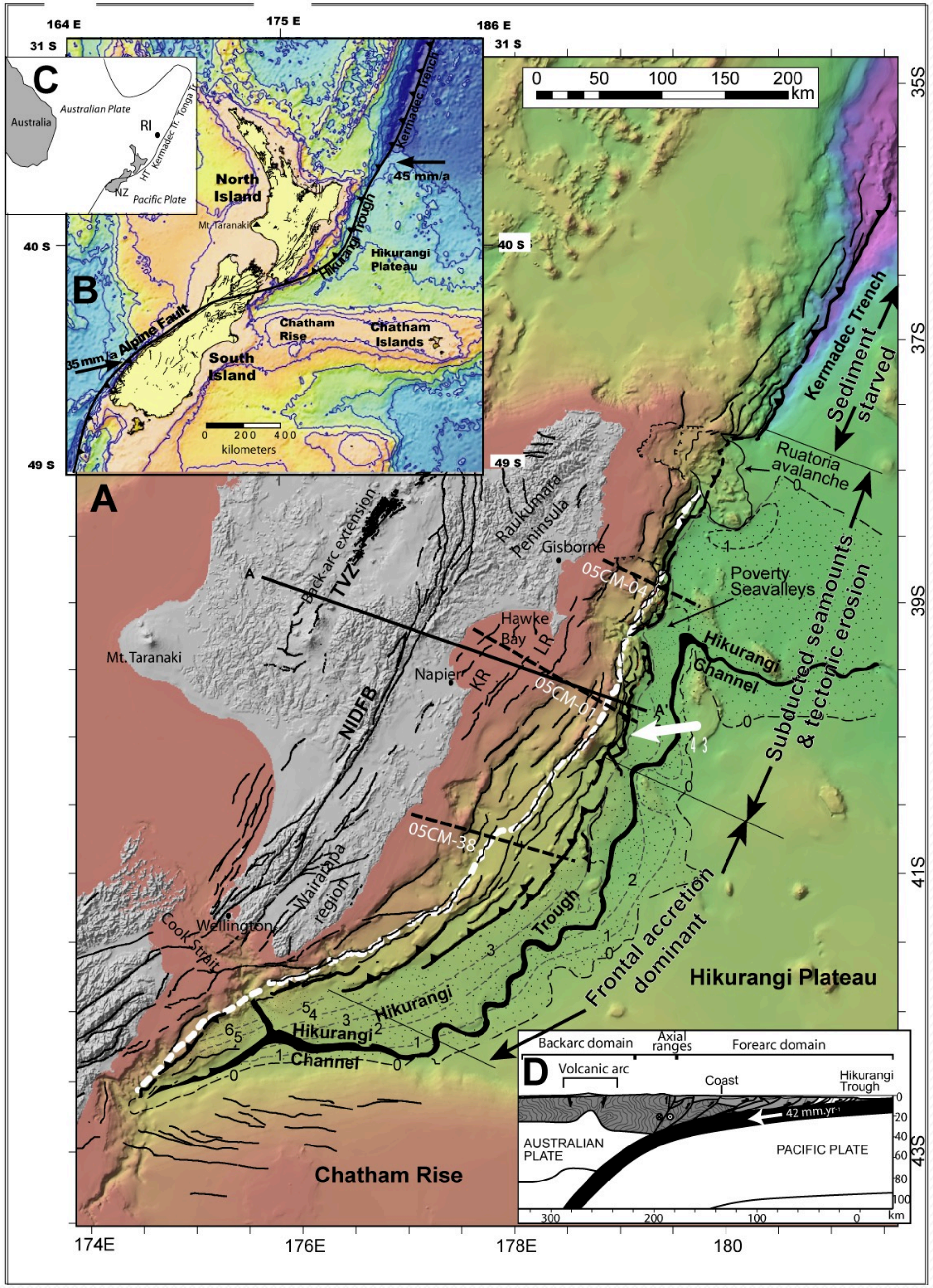
- we do not know exactly the underlying mechanisms promoting one fault behavior vs. another (i.e. the role of fluids in the transition from stable to unstable sliding);
- we do not now the relationships between "slow earthquakes" and destructive seismic slip (precursor? consequent?);
- we do not know unambiguously the deformation processes and geological signature of the different fault slip styles.

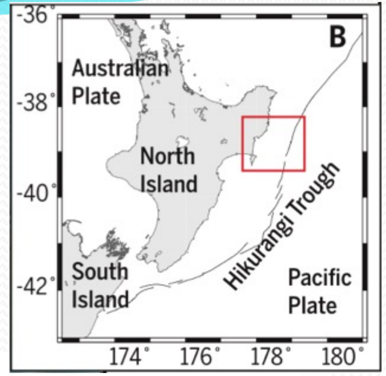


Existing hypotheses to explain "the space between" variety include: **contrasting material properties** entering the plate interface and promoting mixed behavior (Ando et al., '12; Skarbek et al., '12**)** and **low effective stress** (by high fluid pressures) promoting transitional frictional stability (Liu and Rice, '07; Segall et al., '10)

The Hikurangi subduction margin

- Pacific plate is being subducted at the Hikurangi Trough at a rate of ~20 mm/yr beneath South Island and ~60 mm/yr beneath North Island
- Hikurangi Plateau is a Cretaceous large igneous province blanketed by ~1 to 1.5 km of sediment and studded with protruding basaltic seamounts
- Sedimentary cover is thicker at the Southern margin, due to sedimentation being funnelled along the Hikurangi channel from the South Island
- Southern Hikurangi margin has a well-developed accretionary wedge, while the Northern portion of the margin shows smaller prism and seamount subduction.



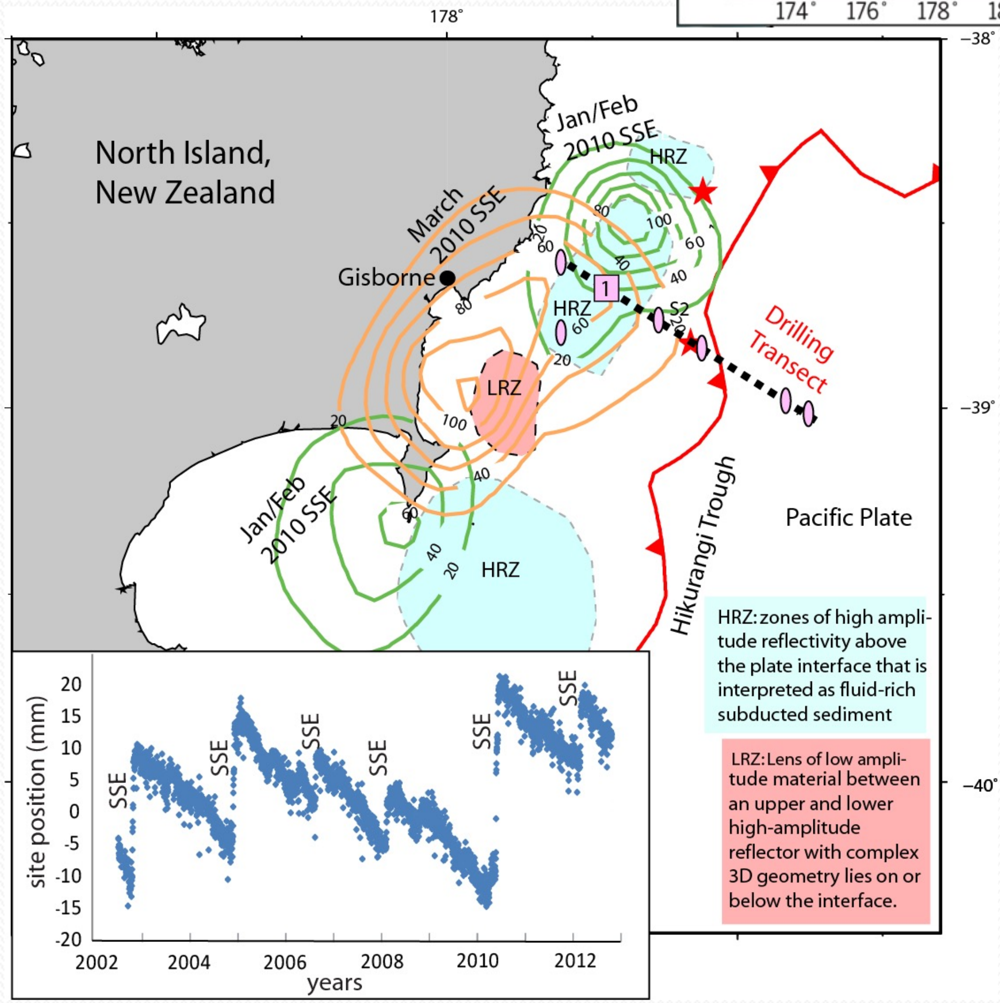


Hikurangi Margin hosts the shallowest geodetically well-documented SSEs on Earth :

The net of continuous GPS measurements indicates:

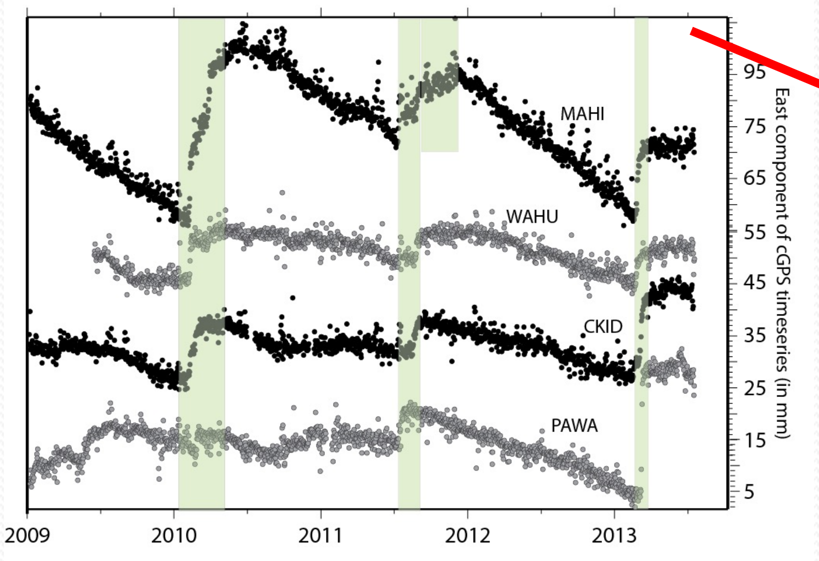
- ✧ SSEs last for days/weeks, recur every 1-2 years, show 1-3 cm of seaward surface displacement measured along the coastline (7-25 cm on the plate interface)

- ✧ Slow slip occurs within 2 km to the trench, potentially all the way to the trench: material hosting SSEs can be reached by drilling.

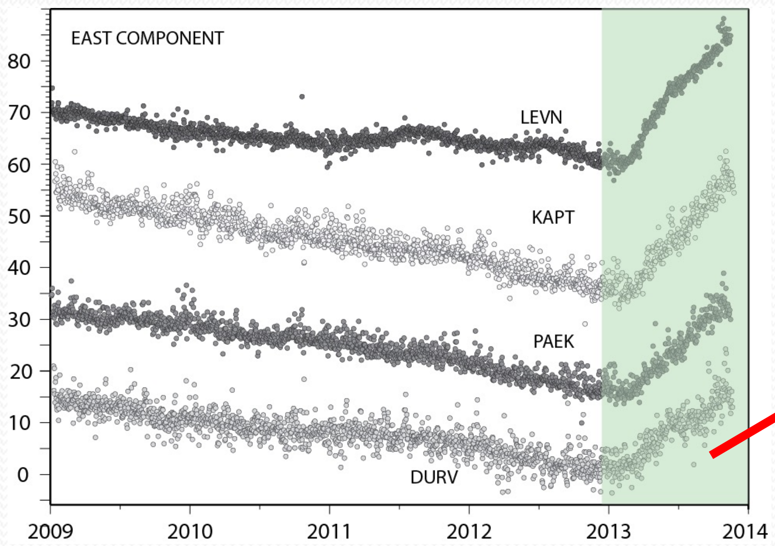


Wallace et al., 2004; 2016

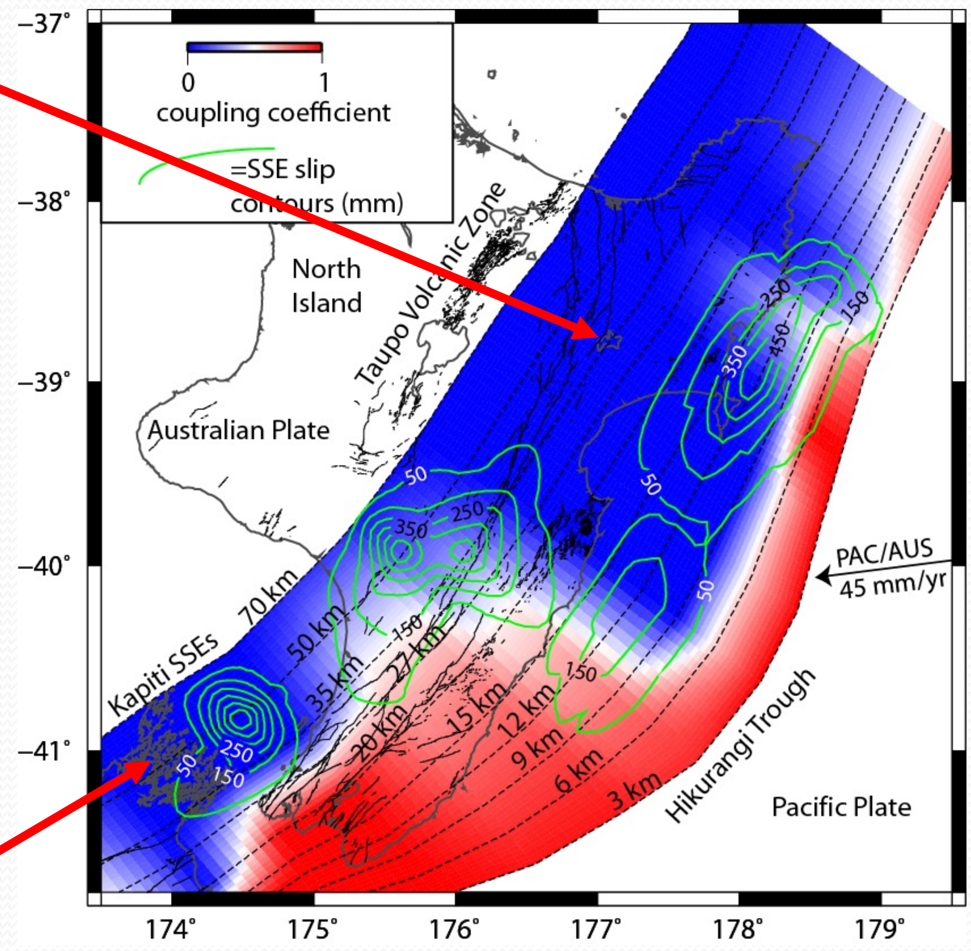
North Island vs. South Island SSEs



North
Shallow, fast, large, frequent



South:
Deep, slow, large, less frequent



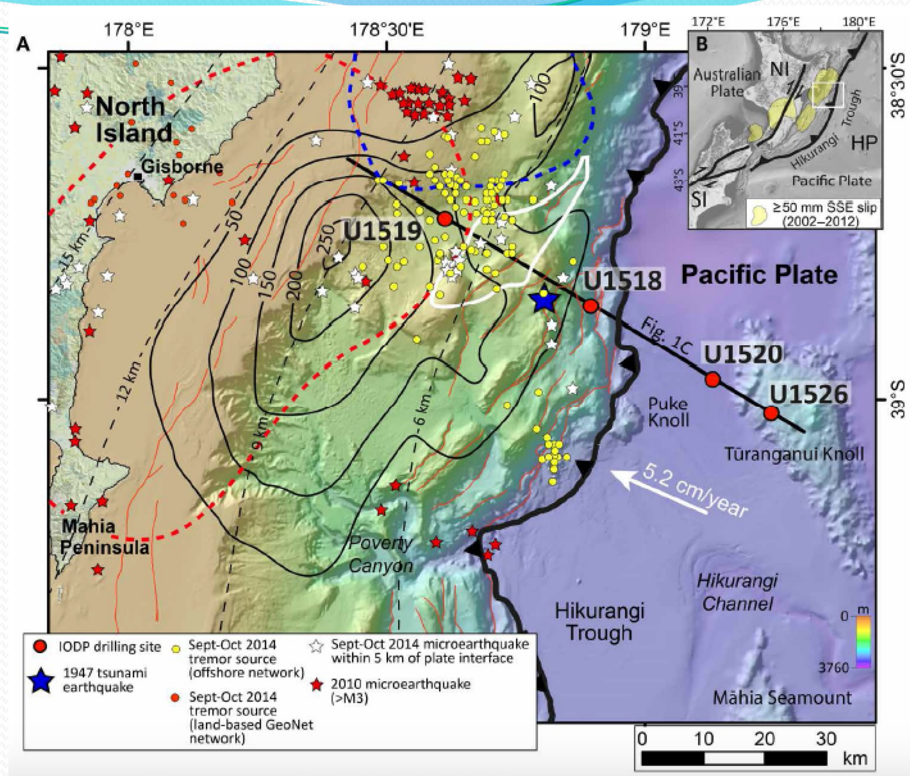
Green contours: cumulative slow slip 2002-2012
Equivalent Mw 6.5-7.0 for deep & shallow SSEs

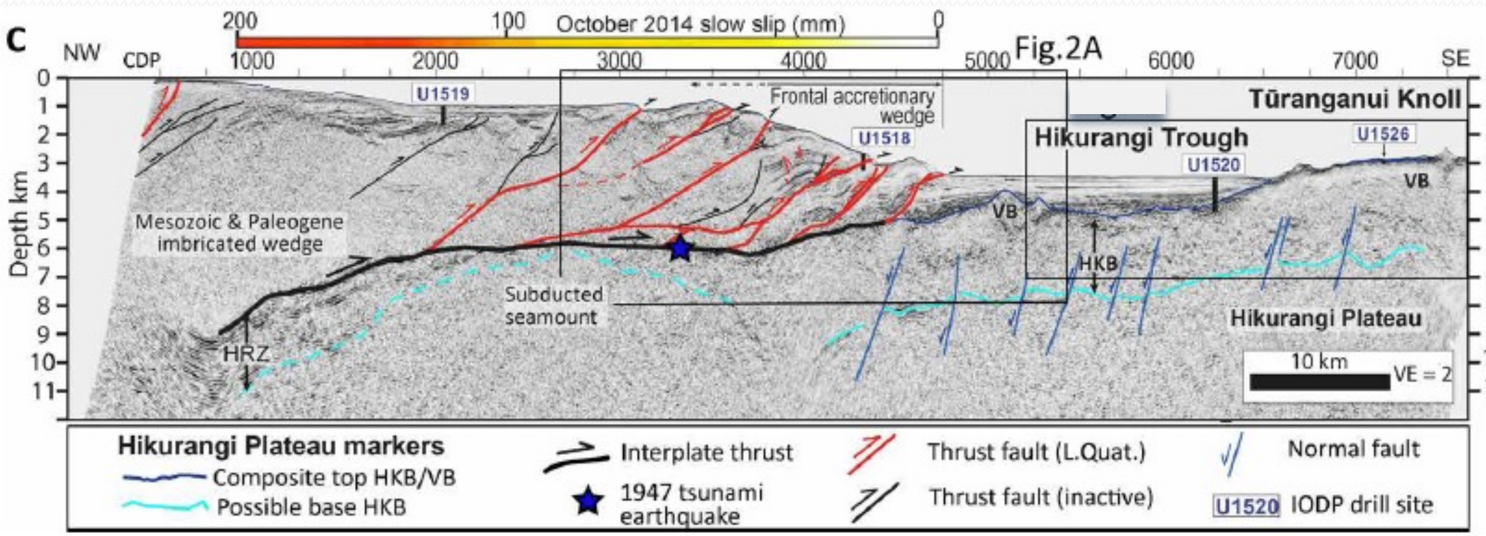
Expedition 375 starts!

2 Expeditions Legs 372 (LWD) and 375 focused on the large, very shallow and frequent SSEs at the North Hikurangi Margin.

The plate interface hosted two Mw 7.0 to 7.2 earthquakes in 1947, which generated 8- to 10-m tsunami along the coast.

Exp 375 provided coring and sampling, and observatory installation, and comprised 58 days at sea, from 8 March to May 5 2018.





Barnes et al., 2020, Science Adv.

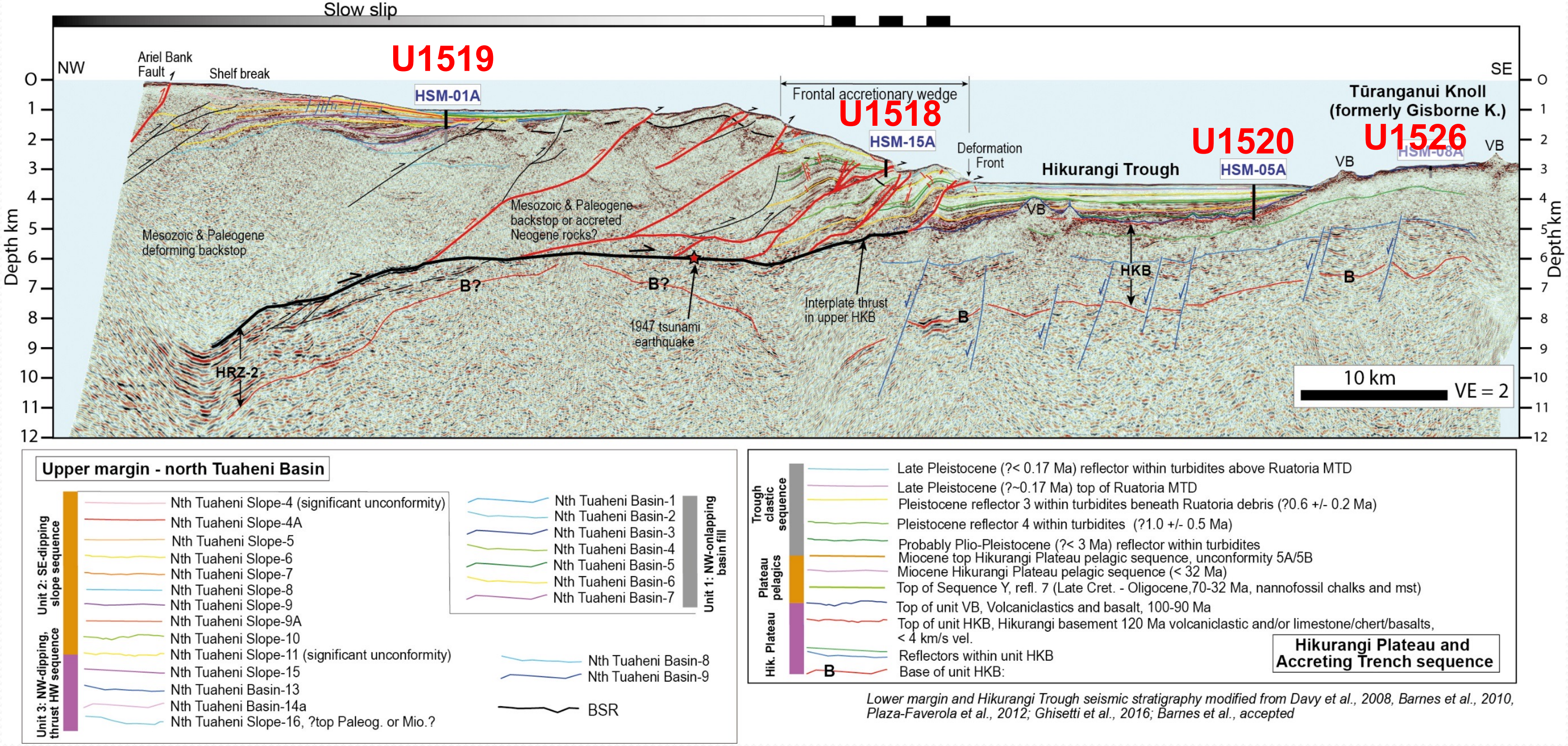
Expedition 375 scientific targets

1) **Characterize** the compositional, thermal, hydrogeological, frictional, geochemical, structural, and diagenetic conditions **the incoming plate and shallow plate boundary fault** near the trench (protolith and initial conditions for fault zone rock at greater depth, which may itself host shallow slow slip)
2) **Characterize** material properties, thermal and stress conditions in **the upper plate** above SSEs source area, and
3) **Monitoring** of deformation, temperature, fluid flow via borehole observatories at an active thrust near deformation front.

In this time together I will show you how we reconstructed the stratigraphy, composition, geometry, and physical properties of the lower plate entering the plate interface, by combining drilling results with regional seismic reflection profiles, in order to check working hypothesis 3:
3. SSEs occur in regions of conditional frictional stability (multiple slip behavior of a single fault patch), i.e. contrasting material properties entering the plate interface may promote mixed slip behavior.

Then I will show how we experimentally texted the ability of the rocks and sediments along the drilled shallow thrust of propagating an earthquake rupture, a societal problem of primary interest given the risk for seismic slip at shallow crustal depths to generate tsunamis

Four Primary sites across seismic profile 05CM-04



Seismic depth section processed by Dan Barker (GNS Science, NZ): 05CM-04 PSTM HDVA-8 model

**Note revised interpretation cf. Science Prospectus 2017*

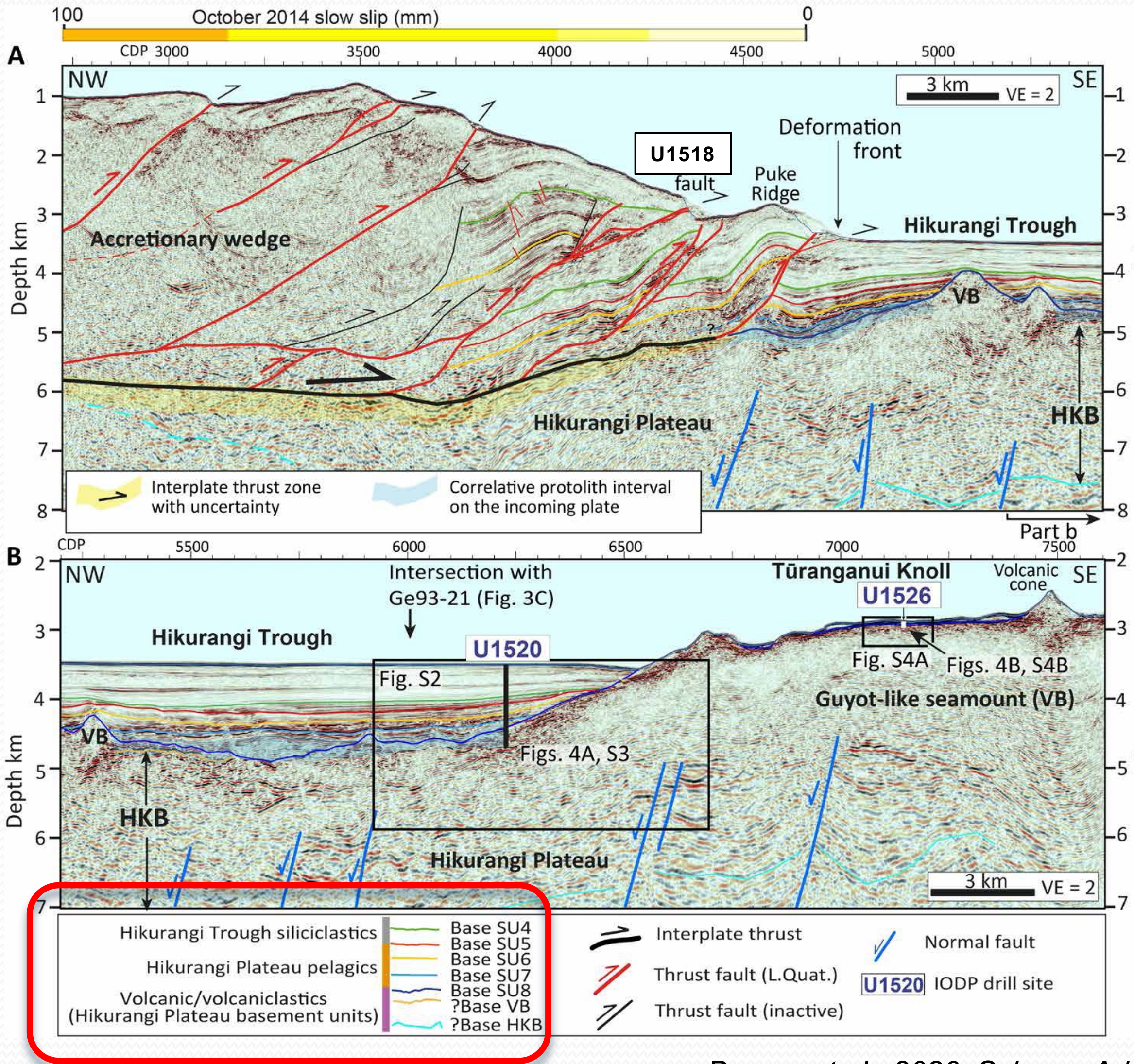
The Primary sites across the incoming plate: U1520 and 1526

What geophysics tells us

Seismic profiles show a typical frontal side of the accretionary prism, with shallow thusts branching off a basal plate interface.

The zoom on the lower plate show a rough topography (top of HKB and VB) with imminent arrival of a seamount into the system.

Seismic units (SU) vs. borehole data correlation



Barnes et al., 2020, Science Adv.

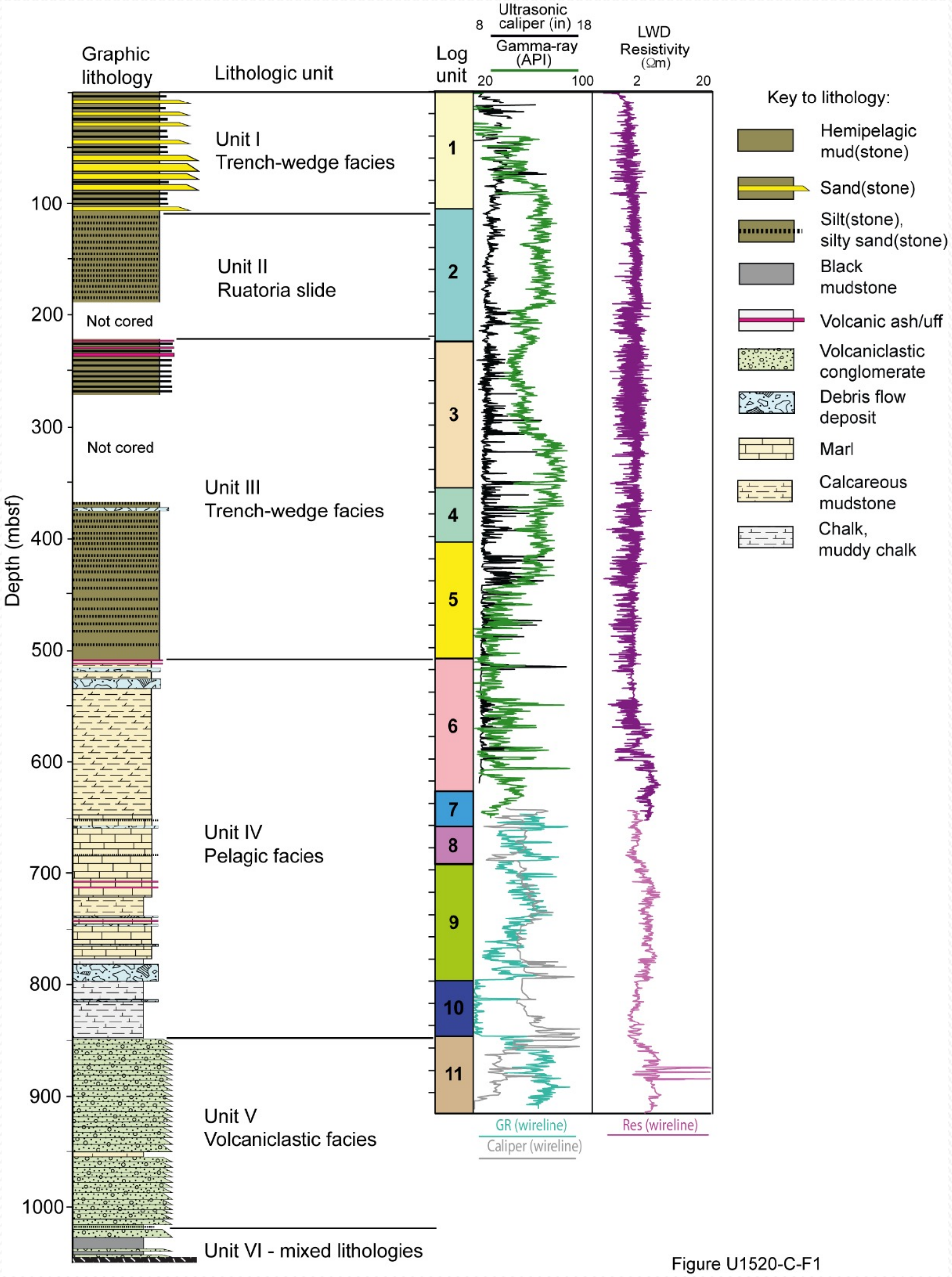


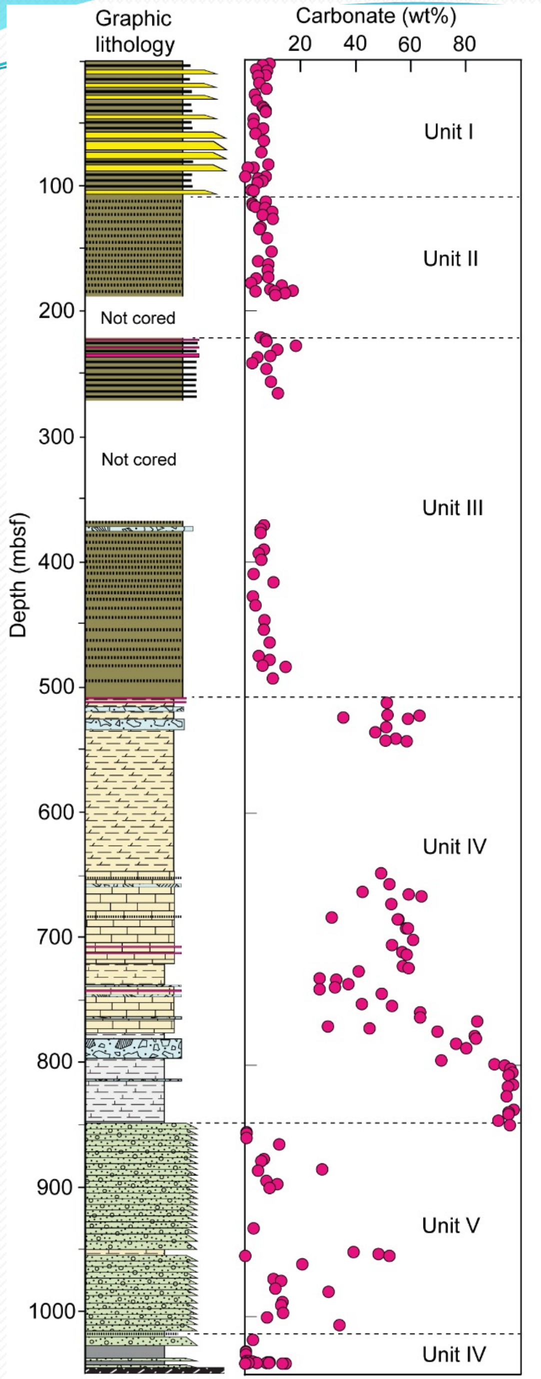
Figure U1520-C-F1

Input site: stratigraphy of Site U1520 reconstructed from Hole D and C

- 6 Units defined on the base of texture, sedimentary structures, thickness of coarse bed, soft-sediment def., carbonate content etc.

- Change from terrigenous-clastic gravity-flow deposits, to a pelagic carbonate sedimentation, down to volcaniclastic gravity-flow system

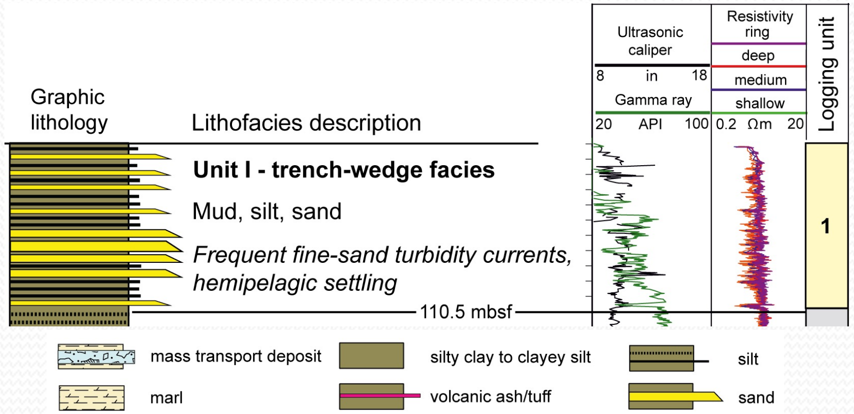
- Early Cretaceous to Holocene



Carbonate content vs. depth

- Change from terrigenous-clastic gravity-flow deposits, to a pelagic carbonate sedimentation, down to volcaniclastic gravity-flow system

Unit I: trench-wedge

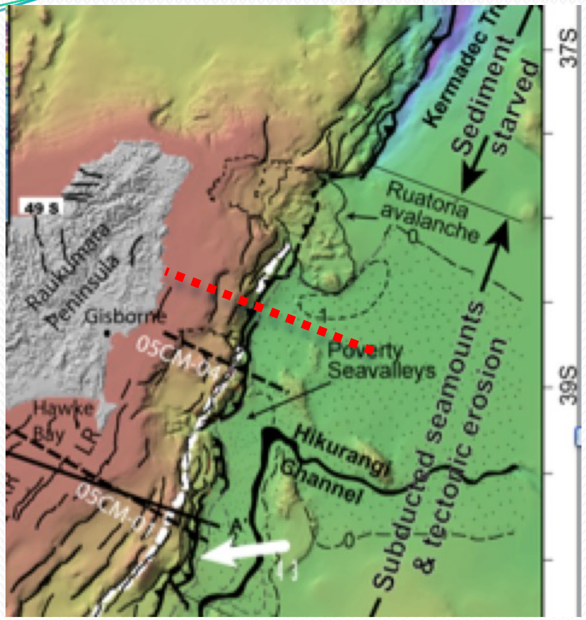


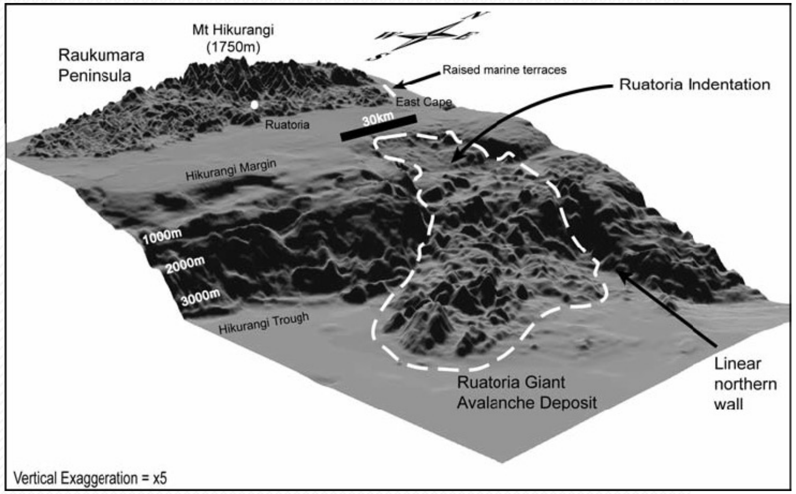
Thin- to medium-bedded turbidites, sharp bases, normal grading.

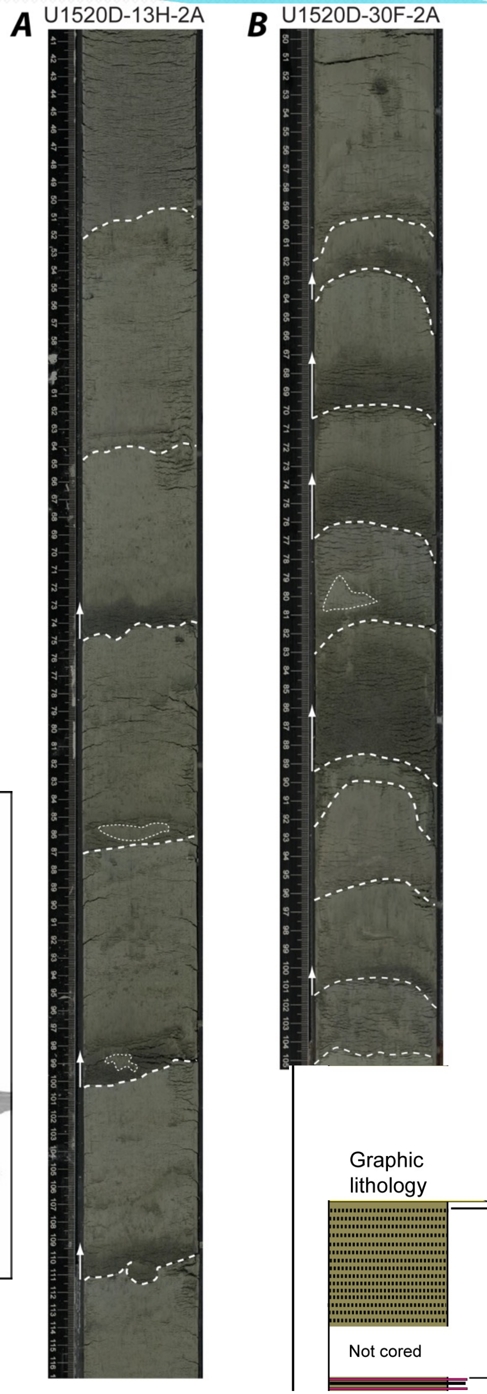
Holocene - Pleistocene

Unit II: Ruatoria avalanche

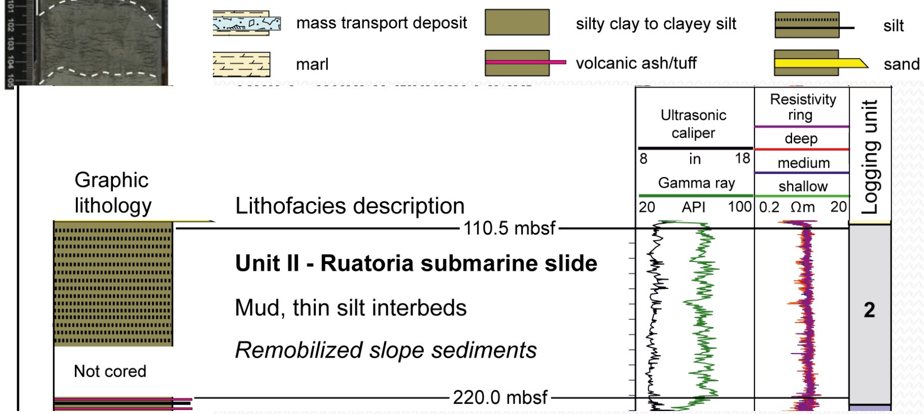
Site U1520





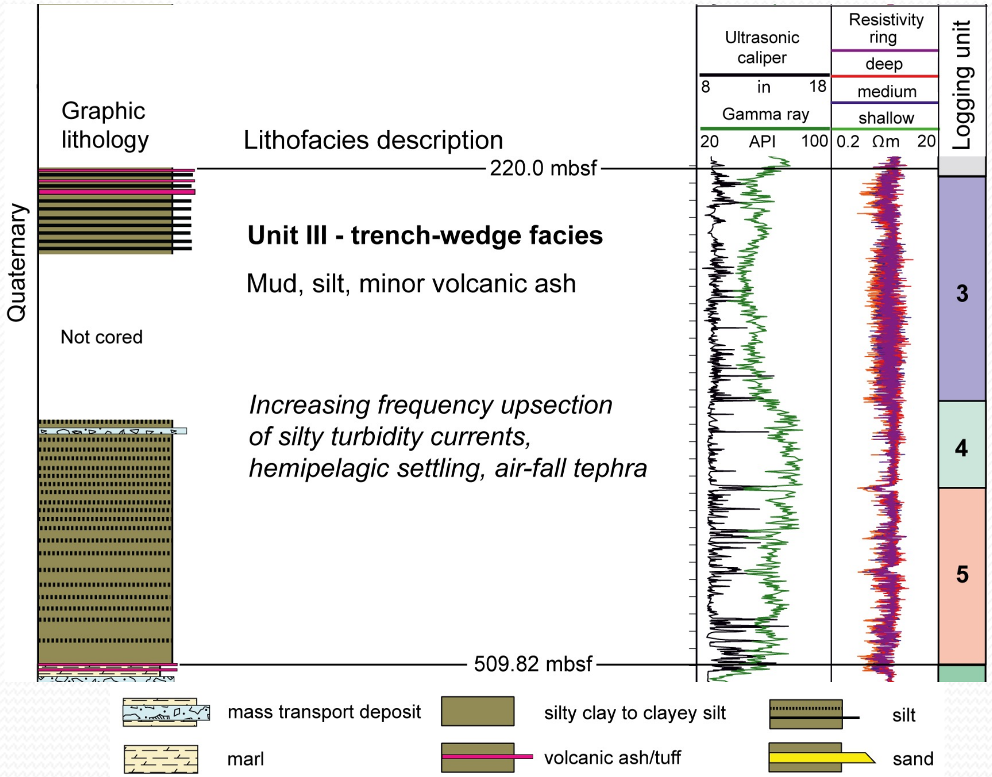


- thin-bedded silty turbidites with nearly equal intervals
- reduction of thickness and frequency of coarse interbeds compared to Unit I
- mud intraclasts and erosional basal contacts
- NO EVIDENCE of gravity-driven remobilization/deformation



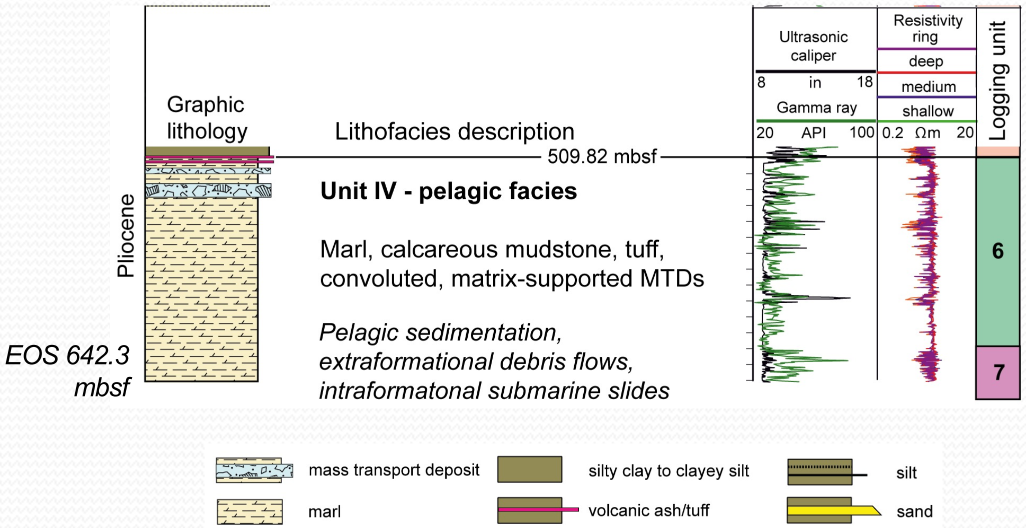
Unit III: trench-wedge

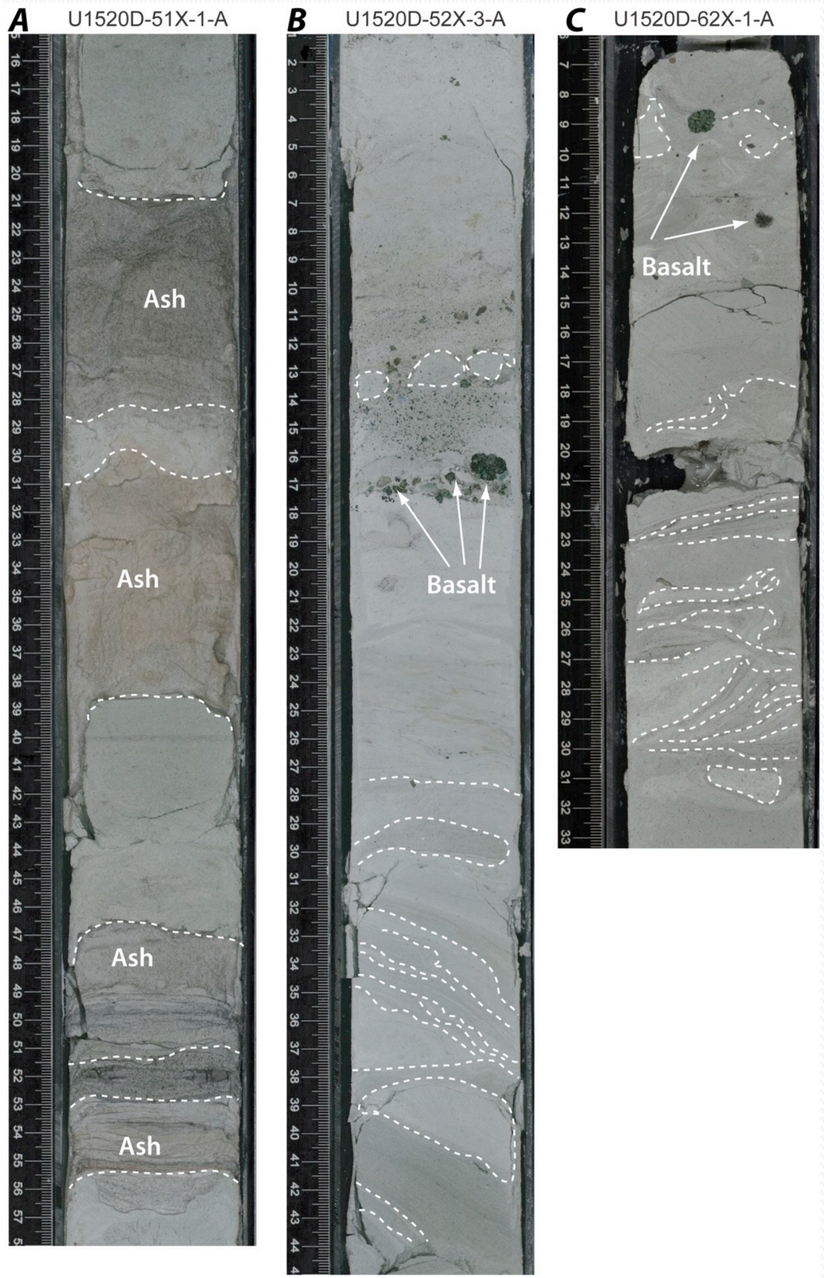
Site U1520



- normally-graded thin-bedded turbidites with planar laminations
- medium- to thick-bedded ash layers
- mass transport deposits (MTDs), convoluted layers, mud “clasts”

Unit IV: Hole D

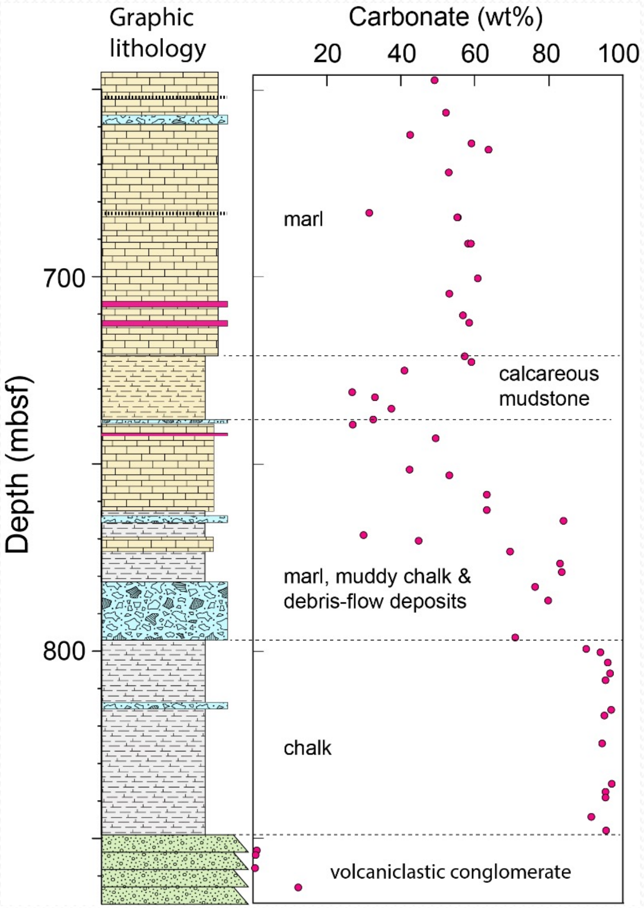




- Light greenish-gray strongly bioturbated marls
- Convoluted marl layers, flow banding structures, block-in-matrix textures, sand- to pebble-size basalt and marl clasts,
- Ash layers

Paleocene to Miocene

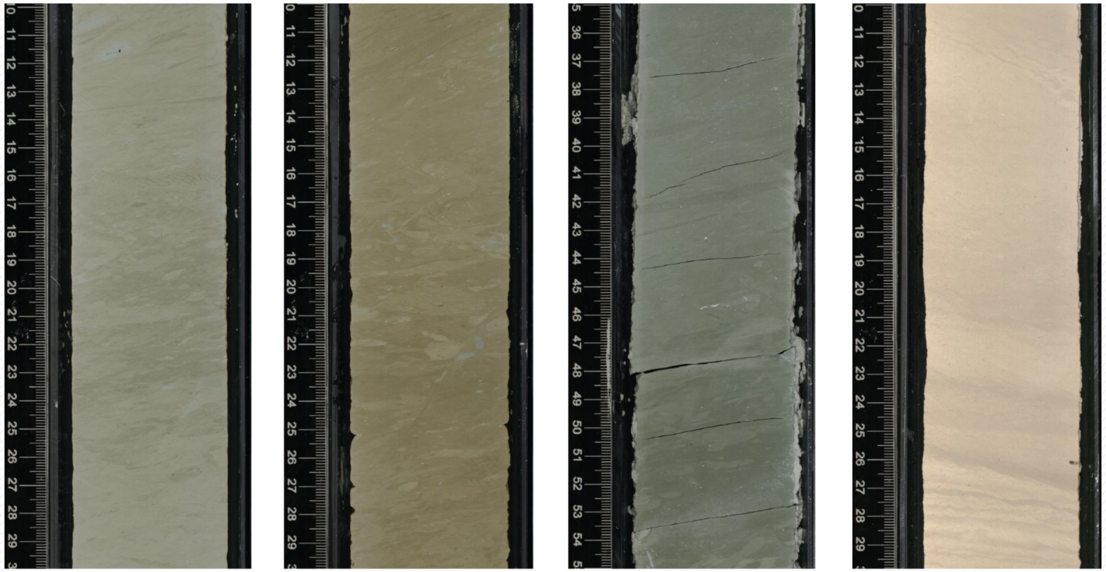
Unit IV: Hole C



Unit IV was recovered in deeper hole as comprising marls, calcareous mudstone, chalk, and interbedded debris-flow deposits.

Paleocene to Miocene

375-U1520C-10R-2A, 10-30 cm | 375-U1520C-10R-3A, 10-30 cm | 375-U1520C-15R-3A, 35-55 cm | 375-U1520C-16R-3A, 10-30 cm



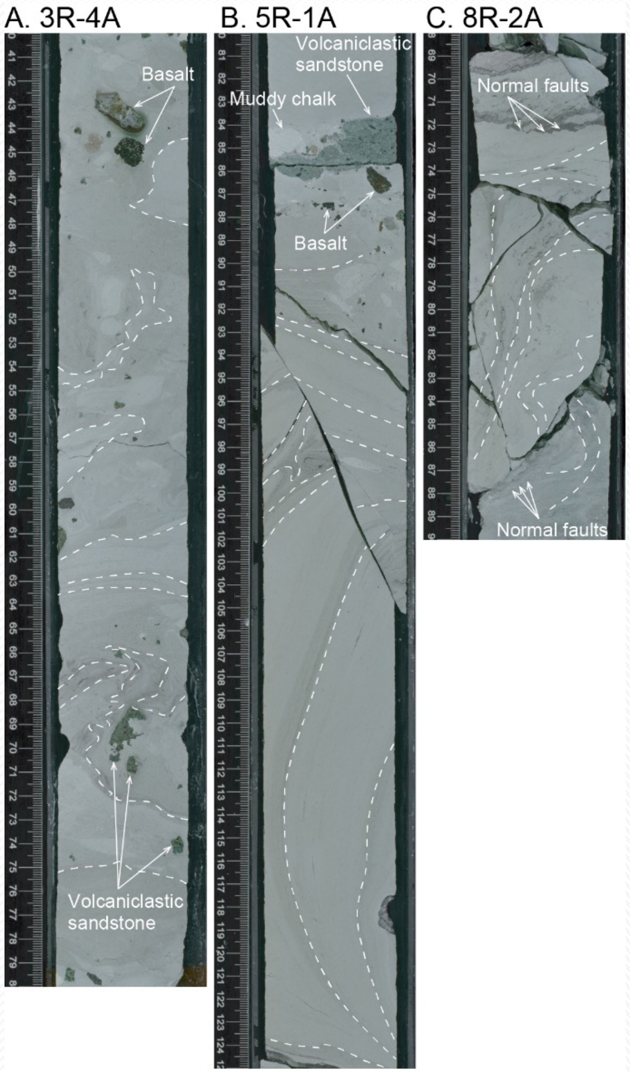
marl (646-721.31 mbsf) | calcareous mudstone (721.31-738.68 mbsf) | marl (738.68-773.26 mbsf) | chalk (773.26-848.45 mbsf)

Unit IV: a zoom in the debris flow deposits

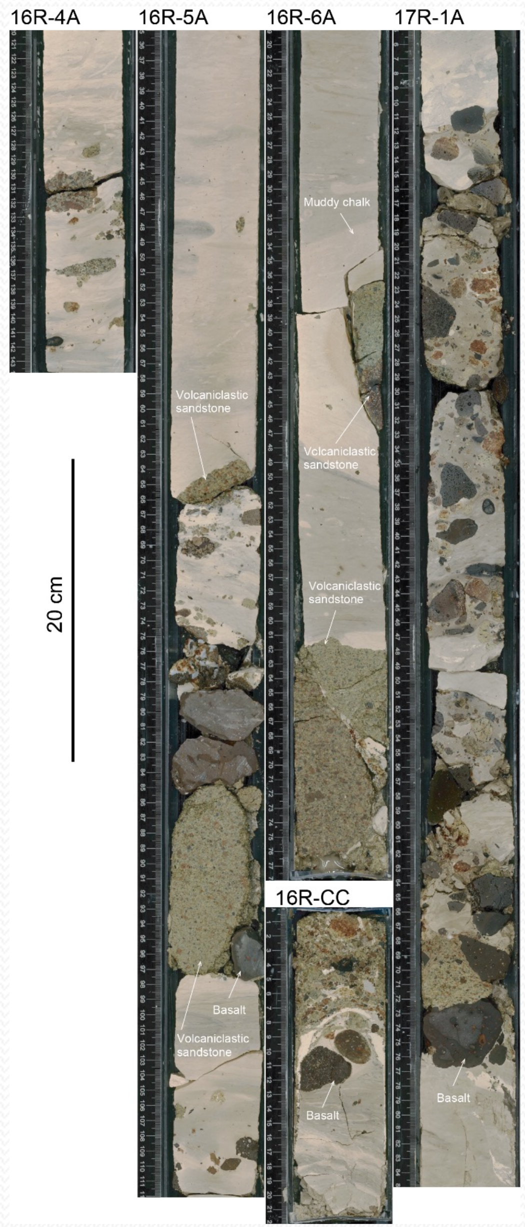
Site U1520

Debris flows:
flow banding structures, block-in-matrix textures, sand- to pebble-size basalt and marl clasts

Convoluted marl beds

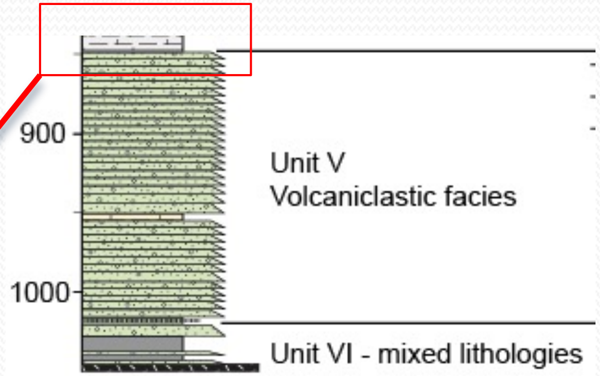


Debris flows

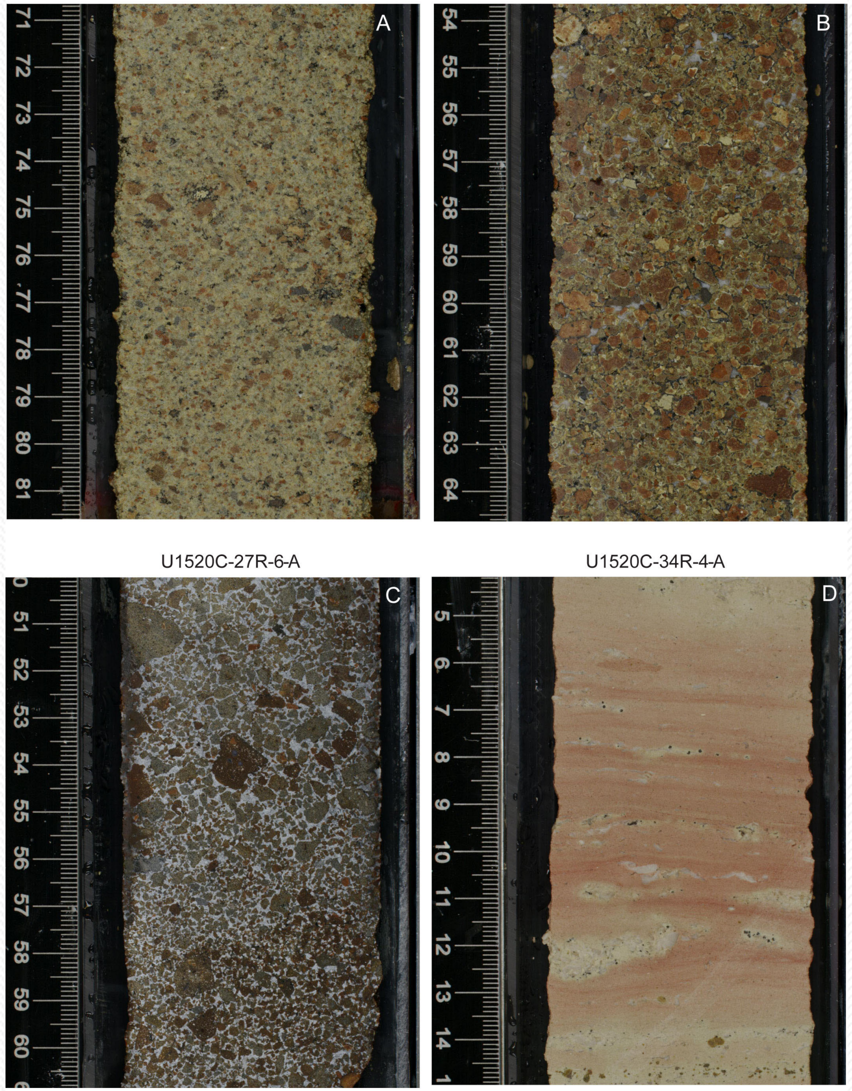


Unit V

U1520C-23R-5-A, 30-59



Unit IV: slow pelagic settling
vs.
Unit V: high-density gravity flow



- Volcaniclastic granule-size Conglomerate

\+

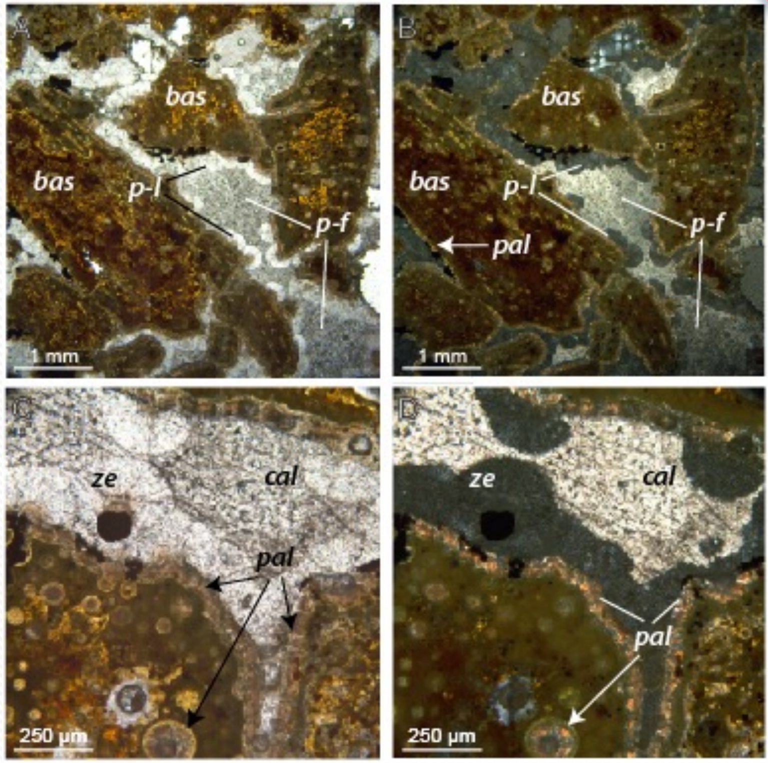
- Marl (+Clayey siltstone, +Basalt)

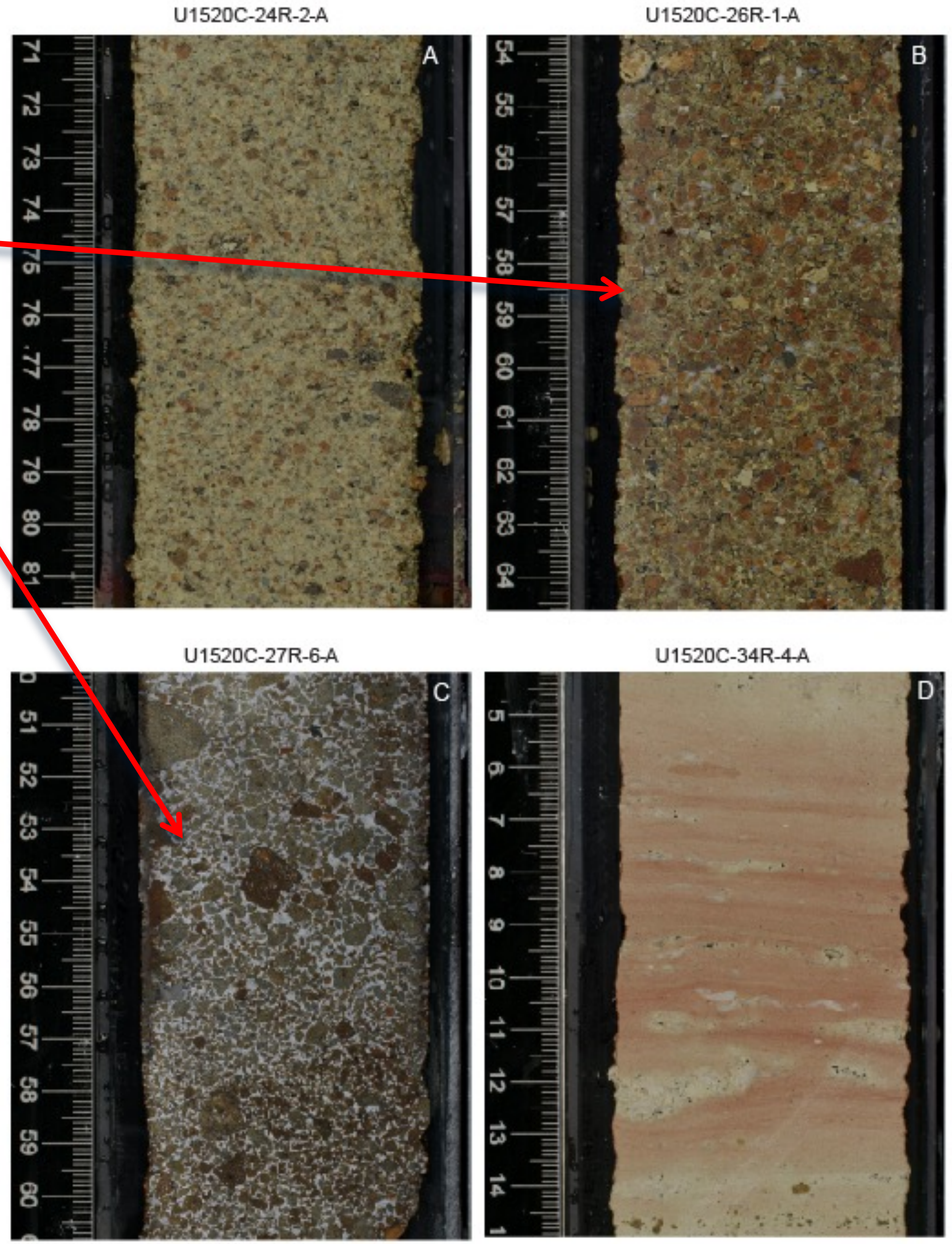
Upper Cretaceous

Grain flow and debris flow mechanisms from the Tūranganui Knoll

Unit V

- Volcaniclastic granule-size conglomerate: clast-supported, clasts are tightly packed bound by pore-filling palagonite, zeolite and calcite cement (strong lithification)



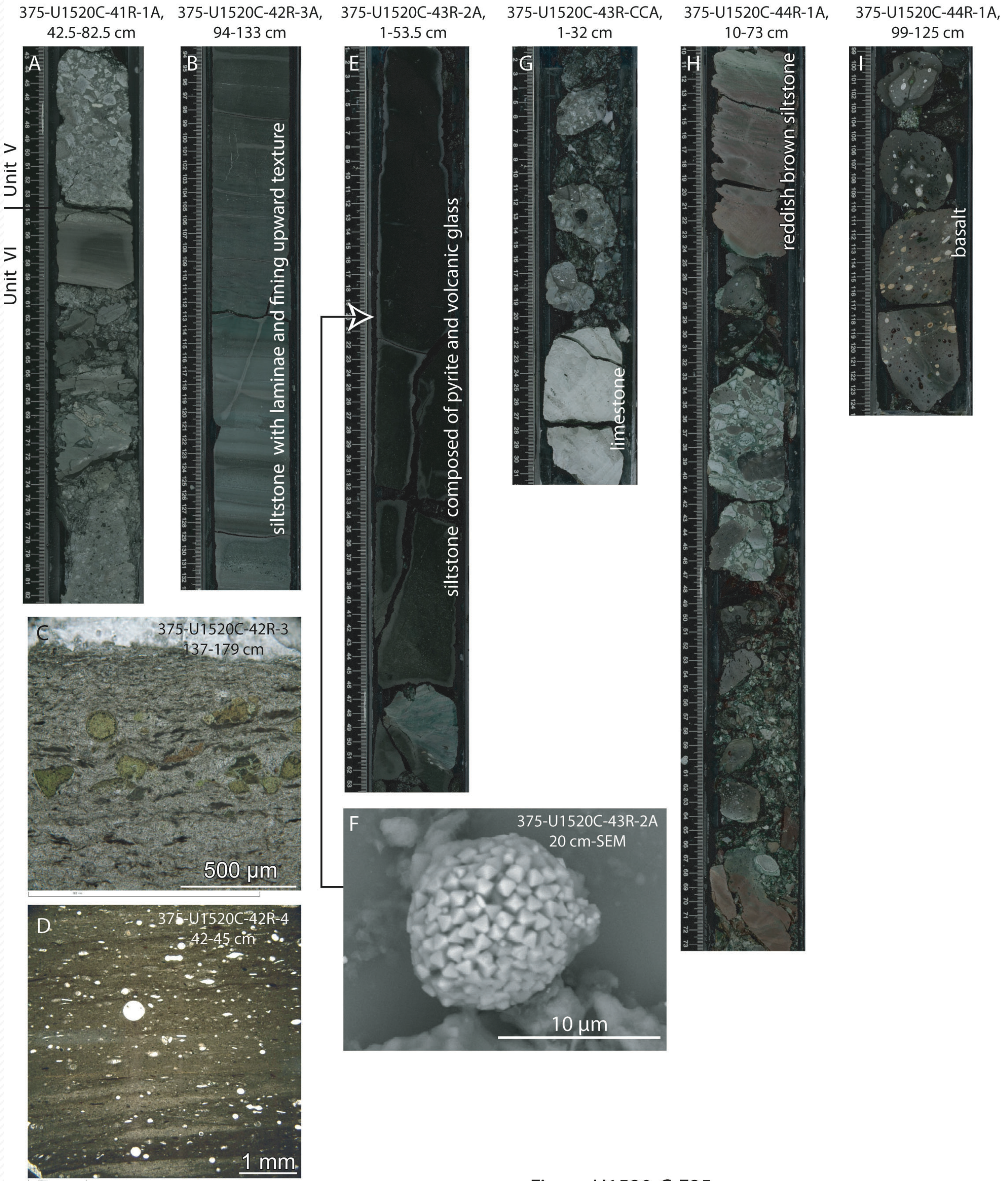


Grain flow and debris flow mechanisms from the Tūranganui Knoll

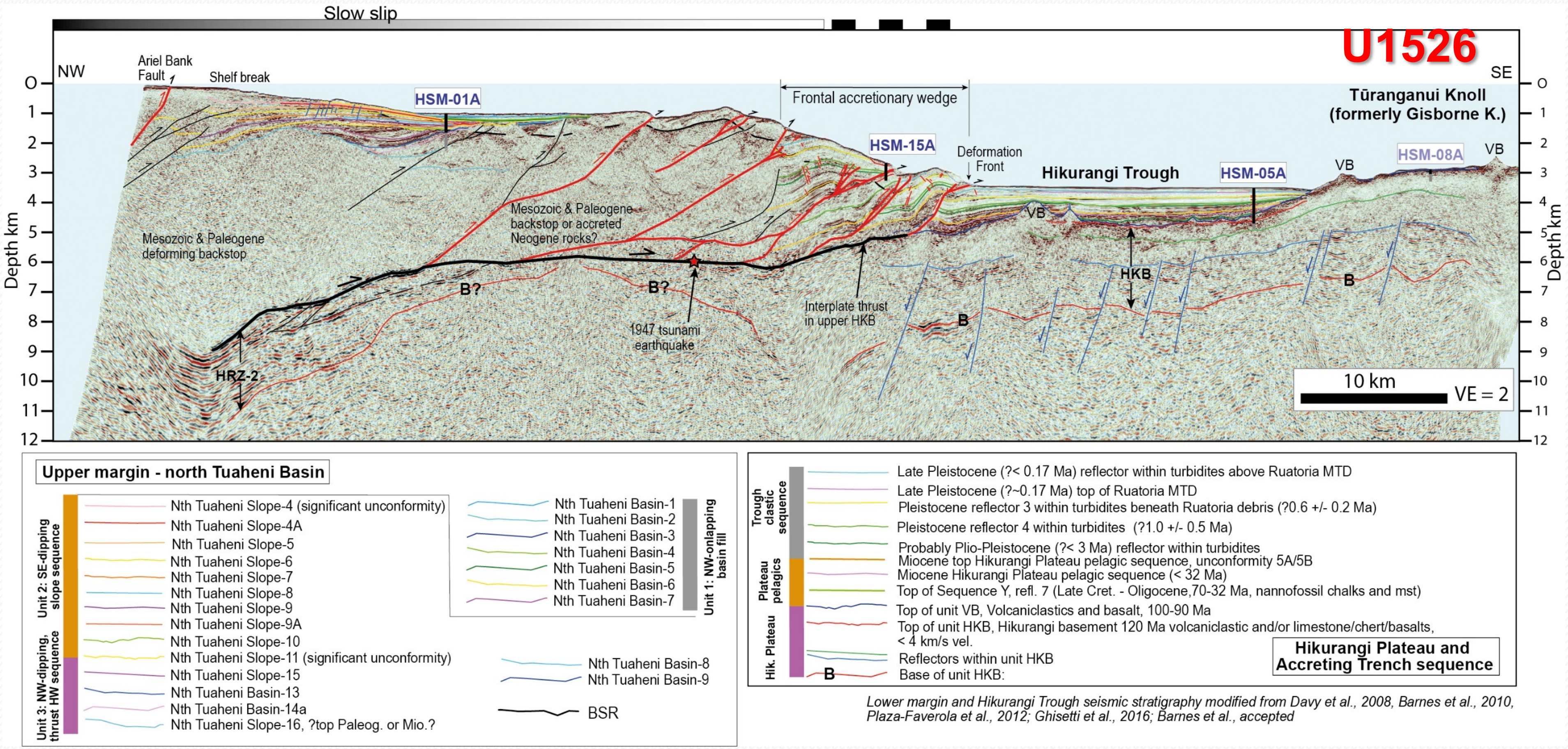
Unit VI

- drilled for > 200 m until basalts
- highly mixed assemblage of volcaniclastic conglomerate, volcaniclastic siltstone, silty claystone with minor limestone and organic-rich siltstone, and basalt with,
- unresolvable stratigraphic organization or thicknesses (poor recovery, coring disturbance, and “biscuiting”),
- distinctive dark blueish-green color is widespread among most of the rock fragments,
- siltstone with pyrite and high values of total organic carbon

Upper Cretaceous

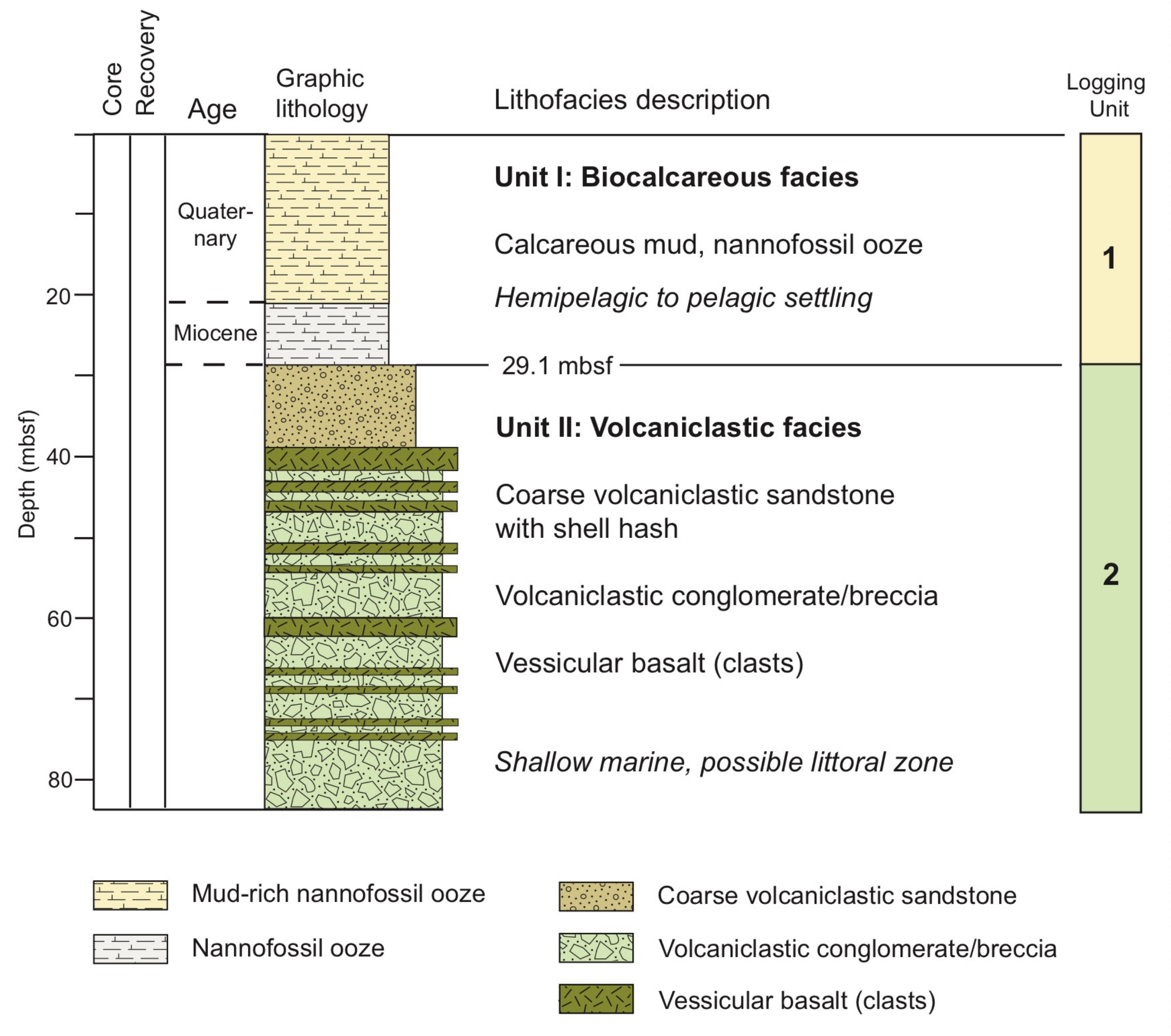


U1526: subducting seamount (Tūranganui Knoll)



Seismic depth section processed by Dan Barker (GNS Science, NZ): 05CM-04 PSTM HDVA-8 model
Interpretation: Phil Barnes
**Note revised interpretation cf. Science Prospectus 2017*

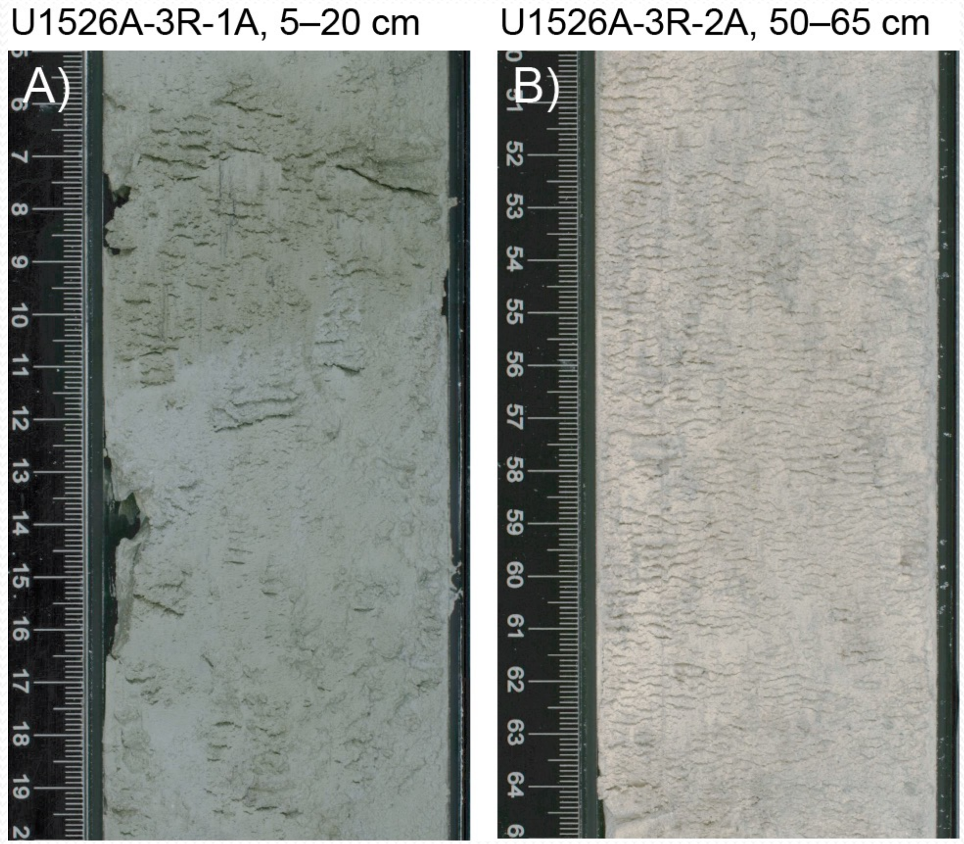
Stratigraphy of Site U1526: the Tūranganoi Knoll

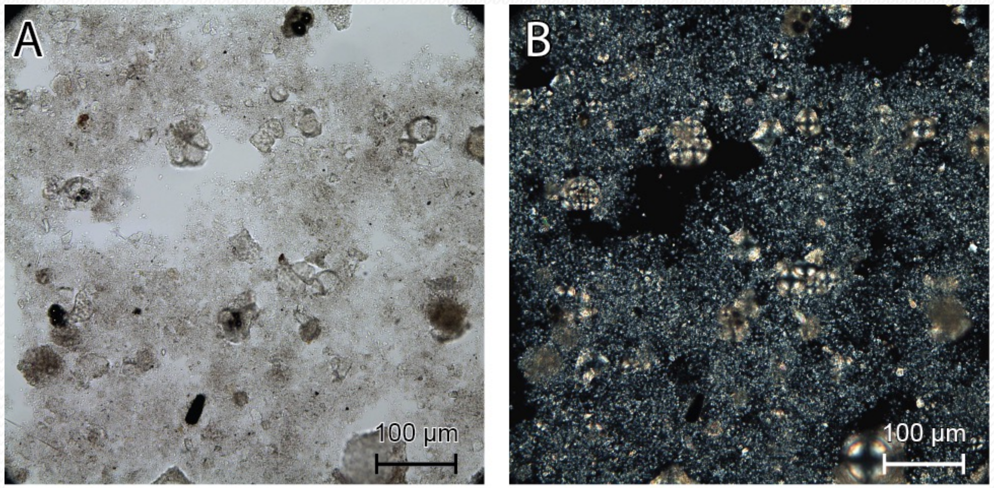


Unit I: Biocalcareous facies

Calcareous mudstone
and nannofossil ooze

(Late Cretaceous to Holocene)





Unit II: Volcaniclastic facies

Site U1526

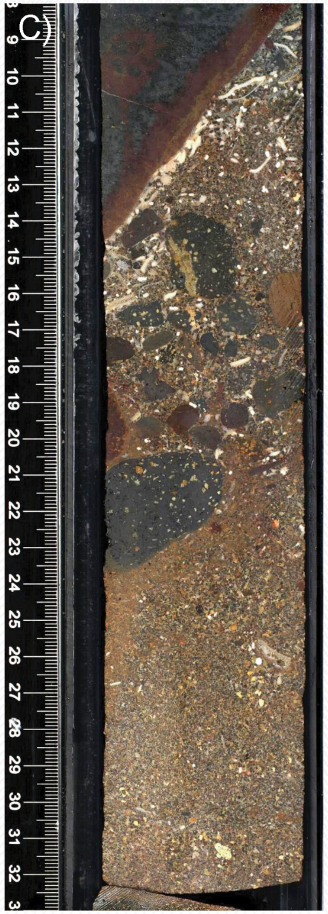
Volcaniclastic coarse sandstone and conglomerate

A) Sandstone w/ basalt, bivalve shells, other calcareous bioclasts, limestone - planar laminated
B) Sandstone to granule-size conglomerate w/ basalt and bivalve shell fragments shells are partly dissolved
C) Pebble-cobble-boulder conglomerate rounded basalt and shell fragments – sandy matrix

U1526A-4R-1A, 5–30 cm

U1526A-4R-1A, 34–59 cm

U1526A-7R-2A, 8–33 cm



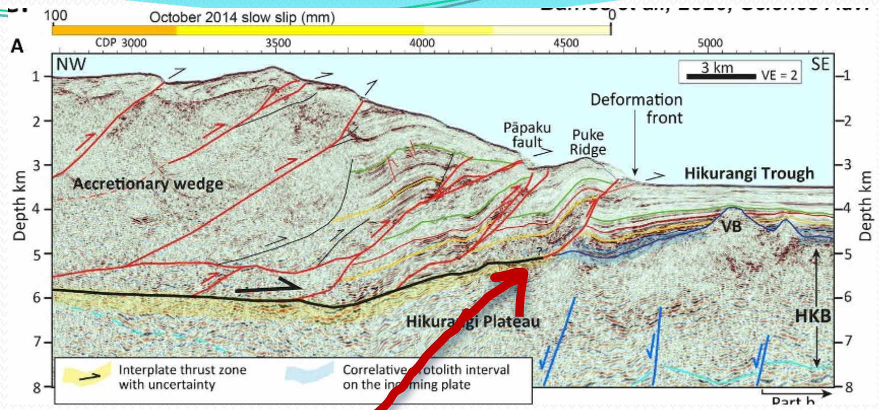
Calcite cementation. Pervasive reddish stain and bivalve suggest very shallow water and temporary subaerial exposure of seamount

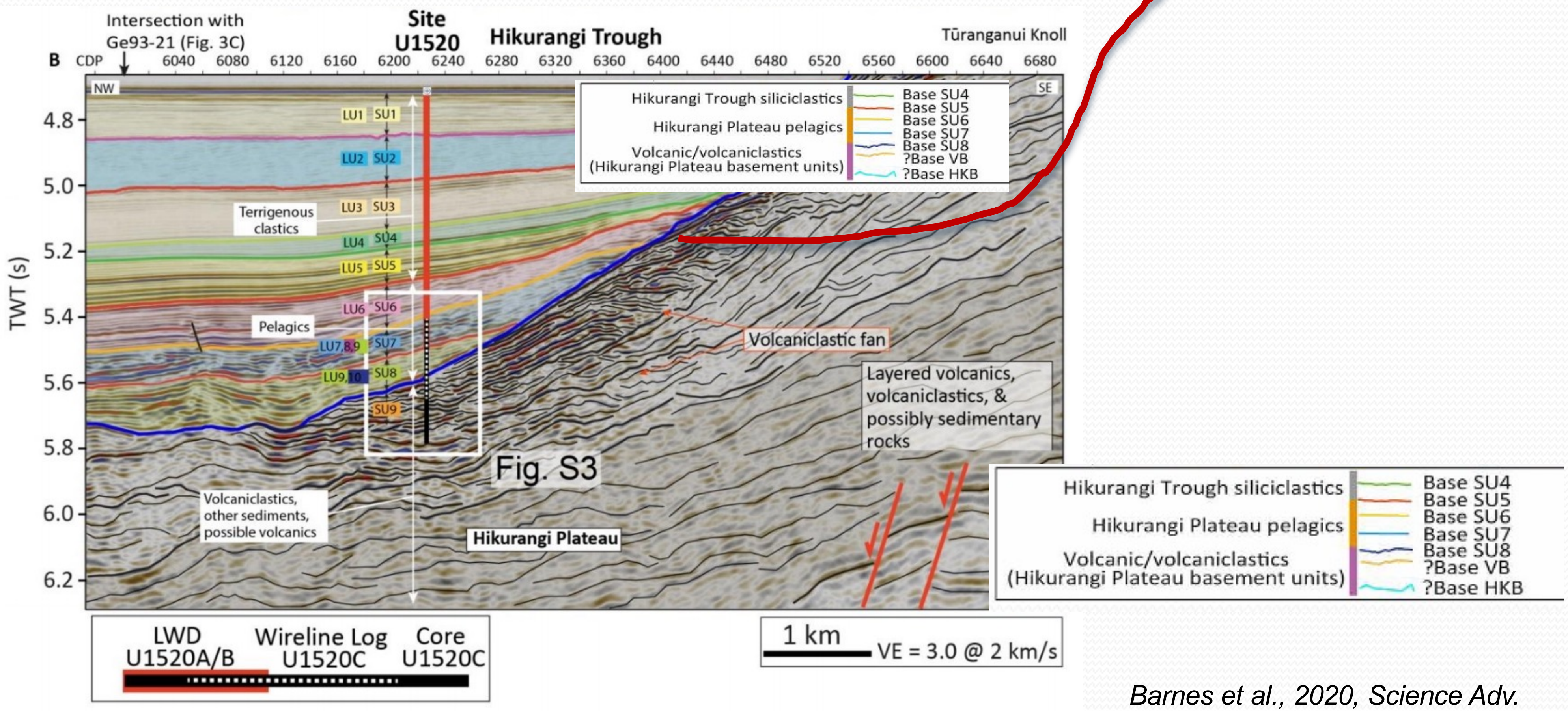
Boulder-size clast of fresh vessicular basalt clay)

Core-log-seismic integration: a "geologic section" of the incoming plate

Core and logging data (LU) tied to seismic profile (SU).

Blue line is the stratigraphic interval correlated down-dip with the plate interface: corresponds to the protolith interval comprising the carbonatic rocks of Unit IV (marls/chalk LU9,10) and the volcaniclastics of Unit V (LU11)

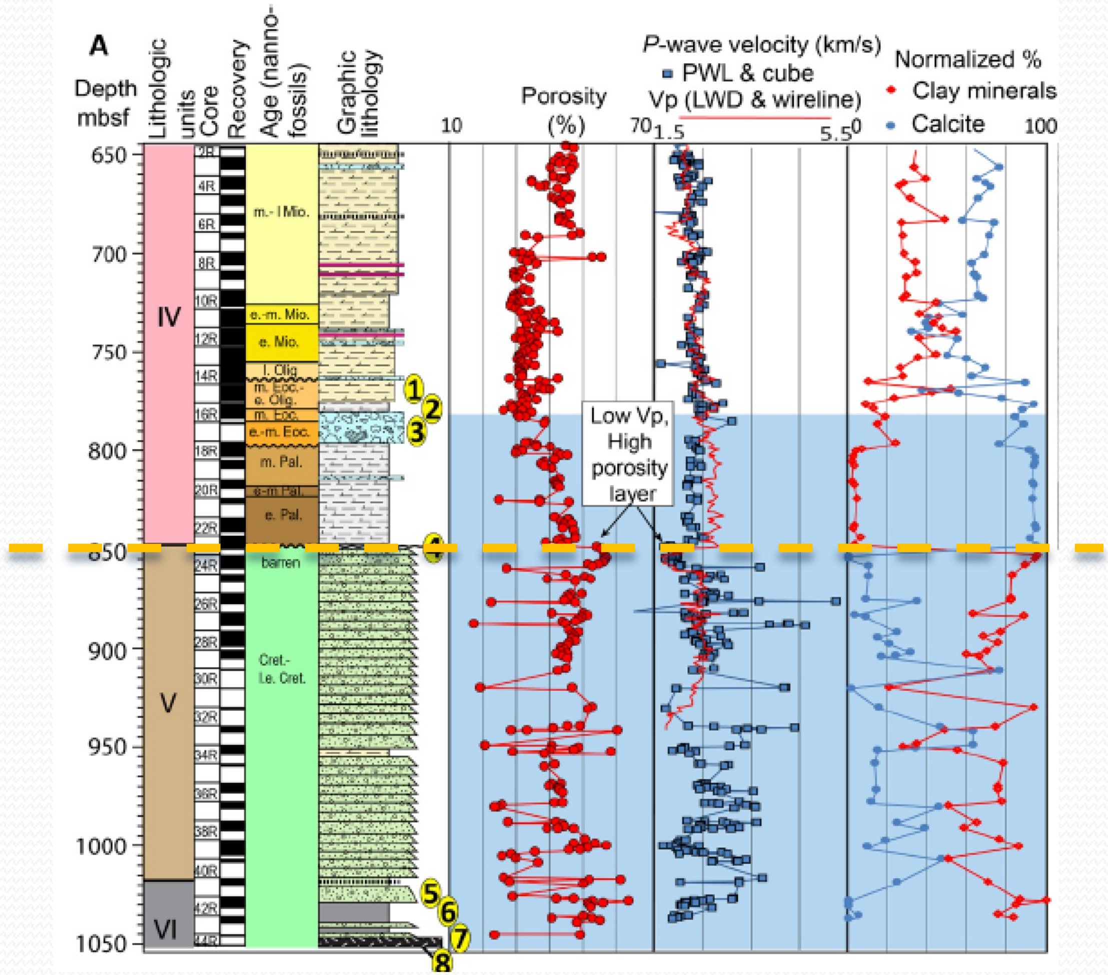




Barnes et al., 2020, Science Adv.

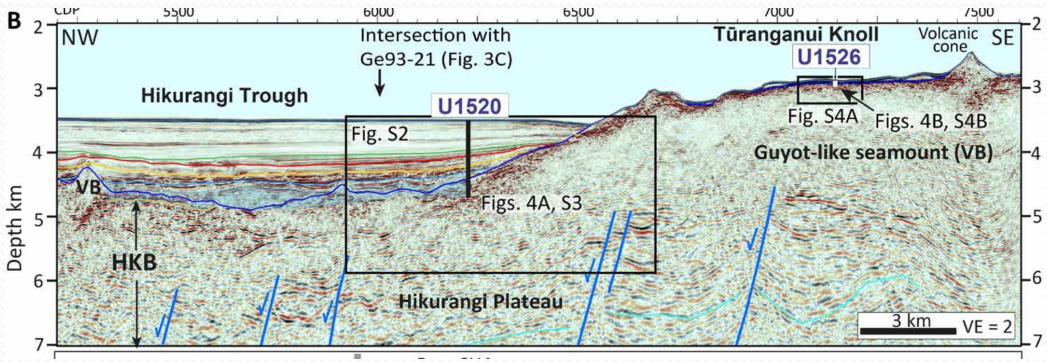
The control of the lower plate structure on the future plate interface:

- The transition from the pelagic Unit IV to the volcaniclastics Unit V is associated to a change in most physical properties.
- The mixed volcaniclastic-dominated assemblage comprising units V and VI (i.e. the upper portion of the Hikurangi Plateau) is characterized by highly heterogeneous physical properties: this variability reflects the highly heterogeneous texture, composition, alteration, and cementation of the conglomerate.

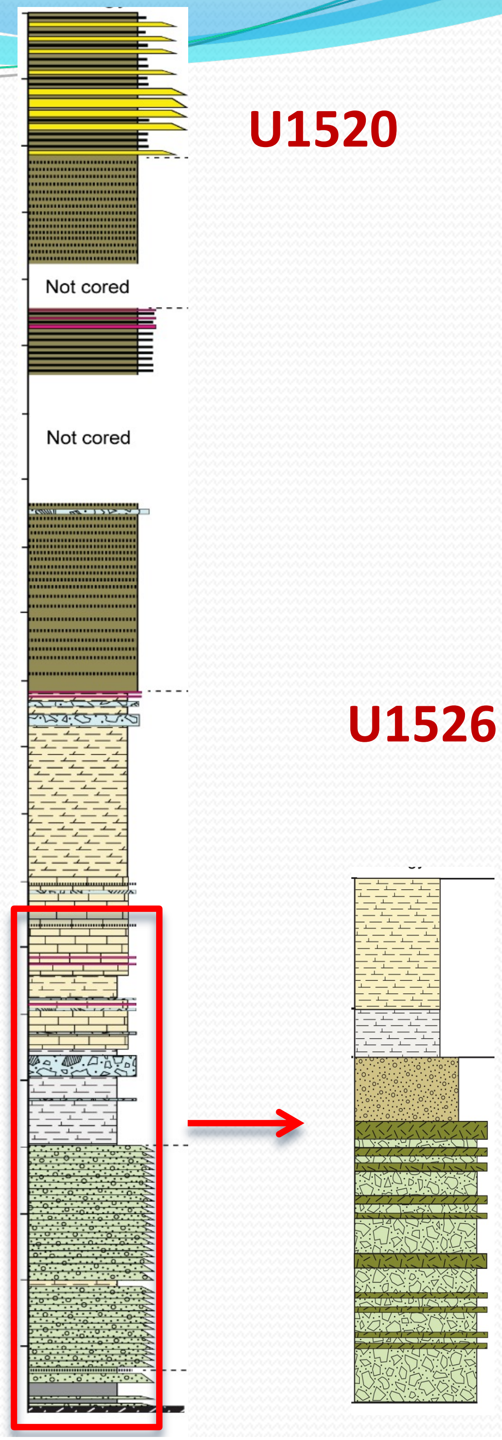


Barnes al., 2020, Science Adv.

Summary: what enters the system



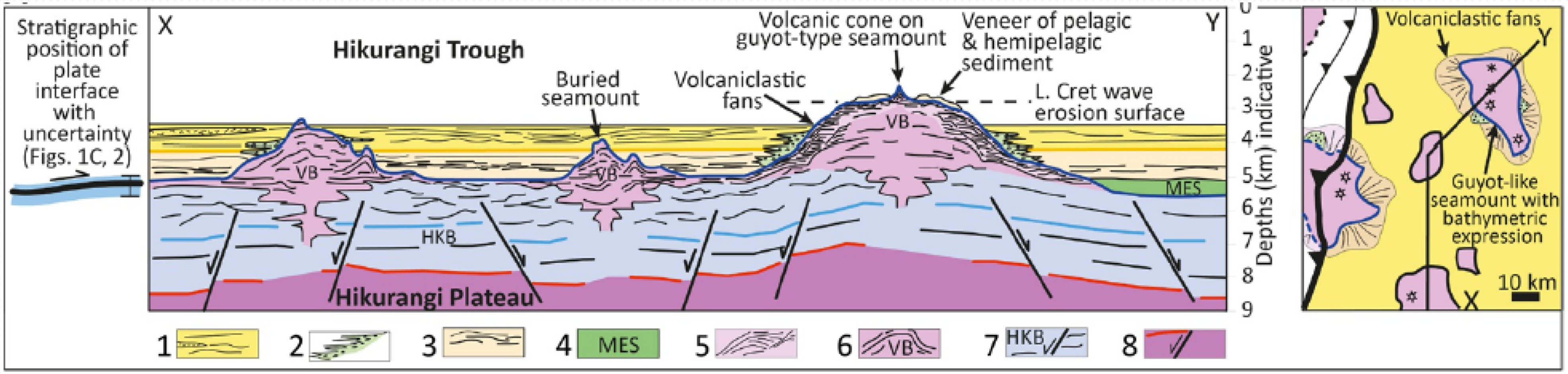
- Highly heterogeneous assemblage of lithologies (turbiditic mud, calcareous marl, calcareous ooze, chalk, MTD, volcaniclastic sands and conglomerate and basalt), with widely varying physical properties, and rough topography.
- Heterogeneity of grain size, sorting and cementation in volcaniclastics are identified.
- Plate interface seems to project to a stratigraphic interval comprising mainly carbonates and volcaniclastic sediments (widely altered to smectite clay) and basalt.
- Lithologies in U1526 can correspond to that at the bottom of U1520.
- The volcaniclastic-dominated interval is not typical of all subduction zones but may be a common feature where seamounts and ridges are subducting.



Summary: what enters the system

Barnes et al., *Science Adv.*, 2020

Possible stratigraphic architecture of the subducting plateau



The rough subducting topography contribute to the wide range of lithological assemblages on the incoming plate approaching the subduction sytsem.

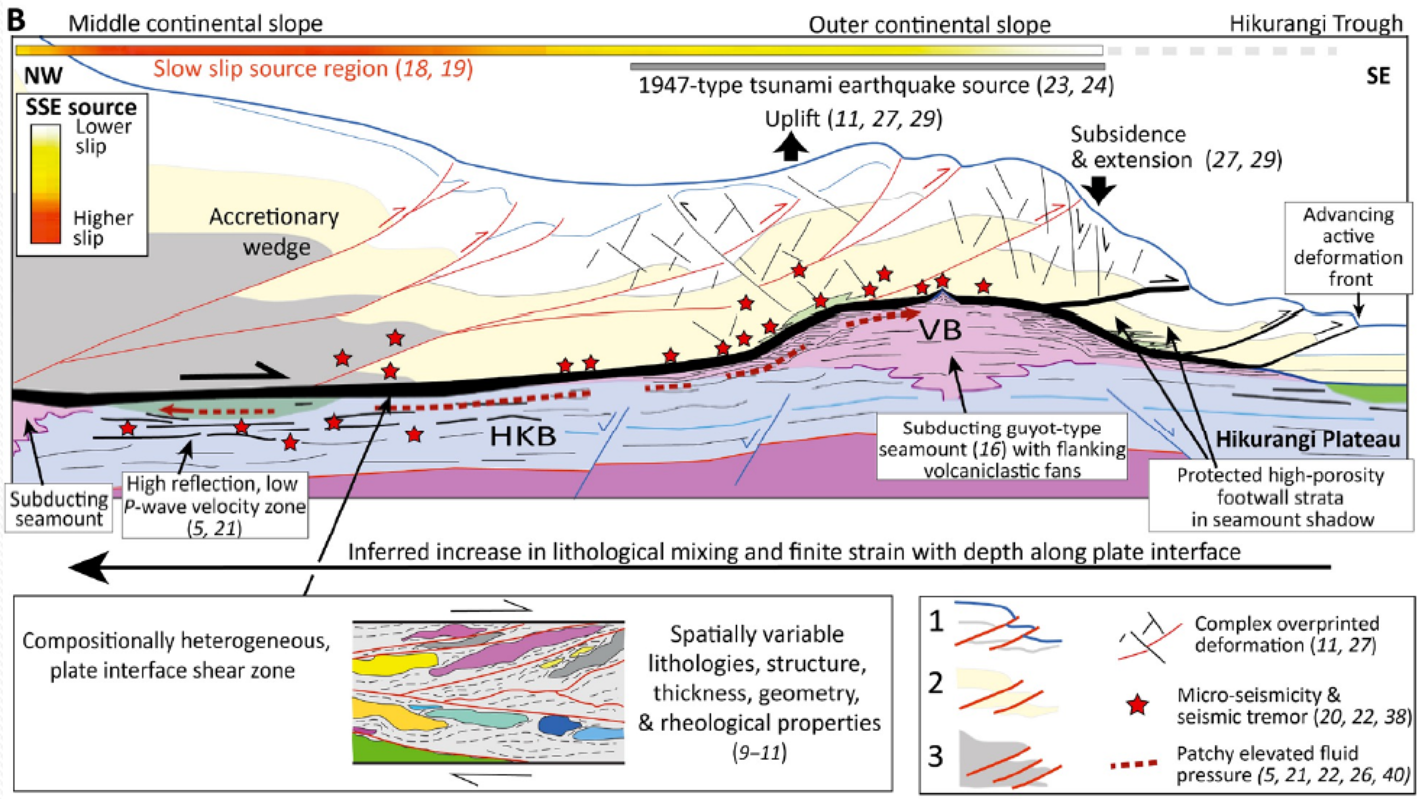
Summary

Possible evolution of knoll subduction and seismic character

Different lithological mixing may occur during deformation across the plate interface leading to a fault zone with a highly variable suite of rocks and marked variations in cohesion, elastic moduli, strength, and inferred frictional behaviour

+

Geodetic and seismological data indicate enigmatic co-existence of patchy (and overlapping)
seismic and aseismic slip behavior at Hikurangi



Geometrically irregular fault zone with variable thickness and strain distribution, and comprising a mosaic of diverse lithologies with markedly different mechanical properties **may promote different slip behavior (?)**

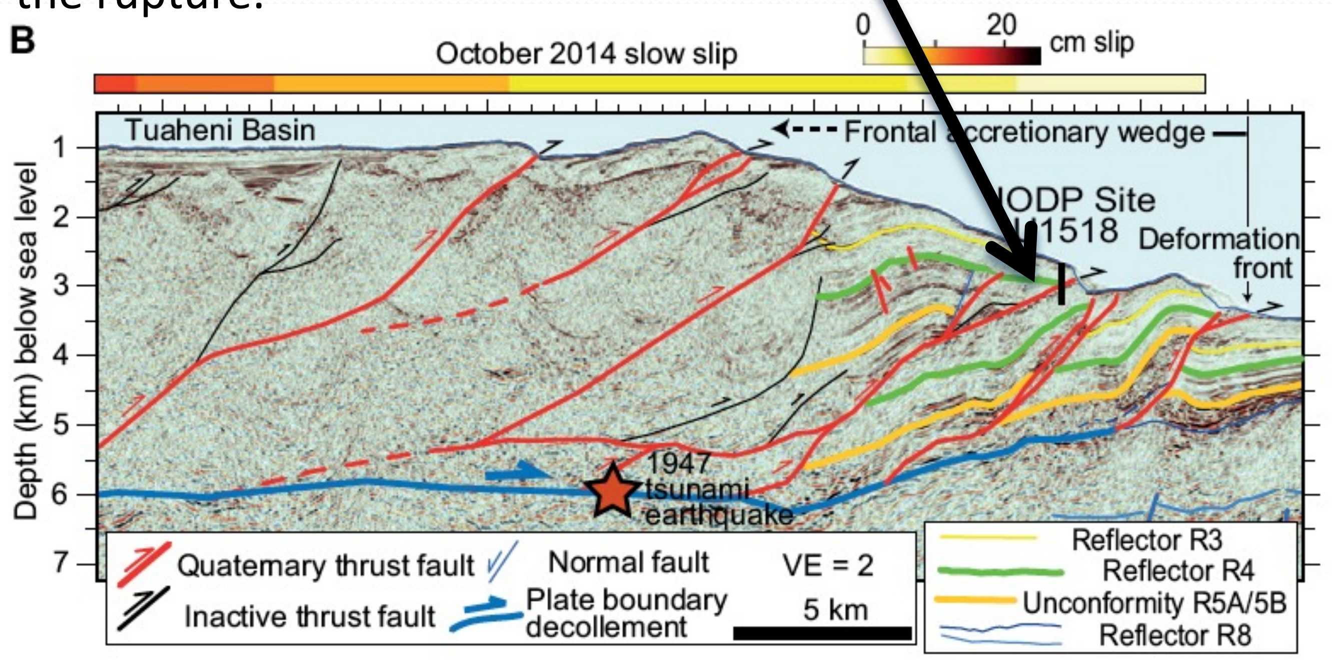
Barnes et al., Science Adv., 2020

What about earthquakes along the the Hikurangi margin?

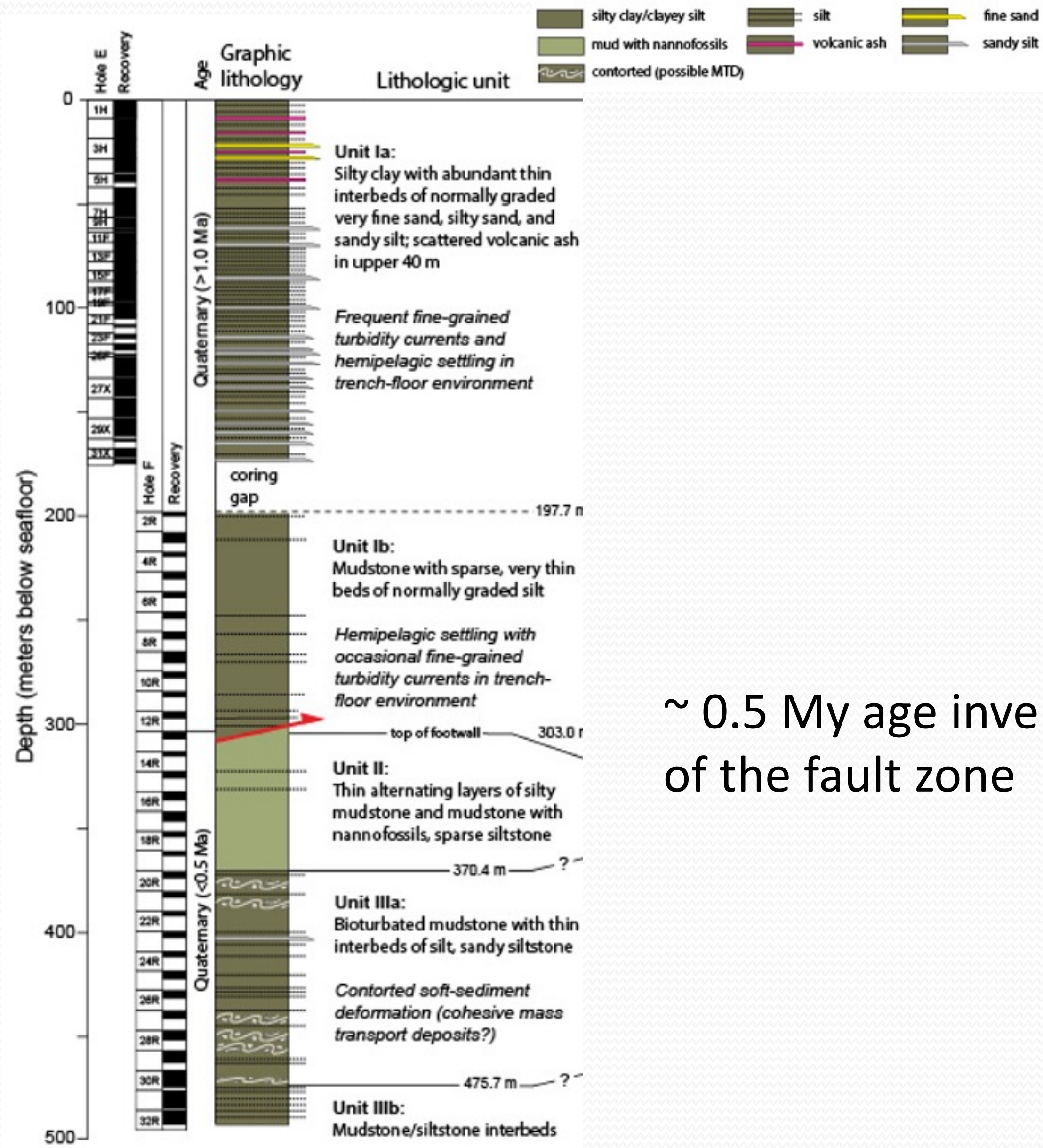
- H … or
- N … hrust f
- U … erface v … EQ r

COULD SHALLOW, NORMALLY CREEPING PĀPAKU FAULT PROPAGATE A SEISMIC RUPTURE NUCLEATING AT DEPTH?

Large slip displacements during tsunamogenic earthquakes are attributed to low coseismic shear strength in fluid-saturated and non-lithified clay-rich fault rocks.
Theoretical studies suggest that thermal pressurisation of fluids in low-permeability faults can reduce the dynamic strength of faults during seismic slip, i.e. the energy required to propagate the rupture.



U1518: the Pāpaku shallow thrust



~ 0.5 My age inversion at top of the fault zone

U1518: the Pāpaku shallow thrust

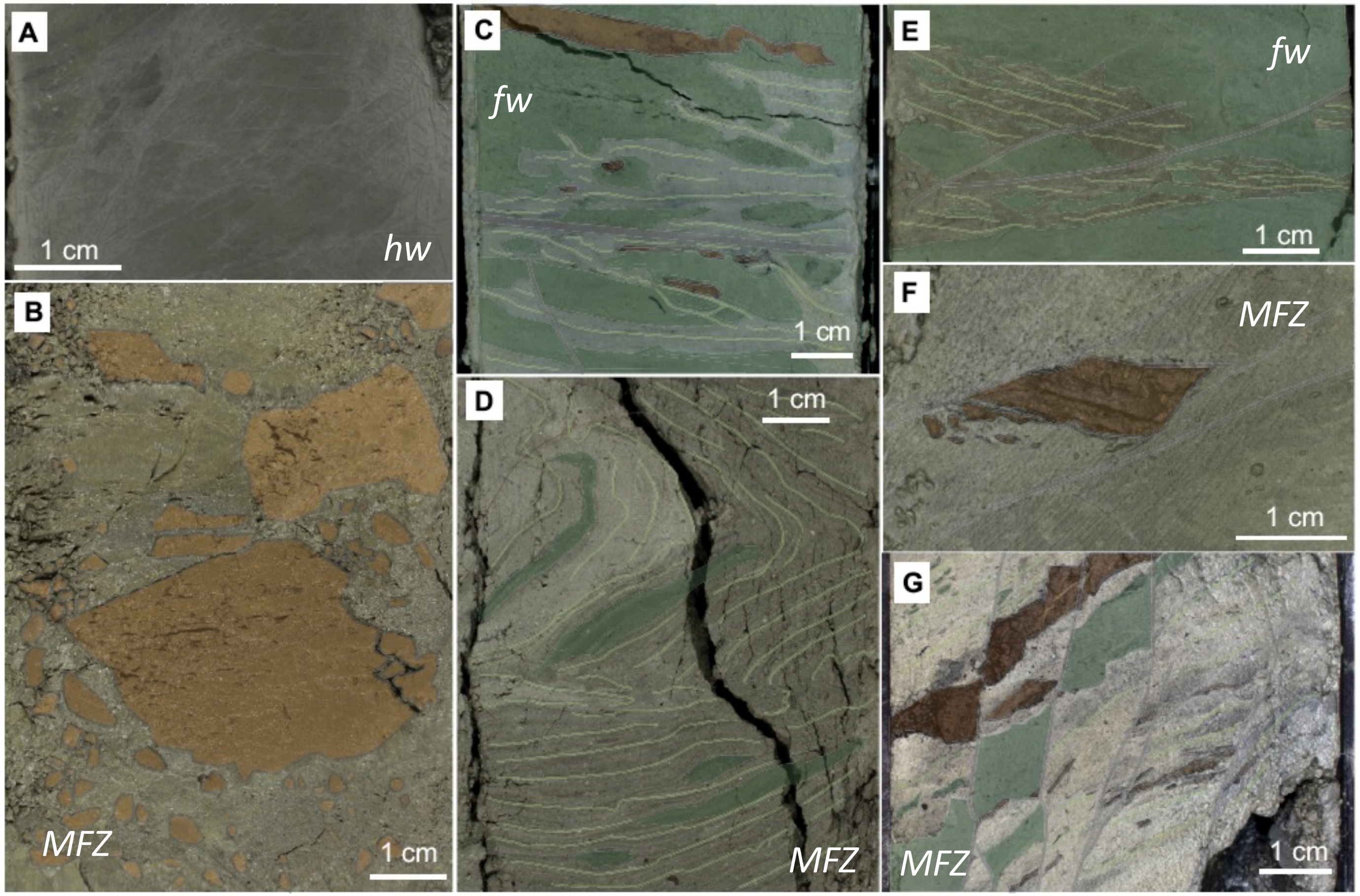
~60-m-thick fault zone with two high-strain zones separated by less-deformed sediments.

HANGING WALL: hemipelagic deposits Early to Mid Pleistocene.

Sets of regularly spaced filled fractures, no evidence of shear. Dominantly rigid compared to the footwall and fault zone. Sharp transition to MFZ

FOOTWALL: bioturbated hemipelagic deposits Mid-Late Pleistocene.

Concentrate most of deformation. Pervasive ductile structures (dismembered beds). Less rigid than HW.



MFZ: Sharp transition to the hanging wall. Lithologically similar to footwall.

Mix of intensely brecciated, fractured, and flow banded, dismembered ductily sheared silt and mud (ca. 18 m thick)

Brittle deformation also comprises faults healed by fine clays which crosscut ductile structures.

brittle vs. ductile deformation either cyclic, or brittle deformation progressively became more dominant w/ lithification

COULD SHALLOW, NORMALLY CREEPING PAPAKU FAULT PROPAGATE A SEISMIC RUPTURE NUCLEATING AT DEPTH?

On selected samples from main fault zone, hanging wall and footwall, we performed:

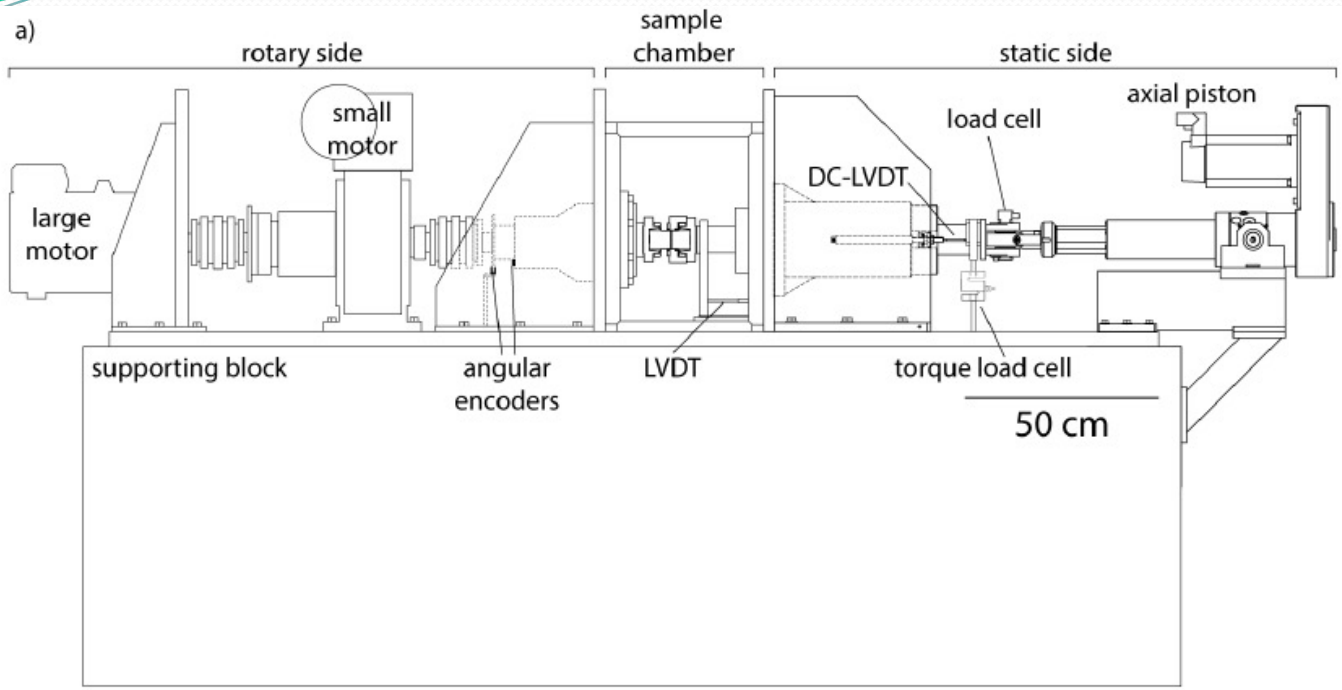
- high velocity friction experiments (SHIVA, INGV, Rome) using an innovative experimental setup allowing fluid saturation and the measurement of pore pressure and temperature.

- Samples: 12R1 (HW, ~9 m above the fault zone), 14R1A (FC-MFZ), and 21R3 (FW, ~19 m below the fault zone).

All clay-rich sediments with an average mineral composition of:
45.4±2.1 wt.% total clay minerals (smectite + illite + chlorite + kaolinite),
28.7±0.8 wt.% quartz,
17.2±0.6 wt.% feldspars,
10.8±0.8 wt.% calcite

Aretusini et al., Nat. Comm, accepted

SHIVA (**S**low to **HI**gh **V**elocity **A**pparatus) @ INGV, Rome



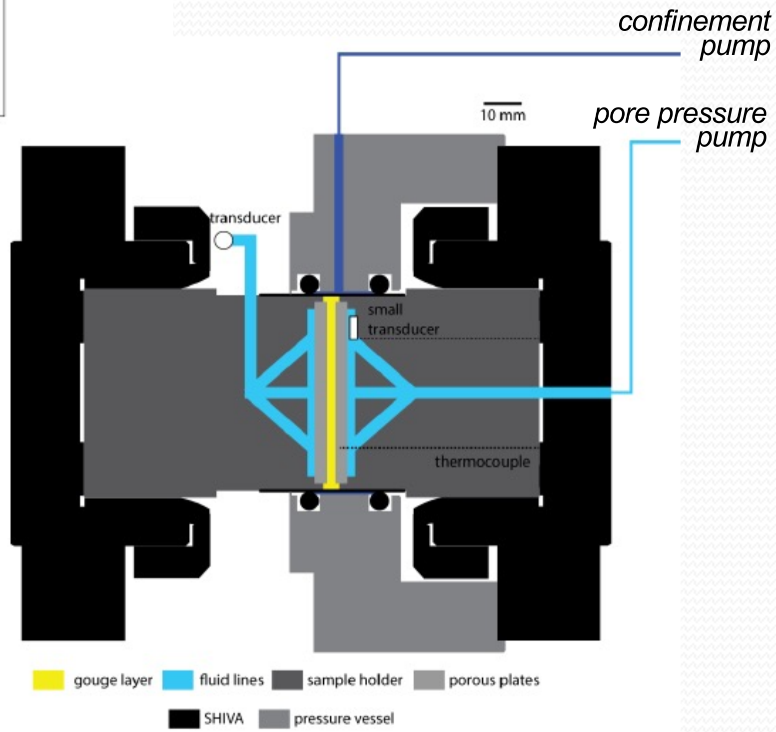
$s_n < 60$ MPa

$v = 10$ mm/s – 5 m/s

d = infinite

Power 300 kW

Torque 1100 Nm



(new set up and experiments performed by Dr. Stefano Aretusini and Dr. Elena Spagnuolo)

Sample chamber and sample holder

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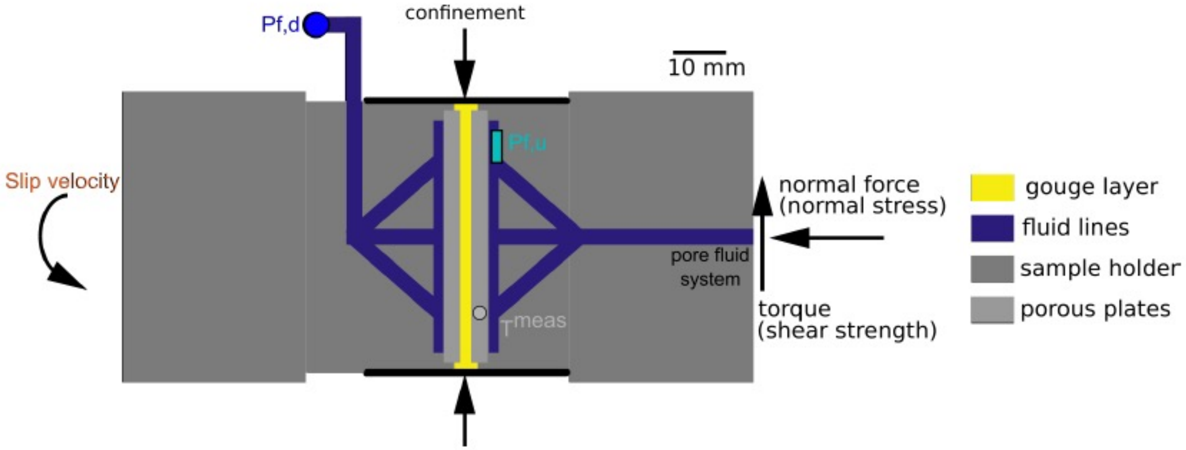
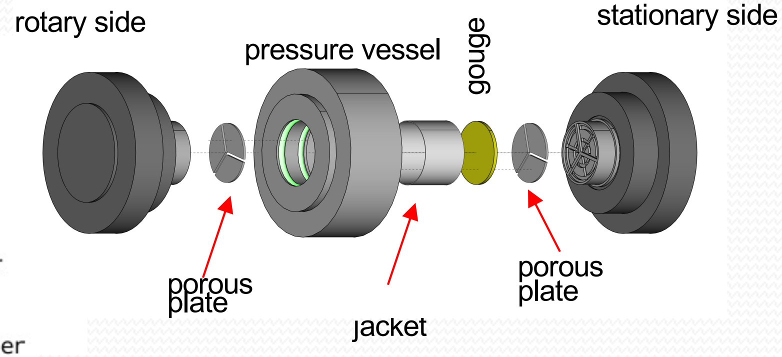
The new experimental setup for exp in controlled fluid pressure





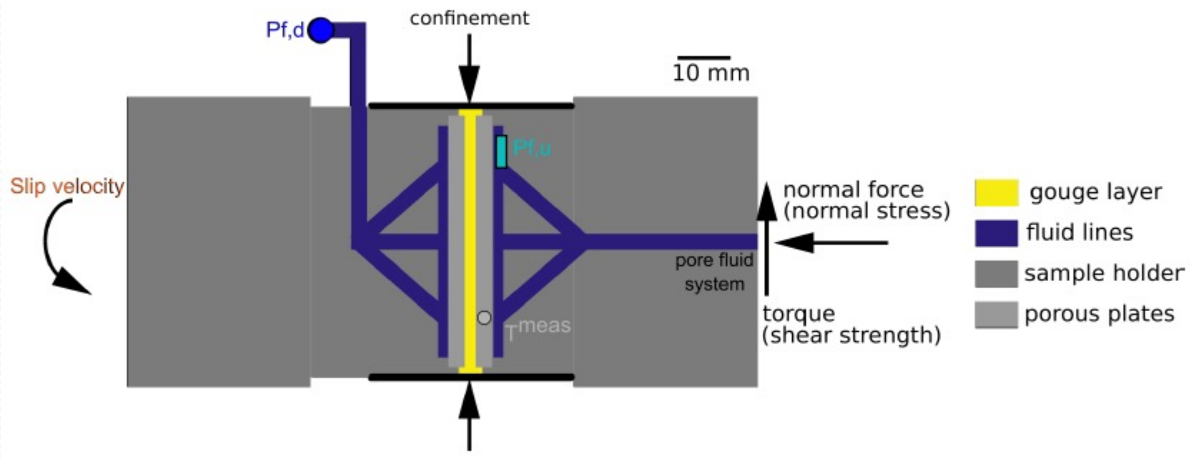
- gouge layers (250 µm grain size), ca. 4.5 mm thick, between two sample holders with steel porous plates, and jacketed with a PVC shrink tube.
- the jacketed sample is inserted into a water-filled pressure vessel to provide a confining pressure (P_c),
- pore fluid (distilled water) is injected into the gouge layer from the static side and monitored with transducers on the rotational ($P_{f,d}$ = pressure downstream) and on the static side of the sample ($P_{f,u}$ = pressure upstream).
- Normally normal stress, axial shortening, displacement, velocity, shear strength (evolution of material strength) are measured. In these experiments we added (i) **pore pressure**, (ii) **temperature at the edge of the gouge layer** with a thermocouple.
- fault gouge was tested without adding water for room humidity conditions. To impose water dampened conditions, deionized water was added to the gouge layer so that it was only partially saturated.

The new experimental setup for exp in controlled fluid pressure

10 experiments to measure the dynamic evolution of the shear strength :

6 fluid-pressurized tests on FC, HW and FW,

- S_n = 6 MPa, P_c = 4 MPa, P_f = 3 MPa
- room temperature (25°C)
- for each experiment, first we gradually increased S_n and P_c, and then P_f



- P_f is equilibrated between the two sides of the gouge layer before shear pulses to ensure saturation

4 additional tests on FC samples under room humidity and water dampened conditions, at room temperature (25° C) and normal stress of 3 MPa (i.e. effective normal stress identical to the pressurised experiments)

Samples: 12R1 (HW), 14R1A (FC), and 21R3 (FW)

- PRE-SHEAR: slip pulse at 10 µm/s for 0.01 m of slip, to achieve compaction
- after equilibration of pressure FAST SLIP PULSE at 0.8 m/s for 0.4 m of slip (i.e. a moderate (Mw 6.0-6.5) tsunamigenic earthquake)

Results: mechanical behavior across Pāpaku thrust materials

Anatomy of the seismic velocity slip pulse (pressurized test)

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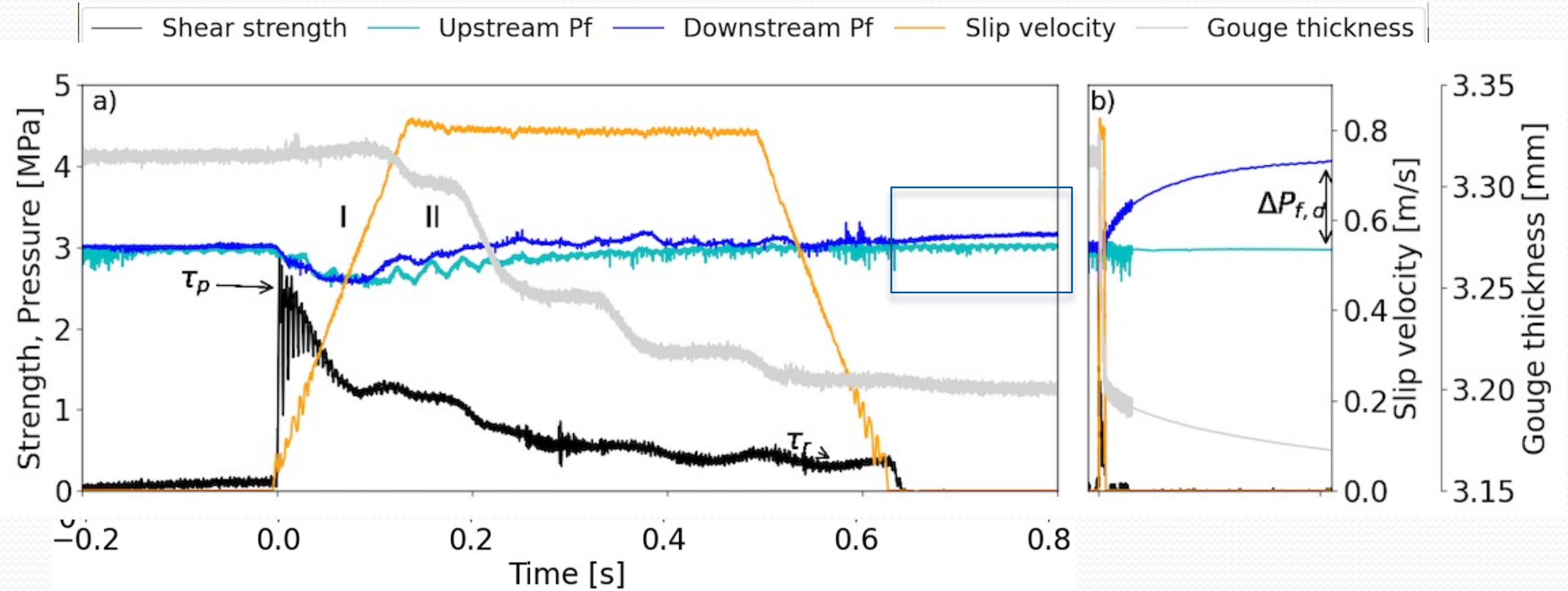


Independently of fault material, in all the pressurized experiments P_f increase in different ways and at different times during/after the fast slip pulses:

- P_f decrease after the onset of slip associated to a **gouge layer thickness increase**
- the maximum downstream increase ΔP_f (= $P_{f,d}$ - $P_{f,u}$) accompanied by **gouge layer thickness reduction**
- **shear strength decays is different** in different materials (i.e. different slip weakening distance D_W)

Results: mechanical behavior across Pāpaku thrust materials

What do the experiments suggest?

Pāpaku Thurst materials, when sheared at seismic velocities:

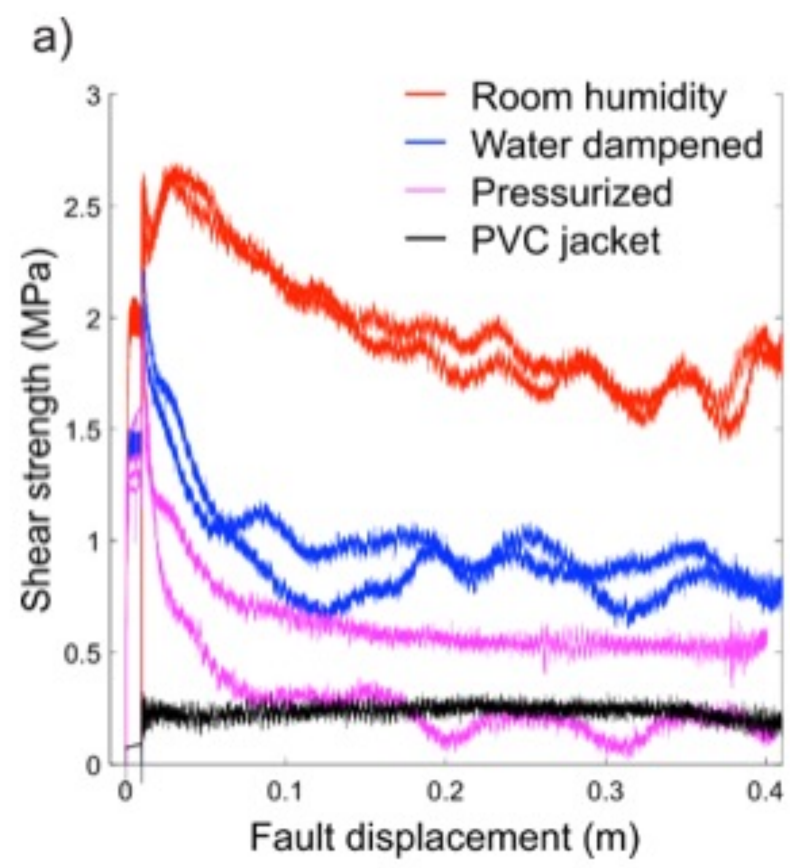
1) Shear strength decay = DYNAMIC WEAKENING, in ALL SETS of experiments

(depends on peak strength, residual strength, and slip weakening distance);

In pressurized experiments

2) Decrease in pore fluids pressure at onset of slip and thickening of the gouge layer - possibly suggesting shear enhanced dilatancy?

3) Pressurization of pore fluids during/after the slip pulse associated with thickness reduction of the gouge



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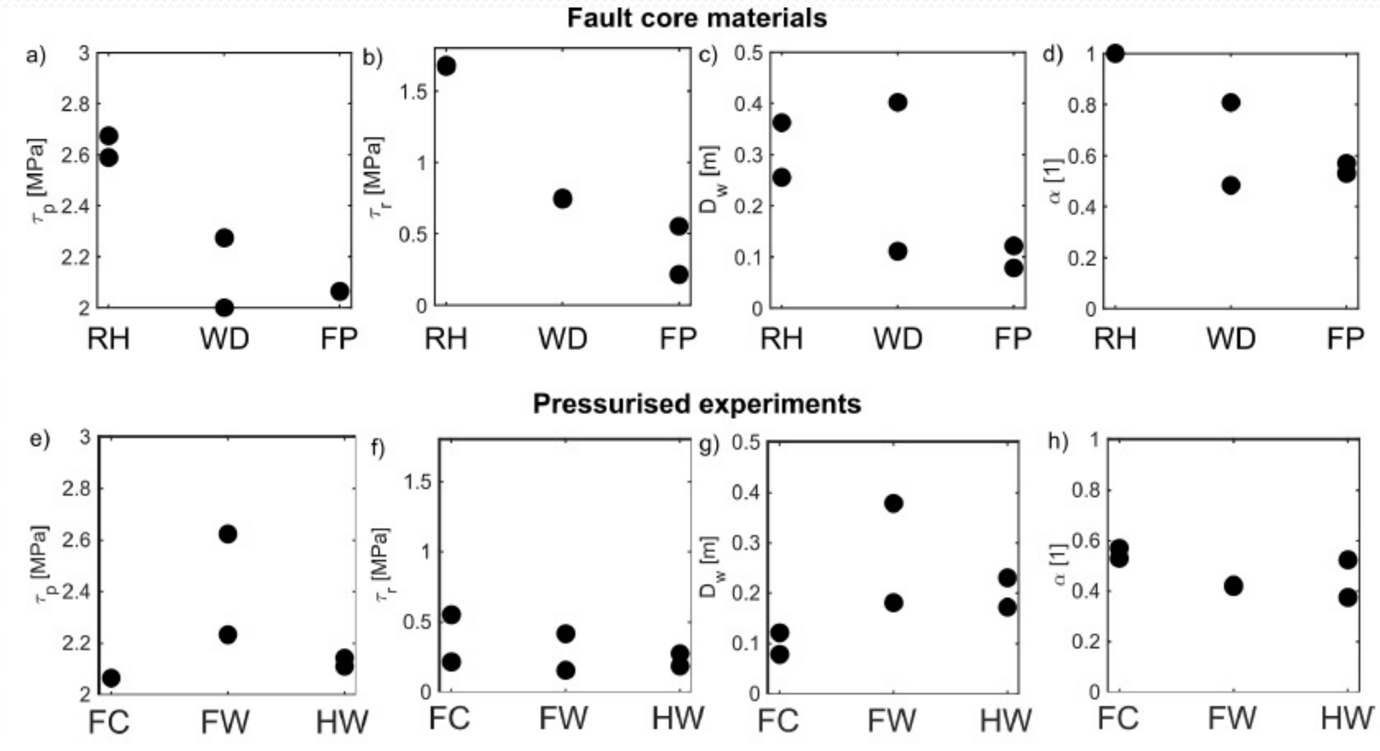
Results: mechanical behavior across Pāpaku thrust materials

In particular:



- FC materials showed the **lowest** peak strength (τ_p), residual strength (τ_r), and slip weakening distance (D_w) **under fluid pressurised** conditions than under water dampened and room humidity conditions
- In fluid pressurised experiments, FC materials had the **lowest slip weakening distance** with respect to HW and FW materials.

Aretusini et al., Nat. Comm, accepted

Dynamic weakening and pressurization

Several mechanisms can account for pore fluid pressure increase, decrease in shear strength and effective normal stress (see *Aretusini et al., Nat.Comm. f*or references):

1) *thermal pressurisation*, i.e. pressure increase by frictional heating
2) *dehydration* (frictional heating causes clay minerals water dissociation),
3) *mechanical pressurisation*, i.e. pore fluid pressurises because the pore volume decreases by compaction during shear

Evolution of temperature across gouge (in room humidity and water dampened exp.):

The maximum temperature rise at the centre and edge of the gouge layer was calculated with numerical methods to simulate T evolution.
Then the modelled T at the edge of the gouge was compared to the temperature measured during the experiments:

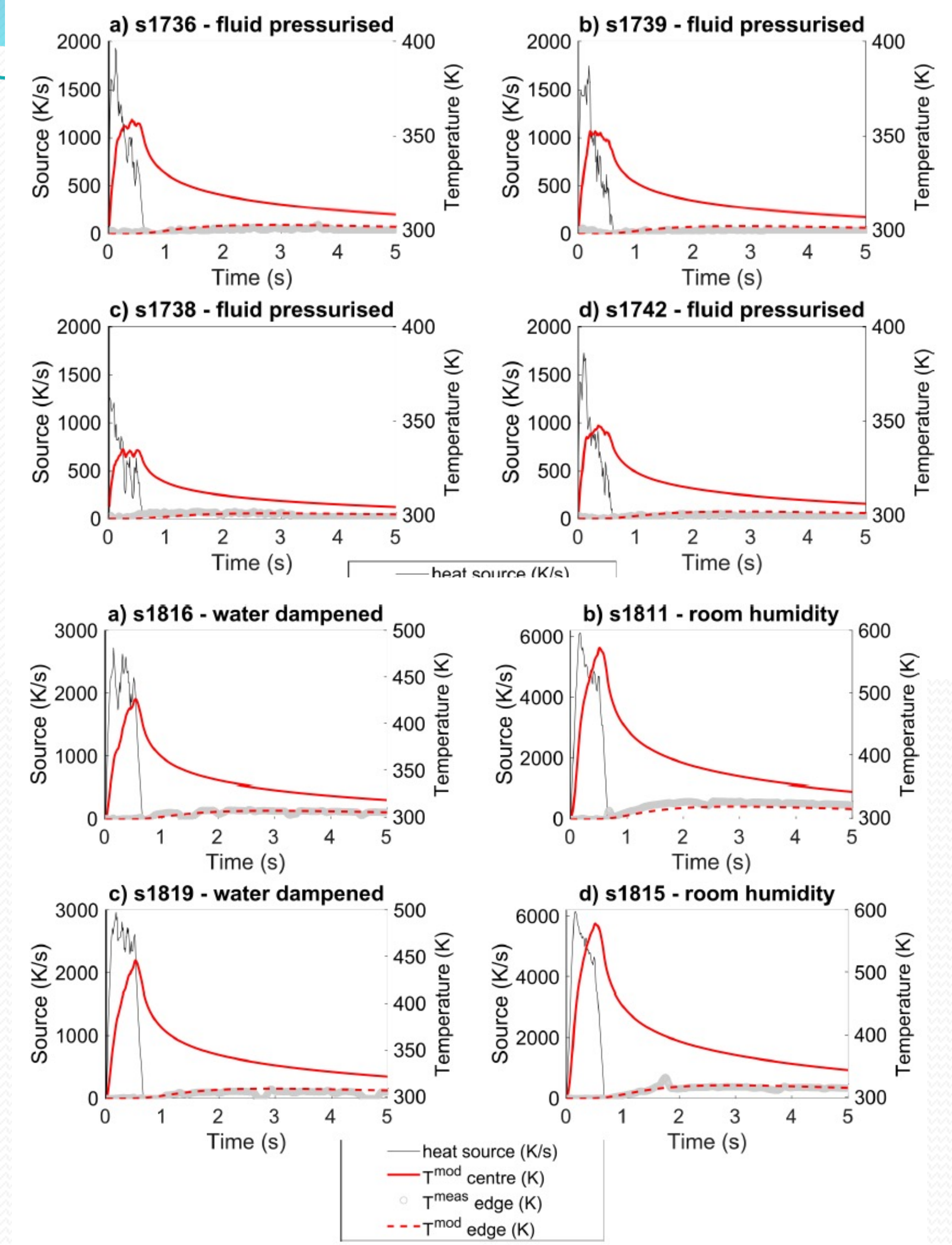
- T measured with the thermocouple was reproduced by the estimated temperature ca. 1 mm away from the gouge layer;
- Therefore, the T modelled at the center of the gouge during seismic slip pulse can be then used to discuss the active pressurization mechanism.

Dynamic weakening and pressurization

Estimated maximum temperature and pressurization mechanisms

In the room humidity experiments, the absence of water and the **highest estimated maximum temperature** suggest that dehydration and/or a thermally- activated processes are dominant in governing dynamic weakening.

In presence of pore fluids, dynamic weakening is associated with **pore fluid pressure increase**, and the **estimated maximum temperature** in the centre of the slipping zone **is lower**.

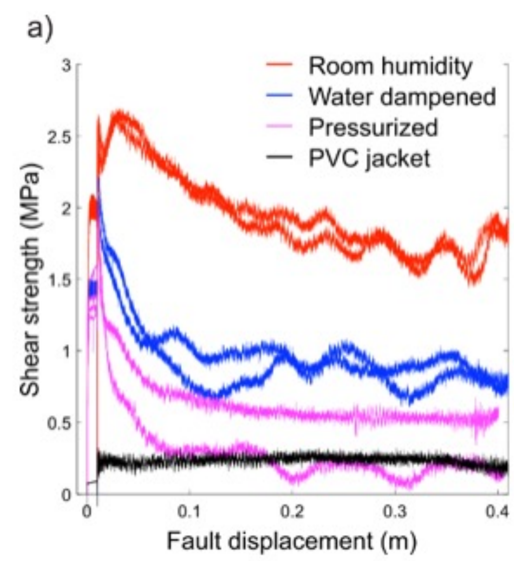


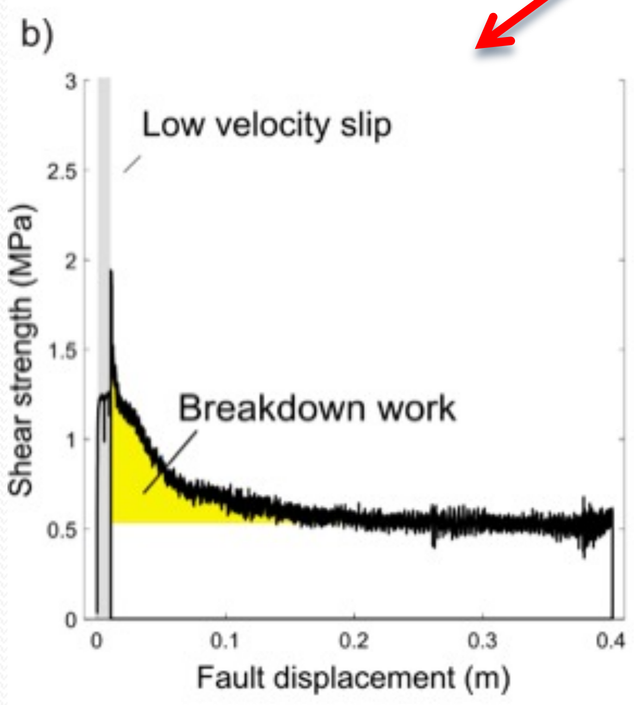
A combination of thermal pressurisation, dehydration and shear compaction drove the pore fluid pressure increase and therefore the shear strength reduction.

Aretusini et al., Nat. Comm, accepted

Estimation of the breakdown work

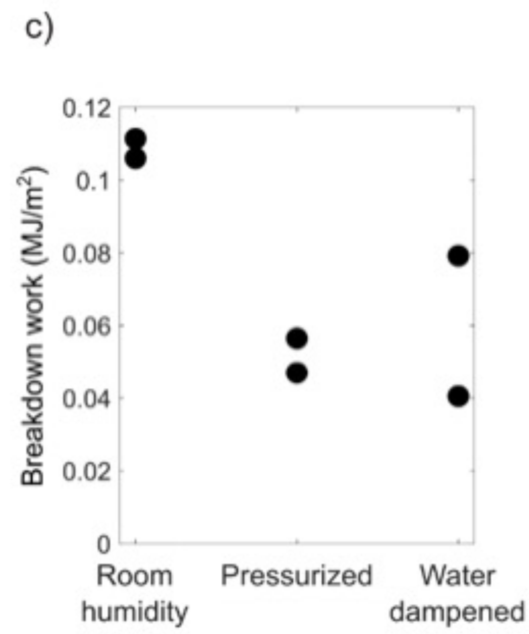
W_b = energy dissipated during the loss of strength.
Calculated from the shear strength variation with displacement, it controls earthquake rupture propagation: smaller W_b, increasing ease of rupture propagation.
Depends also on slip weakening distance D_w





FC materials under fluid pressurised conditions have the lowest residual stress and smallest slip weakening distance;

Pāpaku thrust FC materials have the lowest W_b when deformed under fluid pressurized or water dampened conditions with respect to tests at room humidity.



Take away messages

- **Pressurization** with seismic slip at 0.8 m/s is observed in fault core and damage zones, associated with **dyamic weakening**
- The presence of liquid water activates fluid-driven processes which reduce the energy required to propagate seismic rupture W_b more efficiently than thermally-driven processes activated under room humidity conditions.
- The lower W_b in fluid-pressurised conditions can be explained by the faster initial dynamic weakening and shorter D_w than in the other environmental conditions.

↓

The coseismic mechanical pressurisation of fluids (enhanced by the low permeability of the fault), reduces the energy required to propagate upward an earthquake rupture

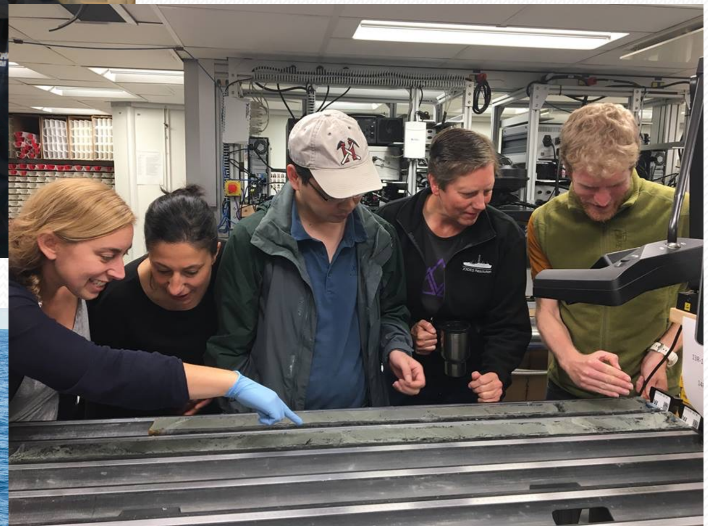
Fluid-pressurised faults are demonstrably prone to seismic slip if perturbed by arrival of a seismic rupture, i.e. when activated, Pāpaku splay can propagate slip easily up to the trench.

- Fault core have lower W_b compared with HW and FW (shorter D_w).

↓

Seismic slip at shallow depths can propagate in any of these materials and/or
FC materials at Pāpaku fault can be the slightly most favourable to propagate fault slip if perturbed by a seismic rupture






GRAZIE!