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Episodic stress tensor and fluid pressure cycling in subducting oceanic crust during Northern Hikurangi SSEs

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1. Overview

- Globally, SSE occurrence has been linked to the presence[1,2] of, and fluctuations in near-lithostatic fluid pressure within the megathrust and subducting oceanic crust.
- The Northern Hikurangi subduction zone hosts large, shallow, 2-3 week long SSEs every 1-2 years, as well as smaller transients several times a year[3].
- In 2014-2015, the HOBITSS experiment recorded four SSEs (#1-4, Figure 1) on a network of ocean bottom absolute pressure gauges and seismometers.
- We use earthquake focal mechanisms recorded by HOBITSS to calculate the shape of the stress tensor, and use this as a proxy to monitor temporal changes in fluid pressure in the downgoing plate, where hydrothermal fluids are sourced, and compare these changes with SSE timing to investigate controls on SSE episodicity.

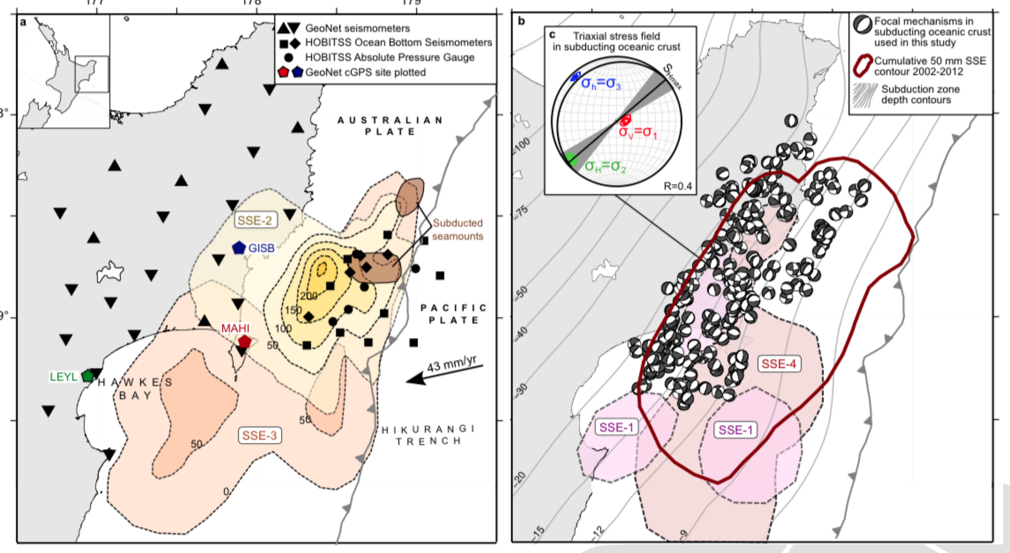

Figure 1 (above): Overview of northern Hikurangi and the seismic and geodetic networks, SSEs and seismicity utilised in this study. **a:** shaded contours show geodetic slip models for two large SSEs (#2 and #3). **b:** Lower plate focal mechanisms used for stress analysis. Contours show two smaller transients (#1 and #4). Inset shows triaxial stress field for all events

KEY POINTS

1. Crustal stresses and fluid pressures within subducting oceanic crust evolve before and during slow slip events.

2. More strike-slip earthquakes and a lower stress ratio occur in the lead up to SSEs which we attribute to elevated fluid pressures in the slab.

3. Observations consistent with a megathrust 'valving' model, whereby fluid pressure and permeability influence SSE timing.

4. Spatial distribution of slab and interface seismicity indicates heterogeneous hydrological coupling between lower and upper plates.

2. Stress and P_f evolution through SSEs

- Using a damped temporal stress inversion method[4] we calculate temporal changes in the retrieved stress ratio, R_{retr}, where $R_{retr} = (S_1-S_2)/(S_1-S_3)$. R_{retr} has been show to negatively correlate with P_f during geothermal injection under a normal faulting regime[5]. This is because under elevated P_f conditions, a broader faulting population is active, meaning increased strike-slip faulting is anticipated alongside normal faulting (Figure 2b). The negative correlation may also have a physical basis owing to anisotropic poroelasticity effects in tensionally fractured subducting oceanic crust (Figure 2a,b)[6].
- We observe a mix of strike-slip and normal faulting in the subducting plate (Figure 2c) alongside minima in R_{retr} (Figure 3 b,c,d) immediately prior to SSE initiation (Figure 2c). We also observe a subsequent change to purely normal faulting (Figure 2d) and an increase in R_{retr} by the end of SSEs (Figure 3 b,c,d). Together, these observations indicate elevated P_f prior to SSE initiation, and a drop in P_f during each SSE.

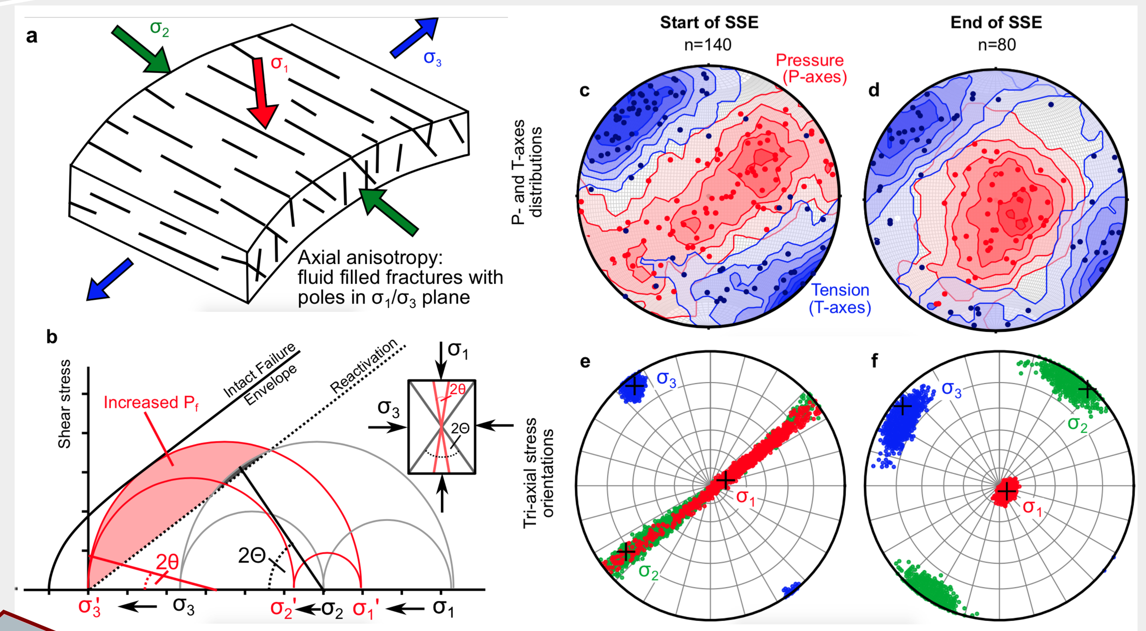

Figure 2 (right):Links between instraslab faulting and P_f changes. **a:** schematic of tensional, bending-related fractures in lower plate. **b:** Mohr diagram showing effect of increasing P_f (red) on fractures with orientation as in a. **c,d:** orientations of P (red) and T (blue) axes of focal mechanisms at SSE initiation and shutdown respectively. **e,f: T**riaxial stress orientations at SSE initiation and shutdown respectively.

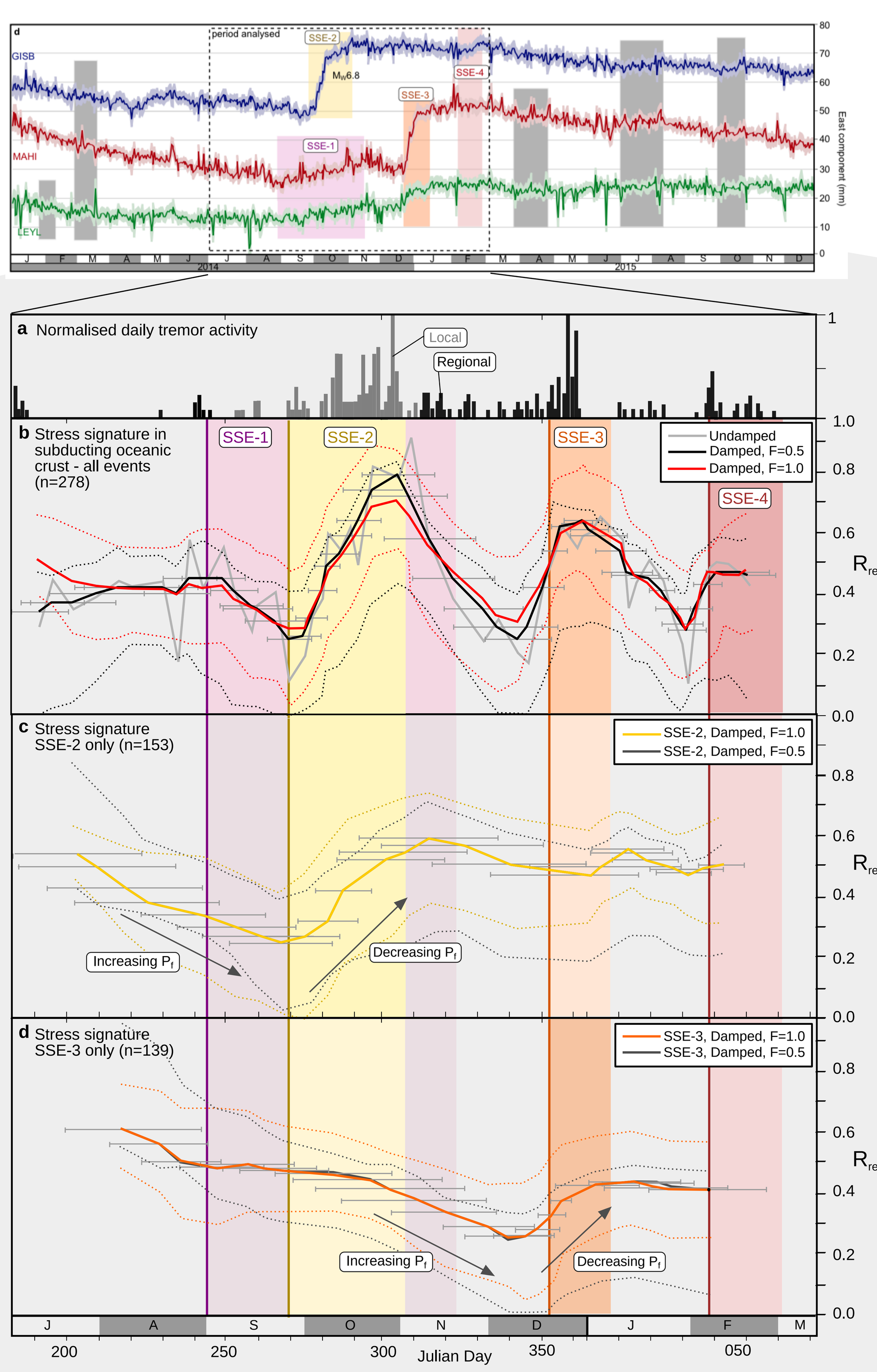

Figure 3 (right): Observed stress tensor changes during northern Hikurangi SSEs. a: Normalised daily tremor detections. **b:** Temporal variations in the retrieved stress ratio (R_{retr}) within subducting oceanic crust. SSE timings shown by coloured bars. **c, d:** same as in b but for earthquakes occurring beneath SSEs #2 and #3 only respectively.

3. Evidence for megathrust 'valving' behaviour

- Instead, we favour a 'valving' type model[7,8,9] of megathrust behaviour to explain our observations. We propose that our R_{retr} changes represent transient fluctuations in P_f within fault zones in the subducting oceanic crust, which migrate (down a pressure gradient) into the overlying interface, causing an increase in P_f sufficient to trigger slip.
- The consistent minima in R_{retr} prior to SSE initiation (Figure 3b,c,d) implies some critical pressure threshold may be reached, triggering slip.
- As interface slip occurs, strain-induced fracture opening produces a concomitant drop in P_f as fast crack propagation exceeds fluid advection rate. P_f may also decrease as increased permeability allows drainage from intraslab faults into the interface shear zone and overlying plate.
- Subsequent, slower increases in P_f (lowering in R_{retr}) occur as slab fractures become resealed by precipitate hosting fluid advection and diffusion and permeability is reduced.
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- Our observed changes occur within the highest Vp/Vs zone of the downgoing plate (>1.9), consistent with a zone of hgh fluid pressure beneath the downdip extent of slow slip.
- Stress modelling of Coulomb failure stress changes imposed by the SSE in the currounding crust reveal these processes cannot explain the timing nor magnitude of our observed stress tensor changes.

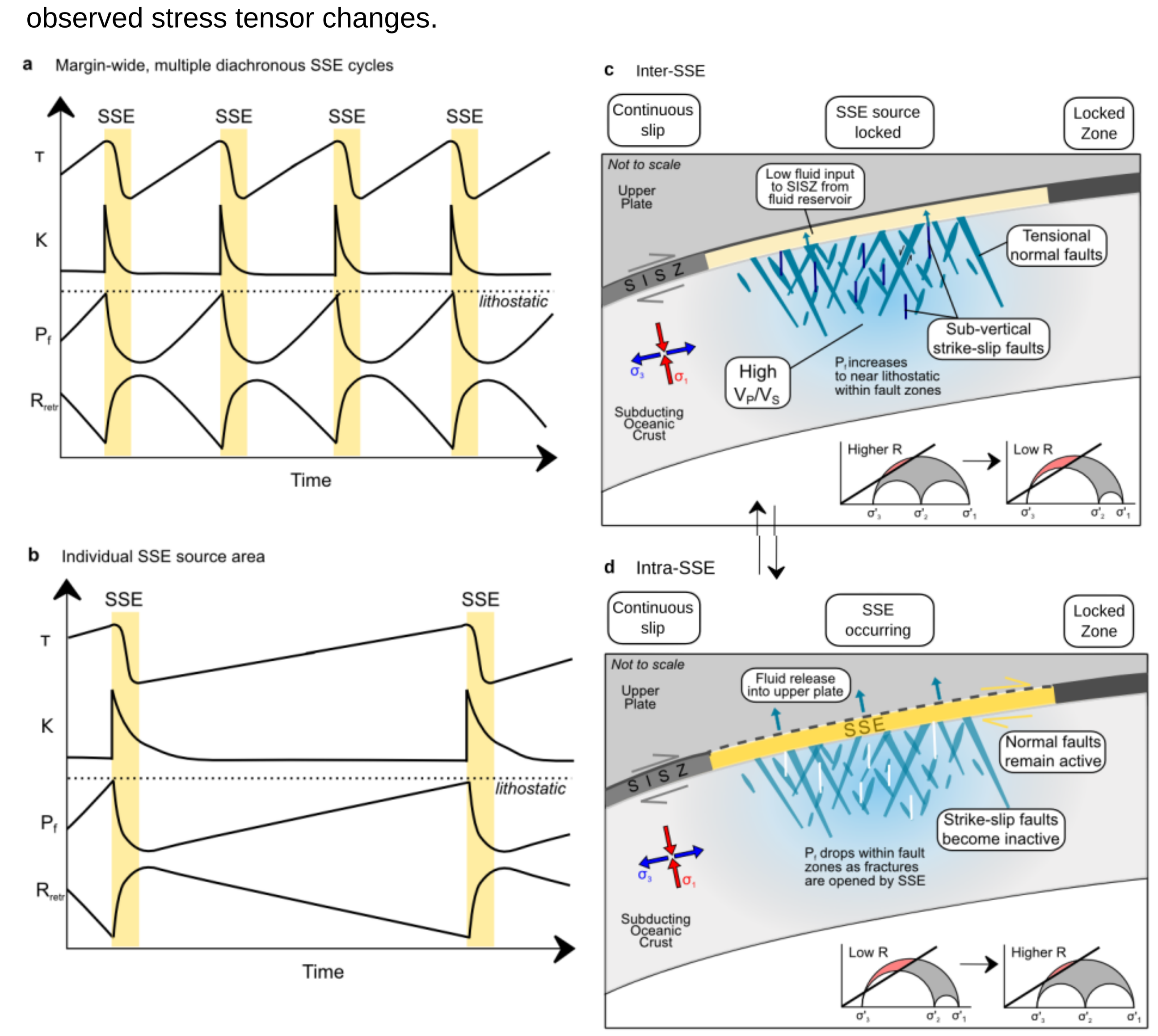


Figure 4 (left): Physical model of fluid accumulation and release and the effect on the stress tensor. a,b: Periodic variability in key physical parameters across the margin (a) and for an individual source area (b). Changes for the whole margin appear faster because of multiple interferring, diachronous SSE cycles. Pf accumulates beneath a particular SSE slip zone over several months. **c:** Schematic for Inter-SSE period. **d:** Schematic for Intra-SSE period.

4: A spatially heterogeneous process

- These strike-slip events do not occur homogeneously through the lower plate and their occurrence is spatially clustered (green events, Figure 5). Clusters locate at the down-dip edge of the highest cumulative SSE slip contours, and also correspond to:
  - Patches of high interface resistivity (constraint by MT data, Figure 5)
  - Interface microseismicity clusters (red and orange events, Figure 5)
  - Seismicity swarms that preceed SSEs (e.g. 2019 SSE, yellow events, Figure 5)
  - Loctions of surface hot springs and mud volcanoes (yellow stars, Figure 5)
  - Highest Vp/Vs zones in lower crust
  - Burst type-repeating earthquakes and upper place seismicity (which is otherwise sparse)

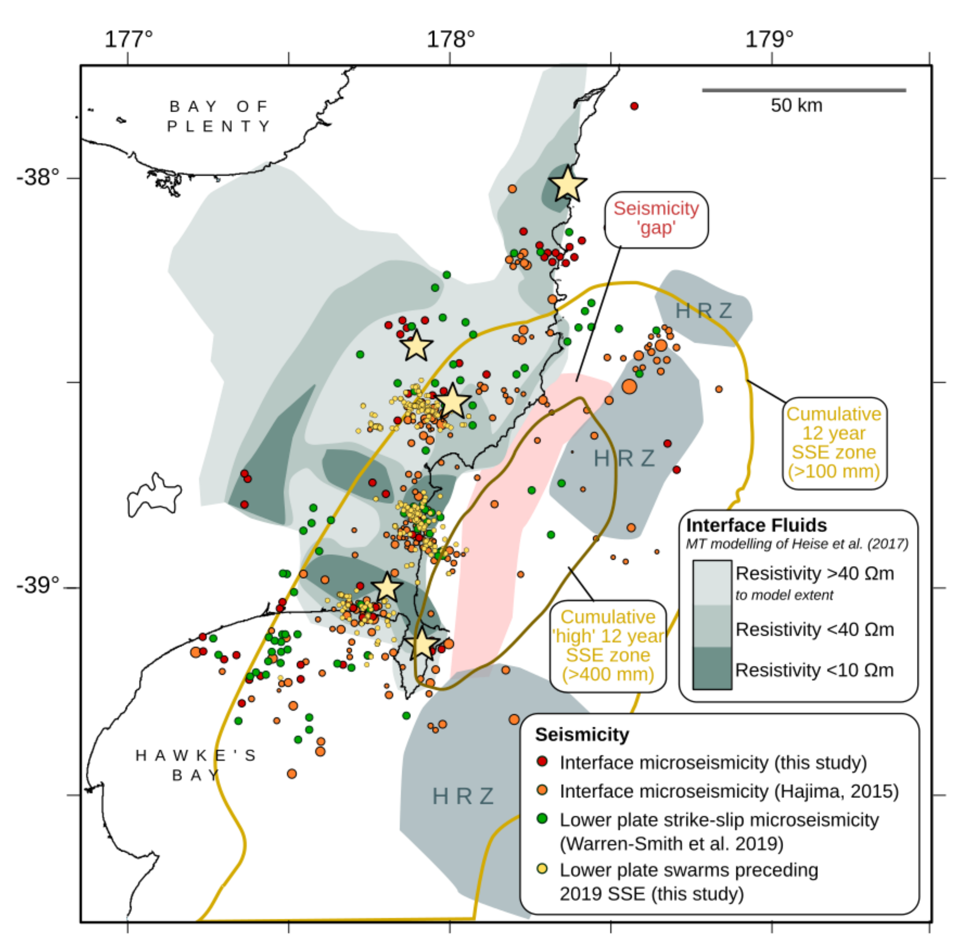


Figure 5 (above. left): Observations of spatially clustered seismicity patterns in relation to SSEs and interface fluids. Clusters in lower plate strike-slip earthquakes (green) are observed to correlate with clusters of interface seismicity (red, orange) and lower-plate swarms that preceed SSEs by a few weeks (yellow). These clusters also correlate with high MT observed interface resistivity and surface hot springs and mud volcanoes (yellow stars), indicating regions of elevated fluid presence and pressure.

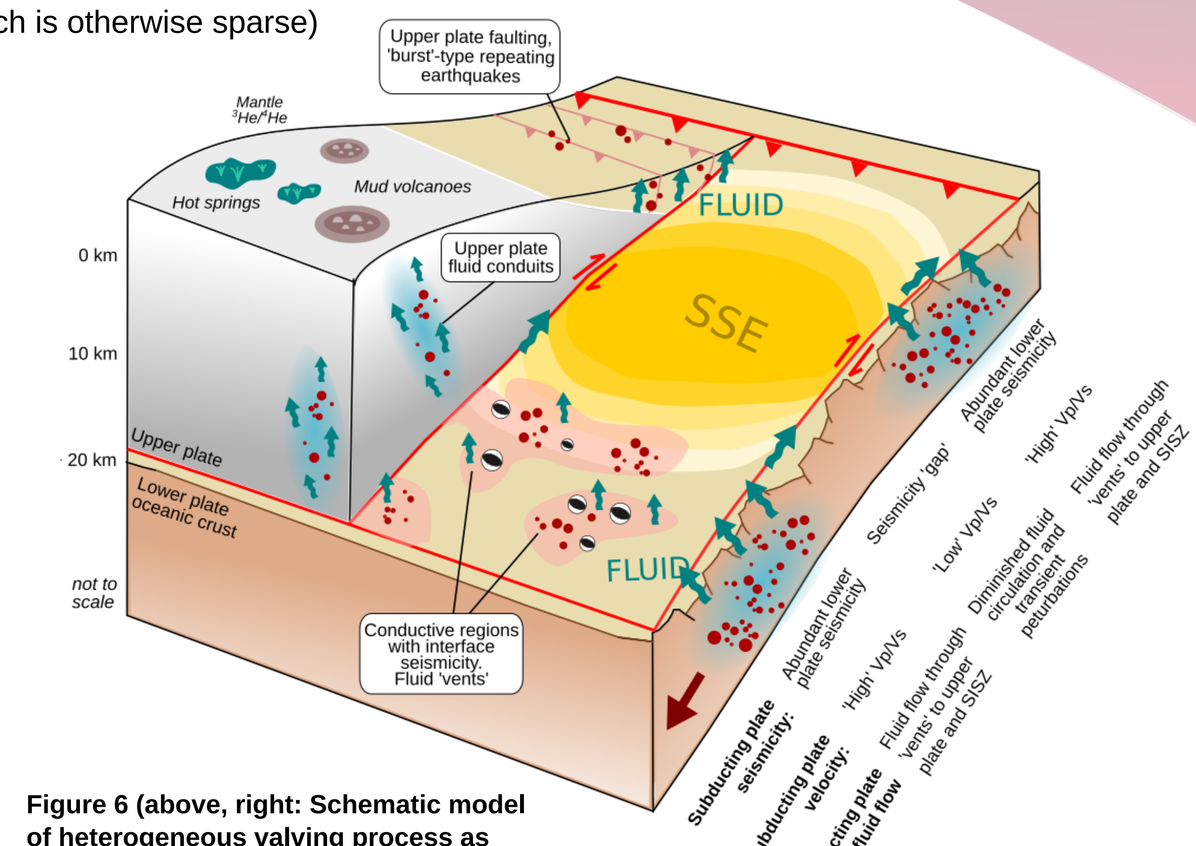
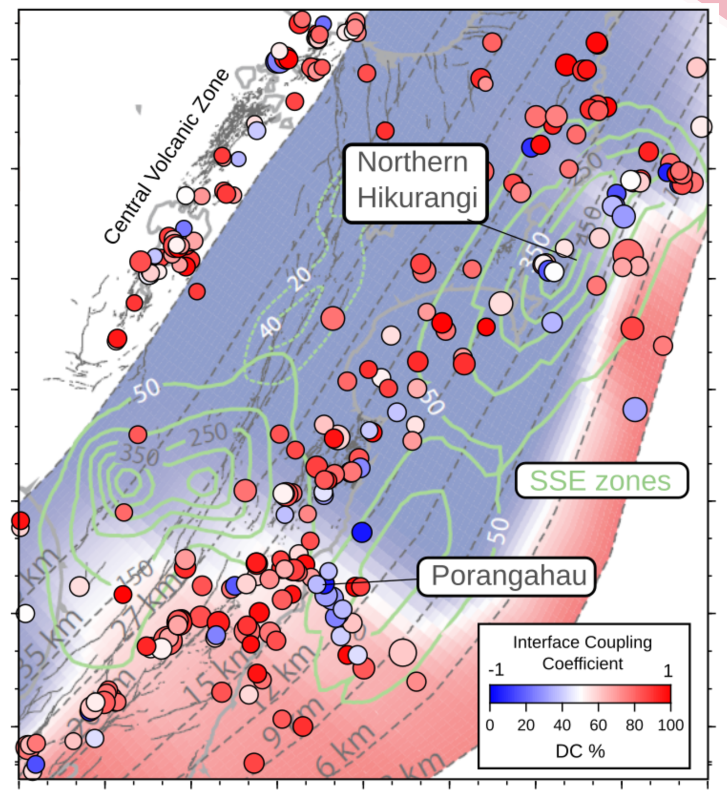


Figure 6 (above, right: Schematic model of heterogeneous valving process as control on seismicity and crustal structure in the Northern Hikurangi.

- Together, these observations suggest that 'valving' is not spatially uniform, and that discreet patches of (temporally variable) higher permeability and hydrological coupling exist between the lower and upper plates. These 'fluid vent' sites may leak fluid into the upper plate, diminishing up-dip fluid flow within the slab and contributing to the 'seismicity gap' observed immediately up-dip (Figure 6).

Figure 7 (below): Preliminary double couple component of moment tensor values along the Hikurangi (red-blue circles) atop the geodetically derived coupling coefficient (red-blue background shading).



Work is ongoing to investigate the seismic signature of fluid-processes in moment tensor calculations along the HIkurangi. Preliminary results indicate systematically lower double-couple components in zones of episodic slow slip (N. Hikurangi, and Porangahau). Porangahau is a region susceptible to dynamic triggering of tremor and seismicity, and exhibits high interface seismic reflectivity. Further work will calculate MTs for smaller earthquakes than is currently routinely enabled.

References

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