Elastic Properties of Subduction Zone Materials in the Large Shallow Slip Environment for the Tohoku 2011 Earthquake: Implications of a Compliant Wedge on Earthquake Rupture and Tsunamigenesis

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Introduction

The 11 March 2011 Tohoku-Oki earthquake ruptured through the shallowest part of the subduction zone, producing tens of meters of displacement at the seafloor and a devastating tsunami. One year after the Tohoku-Oki earthquake, the Integrated Ocean Drilling Program Expedition 343/343T, known as JFAST, was undertaken. Three boreholes were drilled in the frontal prism of the Japan Trench subduction zone about 200 km east of the Oshika Peninsula to depths of about 850 mbsf. We report laboratory ultrasonic velocity measurements performed at elevated pressures, as well as calculated dynamic elastic moduli, for samples recovered during JFAST.

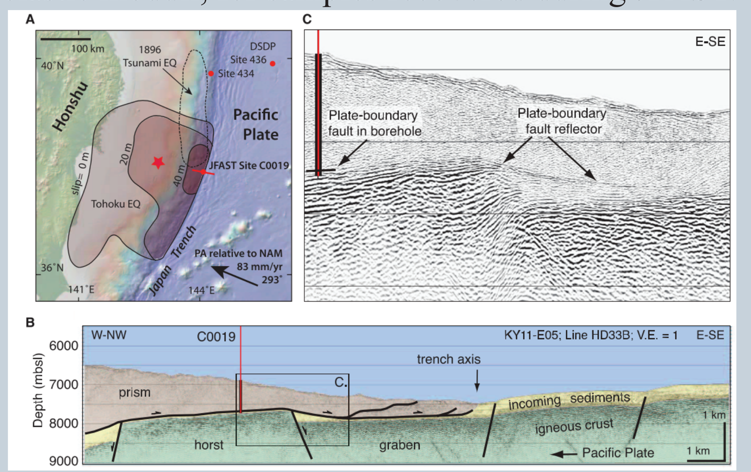


Fig. 1: Location and structural setting for the JFAST drill site. (A) Red dots indicate ocean drilling sites. Red star is the epicenter of the Tohoku-Oki earthquake. Contours show the coseismic slip inferred from various data sets. (B) A portion of the inline seismic profile showing the location of the boreholes. (C) Seismic data show the presence of a faint but continuous reflector, interpreted as the plate-boundary fault. From Chester et al. (2013).

Elastic and mechanical properties of faults and host rocks are controlling factors in fault strength, earthquake generation and propagation, and slip stabilization. An understanding of these properties and their depth dependence is essential to accurate modelling of earthquake rupture. We present initial results from dynamic rupture models which incorporate low-rigidity frontal fault materials, as well as plans for future work involving detailed models of subduction zone rigidity.

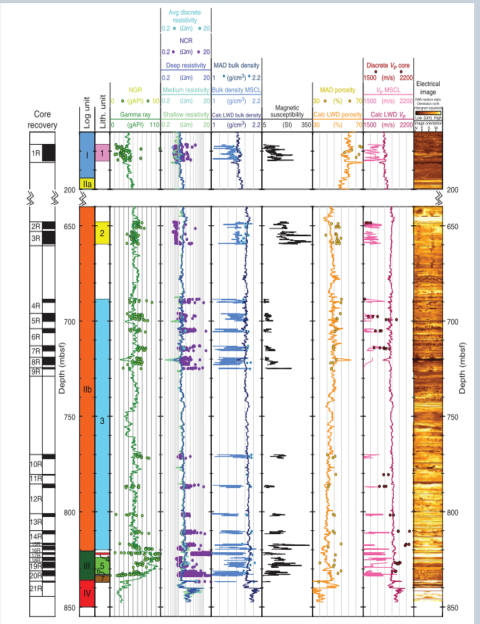


Fig. 2: Core-log-seismic integration summary diagram of JFAST data. From Expedition 343/343T Scientists (2013).

Methods

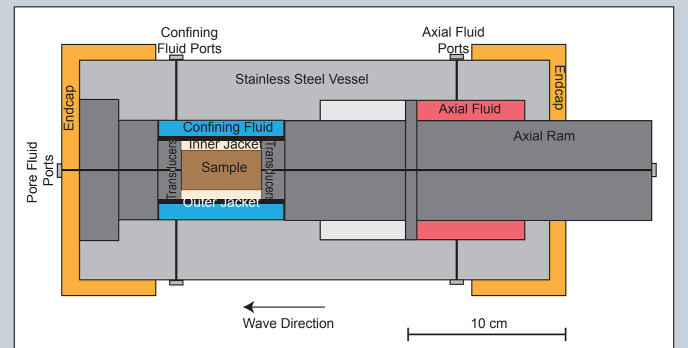
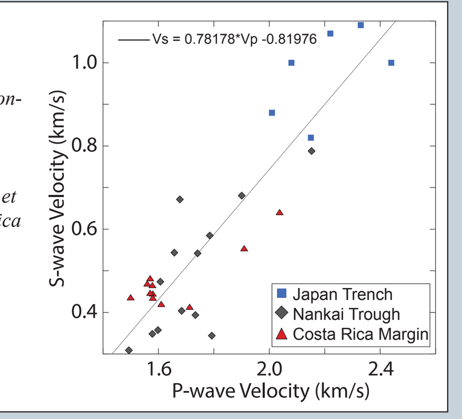


Fig. 3: Internal configuration of the triaxial pressure vessel.

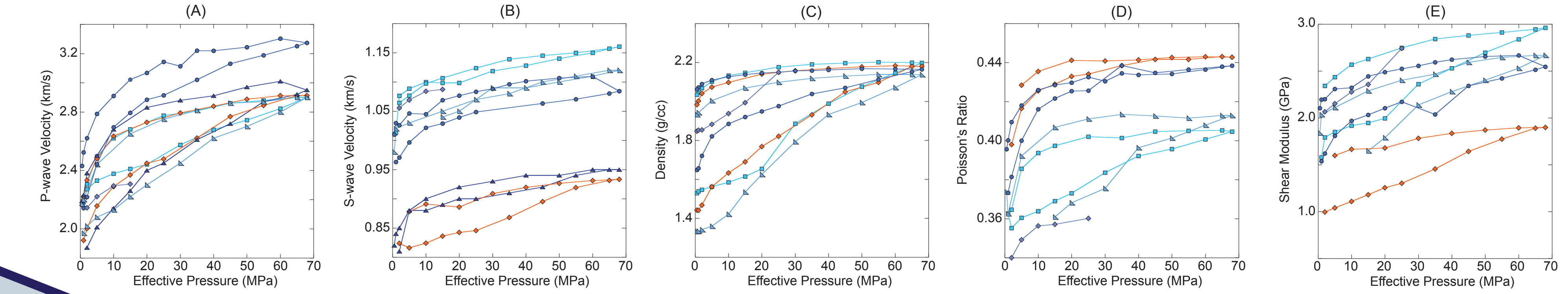
Ultrasonic velocity experiments were carried out on five core samples from JFAST. Four samples came from hanging wall grey mudstone and one sample came from the underthrust brown mudstone. Core plugs were placed into a triaxial pressure vessel with independent control of axial, confining, and pore-fluid pressure (fig. 3). Pore pressure was held at 1 MPa and velocities were measured at a range of effective pressures between0.5 and 70 MPa.

These velocity measurements were then combined with reported measurements of drill core from the Costa Rica Margin and Nankai Trough to derive a Vp-Vs relationship that was used to calculate Vs for samples on which only Vp had been measured (fig. 4). The dynamic elastic moduli for samples from the Japan Trench, Nankai Trough, Costa Rica, Cascadia, and Barbados ridge subduction zones were calculated and compared.

Fig. 4: Linear Vp-Vs relationship derived from measurements of drill core from the Japan Trench (this study), Nankai Trough (Schumann et al., 2014), and the Costa Rica Margin (Gettemy & Tobin, 2003).



Laboratory Results



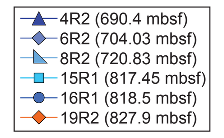


Fig. 5: Variations in (A) Vp, (B) Vs, (C) density, (D) Poisson's ratio, and (E) shear modulus with effective pressure for JFAST core samples Five samples are from lithologic unit 3, grey mudstone (blue markers), in the hanging wall and one sample is from unit 5, underthrust brown mudstone (orange marker).

Low shear modulus and high Poisson's ratio are not unexpected for soft, saturated mudstone and appears to be common in shallow subduction zone material. However, these experimentally derived moduli values are much lower than those commonly used in earthquake models (Shear ~17 to 30 GPa), and Poisson's ratio much higher (typical Poisson's ~0.25).

Velocities for both JFAST lithologic units examined are similar, ranging from 1.8 to 3.4 km/s for Vp and o.8 to 1.15 km/s for Vs over a range of effective pressures from 0.5 to 68 MPa (fig. 5). At the estimated in situ effective pressure of 5 MPa, Vp ranges from 0.7 to 1.0 km/s. The resulting dynamic shear modulus is low, less than 3 GPa, and Poisson's ratio is high, between 0.34 and 0.44.

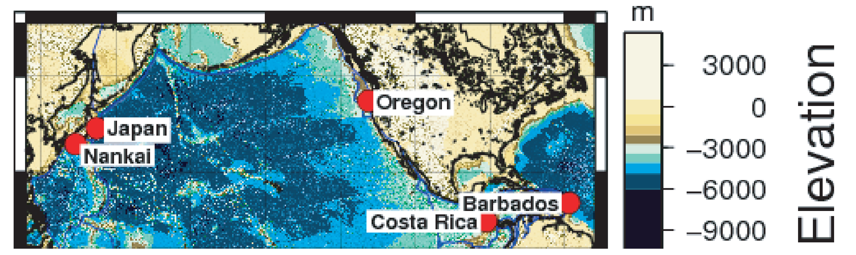
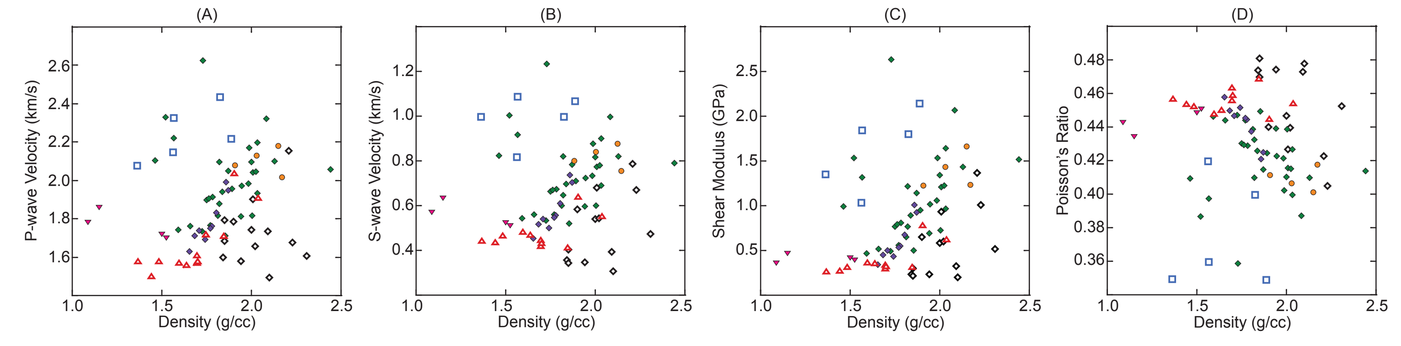


Fig. 6: Map of subduction zones where velocity measurements have been performed on drill core samples. These measurements were used in this study to examine the elastic properties of the shallow subduction zone.



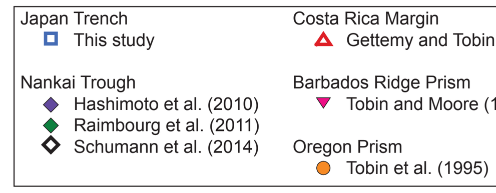


Fig. 7: Variations in (A) Vp, (B) Vs, (C) shear modulus, and (D) Poisson's ratio with density as measured for drill core samples at estimated in situ pressures from the Japan Trench, Nankai Trough, Costa Rica Margin, Barbados Ridge accretionary prism, and Oregon accretionary prism. Solid markers indicate the S-wave velocity was calculated at that location.

Similar samples from other subduction zones (fig. 6) have similarly low velocities with Vp ranging from 1.5 to 2.8 km/s and Vs from 0.2 to 1.4 km/s (fig. 7). The resulting calculated elastic moduli support the JFAST results. The shear modulus of all samples is less than 3 GPa and the Poisson's ratio is high, between 0.34 and 0.5.

Conclusions

- At an estimated in situ pressure of 5 MPa in the frontal prism, Japan Trench mudstones above and below the décollement have similar velocities of 2.0 to 2.4 km/s for Vp and 0.7 to 1.0 km/s for Vs.
- Mudstones from the Japan Trench and other subduction zones have very low shear moduli (< 3 GPa) and high Poisson's ratio (0.34 to 0.48). These values are reasonable for soft, saturated material but are significantly lower than the moduli commonly assumed in earthquake rupture modelling.
- Including low-rigidity layers in earthquake rupture models of the Tohoku-Oki earthquake significantly increases the slip on the fault.
- Preliminary work indicates that the presence of low-rigidity materials off-fault leads to increased slip velocity, slip, and seafloor deformation.

Dynamic Rupture Models

Low rigidity materials were introduced into the dynamic rupture model used by Kozdon and Dunham (2013) to simulate the Tohoku-Oki earthquake. The model assumes the medium is an isotropic, linearly elastic solid with piecewise constant material properties. The model accounts for different frictional properties (velocity-strengthening) along the uppermost section of the fault but does not explicitly include the frontal prism. Model geometry and original material parameters were based on wide-angle refraction data from Miura et al. (2001, 2005). The revised material parameters are based on laboratory data and wide-angle refraction data (table 1). The initial revision of material parameters exaggerated the thickness of the low rigidity layers.

There is a substantial difference between the slips resulting from the original and new, low-rigidity models (fig. 10). This is especially evident when the rupture enters the low-rigidity layers. Here the slip is amplified more than is realistic. These high magnitudes of slip are likely related to the exaggerated thicknesses of the low rigidity layers. The majority of slip occurs as displacement of the hanging wall while the footwall remains relatively stationary.

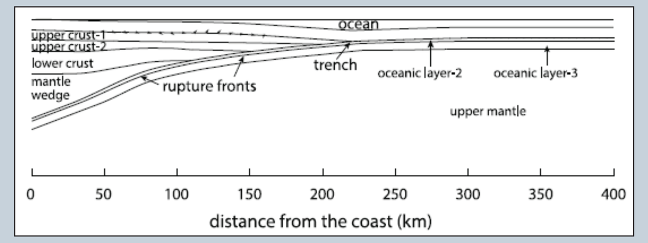


Table 1: Material Parameters

Original Parameters (Kozdon & Dunham, 2013)

	P-wave speed (km/s)	S-wave speed (km/s)	Density (kg/m3)	Shear Modulus (Gpa)	Poisson's Ratio
upper crust-1	4.8	2.8	2200	17.2	0.24
upper crust-2	5.5	3.2	2600	26.6	0.24
lower crust	7	4	2800	44.8	0.26
mantle wedge	8	4.6	3200	67.7	0.25
oceanic layer-2	5.5	3.2	2600	26.6	0.24
oceanic layer-3	6.8	3.9	2800	42.6	0.25
upper mantle	8	4.6	3200	67.7	0.25

New Parameters

	P-wave speed (km/s)	S-wave speed (km/s)	Density (kg/m3)	Shear Modulus (Gpa)	Poisson's Ratio
upper crust-1	1.96	0.94	1886	1.7	0.35
upper crust-2	2.44	1.06	2075	2.3	0.38
lower crust	6	3.47	2717	32.7	0.25
mantle wedge	8	4.51	3291	66.9	0.27
oceanic layer-2	2.43	1.05	2074	2.3	0.39
oceanic layer-3	6	3.47	2717	32.7	0.25
upper mantle	8	4.51	3291	66.9	0.27

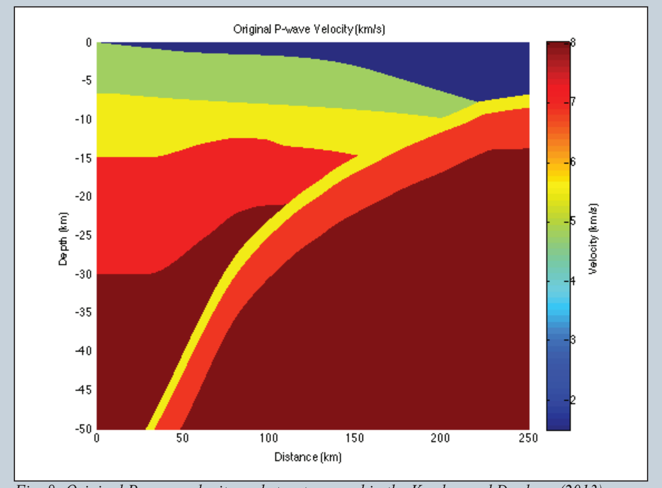


Fig. 8: Original P-wave velocity and structure used in the Kozdon and Dunham (2013) model.

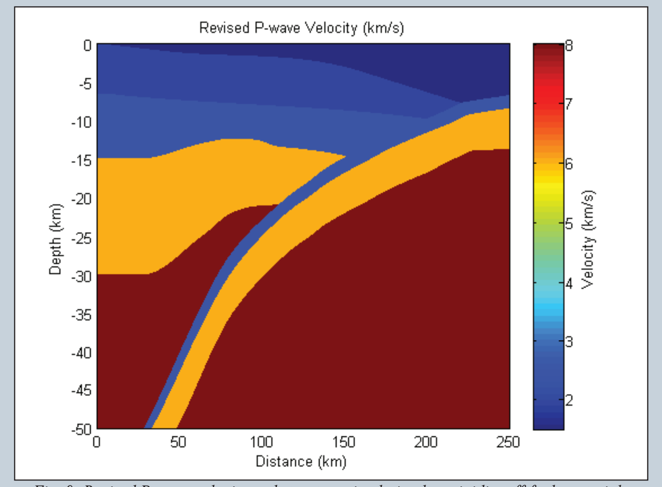
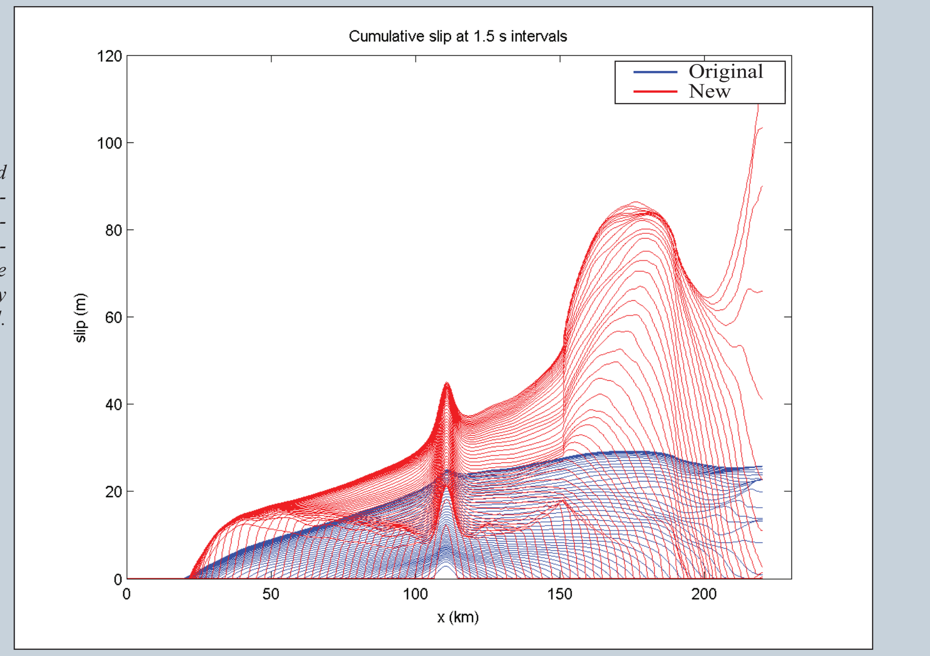


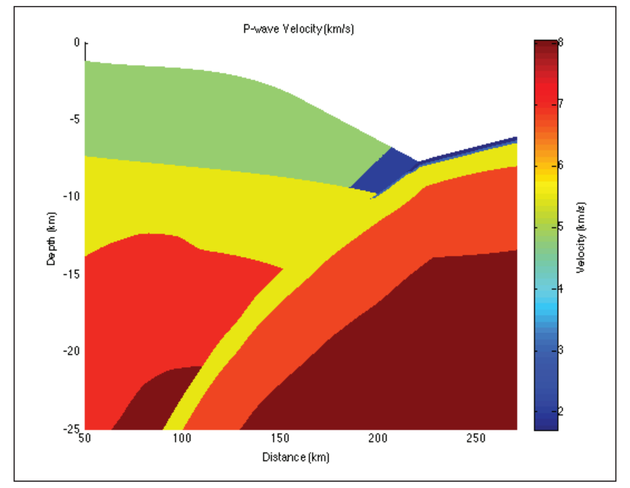
Fig. 9: Revised P-wave velocity and structure simulating low-rigidity off-fault material.

Fig. 10: Cumulative slip (plotted every 5 s) using the original parameters (blue) and the new parameters (red). There is a significant increase in the slip when the rupture encounters the low rigidity material.



Future Work

Fig. 11: P-wave velocity model defining a low-rigidity frontal prism and thin layer of subducting sediments while maintaining original material properties in other regions.



Effects of compliant wedge and subducting sediments:

- Use original material parameters of Kozdon and Dunham (2013) but include a low-rigidity frontal prism and a thin layer of subducting sediments.
- Anticipate an increase in the model slip over the original model but not at the magnitudes seen in the initial revision
- Examine the effects of the frontal prism and subducting sediments combined and separately

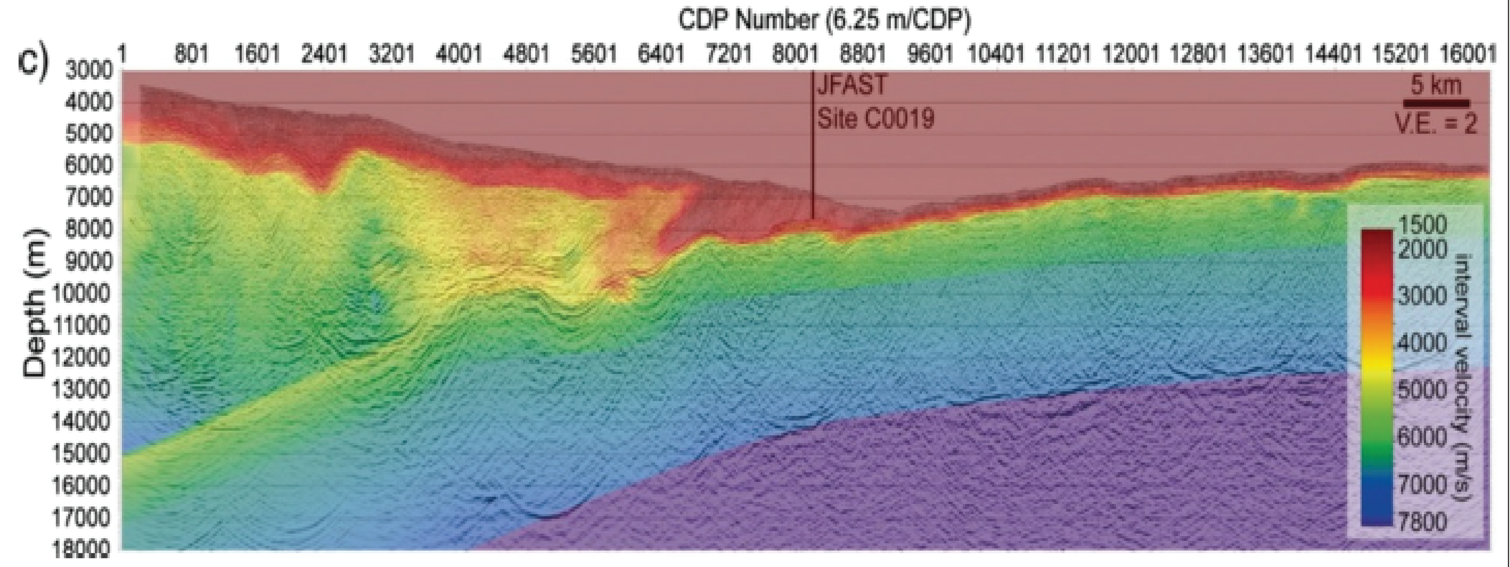


Fig. 12: Velocity model of the JFAST site overlain on PSDM seismic section from Nakamura et al. (2014). Velocity model will be used to determine the rigidity of the subduction zone.

Detailed model of the Japan Trench:

- Use velocity model from Nakamura et al. (2014) and laboratory measurements from IODP Exp. 343 and earlier ODP expeditions to estimate P-wave velocity near the trench.
- Estimate S-wave velocity and density using tomography and available core measurements

Acknowledgements

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