Using P- to S- wave conversions from controlled sources to determine the shear-wave velocity structure along Hikurangi Margin Forearc, New Zealand

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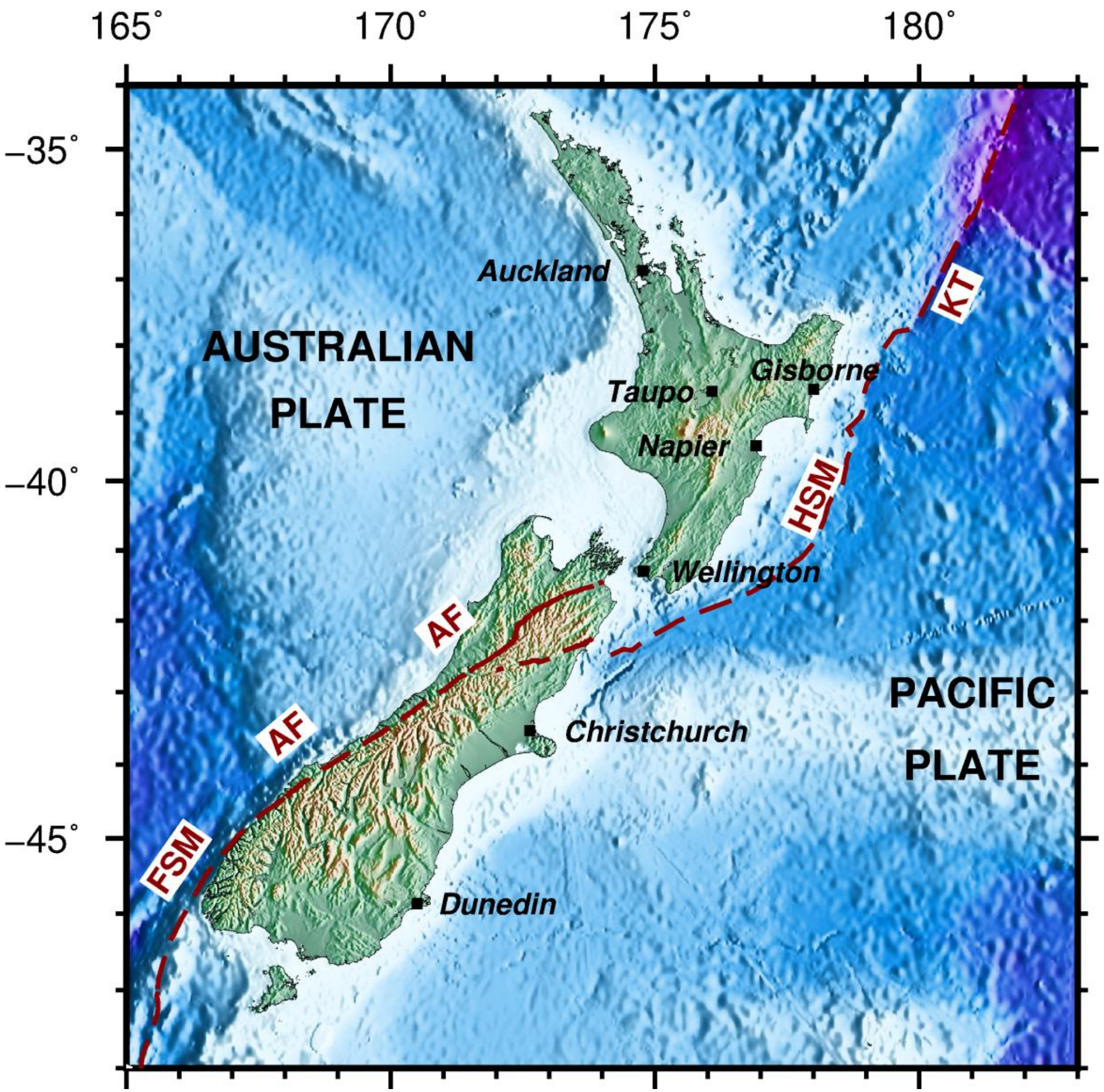
Introduction

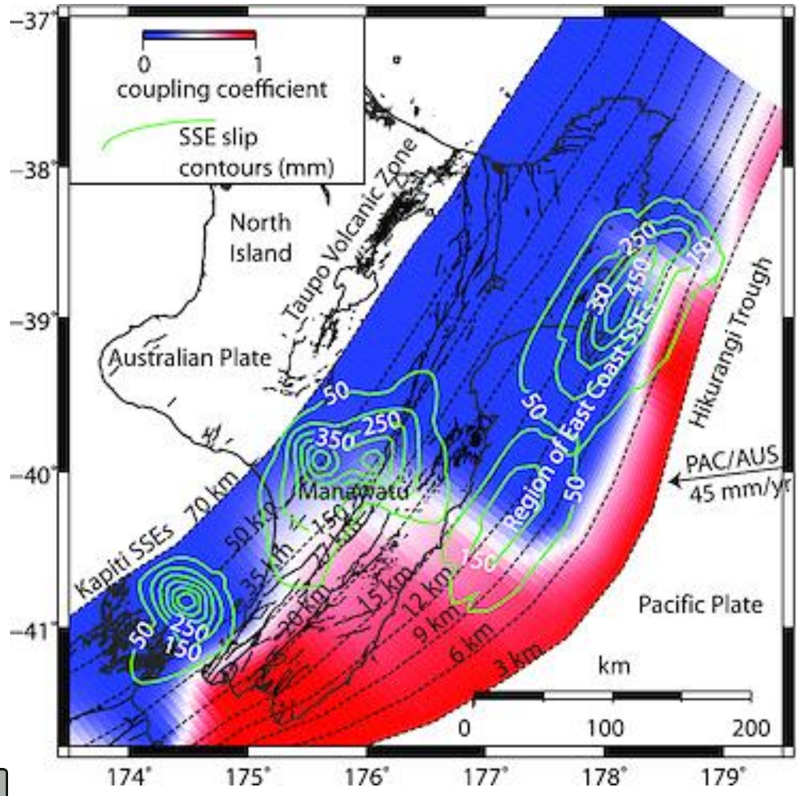
- Hikurangi margin marks the subduction of the Pacific Plate under the Australian Plate off the east coast of the North Island of New Zealand.
- Geodetic observations indicate along-strike variations in subduction-thrust slip behavior along the Hikurangi margin.
  - Subduction-thrust of the southern segment of the margin is locked on the 30-100-year scale
  - In the northern segment it displays periodic slow-slip on the 1-2-year scale.



Tectonic setting around New Zealand.
AF-Alpine Fault
FSM-Fiordland subduction margin
HSM-Hikurangi subduction margin
KT-Kermadec Trench

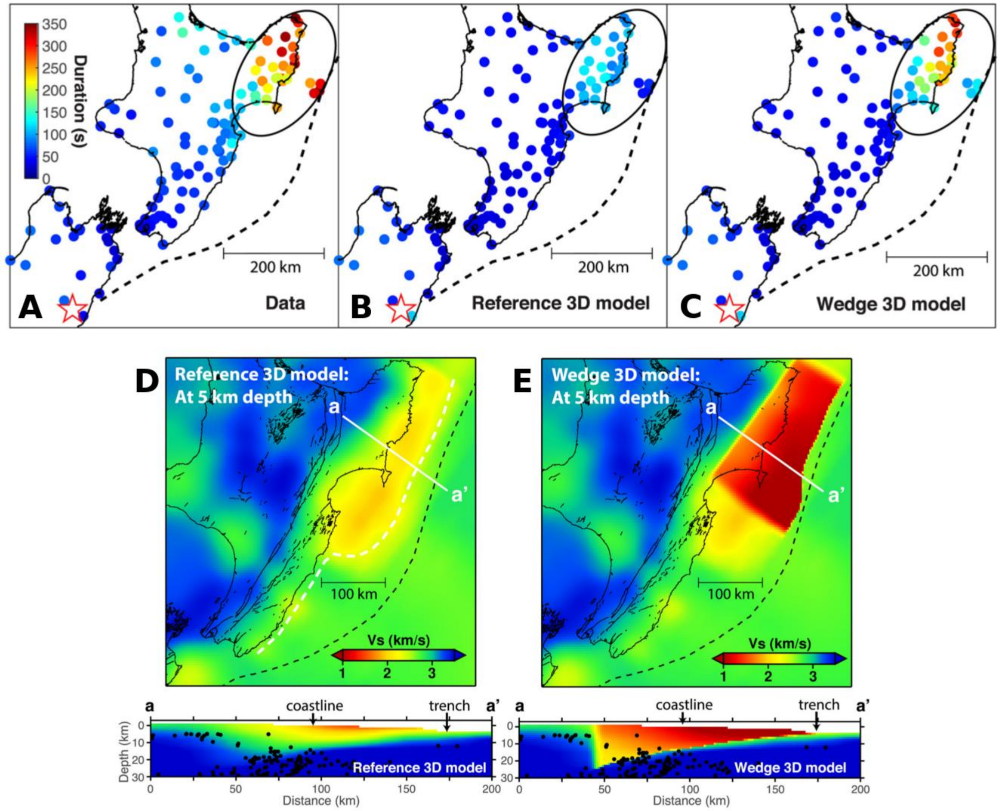
Context and Rationale

- Along-strike variation in subduction thrust-slip behavior
  - Hypothesised to be due to spatial variations in porosity, potentially linked with elevated pore-pressure



Wallace et al. (2012)

- Ultra-long duration seismic ground motion in the northern Hikurangi margin
  - Attributed to be due to a sediment wedge with low shear-wave speeds



Kaneko et al. (2019)

Seismic Wave Velocity

- V_P
  - Compressional (P) - wave velocity
  - Function of bulk modulus, shear modulus and density
  - Ambiguous indicator of a rock's lithology

- V_S
  - Shear (S) - wave velocity
  - Function of shear modulus and density

- V_P/V_S
  - Directly related to the Poisson's ratio
  - Diagnostic property of a rock's degree of consolidation and porosity
    - Consolidated sediments and crystalline rocks = 1.6 – 1.9
    - Unconsolidated sediments = 2.0 – 4.0

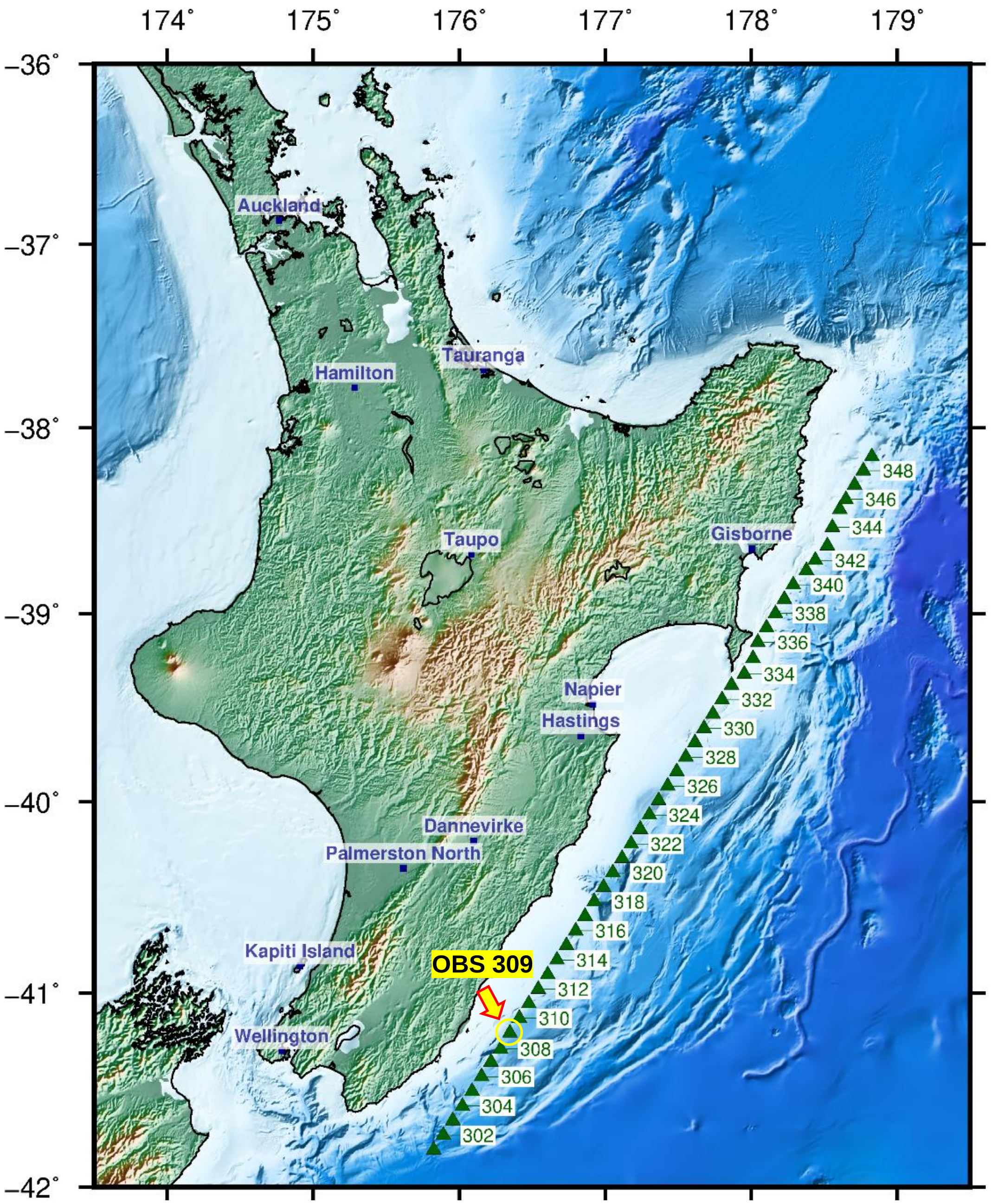
Mode-converted waves from controlled sources in OBS data

- Most controlled-source ocean bottom seismic studies focus on determining the compressional (P-) wave velocity structure.
- By identifying mode-converted waves in the ocean bottom seismometers, the shear (S-) wave velocity structure can be estimated.
- V_P/V_S ratio can be determined more accurately than passive-source seismic tomographic methods.
  - Time and location of controlled-sources known accurately from GPS clocks.
- Uncertainties can be quantified.
- Closely spaced controlled-sources provide higher resolution and better ray coverage in offshore regions.

Controlled-source Seismic Data

Seismogenesis at Hikurangi Integrated Research Experiment (SHIRE)

- Controlled-source seismic data acquired in 2017 by *R/V Marcus G Langseth* and *R/V Tangaroa*
- 49 ocean bottom seismometers (OBS) of SHIRE03 transect along Hikurangi forearc
  - Multicomponent
    - Triaxial seismometer
    - Hydrophone
  - ~10 km spacing along Hikurangi forearc
- Multichannel seismic (MCS) acquisition
  - 12.7 km long streamer
  - Airgun source spaced 50 - 100 m



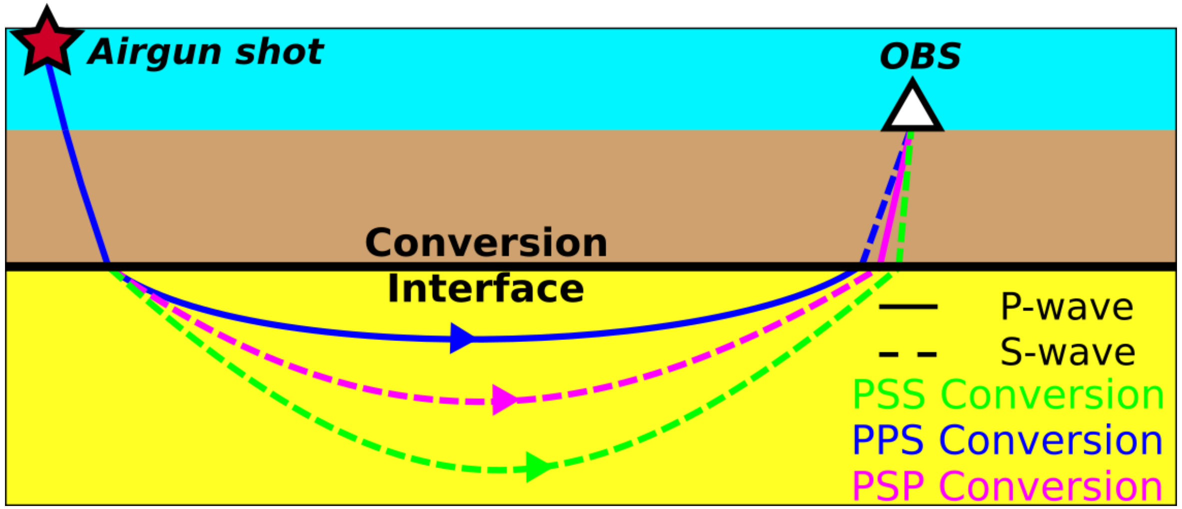
Ocean bottom seismometer stations along SHIRE03 transect

Methodology

- **Processing OBS gathers**
  - Determining orientation of horizontal components of each OBS
  - Rotation of the horizontal components into radial and transverse components
- **Improving signal to noise ratio**
  - Bandpass filtering (1-20 Hz)
  - Automatic gain control
  - Predictive deconvolution
- **Identification of mode-converted waves**
- **Estimation of V_P/V_S**

Types of mode-converted waves

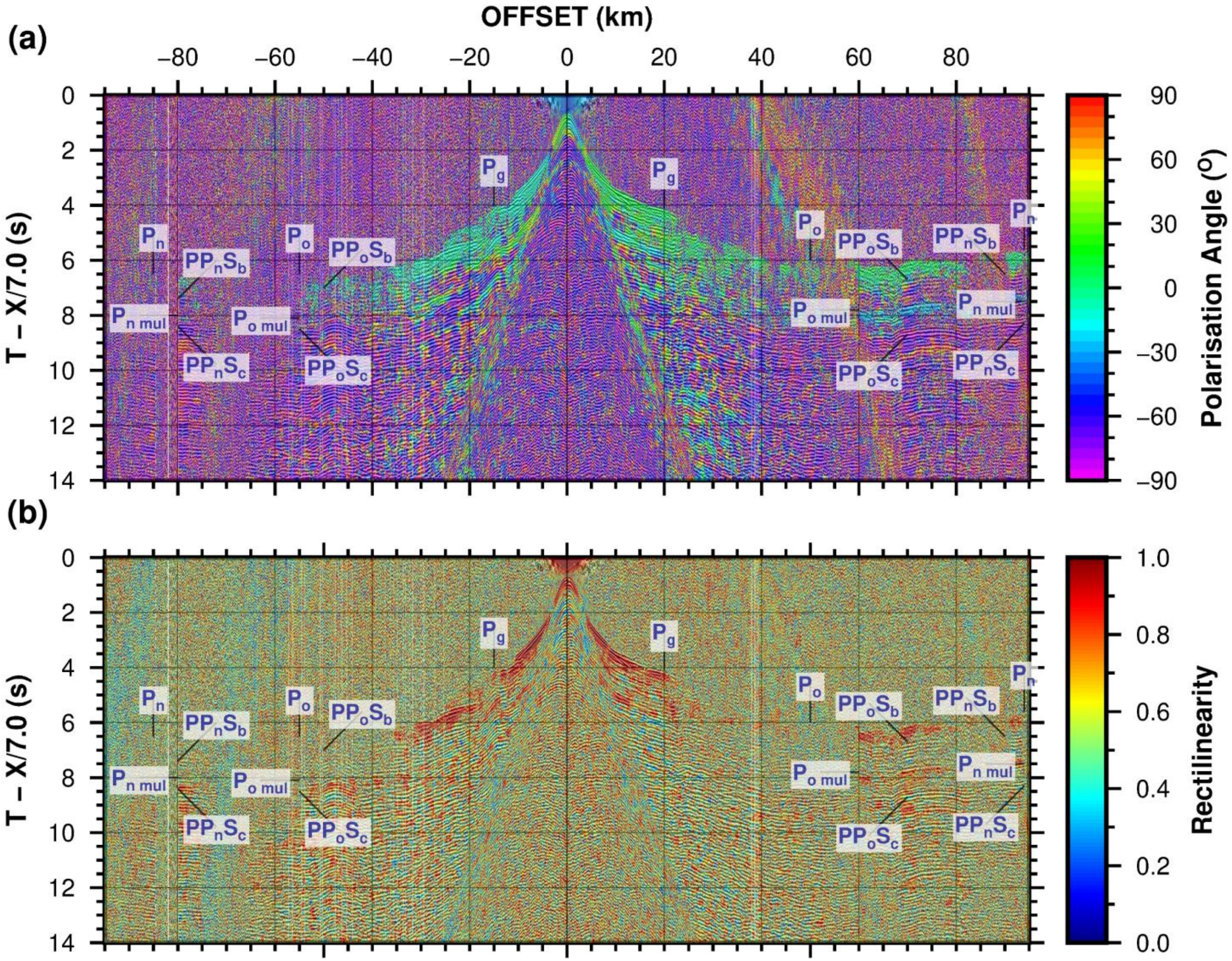
- **PSS**
  - Down-going P-wave converts to S-wave at an interface
  - Slow apparent velocity
  - Not recorded by hydrophone
- **PPS**
  - Up-going P-wave converts to S-wave at an interface
  - Lags behind the P-phase
  - Same apparent velocity as P-phase
  - Not recorded by hydrophone
- **PSP**
  - Down-going P-wave converts to an S-wave at an interface and again to P-wave on its way up to the OBS
  - Slower apparent velocity
  - Recorded by hydrophone



Types of mode-converted waves observable in an ocean bottom seismometer from airgun sources

Identification of mode-converted waves

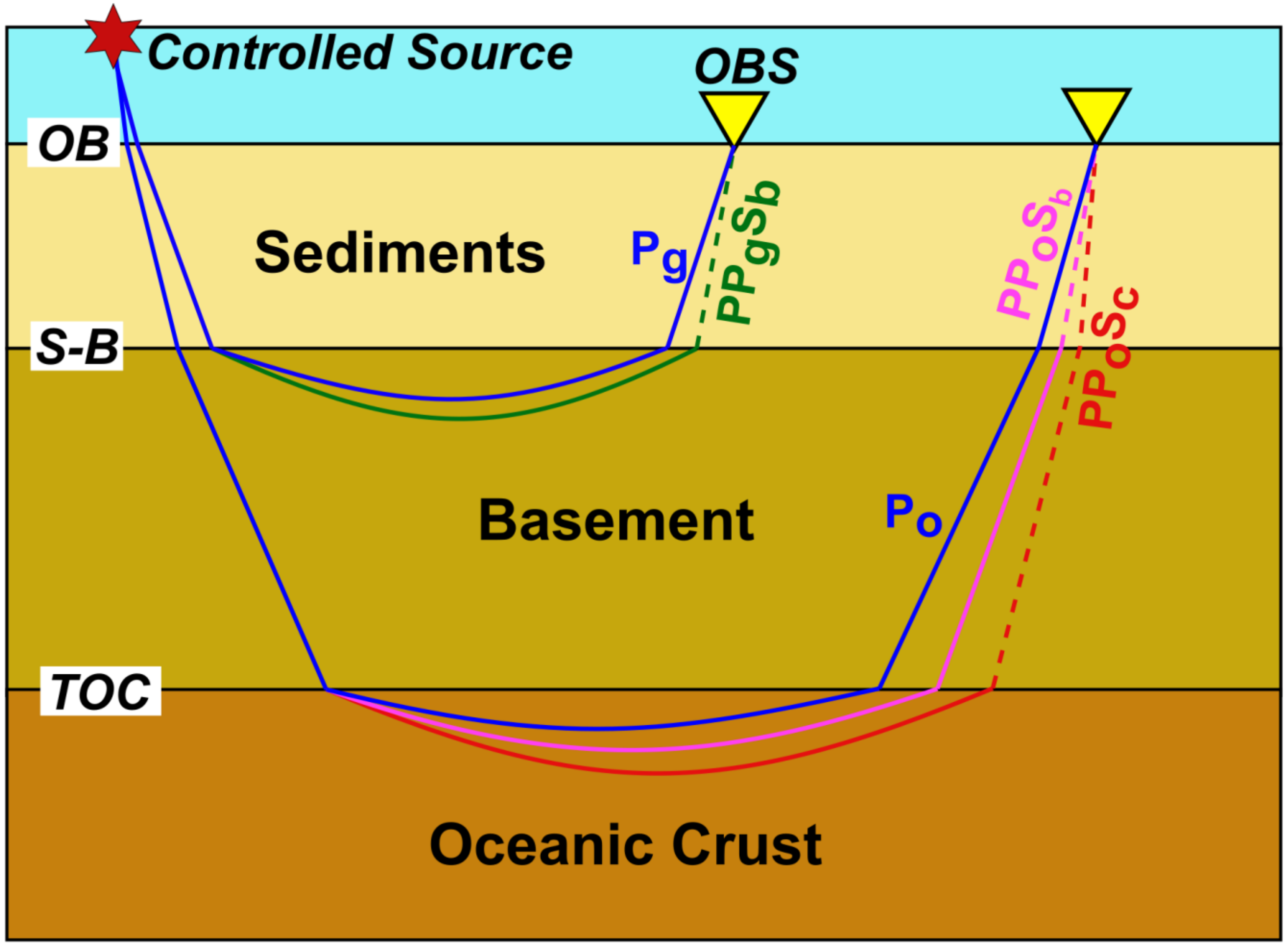
- **Mode converted waves are identified in the radial and transverse components**
- **Following approaches are used to identify different mode-converted waves**
  - **Polarisation angle of arrivals**
    - A measure of the polarisation angle of the particle motion from the three seismograph components (Flinn, 1965)
    - Distinguish incoming S-waves to OBS
      - Incoming S-waves have higher polarization angles (e.g. PP_nS_b)
  - **Rectilinearity of arrivals**
    - A measure of the the linearity of the particle motion from the three seismograph components.
    - Can be define as 1 – ellipticity (Flinn, 1965)
    - Distinguish water column multiples
      - Water column multiples are linear (e.g. P_o mul)
  - **Hydrophone component**
    - Does not record incoming S-waves
  - **Apparent velocity**
    - Horizontal slowness
    - Identify S-wave refractions



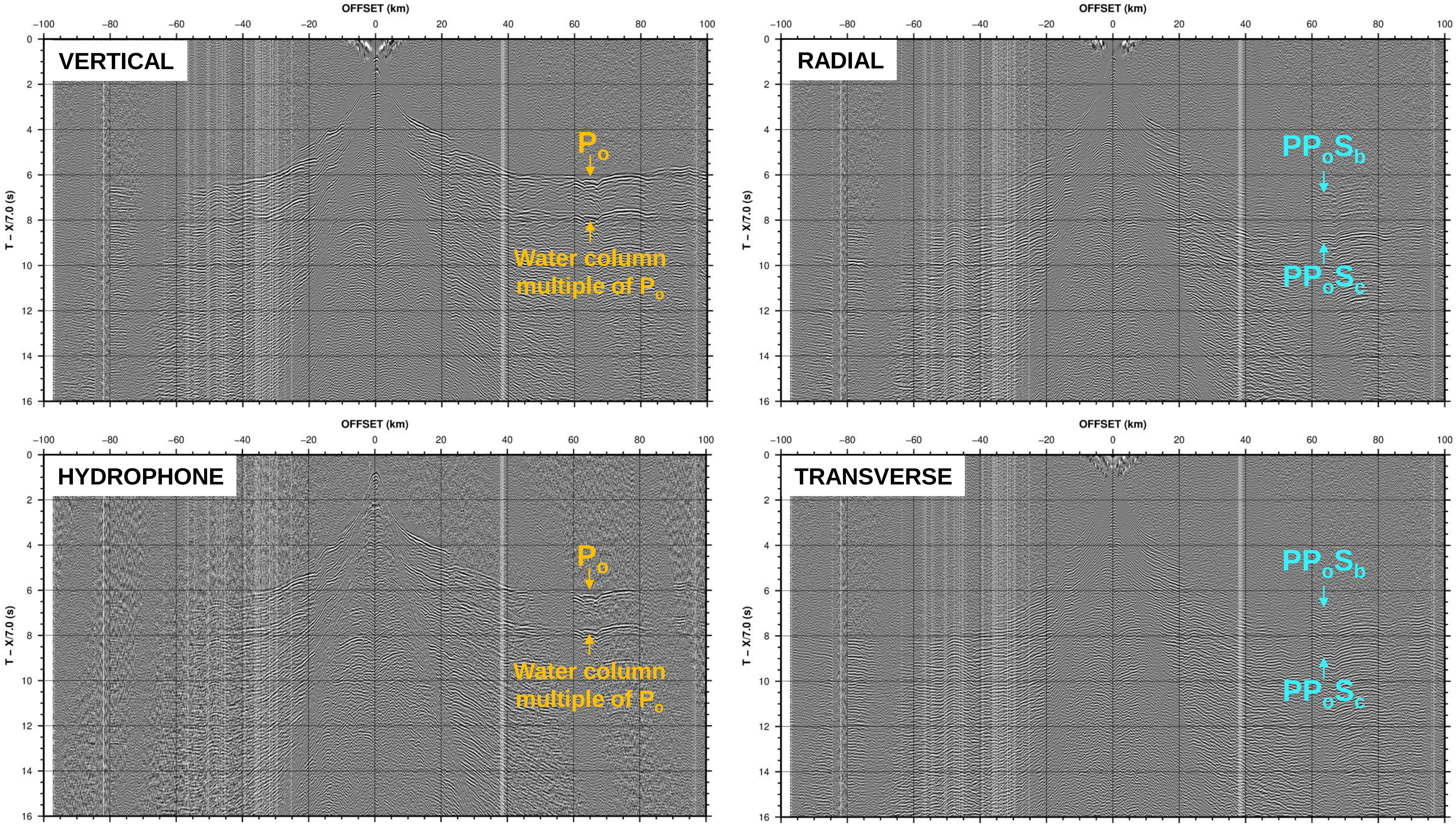
Polarisation angles (top) and rectilinearity (bottom) of the arrivals windowed every 50 msec, overlain on top of the radial component at OBS309

Identified mode-converted phases

- **PPS Converted Waves**
  - Can be used to estimate V_P/V_S above the converting interface
    - PP_gS_b
    - PP_oS_b
    - PP_oS_c
- **PSS Converted Waves**
  - Some hardly distinguishable candidates



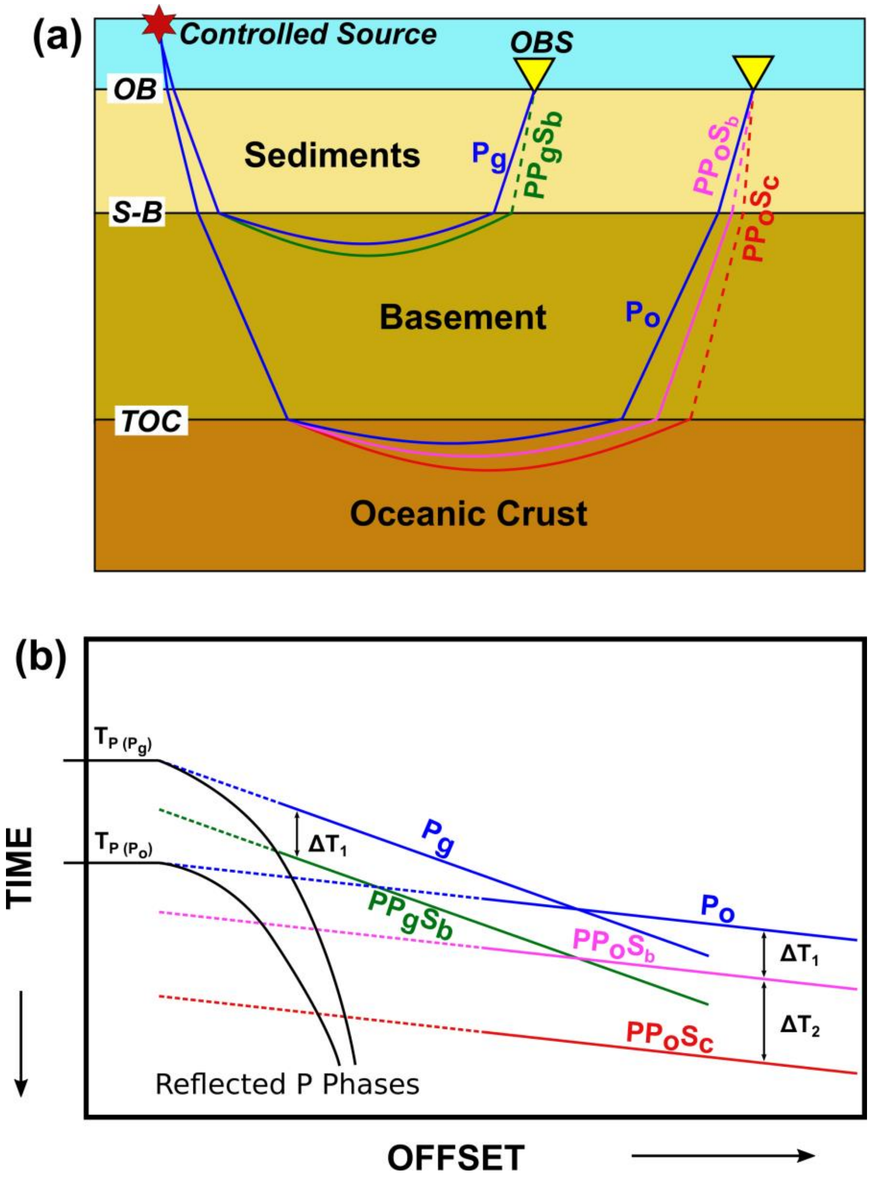
OB = Ocean Bottom, **S-B** = Sediment-Basement, **TOC** = Top of Oceanic Crust



OBS gather records of vertical, hydrophone, radial and transverse components at OBS station 309

Average V_P/V_S from PPS phases

- $\dfrac{V_P}{V_S} = \dfrac{2\Delta T+(t_p - t_{psf})}{(t_p - t_{psf})}$ (Tsuji et al., 2011)
    - ΔT = Time lag between P phase and PPS phase
    - t_p = Zero offset travel time of P phase
    - t_{psf} = Zero offset sea-floor reflection time

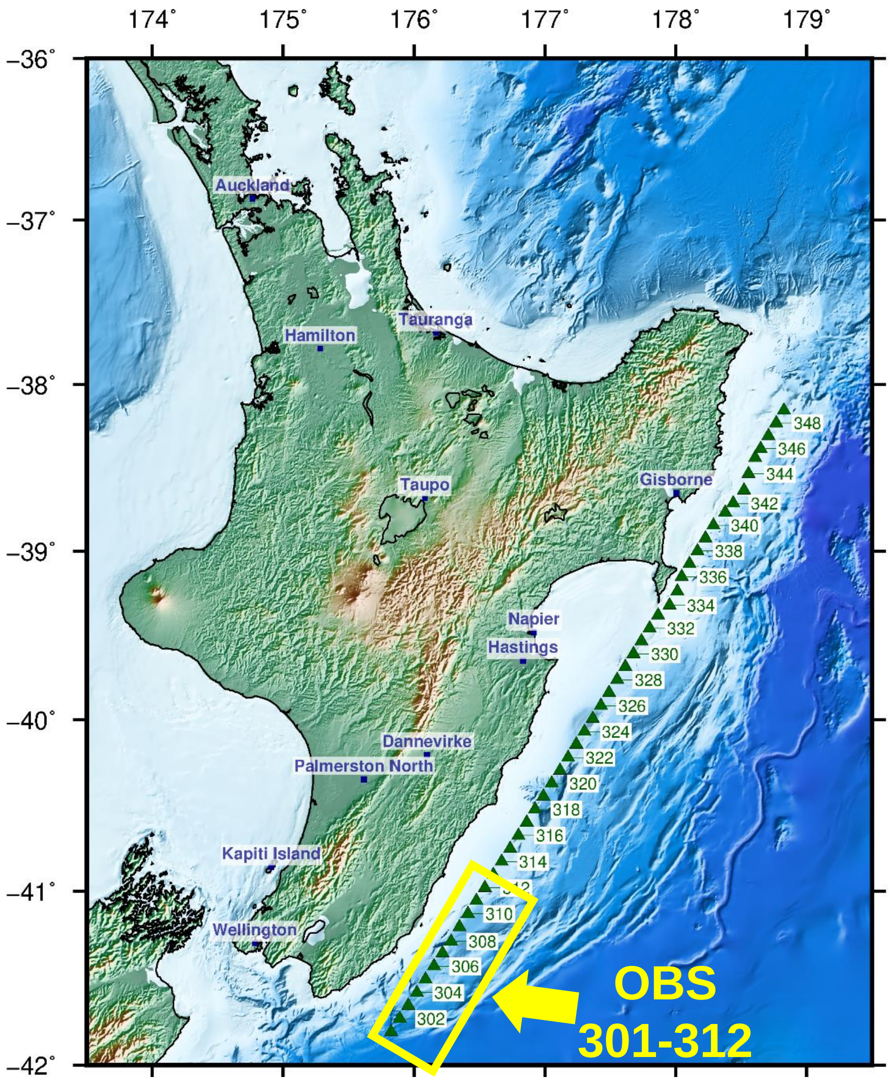


Results and Discussion

- **Average V_P/V_S of the forearc in the southern Hikurangi margin**
  - **≈1.70 (between OBS301-312)**
  - **Indicates the presence of consolidated sediments with low pore-pressure**
  - Determined from the time lag of the observed PPS converted waves
  - Impedance contrasts at the top of oceanic crust and the sediment-basement interface for an up-going wave are sufficient to generate S-waves

- **PSS converted waves**
  - Were not observed
  - Impedance contrasts at the interfaces for a down-going wave are not sufficient to generate S-waves

- **Next steps …**
  - Extending the study to the north to estimate of V_P/V_S in the northern Hikurangi forearc



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