Seismic Imaging, Arc Magamtism and Megathrust Earthquake under the Western Pacific Subduction Zone

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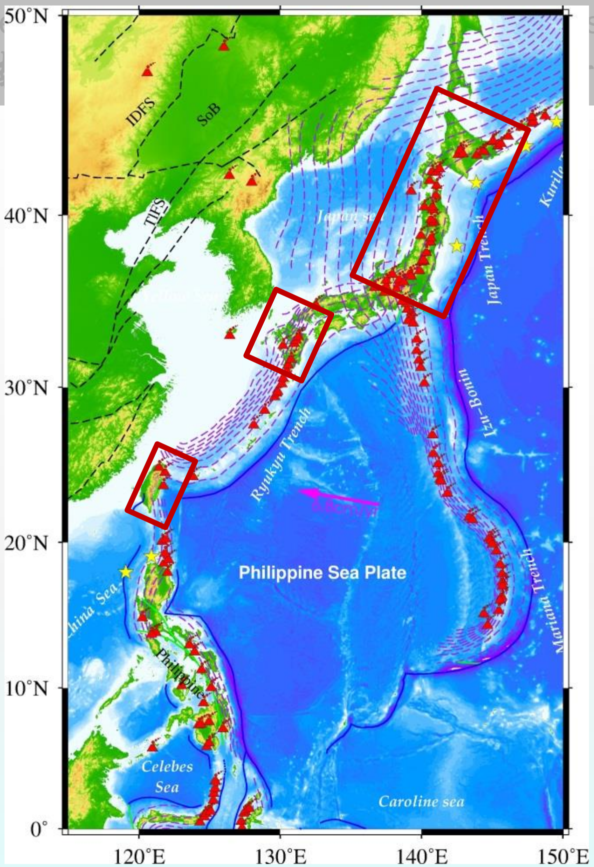
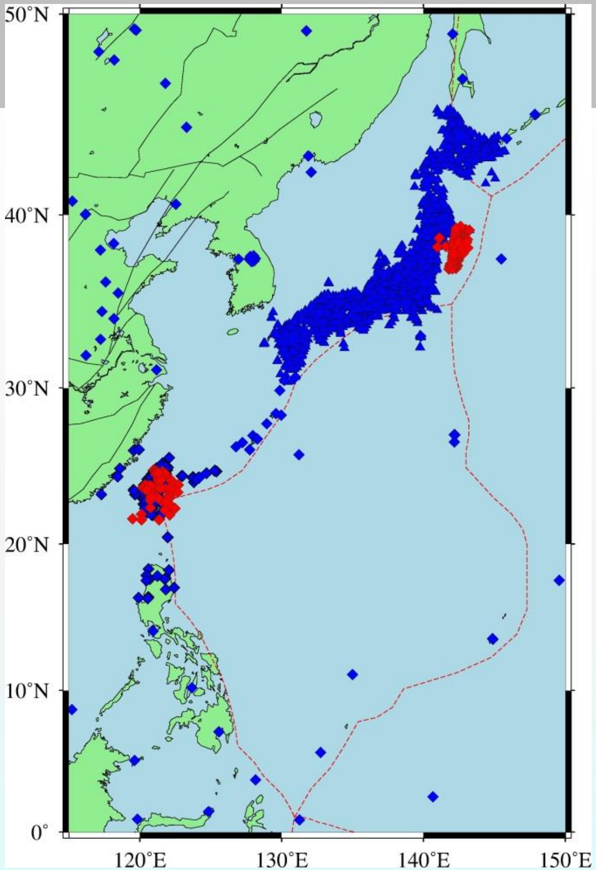
Motivation

Arc magmatism and megathrust earthquake occurrence in a subduction zone are deemed to attribute to structural heterogeneities, fluid contents, depth of subducting oceanic crust, and etc. However, how these factors affect them is unclear. The West Pacific subduction zone is regarded as one of the best Laboratory for seismologists to examine these processes due to the densest seismic networks recording numerous earthquakes.





Tectonic map (left) and seismic stations (right) of the western Pacific subduction zone. Red triangles indicate active volcanoes and yellow stars show the great earthquakes (M>8.0). Red dashed line show isobath of upper interface of the subducting plates. Blue triangles and red squares show permanent and temporary seismic stations, respectively.

Methodology

To obtain the stable solutions of Vp, Vs and Vp/Vs (or Poisson's ratio, σ) in the study region, we applied a joint inversion method of seismic velocity and Vp/Vs ratio for the well selected travel times of the P and S-wave source-receiver pairs. Following is the essence of the Vp and Vp/Vs (or σ) tomographic inversion. The travel time (t_p) of P wave from a source to a receiver can be written as

$$t_p = \int_p s_p dl_p = \int_p s_p^{ref}(1+q)dl_p = t_p^{ref} + \int_p q s_p^{ref} dl_p \qquad (1)$$

where s_p is P-wave slowness at a raypath increment dl_p, q is the first-order perturbation in s_p from its reference value s_p^{ref}, and t_p^{ref} is the reference P-wave travel time calculated with s_p^{ref}. The travel time (t_s) of S wave can be written as

$$t_s = \int_s \frac{S_s}{S_p} s_p dl_s = \int_s \left[\left(\frac{S_s}{S_p}\right)^{ref}(1+r) \right] [s_p^{ref}(1+q)] dl_s$$

$$\approx \int_s \left(\frac{S_s}{S_p}\right)^{ref} s_p^{ref} dl_s + \int_s \left(\frac{S_s}{S_p}\right)^{ref} s_p^{ref}(q+r)dl_s$$

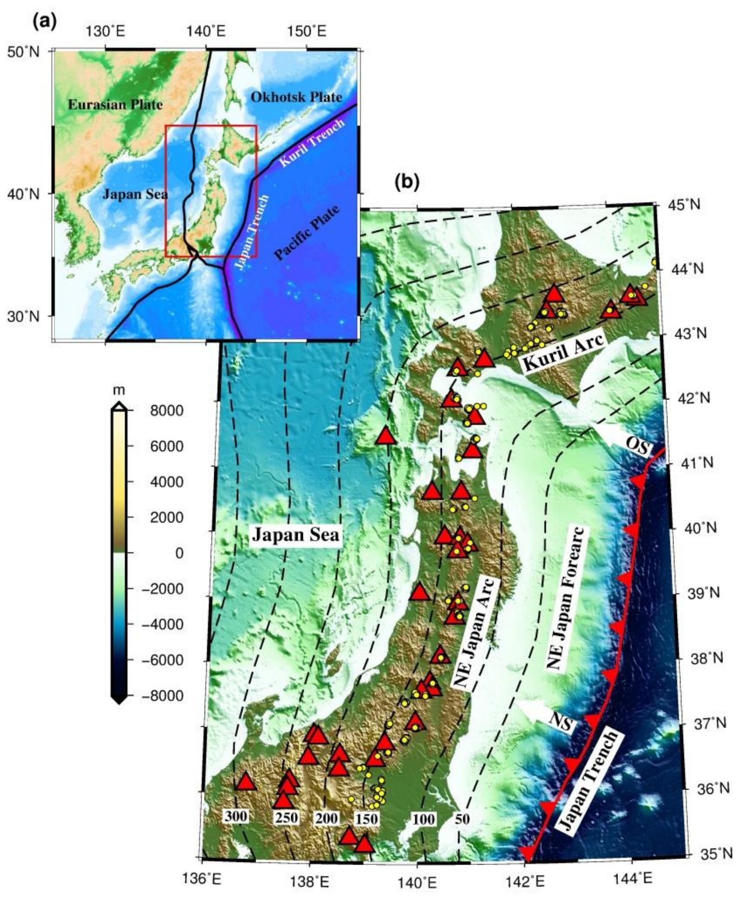
$$= \int_s s_s^{ref} dl_s + \int_s s_s^{ref}(q+r)dl_s$$

$$= t_s^{ref} + \int_s s_s^{ref}(q+r)dl_s \qquad (2)$$

To solve (1) and (2) simultaneously for two unknowns q and r using the residual data t_p-t_p^{ref} and t_s- t_s^{ref} for the same source-receiver pairs. Note that in (1) is the relative P-wave slowness perturbation along the reference P-wave ray-path whereas q in (2) is that along the reference S-wave ray-path. Solving Eqs. (1) and (2) for q and r is equivalent to the simultaneous inversion of the P and S residuals for the 3-D structures of Vp and Vp/Vs (or σ).

Seismic tomography in the NE Japan subduction zone

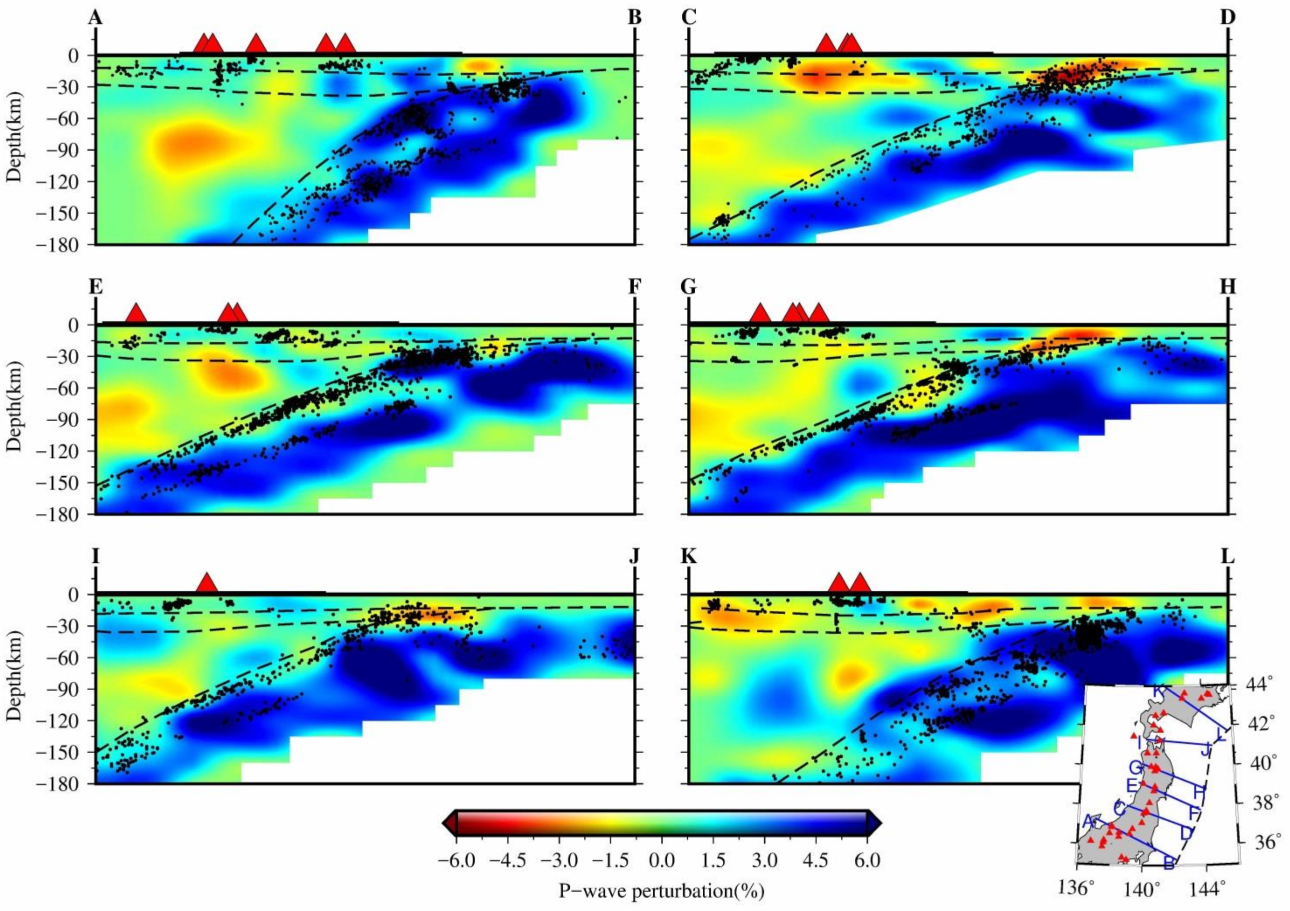
In this study, we determined seismic velocities and Vp/Vs ratio images behind the Japan Trench to reveal their comprehensive effects on melting relations of hydrated oceanic plate and arc magmatism in the mantle wedge. We seek to investigate the relationship of these parameter anomalies and the partial melting of the slab, which in turn affect the arc magmatism.



Profiles of P-wave velocity in the NE Japan subduction zone

Results & Discussions

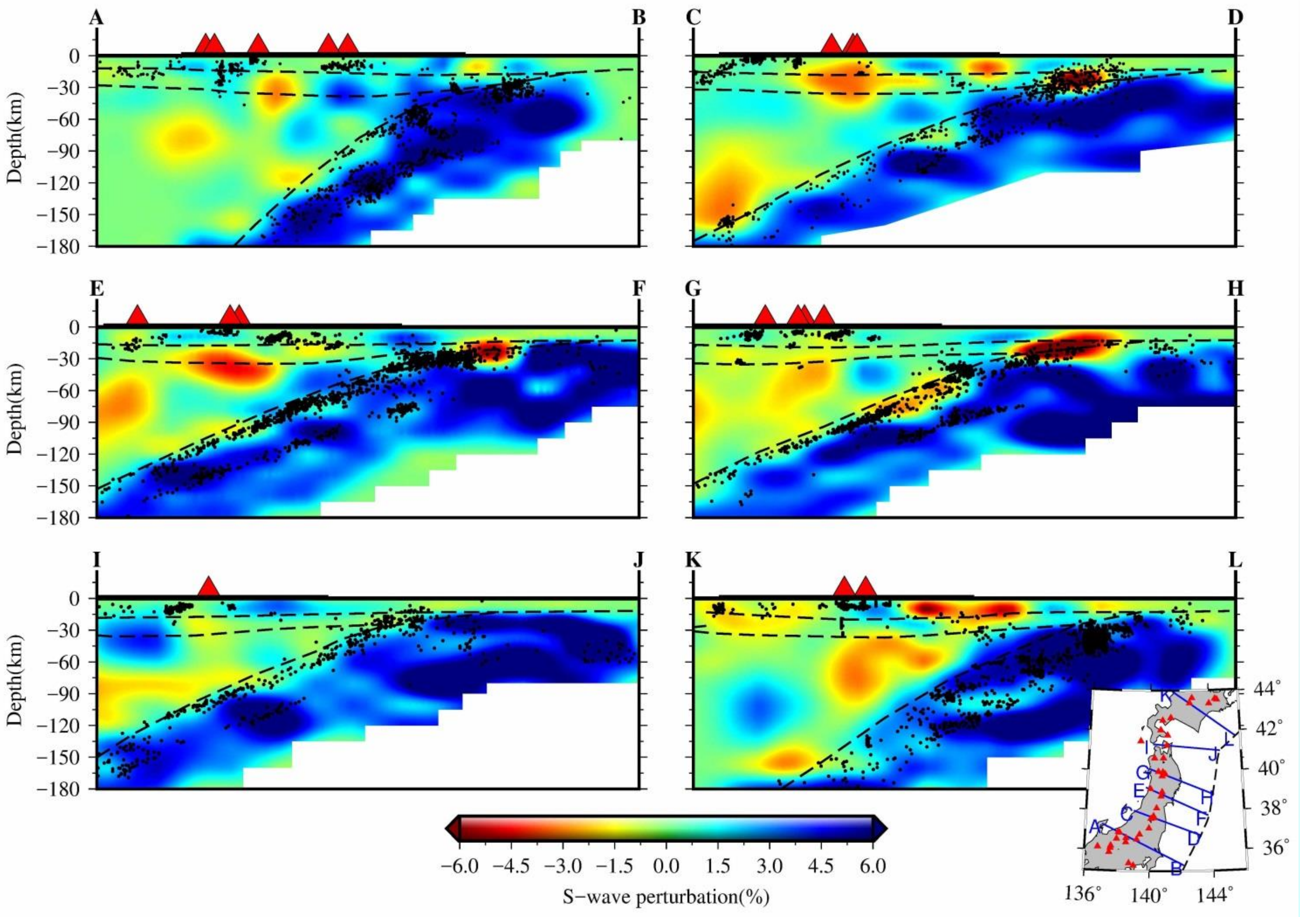
High-Vp anomalies of the cold subducting Pacific slab and low-Vp anomalies in the hot mantle wedge were imaged clearly; Strong slow velocity anomalies imaged continuously along the volcanic front are generally parallel to the down-dip direction of the subducting Pacific plate from the crust to the mantle wedge to a depth of ~150 km.



Profiles of S-wave velocity in the NE Japan subduction zone

Results & Discussions

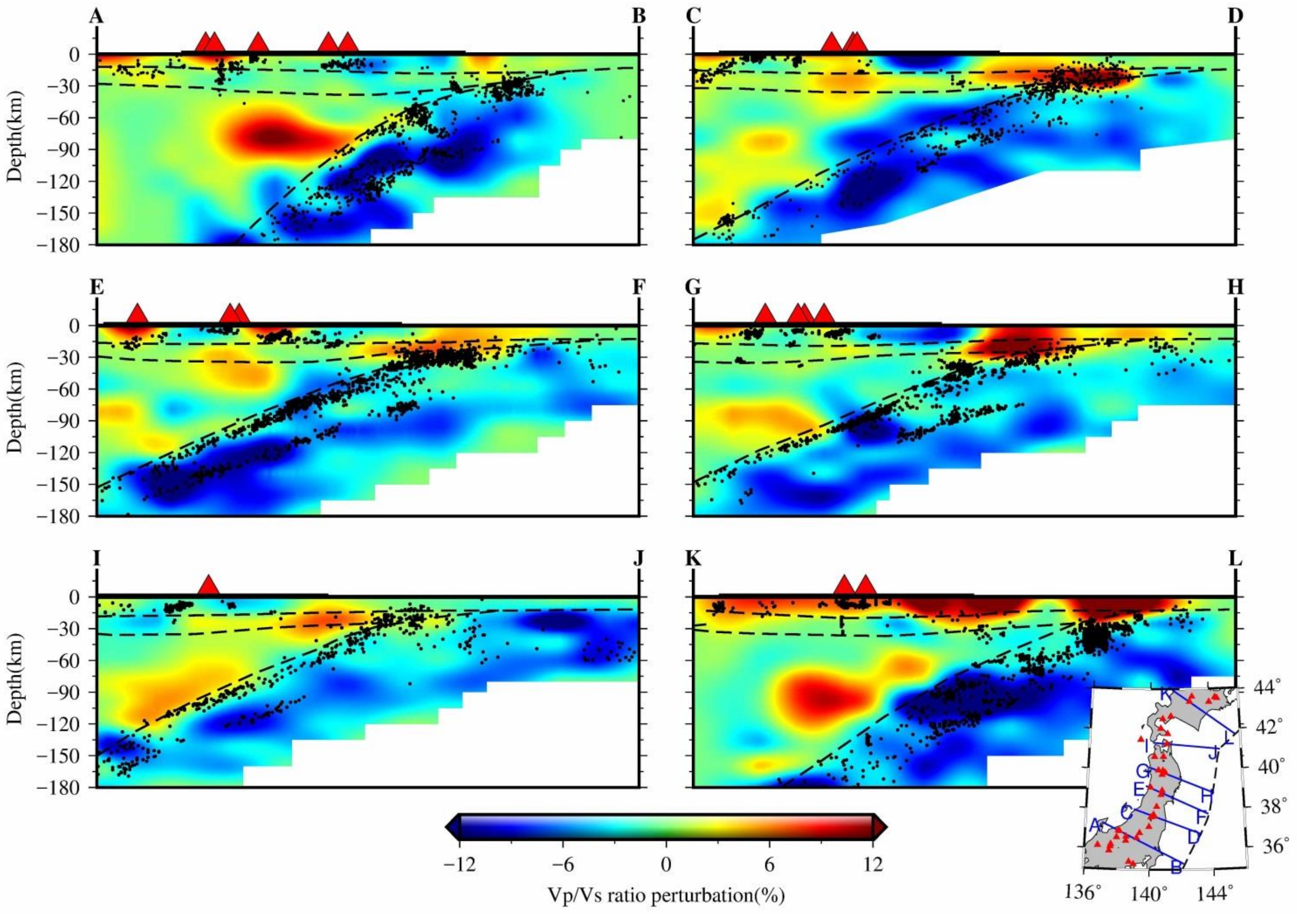
The S-wave and P-wave velocity images are similar to each other, although the Vs perturbations are larger than those of Vp. Strong low-Vs anomalies are imaged continuously along the volcanic front from the crust to the mantle wedge to a depth of ~150 km.



Profiles of Vp/Vs ratio in the NE Japan subduction zone

Results & Discussions

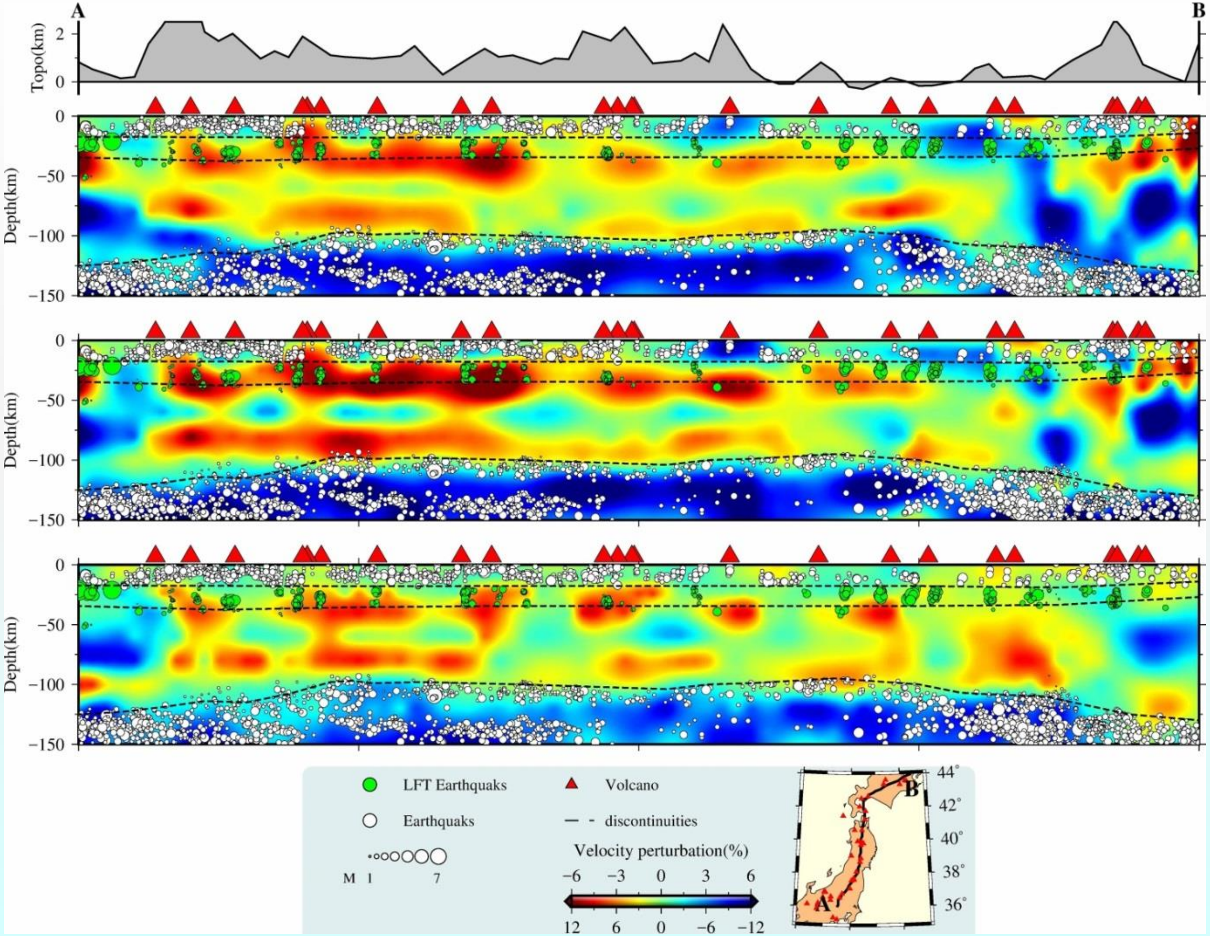
The jointly inverted Vp/Vs images show well consistence with the anomalous features of Vp and Vs structures. High-Vp/Vs anomalies are imaged continuously along the volcanic front from the crust to the mantle wedge to a depth of ~150 km. This low-V and high-Vp/Vs bodies in the mantle wedge might indicate melting or partial melting there.



Profiles along volcanic front in the NE Japan subduction zone

Results & Discussions

Strong low-V and high-Vp/Vs anomalies are clearly imaged under the island arc, indicating melting or partial melting associated with the arc magmatism in the mantle wedge of the NE Japan subduction zone. Most of the low-frequency-volcanic (LFV) earthquakes (green dots), occurred around the low-V and high-Vp/Vs bodies, reflecting the movement of the magma chamber.

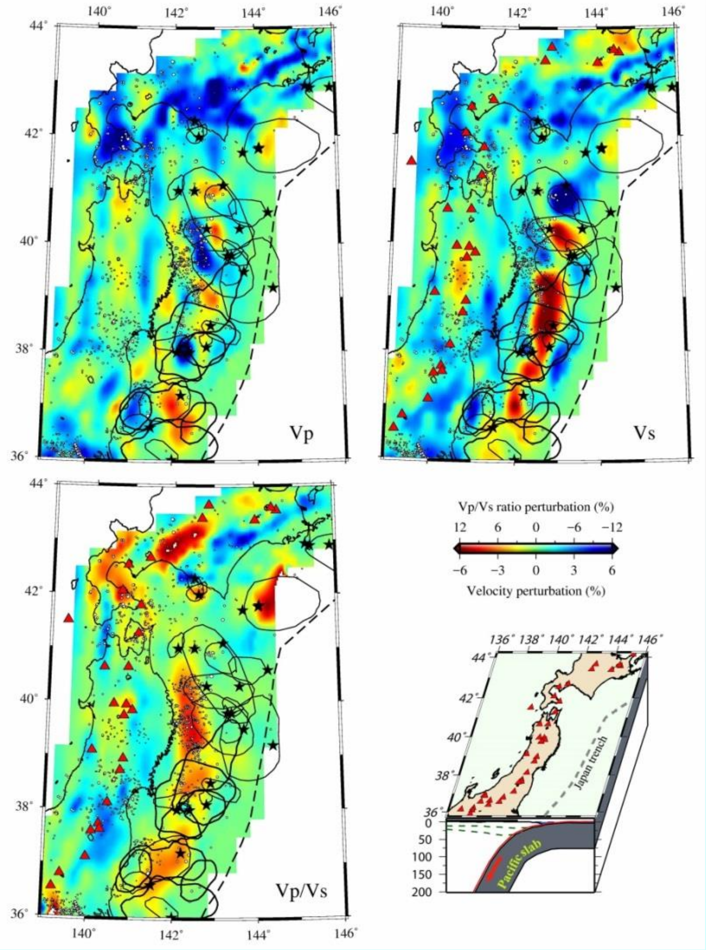


Seismic slices along the boundary of the subducting Pacific slab

Results & Discussions

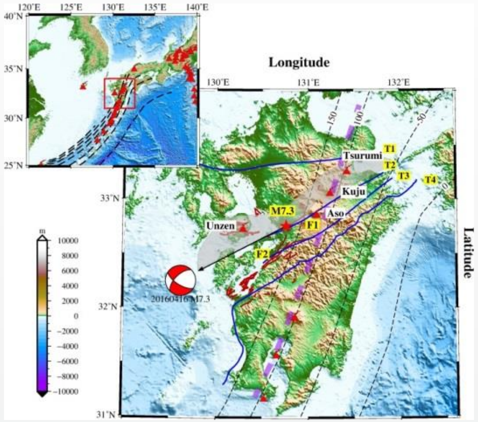
Red triangles denote active volcanoes along NE Japan and Kuril arcs. The contour lines show distribution of rupture areas of the great earthquakes (epicenters as black stars) (M≥7.5).

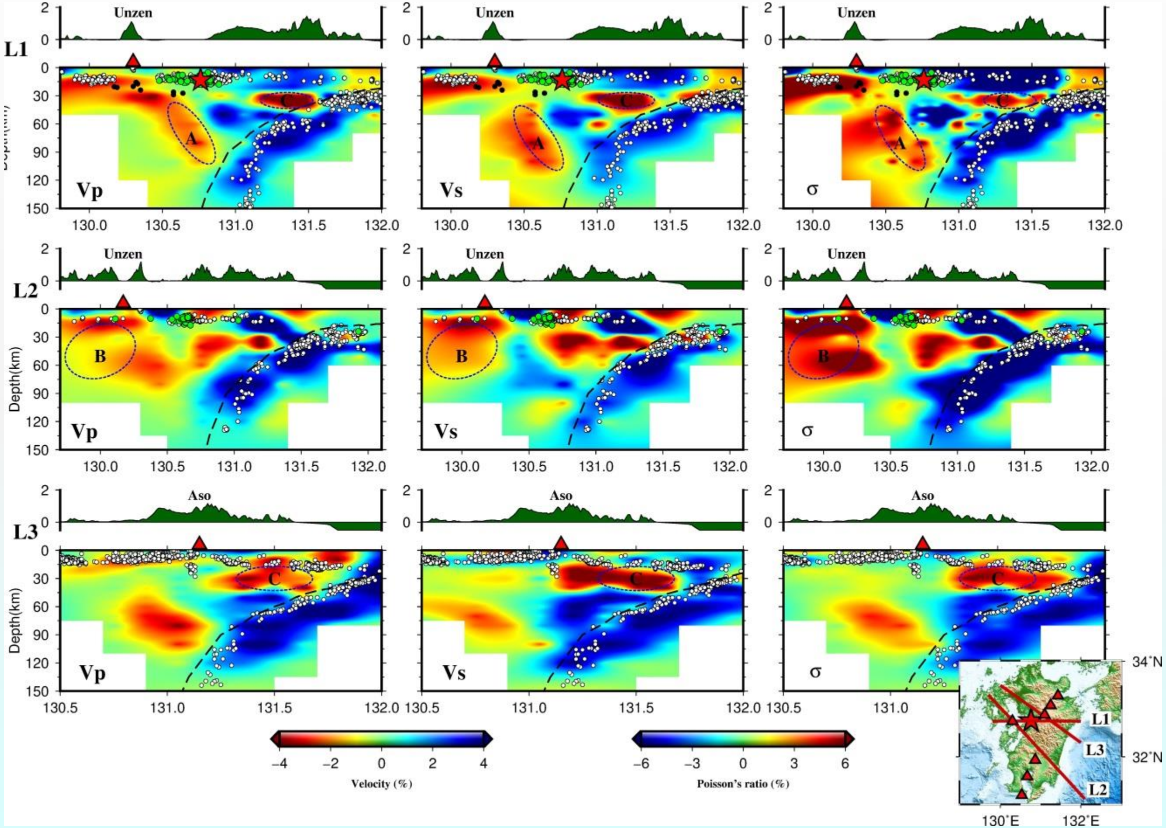
More than 95% of the great interplate earthquakes (M ≥ 7.5) occurred around the low-V and high-Vp/Vs zones, indicating weakly coupled parts of the subducting slab boundary. The high-V and low-Vp/Vs patches might reflect the asperity (strongly coupling) of upper interface of the subducting Pacific slab.



Seismic profiles in the Kyushu subduction zone

Results & Discussions



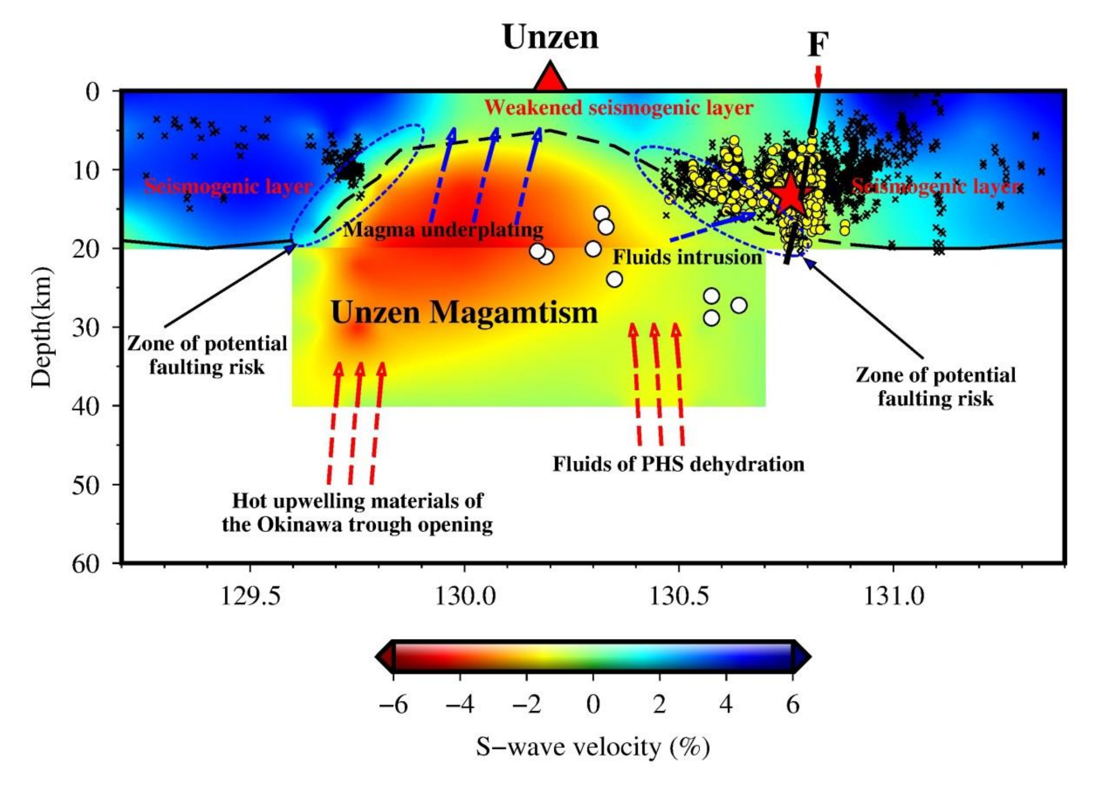


Two low-V and high-σ bodies under the Unzen volcano are clearly imaged in the mantle wedge, indicating that the magmatism might have been enrichened both by extensive dehydration of the subducting Philippine Sea slab (body A) and hot mantle upwelling associated with opening of the Okinawa Trough (body B).

Original of the Unzen volcano in the Kyushu subduction zone

Results & Discussions

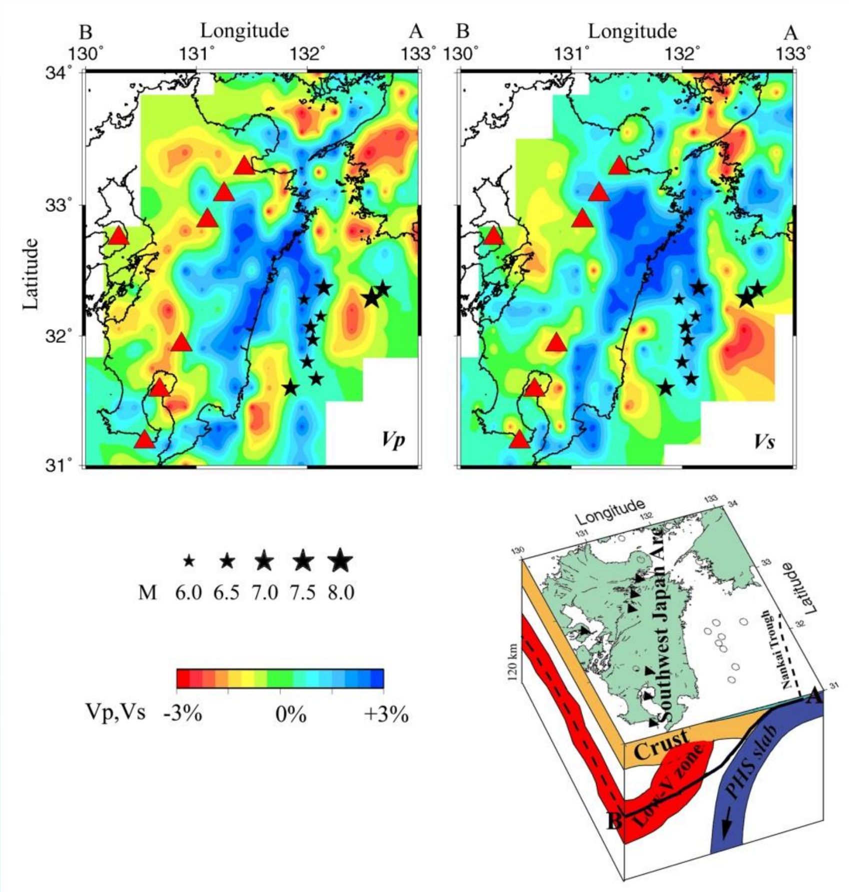
Low Vp, Vs, and high σ values under the Unzen volcano are the result of fluids and melting (or partial melting) associated with dehydration of the Philippine Sea slab and hot upwelling materials. These multiple-sources of fluids and/or melting would provide more abundant magma for Unzen magmatism than the other volcanism. Fluids associated with the Unzen magmatism intruding into the source area plays a key role in initiation of the 2016 Kumamoto earthquake (red star) and its rupture process.



Seismic slices along the boundary of the subducting PHS slab

Results & Discussions

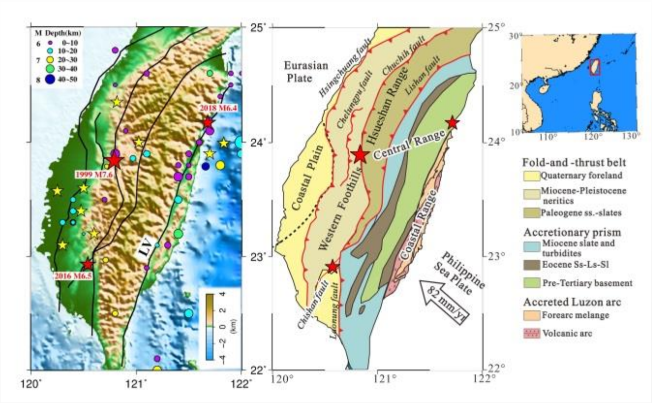
Most of the large interplate earthquakes (M ≥ 6.0) occurred around the low-velocity zones or within the high velocity zones during the period from 1923 to 1998, which inferred the existence of weakly coupled patches along the upper boundary of the subducting Philippine Sea slab . Similar features were revealed under the forearc area of NE Japan, which may reflect a common feature on the interplate coupling and on the spatial distribution of thrust earthquakes in subduction zones.



Seismic profiles in Taiwan subduction zone

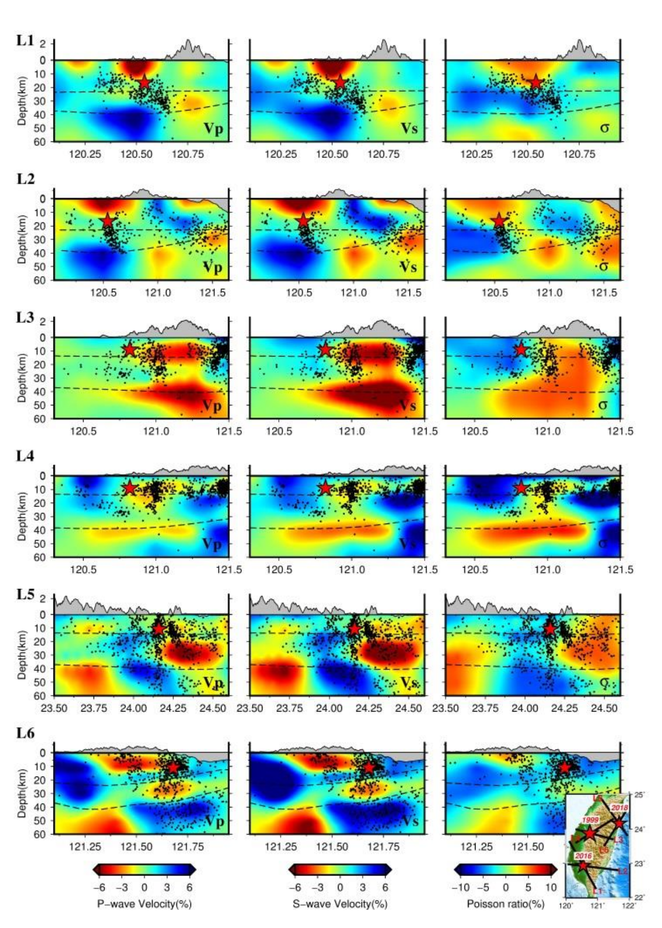
Results & Discussions

The observed low-Vp and low-Vs belt across the 2016 Meinung earthquake source (L1 & L2) presumably corresponds to the Oligocene-Pleistocene siliciclastic sequences accumulated in the western Taiwan foreland basin.



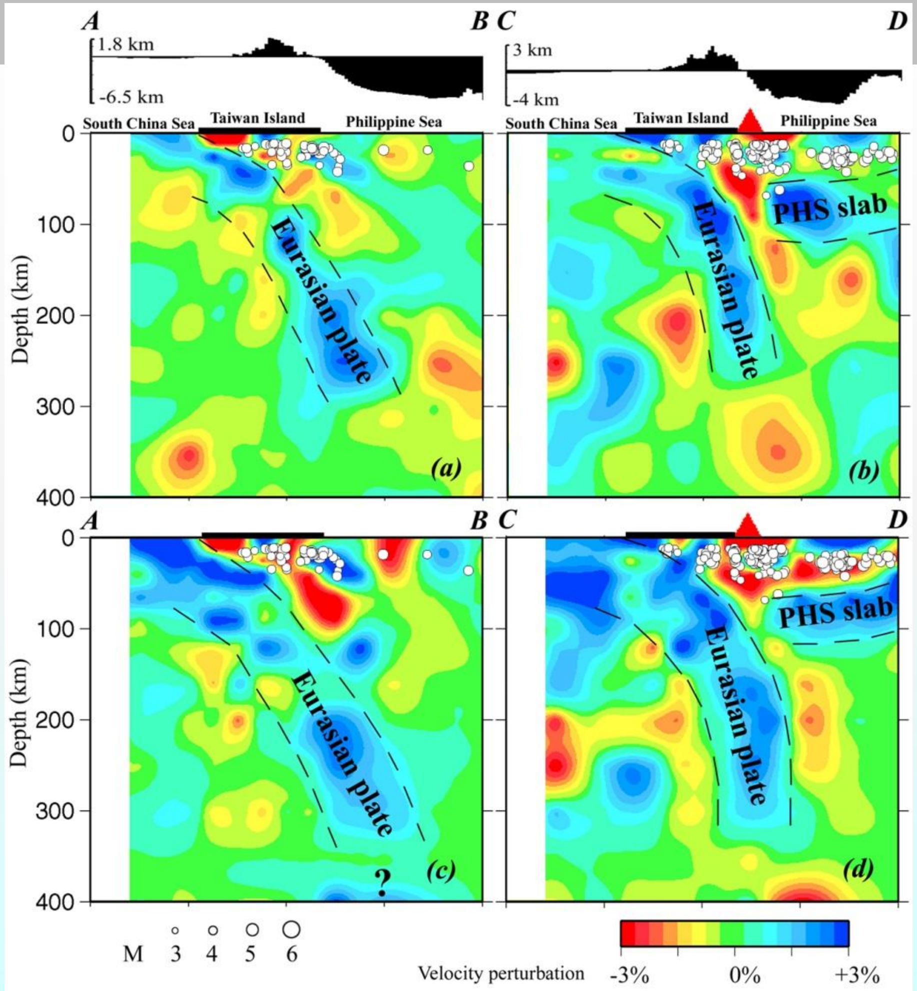
The 1999 Chi-Chi earthquake (L3 & L4) is between a prominent low-Vp, low-Vs and high-σ zone under the Central Range, reflecting the significant neotectonic uplift and shortening from the collision between Eurasia and Philippine Sea plates, and the relatively high-Vp, high-Vs, and low-σ zone beneath the Western Foothills.

The 2018 Hualien earthquake (L5 & L6) occurred on the edge of a sandwich-like structure with negative-positive-negative variations of V and σ in both lateral and vertical directions, indicating the source region may be caused by the structural variations from arc collapse to subduction in the E–W.



Results & Discussions

This down-going model of the Eurasian lithosphere implies that the tectonic framework of Taiwan has been changing from subduction in the south (profile AB) to collision in the north (profile CD), which provides geophysical evidence supporting the previous proposed models. The subducted Eurasian lithosphere colliding with the subducted Philippine Sea plate would have contributed to the mountain building, active seismicity and crustal deformation in the study region due to the lower part of the Eurasian continental plate subducted beneath South Taiwan.



Summary Remarks

- ✓ High resolution 3-D seismic images were determined by inverting a large number of arrival times of the P and S wave source-receiver pairs along the western Pacific subduction zone.

- ✓ A weakened layer with ~10 km thickness of low-Vp, Vs, high-Vp/Vs extended downwards ~150 km depths along the subducting Pacific slab upper interface is revealed, indicating partial melting of the subducted oceanic crust.

- ✓ Strong slow-V and high-Vp/Vs anomalies are revealed at depths of 60~150 km underneath the volcanic front, which are caused mainly by melting or partial melting of the mantle wedge associated with fluids released from extensive dehydration of the subducting oceanic crust.

- ✓ Most of the great interplate earthquakes (M ≥ 7.5) occurred around the low-V and high-Vp/Vs zones, indicating weakly coupled parts of the subducting slab boundary.

- ✓ The dehydration process of the subducting oceanic crust play a fundmental role in both slab melting and arc magmatism under the western Pacific subduction zone.

Thank you