3D Subsurface Imaging Using Off Sanriku Ocean-bottom Distributed Acoustic Sensing (DAS) Cable Data, Japan

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Introduction

Marine sediment characterization holds significant importance for various applications in geotechnical engineering, seismic hazard assessment, and hydrocarbon exploration. Additionally, understanding the oceanic lithosphere structure in subduction settings is crucial for comprehending earthquake genesis and geodynamics. However, precise seismic subsurface imaging traditionally relies on costly active seismic surveys conducted during offshore campaigns, which are not only expensive but also limited in coverage. This limitation hinders our ability to comprehensively characterize marine sedimentary layers and deeper structures.

Many disciplines of earth research stand to benefit from the ability to utilize pre-existing communications fiber-optic networks as seismic arrays, providing tens of thousands of sensing locations in areas where seismologists have traditionally lacked access. Moreover, considering that the ocean covers 70% of the planet's surface, and seismometer coverage is limited to a few permanent ocean bottom seismometers, this idle and accessible infrastructure can be leveraged by DAS to fill many significant gaps in ocean-basin seismic coverage. The seismic tsunami observation system, deployed off the Sanriku region by the Earthquake Research Institute at the University of Tokyo in 1996, employs optical fiber for data transmission and incorporates Distributed Acoustic Sensing (DAS) technology with observations commencing in February 2019 (Shinohara et al., 2019 and 2022).

Recent advancements offer promising avenues for cost-effective solutions using Distributed Acoustic Sensing (DAS) recordings. Spica et al. (2020) and Fukushima et al. (2022) demonstrated the potential of ambient noise imaging for estimating 2D Vs structures in marine sediments. However, their studies were constrained to shallow depths and a limited 50 km cable length. To overcome these limitations, we carried out experiments utilizing ocean-bottom dark fibers for high-resolution 3D subsurface imaging using 3D finite-element travel-time tomography.

The DAS is an emerging technology where standard fiber-optic cables used for telecommunications are repurposed as a long series of single-component, in-line strain or strain-rate sensors with sensing point separations as small as 1 m or less. The DAS approach uses a laser interrogator unit at one end of the fiber that employs short pulses to illuminate the fiber and then performs high-rate optical interferometry of the Rayleigh backscattered light. The backscattered photons return to the interrogator unit at a rate that is proportional to how far they have traveled along the linear fiber. Distributed optic sensors use optical time-domain reflectometry (OTDR)- a series of pulses are transmitted into the fibre by an interrogator and the backscattered signal is detected, amplified and digitised. The retrieved phase shift is quasi- linearly proportional to the change in strain.

$$\epsilon_{xx} = \frac{\lambda}{4\,\pi n_c\,\xi L_G}\ \ \Delta\,\phi$$

where ϵ_{xx} is the principal strain for the x-direction, is the incident wavelength (~1500 nm) of used laser light in a vacuum, nc is the refraction index of a fiber, L_G is the gauge length, ξ is the optical-elastic coefficient for the fiber direction in isotropic media (usually set to 0.78), and ΔΦ is the phase of a DAS measurement.

Accurate shear-wave velocities obtained through high-resolution 3D travel time tomography are crucial for deciphering the rheology of the overriding plate, enhancing earthquake location accuracy, imaging deeper structures to understand geodynamics, and determining hypocenter positions with greater precision. Thus, the utilization of dark fibers holds immense promise in advancing our knowledge of marine sedimentary environments and subduction dynamics, while offering a practical and economical solution for oceanic subsurface imaging.

The Sanriku DAS cable lies over the Okhotsk Plate in northeastern Japan, and experiences significant tsunamis due to the subduction of the Pacific Plate from the east, as seen in events like the Tohoku earthquake (Mw 9.1, Depth 29 km) (Figure 1).

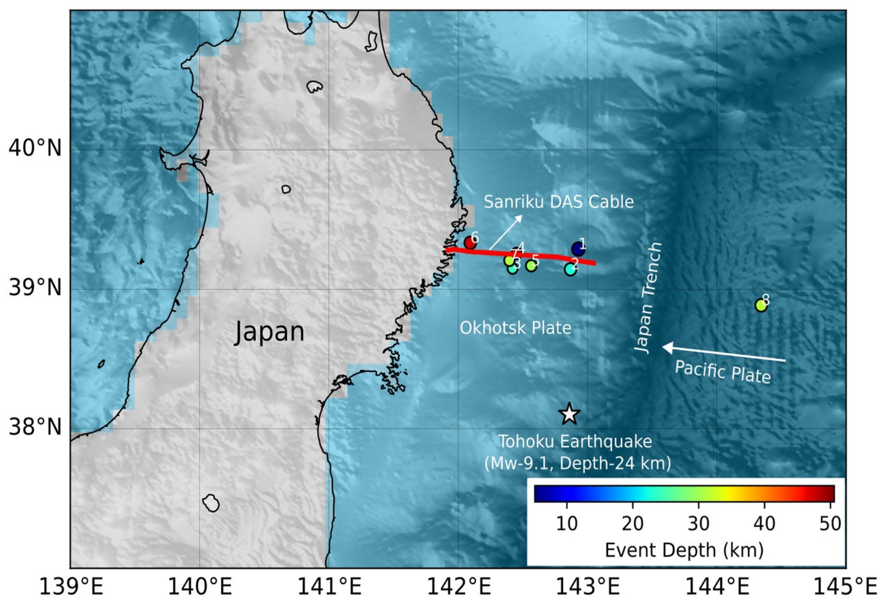

Figure 1: Tectonic map of the study region showing the off Sanriku DAS cable over the Okhotsk Plate. Earthquake locations are indicated by circles, with their hypocenters represented by the colorbar. The Tohoku earthquake, near the cable location in the south, is denoted by the star symbol.

The primary aim of this research is to produce a precise, high-resolution 3D subsurface S-wave image using ocean-bottom off Sanriku DAS data. This is crucial for comprehending the geometry of Neogene marine sediments atop the Cretaceous basement, as well as deciphering the overlying plate and subduction slab structures.

Data and Method

In this tomography study, we selected high-quality DAS recordings from the eight earthquakes occurring nearby the DAS cable, with hypocenters located within a range of 0 to 50 km (Figure 1). Two types of interrogator units recorded these earthquakes: AP Sense and Opta Sense. AP Sense units captured earthquakes 1, 3, and 5, covering 70 kilometers with a 5-meter channel interval and a sampling frequency of 500 Hz. Opta Sense units recorded earthquakes 2, 4, 6, 7, and 8, covering 100 kilometers, with a 2-meter channel interval and a sampling frequency of 400 Hz. Following data acquisition, a bandpass filter ranging from 2 to 30 Hz was applied, followed by normalization and trimming into 1-minute traces to facilitate further analysis.

The initial reference model was derived from the 2D complex P-wave velocity model using active seismic experiments (Takahashi et al., 2004) and converted into S-wave velocities using a Vp/Vs ratio of 1.77. Additionally, an average Neogene sediment velocity of 0.65 km/s was adopted from Fukushima et al. (2022).

To handle the vast volume of strain waveform data, machine learning-based auto-phase picking tools such as EQTransformer and PhaseNet were employed for the Sanriku DAS data (Figure 2). Furthermore, the RANSAC linear regression method was utilized to remove outliers from the auto-picked direct S-wave travel times data (Figure 2), resulting in a total of 2,06,037 arrivals.

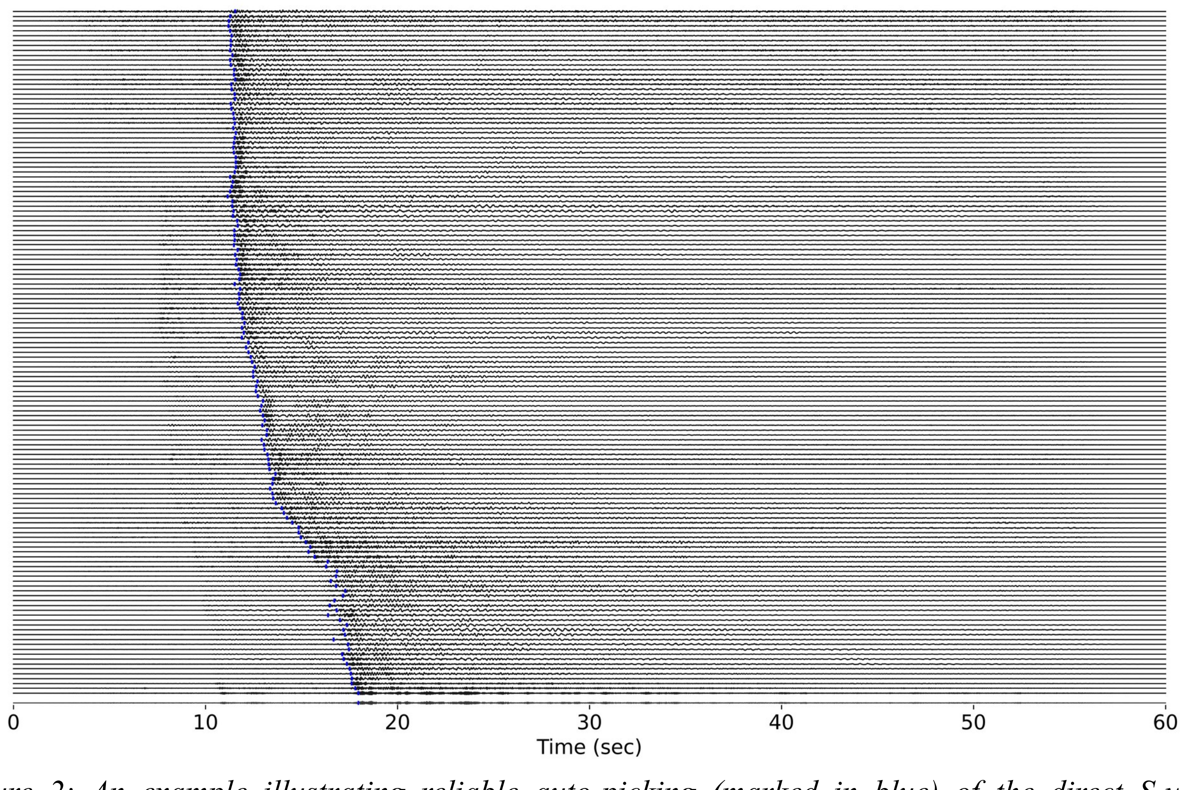

Figure 2: An example illustrating reliable auto-picking (marked in blue) of the direct S-wave arrivals with a 50-channel spacing for earthquake 5 (Figure 1).

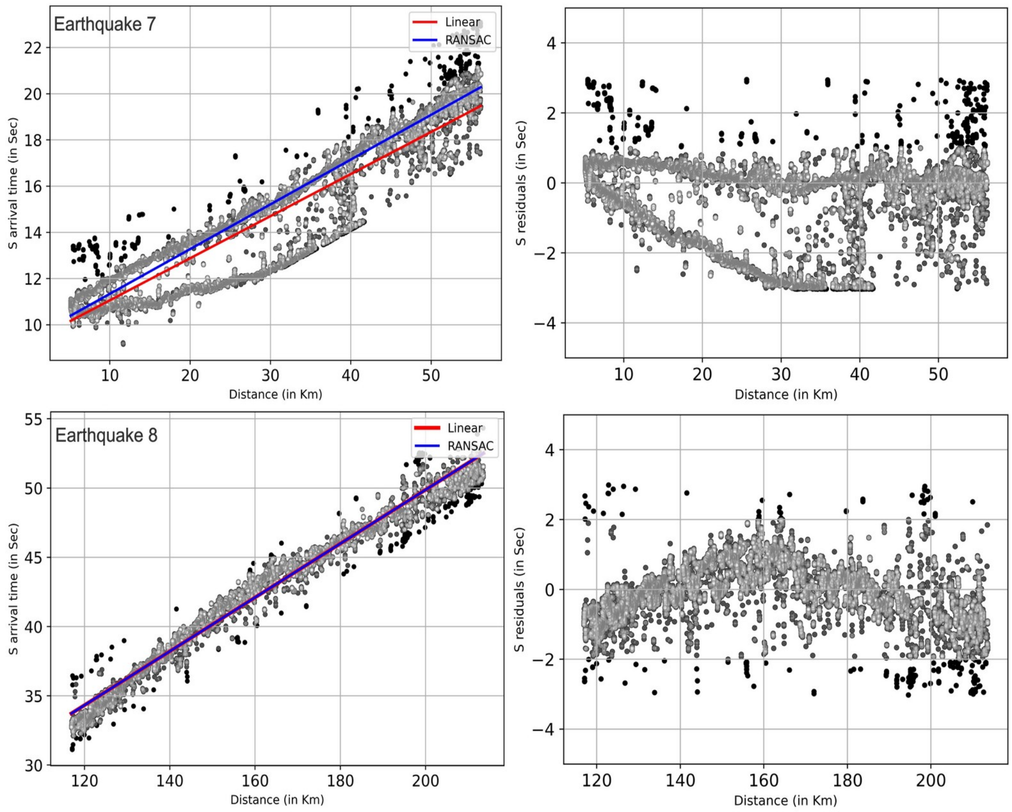

Figure 3: Example of direct S-wave arrival times plotted against epicentral distance. Outliers have been removed using the RANSAC regression method. The travel times themselves provide valuable information about changes in the sub-surface properties.

Subsequently, 3D tetrahedral meshes were generated (E-W direction: 215 km, N-S direction: 56 km, and depth: 60 km) with a 2 km interval (~0.018º resolution) using GMSH software (Figure 3). Given the complexity of the tectonic region, reliable ray tracing was essential for computing theoretical travel times and the length matrix (matrix of partial derivatives of travel time with respect to slowness). Three 3D ray-tracing algorithms were employed: Fast-sweeping Method (FSM), Short-Path Method (SPM), and Dynamic Short-Path Method (DSPM) (Figure 3). The distance versus direct S-wave arrival times plot shown in Figure 4.

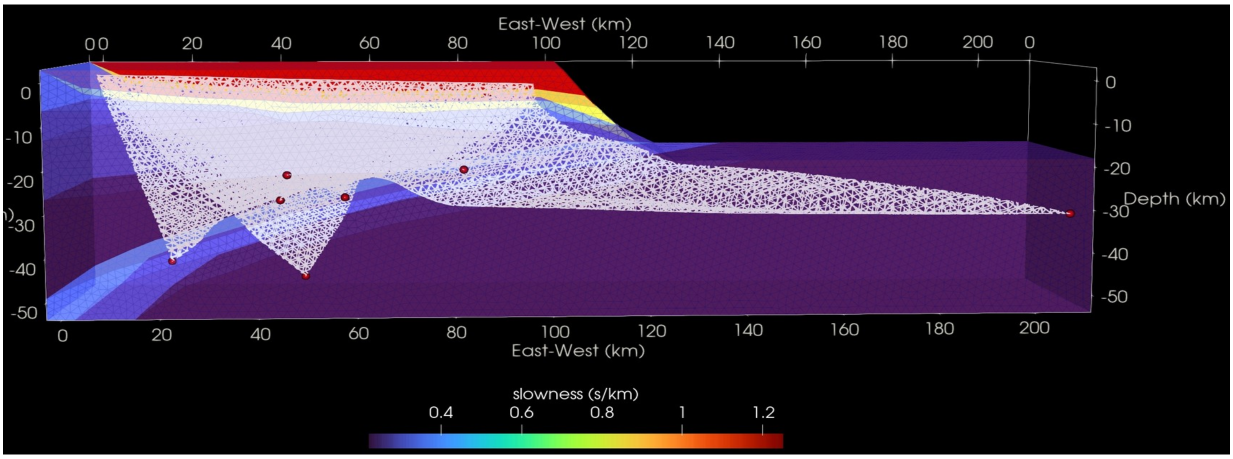

Figure 3: Unstructured 3D tetrahedral meshes generated using GMSH software. White dots represent ray paths from earthquakes to off Sanriku DAS cable locations.

Finally, the large-scale 3D finite-element tomography inversion problem was solved using the LSMR iterative least-squares algorithm, with the damping parameter fixed at the maximum curvature point (300) of the L-curve.

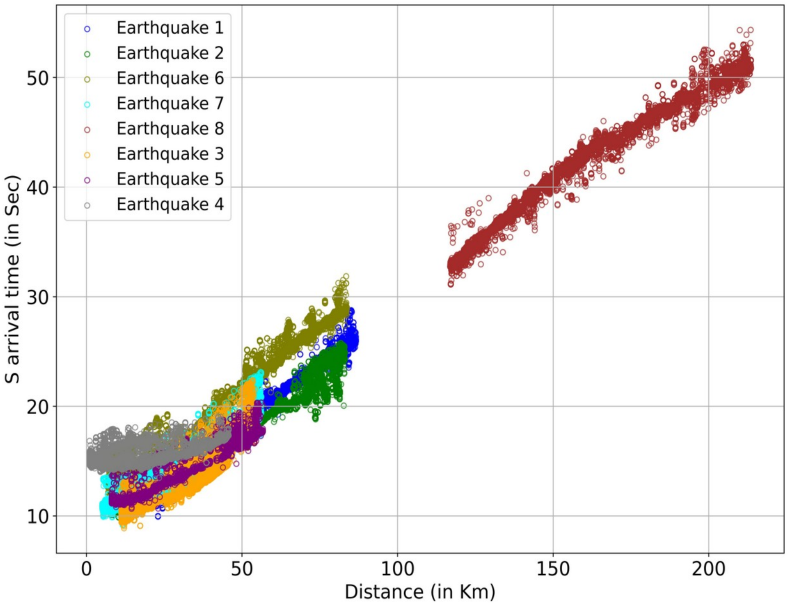

Figure 4: Distance versus direct S-wave arrival times plot. Different colored circles represent selected earthquakes.

Preliminary Results

The forward 3D ray-tracing for updating the S-wave velocity from the initial reference model was conducted. We carried out a number of tests, and the minimum RMS error between observed and theoretical travel times is approximately ~1 sec, as given by the model shown in Figure 5. Furthermore, we used this model as an initial model and conducted 3D ray-tracing for the generation of the length matrix (matrix of partial derivatives of travel time with respect to slowness). We utilized the observed direct S-wave and this length matrix for the travel time tomography inversion. After inversion, the final tomography image is shown in Figure 6.

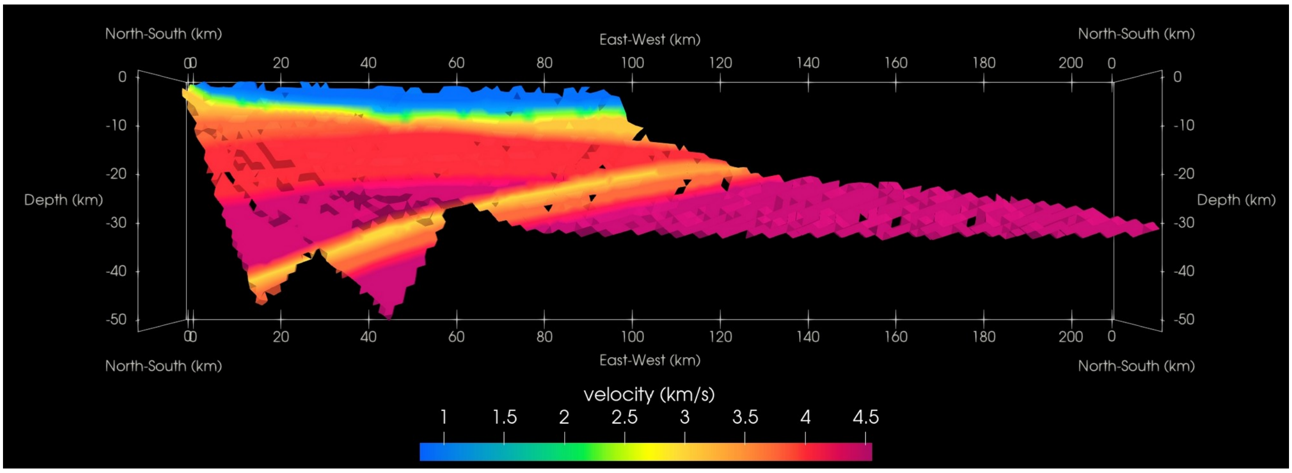

Figure 5: The final S-wave velocity model below the off Sanriku region using forward 3D ray tracing.

These results reveal evidence of very slow S-wave velocities (~0.8 to 1.0 km/s), which could be associated with Neogene sediments beneath the Sanriku DAS cable, offering potential applications in resource exploration, improving earthquake locations, and geo-technical applications. Additionally, observations include a thin layer of Cretaceous sediments (2.0 to 2.5 km/s), the heterogeneous nature of the mantle wedge revealed by a wide range of S-wave velocity changes (4.4 to 4.8 km/s), and clear evidence of the subducting Pacific plate characterized by faster S-wave velocities (~4.5 km/s).

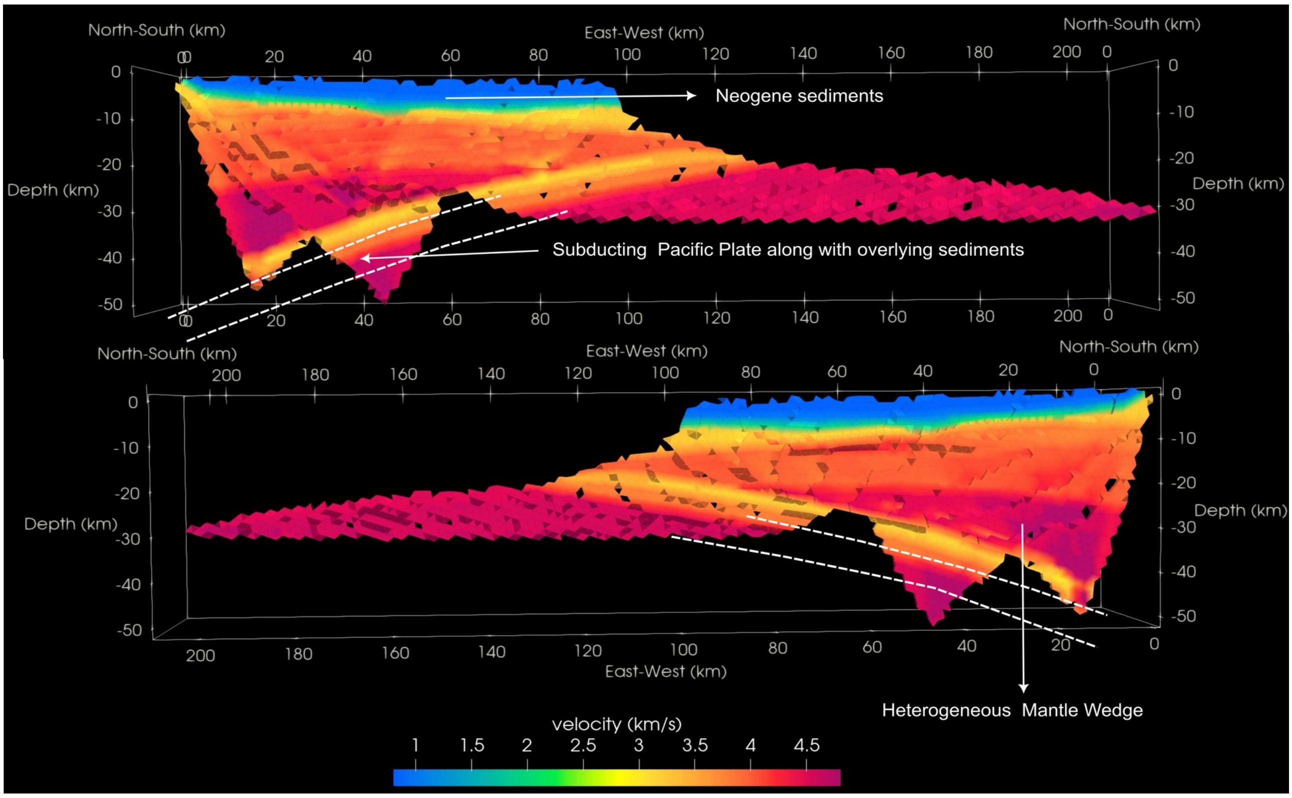

Figure 6: The 3D finite-element tomography image of the off Sanriku region.

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