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# Structure of the Tokai segment from the integrated high-resolution seismic imaging - a case study from the eastern Nankai Trough

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## SUMMARY

Subduction zones around the world remain one of the most important targets of geophysical investigations. This is because the megathrusts at convergent margins are the sites of the largest earthquakes ever recorded. The factors that control these earthquakes, as well as the evolution of accretionary wedges are still subject of geological and geophysical interpretation. Given that subduction zones are generally located offshore, approaches from the field of marine geophysical imaging - in particular seismic acquisition and processing techniques - are the methods of choice to investigate these sites. In this study we combine the results of waveform modeling, inversion and migration methods applied to the ocean-bottom seismometer (OBS) data and multi-channel seismic (MCS) data acquired in the Tokai segment of the eastern Nankai Trough. We use high-resolution velocity model derived with full-waveform inversion (FWI) and its attributes together with the reflectivity profile derived with Kirchhoff pre-stack depth migration (K-PSDM) to build a data-driven geological interpretation of the region. We focus on the nature of the subducting oceanic crust, geometry of the megathrust and splay faults, subducting front, complex accretionary wedge and the paleo-prism acting as a backstop. In particular we are able to image in great detail the complex deformation associated to the subduction of seamounts. We perform waveform and ray modeling in the FWI velocity model to analyse wave propagation within the accretionary wedge, making it possible to associate different structures directly to the arrivals in the OBS data. We support our seismic-derived results with bathymetry, magnetic and gravity data and show that they are consistent with our geologic interpretation of the structural elements that shape the Tokai segment.

## INTRODUCTION

Megathrusts at convergent margins are the sites of the nucleation and propagation of the largest earthquakes. Various types of data are collected around subduction zones to analyse their structural and geodynamical properties and study their seismogenic nature. The off-shore subduction zones are ideal sites for large-scale active-source seismic studies that can probe the lithosphere down to the upper mantle and determine the structure and deformation of the underlying setting. Redundant seismic wavefield generated by these experiments illuminates the various deep structural elements therein and allows for the geometry of the megathrust and other faults of the accretionary wedge to be reconstructed. These seismic data coupled with the cutting-edge processing techniques have made it possible to image the structures associated with seamount subduction, whose effect on the long-term strain accumulation and megathrust earthquake ruptures in subduction zones is still not well understood. It has long been thought that subduction of seafloor topography causes widespread deformation in the accretionary wedge (e.g. Lallemand et al. (1986)). However, due to the difficulties of obtaining coherent seismic images in such a complexly deformed regions, their deformation has been hitherto studied using mostly numerical and analogue models.

The Nankai Trough (NT), offshore Japan (Fig. 1), is a site of intensive geophysical investigations due to its high seismic hazard. There, the Philippine Sea Plate subducts below the Eurasian Plate towards the northwest, forming a sediment dominated accretionary prism. Despite the numerous marine geophysical surveys, the reliability of the existing subsurface reconstructions strongly relies not only on the quality

of the recorded data but also on the robustness of the applied processing techniques. Unfortunately, often the existing studies focus on the single type of observation that is processed using a single method, that drastically limits the quality of the final imaging product and therefore the accuracy of its geologic interpretation. In this study we showcase an updated approach to these studies, consisting of the processing of complementary OBS and MCS seismic data with FWI-based velocity model building and K-PSDM imaging techniques that results in unprecedented imaging of complex geologic region. We show how the structural information extracted from the wide-angle and reflection data correlate and complement each other. This allowed us to interpret for the first time the complex structural framework of the TS.

## TOKAI SEGMENT

Though the overall structure of the wedge in the TS is similar to that of the rest of the NT there are some important features that make it different. Due to the complex geodynamic setting caused by the triple junctions, the TS is characterized by a narrower and steeper accretionary prism with more complex bathymetry than the rest of the NT. The eastern boundary of the TS is marked by the Izu-Bonin arc, formed by the subduction of the Pacific Plate underneath the Philippine Sea Plate. South of the TS is marked by the large volcanic ridge - Zenisu Ridge (Fig. 1) - which has been over-printed by southward verging intraplate thrusting that accommodates a portion of the Philippine Sea Plate convergence. Further south, there are a series of similar W-NW striking sub-parallel volcanic ridges on the western flank of the Izu-Bonin arc. Several authors have suggested that the structure and seismogenic behaviour of the TS is differentiated from the rest of the NT by the cyclic subduction of these volcanic ridges (Le Pichon et al., 1996; Kodaira et al., 2003). The western edge of the TS roughly coincides with the

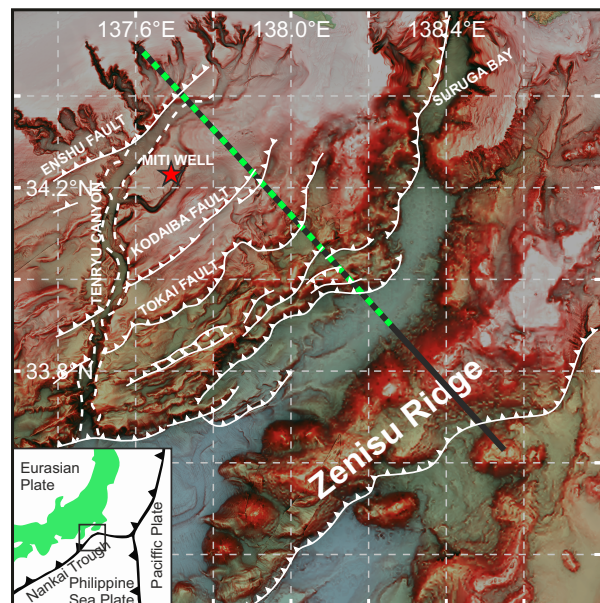


Figure 1: TKY-21 survey location in the eastern Nankai Trough with location of the main faults. The black and dotted green lines represent the OBS shot and the receiver lines respectively.

location of the Tenryu Canyon (Fig. 1). Measurements of structural features on the walls of this canyon suggest that there is a change in orientation of folds in the prism there, as well as abundant subsidiary strike-slip faulting, suggesting that the boundary may be defined by large scale transcurrent faulting (Hayman et al., 2011). This change in fault geometry is likely due to the subduction of the topographic highs.

## METHODS AND DATA

For academic regional-scale seismic imaging case studies, like those targeting subduction zones, typically 2D sparse OBS deployments (more than 5 km OBS spacing) are acquired for the purpose of subsequent velocity model building with ray-based travel-time tomography. As long as one is unable to pre-interpret and associate given reflected phases with a certain interface in the subsurface these inversions are only constrained by first-arrival traveltimes, and therefore the resolution of the reconstruction is implicitly limited by the first arrivals Fresnel's zone. On the other hand, the MCS data in academic studies are generally acquired with short streamers (~5 km). The resulting data - processed using migration techniques - are able to provide seismic images with high wavenumber content and potentially guide the geological interpretation (although the quality of the image decreases rapidly at depths exceeding approximate length of the streamer). Moreover, if the processing of the MCS data relies only on time-domain migration the resulting reflectivity image is inaccurate in terms of shape and position of the interfaces. Because of these issues, inherently smooth velocity models and imprecisely migrated sections should not be over-interpreted, and the prevalence of this type of result highlights the need for the development and application of advanced seismic imaging techniques to accurately image subduction zone geometries (Górszczyk and Operto, 2021).

The technical development of state-of-the-art, regional-scale seismic imaging techniques during recent years, allows now to conduct more exhaustive geological studies of the deep crust. In terms of data acquisition, 3D OBS and MCS surveys start to emerge (e.g. (Morgan et al., 2016; Davy et al., 2016) providing high-quality datasets. On the other hand, rapidly increasing computing power makes it possible to couple those volumetric datasets with leading-edge seismic imaging approaches routinely applied in the hydrocarbon exploration industry. In particular, wave-based inversion methods - like FWI - can be applied to wide-angle OBS data for the purpose of high-resolution velocity model reconstruction (Górszczyk et al., 2017). At the same time, short streamer MCS data can be subject of depth migration methods to image reflectivity at greater depths than before - provided that the velocity model is accurate. The resulting images in the depth-domain provide detailed and complementary information about the subsurface properties that allows for high confidence geological interpretation.

This seismic imaging scheme was recently applied to the archival seismic data acquired in the eastern part of the NT (Tokai Segment (TS), Górszczyk et al. (2019)). Successful combination of two seismic datasets with FWI and K-PSDM greatly enhanced our capacity to carry out detailed geologic interpretation. The corner stone of our approach consists of the acoustic time-domain FWI results obtained from the OBS data recorded by JAMSTEC along TKY-21 profile in 2001 (100 receivers deployed with 1 km spacing) see Fig.1). We pushed the inversion up to 15 Hz that fully exploit the frequency content of the diving and refracted waves, as well as the wide-angle reflections used during our inversion. The FWI velocity model from OBS data coupled with K-PSDM of the short streamer (4.5 km) MCS data acquired along the same 2D profile produced flat common image gathers, indicating kinematic accuracy of the background velocity field. The final reflectivity section demonstrates a good structural agreement with the FWI velocity model. To better underline the velocity variations we take an average of spatial derivatives calculated in horizontal and vertical direction of the FWI model. The resulting image superimposed with the migrated section (Fig. 3b) provides fine-scale complementary information about the structure that in locally is difficult to interpret from the reflectivity image only.

## RESULTS: WAVEFORM AND RAY MODELLING

Before carrying out a detailed geological discussion we first corroborate our results with wide-angle data modeling. With this exercise we start the overall structural interpretation of the FWI velocity model that allows us to understand dependencies between the structure in the model and the recorded wavefield to increase the confidence of the further interpretation. Since the velocity values in the FWI model span from 1500 m/s to more than 8000 m/s, the recovered structure can be better underlined after the velocity trend with depth is removed. This leads to the positive/negative (red/blue) velocity perturbation model presented in the background of Fig. 2b. Different structural features of various scales are clearly visible in the detrended profile. The validity of this model is tested through waveform and ray tracing. In Fig. 2a we show the OBS gather for the receiver located in the central part of the profile. We assign four different reflectors within the prism (the black lines in Fig. 2b) to the corresponding reflections present in the OBS gather. By following the rays (Fig. 2b) that cause the weak first-arrivals marked by the magenta solid line (-30 km to -10 km in Fig. 2a), one can observe how the wavefront is channelled within the higher-velocity dipping structure of the prism and travels through the backstop ahead of the energetic arrival that took slightly different path during the first few seconds of propagation. We observe variations of the first arrivals marked by light-blue and blue lines in Fig. 2a that are associated with the wavefronts and rays sampling thrusts located towards the frontal part of the prism. Further, red and yellow lines in Fig. 2a mark the Pg and Pn arrivals (see corresponding rays and wavefronts in Fig. 2b). Note, that despite the fact that those waves are penetrating in the deepest regions of the model, they are still sensitive to the velocity and bathymetry changes in the frontal accretionary wedge and trench, which is evident from distortions of the arrivals that they produce.

## RESULTS: STRUCTURE OF THE TOKAI WEDGE FROM SEISMIC DATA

We present detailed interpretation that was obtained using the combination of images derived from velocity model and reflectivity section. A complementary information combined together consolidates the final structure of the TS described hereafter.

### Accretionary prism

Based on the changes in deformation style evident from the velocity variations (e.g. in Figure 3b) the accretionary wedge of the TS can be generally divided into four sub-units. The differences in the underlying wedge structure is reflected by the strongly heterogeneous nature of the bathymetry along the profile that is imaged in Fig. 3a. Mapping some of the scars in the seabed to the section in Fig. 3b allows us to track their extension in the subsurface and couple them with the underlying features like sedimentary basins, faults, folds or canyons.

First we delineate the incoming sediments (or weakly deformed unit; blue-shaded area in Fig. 3c). This sub-section corresponds to the strata of the Suruga trench, which has not yet been incorporated into the accretionary wedge and shows a general northward dip.

Towards the north-west we outline the outer wedge (magenta-shaded area in Fig 3c). It is limited to the south by the frontal thrust of the wedge that causes the initial bathymetric expression of the prism, and is defined by a shallowing in bathymetry from ~3.7 km depth to ~2.4 km depth. The decollement at the base of the frontal thrust is deformed as it passes over a series of topography highs. The next structure to the north we interpret as an imbricate fan that creates a local bathymetric high at a depth of ~2.3 km (80 km of distance). Sharp velocity gradients in Fig. 3b underline very well the main interfaces within this unit. The internal geometry of this structure is complex. There is an evidence of older faults being folded by younger ones, and out-of-sequence thrusting cutting through the sequence. These faults reach the seafloor and create a break in slope there. Further north still, the structural style is maintained, forming a second bathymetric culmination (72 km of distance) that creates another wedgetop basin. In both cases the wedgetop basins bury thrust sheets that nevertheless deform strata within them. The reflections are well imaged in this part of

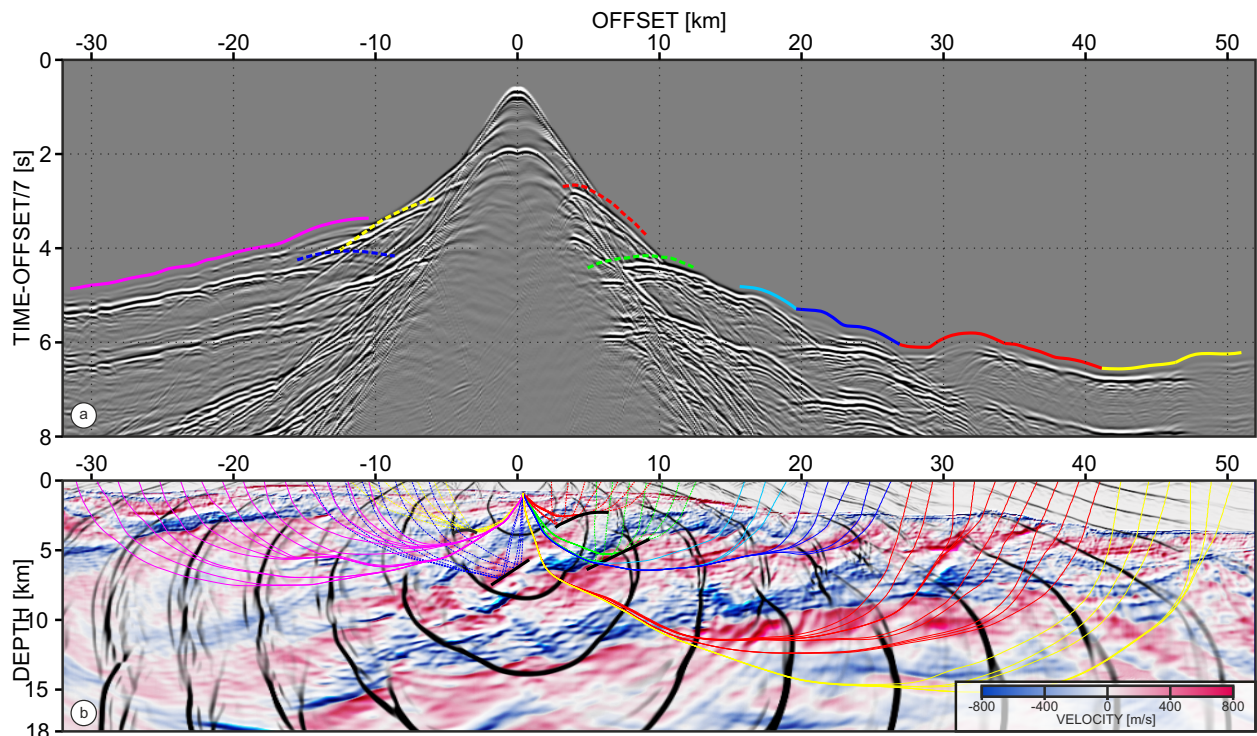


Figure 2: (a) OBS gather with with picked arrivals - dashed lines mark wide-angle reflections and solid lines mark refracted and diving waves. (b) Detrended model with superimposed raypaths corresponding to the arrivals picked (a) and wavefront snapshots extracted at each 2 s of propagation.

the accretionary prism and it is apparent that all the thrusts sole into a common decollement. Beneath this decollement the reflections are tenuous and disturbed suggesting significant out-of-the-plane scattering that hampers correct depth migration in 2D. However the velocity model shows a high velocity zones that could correspond to a second subducted seamount.

The middle wedge (yellow-shaded area) is defined by a sharp change in bathymetry, with a shallowing occurring where the thrust that forms its eastern boundary reaches the seafloor. The water depth decreases gradually until it reaches a depth of  $\sim 0.8$  km. The transition between the well imaged thrust sheets of the outer wedge, and the thicker, crudely imaged thrust sheets on the middle wedge is a fault referred to as the Tokai thrust. This fault is underlain and folded by a duplex formed at the transition between the middle and the outer wedge. Though the deeper reflections are not ideally imaged, there is a band of southward-dipping reflections, which combined with an abrupt change in velocity there leads us to interpret a duplex. In the middle wedge proper, the reflections are faint, but combined with the high resolution velocity model, allow to infer the general geometry of its internal stratigraphy. The first thrust sheet has well imaged shallow reflections, but poorly imaged deeper ones. The shallow reflections show folding that is consistent with a decollement shallower than the present one. We interpret the middle wedge to extend another thrust sheet to the north. This structure is also defined using a combination of faint reflections and changes in the velocity model. There is a culmination associated to this feature that deformed the lower section of the overlying strata, suggesting that this fault was active out of sequence. However, the present seafloor morphology indicates that this is no longer the case.

The inner wedge has much less reflectivity, and what is present has lower frequencies, than the outer or middle wedge. The thrust that corresponds to the boundary between the inner and middle wedge is generally referred to as the Kodaiba thrust, and is similar to the Tokai thrust in that it separates areas of different reflectivity and structural styles. The internal structure of the inner wedge is complex, and thus can only be outlined in a general manner once reflectivity section is combined with the velocity model attributes. Few pronounced velocity perturbations around 30 km of model distance and between 5 km and

12 km depth correlate with broad-wavelength uplift of the sediments of the overlying forearc basin. The thrust sheets that can be recognized in this region do not reach the oceanic crust, and rather they appear to sole into a decollement a few km above the plate interface. This region is generally considered the backstop of the accretionary wedge, implying that it is rigid. However, the base of the forearc basin is warped at a wave-length similar to that of the thrust-spacing, suggesting that there has been some out of sequence slip on these faults.

#### Subducting plate

The oceanic crust is characterized by an abrupt increase in seismic velocities that makes it easily identifiable in the velocity gradient image (Fig. 3b). The crust of the Philippine Plate, has some reflectivity that likely corresponds to sediments deposited on it. The subducting plate is also characterized by a series of seamounts that are presumably analogous to those observed on the modern seafloor on the western flank of the Izu-Bonin arc in this region. These seamounts are smaller than the one imaged by Martin (2003) in TS and have a height of up to  $\sim 2$  km above the top of the oceanic crust. Several of these features can be observed underneath the accretionary prism (at 57 km, 70 km, 80 km). In Fig 3b there is a sharp and wavy velocity contrast at the base of the oceanic crust that is interpreted as the Moho (black line Fig 3c).

#### Megathrust fault

The megathrust, is marked by a continuous reflection beneath the accretionary prism, that is located above the seamounts on the oceanic crust (solid cyan line in Fig. 3c). At distance of 50 km and depth  $\sim 10$  km, there is a decollement step-down and we start to observe a band of pronounced reflectors  $\sim 1$  km thick, consistent with previous observations by Nedimović et al. (2003) for Cascadia and by Bécel et al. (2017) for Alaska. This area corresponds to a low velocity zone, which could be due to either a thick damage zone associated to the subduction zone megathrust, or sediments on the subducting plate. At  $\sim 13$  km depth, and the fault reflections have a greater amplitude corresponding most likely to the basal detachment from which faults such as the Kodaiba and Tokai branch off.

#### Forearc basin

The forearc basin is well imaged in our seismic line. The base of the basin is an unconformity showing evidence of out of sequence

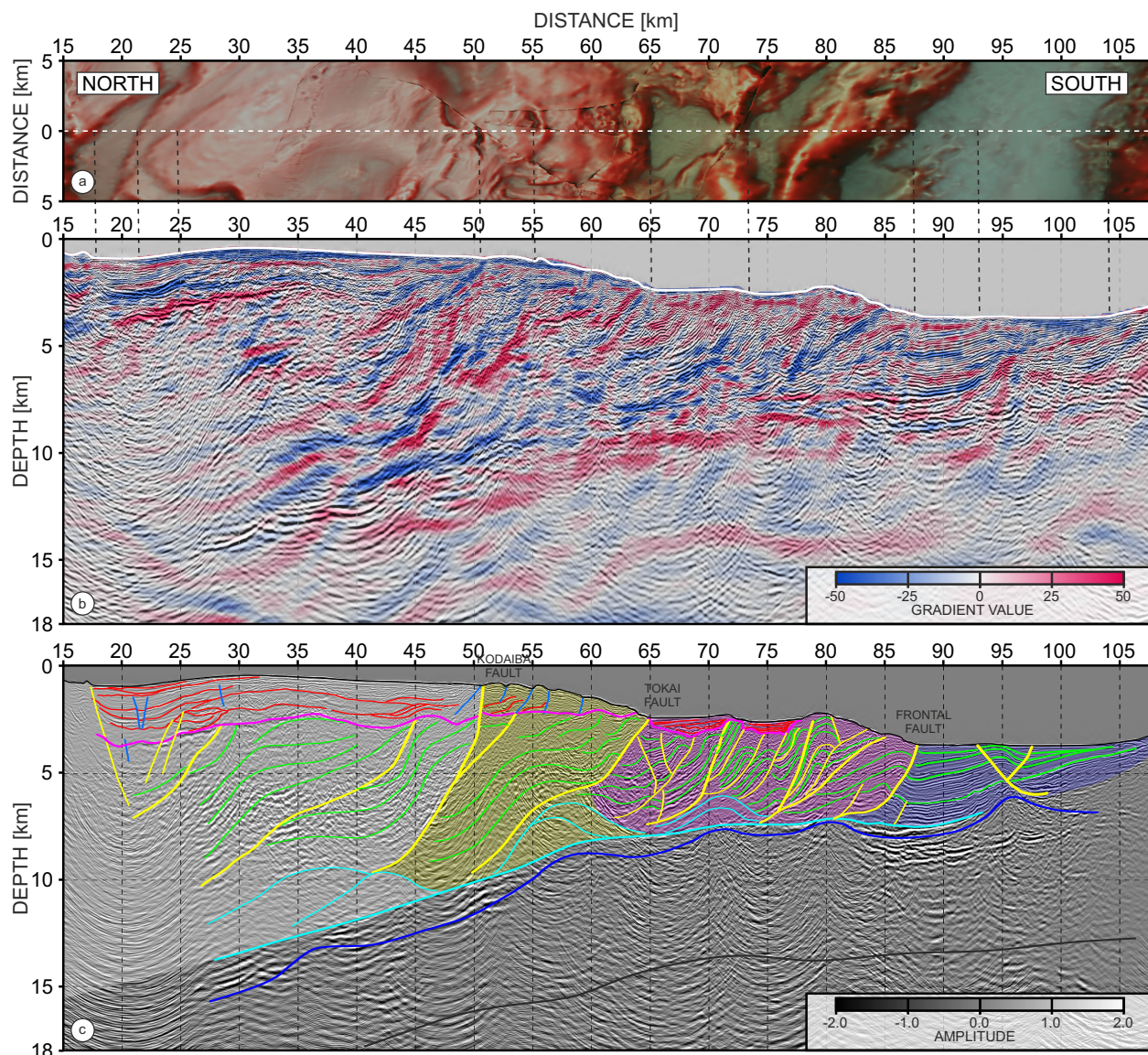


Figure 3: (a) Bathymetry relief image around seismic profile Yamashita et al. (2017). (b) K-PSDM section superimposed on the image of the average vertical and horizontal spatial derivative of the FWI model. (c) K-PSDM section with structural interpretation.

thrusting that created an irregular bathymetry on which the basin was formed. The wavelength of this deformation is shorter for the middle wedge than for the inner wedge. As the basin was filled, there was continued deformation, as evidenced by several internal unconformities in the forearc strata. The oldest of these truncates the inner wedge thrust sheets, and is subsequently folded by them, suggesting out of sequence thrusting happening here. The seafloor expression of the basin is warped at a larger wavelength than those of the thrust sheets, but similar to that of the underplated material proposed beneath the wedge. The basin fill is generally layered except in two intervals in the middle of the basin where the seismic character is similar to that found in basin floor fans (Saller et al., 2004). These intervals, which coalesce towards the middle of the basin, are  $\sim 0.5$ - $0.7$  km in thickness, and  $\sim 16$ - $18$  km in length. These deposits are likely related to sediment input from the Tenryu river.

## CONCLUSION

Recent advances in geophysical imaging - especially FWI from OBS data - significantly change the way deep crustal targets are imaged. We presented the structural interpretation based on the combined imaging of the OBS and MCS data from the TS. The quality of the resulting images, clearly demonstrates the potential of this kind of imaging for tak-

ing a significant leap forward in the studies of subduction zones. This development shall allow us to derive robust geologic models and place precise constraints than it has been hitherto possible due to the limitations of the seismic imaging. The great number of studies published in recent years about the effect of seamount subduction on megathrust earthquake nucleation, as well as the effects of its associated deformation on inter-seismic coupling of the megathrust, highlights the increasing interest in the subduction zones. This in turn indicates the need of further development of the leading-edge seismic imaging methods and the data acquisition techniques to increase the abilities of reconstruction of these tectonic settings.

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