Philippine Sea and East Asian plate tectonics since 52 Ma constrained by new subducted slab reconstruction methods

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The Philippine Sea plate is a large marginal sea between the major Pacific, Indo-Australia and Eurasia/Sundaland plates. The history of Philippine Sea plate motions since its inception around 52 Ma is controversial and uncertain, due in large part to lost lithospheric record at the circum-Philippine Sea plate subduction zones and other East Asia convergent plate boundaries. Nonetheless, continued research on the Philippine Sea plate is motivated by its importance for northeast Asia tectonics, including Taiwan, the Philippines, SW Japan-Ryukyus, the South China Sea, the Izu-Bonin-Marianas arcs, and other southeast Asia marginal seas.

In this study we show a Philippine Sea and adjacent East Asia plate tectonic reconstruction back to 52Ma constrained by twenty-eight slabs mapped in 3D from global tomography, with a total subducted area of ~25% of global oceanic lithosphere. New slab constraints include subducted parts of existing Pacific, Indo-Australian, and Philippine Sea oceans, plus the wholly subducted proto-South China Sea and the newly discovered "East Asian Sea" ocean. Mapped slabs were structurally restored to a spherical Earth surface using newly-developed unfolding methodologies and input to globally-consistent plate reconstructions using Gplates software.

Important new constraints include:
(1) the northern Philippine Sea Ryukyu slab is short (~1000 km) relative to >2000km northward Philippine Sea motion constrained by paleomagnetism. This requires an intervening, now-subducted ocean south of the Ryukyus and SW Japan in the Eocene. Our plate reconstructions show this to be the 'East Asia Sea' and the Pacific;
(2) the Marianas Pacific subduction zone remained within ±200 km of its present location since 48±10Ma based on a slab wall extending to >1000km depths;
(3) a major (8000 km x 2500 km) swath of lower mantle flat slabs represents a vanished "East Asia Sea" ocean that existed between the Pacific and Indian Oceans at 52Ma. The northern East Asia Sea played the role of the proto-Philippine Sea;
(4) the Caroline backarc basin moved with the Pacific based on an overlapping and coeval Caroline LIPS and hotspot track and proto-Caroline slab locations.

Our preferred plate model involves a Philippine Sea origin near the Manus plume (150°E/0°) at a Pacific-East Asian Sea junction. Large westward motion and post-40Ma clockwise rotation (~60°) were driven by late Eocene-Oligocene collision with the Caroline/Pacific plate. We predict a Miocene arc-arc collision between a northern Philippine Sea arc and the SW Japan-Ryukyu continental margin. Our observed slab age-depths fit within a 1.8±0.8 cm lower mantle sinking rate. Digital files, including plate-model animations and Gplates compatible unfolded slab shapes and rotation files will become publically available to serve as a platform for further refinements or testing alternative tectonic scenarios.

Keywords: Philippine Sea plate, plate tectonic reconstructions, subducted slabs

Early Cenozoic large plate tectonic reorganization in the Pacific Ocean and its record in accretionary complex in western Pacific margin

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Late Paleocene to early Eocene (~50 -42 Ma) is regarded as a period of large organization of the Pacific and other plates and appears to have taken place related tectonic events along the circum-Pacific subduction zone. A hypothesis suggests that it might have been caused by subduction initiation along the Izu-Bonin-Mariana margin following the subduction of the Izanagi-Pacific oceanic ridge, and resulted in the change in moving vector of the Pacific Plate. The hypothesis has been controversial but revived with new observations of stagnant slabs beneath the Asian continent and others.
We examined the geology of the late Cretaceous and early Cenozoic accretion complexes of the Shimanto Belt and others in the Japanese islands. In that period, the Japanese islands were located along the continental margin because it was the before the Oligo-Miocene rifting and opening of the Japan Sea.
The Shimanto belt is subdivided into two subbelts; northern and southern subbelts. The youngest portion of the northern Shimanto belt is the latest Cretaceous to the earliest Paleocene in age and includes N-MORB type basaltic blocks with a short age gap with terrigenous trench filling sediments. Previous studies hypothesized that in-situ magmatic eruption in the trench but it was denied by detailed geological, structural, and chemical investigation for the relationship between the basalt and surroundings. Instead of the in-situ eruption hypothesis, very hot plate subduction and seismogenic megathrusting is proposed. Other parts of the late Cretaceous northern Shimanto Belt indicate oceanic plate older than the terrigenous trench filling sediments was subducted. This observation is inconsistent with the commonly popular ~80 Ma Kula-Pacific ridge subduction hypothesis.
Between the northern and southern Shimanto Belts, is recognized a large tectonic gap named the Nobeoka thrust in Kyushu and the Aki Tectonic Line in Shikoku. Several m.y. age gap is common between the subbelts and northernmost portion of the southern Shimanto belts is composed dominantly of Eocene terrigeous sediments of accretionary complex. Locally they include basaltic blocks without thick pelagic sediments but just hemipelagic shale. Thermal overprints reconstructed by illite crystalinity, vitrinite reflectance, and fission track ages of zircons are high in general and dated mainly in Eocene just after the deposition.
These facts suggest the rapid development of accretionary prism after the tectonic break in earliest Paleocene took place with thermal event.
The other prominent Eocene event is the development of the coal mine fields from Kyushu, mainland Honshu to Hokkaido, and Sakhalin, Russia along the Asian continental margin more that 2,000 km. These regional developments of coal fields along the Asian margin after the Paleocene tectonic break in the accretion complex are quite prominent and informative. We suggest that all these events in early Cenozoic might have been related to global scale reorganization of plate tectonics.

Dynamic of the Japan subduction system

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The geometry of the Mariana-Izu-Bonin (IBM)-Japan slab consists of a large cusp where the undulation of the trench is accompanied by a corresponding variation in slab dip, varying form sub-vertical beneath the Marianas to shallow dipping beneath Japan. The origin and the cause of these variations are still poorly understood.We reconstruct the backarc extensional system of the Philippine plate, showing that the triple junction between the IBM, Ryuku, and Japan migrated northward during the last 40 Ma reaching its present-day position. We balance back the subduction system on time, starting from recent tomographic models and using an absolute reference frame plate reconstruction model. Our kinematic model suggests that the evolution and the geometry of the Japan slab is controlled by the interaction with the surrounding slabs. We test this hypothesis with simple laboratory experiments. Our preliminary results suggest that the slab geometry is influenced by local and plate-scale mantle flow.

Keywords: subduction, Mariana-Izu-Bonin, geodynamic modeling

Joint inversion of body-wave and surface-wave data for the fine 3-D structure of Japan subduction zone

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We determined high-resolution P and S wave velocity tomography of the Japan subduction zone down to a depth of 700 km by conducting joint inversions of a large number of high-quality arrival-time data of local earthquakes and teleseismic events which are newly collected for this study. We also determined 2-D phase-velocity images of fundamental-mode Rayleigh waves at periods of 20 to 150 s beneath Japan and the surrounding oceanic regions using amplitude and phase data of teleseismic Rayleigh waves. A detailed 3-D S-wave tomography of the study region is obtained by jointly inverting S-wave arrival times of local and teleseismic events and the Rayleigh-wave phase-velocity data. Our inversion results reveal the subducting Pacific and Philippine Sea slabs clearly as dipping high-velocity zones from a 1-D starting velocity model. Prominent low-velocity (low-V) anomalies are revealed in the mantle wedge above the slabs and in the mantle below the Pacific slab. The distinct velocity contrasts between the subducting slabs and the surrounding mantle reflect significant lateral variations in temperature as well as water content and/or the degree of partial melting. The low-V anomalies in the mantle wedge are attributed to slab dehydration and corner flows in the mantle wedge. A sheet-like low-V zone is revealed under the Pacific slab beneath NE Japan, which may reflect hot upwelling from the deeper mantle and subduction of a plume-fed asthenosphere as well. Our present results indicate that joint inversions of different seismic data are very effective and important for obtaining robust tomographic images of the crust and mantle.

Reference

Liu, X., D. Zhao (2016) P and S wave tomography of Japan subduction zone from joint inversions of local and teleseismic travel times and surface-wave data. *Phys. Earth Planet. Inter*. 252, 1-22.

Keywords: Japan subduction zone, Pacific slab, Philippine Sea slab

Structural evolution of the southern margin of the Sea of Japan: implications from recently obtained seismic data

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The Japan arc is located in a highly active tectonic region, with earthquakes and tsunami hazard on both the Pacific and Sea of Japan side. After the tsunami disaster as the result of the 2001 Off-Tohoku earthquake (M9) along the northeast coast of Japan, the Japanese government initiated an extensive evaluation of the tsunami hazard. Not only does this evaluation span the Pacific coast of Japan, but also the western shore of the Japan arc along the Sea of Japan. To develop a tsunami source-fault model of this area, a better understanding of the present-day structural geometry of this region is necessary. Therefore, the structural evolution of the Sea of Japan is assessed. Here, we examine the development offshore of the San'in region, Kyushu, using a subsurface dataset that covers ~1,000 km^2 including well log data and recently obtained 2D seismic reflection profiles.

The southern margin of the Sea of Japan is a structurally complex area that formed as a result of several tectonic events during the last 25 Ma including: (i) back arc rifting and rotation, (ii) post-rift compression, (iii) weak thrusting, and (iv) strike-slip deformation. This region is previously studied extensively using gravity, paleomagnetic, borehole, and limited 2D seismic data. However, due to the limited spatial and temporal resolution of the data available and methods applied, the development of this region is not yet well constrained. Nevertheless, multiple hypotheses on its structural evolution were forwarded.

We present preliminary results of comprehensive analyses of well data and the seismic profiles obtained in 2013. The 2D seismic reflection profiles were acquired using 1950 cu. in. airgun and 2100 m streamer cable, and have a total length of ~680 km. The profiles were migrated and depth converted, imaging up to 5 km. On the seismic profiles we observe igneous bodies and large basement blocks, as well as rift-related, syn-rift sediment filled grabens and half-grabens, of which some are inverted. These structures are interpreted to be the result of a complicated development, linked to multiple large-scale tectonic events. During the rifting and opening stage (25 –14 Ma), subduction of the Pacific and Philippine Sea plates along the east coast of Japan resulted in back-arc rifting and the initial opening of the Sea of Japan. The rift event is associated with clock-wise rotation of the southwest Japan arc (17.5 –15.8 Ma), with its pivot point located approximately in the south west of the study area. Rift structures filled by syn-rift sediments formed trending parallel to the southwest Japan arc. The opening of the Sea of Japan ceased due to the collision of the Izu-Bonin-Mariana arc system and the Japan arc along the eastern side of Japan. Soon after this event, the former marginal rift zone along the west coast of Japan was exposed to shortening (14 –5 Ma) due to the northward movement of the young Shikoku basin within the Philippine Sea plate. The high thermal buoyancy of the Shikoku basin resulted in resistance along the Nankai trough causing thrusting and selective inversion along previously developed rift structures and the development of the Shinji fold belt. Subsequently, when subduction of the Shikoku basin began (5 –1 Ma), the shortening rate decreased and the deformed structures were covered by sub-horizontal Pliocene sediments. At 1 Ma, a northwesterly shift of the Philippine Sea plate produced a major change in stress regime, causing reactivation of reverse faults to strike-slip. We use the understanding of the development of the southern margin of the Sea of Japan to improve the current tsunami source-fault model.

Keywords: Tsunami source-fault model, Sea of Japan, Seismic reflection data, Structural evolution, Crustal deformation, San'in region

Crustal and tectonic evolution of accretionary orogens in NE Asia and comparison with the Central Asian Orogenic Belt

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The Northeast Asian Orogenic Belt (NAOB) is a Mesozoic-Cenozoic accretionary orogenic collage, and it constitutes the northern and principal part of the “Nipponides” [1]. The orogenic style of the Nipponides has much in common with that of the Central Asian Orogenic Belt (CAOB) or the “Altaides” [1, 2]. The tectonic framework of the NAOB was formed in Mesozoic and Cenozoic, and it continues to evolve along the modern Pacific arc-trench systems. Generally, an oceanward younging of tectonic units may be discerned, but such a simple pattern is disrupted in many places by extensive strike-slip faulting, most of which is left lateral. In this talk, the issue of crustal evolution in the sector of Sikhote-Alin, Sakhalin and Japanese Islands will be discussed based on the geochemical and isotopic analyses of granitoids that intruded in various tectonostratigraphic terrains.

The majority of granitoids in the NE Asian Orogenic Belt formed from Jurassic to late Cenozoic, with Cretaceous as the dominant period of granitic magmatism and silicic volcanism. Though remnants of Paleozoic granitoids have been preserved in Japan [3], most granitic rocks were emplaced in the Mesozoic and Cenozoic times. Cretaceous granitoids are widespread in Sikhote-Alin [4] and Japan. However, granitoids were emplaced only in the Cenozoic in Sakhalin (ca. 44 - 42 Ma) and Hokkaido (45, 37 and 18 Ma) [5]. Most granitoids from Sikhote-Alin have I_{Sr} = 0.7040 to 0.7083, and $e_{Nd}(T)$ = +3.0 to -6.0 (mostly 0 to -5). The Sr-Nd isotopic data fall within the range of granitoids from SW Japan (0.704 to 0.712; +5.0 to -13.0), and the data of Cretaceous granitoids from Sikhote-Alin and SW Japan overlap almost completely. Cenozoic granitoids of Hokkaido are characterized by I_{Sr} = 0.7044 to 0.7061, $e_{Nd}(T)$ = +1.0 to +4.7, and Sm-Nd model-1 ages = 400-1000 Ma. They are remarkably similar to Sakhalin granitoids with I_{Sr} = 0.7047 to 0.7050, $\varepsilon_{Nd}(T)$ = +2.8 to +3.7, and model-1 ages of 700-1100 Ma. The isotopic data suggest that the granitoids of NAOB were generated by partial melting of sources with mixed lithologies, including subducted accretionary complexes and probably some hidden Paleozoic to Proterozoic basement rocks. The Nd isotopic data also suggest a proportion of 30-77% of juvenile component in the generation of Sikhote-Alin granitoids, whereas the proportion is much higher for the Cenozoic granitoids of Hokkaido and Sakhalin (about 65-95%). In any case, a significant amount of juvenile crust was produced and added to the NE Asian Orogenic Belt.

Many workers have proposed a geological correlation between Sikhote-Alin and Japan, as well as between Sakhalin and Hokkaido, based on several lines of evidence including lithostratigraphy, biostratigraphy (radiolarian assemblages) and geological structures [6]. The present work lends support to the general scenario. However, the significant difference between SW Japan and NE Japan in their crustal composition and probably tectonic evolution has to be reckoned. The two geologic entities might have evolved in very different ways. A brief comparison of crustal evolution in the NAOB and CAOB will be presented. (Supported by MOST 104-2913-M-002-005, Taiwan)

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Keywords: NE Asia, accretionary orogen, Nipponides, grantoid, Sr-Nd isotopes, crustal evolution

Greater South China: it was larger than previously believed

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Long-remaining unsolved issues include the Neoproterozoic to Paleozoic geotectonics of proto-Japan, in particular, precise timing of the onset of the Pacific sudbduction (or tectonic turnover from a passive to an active margin) and the homeland o f Japan (North China or South China). To date, the nascent development of an arc-trench system of proto-Japan is reasonably constrained in timing to the early Cambrian or slightly older age. The other new view recently given by zircon chronology was the identification of older Precambrian detrital zircons and xenocrysts, in particular, the Neoproterozoic grains with similar ages to those of the South China basement. The North China block has been tradi tionally regarded as the homeland continent, along which Japan evolved. Detrital zircons of so-called Pan-African ages (ca. 1200-600 Ma) are identified, however, in various Paleozoic sandstones (Nakama et al., 2010; Isozaki et al., 20 14); in addition, zircon xenocrysts of the similar ages were also recognized in the Paleozoic granitoids (Aoki et al., 2015) . These ages are extremely rare in the North China block, whereas dominant in South China. The latest identification of the extensive Paleo- to Mesoproterozoic crusts in the Cathaysian part of South China cleared the difficulty in correlating Japan with South China. These data confirmed that Paleozoic Japan corresponded to an eastern extension of South China block prior to the Triassic collision with North China. This requires that the original South China block was much larger than the present conterminous mainland part, i.e., longer for more than 200 km to the northeast up to NE Japan, and the Greater South China (GSC) was proposed particularly for proper paleogeographic reconstruction of East Asia (Isozaki, 2014). The lastest information on the detrital zircon age spectra from the Paelozoic sandstones of the Sergeevka belt in Primorye (Far East Russia) further suggests that this domain resembles Japan, and South China in terms of sedimentary settings and provenance . In short, the GSC becomes much larger, nealry twice larger, than previsouly imagined.

Keywords: South China, Japan, Primorye, CAOB

The influence of upper plate tectonic inheritance in the southern Taiwan arc-continent collision

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Seismogenic strain inversions offshore SE Taiwan suggest that the Luzon forearc is detached from the Philippine Sea Plate (PSP) creating a forearc sliver. Both the origin and the fate of the forearc sliver remain unresolved, although tomographic work suggests that it exists at depth in the suture zone of the Taiwan orogen. I suggest this forearc material might play a role in the geodynamics of the collision. Recent studies of seismogenic strain, metamorphic fabrics and brittle deformation in the southern Taiwan mountains reveal non-recoverable strain patterns that are difficult to understand in the context of the ongoing collision. In spite NW motion of the Luzon volcanic arc at ~80 mm/yr relative to the Eurasian passive margin, the dominant expression of seismogenic strain and brittle faults is NE-SW maximum principal stretching. Extension is at a high angle to the PSP convergence vector and at a low angle to the strike of the slate and schist that dominates the southern Central Range. The stretching is expressed in inversions of focal mechanisms as preferred nodal planes with steep WSW and ENE dips accommodating normal motion, and as near vertical preferred nodal planes accommodating strike slip motion. These structural geometries are focused where peak temperature proxies reveal maximum temperatures, and leveling data reveal short-term uplift rates at their highest. To date, nearly all studies of the southern Central Range have sought to explain the uplift history and thermal structure in profiles constructed normal to the strike of the range. The predominance of structures accommodating NE-SW stretching suggests the possibility that crustal thinning and strike slip are playing a role in bringing metamorphic rocks to the surface. If this is correct, the rocks very clearly record non-plane finite strain and it is important to examine profiles constructed at high angles to the dominant strike of these structures (~N15W). Recent unpublished Ar-Ar ages suggest that these kinematics may be relatively young. In the Yuli belt, just west of the Longitudinal Valley, and in the easternmost slate belt the youngest metamorphic foliations generally dip shallowly and are marked by stretching lineations that plunge gently NE to NNE. Preliminary crystallization ages for minerals defining these fabrics are ~1 Ma. Importantly, the Yuli belt includes mantle-derived, high-pressure metamorphic blocks that tomographic, seismic and petrophysical data suggest are connected to their source at ~40-50 km by an east-dipping seismic (high) velocity anomaly. Exhumation of mantle-derived, high-pressure metamorphic rocks from such depths in a subduction channel would not necessarily predict shallow plunging stretching lineations. The relation between the shallow plunging stretching direction and the recrystallization depths for these rocks therefore remains an important question. It is possible that the shallow fabrics are a relatively recent transpressional overprint superimposed on a longer history of updip subduction channel flow. The influence of a tectonically buried forearc sliver is also important. The rocks of the forearc sliver may in effect form the leading edge of the Luzon volcanic arc backstop, making them a viable source for the high-pressure mantle rocks now at the surface in the Yuli belt. In addition to hosting a putative subduction channel marked by a coherent seismic velocity anomaly, this part of the collision is noteworthy for a voluminous aseismic zone that appears to reach the Earth surface in the Central Range east of the Yuli belt. Seismogenic strain in the rocks that span this enigmatic shoaling of the brittle-ductile transition varies systematically, suggesting a relatively strong contrast in rheology. Establishing the nature and origin of this aseismic volume will likely shed light on the geodynamics of the Taiwan arc-continent collision.

Keywords: Taiwan, seismogenic strain, collision, exhumation, normal fault

Orogenic processes in Taiwan and the role of changes in motion of the Philippine Sea Plate

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The Taiwan orogenic belt is often treated as a steady, southward propagating orogenic system with a steady erosion rate of 4–6 mm/yr since the collision began, 6-5 Ma. A few recent studies of the exhumation history, however, suggest that the collision was initially simultaneous and that the tectonic setting may have been more complicated. To better understand orogenic processes in Taiwan and their relation to past plate motions we evaluate the exhumation history in more detail and compare this history to different interpretations of orogenic evolution and to possible changes in motion of the Philippine Sea Plate 15 Ma to present. A more detailed view of the exhumation history comes from four new age-elevation transects from, north to south, the Central Cross-Island Hwy, the South Cross-Island Hwy, Mt Yu and an area around Small Ghost Lake in southern Taiwan. Mt Yu, is from the western Central Range whereas the remaining three are from the eastern part of the range. The age-elevation transects are based on 106 new and previously published (U-Th)/He and fission track ages of detrital zircon and apatite grains. The results show that all four sites record similar exhumation histories from about 5 Ma to the present, with slow apparent exhumation cooling (~ 0.1 mm/yr) from 5 Ma to about 1.5 to 2 Ma, moderate apparent exhumation cooling (3-5 mm/yr) from about 2 to 0.5 Ma and relatively fast exhumation cooling (5-8 mm/yr) from 0.5 Ma to present. Although several interpretations of the progressively increasing rate of exhumation cooling since 5 Ma are possible, we focus on two end-member hypotheses: 1) progressively thicker crust, possibly continental in composition, is subducted and possibly underplated and 2) the rate of convergence between the PSP and Eurasia plates increases at ~2 Ma and again at 0.5 Ma, which leads to greater shortening and higher rates of exhumation in the Central Range. To evaluate these hypotheses we examine the crustal structure in Taiwan using Vp and Vs tomography (Huang et al., 2015) and re-examine geologic and geophysical evidence for changes in motion of the PSP 15 Ma to present.

Keywords: plate tectonics, orogenic processes, collisions

Arc volcanism, forearc seismogenesis and interplate coupling in the Kuril-NE Japan subduction zone

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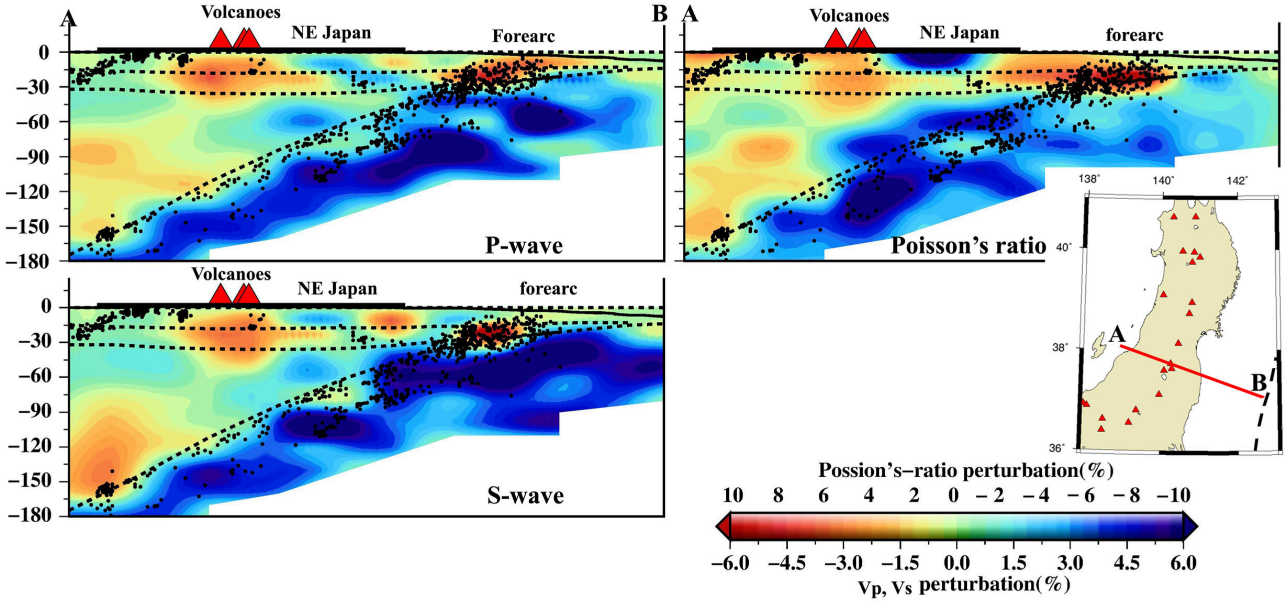
Subduction of the Pacific plate into the entire Kuril-NE (northeastern) Japan arc plays important roles in tectonic evolution, repeated occurrences of megathrust earthquakes (M >7.5) and arc volcanism and genesis of inland earthquakes. To improve our knowledge of crustal and upper mantle structures through tomographic imaging, we determined the three-dimensional (3-D) velocity (Vp, Vs) and Vp/Vs structures under the Kuril-NE Japan subduction zone. In this study, three groups of data sets are included in the hypocenter location process simultaneously with tomographic inversion. The first data group includes 385 offshore earthquakes, from which 2843 sP depth phases were identified. The second data group includes 3546 offshore earthquakes that occurred close to the first data group. The third group includes 13,603 onshore earthquakes that are located within the land-based seismic stations. The offshore hypoceters were relocated using the Master event location method (Wang and Zhao, 2006b, c). As a result, 3546 offshore earthquakes were selected from a large number of offshore earthquakes. Finally, a total of 413,032 P- and S-wave source-receiver pairs were collected from the 17,534 onshore and offshore earthquakes for imaging the P- and S-wave velocity and Vp/Vs structures.
A new method to invert Vp and Vp/Vs images simultaneously using a large number of high-quality arrival times of P-wave and S-wave source-receiver pairs from both onshore and offshore earthquakes is presented, indicating that the inverted Vp and Vp/Vs models are mutually correlative compared with the previous models. The hypocenters of the offshore earthquakes relocated by using sP phases jointly with the master-event location (MEL) method, enabling us to reliably image seismic structures not only under the onshore areas but also under the offshore areas. The Vp, Vs and Vp/Vs models provide compelling evidence for a highly hydrated and serpentinized forearc mantle and the fluids related to low-velocity and high-Vp/Vs anomalies associated with the slab dehydration (Figure 1). Significant slow anomalous Vp and Vs with a high-Vp/Vs ratio are clearly imaged along the volcanic front with an extended depth of ?100 km under the Kuril-NE Japan arc, showing good consistency with the results of previous studies, which is caused mainly by the fluids associated with the extensive dehydration of the subducting Pacific slab. More than 85% of the historical megathrust earthquakes (M >7.5) occurred in or around the high-velocity areas along the upper interface of the subducting slab under the forearc regions, suggesting strong interplate coupling (asperities) with the subducting slab. Alternatively, prominent low-velocity areas with high-Vp/Vs anomalies are revealed along the slab's upper boundary in the offshore regions, which may reflect weak coupled or decoupled patches (aseismicity) of the plates caused by serpentinization of the forearc mantle wedge. Our study suggests that the fluid-related anomalies under the Kuril-NE Japan arc system, attributed to various processes such as slab dehydration and serpentinization of the forearc mantle wedge, are contributed mainly by arc magmatism, interplate coupling and the repeated generation of megathrust earthquakes.

Keywords: Subduction zone, Forearc seismotectonics, Arc magmatism


Volcanoes
NE Japan
Forearc
P-wave
S-wave
forearc
Poisson's ratio
A
B
Possion's–ratio perturbation(%)
Vp, Vs perturbation(%)

Lithospheric structure and composition of the Southern Marianas

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The 3000 km long Izu-Bonin-Mariana (IBM) arc system is an outstanding example of an intraoceanic convergent plate margin. The IBM forearc is a typical nonaccretionary convergent plate margin; the inner trench slope exposes lithologies found in many ophiolites including several km of mantle. To more clearly delineate the geology of the forearc, we have been investigating a ~700 km long region of the Mariana forearc south of ~13°N near Guam to the Yap Trench junction in 6 expeditions with the DSV Shinkai 6500 and deep-tow camera since 2006. Except for a few expeditions in 1970’s, there have been no studies of the southern Mariana forearc west of the Challenger Deep. Data from our expeditions therefore provide a new perspective on the lithospheric structure and composition of the southern Mariana forearc. Most strikingly, mantle peridotite extensively crops out and has been sampled from the inner trench wall along the southernmost Mariana forearc.
Peridotites from the southwesternmost Mariana forearc near the Yap Trench junction area are strikingly fresh and have fertile compositions similar to those from the Parece Vela backarc basin [Ohara et al., 2003, G3]. The freshness of the peridotites indicates continuing protrusion of backarc-basin peridotite along the inner trench slope near the Yap Trench junction, possibly as a result of continuing backarc extension or collision of the Caroline Ridge.
Peridotites from near the Challenger Deep are exposed below the Moho as shallow as ~4500 m bsl and are heterogeneous, ranging from fertile lherzolites (i.e., backarc basin-like) to depleted harzburgites (i.e., forearc-like). In addition, we found that the forearc northeast of the Challenger Deep experienced rifting unusually close to the trench axis, exposing young (~ 3 Ma) basaltic lava with Mariana Trough backarc basin affinity [Ribeiro et al., 2013, Island Arc]. Earthquake foci also indicate that the forearc northeast of the Challenger Deep is a region of strong extension, and bathymetric data indicate that multiple tectonic rifts dissect it, indicating that diffuse extension occurs in the forearc.
We now argue that the southern Mariana forearc northeast of the Challenger Deep has heterogeneous lithospheric structure and composition, a mixture of those of backarc and forearc. A serpentinite-hosted ecosystem, the Shinkai Seep Field [SSF; Ohara et al., 2012, PNAS] is located in this area. SSF is a diffuse cold seep, serpentinite-hosted system that hosts an ecosystem mainly consisting of vesicomyid clams. We have tried to find other such seeps along the southern Mariana forearc during 2013 to 2015 expeditions, but no such seeps have yet been found, partly because these seeps are low-T and do not provide much of a thermochemical plume in the water column. We hypothesize that SSF vent fluid originated from seawater circulated within the shallow crust driven by the heat of young backarc-like magmatic intrusions. This mechanism is similar to that proposed for the Lost City hydrothermal field in the Mid-Atlantic Ridge [Allen and Seyfried, 2004, GCA]. We hypothesize that lithospheric mantle associated with forearc rifting is necessary for SSF-type seeps. This in turn suggests that finding where recent igneous activity has occurred in the southern Mariana forearc northeast of the Challenger Deep is the best strategy for finding new SSF-like seeps.

Keywords: southern Mariana forearc, peridotite, Shinkai Seep Field

The dynamics of double slab subduction from numerical and semi-analytic models

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Regional interactions between multiple subducting slabs have been proposed to explain enigmatic slab kinematics at a number of subduction zones, a pertinent example being the advancing motion (i.e. toward the upper plate) of the Izu-Bonin trench (Cizkova & Bina, 2014). An additional, important example is the rapid pre-collisional plate convergence of India and Eurasia during the Late Cretaceous, which is hypothesized to be due to the existence of two north-dipping subduction zones (e.g. Jagoutz et al., 2015). However, dynamically consistent 3-D numerical models of double subduction have yet to be explored, and so the physics of such double slab systems remain poorly understood. Here we augment fully numerical finite element models (CitcomCU) with semi-analytic subduction models (FAST: updated from Royden & Husson, 2006) to explore how subducting slab kinematics, particularly trench and plate motions, can be affected by the presence of an additional slab, with all of the possible slab dip direction permutations. A second subducting slab gives rise to more complex dynamic pressure and mantle flow fields and, for double slab systems within which the two slabs dip in the same direction (e.g. Izu-Bonin and Ryuku trenches, Late Cretaceous India-Eurasia), an additional slab pull force that is transmitted across the subduction zone interface. While the general relationships among plate velocity, trench velocity, asthenospheric pressure drop, and plate coupling modes are similar to those observed for the single slab case, we find that multiple subducting slabs can interact with each other and indeed induce slab kinematics that deviate significantly from those observed for the equivalent single slab models. Double subduction therefore provides a geodynamic mechanism to induce slab kinematics which differ drastically from those predicted from single slab experimental/modeling studies.
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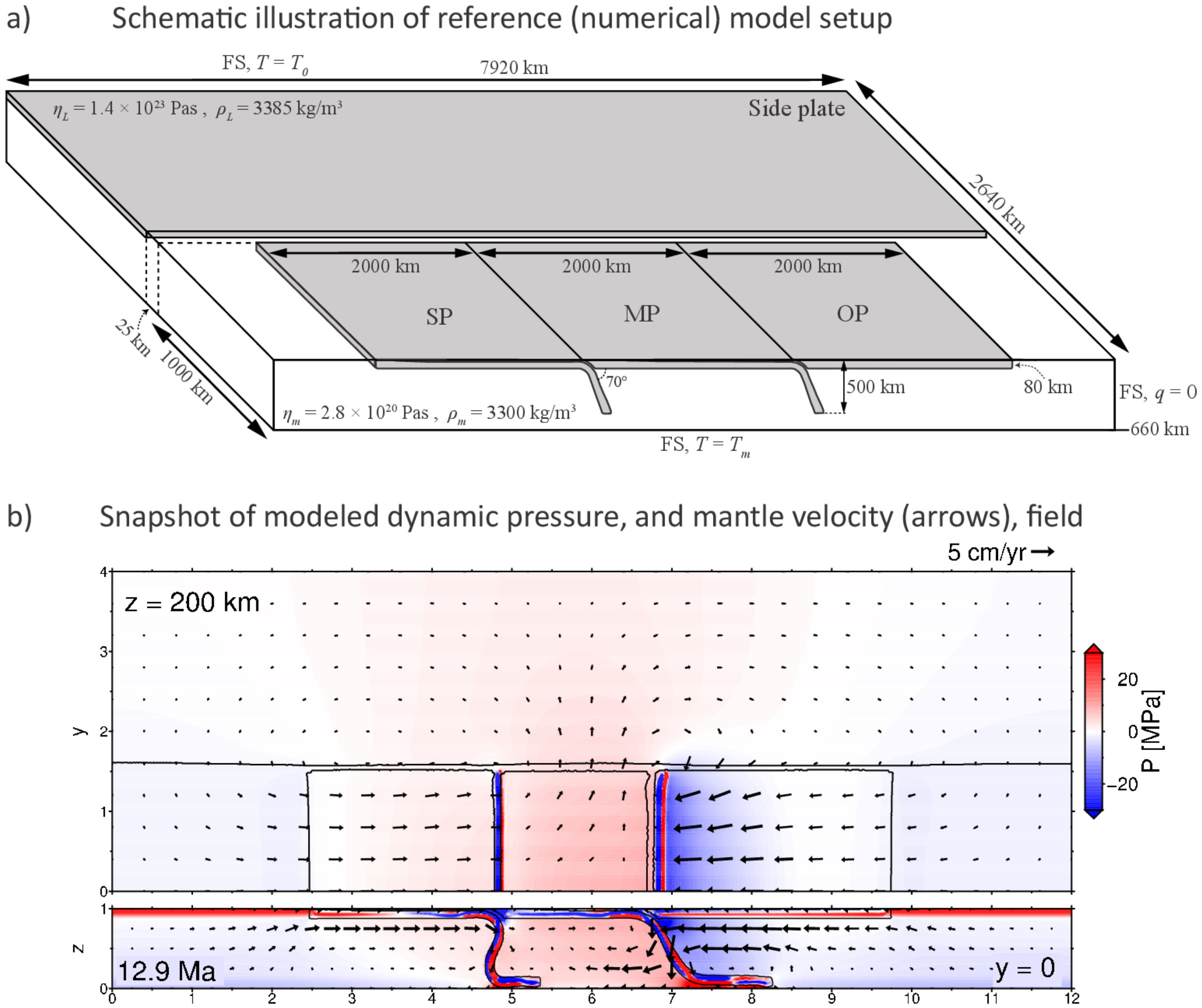
Zhong, S., 2006, J. Geophys. Res., 111, doi: 10.1029/2005JB003972.

Keywords: Subduction, Convergence rates, Trench motion, Mantle wedge, Slab coupling


a) Schematic illustration of reference (numerical) model setup
FS, $T = T_0$
7920 km
$\eta_L = 1.4 \times 10^{23}$ Pas, $\rho_L = 3385$ kg/m³
Side plate
2640 km
2000 km
2000 km
2000 km
SP
MP
OP
25 km
1000 km
70°
500 km
80 km
FS, $q = 0$
660 km
$\eta_m = 2.8 \times 10^{20}$ Pas, $\rho_m = 3300$ kg/m³
FS, $T = T_m$
b) Snapshot of modeled dynamic pressure, and mantle velocity (arrows), field
5 cm/yr
z = 200 km
y
z
12.9 Ma
y = 0
P [MPa]
20
0
−20

Arc-Arc Collision Structure in the Southernmost Part of the Kuril Trench Region -Overview of Results from Integrated Renalyses for Controlled Source Seismiata in the Hidaka Collision Zone-

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The southernmost part of the Kuril trench is known as an arc-arc collision zone. Since the middle of the Miocene, the Kuril forearc has been colliding against the NE Japan arc to form very complicated and unique tectonic environment in the middle part of the Hokkaido Island (the Hidaka Collision Zone (HCZ)). In this region, several seismic reflection/refraction experiments were undertaken (Arita et al., 1998; Tsumura et al., 1999; Ito et al., 2000, Iwasaki et al., 2004). Our integrated reinterpretation for these data sets, which started in 2012, revealed detailed and new structural features and their regional difference within the HCZ.

In the southern part of the HCZ, the crustal delamination associated with the collision was clearly imaged by applying CRS/MDRS method to the seismic reflection data (Tsumura et al., 2014). Namely, the upper 22-23 km crust of the Kuril arc is off-scrapped and obducted along the Hidaka Main Thrust (HMT), while the lower part of the crust is descending down to reach the subducted Pacific plate.

In the northern part of the HCZ, the HMT is also well imaged both by seismic reflection processing and refraction/wide-angle reflection analysis, but the delamination structure as obtained in the southern HCZ is not clearly seen. Around the HMT, the crystalline basement is almost outcropped. In the west of the HMT, several eastward dipping layering is found down to a depth of 7-8 km, probably corresponding to fragments of Cretaceous subduction/arc complexes or deformation interfaces branched from the HMT. The relatively higher velocity in the uppermost crust just east of the HMT represents the base of the obducted middle or (upper part of) lower crust of Kuril arc. The upper crustal structure in the hinterland (the Tokachi Basin) is characterized by 5-7 km thick undulated sedimentary layers which were deformed by faulting in some places.

The most important finding in the northern HCZ is a clear image of the NE Japan arc crust descending eastward to a depth of about 40 km under the hinterland side. Our refraction/wide-angle reflection analysis revealed the very complicated structure above the descending NE Japan arc. Strong dipping reflectors with a velocity contrast of 0.5-1 km/s are distributed in a depth range of 10-35 km in the HCZ west of the HMT. Our result shows that the subducted NE Japan arc meets the Kuril arc 20-40 km east of the HMT at a depth of 20-30 km. Although the Moho of the Kuril arc is not determined, our data provide no evidence for a shallow Moho (< 30 km) as indicated by tomography studies.

The obduction of the upper Kuril crust starts at a deeper crustal level of at least 27-30 km and more easterly (~20 km) of the HMT as compared with the case in the southern HCZ. If the metamorphic rocks outcropped east of the HMT are the same crustal materials shallower than 22-23 km depth as in the case of the southern HCZ, the deeper crustal portion originally situated at 23-27~30 km depth must exist in the western side of the present HMT. The very strong and deep reflectors found west of the HMT might result from the mixture of upper crustal (low velocity) materials of the NE Japan arc and middle/lower crustal (high velocity) materials of the Kuril arc.

Keywords: arc-arc collision, Hidaka, crustal delamination, NE Japan arc, Kuril arc

Major variations in vitrinite reflectance and consolidation characteristics within a post-middle Miocene forearc basin, central Japan

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Forearc basin sediments near the oceanward margin preserve tectonic information related to plate subduction. The post-middle Miocene Boso forearc basin, central Japan, records major differences in structure, paleo-maximum temperature, and consolidation state between below (Miura Group) and above (Kazusa Group) the Kurotaki Unconformity, which formed at ca. 3 Ma. Many fault systems below the unconformity are characterized by a disaggregation-band-like inner fabric that apparently formed soon after sedimentation, whereas there are few of this type of fault system above the unconformity. Vitrinite reflectance values (Ro) are 0.38%–0.44% and 0.16%–0.22% below and above the unconformity, respectively. The consolidation yield stress (p_c) in the Miura Group (23.7 MPa in the Anno Formation; 31.0 MPa in the Amatsu Formation) is much greater than that in the Kazusa Group (7.5 MPa in the Umegase Formation; 7.6 MPa in the Ohtadai Formation). These clear differences in vitrinite reflectance and consolidation characteristics above and below the unconformity are attributed to a change in the convergence direction of the Philippine Sea Plate, which resulted in the Miura Group being uplifted and eroded by ~2000 m before sedimentation of the Kazusa Group. The forearc basin, especially near the trench-slope break, records structural and physical properties reflecting the plate-tectonic environment and the development of the trench-slope.

Keywords: Forearc basin, Boso Peninsula, Vitrinite reflectance, Consolidation test

Crustal structure and opening process on the back-arc basin in the southwestern margin of the Japan Sea

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The Japan Sea is one of very well studied back-arc basins in the northwestern Pacific. Based on geophysical, geological, and petrological results, it is suggested that the back-arc opening of the Japan Sea was taken from the Early Oligocene to the Middle Miocene (e.g., Tamaki et al., 1992).
From 3.5 Ma, in the eastern and southwestern margins, the crustal shortening by a strong compression occurred (e.g., Sato, 1994, Itoh et al., 1997). The deformation such as active faults and folds has developed in these margins because of these opening and shortening (e.g., Okamura et al., 2007). Recently, in the eastern margin of the Japan Sea, it was found from the result that the deformation zone affected by the shortening and back-arc opening is distributed on the rifted island arc crust, and on a structural boundary between this arc crust and the thicker oceanic crust in the northern part only by the seismic survey (No et al., 2014, Sato et al., 2014). This result shows that the back-arc opening process and the crustal structure formed by this opening may have connection with this deformation process. Although the southwestern margin of the Japan Sea seems to have the region of the complex formation process, we have little information about the crustal structure formed by back-arc opening, and the detailed opening process in this margin. To obtain this information, the active-source seismic survey using ocean bottom seismographs (OBSs), and multi-channel streamer system (MCS) was undertaken from the arc to the back-arc basin of the southwestern margin of the Japan Sea off Echizen-misaki cape, Fukui Prefecture in 2015.
This seismic survey using 54 OBSs and a tuned air-gun array (7,800 cu. inch) was conducted from the continental shelf off Echizen-misaki cape, Fukui Prefcture, Oki Trough, Oki Ridge, Yamato Basin to the Kita-Oki Bank, in the southwestern margin of the Japan Sea. This survey line has about 270 km length. In record sections of several OBSs and land stations, not only the first arrived phases but also later phases reflected from interfaces in the crust and uppermost mantle are visible.
The Oki Ridge has about 20 km of the crustal thickness. The upper part of the crust with P-wave velocity of 5.4-6.2 km/s corresponding to the continental upper crust has about 10 km. This shows that the Oki Ridge may have the character of the continental crust. On the other hand, the crust in the Yamato Basin and Oki Trough has 13 and 15 km thick, respectively. These are thinner than that the Oki Ridge. The Yamato Basin and Oki Trough do not have the character of the typical continental crust. The upper part of the crust in the continental shelf area has 10 km with a lateral variation. This crust may have the continental crustal type because the P-wave velocity distribution is similar to that of the continental upper crust in Korean Peninsula (Cho et al., 2006). And, this variation may correspond to the distribution of the deformation. This crustal structure in the southwestern margin of the Japan Sea off Fukui differs from that in the northern part of the eastern margin (No et al., 2006). This might show that the southwestern margin off Fukui is different from the northern one on the back-arc opening process.

Keywords: Japan Sea, back-arc basin, crustal structure, opening process

Multi-disciplinary approaches toward understanding the fault slip behaviors from surface to depth: a case study of the Chihshang Fault in eastern Taiwan

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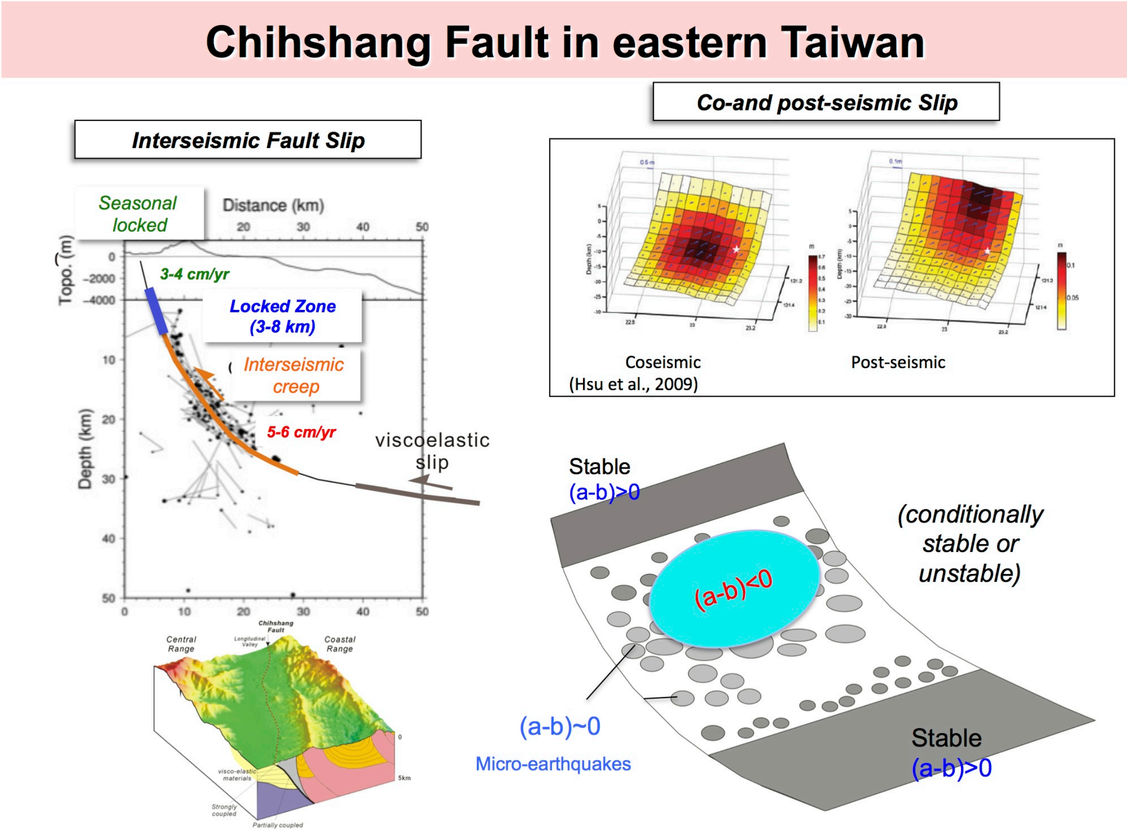
Based on a multi-disciplinary approach, including geological survey, geodetic GPS and leveling measurements, seismology, frictional properties modeling, kinematics dislocation modeling, hydraulic experiments and analyses and geophysical surveys, we aim at better characterizing the slip behaviors of an active fault from surface to depth and their spatial and temporal variations. Our case study is the Chihshang Fault, which we treat as an example of an on-land mega-thrust at the converging plate suture between the Philippine Sea plate and Eurasia. The geometry of the Chihshang Fault is characterized by a 35-km-long, 25-30-km deep patch, which exhibits a listric shape with dip angle of about 60-70° at the shallow kilometers and of about 20-30° at the depth of 20-30 km. GPS and leveling data indicate that the Chihshang Fault is creeping at a rather high rate of about 3-5 cm/yr for mostly the whole patch during the interseismic peripod. According to seismological studies, the slippage on the fault is accompanied by abundant micro-seismicity distributed on the fault patch at the depths of 5 to 25 kilometers. Amongst this seismicity, repeating earthquakes were observed at some places, especially near the northern edge of the fault patch. It seemed that these numerous interseismic micro-earthquakes had released a substantial part of the strain accumulated on the fault induced by the plate convergence or the attachment of the Luzon arc to the Chinese continental margin. However, the 2003 Mw=6.8 Chengkung earthquake suggests otherwise. How the strain accumulated to produce the Chengkung earthquake is still under investigation. But we do observe a significant decrease of surface fault creeping rate of about 25%, starting about 3-4 years before the Chengkung earthquake, which is also suspected to be due to effect of 1999 Mw=7.5 Chi-Chi earthquake (e.g., stress transfer). It is worthy note that the creep meters data along the surface fault zones at Chihshang site revealed a clear seasonal variation, implying a dry-season lock with no or very little slip. Numerical modeling by applying frictional instability laws suggested this seasonal slip/stress perturbation in relation with rainy season is confined within the upper hundreds of meters level, with a positive value of frictional property (a-b). We tend to interpret that this frictional property is related to the unconsolidated alluvial deposits, which cover the Longitudinal Valley for a thickness estimated to be about 3-5 hundreds meters. Indeed the propagation of the Chengkung earthquake co-seismic slip had decreased drastically in the uppermost 1-2 kilometers. And the accumulated strain in the upper segment of the fault has been released by rapid post-seismic slip following the earthquake. This is also consistent with the dynamic effect on the frictional property of the fault.

Keywords: active fault, creep, earthquake, frictional property


Chihshang Fault in eastern Taiwan
Co-and post-seismic Slip
Interseismic Fault Slip
Seasonal locked
Distance (km)
Topo. (m)
3-4 cm/yr
Locked Zone (3-8 km)
Interseismic creep
5-6 cm/yr
viscoelastic slip
Depth (km)
Central Range
Chihshang Fault
Coastal Range
Coseismic
(Hsu et al., 2009)
Post-seismic
Stable
(a-b)>0
(conditionally stable or unstable)
(a-b)<0
(a-b)~0
Micro-earthquakes
Stable
(a-b)>0

Tomography of the source zone of the 2016 South Taiwan earthquake

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On February 6, 2016, a *M*w 6.4 earthquake occurred in Kaohsiung City, southern Taiwan, at a depth of 17 km (hereinafter we call it the 2016 South Taiwan earthquake). It caused 116 fatalities and widespread damage to infrastructures, especially in the Tainan city. To clarify the generating mechanism of this damaging earthquake, we conducted seismic tomography for high-resolution 3-D *V*p, *V*s and Poisson’s ratio (σ) structures in the epicentral area. We used 91,703 *P*- and 51,718 *S*-wave arrival times from 7,038 local earthquakes (0.6≤*M*≤5.8) recorded at 41 seismic stations operated by the Central Weather Bureau in South Taiwan during 2000-2011.

Our tomographic images reveal significant variations of up to 6% for *V*p and *V*s, and 10% for Poisson’s ratio in the crust and uppermost mantle beneath South Taiwan. In the upper crust (depth≤ 10 km), the most remarkable feature is low-*V*p, low-*V*s and high-σ anomalies in areas with known active faults in the southwest and easternmost parts of Taiwan. In contrast, high-*V*p, high-*V*s and low-σ anomalies become dominant in the lower crust. The hypocenter of the 2016 South Taiwan earthquake is located in a boundary zone where seismic velocity and Poisson’s ratio change drastically in both the horizontal and vertical directions. Furthermore, the hypocenter is underlain by a vertically elongated high-σ anomaly at depths of 23-40 km, which may reflect ascending fluids from the upper (or uppermost) mantle.

The low-*V* and high-σ anomalies in the upper crust coincide with areas of low heat flow (Hsieh et al., 2014), negative Bouguer gravity anomaly (Yen and Hsieh, 2010), and low magnetotelluric resistivity (Bertrand et al., 2012), which may reflect crustal fluids contained in the young fold-and-thrust belt and the dehydration of the subducting Eurasian plate (slab). The South Taiwan source zone also corresponds to an area of the maximum stress loading rate induced by erosion (Steer et al., 2014). These results suggest that the 2016 South Taiwan earthquake was triggered by the ascending fluids from the Eurasian slab dehydration, invading into an active fault with a high loading rate.

Keywords: 2016 South Taiwan earthquake, Seismic tomography, Crustal fluids

Tectonic Features and Megathrust System Offshore South Taiwan

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Located in the Taiwan-Luzon convergent belt, offshore southern Taiwan is one of the ideal natural laboratories to study magatrust faults. Morphotectonic features offshore southern Taiwan suggests that the width of the collisional wedge decreases southward and connects to the northernmost part of the Manila subduction system. Reflection seismic profiles across the southernmost Taiwan collisional belt reveal not only fold-thrust belt in the frontal (western) part of the collisional wedge, but a magatrust system with splay faults, which is also supported by OBS velocity profiles. In order to better understand this megathrust system and its variations from south to north, as the tectonic processes changes from subduction in the area offshore south Taiwan to collision on land Taiwan, we analyze a series of large-offset deep seismic reflection profiles that ran across this megathrust fault system. Decollement has clearly been observed below the lower slope domain of the accretionary wedge. The range of the decollement increases from south to north, inferring that the continental materials have been carried into the subduction zone and the subduction angle decreases from south to north. The crustal velocity model derived from OBS data suggests the possible existence of tectonic underplating beneath this collisional belt. The existence of the megathrust system represents this area have high potential of seismic and tsunami threat.

Keywords: offshore southern Taiwan, collisional belt, OBS

Interpretation of seismic waveform at regional distance for determining focal depth: a case study in Sulawesi Island, Indonesia

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Sulawesi Island, one of the five largest islands in Indonesia, has high seismic activities due to complex tectonic structures related to some active faults (e.g., Palu Koro, Matano and Hamilton faults) and subduction zones. Reliable focal depths of crustal earthquakes are necessary to understand seismotectonics of the crustal layer in Sulawesi Island and its vicinity. However, due to the sparse seismic network, direct P- and S-wave arrival times are not precise to estimate the focal depths in the study area. To obtain more precise focal depths, this study analyzed waveforms of some swarm earthquakes in four areas of interest in Sulawesi Island and considered the effect of sedimentary layer on seismic wave propagation which yields more reflected phases in seismograms. We have selected swarm crustal earthquakes with 5-30 km focal depth range and ≤3.5 deg for station-event distance. In this study, we focused on preliminary depth phases by comparing synthetic and observed seismograms. We calculated the envelope of the seismograms in order to find different peaks of reflected phases clearly. Synthetic seismograms were generated using the reflectivity method with crustal velocity model derived from CRUST 1.0 and IASP 91 and different thickness of sedimentary layers. By the comparison, we could estimate possible pairs of focal depth for crustal earthquakes and apparent thickness of sedimentary layer along the path from each earthquake. Our study showed that the existence of ocean basins and sedimentary layer led to more complex seismograms in the study area. Therefore, we need to consider the waveform complexity for focal depth determination.

Keywords: Crustal earthquakes, Sulawesi Island, Reflected phases, Synthetic seismograms

Morphology of the stagnant slab from the northern Okhotsk arc to the northeastern Japan arc and its geodynamic implications

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The slab morphology as revealed by the seismic tomography is supposed to have much information on the physical properties of mantle transition zone, viscosity structure, geologic history and e.t.c. Incorporating the results of seismic tomography and the geologic history around the northeastern Japan arc with 2D numerical geodynamic models, Honda (2016) concluded that the stagnant slab there is the accumulated slab from the time when the ridge plate boundary between the Izanagi and Pacific plate subducted there around 60 Ma. The similar subduction history can be expected also around the northern Okhotsk arc. However, the slab morphology of each region is quite different, that is, the significant slab stagnation around the northeastern Japan arc versus the slab penetration around the northern Okhotsk arc. Honda (2016) also noticed that the slab stagnation around the northeastern Japan zone requires steeper Clapeyron slope than that estimated by the experiments. In this presentation, I seek the consistent answer to these problems based on the dynamics of hot subslab mantle under the Pacific plate (Morishige et al., 2010; Ismail-Zadeh et al. 2013), because it gives the additional force to support the negative buoyancy of the slab in addition to the endothermic phase change at 660 km and it shows the along-arc variations. An example of results is shown in the figure. Upper figures are derived from the seismic tomography following the procedure described in Honda (2016). The lower figures are derived from the numerical models described in Honda (2016).

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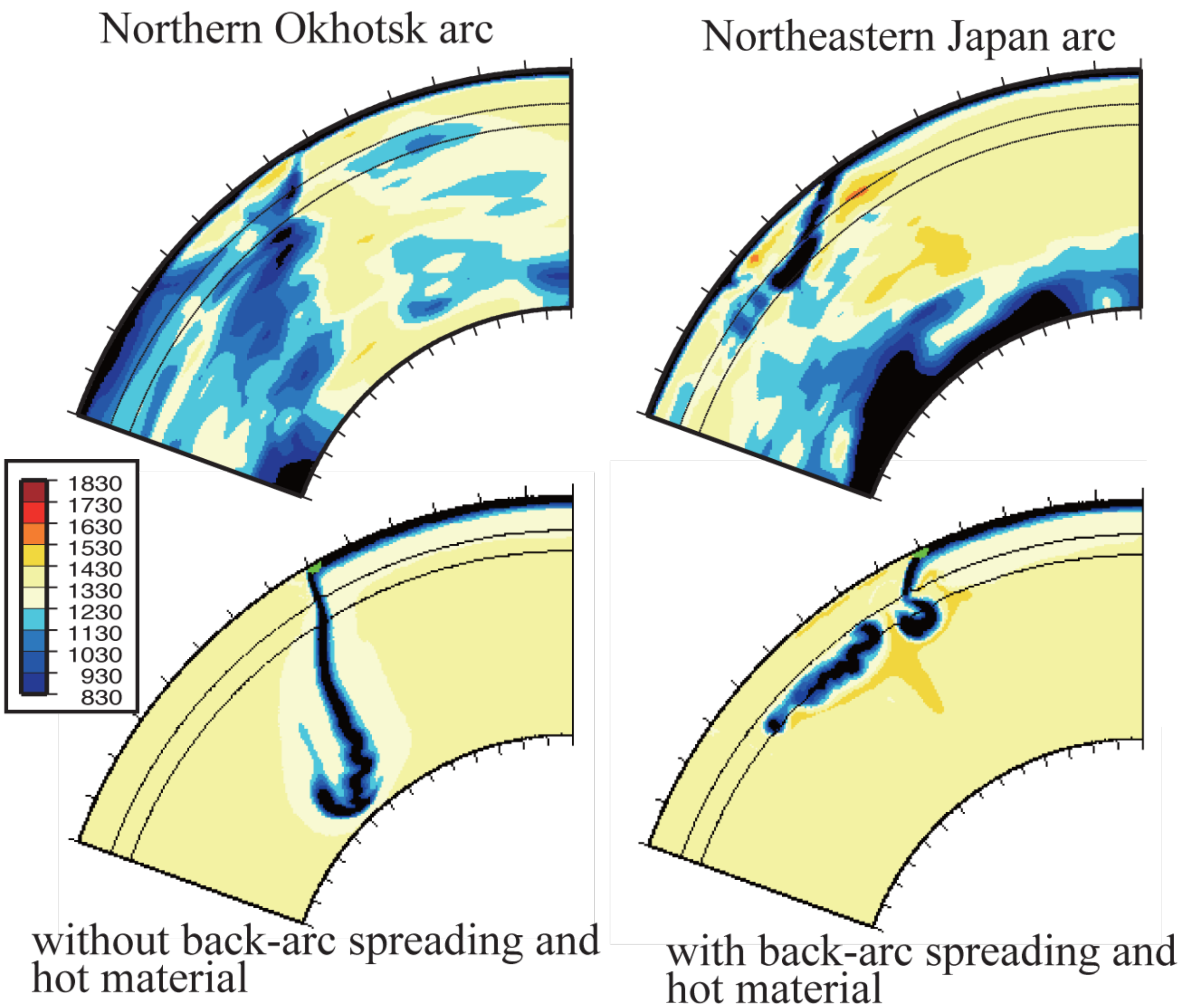
Keywords: subduction zone, stagnant slab, geodynamics, Okhotsk, northeast Japan


Northern Okhotsk arc
Northeastern Japan arc
1830
1730
1630
1530
1430
1330
1230
1130
1030
930
830
without back-arc spreading and hot material
with back-arc spreading and hot material