Stagnant slab tectonics of the Japan and northern Tonga slabs

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Seismic tomography has revealed enigmatic stagnant slab anomalies under Japan, Korea and NE China (i.e. the Japan slab). The stagnant slabs flatten near the mantle transition zone around ~410 to 660 km depths and extend >2000 km westward from the NW Pacific subduction zones. The location of the outboard stagnant slabs far inland under Eurasia cannot be explained by slab rollback alone and pose a challenge to our current understanding of subducted slab dynamics, in which slabs sink vertically over time with minimal lateral motion.

In this study, we use new and recently published 3D slab mapping, slab unfolding and plate reconstruction constraints (Wu et al., 2016, JGR) from MITP08 and GAP_P4 global tomography (Li et al., 2008, G3; Fukao et al., 2013, JGR). We show that the Japan stagnant slabs are best reconstructed as Pacific slabs that subducted in the Cenozoic after Pacific-Izanagi ridge subduction between 60 to 50 Ma. Mantle flow forward models reproduce our Japan slab reconstruction results (Seton et al., 2015, GRL). Our reconstruction implies the Japan slabs moved laterally westwards within the upper mantle and transition zone after subduction at near-plate tectonic rates (~2 cm/yr over 50 Ma), indicating a greater lateral mobility of slabs within the upper mantle and transition zone than previously recognized.

Using our Japan slab subduction model, we re-examine the enigmatic Vityaz deep earthquakes under the Fiji Basin, which are widely thought to be a globally-unique case of seismicity within a foundered and detached slab. Our Tonga slab mapping shows the Vityaz earthquakes are actually part of a >2500 km-long mega-Wadati-Benioff zone of the northern Tonga stagnant slab. Our slab reconstruction suggests the northern Tonga slab moved laterally westward in a similar fashion to the Japan slabs, but at a faster rate of >5 cm/yr over 15 Ma within the upper ~660 km. Our results suggest that earthquakes can be produced thousands of kilometers away from a subduction zone from lateral movements of still-attached but mobile stagnant slabs within the uppermost ~660 km mantle.

Keywords: Stagnant slabs, seismic tomography, Japan slab, Tonga slab, Izanagi plate

Seismic imaging of the subducting Philippine Sea plate

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We use the updated methods of seismic tomography to study the 3-D crustal and mantle structure of the western Pacific subduction zones. The subducting Pacific and Philippine Sea (PHS) slabs are imaged clearly. Our results show that the PHS plate has subducted aseismically down to ~460 km depth under the Japan Sea, Tsushima Strait and East China Sea. The aseismic PHS slab is visible in two areas: one is under the Japan Sea off western Honshu, and the other is under East China Sea off western Kyushu. However, the aseismic PHS slab is not visible between the two areas, where a slab window has formed. The slab window is located beneath the center of the study region where many teleseismic rays crisscross. Detailed synthetic tests were conducted, which indicate that both the aseismic PHS slab and the slab window are robust features. The slab window may be caused by the subducted Kyushu-Palau Ridge and Kinan Seamount Chain where the PHS slab may be segmented. Hot mantle upwelling is revealed in the big mantle wedge (BMW) above the Pacific slab, which may have facilitated the formation of the PHS slab window.
Our P-wave anisotropy tomography shows that the fast-velocity direction (FVD) in the subducting PHS slab beneath the Ryukyu arc is NE-SW (trench parallel), which is consistent with the spreading direction of the West Philippine Basin during its initial opening stage, suggesting that it may reflect the fossil anisotropy. Significant FVD variations with depth are revealed in the subducting Pacific slab beneath the NE Japan arc, which may be caused by slab dehydration that changed elastic properties of the slab with depth. The FVD in the mantle wedge beneath the NE Japan and Ryukyu arcs is trench normal, which reflects subduction-induced convection. Beneath the Kuril and Izu-Bonin arcs where oblique subduction occurs, the FVD in the mantle wedge is nearly normal to the moving direction of the down-going Pacific plate, suggesting that the oblique subduction together with the complex slab morphology have disturbed the mantle flow.

Keywords: Philippine Sea plate, Pacific plate, Aseismic slab, Earthquakes, Seismic tomography

The origin of the early Cenozoic belt-boundary thrust and the Izanagi-Pacific ridge subduction in the western Pacific margin

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The belt-boundary thrust within the Cretaceous-Tertiary accretionary complex in the Shimanto Belt, SW Japan extends more than ˜1,000 km along the Japanese islands. A common understanding of the thrust is an out-of-sequence thrust as a result of continuous accretion since the late Cretaceous period and kinematic reason to keep a critically tapered wedge. The timing of the accretion-gap and thrusting, however, coincides with encounter of the Paleocene-early Eocene Izanagi-Pacific spreading ridge with the trench along the western Pacific margin, which is recently re-hypothesized younger than the previous assumption of Kula-Pacific ridge subduction in the late Cretaceous period. Cessation of magmatic activity along the continental margin, and unconformity in the forearc basin with uplift and subsidence is consistently explained by the ridge subduction hypothesis. This is not only in SW Japan but also more northern Asian margin in Hokkaido and Sakhalin, and Shikote-Alin. This Paleocene-early Eocene ridge subduction hypothesis is also consistent with recently acquired tomographic image beneath the Asian continent. The timing of the Izanagi-Pacific ridge subduction along the western Pacific margin lets to revive the classic hypotheses for a great reorganization of the Pacific plate motion represented as the Emperior-Hawai bend between the ˜47 Ma to 42 Ma due to the change in subduction torque balance, and the Oligo-Miocene back-arc spreading following the ridge subduction in the western Pacific margin.

Structural evolution of the Tsushima Strait, Southern Sea of Japan, and its role in active faulting

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The Japanese island arc is situated in a highly active tectonic area, with earthquakes and tsunami hazard on both the Pacific and Sea of Japan coasts. Following the tsunami disaster produced by the 2001 off-Tohoku earthquake (M9), the Japanese government started an intense evaluation of tsunami hazard spanning the both coastlines. Due to the lack of historical records of tsunamis along the western margin of Japan, hazard assessment is based on structural analyses of on- and offshore data. Here, we investigate the structural evolution of the Tsushima Strait, southern margin of the Sea of Japan, to get better constraints on the structural geometry of this region and develop a present-day tsunami source-fault model.

The Tsushima Strait is a structurally complex area that formed as the result of several regional tectonic events during the last 25 Ma that include back arc rifting and rotation, post-rift compression, weak thrusting, and strike-slip deformation. Previous work in this area is mainly based on onshore sedimentological, biostratigraphic, and paleomagnetic analyses, either on Kyushu and SW Honshu, or Tsushima Island, and only few studies include offshore subsurface data. However, the evolution of this region is not yet well understood, as conflicting hypotheses have been forwarded due to the limited resolution of the data available and methods applied.

In this study we use an extensive offshore subsurface dataset spanning ~625 km along SW Japan and ~150 km offshore in the Tsushima Strait. The data includes 2D seismic reflection profiles with a spacing between 2 –20 km imaging up to 7000 metres depth and 8 wells including detailed completion logs. We observe large basement blocks and igneous bodies, as well as rift-related grabens and half-grabens filled with syn-rift deposits, of which some are inverted. On several locations, these structures are cross-cut by strike-parallel reverse faults, or orthogonally trending flower structures. The observations are interpreted to be the result of a complicated geometrical development of the Tsushima Strait, related to the structural evolution of the Japan island arc and the Sea of Japan.

We argue that multiple, small, basins formed parallel to the Japan arc, during back arc rifting as a result of the subduction of the Pacific and Philippine Sea plates along the east coast of Japan initiating the opening of the sea of Japan (25 –14 Ma). Based on previous palaeomagnetic studies, clock-wise rotation of the SW Japan arc with its pivot point located in the SW of the Tsushima Strait occurred at the end of the rifting phase (17.9 –15.9 Ma), filling the basins with shallow to deep marine syn-rift sediments. From 14 –5 Ma, the marginal rift zone was then exposed to a compressional stress, resulting reverse faults and selective inversion in the Tsushima Strait. We link this shortening phase to the collision of the Izu-Bonin-Mariana arc system onto the Japan along its eastern side and the northward movement of the young Shikoku Basin within the Philippine Sea Plate. Previous work suggests that the high thermal buoyancy of the Shikoku Basin caused resistance along the Nankai trough leading to shortening. Subsequently, we propose that the sub-horizontal Pliocene sediments that cover the compressional structures mark the subduction of the Shikoku basin (5 –1 Ma). Lastly, the reactivation of reverse faults to strike-slip is assumed to represent another major change in stress regime at 1 Ma, as a result of a

northwesterly shift of the Philippine Sea plate and the opening of the Okinawa trough. The present-day active source-faults are defined in at least two different groups: 1) NW-trending, near vertical strike-slip faults, and 2) NNE- to ENE-trending steep (~70°) faults. The former group of active strike-slip faults are interpreted as the result of the current rotated stress field around Kyushu, and the latter to reactivation of the earlier Palaeogene and Neogene structures.

Keywords: Tsushima Strait, Structural evolution, Tsunami source-fault model, Crustal deformation, Sea of Japan, Seismic reflection data

Evolutionary process of the Nankai inner accretionary prism estimated by vitrinite reflectance analysis and zircon U-Pb age dating of deep borehole samples

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The Nankai accretionary prism has been grown with the plate convergence between the Eurasian/Amur and the Philippine Sea Plate. To evaluate the evolutionary processes of the Nankai inner accretionary wedge, we performed vitrinite reflectance analysis and detrital zircon U-Pb age dating using cuttings retrieved from the Integrated Ocean Drilling Program (IODP) Site C0002 located within the Kumano Basin and penetrates the inner accretionary wedge down to 3058.5 m below the seafloor (mbsf).
Although Ro values of vitrinite reflectance tend to increase with depth, there are two reversals (1300–1500 mbsf and 2400–2600 mbsf) of Ro values. The youngest detrital zircon U-Pb age of the cuttings from 2600.5 mbsf is ~7.41 Ma, which is obviously younger than shipboard nannofossil ages (9.56–10.54 Ma) at 2245.5 mbsf. Both Ro values and the youngest detrital zircon U-Pb ages show a reversal between 2400-2600 mbsf, suggesting the existence of a thrust fault with sufficient displacement to offset both paleothermal structure and sediment age.
Despite similar depositonal age and paleogeothermal gradient, lithofacies in the hanging- and footwall of the 2400–2600 mbsf thrust fault are different; volcaniclastic sediments are rare in the footwall. The lack of volcaniclastic sediments corresponding to the Middle Shikoku Basin facies in the footwall of the thrust suggests that sediments below ~2600 mbsfhave similar sedimentation background to that of present off-Muroto input site sediments.Taking these information consideration, a synthesized model of tectonic evolutionary process of deep portion of the Nankai inner accretionary wedge is as follows: 1) 4 Ma: hemipelagic sediments, which deposited similar environment of present off-Muroto input, have accreted (~4 Ma corresponds to the age of unconformity between forearc basin and accretionary prism (Kinoshita et al., 2009)). 2) 2 Ma: The megasplay fault was activated (Strasser et al., 2009), and Site C0002 sediments moved into inner wedge. Moving direction of the Philippine Sea Plate became NNW to WNW (Kamata and Kodama, 1999). 3) present: inner accretionary wedge has been buried with formation of Kumano forearc basin. Sediments existed offshore of the ~4 Ma source area of Site C0002 have moved to off-Muroto input with the motion of the Philippine Sea Plate.

Keywords: Philippine Sea Plate, vitrinite reflectance, detrital zircon U-Pb age

Pattern of SKS splitting across the Taiwan orogen controlled by double subduction, not collision

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To examine the concept of coherent deformation in the Taiwan orogeny we re-measured previously reported SKS splitting data and added new data. The evidence for geology-sensitive SKS delay times across central Taiwan proposed previously is largely dismissed by a rigorous quality control procedure. We examine the pattern of anisotropy manifested at various depths along the SKS path against a dynamic model in which collision and double subduction are considered. The best correlation of splitting pattern with that predicted from the dynamic model is found at 200-300 km, suggesting a deep-seated source of anisotropy. We quantified the vertical length scale for coherent deformation in the dynamic model using strain-rate tensors cross-correlation over depths. The vertical length scale increases from less than 50 km at crustal and lithosphere level to 100-150 km in the asthenosphere, which corroborates the notion that the apparent orogen-parallel, large-delay time SKS splitting are likely contributed from the coherent deformation in the asthenosphere. This deep-rooted dynamics is mainly driven by the double subductions at the Ryukyu and the Manila trenches.

Keywords: SKS splitting, double subduction, Taiwan orogen

Role of double subduction and retrowedge thrusting in consuming fast plate convergence in the Taiwan arc-continent collision

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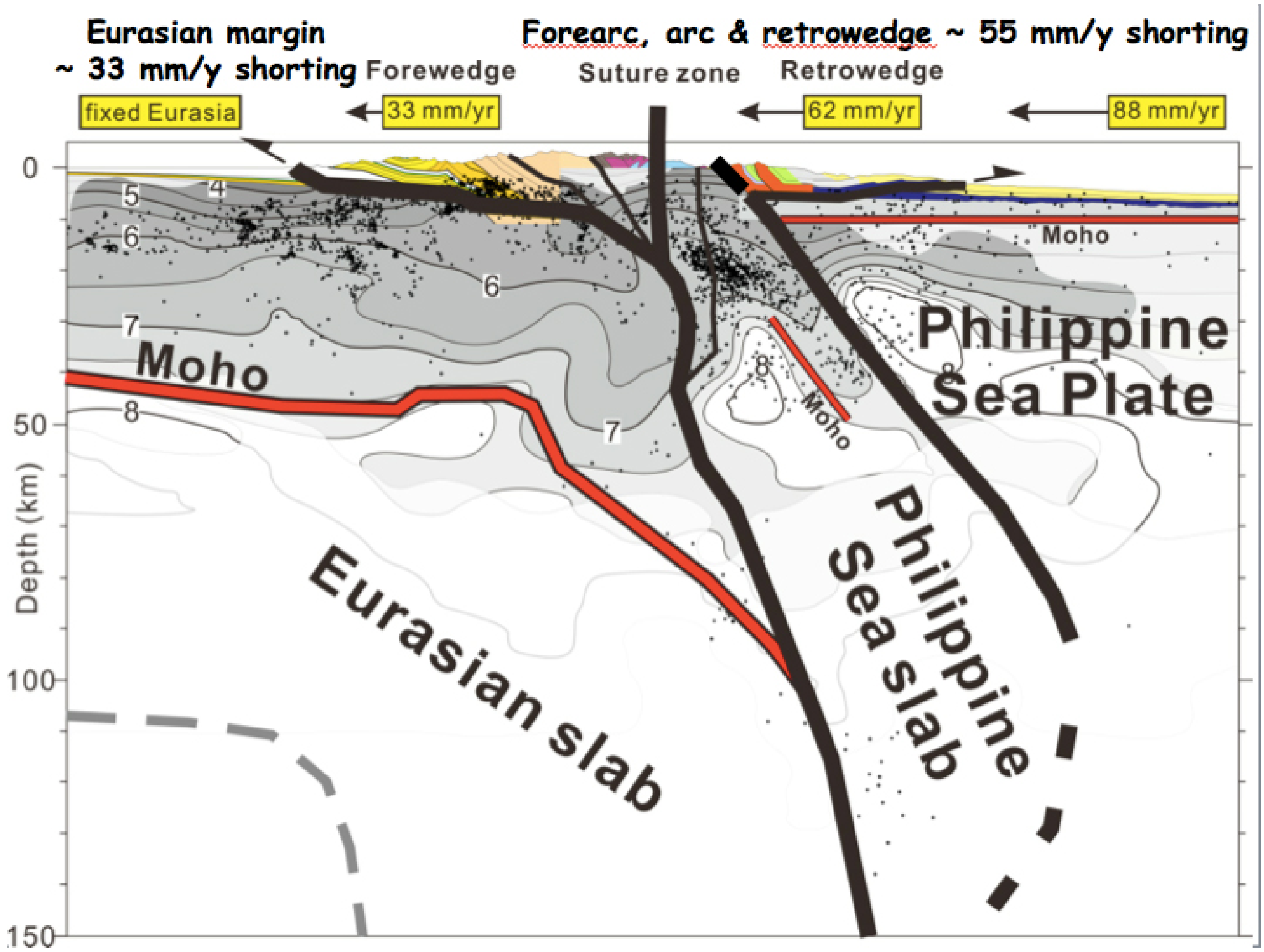
Retrowedge thrust belts commonly develop on the backsides of collisional mountain belts, displaying a vergence opposite to the overall foreland vergence and to the presumed deep-seated subduction polarity. For example, the Southern Alps are a well-known retrowedge whose structures verge southward over the Adria plate, in contrast with the general north vergence of Alpine structure over the European foreland. Numerous models have been constructed to explain the deep structure of such bivergent collisional mountain belts in relation to subduction polarity. However, the details of how these upper crustal thrust belts root into the lower crust and link to the subducting mantle lithosphere, defining the fundamental collisional kinematics, remains relatively unconstrained from a direct observational point of view.
Here we present a synthesis of new observational constraints on the deep crustal and lithospheric structure of the currently active (~25-30mm/y) retrowedge thrust belt within the larger (90mm/y) Taiwan arc-continent collision between the Philippine Sea plate and the Eurasian stable continental margin. We make use of high-resolution local and global tomography and abundant well-located seismicity to define the deep structure and we use geodesy, surface geology, high-resolution bathymetry and new pre-stack depth migration of reflection profiles in the retrowedge thrust belt to define upper crustal structure and kinematics.
The western Taiwan prowedge thrust belt has been converging with Eurasia at ~30mm/y based on geodesy, neotectonic observations (30Ka), and forland basin migration rate (~3-3.5Ma). This equals the long-term subduction rate of Eurasia based on ~450km of subducted slab since the onset of Eurasian subduction at ~15Ma. The remaining ~60mm/y of current plate convergence is taken up by deformation of edge of the Philippine Sea since ~2Ma. Within the upper crust, approximately 60% of this convergence (30-35mm/y) is taken up by west-vergent thrusting of the arc and forearc basin for a total of ~100km shortening. The remaining shortening of the upper crust (25-30mm/y) is taken in the retrowedge for a total ~30km shortening of the Cretaceous and younger sedimentary cover of the Philippine Sea plate (Huatung basin) to the east of the arc, which we document below. The upper crustal shortening is accommodated by secondary west-vergent subduction of lower crust and mantle lithosphere of the arc, forearc basin and the Huatung basin, which is imaged tomographically.
The active thrust front of the 40km wide retrowedge is observed in high-resolution bathymetry as seafloor scarps that extend 130-200km along strike. We image the underlying structure using pre-stack depth migration in areas of high bathymetric relief and deep submarine canyons cutting through the thrust belt. Reflection profiles show a shallow 2-3km detachment near the base of the Huatung basin stratigraphy with the overlying Cretaceous and younger strata forming east-vergent imbrications. The frontal thrust sheet shows a total ~26km shortening with overlying Pleistocene growth strata. The retrowedge detachment appears to join the west-vergent prowedge of the arc and forearch basin near the shoreline, which appears to be the takeoff point of secondary subduction of Philippine Sea lithosphere.

Keywords: Subduction, Retrowedge thrust belt, Taiwan, Arc-continent collision


Eurasian margin
~ 33 mm/y shorting
Forewedge
Forearc, arc & retrowedge ~ 55 mm/y shorting
Suture zone
Retrowedge
fixed Eurasia
33 mm/yr
62 mm/yr
88 mm/yr
0
50
100
150
Depth (km)
4
5
6
6
7
7
8
8
Moho
Moho
Moho
Philippine Sea Plate
Eurasian slab
Philippine Sea slab

Active dehydration, detachment and flow of transitional continental crust in an arc-continent collision, Taiwan

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Integration of recent Vp and Vs tomographic models (Huang et al., 2014) with recently recognized mid- to lower-crustal tremors (Chuang et al., 2014), a near-vertical zone of high conductivity (Bertrand et al., 2012) and He isotope ratios collected from groundwaters (Chen et al., this meeting, 2017) in southern Taiwan suggests that stretched continental crust is detached from the subducting mantle of the Eurasia plate during the early stages of the arc-continent collision in Taiwan. In southern Taiwan, vertical sections of the tomographic models show an east-dipping, asymmetric lobe of low P-wave velocity, probably stretched continental crust, projecting down dip to a band of seismicity interpreted as the Wadati-Benioff zone of the subducting Eurasian plate. Approximately 20 km to the north, the Wadati-Benioff zone is absent and the east-dipping lobe appears to have separated, forming two shallower, sub-vertical lobes separated by a band of seismic tremors and a cylindrical-shaped zone of high conductivity. The tremors and the zone of high conductivity extend to nearly 40 km, which is close to the crust-mantle boundary in this area. Chuang et al. (2014) proposed that the tremors represent a zone of deformation and dehydration associated with prograde metamorphism as the low-velocity crust was progressively subducted. The sub-vertical zone of high conductivity is consistent with this interpretation. He isotope ratios of groundwaters, rock outcrops and hot springs collected along the Tulunwang fault show significant mantle contamination (Chen et al., this meeting, 2017). We propose that the Tulunwant fault projects down dip to the east to the zone of tremors, defining a crustal-scale shear zone that accommodates initial detachment of at least the middle and upper crust from the subducting Eurasian lithosphere.

Distinctively out-of-phase 7.5 and 6.5 km/sec isovelocity surfaces also suggest separation of the middle and upper crust from the subducting lithosphere. For example, the 7.5 km/sec surface, approximately the bottom of the lower crust (or Moho), forms a broad, smooth synformal structure that trends north parallel to the bend of the subducting Eurasian lithosphere. In contrast, the 6.5 km/sec surface shows higher amplitude, shorter wavelength undulations that trend northeast, parallel to the structural and topographic grain of the collision. The subsurface form of the 6.5 km/sec surface also correlates positively with the surface topography whereas the 7.5 km/sec surface shows a negative correlation, consistent with flow and mobility of the middle and lower crust in an arc-continent collision.

Keywords: collision, detachment, subduction

A Major out of Sequence fault in Central Range of Taiwan Orogenic belt

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Taiwan mountain belt results from collision between Eurasia continental crust and Philippine Sea plate that result in exposing the metamorphic complex with high exhumation rate in eastern Central Range of Taiwan orogenic belt. In this study we combine with field survey, zircon fission track (ZFT), metamorphic grade, and tomography image to identify there exists a major out of sequence fault (MOSF) in eastern Central Range of Taiwan orogenic belt. This MOSF can be separated into three segments and it extends from north to south of central Range and the total length is more than 250 km. The ZFT shows total annealing age of ca.1-3 Ma on the hanging wall and partial annealing ages on the foot wall. The exhumation rate is ca. further acceleration in exhumation from ca. 0.5 Ma to present (4–8 mm/yr). The seismicity data indicates the MOSF is still active from central to southern central Range.
We consider that the MOSF is related with crustal channel flow in depth. To the western side of crustal flow it shows thrusting mechanism associated with MOSF and the normal faults (or normal shearing zone) develop in eastern side of the crustal channel flow. This crustal channel flow is also related with exposing the metamorphic complex in Central Range that is important mechanism for the mountain building process of Taiwan orogenic belt.

Keywords: Taiwan Orogenic belt, out of sequence fault, thermochronology

Normal faulting and structural analyses in eastern edge of Central Range in eastern Taiwan: an exhumed subduction fore-arc accretionary prism?

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Based mainly on field structural investigations and combing available geophysical, geochemical and geochronological information, this study intends to delineate the deformation structures and their implications for tectonic evolution in the schist/slate belt in eastern margin of the Central Range in eastern Taiwan, while exhumed rapidly after subducted (?) and collided with the leading edge of the NW-moving Philippine Sea plate and the Luzon arc subsequently. Field observations indicate that the slate belt (Xin-gao Fm.) in eastern edge of the Central Range shows a general shallow E-dipping main cleavage, in contrast to a W-dipping schistosity in the older and more deformed metamorphic schist belt (Tananao complex). In-between, the Yuli belt, a intensively sheared quarz-mica schist with some ultramafic bodies, which recently was interpreted as an exhumed subduction channel, represents the contact between the above two units. Brittle normal faults at outcrop scale were found in the Xin-gao slate Fm. that shows a E-W (NE-SW to SE-NW) extension, which seems to be consistent with the extension strain derived from GPS measurement as well as focal mechanisms of several shallow earthquakes in the eastern Central Range. As a result, we tend to interpret this E-W extension, which is either perpendicular or obliquely sub-perpendicular to the mountain belt, is provoked by rapid exhumation of the Yuli belt and the Xin-gao Fm since 15-18 Ma. Tentatively, we propose a geological/tectonic evolution model for reconstructing the development of deformation fabrics in space (i.e., the different rock units, Tananao complex, Yuli belt, and Xin-gao Fm) and time (i.e., from burial stage, to subducation, to exhumation).

Keywords: Taiwan, normal fault, Central Range, metamorphic fabrics

The Chimei submarine canyon and fan: A record of Taiwan arc-continent collision

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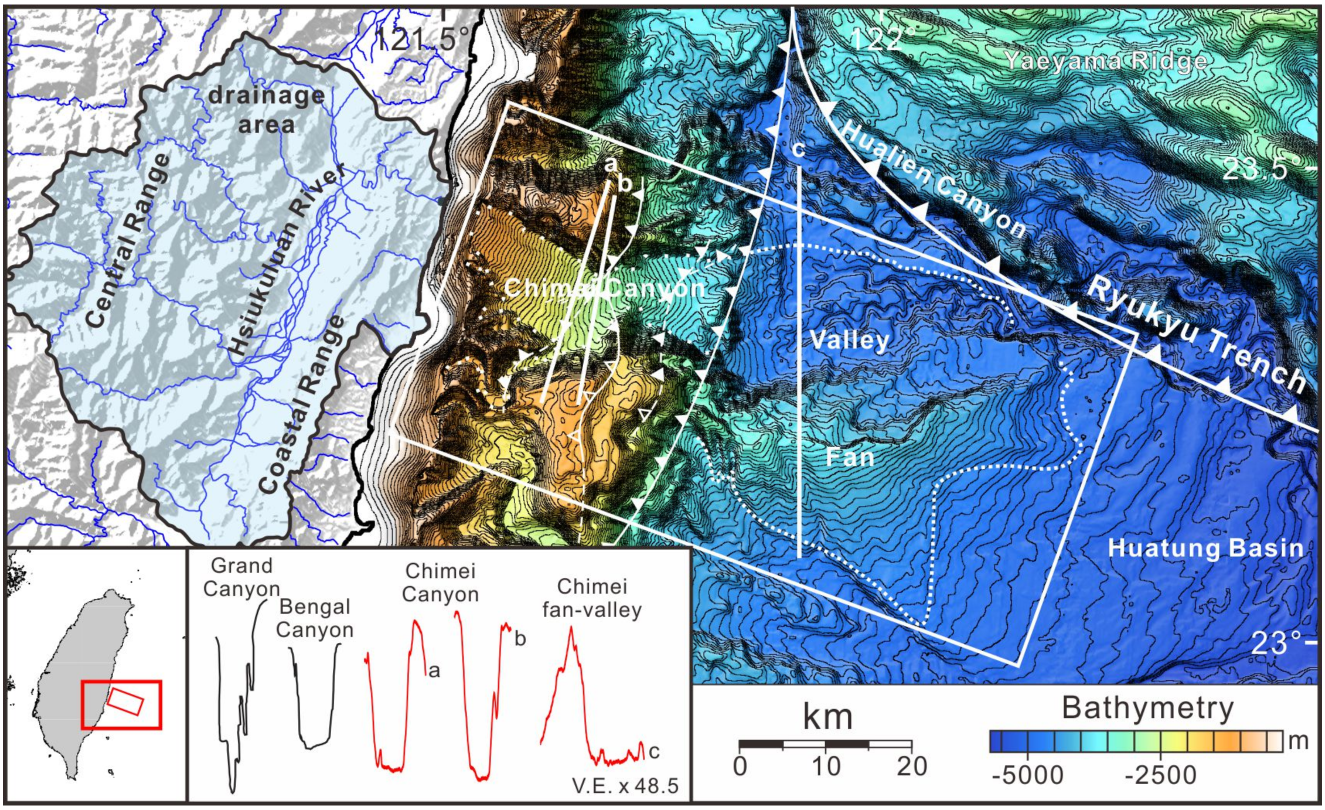
The Chimei submarine canyon, which is located on the deforming Philippine Sea plate just east of the Luzon arc, delivers sediments from the Taiwan orogen into the deep sea, forming the Chimei submarine fan complex. We present new constraints on the history of Taiwan arc-continent collision as recorded by the Chimei submarine canyon and fan. We used a combination of multichannel seismic reflection profiles and high-resolution bathymetry to study the morphology and stratigraphic sequences of the Chimei submarine canyon and fan, as well as the underlying pre-fan deep-sea strata. The Chimei submarine canyon is fed largely by the Hsiukuluan River, which is the only river to cut across and incise the uplifting Taiwan Coastal Range, and merges tributaries that drain both the eastern Central Range (accretionary wedge) and the Coastal Range (deformed Luzon arc and forearc basin). The 500 m deep Chimei submarine canyon cuts through an uplifting east-vergent submarine thrust belt as it descends to nearly 5000 m water depth, where it crosses the frontal active thrust to empty into the Chimei fan complex deposited on the stable Huatung Basin to the east. Huge sediment fluxes are fed through the Chimei submarine canyon during typhoons, which results in a 10 km wide and planar canyon bottom shaped by strong submarine erosion and empties into the largest submarine fan-valley system at the foot of the canyon in the Huatung Basin, with a present area of ~2087 km2 and a maximum thickness of ~2 km. The currently active channel system eventually empties into the Ryukyu trench to the northeast where the distal Chimei fan is impinging on the Ryukyu accretionary wedge.

The Chimei fan was deposited above a seismic sequence boundary that separates more transparent and chaotic middle and upper sequences (fan sequences) from the underlying continuous and concordant lower (pre-fan) sequence. The seismic facies in lower sequence shows continuous and parallel seismic reflections that onlap upon the Huatung Basin oceanic crust, which we interpreted it to be original deep sea sediments of the Huatung Basin. Most lower-fan seismic characteristics are shown in the middle sequence and upper-fan characteristics are shown in upper sequence. Based on their seismic facies characteristics, we interpret the middle and upper sequences to be composed of orogenic sediments from Taiwan arc-continent collision. The different seismic facies within each sequence of the Chimei fan record a progression of Taiwan orogeny: (1) During initial arc-continent collision, sediments were delivered from the Central Range to the Huatung Basin and initial Chimei submarine fan was formed. (2) After the Luzon arc has uplifted above sea-level, the Chimei submarine canyon and deep-sea valley was formed along the topographic low of the Luzon arc, northern part of the Chimei fan has been eroded away, and only southern part of fan behind topographic high of arc has been preserved. It is anticipated that future sampling of the uplifted strata of the Chimei submarine canyon, Chimei fan complex and pre-fan sequences through a variety of means, including coring and ocean drilling will provide much insight into the dynamics of collisional mountain belts.

Keywords: sedimentary record of tectonics, submarine canyon, submarine fan, Taiwan arc-continent collision , seismic reflection profile



Lithospheric structure of East Sea of Korea from teleseismic receiver functions: Seismic evidence of ancient back-arc basin opening

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We investigate lithospheric seismic structure beneath Ulleung back-arc basin in East Sea of Korea, which opened ~28 Ma due to Pacific Plate subduction. Formation of ocean basin in response to subduction typically causes characteristic features such as thinned crust and trench-normal fast-velocity directions in the mantle. Previous seismic studies reported a presence of a thick crust (thicker than normal oceanic crust) and prominent low-velocity anomaly in the lithospheric upper mantle (at ~100 km depth) beneath East Sea. Also, shear-wave splitting and tomography results show trench-normal fast-velocity directions beneath the oceanic basin.

We constrain azimuthal anisotropy of crust and lithosphere of the volcanic islands (Jeju, Ulleung, and Dok islands) by modeling amplitude variations of both radial- and transverse-component receiver functions (RFs) by back-azimuths. Our analysis results show that all islands commonly have thicker crust (more than 20 km). In particular, under Jeju Island, we observe a large variation in crustal thickness (18-26 km). The thinnest part of the crust is observed in the middle of the island along a N-S direction. Modeling of the transverse RFs requires an existence of a dipping Moho and localized anisotropy above the Moho. Also, a presence of paleo-oceanic sediments shifts the arrival time of a direct P wave in the radial RFs by 0.5 s. Crustal structure of Ulleung Island includes a dipping Moho with strike roughly parallel to contour line of the island. Under Dok Island, we observe large variations in amplitudes of the transverse RFs in back-azimuthal domain, suggesting a similar crustal structure as that in Ulleung Island.

Our teleseismic constraints on the structure and anisotropy provide an insight on the opening of the ancient back-arc basin in East Sea. Direction of anisotropy under Jeju Island is along a N-E direction, and is consistent with the constraints from previous body-wave anisotropy studies. Also, this direction is along the mantle shear which might have induced focusing of the magmatism, causing the monogenetic volcanism of the island (Brenna et al., 2012). Also the dipping Moho structure beneath Ulleung Island can be a geophysical evidence of an existence of continental block suggested in geochemical studies (Jolivet et al., 1992; Kim et al., 2008). Variable Moho depths under Jeju Island may be related with the activity of Mt. Halla, the largest shield volcano of the island.

Keywords: Back-arc basin opening, Receiver Function, Seismic anisotropy, Ulleung Basin, Volcanic island

Stress field did not change at 15 Ma in SW Japan: Counterevidence from dike orientations

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The drastic change in dike orientations at 15 Ma in SW Japan has been thought to indicate the termination of the extensional tectonics accompanied by the Japan Sea opening. We found counterevidence to this picture in the Tajima-Myokensan area, northern Hyogo Prefecture, SW Japan—a representative area where previous researchers reported an older ENE-trending eight dikes and a younger NNW-trending 51 ones (Kobayashi, 1979a, b; Tsunakawa, 1983). The host strata lie subhorizontally, which make tilt correction unnecessary. They judged the stress regimes from the faults that were activated before and after 15 Ma. However, it is difficult to determine the timing of faulting, because few syntectonic deposits along faults have been found in SW Japan.

The recent development of paleostress analysis of dilational fractures allows us to determine all the three stress axes, stress ratio and driving pressure of magma from dike orientations. In case dikes were resulted from polyphase tectonics, the technique not only separates the stresses, but also determines the appropriate number of stresses (Yamaji and Sato, 2011).

In this study, we measured the 388 orientations of dikes and sills in the Early to early Middle Miocene strata called the Hokutan Group, and applied the latest technique by Yamaji and Sato (2011) to them. It was found that NE-SW extensional stress with a low stress ratio was found from the group. The base and top horizons are correlated to ca. 20 and 14 Ma, respectively (e.g., Takayasu et al., 1992). We obtained three couples of fission-track ages between ca. 17 and 13 Ma, which was consistent with the youngest fractions of the U-Pb ages of the same samples. Therefore, stress condition did not change at 15 Ma in this area.

Keywords: Miocene, paleostress, Southwest Japan, Japan Sea

Deep focus earthquakes and slab-like structure beneath Northeast China and surrounding regions

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Earthquakes with hypocentral depth >60 km are generally observed only in areas of subduction zone. Northeast China is one of good places for studying deep-focus earthquakes and subducting slabs. The deep seismicity forms narrow, inclined Wadati-Benioff zones which sometimes are continuous throughout the upper mantle and outline the shape of subducting slabs. Consequently, the deep seismicity zones also correlate well with the subducting slabs, as shown in regional/global tomography studies. Two issues are included in this proposition: namely, the mechanisms of deep-focus earthquake and the fate of subducted slab. Note that both of the included issues are debated topics. Three major hypotheses suggested for the mechanism of earthquakes are brittle shear failure in the subducting slab, polymorphic phase transformations, and sudden minerals transformation. The fate of slab whether or not it subducted into the lower mantle remains uncertain. So the relationship between shapes of subduction slabs and deep-focus seismicity zones is not a simple link to each other as mentioned above.

The relationship between slab shape and deep-focus seismicity is variously dependent on several physical mechanisms producing seismicity within Wadati-Benioff zones. Two items are required for earthquake activity, a source of stress and a material undergoing unstable strain localization. In the western Pacific, a reasonable relationship between the slabs and seismicity zones is provided through slab buckling by Myhill study (2013). This mechanical model of deep-focus earthquakes is based on slab buckling. Apperson and Frohlich (1987) supposed that the majority of deep-focus earthquake physical mechanisms are not explained by slab shape in any simple way due to the uncertain role of slab morphology. Another physical mechanism is volume changes within subducting slabs, which providing an alternative to stresses associated with deep-focus seismicity. Inside or around the subducted oceanic lithosphere, that olivine phase transformation has been considered as volumetric reduction, which caused deep-focus earthquake.

Both slab buckling and volume change can explain well the clustering of deep-focus earthquakes observed in depth distributions within subduction zone. Note there is a lack of intense seismicity in the mantle transition zone beneath the Changbaishan volcanic site where oceanic lithosphere was observed by several tomographic studies. Neither slab buckling or volume change can interpret this possible gap in earthquake prone area beneath Changbaishan volcanic site.

In Northeast China area, we derived a 3D P and S velocity model to 800 km depth using P and S joint inversion method. The data used here were recorded by a temporary deployment as well as the permanent stations coexisted during the same period. We constrain an integrated model based on previous and this study, and thus give a possible explanation for few deep-focus seismicities occurring within the subducted oceanic lithosphere and surrounding area beneath Changbaishan volcanic site.

The main conclusions are: 1) not all of the deep-focus seismicities occurred in high-V anomaly zones because of the different physical mechanisms of deep earthquake. 2) A part of the deep-focus seismicities were due to the brittle shear failure in the subducting slab while other part of the deep-focus seismicities stemmed from volume change. 3) The piled up small slab block zones seem to be broader than the known deep seismicity zone because of the horizontal flow.

Keywords: deep focus earthquake, slab-like, tomography

3-D upper mantle structure beneath the Sea of Japan with inter-station surface-wave analysis using multiple seismic arrays

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The Sea of Japan is one of the typical back-arc basins in the western Pacific, comprising three major basins (Japan, Yamato and Tsushima Basins) and Yamato and North Yamato Rises in its center. In addition to such characteristic sea-floor topography, the crustal thickness beneath this marginal sea is variable, reflecting the complex tectonic history of the back-arc spreading, which had occurred from 30 to 10 Ma. Thus, the seismic structure in the crust and upper mantle beneath the Sea of Japan is likely to reflect its complex tectonic history including back-arc spreading and the subsequent formation of the Japanese islands.

The 3-D upper mantle structure around the Japanese islands has been investigated by Yoshizawa et al. (2010, PEPI), based on inter-station dispersion measurements of surface waves primarily using permanent broad-band seismic stations deployed throughout Japan (F-net) and some stations of the Global Seismic Network in east Asia. However, this earlier model had insufficient lateral resolution for most areas in the Sea of Japan, due to the limited ray path coverage. In this study, in addition to the permanent seismic networks in Japan and east Asia, we employ temporary broadband seismic arrays in Northeast China (NECESSArray) with 120 stations from 2009 to 2011, and in Far-east region of Russia with 8 stations since 2005. By combining all these multiple seismic arrays, we are able to collect a large number of inter-station paths across the Sea of Japan, which can be of help in enhancing the horizontal resolution of surface-wave tomography model.

For the inter-station phase speed measurements of this study, we used a fully non-linear waveform fitting technique developed by Hamada & Yoshizawa (2015, GJI). Through the waveform analysis of the combined data sets in the period range between 25 and 130 seconds, we collected about 12000 new measurements of phase speeds using events with moment magnitude greater than 6.0 from 2002 to 2016. With the additional data sets from arrays in Northeast China and Far-East Russia, we are now able to resolve the smaller scale heterogeneity of about 1.5 degrees or less in the Sea of Japan. The updated 3-D upper mantle structure show significant fast shear wave speed anomalies in the top 55-65 km, representing the oceanic-type lithosphere, while the conspicuous slow anomalies are found beneath 70 km depth in most areas under the Sea of Japan. The lithospheric thickness varies slightly from place to place, suggesting relatively thicker lithosphere in the eastern margin of the Japan Basin as well as Yamato Basin. Slow anomalies in the asthenosphere are more enhanced under the Japan Basin, compared with the other basins. This slow anomaly tends to be more enhanced in the western part of the Japan Basin near the continental margin, which may be mixed with the strong local slow anomaly right beneath the Changbaishan Volcano in the border between China and North Korea, mainly due to the smearing effects caused by biased azimuthal coverage of surface wave paths in this region.

Keywords: upper mantle, surface waves, Sea of Japan

Petrological and geochemical features of gabbros and relatively primitive basalts from Nikoro Group, Tokoro belt, eastern Hokkaido: Implications for the geodynamic setting

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The Tokoro belt is a subduction complex located in eastern Hokkaido, Japan. The Tokoro belt was formed by the subduction of Kula plate during the Late Cretaceous and consists of three stratigraphic units: the Nikoro, Yubetsu, and Saroma groups. The Nikoro Group is composed mainly of Late Jurassic to Early Cretaceous igneous rocks intercalated with bedded (or lenticular) chert and limestone. Igneous rocks are made up of basaltic and trachytic pillow lavas, hyaloclastites, dolerite, trachyte dikes, and ultramafic-mafic cumulates. Based on their geological characteristics, whole-rock (WR) major and minor elements, and clinopyroxene (Cpx) major element (MJ) geochemistry, these rocks are presumably derived from fragments of seamounts. In this study, we re-evaluate geochemical features of igneous rocks from the Nikoro Group based on WR and Cpx geochemistry, including trace elements (TEs).

Gabbros show ophitic texture and contain fresh, large oikocrystic Cpx. TE composition of Cpx from gabbros and WR geochemistry of gabbroic rocks are almost identical to the Cpx microphenocrysts of basalts and the WR geochemistry of basalts, respectively. This evidence suggests Cpx-melt partition coefficients for TE remained constant with almost no modification and the gabbroic rocks represent the melt composition. Although these rocks are slightly evolved (Mg# = 0.63), their compositions are among the most primitive rock compositions previously reported from this area. Whole rock TEs show ocean island basalt (OIB) type patterns as well as 'garnet signatures' (e.g., $[Sm/Yb]_N > 1$). These geochemical features support seamount origin. In further detail, gabbros and the relatively primitive basalts show rather flat TE patterns compared to the 'typical' OIB. After correcting the gabbros and basalts (MgO>7 wt%) for the fractionation effect to Mg# = 0.72, composition X_{72} suggests a significantly shallow lithosphere–asthenosphere boundary depth of ~0 km. WR $[Sm/Yb]_N$ ratios also show the same results. These geochemical results constrain the geodynamic setting of the Nikoro Group; the OIBs erupted through very thin lithosphere. Such a tectonic setting is limited to the ridge–hotspot interaction area.

Keywords: Tokoro belt, Nikoro Group, Ocean island basalt (OIB)

Velocity structure of uppermost mantle from Pn tomography beneath the southeastern margin of the Tibetan Plateau

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Since the late Cenozoic, structural deformation and seismic activity of the southeastern margin of Tibetan Plateau have become very strong. The southeastern margin of the Tibetan Plateau is characterized by strong seismicity and crustal deformation. It is an ideal region to investigate the lateral growth of the plateau and southeastward escape of the crustal material. The velocity structure and anisotropy of the uppermost mantle are important constraints on the crustal and mantle rheology.The Pn phases, which propagate along the bottom boundary of Moho, are critical information to study the velocity structure and anisotropy of the uppermost mantle.
In our work we have selected travel times of Pn arrivals as reported in the Annual Bulletin of Chinese Earthquakes(ABCE) and regional seismic network of provinces. A two-dimensional tomography method is employed to find regional variation of Pn velocity in the uppermost mantle beneath the southeastern margin of the Tibetan Plateau. In the most study area 2 degrees are well resolved.The main results show the relations of Pn velocity variation to regional tectonic structure, Moho depth and earth’s heatflow. Pn velocity structure is close to the regional tectonic structure: Low Pn velocities are found on the intense tectonic activity area, such as the west of SiChuan-YunNan block . High Pn velocities are on the tectonic stability area,beneath SiChuan Plain. Quantitative analysis result indicates that Pn velocity is positively correlated with crust thickness and negatively correlated with Earth’s heatflow.
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Keywords: Tibetan Plateau, uppermost mantle, Pn tomography

Dissolved helium isotopes in groundwater: Implication for subduction of continental crust in an active arc-continent collision

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Here we use helium isotopes in groundwater from along the Chauchou/Tulungwan fault system in southern Taiwan to evaluate the involvement of the upper mantle in an active arc-continental collision. Helium isotope ratios of sixteen groundwater samples, four bedrock samples, and one hot spring sample, collected along 10 km on the fault, were measured and reported as R_A (relative to an air helium isotope ratio ($^3He/^4He$) of 1.39 $\times 10^{-6}$). Measured groundwater helium isotope ratios, ranging from 0.07 to 1.00 R_A , express a clear mixing model with three endmembers of air (1.00 R_A), crust (0.06 R_A) and upper mantle (8 R_A). Samples from southern part of the fault show normal distribution of crustal signal. By correcting the helium from air-contamination, samples from northern part of the fault with 0.30-0.78 R_A reveal significant upper mantle signal. The Chauchou/Tulungwan fault system, in the area of detected mantle-derived fluids, projects down dip to a zone of ambient tremors and a nearby zone of high conductivity; both features extend to nearly 40 km, which is close to the crust-mantle boundary in this area. These observations suggest that mantle-derived fluids penetrate the crust through the zone of the tremor activity, reaching the surface long the Tulugwan fault zone. This study shows that non-volcanic, mantle-derived fluids can be involved in tectonic processes associated with an active arc-continent collision zone.

Keywords: Chauchou fault, noble gas, active tectonics, mantle-derived fluids

Moho Depth of The South China Sea Basin from Three-dimensional gravity inversion with control points and its characteristic

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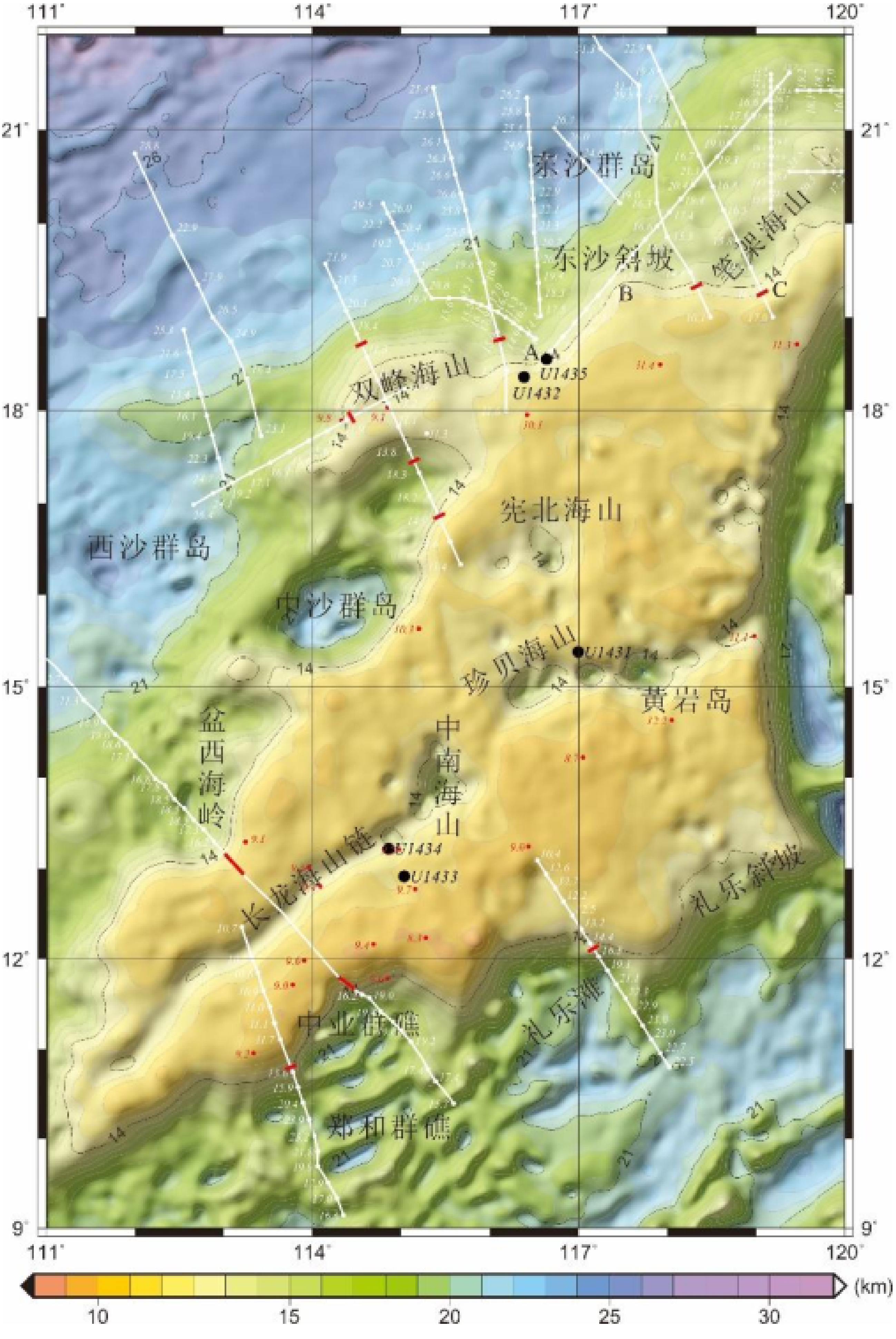
Over most of the South China Sea basin, the Moho depth ranges between 8˜14km, the crustal thickness is 3˜9km.

Keywords: South China Sea Basin, Moho depth, Known control points, Thermal gravity anomaly


111°
114°
117°
120°
21°
18°
15°
12°
9°
东沙群岛
东沙斜坡
笔架海山
双峰海山
宪北海山
西沙群岛
中沙群岛
珍贝海山
黄岩岛
盆西海岭
中南海山
长龙海山链
礼乐斜坡
礼乐滩
中业群礁
郑和群礁
A
B
C
U1435
U1432
U1431
U1434
U1433
10
15
20
25
30
(km)

The tectonic boundaries of the Jiangnan belt in South China: insights from potential-field anomalies

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The tectonic boundaries of the Jiangnan belt in South China, which developed during the Neoproterozoic, has remained unknown or controversial for decades. A long NW-trending deep seismic reflection profile across the Yangtze and Cathaysia blocks in South China was conducted by the SinoProbe-02 project for the first time in 2010–2012. From the analysis and interpretation of this seismic data, 2-D gravity modeling was proposed, suggesting that both Yangtze and Cathaysia blocks are notably different in crustal structure, and that the northern boundary of the central Jiangnan belt is bounded by Fangjingshan and the southern boundary is bounded by Qidong county. Then the regional gravity and magnetic anomalies were analyzed and interpreted comprehensively, showing that Yangtze and Cathaysia blocks have distinct features of gravity and magnetic anomalies due to various crustal structures and tectonic deformation. The results indicate that the northern boundary of the Jiangnan belt is located in the Shitai–Jiujiang–Dayong–Tongren–Hechi–Baise line, and the southern boundary is located in the Shaoxing–Jiangshan–Pingxiang–Qidong– Yongzhou–Guigang–Nanning line, which possibly represents a Neoproterozoic suture between Yangtze and Cathatsia blocks.

Keywords: South China, crustal structure, tectonic boundary, gravity and magnetic

Lithospheric rebuilding of the Alashan and ordos by upper mantle upwelling: evidence from multiscale teleseismic tomography

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Between 2013 and 2015, The China Seismic Array-2 experiment operated 670 broadband seismic stations with an average station spacing of 35km. This seismic array located in northeastern Tibet and covered the Qilian Mountains, Qaidam Basin, and part of Songpan-Ganzi, Gobi-Alashan, Yangzi, and Ordos terrane. ~90,000 P-wave relative travel times from ~300 teleseismic events were picked by cross-correlation method. A new multiscale seismic traveltime tomography technique with sparsity constrains were used to map the upper mantle P-wave velocity structure beneath northeastern Tibet. The seismic tomography algorithm employs sparsity constrains on the wavelet representation velocity model via the L1-norm regularization. This algorithm can efficiently deal with the uneven-sampled volume, and give multiscale images of the model.

Our preliminary results can be summarized as follows: 1) in the upper mantle down to 200km, significate low-velocity anomalies exist beneath the northeastern Tibet, and slight high-velocity anomalies beneath the Qaidam basin; 2)under Gobi-Alashan, Yangzi, and Ordos, high-velocity anomalies appear to extend to a depth of ~250km, this high-velocity may correspond to the lithosphere; 3) there exist relative high-velocity anomalies at depth of 250km-350km underneath north Tibet, which suggests lithospheric delamination; 4) there exist low-velocity anomalie from depth of 500km under Qinlin extented to uppermantle of the north part of Ordos and eastern margin of Gabi-Alashan terrane, which implied the upper mantle upwelling transform and rebuild the lithosphere of Gabi-Alashan and Ordos.

Keywords: upper mantle upwelling, Alashan, Ordos, multisacle seismic tomography

