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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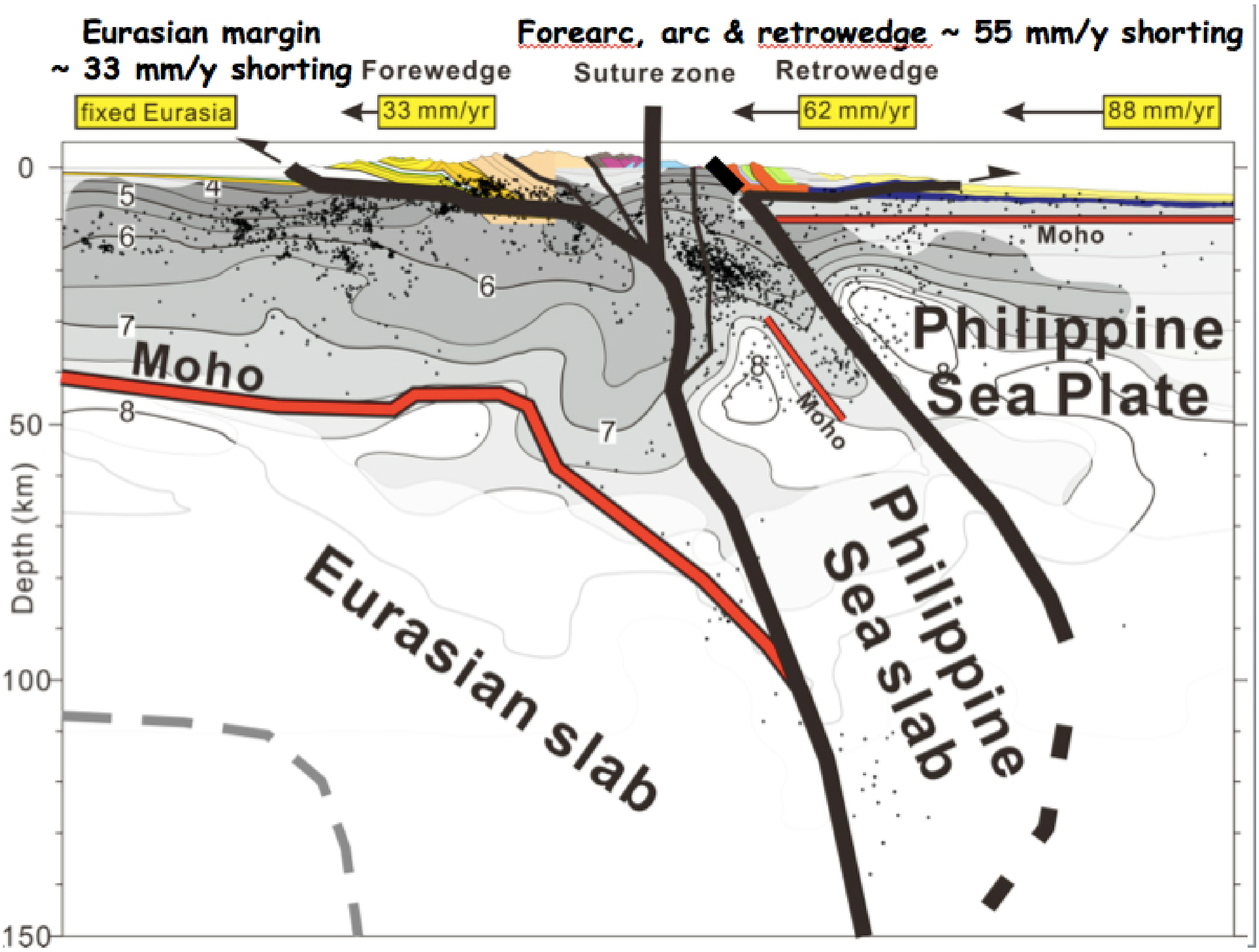
Retrowedge thrust belts commonly develop on the backsides of collisional mountain belts, displaying a vergence opposite to the overall foreland vergence and to the presumed deep-seated subduction polarity. For example, the Southern Alps are a well-known retrowedge whose structures verge southward over 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
Moho
Philippine Sea Plate
Moho
Philippine Sea slab
Eurasian slab
Depth (km)
0
50
100
150

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