議程 / Agenda

Date：103 年 4 月 24 日(星期四) / April 24, 2014 (Thursday)

Location：地質科學系大講堂 / B1 Conference Room

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Daily Variations of Methane Flux from Submarine Mud Volcanoes in Southwest Taiwan

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Keywords: Mud volcano, methane flux, SW Taiwan, Time variations

Submarine mud volcanoes are features that episodically emit gases, fluids, and mud onto the seafloor. Methane is the representative gas transport by mud volcanoes efficiently from deep buried sediment to the water column, and potentially to the atmosphere as a greenhouse gas. An active mud volcano, site-G96, located at the upper slope of southwest Taiwan, has plume from the top of mud volcano (360 m) direct to the sea surface. We can observe the bubbles at the sea surface.

This study was conducted during cruise OR3-1693 in June 2013. To understand the activity of gas emis- sions of mud volcano, we utilized the 38kz echo sounder to scan back and forth over the site-G96 and obtained 53 acoustic images of plumes. Five water column samples were collected above the venting of G96 at the tidal maximum and minimum. Three gravity cores were taken at the mudflow site of G96.

The results show high concentration of methane (38,522ul/l) and shallow depth of sulfate methane transi- tion zone (~70cm) in the cored sediment profiles. The C1/(C2+C3) ratios from cored sediments are in the range of 29-392, indicating that the methane gas is mostly thermogenic in origin. Calculated areas of the plumes from echo sounder images show good correlation with the tide variations during the survey on 1st -2nd June 2013. Flux of methane from the water column to atmosphere can be estimated by diffusive exchange equation, showing that gas emission from an active mud volcano could be largely various (0.065, 3.426, 3.414, 0, 41.739umol m-2 d-1) from time to time, at least, in this study.

Helium Isotopes of Fluids from Submarine Volcanoes in the South-Okinawa Trough

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Keywords: 3He/4He, dissolved gases, Okinawa Trough, Kueishantao, hydrothermal plumes

Many active submarine volcanoes have been found in southern Okinawa Trough. Water column samples from the hydrothermal plumes above venting volcanoes were collected during the OR2-1897 and -1984 cruises. Meanwhile, diving at shallower depths were conducted several times to collect the water samples near the venting sites. In total, 122 water samples from various depths in the offshore area of NE Taiwan were collected for dissolved gases and helium isotopes measurement.

The dissolved gases of water column samples show that the CO2 concentration and the alkalinity increase with depth and become higher at the bottom, while the result of O2 concentration shows a reverse pattern. The 3He/4He ratios near the vicinity of active Kueishantao volcano show highest value, up to 5.5 RA, where RA is the atmospheric ratios of 1.39 x 10-6. The plot of 3He/4He and 3He/20Ne ratios suggests that there may be different sources in this region. Furthermore, we will estimate the helium flux from the venting volcanoes in this area.

3D Geological Structure and Potentials of Geothermal Power in the Tatun Volcano Group

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Keywords: Tatun Volcano Group, Geothermal energy, Volume method, Heat flow, Geothermal gradient, Enhanced Geothermal System, subsurface 3D modeling

Recent energy issues have concentrated the attention on finding alternative ones. National demands for renewable and sustainable energy increase rapidly, especially the geothermal power production, which is viewed as the most potential opportunity. Many explorations on geothermal energy have been accomplished in the Tatun Volcano Group (TVG) since 1968, but the work was interrupted due to the corrosion problem. Given technological development such as corrosion-resistant alloy, in-situ pH neutralization and binary cycle, it is bound to be viable to generate geothermal power in TVG. Hence, this study compiles exploration data including resistivity survey, magnetic prospecting, gravity method, drilling data etc., as the basis to evaluate the geothermal power potential.

This study constructs a 3D geological structure and temperature distribution model underneath TVG, the 136^{o}C isosurface indicates that the heat source is located beneath between the Chishinshan Mt. and Dayoukun, then drives the thermal fluid transporting toward the E-W direction. This result is coincident with numerous geophysical studies and surface manifestations. According to the 3D structure model, the reservoir- Wuchishan formation- has subsided over 1000m at the heat source center.

Based on previous data and the probabilistic volumetric method proposed by Geotherm EX Inc., modified from the approach introduced by the USGS, we evaluate the geothermal power potential in TVG. Meanwhile, the Monte Carlo simulation technique has used to calculate the probability distribution of potentially recoverable energy reserves. The results show that the mean value is 426 Mw, and P50 is 419 Mw for 30 years, separately, with lower limitation being 350MW from the data of heat flow relationships. Furthermore, the power potential of enhanced geothermal system in TVG is also estimated by the quantitative model proposed by Massachusetts Institute of Technology (MIT 2006). The results suggest that the values are 3,221 MW and 805MW if recovery factors are 20% and 5%, respectively.

The sediment discharge and river chemistry of Linpien River

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Keywords: Linpien River, sediment discharge, river chemistry, major element

Based on the analyses of sediment discharge and river chemistry of Linpien River from 1982 to 2012, the annual sediment discharges ranged from 0.06 Mt to 8.08 Mt, with an average of 1.38 Mt. The sediment discharge yielded during wet seasons (May to October) contributes 98.49 % to the annual sediment discharge. In addition, the average sediment discharge produced during typhoon events contributes 67.68 % to the annual sediment discharge and the average landslide ratio for five typhoon events during 2005~2012 is 6.46 %. It implies that the factor of high rainfall during wet seasons or typhoons controls the variations of sediment discharges in the Linpien River.

The results of river chemistry collected at the most downstream site, Sinpi station, shows that the average concentrations of major cations for Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} are 53.0 %, 27.2 %, 16.7 %, and 3.1%, respectively. During September 2013 to January 2012, the concentrations of Na^{+} and K^{+} in dry seasons are significantly higher than that in wet seasons, while the seasonal variations of the concentrations of Ca^{2+} and Mg^{2+} are not significant. From the analyses of water samples collected at 14 sites in the basin, the Ca-Mg-Na+K ternary diagram shows that the river chemistry of Linpien River is mainly dominated by the weathering of silicate. The average concentrations of all anions at Sinpi Bridge are 2-15 fold higher than other sites. The concentrations of Na^{+} and K^{+} in Linpien River and Lili River, the main tributary of Linpien River, are significantly different, which can be attributed to the distributions of rocks which have different chemical weathering products.

Zircon U-Pb and Hf isotopic constraints on the origin of glaucophane-bearing rocks from the Yuli belt, eastern Taiwan

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Keywords: Zircon U-Pb age, Hf isotope, Bulk geochemistry, Blueschist, Yuli belt

This paper reports for the first time combined in-situ analyses of zircon U-Pb and Lu-Hf isotopic data of glaucophane-bearing rocks (blueschist) from Juisui area, the Yuli belt, eastern Taiwan. Four blueschist samples were collected for this investigation. As our new zircon U-Pb ages presented here, three out of four samples contain sufficient magmatic zircons, which yielded mean 206Pb/238U ages of 15.4 ± 0.4 Ma, 15.5 ± 0.3 Ma and 16.0 ± 0.2 Ma, respectively, with overall wide-distributed εHf(T) values from -4.5 to +27.3 (i.e., ~32-ε units).

Geochemical analyses of the four blueschists yielded the following results: SiO2 contents range from 40 to 61 wt.% with very high MnO from 0.6 to 1.9 wt.%. The REE patterns show mildly enriched in LREEs [(La/Yb)N = ~7] with incompatible trace element features similar to those of subduction-related lavas, characterized by depletions in HFSE (Nb, Ta, Ti). Moreover, all the blueschist samples gave significant negative Ce anomalies in their normalized REE patterns.

From our new zircon U-Pb, Hf isotopic and bulk geochemical results, the protolith of the blueschists in the Yuli belt was product of the middle Miocene subduction-related magmatism, which was suggested the youngest protolith of the blueschists worldwide. In addition, the protolith was sourced from enriched (continental) and depleted (mantle-derived) plus Mn-rich deep-sea compositions. The protolith had undergone a high-pressure epidote-amphibolite facies to blueschist facies metamorphism and eventually rapidly exhumed and accreted to the eastern slope of the Central Range during the late Cenozoic. In this paper, we suggested that the blueschist facies metamorphism of the Juisui blueschists or the entire Yuli belt should have taken place after ~16 Ma, instead of the late Cretaceous as previously argued, moreover, the consensus of “paired metamorphic belts” of Taiwan should be thus falsified.

The Thermal-Mechanical Evolution of Middle Hsuehshan Range, Taiwan: Using Numerical Modeling and Zircon Fission Track Ages

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Keywords: Taiwan, Hsuehshan Range, age-elevation relationship, zircon fission track, Wide-zoned Closure, numerical model.

Located in northern Taiwan, the Hsuehshan Range is the second largest range and has its own special lithology, structural and thermochronological features with high exhumation rate. In most previous studies of forward modeling of Taiwan mountain building, however, the existence of the Hsuehshan Range was ignored. Its thermal-mechanical evolution should be investigated in addition to the evolution of Taiwan mountain range. Moreover, in the aspect of thermochronology, most of the previous studies that discussed the age-elevation relationship do not consider the effect of cooling rate on closure temperature. In this study, we simulate this effect numerically and discuss local exhumation rate in middle Hsuehshan Range using six new zircon fission track ages together with previously published data via the 1-D thermal advection-diffusion model. Furthermore, for the purpose of applying the cooling-rate-closure-temperature relationship to 2-D model and testing the assumption of the initial tectonic framework of the Hsuehshan Range, we simulate the formation of the Hsuehshan Range by introducing the 2-D thermal-mechanical model and compared the modeling predictions with real geochemical data. In the 1-D model, we found a unique phenomenon that we call "Wide-zoned Closure" in the initial stage of orogen. The Wide-zoned Closure signature will induce a spatially vertical zone with similar thermochronological ages. As a result, a vertical profile of thermal age would show a slowly decreasing age trend. By regulating parameters reasonably, the best-fitting 1-D model to the thermochronological data in middle Hsuehshan Range suggests that this area started to exhume with a rate of $5.0\,km/Myr$ around $3.1\,Ma$. On the other hand, the 2-D modeling results imply that the initial lithology setting would influence the deformation behavior of orogen and result in different distribution of thermo-chronological ages. Additionally, the results suggest that the Hsuehshan Range has inherited influence from the Hsuehshan Basin and that the eastern part of the Hsuehshan Range was an active deformation zone in initial stage of orogen.

Using PS-InSAR method analysis surface deformation in Longitudinal Valley Fault from Rueisui to Chishang area

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Keywords: PS-InSAR, Longitudinal Valley Fault, Interseismic deformation

Longitudinal Valley is considered as an active collision boundary between the Philippine Sea Plate and the Eurasian Plate in eastern Taiwan. The 140 km long Longitudinal Valley Fault (LVF) is o the most important suture composed by several fault segments. In 1951, Hualian-Taitung earthquake sequences ruptured four segments along the LVF and causes great damages. In this study, we want to know interseismic deformation between LVF segments for future seismic hazard assessment by Persistent Scatters SAR Interferometry (PS-InSAR). GPS and leveling survey have been useful tools for measuring surface deformation; however the density of stations were relatively sparse and costly. Radar interferometry is now well established technique for monitoring regional active deformation. Many studies indicated that radar interferometry could be used to get millimetric-precision over a large area, thus the PS-InSAR technique was applied in this study together with the prices leveling and GPS measurements. We use StaMPS approach to remove the errors contributed by orbital, topographic and atmospheric effects to obtain mean deformation rate along radar line-of-sight (LOS) by ALOS (advanced land observation satellite) L-band SAR images from 2007 to 2009. According to PS-InSAR result, a sharp gradient of 25-30 mm/yr along the LOS across the Chishang Fault, which imply the creeping behavior dominated in the shallow part of the fault. For the Rueisui segment, a gradient of 8-10 mm/yr along the LOS between Rueisui Fault and Chimei Fault area relative to Longitudinal valley is observed. In addition insignificant interseismic deformation change across both the Yuli fault and the Linding fault, implying the creeping behavior disappeared in the northern segment of the LVF. Comparing with continuous GPS and leveling data, the deformation trend was quite consistent, which shows that our result is reliable and with highly accuracy.

Stratigraphic Architecture and Depositional Evolution of the Plio-Pleistocene Tai-yuan collisional basin, Coastal Range of Eastern Taiwan

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Keywords: Coastal Range, Tai-yuan basin, Stratigraphic architecture, basin analysis

The Tai-yuan basin in Coastal Range of eastern Taiwan is one of the remnant forearc basins of northern Luzon island arc. These basins are made up of Miocene arc-volcanic rocks sharply overlain by over 5 km thick Plio-Pleistocene siliciclastic sedimentary rocks which recorded the geotectonical evolution history of the Taiwan Orogeny. Despite the stratigraphic system is already established during the last 30 years, the lithostratigraphic correlation and lithofacies change within these sedimentary rocks is still not well understood. For this purpose, this study aims to reexamine the stratigraphic subdivision in Tai-yuan basin by investigating several stratigraphic sections, and explore the depositional evolution through composition, paleocurrent, and paleoslope measuring and lithofacies analysis.

The sedimentary rocks are composed mainly by sandy to muddy turbidites and slumped beds, with some unique marker beds sandwiched in the sequence. The variation of sand to mud ratio rhythm among sections implies the presence of considerable facies change. In contrast, several widespread synchronous marker beds, including 5 pebbly mudstones and 2 tuffaceous layers groups are found. Based on these event-stratigraphic marker beds, this study builds up a new 8-units stratigraphic framework including 3 units in Fanshuliao formation (Fsl-I to III) and 5 units in Paliwan formation (Plw-I to V).

Pebbly mudstones were deposited by debris flows in submarine slope and near slop environments. The result of paleoslope and paleocurrent analysis imply that each pebbly mudstone layer was derived from multiple source direction; besides, the clasts composition shows that these sediment are derived from both proto-taiwan accretionary wedge and volcanic arc sides. The tuffaceous layers are mainly white normal graded coarse sandstone which can be classified into the Bouma's Tabce, Tabe, and Tbce divisions as turbidity current deposits. These biotite contained tuffaceous turbidtes are interbedded within Paliwan formation and can be subdivided into lower and upper groups. The lower group shows poor lateral continuity and mainly distributes around the north and south sides of Tai-yuan basin. In contrast, each of upper group layers can be laterally traced in center of basin. These tuffaceous materials are considered to be derived from south-eastern source(s) according to the result of thickness variations and paleocurrent analysis.

By integrating the above-mentioned, in early Pliocene to Pleistocene, the volcanic arc basal of the Tai-yuan basin were onlapped by deep sea fan turbidite sequence mainly derived from north. During this time, several widespread debrites probably triggered by huge earthquakes events and biotite-contained tuffaceous deposits produced by 2 periods of volcanic eruption events are recorded.

The Kinematic Model of the Foreland Basin Development in Northwestern Taiwan

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Keywords: seismic interpretation, subsidence curve, basin flexure

During the Early Pliocene, the Eurasian and Philippine Sea plates obliquely converged and produced an orogenic loading, which flexed a rift-type continental margin and formed a foreland basin in the western Taiwan. The detailed time and process of the foreland basin development still remain in debate and have to discuss. The study area was set to cover, from north to south, the Kuanyin basement high and the Neogene extensional basin center. The study area also extends from the outer foothills, which is closer to the orogeny, to the offshore, which is closer to the craton. Seismic profiles, well logs, field and nanofossils data were used to describe the variation in the lithostratigraphy; constructed structural and time stratigraphy section; designed isopach maps and subsidence curves. In this study, we attempt to reconstruct the tectonic subsidence history, create evolutionary model, simulate the growth of the foreland basin, and investigate the effects of inhomogeneous plate on the later development of the foreland basin in the northwestern Taiwan.

This study constructs the tectonic evolutionary model by using the isopach maps and subsidence curves. Tectonic subsidence curves indicate time-spatial variation in tectonic uplift and subsidence in the foreland basin. During the period of NN12 (5.6-4.4 Ma), tectonic subsidence in the entire study area was mild. Following that, mild tectonic uplift happened and was restricted in the offshore area during the period of NN13~NN15 (4.4-3 Ma), while the offshore area in the northern part of the study area still encountered mild tectonic subsidence, forming a typical asymmetric shape of foreland basin. During the period of NN16 (3-2.6 Ma), rapid subsidence happened and further extended into the entire area of the basin. In the next periods of NN17~NN18 (2.6-1.8 Ma) and lower NN19 (1.8-1.6 Ma), tectonic subsidence rate decreased rapidly especially in the offshore. Finally, since the beginning of period of middle NN19 (1.6Ma-present) a large amount of sediments deposited into and fill the basin because of the encroaching orogenic belt.

Based on the aforementioned results, this study considered that tectonic subsidence rates represent the activity of the orogeny. We proposed that the subsidence happened in the proximal part and uplift happened in the distal part, indicating that the foreland basin started to develop in our study area during 4.4-3 Ma. Isopach maps revealed the typical form of the foreland basin was formed in northern study area. In contrast, the southern study area still maintained the shape of the preextensional basin. The diversity of the basin forms reflected the spatially variable strength of the lithosphere. According to the two-dimensional modeling, not only the lateral change of the lithosphere strength but also the height of the orogeny will influence the basin developed.

The sediment distribution and canyon evolution on the Kaoping Submarine Canyon, offshore south-west Taiwan

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Keywords: Kaoping Submarine Canyon, submarine fan, seismic, fold and thrust, paleocanyon

Kaoping Submarine Canyon is located at the offshore southwest Taiwan. It is originated from the Kaoping River onland Taiwan, which carries sediments derived from the Central Range of Taiwan. Kaoping Submarine Canyon runs through a narrow Kaoping Shelf, a complex bathymetric Kaoping Slope, and then merges into the Manila trench. Therefore, Kaoping Submarine Canyon acts as a major pathway for the transportation of sediments from onland Taiwan to the deep sea area. This canyon can be separated into three parts, the upper reach, the middle reach and the lower reach. This study focused on the lower reach of the canyon. Preivous studies about Kaoping submarine Canyon had suggested that there is a submarine fan around the head of the lower reach, but seldom detailed studies and analysis were carried out in this area. Recently, many studies had pointed out the influence of seafloor topography on the formation and morphology of submarine fans. The objective of this study tries to understand the evolution of the submarine fan based on the sedimentary characteristics and it's influenced by nearby tectonic settings.

For this study, we used multi-channel seismic reflection profiles collected from several cruises of R/V Ocean Researcher 1 and we also have high-resolution large-offset seismic data acquired during the cruise of R/V Langseth in order to figure out the detailed seismic information. We might divide the sediments into 5 units and four boundaries: unit1, homogeneous sediments without perturbation; unit2, inhomogeneous strata without perturbation; unit3, similar to unit1; unit4, channel deposits; unit5, the present sediment. Between each unit, we have a erosional KB1 between unit1 and unit2; unit3 downlapping KB2; unit4 onlapping KB3; and a erosional KB4 between unit4 and unit5. The irregular seafloor is resulting from the faults and folds. Most of the folds here are fault propagation fold, and lies in north to south direction. These folds strongly controlled the direction of the Kaoping Submarine Canyon, which turns from south to southwest when it encountered the first fold. The Canyon turns northeast when it runs into another fold. We can also find paleocanyon underlies the present canyon, which has migrated to the present In addition, we may find some BSR(Bottom simulating reflection) and chimney results from gas.

Understanding the relationship between tectonics and sediments and the evolution stages in the lower reach provide a opportunity to develope an model of the Kaoping Submarine Canyon. With this study, people may have a good chance to evaluate the reservoir to be gas filled or empty.

High frequency guiding behavior from Taiwan subduction zone earthquakes and the inferred slab anisotropy

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Shu-Huei Hung[1], Jyr-Ching Hu[1]

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Keywords：high frequency seismic wave, guided wave, slab anisotropy

Seismic waves traveling up the subducted plate to the forearc stations reveal amplified high-frequency energy, called subduction zone guided waves. In Taiwan, guiding behavior of the subducted Philippine Sea plate (PSP) and Eurasian plate (EP) can be illustrated by large amplitude and long duration high-frequency-coda (3-10Hz), resulting in the anomalously large peak ground acceleration pattern from intermediate-depth earthquakes.

Here we study the high-frequency guiding behavior in the southernmost Ryukyu subduction zone and explore the slab anisotropy from intermediate-depth earthquakes. Using moving window spectra method, we demonstrate the spatial distribution of slab guided waves in Taiwan, how much bigger and longer the high frequency waves can be observed. We also developed an average amplified factor for fast identification of slab guided waves, which provides a hint to where the plate boundary intersects with Taiwan.

We, furthermore, try to determine shear wave splitting parameters from the 34 PSP guided events that are deeper than 100 km with ray path traveling along the subducted slab. The shear wave splitting analysis shows complicated polarization pattern of fast directions, but the delay time is consistent in the studied events. Such slab guided waves derived delay time is in a range of 0.30-0.45 sec, which is larger than crust anisotropy (<0.1sec) inferred in Taiwan. This implies that slab anisotropy is stronger than the crust effect but weaker than the mantle wedge and sub-slab mantle effect (0.5-2.1s) in Taiwan.

On the Near-surface Seismic Anisotropy of Taiwan

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Keyword: Seismic anisotropy, Near-surface structure, Seismic interferometry

We measure the near-surface seismic anisotropy of Taiwan by using the Empirical Green's Functions (EGF) between the newly deployed shallow borehole seismic array and their corresponding overhead surface stations.

Since the inter-station distances of the borehole-surface station pairs are less than 400m, high frequency EGFs are required to accurately measure the azimuthal anisotropy. We compared EGFs derived from three approaches: (1) cross correlation of continuous data, (2) deconvolution of earthquake signals, and (3) cross-correlation of earthquake coda waves from local earthquakes (ML>4). We conclude that probably due to the fact that high frequency sources are weak in the continuous ambient noises, only the earthquake-based methods provide more stable high frequency (3-8 hz) EGFs. Since the application of deconvolution method is limited by the nearby seismicity, most of our results are thus derived by the coda cross-correlation method.

We derived EGFs from about 30 station pairs. We first correct for the borehole sensor orientation, we then measured the Vs azimuthal anisotropy, and evaluate the shallow Vs velocity at each borehole site.

In most of the derived EGFs, we have found clear cos2θpatterns of Vs azimuthal dependence. These results represent direct measurements for the near-surface seismic anisotropy, and they are strongly correlated with the surface geology. In general, the fast axis of Vs anisotropy is sub-parallel to the mountain strike in the mountain area, and perpendicular to the deformation front in the western plain area, suggesting that the observed anisotropy is likely related to the orogeny-induced foliation in mountain ranges and stress-aligned cracks in western plains, respectively. The strong near-surface anisotropy also implies that delay times contributed by the shallow crust might be underestimated in studies of the shear-wave splitting measurements.

Resolving the crustal seismic anisotropy of Taiwan using ambient seismic noises

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Keywords: ambient noise tomography, crustal anisotropy

We construct 3D isotropic/anisotropic crustal models of Taiwan using ambient noises tomography. We have collected an unprecedented data amount for the noise tomography in Taiwan using continuous data from two island-wide broad-band networks and the temporary arrays deployed by the TAIGER (TAiwan Integrated GEodynamics Research) project. In our earlier works, we have derived 2D maps of azimuthal anisotropy in the period range from 5 to 20 seconds using this data set. In particular, the effects of irregular azimuthal path distribution are carefully examined and the influences of topography on surface wave dispersion are evaluated using SEM (spectral element method) and removed from data prior to the inversion. In these maps, the pattern of azimuthal anisotropy gradually varies with increasing periods, from convergence-perpendicular striking NNE-SSW trend at shorter periods to near convergence-parallel E-W trend at longer periods, suggesting that there is a strong depth dependence of seismic anisotropy in Taiwan. To further investigate the depth distribution of the observed anisotropy, we developed 3D models of anisotropy. Instead of the commonly used two-step inversion in the construction of 3D models using surface waves, we derive the 3D model in one step using a wavelet-based multi-scale inversion technique. Models of 3D anisotropy display a good correlation to surface geology in the upper crust, in which the anisotropy pattern is dominated by the foliation induced by orogeny. In middle crust, the anisotropy pattern starts migrating to stress-parallel direction, suggesting the existence of a weaker viscosity layer and therefore decoupling in middle to lower crust.

Lithospheric Structure under the Caucasus Mountains from Joint Inversion of Receiver Functions and Rayleigh Wave Dispersion

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Keywords: Caucasus, crustal structure, receiver function, continental collision

The Caucasus mountain belts may be considered as the northernmost boundary of the collision created by the impinging of Arabia to Eurasia. In this study, we jointly invert receiver functions and surface wave data to estimate the velocity structure under a combined seismic network in Georgia covering the central-western part of Greater and Lesser Caucasus. This seismic network consists of 10 broadband stations from the Institute of Earth Sciences, Academia Sinica of Taiwan and 4 from the Georgia Seismic Center. The method can obtain the detail velocity structure with little trade-off between absolute velocity and depth of the discontinuity.

For the surface wave constraints, we extract Rayleigh wave phase dispersion using two-station method and the results indicate that the phase velocity under the Lesser Caucasus is higher than Great Caucasus by 0.25 km/s in average. As for the receiver functions, we select teleseismic earthquakes and deconvolve Z from R components for each station using different Gaussian filters. Because of the azimuthal variations and ray parameter-dependent variations are found at some stations, we first focus on the earthquakes with back azimuth from 90° to 120°.

The Moho depth obtained by joint inversion is about 40-45 km for the stations in the western Greater Caucasus, and it increases by ~5-10 km toward the eastern part of the array under the central Great Caucasus. The results are consistent with the depths from the H-κ stacking. As for the Lesser Caucasus, the Moho depth beneath station TRLT is also around 40-45 km, but is slightly shallower than the previous estimates for this area (~50km). More importantly, we observe a sharp low-velocity layer at the depth of 3-8 km beneath station TRLT, which is located on the volcanic plateau with active earthquake swarms nearby. The low-velocity layer could be associated with a magma chamber underneath, similar to the findings from the receiver function studies in the Altiplano-Puna, Central Andes.

An Improvement of Low-cost Earthquake Early Warning System in Taiwan: Using Arrival-time Order Location Method and Small Arrays

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Keywords: AOL, early warning, Pd, Mpd

An earthquake early warning system has been established in Taiwan. The Seismo-Lab of National Taiwan University used low-cost seismometers called P-alert to build an array which covering almost whole Taiwan (beside mountain area). The advantages of this system are, for example, Low-cost of each seismometer so that the array can be built in very high density. It uses Pd3 to predict the magnitude and ground shaking in according to the waveform in first 3 seconds after P wave arriving. However, due to the P-alert is a low-cost meter, the signal to noise ratio of P-alert is relatively high when comparing with other meters. This disadvantage may cause the uncertainty of locations.

In order to solve this problem, we used arrival-time order location method (AOL).It can provide reference initial value of locations at the beginning of earthquakes, and replace the worse result of inversion. AOL method has better results, which can provide relatively reliable locations as initial value for inversion, in first few seconds after earthquakes. Especially for earthquakes which have M_L 4.5 ~ 5.0. Using the results of AOL method, we can calculate more accurate MPd for early warning.

Estimating Local Vp /Vs Ratios within Similar Earthquake Clusters in Taiwan Region

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Keywords: Taiwan; Vp/Vs ratios; differential times

In general, variations in Vp/Vs ratios may be determinedby using tomographic methods. However, the resolution of local Vp/Vs ratios from tomography is usually limited due to the coarse grid sizes and the regularization operation. Lin and Shearer (2007) proposed that the Vp/Vs ratio could also be estimated within similar earthquake clusters from measuring the P and S differential arrival times with waveform cross-correlation. This technique potentially has higher resolution than typical tomographic inversion method. Benefited by the dense seismic network and high seismicity, Taiwan region is a place very suitable for such approach. In this study, we applied and tested this method on the similar earthquake cluster in the Hualian region. Also, we modified robust misfit function method from the previous study to compute Vp/Vs ratios for both synthetic datasets and earthquake clusters. In comparison with the results from different tomographic models, Vp/Vs ratios determined from our study are much lower. It may indicate the presence of fluids, cracks, or anomalous lithologies within fault zone or source area, which cannot be easily resolved by conventional tomographic method.

A study of along depth spatial relation between mainshock and its aftershock distribution

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Keywords: earthquake sequences, depth-dependent

In order to investigate the depth distributed characteristics between mainshock and its aftershocks, we relocated earthquake catalog of the Central Weather Bureau from 1990 to 2011 using three dimensional velocity model. Double-link algorithm is applied to separate the earthquake catalog into several earthquake sequences. Further, we define two indexes to describe earthquake depth scattering and aftershocks distribution relative to the mainshock for this study purpose. Base on our results, we suggest that the distributed characteristics for each focal type are different. For normal and strike-slip fault, there is an obvious correlation between the mainshock depth and the aftershocks distribution relative to it. For thrust events, the most of the mainshoks occurred in the deeper portion and most of aftershocks distribute in above the mainshock. Furthermore, we find out that the scattering in earthquake sequence is independent from the mainshock magnitude and depth.

Constraints on Shear Wave Velocity Heterogeneity and Anisotropy in D” from Finite-Frequency Differential Traveltime Residual Analysis

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Keywords: lowermantle, D’’, shear wave splitting, anisotropy, seismic heterogeneity,

The D’’ region which lies in the lowermost ~250 km of the mantle has long been postulated as a major thermo-chemical boundary layer in the earth’s dynamic evolution, where the upwelling plumes most likely originate and the downwelling cold slabs terminate. In this study, we collect recorded and available broadband waveforms from earthquakes with epicentral distances of 40 o -145o and magnitudes greater than 5.8 during 2001-2012. A cluster analysis is then adopted to simultaneously group the seismic phases of interest with similar waveforms and measure relative traveltime shifts between them by waveform cross correlation. We construct a dataset of differential traveltime residuals from composite phases, S (Sdiff), SKS, SKKS, ScS and multiply-reflected ScS phases commonly used to constrain elastic wave speed heterogeneity in the lowermost mantle. Our results shows phases passing through the Circum-Pacific Rim generally have negative residuals while those traveling through the central Pacific and Africa have positive residuals which corresponding to the ULVZ at Central Pacific and West of Africa.

We analyze Sdiff splitting in D” region after correcting upper mantle anisotropy from SKS/SKKS splitting results. For those paths traveling through the high-velocity region under the Aleutian subduction zone, the differential SV-SH residuals are small and mostly negative within 1 s, namely, SV arriving earlier than SH. However, finite-frequency sensitivity indicates that the SH arrival would advance the SV while traveling through the isotropic high-velocity D” region. Therefore, the observed Sdiff splitting may reflect the presence of genuine seismic anisotropy. For those paths crossing the NE Pacific region with both high and low velocities, we observe small negative residuals at short distances but large positive residuals at longer distances. Further exploring the finite-frequency effect on apparent split of SVdiff and SHdiff using full-waveform kernels is required in order to constrain truly anisotropic properties in D”.

Using S*m*KS Traveltimes to Investigate the Structure near the Top of the Earth's Outer Core

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Keywords: outer core, Direct-Solution Method (DSM), multiple SKS waves

The solid inner core of the Earth consists of heavy minerals Fe and Ni with a fraction of light elements such as O, S, Si. During the inner core formation, these light elements escape and rise up through the outer core as the result of buoyancy, but their existence is still being debated. Some authors have presented seismological evidence for lowered wave speed beneath the core-mantle boundary (CMB) relative to PREM, suggesting light elements there, but counter argument also exists. In this study, we use traveltime measurements from recorded and modeled SmKS waves to investigate the effect of the velocity under the CMB on the differential traveltimes between SKKS and S3KS waves (TS3KS-TSKKS). Due to the long propagation distance and interference with neighboring phases, the arrival times of SKKS and S3KS waves are difficult to define accurately in the records. Therefore in our analysis we measure both the observed and model-predicted differential traveltime TS3KS-TSKKS by cross-correlating the waveform of Hilbert-transformed S3KS with that of SKKS. We use synthetic seismograms calculated by the Direct-Solution Method (DSM) in a suite of 1D models with different structural profiles under the CMB to examine the existence of a zone of lowered velocity at the top of the outer core. We are conducting a systematic investigation using waveforms available at IRIS from globally distributed large deep earthquakes. More than 100 deep events since 1990 provide ~600 high-quality TS3KS-TSKKS measurements with uneven geographical coverage due to the locations of deep earthquakes. Results indicate clearly that the seismic velocity in the ~400-km zone under the CMB is slightly lower than that in PREM. There is also a suggestion of lateral variation in the distribution of the light materials probably associated with the observed laterally heterogeneous seismic structure in the inner core.

Improve the experimental process to enhance the yield of GEM using liquid carbon source

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Keywords: Graphite Encapsulated Metal (GEM), Nanoparticle, liquid carbon source, yield

Graphite Encapsulated Metal Nanoparticles (GEM) is a spherical core-shell structured composite material which has a diameter ranging from 5–100 nm [1-3]. The core of GEM is metal, and its outer shell is composed of several layers of graphite/graphene which can preserve inner core against severe environment, such as acid erosion and oxidation. Nowadays, several studies have revealed that GEM has a great potential to become a novel materials inclding in hydrogen storage and biomedical materials due to its unique properties. For example, functional groups like carboxyl or hydroxy can be easily attached to the surface of graphite/ graphene layers, which means GEM can be surface modifing and widely apply to delivery carriers or environmental absorbents [4-5].

Following the guidance of the two-step mechanism model [2], we chose the modified tungsten arc discharge method [6], and used n-propanol [7] as the liquid carbon source to synthesize GEM. This is the most practical method for producing a large quantity of GEM because it reduces the amount of carbon debris originating from the Krätschmer–Huffman method [8].Currently, our group has dramatically increased the encapsulation efficiency of GEM, for Co-GEM and Ni-GEM, the encapsulation efficiency was raised from 20-30 wt% to around 80 wt%. However, this method could disturb the arc discharge which brings out the discontinuity of experiment, having difficulty to synthesis large quantity of well-encapsulation efficiency GEM. In order to solve this problem, our group has installed liquid metering pump to regulate the amount of each injection. Furthermore, we calculated the heat loading of the tungsten cathode to figure out the solution of slowing down the melting speed of tungsten cathode owing to the decompose of n-propanol during high temperature. In this paper, we study the experimental parameters of carbon liquid source when it decomposing in vacuum chamber, and find out the best injection rate of inletting liquid carbon source without affecting the arc discharge. In this way, we can make sure the liquid carbon jet direct to the coalescence region produce large quantity of well-encapsulation efficiency GEM, and prolong the single production time to increase the yield.

Geochemical characteristics and petrogenesis of Eocene to Quaternary igneous rocks in the Georgian Caucasus

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Keywords: Arabia-Eurasia collision, Georgian Caucasus, geochemistry, Cenozoic magmatism, Neotethyan subduction

Cenozoic magmatism in the Caucasus-Iran-Anatolia (CIA) region has been related to the subduction and termination of the Neotethyan system from the late Mesozoic to early Miocene. In Georgia, located at the northern part of the CIA region and north of the Ankara-Erzincan/Sevan-Akera suture zone, Cenozoic igneous rocks occurred in three main stages, i.e., middle Eocene (~45 Ma), late Oligocene (~24 Ma) and late Cenozoic (< 3 Ma), respectively, based on our new zircon U-Pb and whole rock Ar-Ar age data. Both the first and third stages consist of basic to felsic rocks. Contrast with the later that plot in the medium- to high-K calc-alkaline suite with a wider range of SiO2 (46-75 wt.%), the former are mainly of intermediate composition (SiO2 ≈ 60 wt.%) and show heterogeneous potassium contents that plot from low- to high-K calc-alkaline to shoshonitic series. The second stage, with SiO2 ranging from 58 to 66 wt.%, is dominated by medium-K calc-alkaline rocks. Trace element data show that all three stages of rocks are characterized by "arc geochemical signatures" such as enrichment in large ion lithophile elements (LILE; e.g., Rb, Ba) and depletion in high field strength elements (HFSE; e.g., Ti, Nb, Ta). Moreover, the second stage and Armeranis volcano of the third stage (SiO2 > 58 wt.%) are adakitic, i.e., with low HREE and Y (5-10 ppm) and high Sr/Y (80-120), which we suggest to have resulted from partial melting of the lower part of thickened mafic crust (>50 km) owing to the Arabia-Eurasia collision. The post-collisional magmatism in the CIA region, initiating ca. 15-11 Ma, has been ascribed to rollback and breakoff of the subducted Neotethyan oceanic slab and/or other geodynamic processes such as delamination of the thickened Eurasian lithosphere. Our Sr-Nd isotope data show that the third stage of magmatism in Georgia have an isotopically uniform mantle source similar to coeval CIA magmas elsewhere and support the notion for a subduction-modified mantle that prevails in the entire CIA region throughout the late Cenozoic. Zircon Hf isotope data obtained from all three stages are also uniform, yielding high and positive $\varepsilon_{Hf}(T)$ values (+1.8 to +20.8), suggesting that the Georgian magmatism was derived from a common mantle source through the middle Eocene to Quaternary.

Geochemical tracers for the groundwater and streams in central mountainous regions of Taiwan

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Keywords: Geochemistry, tracers, noble gas

Noble gases have been considered as sensitive tracers for groundwater due to their unique geochemical characteristics. In this study, groundwater of the monitoring wells and river water were collected for geochemical analysis, including Radon concentration and Helium isotopes, from central mountainous regions of Taiwan to discuss their fluid sources. The results of hydrogen and oxygen isotopic values are -77.8~-36.5‰ and -10.7~-6.3‰ respectively, falling on the local meteoric water line of Taiwan. It revealed that groundwater source in studied area is mainly from the precipitation. The helium isotopic ratios of the samples range from 0.78 to 1.13 Ra. It implies that, in addition to the air-saturated water, there are additional sources for the groundwater in central mountainous regions of Taiwan. Interestingly the water sample from Liwu River was detected high 222Rn concentration, 7.66 kBq/m3, which is much higher than background values in normal river water. It suggests that local groundwater with high 222Rn concentration of 1.38~75.4 kBq/m3 may play important role for the Liwu River. Combined with other geochemical tracers, like 87Sr/86Sr and carbon isotopes of DIC, we will further discuss possible interaction between the groundwater and surface water with bed rocks.

Gas Geochemistry of GroundWater in the Ilan Plain, Northeast Taiwan

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Keywords: ground water, dissolved gases, radon actives, helium isotopes, Ilan Plain

Ilan Plain is located at the northeast Taiwan and has been tectonically spreading due to the westward back-arc rifting of the Okinawa Trough. In previous studies, geological survey, geophysical research, and stratigraphic correlation were conducted to rebuild the aquifer systems in the Ilan Plain. However, few gas geochemical data of ground water are available. In this study, it is first time to systematically analyze the gas geochemistry of ground water from 37 wells to recognize the gas sources/components in the Ilan Plain. Water samples can be classified as three main groups, most samples are classified as sulfate and bicarbonate groups, few samples belong to chloride group due to the contamination of sea water. Based on the major dissolved gases compositions, the ground water samples can be divided into two groups, i.e. CH4-enriched group and N2 enriched group. Ten out of total 37 wells show CH4-enriched affinities with CH4 proportions of 30-50%, in which three wells exhibit very high CH4 contents, up to 70-90%. Two of the CH4-enriched wells are located in the northwest, and the remains are in the southeast of Ilan Plain. The dissolved radon concentrations are in the range of 800-10000 Bq/m3 in the studied area. It is interesting to note that the radon actives are higher in the west mountain areas and gradually decreasing toward the east coast areas. Meanwhile, the oxidation-reduction potential and dissolved oxygen data show positive correlations with the radon actives. It implies that the recharge of the ground water in the Ilan Plain may be from the Hsuehshan Range in west. Furthermore, elevated helium isotopic results suggest that mantle component may play an important role for the gas sources in the southeast and center of the Ilan Plain, where may be corresponding to the extensional structure or the suspected faults in the Ilan Plain.

Distribution and Evolution of Groundwater Contamination at the RCA Taoyuan Plant

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Keywords: groundwater, contamination, remediation, tetrachloroethylene

Soil and groundwater at the Radio Corporation of America (RCA) Taoyuan Plant in Taiwan were found to be contaminated by chlorinated volatile organic compounds (VOCs) in 1987. The major pollutants are tetrachloroethylene (PCE), trichloroethylene (TCE), 1, 1, 1- trichloroethane (1, 1, 1-TCA) and their degradation byproducts. The pollution may be attributed to improper dumping or leakage of chlorinated solvents. These VOCs are dense non-aqueous phase liquids (DNAPLs) which can hardly be dissolved in groundwater. The residual DNAPLs along the migration pathway usually dissolve very slowly in groundwater, and thus become long-term contamination sources. Site characterization, sampling and analysis indicated that the uppermost aquifer is a 20-m thick gravel layer. The deep formation is composed of sand interbedded with mud layers. Groundwater flows northward in the horizontally and downward vertically. Contamination was found primarily in the northwest and north sides of the site. The groundwater contamination cannot be removed by the pump and treat method. Therefore, the Taoyuan plant becomes the first groundwater pollution remediation site announced by the government. Enhanced reductive dechlorination method has been applied to the site to remove contaminants since 2005. The groundwater became anaerobic environment, accelerating the degradation of contaminants by injecting chemical materials. The concentration of PCE in the groundwater reduced significantly seven years later, while the concentration of vinyl chloride (VC) biodegraded from PCE increased considerably and still partially higher than the groundwater pollution standard. The higher toxicity of VC may cause another problem of groundwater contamination. Besides, the concentration of contaminants off-site became higher. An effective solution for the cleanup of vinyl chloride and off-site contamination must be considered in the future.

Interseismic deformation along the middle part of the Longitudinal Valley, eastern Taiwan

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Keywords: GPS, Interseismic velocity, Longitudinal Valley, Taiwan

The Longitudinal Valley in eastern Taiwan is generally considered as the suture between the Philippine Sea plate and the Eurasian plate. Many historical large earthquakes occurred along this suture. The southern part of the Longitudinal Valley has attracted many studies, mostly due to the rapid-creeping Chihshang segment of the Longitudinal Valley fault. However, only a few detailed studies focused on the middle part of the valley. In order to understand the interseismic deformation patterns along the middle part of the Longitudinal Valley, we analyzed GPS (Global Positioning System) measurements and leveling results to obtain the velocity field and strain pattern of the area. We calculated the GPS velocity field from continuous stations installed by the Central Weather Bureau and Academia Sinica that have been measured in the past twelve years, as well as campaign-mode stations measured at least annually from 2003-2012. Our analysis is intended to understand the activities of the Longitudinal Valley fault and the Central Range fault in the Rueisuei and Yuli areas, in the middle part of the valley.

We calculated the velocity field and velocity cross-sections across the middle segments of the Longitudinal Valley fault and the Central Range fault, and derived interseismic dislocation model for these two faults using the data from GPS and leveling. The results show that the Rueisuei and Yuli areas are characterized by compressional deformation in northwest-southeast direction. In the northern Rueisuei area, the Central Range fault appears to have higher rates of reverse motion than in southern Rueisuei area. The Longitudinal Valley fault appears to have higher rates of both reverse and sinistral motions in the southern Rueisuei area. Our geodetic analysis provides new observations of interseismic deformation patterns of the middle segments of the Longitudinal Valley fault and the Central Range fault. These new observations will enable us to further understand the earthquake hazard potential of this part of the Longitudinal Valley suture.

Structural evolution of the Chimei Fault, Coastal Range, eastern Taiwan

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Keywords: fault zone, damage zone, paleostress analysis, reverse fault

The Chimei Fault, which thrusts the Tuluanshan Formation over the Paliwan Formation, is the only major fault cutting across the entire Coastal Range. Though previously regarded as a reverse fault, recent investigations show that the fault zone comprises varying structure features indicative of a more complicated character as illustrated by the excellent exposures along the Hsiukuluan River near the Chimei Village.

The Chimei Fault and a subsidiary shear plane located in the footwall divide the fault zone into the hanging wall damage zone, the footwall fold zone, and the footwall damage zone. Fault slip data within these components show different paleostress patterns and are grouped into 3 sets. The first set, showing strike-slip movement with NE-SW compression, is identified by the slickensides filled with gypsum veins in the hanging wall damage zone. The folds that deformed under insufficiently consolidated condition in the footwall fold zone, indicating N-S compression, dominate the second set. The third set, comprising only brittle faults, is recorded in the footwall damage zone, showing NW-SE compression.

The first set is deemed to fracture prior to the formation of the footwall since mineral-vein intrusions are confined to the hanging wall. The folds of the second set demonstrate the initial deformation in the footwall before the fault rock becomes completely consolidated, followed by the third set until the footwall is uplifted to the shallower brittle regime. The 3 sets illustrate a three-stage structural evolution of the Chimei Fault, constructing an in-sequence reverse fault zone: (1) NE-SW compression with strike-slip movement; (2) N-S compression with reverse component; (3) NW-SE compression with reverse component.

The Engineering Geological and Topographic Characteristics of Debris Flow in the Chishan River and Laonong River of Kaohsiung

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Keywords: Debris flow, Chishan River , Laonong River

This study is aimed to investigate the engineering geological and topographic characteristics of debris flow occurred in the catchments of the Chishan river and Laonong river during 2009 Typhoon Morakot. The study methods include field geomorphological investigations, satellite images and geomaterial testing.

According to the interpretations of the satellite images and the topographic analyses, the watersheds existing debris flow mostly have areas of >0.1 km2, and the main channel lengths of >1000 m. The experimental results of sieve analyses show that 76% of deposited material are of gravel particles, and only <10% of deposited material is of fine particles. The average compressive strengths of rock on the both sides of valley range from 27 MPa to 80 MPa. In addition, the field investigations demonstrated that the rock discontinuities developed very well, with the average volumetric joint count of 12.2 m-3, and formed various types of failure models, such as dip slope and wedge failure, which provided a large volume of deposited materials. These results suggest that the strength of rock may not be the main factor that controls the possibility of debris flow occurrence. Furthermore, it could be resulted from the weak plane of the interbedding or the geological structures. The interpretations of satellite images and field investigations as well reveal that the landslides occurring at originated areas of debris flows may be the source of deposited materials.

Reevaluation on the fault geometry and segmentation of the Longmen Shan fault zone by the co-seismic horizontal displacements given by the SPOT imagery for 2008 Wenchuan Earthquake

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Keywords: Wenchuan Earthquake, Longmen Shan fault system, co-seismic surface deformation, fault geometry

2008 Wenchuan earthquake (Mw 7.9) produced two major parallel surface ruptures [i.e., the Beichuan-Yingxiu Fault (BYF) and Guanxian-Jiangyou Fault (GJF)] associated with previously published Longmenshan fault zone system striking roughly NE and the ruptures extended to 240 km and 70 km for BYF and GJF respectively. As mapped result, there was actually a 7 km long NW-striking rupture (Xiaoyudong Fault) observed connecting above two major surface ruptures. Such a spatial relationship among these surface ruptures is unusual and must have certain reason behind which is our target. Our study on ground displacement using comparison of the SPOT imageries taken before and after earthquake can produce ground displacements distributed in a large area. Such a co-seismic ground movement may yield clues to explain the question above. Across the GJF, our results show the thrust and strike-slip component were <1m and ~3m respectively in the north (north of Hanwang, Lat. 31.45°-31.5°). To the central area, the thrust and strike-slip component were 3-5m and ~2m respectively (Jinhua to Hanwang, Lat. 31.35°-31.45°). They became 2m and 1m to the southern end (south of Jinhua, Lat. 31.2°-31.35°). The detailed fault geometry of the GJF could be constrained by this pattern in the 2008 Wenchunan earthquake. From Beichuan northward all the ground displacements slipped parallel to the fault, suggesting a pure strike-slip fault with no clear segmentation. On the other hand, to the south of the GJF, the displacements show a direction consistently towards SE mainly perpendicular to the fault trace. It only makes a direction change before and after the Xiaoyudong Fault, implying the southern segment terminates at the location where the Xiaoyudong developed. Based on the results above, the first order segmentation of the entire Longmenshan fault can be divided in to three segments, which is consistent with general characteristics delineated by the geological mapping. We therefore prefer the models which proposed three major segments for the Longmenshan fault system. However, the details need to further work out by other high resolution methods.

Activity of the eastern Karakoram-Jiali fault zone in Tibetan

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Keywords: Active faults, Tibet, characteristic slip, crust flow

The Karakoram-Jiali fault zone (KJFZ) is the only major dextral fault in Tibet, which plays an important role in the eastward extrusion of the Tibetan Plateau. Armijo et al. (1989) first recognized the KJFZ and proposed it as the structure along which eastward movement of the Qiangtang terrane relative to the Lhasa terrane. Our study focuses the activity of the eastern KJFZ, included with the Jiali fault (JF), and the Gyaring Co fault (GCF). By interpreting high resolution satellite images, we are able to remap those two faults. Several kind age methods were used included with radiocarbon, cosmogenic raionuclide, and optically stimulated luminescence (OSL).

The GCF, is one of an en echelon faults of the KJFZ, has been reported as a dextral fault, striking N50°-60°W at a rate of ca. 10 to 20 mm/yr (Armijo et al., 1989). According to our OSL ages, new slip rate of the GCF can be estimated as 14.6±3.1 mm/yr since ca. 50ka. This study also focuses on a section of the western segment of the GCF, where the slip has been recognized to have occurred at 3.0±1.6 m more than 7 times. This ~3 m slip implies MW7.2-7.4 earthquakes recurring to the western segment in every 200 yrs, while reaching about MW7.7 if both segments could break at the same time. In JF, the main Jiali fault becomes less active since late Pleistocene. Our field investigation found there may have been only one small event during the Holocene, but none in the late Pleistocene. The Nagqu fault (NF), previously mapped as the horsetail of the JF, shows many lines of active fault evidence. Our research shows slip rate of the NF is ~15 mm/yr, which shows as fast as the GCF.

The GCF and the NF are similar with another en echelon minor fault, named the Beng Co fault (BCF), which was occurred 1951 M8 event. Such a high slip rate suggests recently the central en echelon minor faults of the original KJFZ kinematically different from the Karakoram and Jiali faults to the west and east respectively. Turning to inactive along the main Jiali fault may be attributed to the orientation of the Jiali fault, which is parallel to the extension axis and has no differential stress acting across it. On the other hand, the subsidiary faults play essential roles in accommodating the stress in a certain tectonic system, implying the crustal flow should be considered.

A three-dimensional double-difference earthquake location algorithm and application to the 2013 Ruisui, Taiwan, earthquake sequence

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Keywords: double-difference, earthquake relocation

Double-difference earthquake location algorithm (Waldhauser and Ellsworth, 2000) is one of the methods used in earthquake relocation. This algorithm minimizes the travel time residuals by using earthquake pairs which are very close in distance recorded by same station. The travel time residuals may be reduced by this procedure because the ray paths between the event-station pairs are very similar. The most widely used double-difference earthquake relocation program hypoDD (Waldhauser and Ellsworth, 2000; Waldhauser, 2001) only supported using one-dimensional velocity model in the relocation process. To improve the relocation result by using higher resolution velocity model, we developed a double-difference earthquake relocation program using three-dimensional velocity model (3D-DD). Moreover, we also joint single-event relocation method with double-difference location algorithm during the inversion procedure, in order to prevent losing the relocation results when double-difference location algorithm is only used. The performance of the program was tested by a synthetic test. A set of synthetic data used in the test was generated by pseudo-bending ray tracing method (Um and Thurber, 1987; Koketsu and Sekine, 1998). The location error of 3D-DD is smaller than the error of hypoDD and a three-dimensional single-event earthquake relocation program 3DLOC (Wu et al., 2003). We also apply our method on Ruisui ML6.3 earthquake sequence relocation. Mainshock of this event occurred on October 31st, 2013, epicenter is located on the township of Ruisui, Taiwan. In comparison the results from 3D-DD and 3DLOC, the hypocentral distribution from 3D-DD are much more concentrated and linear. The location error and residual became obviously smaller after relocated by our method.

Coseismic Velocity Reduction Correlated with Volumetric Strain Change Induced by Two Recent Large Earthquakes in Central Range of Taiwan

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Keywords: ambient noise, coda wave , volumetric strain, coseismic slip

Coseismic velocity reduction has been considered to be mediated by perturbations of stress and strain conditions in the crust and/or increased permeability/porosity of fractured rocks within the quake-damaged zones. To investigate potential changes and causes in crustal strains and rock properties associated with the earthquake rupture after the two large earthquakes, Jiasian and Nantou, (Mw > 6 and focal depth >20 km) occurring in southcentral Taiwan, we construct empirical Green's functions (EGFs) from cross-correlation functions (CCFs) of continuous ambient noise between available station pairs near the epicenters from the short-period Central Weather Bureau Seismic Network (CWBSN) and the Broadband Array in Taiwan for Seismology (BATS). The temporal variations in seismic velocity perturbations are estimated by measuring the relative time delay of late-arriving coda waves between short-term and long-term stacked EGFs.

The resulting EGFs at 0.1-0.9 Hz show the statistically significant coseismic velocity reduction after both the events. The velocity drop is detected mostly convincingly from the pairs with the interstation paths traversing through the hanging-wall block of the ruptured fault. The sensitivity of surface wave coda arrivals to shear wave speed within the dominant frequency range of 3-5 s is confined in the upper 10-15 km, where the crust mostly experienced the coseismic dilatational strain change induced by the slip distribution from the finite-fault models. Compared with the coseismic slip distribution from GPS data and finite-fault inversion, peak ground velocity, and slip-induced volumetric strain, we suggest the coseismic velocity reduction associated with these two events is plausibly caused by the induced dilatational strain in the shallow part of the crust above the ruptured faults.

Full-Wave Effects on Shear-Wave Splitting

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Keywords: full-wave sensitivity kernel, shear-wave splitting, seismic anisotropy

Seismic anisotropy in the mantle plays an important role in our understanding of the Earth's internal dynamics, and shear-wave splitting has always been a powerful observable in the investigation of seismic anisotropy. So far the interpretation of shear-wave splitting in terms of anisotropy has been largely based on the ray-theory modeling of a single vertically incident plane SKS or SKKS wave, which is a strong assumption and results in the rejection of measurements in many cases, thus severely limits our ability to make full use of shear-wave splitting data to resolve the spatial variations in anisotropy. In this study, we adopt an approach to the inversion of 3D anisotropy structure using the sensitivity (Fréchet) kernels calculated by an efficient and flexible full-wave algorithm based on the normal-mode theory. Predictions of SKS splitting by these full-wave sensitivity kernels demonstrate a significant bias in ray-theory treatment caused by the unaccounted interference between the SKS wave and other contaminating phases with similar arrival times. The full-wave sensitivity kernels accurately account for all the interactions of multiple phases for a wide range of epicentral distances. The full-wave kernels not only widen the possibilities in the source-receiver geometry in making shear-wave splitting measurements, but also provide the capability for tomographic inversion to resolve vertical and lateral variations in the anisotropic structure.

Study Anatomy of T-Waves Using their Arrival Times and Amplitudes Recorded from 60 earthquakes Offshore Taiwan

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Keywords: T-wave, T-phase, Taiwan, ocean bottom seismometer, acoustic waves

T-waves are seismic energies that have at least partially propagated through a water body. Such waves can propagate long distances, thus are useful for studying small abyssal plain earthquakes at far distances. However, factors controlling the amplitude and duration of T-waves are still not clear. It is also advantageous if we know where the energy enters into the water column and which parts of the T-wave is arriving from the crust or from the water column near the receiver side. Here, we deployed broadband ocean bottom seismographs (OBSs) offshore Taiwan. One OBS, at a water depth of 4726 m, recorded T-waves from 60 Mw>3.3 Taiwan earthquakes. For these earthquakes that are well-located by a dense land seismic network, we forward-calculated the travel times of the different parts of a P- and S-wave convert to T-wave, and correlated them with different paths from the earthquakes to the OBS through different conversion points at Sound Fixing and Ranging (SOFAR) channel depth along the 1000 m bathymetry contour line. The end of the observed T-wave was associated with the paths with furthest available conversion points in the regional bathymetry, and the waveform gap consistent to the gap of bathymetry contour. However, arrival times of a few abyssal earthquakes show that those T-waves are converted directed from the deep seafloor near the sources, instead of entering from the SOFAR channel. T-wave amplitudes are correlated with P- and S-wave radiation patterns. Similar T-wave duration analyses have also been done using an island seismic station, and consistent results were found. Furthermore, we have used the ratio of ground motions to water pressure to determine if the T-wave is arriving as ground motions or as acoustic waves from the water column. Such method can help us to determine the different paths of the T-waves recorded by the OBSs.

The correlation between shear wave velocity and topography of D” discontinuity beneath Central American

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Keywords: lowermost mantle, mantle dynamics, D”, triplication phase

Commonly observed triplication arrivals generated by shear wave interaction with a sharp velocity jump at the top of the D” region have been accustomed to argue for the widespread presence of the D” discontinuity beneath the Caribbean and Central America. However, the intertwined relationship between the topography of the D” discontinuity and heterogeneity of shear wave velocity is still poorly resolved. In this work, we aim to explore the spatial correlation of the D” discontinuity topography with shear wave velocity fluctuations by modeling triplication waveforms from deep earthquakes in the South America subduction zone recorded by dense transportable USArray and permanent broadband stations in North America and Canada. The source-receiver configuration is suitable for observing triplication waves that bottom and sample the D” region extensively beneath the Central America and the Caribbean. Dividing the densely-distributed stations across the North America into several linear corridors, we conduct forward waveform modeling to seek an optimal 1-D velocity model in the lowermost mantle which best fits both differential travel times of ScS-S and Scd-S and waveform similarity recorded by each event-station pair along each corridor. Though triplication shear waves emerge frequently between direct S and ScS waves across our study area as reported in previous studies, there are still a number of localized regions sampled by shear waves which contain weak/no or extremely strong triplications. In addition, the regions detected with relatively higher shear wave velocities generally coincide with the shoaling of the D” discontinuity and vice versa. Our observation and modeling results imply that there exists strong lateral velocity heterogeneity and gradient in D” as well as significant topographic undulation of the D” discontinuity on regional scales.

Crustal Anisotropy beneath the Hi-CLIMB Array in Tibet from Modeling Receiver Functions

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Keywords: Continental collision; Tibetan Plateau; receiver function; crustal anisotropy; Moho

It is well known that the India-Eurasia collision beginning at about 50-55 Ma ago results in the world's highest Himalayan mountains and largest Tibetan Plateau with an average elevation of 5 km and crustal thickness of 70 km. Over the past two decades, temporal broadband arrays steadily deployed in the vast area of the plateau have greatly improved constraints on seismic structures beneath this key collision zone with unprecedented resolution.

Strain-induced seismic anisotropy is commonly used as a proxy to map the distribution and characteristics of lithospheric deformation. Chen et al. [2010] analyzed birefringence of teleseismic S and SKS phases recorded by available stations along three N-S transects across the Himalayan-Tibetan collision zone. The resulting differential arrival times between two orthogonally-polarized shear waves indicate a sudden increase from null splitting in southern Tibet to about 1 s at 75 km north of the Indus-Yalung suture (IYS), which marks the southern terminus of the anisotropic Eurasian mantle lithosphere. The fast polarization direction is predominantly E-W to NE-SW, aligned parallel to strike-slip faulting formed concurrently with mountain building.

Because teleseismic shear waves potentially sample multiple layers of seismically anisotropic structures in the crust, lithospheric mantle, asthenosphere and even the D" region at the base of the mantle, it would be difficult to distinguish seismic anisotropy contributed from the crust and underlying mantle and constrain multiply-layered anisotropy with depth-varying fabrics and strength possibly present in the two colliding continents. In this study, we focus on investigation of the crustal anisotropy beneath the Tibetan Plateau by modeling radial and transverse receiver functions observed along a linear seismic array deployed by Project Hi-CLIMB (Himalayan-Tibetan Continental Lithosphere during Mountain Building), one of the largest-scale field experiments across the west and central Tibet.

Receiver function (RF) is calculated from the deconvolution of the horizontal (radial or transverse) components of a seismogram by the vertical component to isolate P-to-S conversions at seismic discontinuities, for instance, the Pms phase converted at the Moho. In a layered isotropic medium, the Pms phase, like SKS, is radially polarized and only appears in radial receiver function. The emergence of Pms energy on transverse receiver function would indicate the presence of crustal anisotropy beneath stations. Modeling synthetic RFs indicates that the change in the thickness of crustal anisotropic layers would alter the Pms waveforms significantly. In addition, the polarity of the Pms phases would vary with the backazimuth, strongly depending on the orientation of the fast-axis. As a result, we can examine the Pms waveforms varying with backazimuth to characterize the crustal anisotropy.

Teleseismic P-wave coda from earthquakes with magnitudes greater than 5.5 and epicentral distances between 30o and 90o are first selected for receiver function calculations using an iterative time-domain deconvolution (Ligorria and Ammon, 1999). After applying the moveout corrections based on a reference ray parameter to all the obtained RFs at each station, those with good signal-to-noise ratios are stacked by backazimuth in every 20o bin. We observe clear P-to-S conversions at the mid-crustal discontinuity and Moho, which arrive about 5 and 10 s after the direct P in the radial RFs, respectively. Between these two converted phases, a negative phase whose amplitude and arrival time vary with backazimuth is considered as evidence for the presence of seismic anisotropy in the lower crust. The P phases with the polarity reversal in every 90o of backazimuth often appear in the transverse RFs, suggesting that the upper crust is also anisotropic. To quantitatively characterize the depth-varying anisotropic structure in the crust under the plateau, we combine azimuth-dependent RFs in both radial and transverse components to invert for 1D layered anisotropic velocity models under stations. Because the inverse problem is highly non-linear with many model parameters, we choose a neighborhood algorithm that searches the global minimum of an optimized function, defined as the correlation coefficient between observed and synthetic waveforms of both radial and transverse RFs, to obtain the optimal model. The potential variation in crustal anisotropy across different parts of central Tibet will be discussed and compared with those obtained from SKS splitting.