From active faults to seismogenic sources: progress, issues and challenges

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As one of the most tectonically active areas in the world, the island of Taiwan is characterized by frequent seismic activities and numerous active faults. As a result, one of the most crucial tasks for Earth scientists in Taiwan is to understand, assess, and mitigate future seismic hazards of the island. To achieve this, models of earthquake hazard, risk, and related social and economic impact of Taiwan need to be established through multidisciplinary collaborations, and the very first step toward this would be to construct a complete and updated seismogenic structure database for Taiwan.
One such database has been constructed in the past several years based on reviews of existing active structure databases and new information for structures that have not been thoroughly analyzed before. For example, the Central Geological Survey of Taiwan has published a comprehensive database of active faults in Taiwan, including all of the historically ruptured faults. Many other active structures, such as blind faults or folds that can be identified from geomorphic or structural analysis, have also been mapped and reported in several previous investigations. On the basis of such information, a preliminary version of this database has already been released and published earlier in 2016. This preliminary database includes primarily on-land structures, but has not included offshore structures that may also pose significant seismic hazards.
Therefore, we have been working on updating the seismogenic structure database in the effort to obtain sufficient data for offshore structures. In addition, based on historical earthquake events, we have also been working on proposing earthquake scenarios that involve ruptures of multiple structures, or only partial segments of a given seismogenic structure. These new additions and considerations, however, also created new challenges for the construction of the database. For example, many parameters, especially the long-term slip rates, of the offshore structures are extremely difficult to determine. The proposed frequency of multi-structure or segmented rupture events would also significantly influence the recurrence interval calculations. Although this seismogenic structure database would undoubtedly provide significant constraints for the calculations of seismic hazards in Taiwan, we suggest that the issues and challenges we identified will constitute the next most important questions to be solved for future seismic hazard assessment studies.

Keywords: seismic hazard assessment, active faults, seismogenic sources, Taiwan

Toward better fault hazard assessment: Lessons from the 2016 Kumamoto, Japan, earthquake

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The 16 April 2016 Mw=7.0 (Mjma=7.3) Kumamoto earthquake struck the city of Kumamoto, towns of Mashiki, Nishihara and Minami-Aso in central Kyushu, southwest Japan, and brought significant damage to buildings, killing 50 people. An ENE-trending ~31-km-long surface rupture emerged during the earthquake along the previously mapped Futagawa and northern Hinagu faults (Kumahara et al., 2016 JpGU abstract). The rupture zone also included a previously unknown 5-km-long fault within the Aso Caldera, one of the active volcanos in Kyushu island. The hypocenter is located ~5 km west from the junction of the Futagawa and Hinagu faults those strikes compose of a 25°-transpressional bend. The 14 April 2016 Mw=6.2 (Mjma=6.5) earthquake, claimed as a foreshock, was preceded on the Hinagu fault zone, 2.5 km south of the fault junction. From the viewpoints of fault displacement hazard assessment, we here present three key features as lessons learnt from the Kumamoto earthquake.

1) Unpredictable multiple scale en echelon step-overs and short conjugate faults

The rupture zone is mostly composed of right-lateral slip sections, with a maximum of 2.5 m coseismic slip. On a scale of 1:50,000 map, most of the rupture traces preoccupied the previously mapped faults that already display fault branching and multiple parallel traces, except the ones inside the Aso Caldera. However, observed surface breaks are much more complex than the inferred ones in large scale maps. A remarkable feature was left-stepping en echelon step-overs on various scales from meters to a few kilometers. The other significant characteristic is several short NW-trending left-lateral faults (up to ~300 m) as a conjugate fault to the primary right-lateral fault. These unpredictable features are probably due to the combination of thick unconsolidated volcanic sediments derived from the caldera and complex structure in and around the fault junction.

2) Coseismic slip partitioning

Another noteworthy feature observed in the field are ~10-km-long segmented normal fault scarps, dipping to the north-west, mostly along the previously mapped Idenokuchi fault (Research Group for Active Faults of Japan, 1991), 1.2 to 2.0 km south of and subparallel to the Futagawa fault. The maximum amount of coseismic throw on the Idenokuchi fault is ~2 m, which is nearly equivalent to the maximum slip on the strike-slip rupture. The locations and slip motions of the 2016 rupture also manifest as interferogram fringe offsets in InSAR images. Together with geodetic and seismic inversions of subsurface fault slip, we illustrate a schematic structural model where oblique motion occurred on a north-west-dipping subsurface fault and the slip is partitioned at the surface into strike-slip and normal fault scarps (Toda et al., 2016, Earth Planets, and Space). The Kumamoto case would be the second significant slip-partitioned earthquake around the globe.

3) Triggered slips on short peripheral faults

Multiple InSAR images for the Kumamoto earthquake consistently display more than 200 triggered fault slips as offsets of interferogram fringes around the primary rupture zone (e.g., Fujiwara et al. 2016, Earth Planets, and Space). While slips on most of them are smaller than a range of one interferogram fringe (~12 cm), significant multiple slips larger than 20 cm occurred in a part of the mountainous outer rim of the Aso caldera, ~15 km far away from the main rupture zone, without any significant aftershocks. We found a ~6-km-long NW-trending discontinuous minor breaks bisecting the urbanized area of Kumamoto (Goto et al., 2017, Earth Planets, and Space), which might have been related to local damage. The post-earthquake geomorphic investigation using vertically exaggerated anaglyph images suggests these fractures occurred

on the pre-existing faint normal fault scarps.

Keywords: Kumamoto earthquake, active fault, surface rupture

Inter-seismic behavior and Indian Ocean Dipole records along the western Myanmar subduction zone recorded by coral microatolls

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The Sunda megathrust is one of the major plate boundaries in South Asia, along which the Indian-Australian plate subducts northeastward beneath the Burma micro-plate offshore western Myanmar. In the past several centuries, the 1762 Arakan earthquake was the only giant event occurred along this plate boundary, and caused significant co-seismic uplift along a large stretch of the western Myanmar coast. In previous studies, the magnitude of the event and the potential seismogenic structures were analyzed based on uplifted coastal features on the Ramree and Man-Aung Islands, two of the largest coastal islands of western Myanmar. However, constraints on the inter-seismic behavior of this plate boundary are still very limited, particularly due to the lack of high resolution instrumental records in this area. Therefore, we utilized coral microatolls as natural tide gauge to analyze relative sea-level history and to obtain information of land-level change during the inter-seismic period.
For some coral genus such as *Porites*, the highest level of survival (HLS) is constrained within a few centimeters of the lowest tide level. Therefore, once the relationship between HLS and the sea level is established, the morphology of the microatolls can provide us the relative sea-level history based on the patterns of their annual growth bands under x-radiographs. U-Th dating technique can constrain the age of the coral, and we can also identify sea level anomalies caused by climatic events through oxygen isotope analysis.
We collected several slabs of coral microatolls from the intertidal zone near Leik-Ka-Maw, a small village in northwestern Ramree Island, approximately 80 km away from the trench. The microatolls were uplifted and killed during a local earthquake event in 1848, and preserved HLS records of about 80 years between the 1762 Arakan earthquake and the 1848 event. Our results show that the coral recorded a HLS rise at a rate about 6 mm/yr, which represents land-level subsidence during the inter-seismic period. Several temporary HLS die-down events are also present, likely produced by Indian Ocean Dipole (IOD) events based on the microatoll morphology and results of oxygen isotope analysis. We hope our results would provide additional constraints for improving the earthquake recurrence interval calculations for hazard assessments in this populous area.

Keywords: Myanmar, inter-seismic deformation, coral microatolls, seismic hazard

Reconstruction of the relative sea-level changes over the past centuries by using coral microatolls in the Ryukyu arc.

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The Ryukyu subduction zone, where the Philippine Sea Plate is subducting beneath the Eurasian Plate at rate of 8 cm/yr, may have the potential to generate large megathrust earthquakes. However, only few M8+ earthquakes were reported in the arc over the last 350 years and the GPS data indicate that this subduction zone is likely aseismic. We know however that the interseismic strains rate may vary through time and we need longer records to better characterize the behaviour of subduction zones. Toward this goal, we started to investigate the coral microatolls along the Ryukyu arc. Coral microatolls act as natural tide gauges by recording relative sea-level (RSL) changes with a precision of a few centimeters over several centuries or millennia. They are the only geological marker filling the gap between short-term deformation measured by instrumental geodesy and longer-term deformation recorded by older geological markers.

We found plenty of microatolls between Okinoerabu and Okinawa, where we observed a large variability in shape, from cup-shaped corals indicating submergence at Ie-jima to hat-shaped corals indicating emergence at Yoron. After detailed topographic surveys, we performed a first sampling fieldwork in Itoman and Onna (south and west part of Okinawa, respectively) and in Yoron. We sampled two living corals at each analysed site and an 8-m-diameter fossil microatoll in Yoron. We then reconstructed the RSL changes over the last century with living microatolls and inferred more than three centuries of record from the fossil microatoll of Yoron. In Onna and Itoman, we inferred a slight emergence trend of at best 1 mm/yr over the last 55 years and interrupted by few die downs around 1986, 1995, 2004, and 2016. The longest record observed was in Itoman, where we identified a major submergence trend of about 7 mm/yr that started around 1906. In Yoron, the corals recorded periods of slight to pronounced emergence, alternating with periods of submergence since 1928. Although the inner part of the fossil microatoll in Yoron is very smoothed due to erosion, we inferred a slow submergence of at best 1 mm/yr over about 270 years followed by a major submergence increase over the last decades of the record.

The satellite altimetry indicates a homogeneous regional sea-level rise in the Ryukyus of 3 mm/yr since at least 1992 (probably since 1950 according to sea-level reconstruction*s*) that contrasts with RSL changes recorded by the microatolls of Yoron and Okinawa and with the morphology variability observed among microatolls from the islands we visited. This regional sea-level variability highlighted with microatolls is also supported by the six longest available tide gauges in the Ryukyus whose submergence trends vary between 0.5±0.7 mm/yr at Naze and 4.4±1.5 mm/yr at Nakanoshima over the last 50 years. These first data (corals and tide gauges) collected in the Ryukyu arc imply an additional signal to the absolute sea-level rise that could generate subsidence or uplift at the scale of the arc. This signal may be due to volcanism, local crustal active faults or to the megathrust seismic cycle. The latter source is preferred because volcanoes are far from the studied areas and crustal active faults usually generate a local signal. This signal may be due to interseismic strain accumulation and silent earthquakes. The emergence trend

over the past 55 years could be due to interseismic loading on the megathrust interface that would generate uplift on the surface of few millimeters per year, while the submergence events could be related to coupling changes on the interface (possibly slow events). Finally, we showed that the records from Okinawa differ from those of Yoron. This could be explained by the existence of a long-term seismic barrier between the two islands. Such barriers could be due to the entrance in subduction of submarine ridges, facture zone (Luzon-Okinawa Fracture Zone) and seamonts in front of the area investigated.

Keywords: microatoll , relative sea level , megathrust , Ryukyus

Recognition of inferred active Fangshan transfer fault in Kaohsiung metropolitan area of SW Taiwan by geodetic measurement and SAR interferometry

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The major NNE-SSW trending fold-and-thrust belt in Taiwan orogeny resulted from the oblique collision between the Philippine Sea plate and Eurasian plate. Due to the differential movement of thrust sheets, several NW-SE trending transfer faults were recognized by multisource approaches, such as geomorphological features from high resolution DEM, drainage network anomalies, aerial photographs, SLAR images, SPOT and Landsat images. The southernmost Fangshan transfer fault is located in Kaohsiung metropolitan area which had been categorized as an active by Central Geological Survey in 2000. However this fault is eliminated on the list of active faults in 2010. In this study, we first use the dense GPS network in SW Taiwan to investigate the Fangshan transfer fault by decomposition of GPS velocity field into fault-normal and fault-parallel components. The GPS suggest that the Fangshan transfer fault is a left-lateral fault zone with thrust component accommodating the westward differential motion of thrust sheets on both side of the fault. In addition, the linear pattern of PS-INSAR with significant gradient of LOS rate across the fault suggest that the Fangshan transfer fault is still active. From background seismicity, the shallow events and seismicity are not frequent in the surrounding area of the Fangshan fault, thus the accommodation of deformation is probably aseismic.

Keywords: GNSS, InSAR, Active Fault

Mud-core anticline responsible for anomalous deformation rate in SW Taiwan: Insight from 2016 Mw 6.4 Meinong Earthquake and numerical modeling

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Anomalous strain accommodation across the fold-and-thrust belt in SW Taiwan are revealed by the Continuous GPS, precise leveling and SAR interferometry. The previous block model based on GPS measurement suggested a high seismic risk in SW Taiwan. However, a clear evidence of multiple fault slip along a fold-and-thrust belt at 5-10 km depth was triggered by the 2016 Mw Meinong earthquake at 15-20 km depth. The primary coseismic fault slip was deduced with kinematic model based on seismic and geodetic measurements and triggered fault slip along the shallow fold-and-thrust belt was constrained by SAR interferometry. We hypothesize that the surface coseismic deformation is mainly controlled by a structure related to the shallow detachment at around 5-10 km depth, which a proposed duplex in a region of high pressure and high interseismic uplift rate might be sensitive to stress perturbations induced by moderate lower crustal earthquake. It is surprising to notice that the footwall of Lungchung fault demonstrates a high uplift rate of ~20-30 mm/yr in interseismic period. This anomalous deformation rate might part be related with a ramp duplex located in the footwall and the triggered slip of moderate earthquake in nearby area. In addition, the mechanical heterogeneity of mudstone in the Gutingkeng formation might play a crucial role of anomalous deformation. Consequently, we use an Efficient Unstructured Finite Element method (DynearthSol2D) to simulate and discuss the contrast of viscosity in mudstone and sandstone contributed in deformation pattern and upward mobility. We also want to check the previous hypothesis of mud diapirism and incorporate a new mud-cored anticline model for mechanic explanation of anomalous interseismic deformation occurred in SW Taiwan.

Keywords: mud-core anticline, SAR interferometry, seismic hazard

Imaging the subsurface fault systems with the magnetotelluric surveys in the southern Ilan plain of NE Taiwan

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The high sedimentation rates as well as the frequent human activities have caused the difficulties in mapping the surface traces of the active faults in most of the populated areas of Taiwan. The basement topography of the sedimentary basin, on the other hand, should show the direct results of fault movements and is free from the sedimentary effects. Therefore in the study we attempt to use the magnetotelluric(MT) surveys to delineate the basement topography of the southern Ilan plain, which is consisted of Tertiary metamorphic rocks such as Argillites and Slates. The recent extension of the Okinawa Trough starting from approximately 0.1 Ma involved ENE- and WSW-trending normal faults in the Ilan plain. The plain is therefore thought to be a subsidence basin bounded by the Hsueshan Range in the north and the Central Range in the south. We deployed over 70 MT stations across the plain and tried to map the relief variations of the basement with the inverted resistivity images, since the saturated sediments are relatively conductive and the consolidated rocks are resistive. We found that there are a series of N-S trending horsts and grabens in addition to the pre-existing ENE-WSW normal fault systems in the inverted MT profiles. The preliminary results suggest that a younger N-S trending normal fault system may modify the relief of the basement in the recent stage. The findings of the MT resistivity images provide new information to further review the tectonic explanations of the region in the future.

Keywords: magnetotelluric, Ilan plain, normal fault

A study of the near surface geometries of the Chimei and Chihshang faults with the electrical resistivity imaging surveys in the Yuli area

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The Longitudinal Valley(LV) in eastern Taiwan represents the collision boundary between the Eurasian Plate and the Philippine Sea Plate. The Longitudinal Valley Fault (LVF) is the main active fault having a surface length of about 150km from Hualien to Taitung. A significant surface creeping was found at the Chihshang fault in the south part of LVF. However, the GPS and PSInSAR (Persistent Scatterers InSAR) results showed that the Rueisui Fault and Chimei Fault area in the middle part of LVF had less surface movements than the Chihshan fault area in the south. The junction of the Rueisui, Chimei and Chihshan faults was at the Yuli area. In this study, we try to find the shallow structure of faults between the Chimei fault and Chihshang fault. Six 2D electric resistivity profiles were done alone the Chimei fault in Yuli area. After the field data collecting and 2D inversion of the resistivity measurements, the electrical models show that the Chimei fault and Chihshang fault might not be jointed at where researchers expected before in the Yuli area, and their surface fault traces are separated as two parallel lines in the area. The new evidences from the resistivity measurements suggest that we need to review the conventional fault junction model for the LVF in the Yuli area, and more detailed geophysical surveys are needed in order to resolve the regional fault structures.

Keywords: Longitudinal Valley Fault, electric resistivity, Chimei fault

A Study of the Deformation and Kinematic Characteristics of the Sanyi Thrust Fault by Incorporating the Outcrop Analysis and Resistivity Imaging Results

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For the purposes of hazard mitigation in metropolitan area, it is very important to map the fault trace in order to delineate the susceptibility zones of the active faults. In this study, we focused on the outcrop analysis and near surface resistivity mapping of the fault traces of the Sanyi thrust fault. From the outcrop along the Dajia river, we studied the kinematics and deformation characteristics of the Sanyi fault. The Kweichulin formation forms the hanging wall of the Sanyi Fault and the footwall is composed of the unconsolidated gravels and sands in the study area. We observed that the Sanyi Fault is composed of a major and three minor fault zones. The major fault zone extends about 100 meters, and is consisted of 1.5-m thick fault gouges and breccias. We also conducted electrical resistivity imaging near the outcrop and sites with drilling records. Compared with the data and inverted resistivity images, we concluded that the Kweichulin formation in the hanging wall exhibits a resistivity lower than 100 Ohm-m and the thick gravel layers in the foot wall have a resistivity higher than 100 Ohm-m. With the results we may quick differentiate the hanging wall from the footwall in the area, and to search the possible locations of the fault trace between the hanging wall and footwall. Our study shows the fault trace may pass through the east side of the Fengyuan township, and extends southeastward into the area that between the hill and the alluvial plain of Taichung Basin.

Keywords: Sanyi Fault, resistivity imaging, outcrop

Magnetic Fabrics Analysis across the Central Region of the Chimei Fault in the Coastal Range of Eastern Taiwan

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Taiwan is an ongoing orogen located in the conjunction of two subduction-arc systems with opposite vergences between the Philippine Sea and Eurasian plates. The Coastal Range along the eastern Taiwan is the accreted terrain composited of Luzon arcs and surrounding basins onto the Eurasian crust. The Chimei fault, a typical lithology-contrast fault thrusted the Miocene volcanic Tuluanshan Formation over the Pleistocene sedimentary Paliwan Formation, is the only major reverse fault across the entire Coastal Range. To investigate the deformation pattern and strain history across the Chimei fault, we analyzed oriented samples in the footwall of mudstone and in the hanging wall of volcanic rocks along the Hsiukuluan River via anisotropy of magnetic susceptibility (AMS).
Results of AMS across the central part of the Chimei fault show that the direction of k_{MAX} changed from N-S orientation to sub-vertical and the orientation of k_{MIN} switched from 270/70 to N-S orientation when samples of the footwall were approaching to the fault zone. At the same time, anisotropy was increasing and susceptibility ellipsoid changed from oblate in the fractured zone through prolate in the folded zone to oblate in the faulted zone. Based on identification experiments of magnetic minerals, the major magnetic carrier is magnetite with pseudo-single domain, suggesting paramagnetic minerals control the AMS. With increasing deformation, oblate ellipsoids with strong anisotropy developed within the fault zone highlighted the strain history of the central part of the Chimei fault. As a result, it strongly speculated that stress altered from sub-vertical sedimentary loading to horizontally NW-SE compression during collision stage and current N-S compression orientation could be resulted from 30 degree clockwise rotation during accretion stage.
This study demonstrates that AMS pattern across the Chimei fault is the consequence of finite deformation. Our results of magnetic fabrics evolution across the Chimei fault can provide insights into understanding the tectonic history of Chimei fault.

Keywords: Anisotropy of Magnetic Susceptibility, Chimei Fault, Coastal Range, Taiwan

Fault trace investigation of the blind segment of the Sanyi fault, Central Taiwan

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Sanyi Fault, the reversal active fault, which is extending about 30 km along the foothill and Taichung Basin in central Taiwan. The fault trace of the Sanyi Fault has been covered by the Holocene deposits along the lower river terrace and Taichung basin, which is a blind segment of the fault without displaced landform. In this study, we investigated subsurface fault trace by using boring data and Resistivity Image Profiling Method, and established the subsurface geological profiles cross to the fault trace. According to the subsurface geological profiles, the fault zone character and distribution in the subsurface of the blind segment of the Sanyi Fault are interpreted.

Keywords: Sanyi fault, Central Taiwan

Fault or landslide creeping at Tapo, frontal deformation of Chihshang active fault in eastern Taiwan

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The Chihshang fault forms the south-central segment of the Longitudinal Valley fault, located at the suture between the Philippine Sea plate and the Eurasian plate in eastern Taiwan. In the past century, the fault ruptured twice accompanied by two moderate to large earthquakes during the 1951 Yuli earthquake with a magnitude of 7.1 and the 2003 Chengkung earthquake with a magnitude of 6.8, respectively. It is also well-known as a creep fault in the world. However, the cause of surface deformation, i.e. either fault creep or landslide creep, has been debated for decades at Tapo site where the fault trace passes. In order to resolve this disputation, both geological and geophysical methods have been performed within the past two years. To reveal the shallow subsurface structure, two survey lines for electrical resistivity tomography were conducted and 4 wells for collecting rock cores were drilled up to 30 meters at depth. To analyze and characterize fault activity, some organic layers were dated and a real-time clinometer was installed and has functioned since last May.

Keywords: active fault, Chihshang fault , creeping fault, real-time inclinometer

