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Imaging Taiwan using Land, Ocean-Bottom and Active Source Data - Results of the TAIGER Experiments

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Introduction

As a young and very active orogen, Taiwan provides unique opportunities to examine mountain building produced by the collision of an arc with continent. Near Taiwan the oceanic Philippine Sea plate collides with the margin of the Eurasian plate, forcing the latter to subduct. The convex southeastward shape of the margin leads to the transition in Taiwan from collision in the north to Eurasia subducting under Taiwan in the south. Such transition makes Taiwan a rich environment to study how it take place and what factors control orogeny. Key questions are:

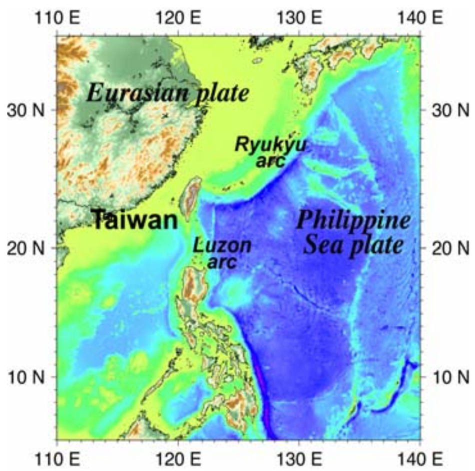
- Does the continental plate subduct? Do both colliding plates experience pervasive deformation?
- In the case of the collision between a continental plate and an island arc, how is the subduction zone geometry that defines the upper and lower plates modified after the introduction of continental lithosphere into the collision zone?
- What are the 3-D rheological and mechanical properties of the crust and the mantle in the orogen and what are the deformation processes involved? Although these questions pertain to studies of any mountain belt, they have been brought into particularly sharp focus on the Taiwan orogeny in recent years.

The Taiwan Integrated Geodynamics Project (TAIGER) was carried out in 2004-2009 a geophysical and geodynamical study of the role of arc-continent collision in the birth and evolution of the Taiwan orogenic belt. This project, in collaboration with Taiwan geoscientists, combined a program of diverse field observations in active- and passive-source seismology, magnetotellurics, and rock properties with geodynamical modeling.

The observational experiments were carried out in 2005-2009 and were often more than twice as large as originally proposed due to synergistic contributions by Taiwan scientists and government science funding. The experiments were designed for crust and lithospheric structure of the Eurasian and Philippine Sea plates, inferences of physical properties and rheology based on seismic velocities, attenuation, gravity densities, reflectivity strain markers, zones of anomalous conductivity, and mantle seismic shear wave flow markers. The larger-than-expected high quality data volumes provide opportunities for expanded analyses to obtain such information at higher resolution and in true 3D.

Tectonics of Taiwan

Taiwan was created by two converging, colliding plates, the Eurasian plate (EUR) to the northwest and the Philippine sea plate (PHS) to the southeast. Taiwan itself is quite compact, 400 long and about 100-130 km wide, but on the island and in its vicinity the complex tectonic regime consists of two subduction zones that are offset from each other (Fig. 1) and a collision zone that varies along its strike. Although some of the variations are clearly related to the geometry of the two subduction zones of different polarities, they are also a result of the evolution of these zones. More specifically it is the collision between the Luzon Arc on PHS and the continental margin of EUR that produced the Taiwan orogeny. It started four to five millions years ago, and recent analysis of thermochronological measurements indicates that the rapid rising may have been achieved perhaps in the last million years (Willett et al., 2003; Lee et al., 2006).



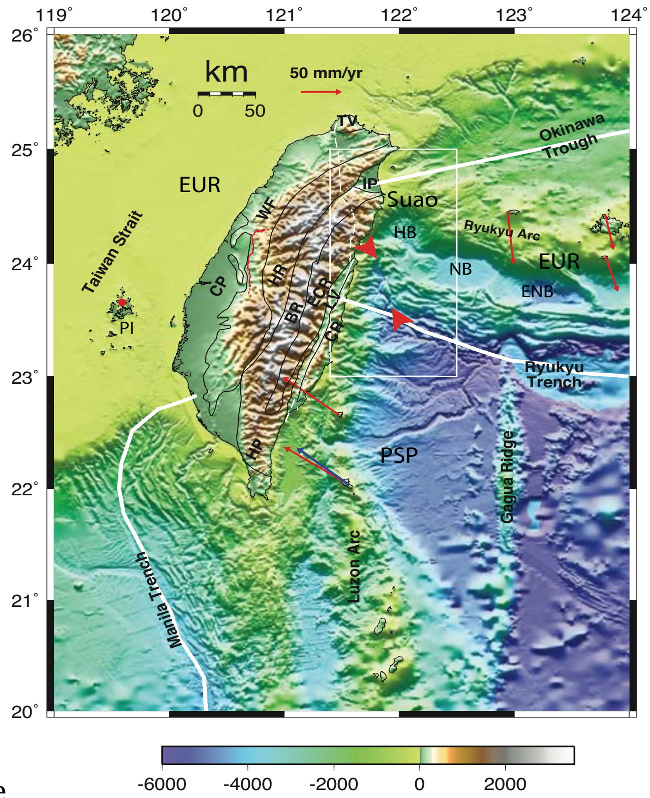


Figure 1. Taiwan is located on the edge of the Asian continent (left). The Ryukyu arc terminates against northern Taiwan and the Luzon arc disappears as it submerges under southern Taiwan (right). Taiwan itself is formed because of the collision of the Asian plate and the Philippine Sea plate.

Taiwan The convergence of EUR and PHS continues at the rate of 8 cm/yr. In central Taiwan the Coastal Range (on PHS) is a contracted suite of former Luzon Arc and peobably the forearc materials and, to the west, the Central Range, the Foothills and the Coastal Plain are, respectively, the highly deformed metamorphic core, the fold-and-thrust belt and the sedimentary trough on the continental shelf. In this section, PHS and EUR are in full collision. South of it, as the continental margin makes a sharper turn, EUR still subducts eastward, with its trench on the western side of Hengchun and the volcanic arc on the east (Fig. 1). Here, incipient collision is apparently in progress, shutting off the volcanoes on the arc, but PHS is advancing westward, thrusting over EUR, carrying a part of southern Taiwan with it. The Central Range however continues southward morphologically, extending onto the Hengchun Ridge south of Taiwan (Fig. 1).Based on existing data a number of tectonic models have been proposed. Some of these are shown in Figure 2.

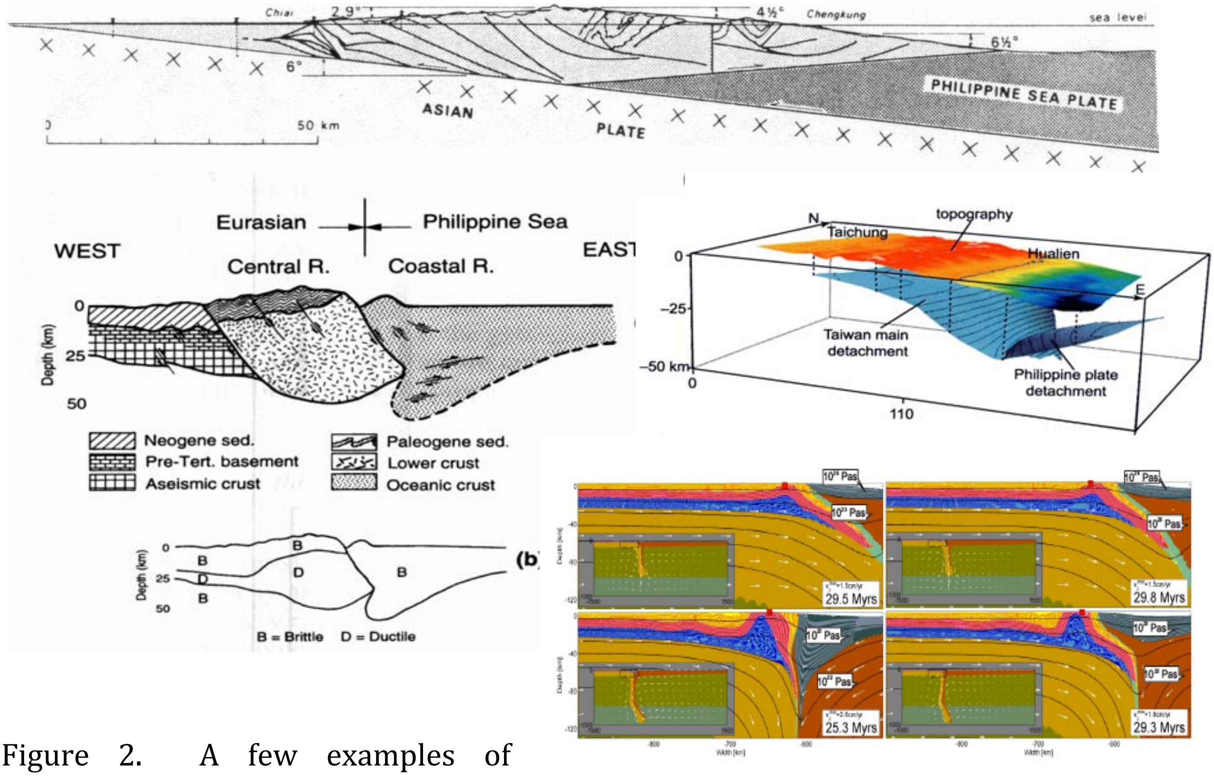


Figure 2. A few examples of proposed models of Taiwan tectonics (top, Suppe, 1987; middle left, Wu et al., 1997; middle right, Carena et al., 2002; lower right, Kaus et al., 2008).

The Suppe "think skinned" model has been widely used to explain the mountain ranges in the world; it is based on geologic mapping in the foothills of the mountains. Wu et al. (1997) proposed the lithospheric model based largely on geology, early tomography in Taiwan and on seismicity. The Carena (200

The active tectonics of Taiwan provide almost a laboratory environment for studying the geological processes of collision. It is particularly suitable for answering fundamental questions of: does continental subduction play an important role in arc-continent collision, is the mass of incoming continental crust balanced by crustal thickening and erosion, how does an orogen evolve through time, and what is the role of a colliding arc producing mountain building. The collision of Luzon volcanic arc and the passive continental margin of Asia that resulted in the creation of the mountains in Taiwan has been viewed as the arch-type of arc-continental collision. Studies of old and young orogens, such as the Alps, Appalachians, Jura and Taiwan, have produced our basic understanding of mountains. Studying a young orogen such as Taiwan presents many advantages as the processes in progress can be directly observed. Much of the understanding of orogeny was reached without an abundance of subsurface information, as the tools for such studies only became available in recent years.

TAIGER acquired detailed existing subsurface data in Taiwan to answer questions raised by earlier studies and it aims to couple observations with geodynamic modeling to gain understanding of orogenic processes. (1) Crustal structures along the 1995 TAICRUST transects were finalized and published (McIntosh et al., 2005), and more recently the results for the southern line were updated (McIntosh, 2009, in progress). The southern transect was particularly important in planning TAIGER and understanding the tectonics of southern Taiwan. (2) Short period earthquake seismic data, the continuous GPS data, leveling data etc. were used jointly to model the collision/subduction in northern Taiwan (Wu et al., 2009). (3) Through TAIGER we found that South Island, New Zealand, is a good analog of Taiwan (Wu et al., 2007).

Myriad questions arose during our work. For example: How did the subduction of Eurasian plate affect the orogeny? How deep is the orogen – hundreds of kilometers as implied by S-splitting? How did the deformation partition in the collisional orogen? Is there a shallow-dipping, through-going detachment across the orogen or is it pushed by the exhuming high ranges? How is the Coastal Range formed during the collision – did the arc obduct, did it thicken, or both? How does erosion influence the orogeny? Southern Taiwan (south of 23^{O}N) overlies the subducting Eurasian plate and is currently moving mostly with the Philippine plate, while in the main part of Taiwan collision is taking place: where is the transition and how different are the mechanisms of mountain building in these two sections? Although these questions are central to studies of any mountain belt, they have been brought into particularly sharp focus on the Taiwan orogeny in recent years.

The Design of TAIGER Project

Geophysical Imaging

As described earlier, the key to test the existing models of Taiwan tectonics is through subsurface imaging using seismic waves. In particular we need to know whether a detachment does exist in the crust, whether the Eurasian plate is actively subducting under Taiwan. Or more generally how do the crust and mantle deform in collision. To obtain these images we need to have sources of seismic energy and seismic receivers.

For sources we have the following two general types:

1) Active sources, namely explosions on land or "airguns" in the ocean water. For explosions we use "wide-angle" reflection/refraction. By themselves they are not sufficient for mapping detailed crustal structures, but with the offshore/onshore recording of air guns we can perform 2-D tomography along the profile and obtain details of crustal structures.
2) Passive sources, i.e., earthquakes. The seismicity is very high in the Taiwan area; about ~20,000 earthquakes of M>2 are recorded by the Taiwan network every year. Also if we have an appropriate network we can also use worldwide earthquakes with seismic rays penetrating the deeper part of the mantle.

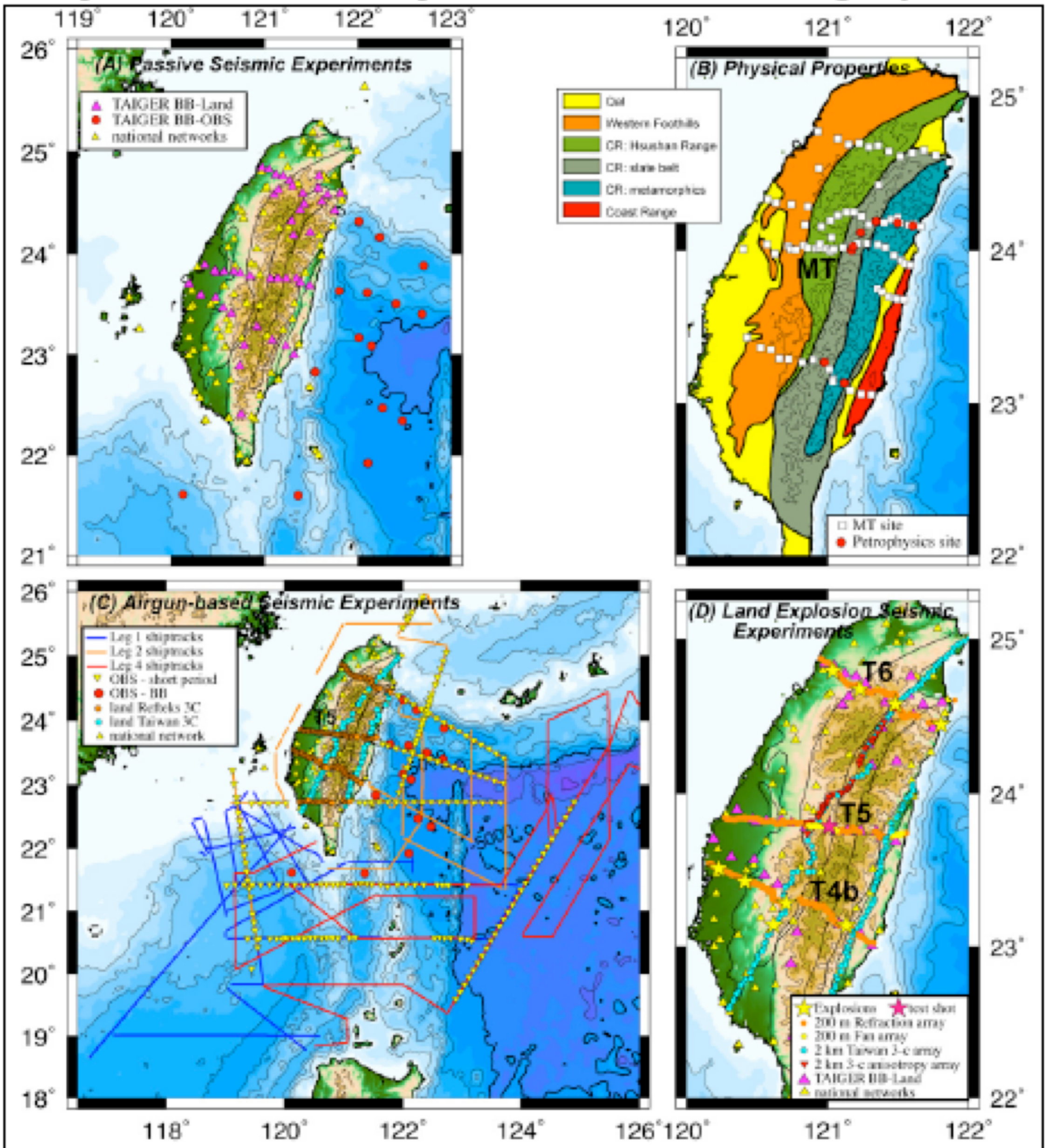


Fig. 3. TAIGER field observations efforts during 2005-2009. (A) Passive seismology experiments involving land broadband (2005-2006) and OBS broadband (2007-2009) deployments. (B) Efforts to derive physical properties: magnetotelluric soundings (2005-2007) and rock samples for petrophysical measurements (2005). (C) Onshore-offshore seismic experiment involving R/V Langseth airgun sources (2009): MCS profiles (ship tracks), OBSIP and Taiwanese short period OBS, PASSCAL and Taiwanese portable 3-component recorders on land. (D) Land explosion experiment (2008) involving PASSCAL Texan recorders and US-Taiwanese 3-component recorders. MT=Fig. 12.

For receivers, there are permanent networks on the island, both short period (~72) and broadband (~40), on the island that have already gathered a large amount of local earthquake and teleseismic data. But to obtain highly resolved spatial images the denser the network the better. But for explosion profiling on land stations are often placed at 200 m spacing and for onshore/offshore recording a spacing of 2 km is common. With these dense networks and the high seismicity in mind, we made sure continuous recordings at these latter stations are implemented so that local earthquakes, or even teleseisms can be recorded well at these stations with sensitive short period seismometers. Of course the active sources are also recorded at the permanent stations. EVERY RECORDED SEISMIC WAVE SAMPLES THE EARTH ALONG ITS PATH AND CAN BE USED IN IMAGING. Previously active and passive studies are usually carried out independently. With the improvement of seismic sensors and the recording capacity it is becoming possible to do the "Crossover" studies as designed for TAIGER.

Because Taiwan is surrounded by water so the land network is limited by the size of the island. The horizontal extent ("aperture") of the network is important, because with teleseismic rays coming in at an angle of 15-40 degrees or so, the larger aperture allows one to sample greater depth.

In addition we also include magnetotellurics profiling in our project in order to have information regarding the fluids in the crust. It measures the electric field induced by time varying ionospheric magnetic field. Fluids play a very important role in deformation, metamorphism and other processes in the crust. Although if both P and S velocities are available then quite sensitive to the changes in fluid content, but the mineral and temperature are also important controlling factors. Resistivity is mainly sensitive to (physically continuous) fluid content and thus can assist in the interpretation of seismic information.

The proposed experiments and the actual experiments are shown in Figure 3. Except for active source and marine profiling in the Taiwan Strait the actual data gathered exceeded the planned amounts.

Geodynamics
As the title of the project indicates we are aiming at understanding the geodynamics of mountain building. The TAIGER observation is a snapshot of the surface velocity and resistivity distribution. We do not know what were the processes that produced the resulting structures. But we know the general distribution of temperatures inside the Earth, the rock properties, the petrological P-T diagrams, the Earth's gravity field, the approximate erosion rate at the surface and the boundary conditions. We also know the differential equations that control the motions of Earth's materials. We can then use the geology of the island to make conjectures of the initial conditions (including plate motions) of the model. Then we will let model go forward. We know an initial model that essentially can reproduce our observations is one that is a candidate as a possible one. We can make many trials to narrow down the choice.

The modeling software was developed by Dr. Luc Lavier of University of Texas at Austin. The program is currently 2-D, but more comprehensive than other codes. A 3-D comprehensive code is still under planning. Although the tectonics of Taiwan is definitely 3-D there are features that can be explained as 2-D collision. We have to choose wisely the aspects of tectonics to study. But it has been quite successful already in explaining some of the processes at work under Taiwan. The program is nicknamed "SAPAN" (sandbox in Chinese.) Some examples will be shown in the powerpoint.

The overall progress of the TAIGER project is shown in Table I.

Table 1.			
Experiment	Action Periods	Status	Team Leaders
I. Geodynamics	2004-2009	2-D comprehensive model Geodynamics sandbox ready	L. Lavier; TAIGER TEAM
II. Petrophysics	Sampling: 2005 Measurements: 05-07 Analysis: 2006-2008	Orthorhombic measurements on samples Correlation with S-splitting	N. Christensen D. Okaya
III.Magnetotellurics	Field work: 2005-2007 Analysis: 2006-2007	MT along 3 land transects	M. Unsworth C. S. Chen
IV. Passive seismology	Deployment 2005/4-2006/4 Demob: 2008/2	Antelope database est. 2007/1 Initial data analysis: 2007 SKS/SKKS-splitting	F. Wu B. Huang
V. Land active source	Field test: 2006/10 Transects: 2008/2-2008/3	11 shots in all; refraction/ wide-angle	D. Okaya C. Wang
VI. Broadband OBS	1st deployment: 2007/11 2nd deployment: 08/05:	10 instruments 07/11-08/05; 20 instruments 08/05-09/06	K. McIntosh C. Lee
VII. Marine MCS/OBS, TAIGER II-Taiwan; Onshore/ offshore	2009/4-2009/7 R/V Langseth 2009/3-2009/6 Land deployment	TAIGER six transects plus "TAIGER II" transects	K. McIntosh C. Liu D. Okaya C. Wang
VIII. Auxiliary Research using other data sources	2004-2009	Local earthquake tomography and seismicity studies Continuous GPS data analysis	F. Wu L. Kuo et al.

1. Seismic experiments at scales to comprehensively study the active orogen as a whole. The TAIGER seismic experiments were designed to illuminate crustal and lithospheric scale targets. The scale of these experiments was at a size that was not previously carried out in Taiwan (Fig. 3). Passive source seismic experiments involved 80 broadband land and OBS instruments distributed across a 3o by 4o region including all of Taiwan and western Philippine Sea, while marine data covered a 7^{o} by 10^{o} area centered just southeast of Taiwan. As a main activity, TAIGER carried out a successful 500 kg test shot using Taiwan personnel and contract personnel; this pilot shot demonstrated that large explosion sources could be carried out safely with Taiwan personnel, thus opening the door for the full-scale TAIGER explosion seismic program.
2. "Pushing the envelope" for cross-over studies. Early in the planning stages of its seismic experiments, TAIGER began to discuss types of seismic analysis that could be carried out by the collection of "crossover" data - earthquake data collected in dense active source arrays, and active source energy collected in spatially 2D passive source arrays. This crossover recording was possible due to the high rate of seismic activity in and around Taiwan (Fig. 4). We emphasized crossover recording as passive and active source experiments were designed and deployed. Active source experiments utilized continuous recording as much as was possible, and passive seismic deployments were overlapped with the active source experiments. Continuously recorded active source data have been

imported into the Antelope earthquake database system to allow easy data reduction and extraction of earthquakes and airgun data from a common data volume with consistent data format and metadata.

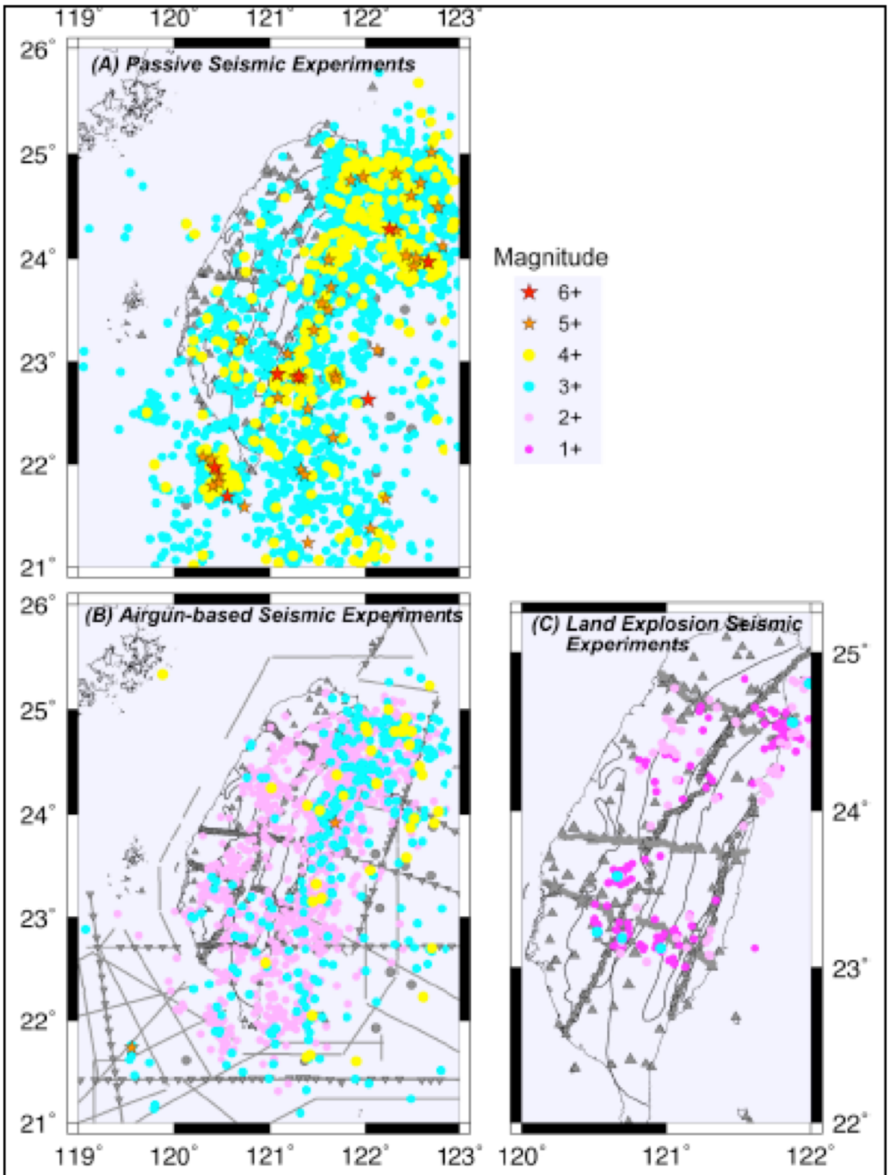


Fig. 4. Earthquakes collected by the seismic field experiments. Details of recording arrays shown in Fig. 3. (A) 22,100+ events representing two years recorded by the land and OBS broadband deployments. (B) 3900+ events representing two months recorded by the onshore-offshore seismic experiment. (C) 360 events representing one month recorded during the land-explosion experiment.

3. Dense spatial resolution. The combination of US and Taiwan instrumentation allowed TAIGER seismic experiments to have dense spatial resolution and significant areal coverage. The land explosion transects crossed the island width with 200 m instrument spacing (coast-to-coast). The land stations of the onshore-offshore experiment were at nominal 2 km spacing, also coast-to-coast. Besides the primary east-west transect arrays, sufficient Taiwan instruments

were available so that long crossarrays running the full north-south length of Taiwan were deployed for both the land explosion and onshore-offshore experiments. Onshore-offshore recording of the airguns provides extensive coverage of the greater Taiwan region and the overall two-plate system.

4. Integration of geophysical data observation and geodynamical analysis (modeling). Progress has been made toward tectonic interpretation of TAIGER experiment data with numerical geodynamical modeling. We use geodynamical analysis as a means to organize and frame our interpretation and our field studies. This work led to the development of the concept of the TAIGER sandbox--modeling tools and benchmark models, which can be used by all project researchers to directly gain physical insights and understand their observational data.

For the up-to-date research results please see the printout of the powerpoint. Also two published papers on the termination of the Ryukyu arc against Taiwan (Wu et al., 2009) and on seismicity after the 1999 Chi-Chi earthquake clarify many of the points discussed in these notes.

Current State of Knowledge

The current overall plate-scale model of Taiwan we construct from TAIGER data, recent GPS measurements (Hsu et al., 2009; Wu et al., 2007), thermochronology (Lee et al., 2006) and geological and seismological studies (Wu et al., 1997; Lacombe et al., 2001) is fully 3-D. In northern Taiwan (north of 23^{O}N) PHS and EUR lithospheres are in collision, while southern Taiwan overlies an actively subducting EUR plate (Fig. 5). North of 23.7^{O}N or so the collision weakens and then stops as the PHS subducts northward along the western extension of the Ryukyu Trench (Wu et al., 2009; reprint). This synopsis places southern Taiwan essentially on PHS and central and northern Taiwan on EUR, in other words there should be a generally EW-trending transition from the south to north in the vicinity of 23^{O}N (Fig. 1). As is normally the case, when continental deformation is involved, if there is a transition it is not likely to be a sharp one.

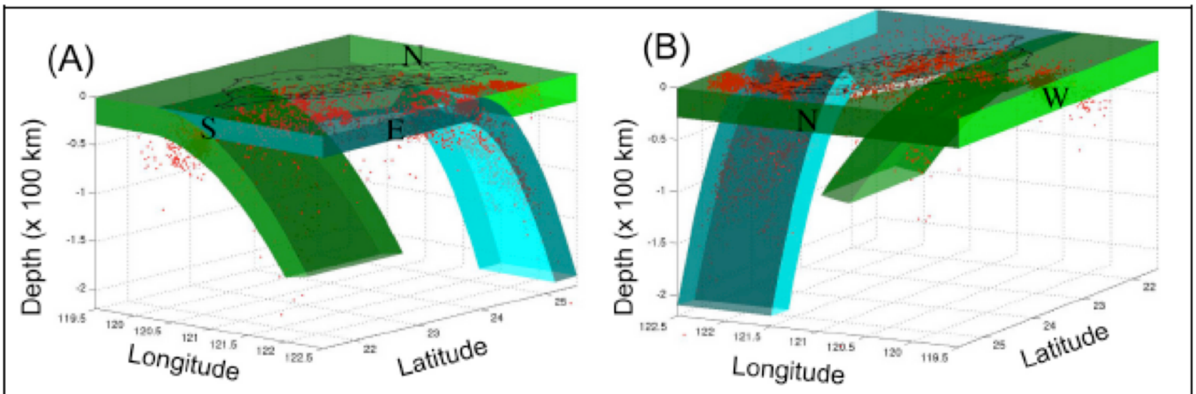


Fig. 5. 3-D schematic view of plate configurations around Taiwan. Here only the segments of subduction zones with recent seismicity are shown. Green color marks the Eurasian plate and blue the Philippine Sea plate. The red dots are hypocenters. (A) View from the southeast seeing the east-dipping Eurasian plate and the north-dipping Philippine Sea plate. Southern Taiwan is carried by the Philippine Sea plate as it moves on top of the Eurasian plate. (B) View from the northwest. These models are constructed using Matlab. Being spatially registered, they will be a framework for our research tasks.

The role that Eurasian plate subduction under Taiwan plays in the Taiwan orogeny can be viewed from several vantage points. That the subduction did occur is incontrovertible – the Luzon Arc was almost certainly associated with this subduction. But what role does it play in the evolution of the Taiwan orogen? The high velocity anomaly we observe (see discussion of TAIGER tomography below) forms a fairly well-defined inclined zone under southern Taiwan. In addition to tomography, recent results of earthquake relocation and a M7.1 earthquake just off to the west of the tip of the Hengchun Peninsula, show that the subducting plate configuration under southern Taiwan is quite clear now. However, the slab becomes steeper north of 23^{O}N and it gradually disappears under northern Taiwan. Farther north the tomographic model shows anomalous zones which contain interesting sections that appear to have "necked": are they real? Are they effects of delamination or slab break-off? The tomography will be refined and velocity modeling of the zone will be tested against P and S delay times to determine the possible range of seismic velocities and whether the materials are continental or oceanic. The interpretation of the along strike variations could be related to the time history of collision as explored in geodynamics modeling (see powerpoint notes and figures).

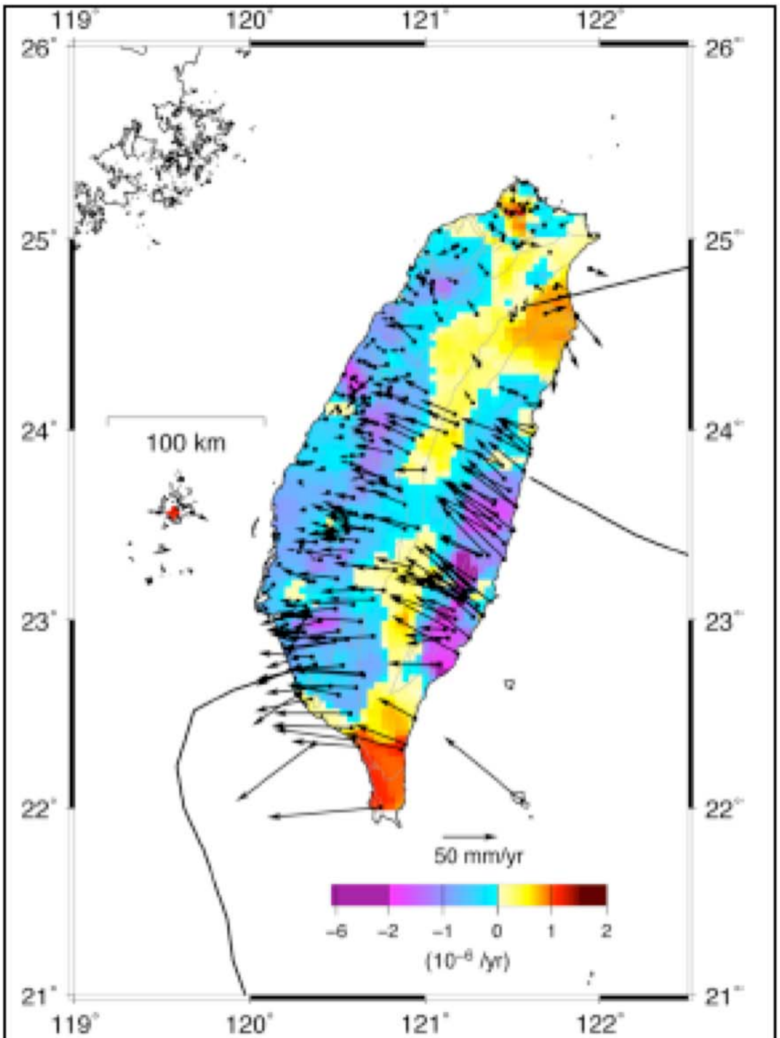


Fig. 6. 2007 velocity vectors from permanent GPS stations and volume strain computed from them (Wu et al., 2007). Notice that the small velocity in western Taiwan north of 23^{O} latitude the velocity vectors dwindle to very small amplitude on the west coast, but to its south the vectors on the west side are often larger. The dilatation strain in the Central Range and NE Taiwan are quite clear; the compression is stronger in the Coastal and Eastern Central Range than in the western Foothills.

The plate model described above presents a paradox for southern Taiwan. As shown quite dramatically in any plots of the recent dense, permanent network GPS data on Taiwan (Fig. 6). If the west coast of southern Taiwan has moved westward relative to the Coastal Plain north of 23^{O}N at the rate shown then

southern Taiwan should be displaced to the west. Despite the abrupt change in motion vector magnitude (from south to north) in western Taiwan, there is no obvious structural break near 23^{O}N. Has
this plate configuration formed so recently that there has been no time to have a significant bend or break? Also, south of 23^{O}N the volcanic arc and the Manila Trench are still 150 km or so apart, but the Hengchun Peninsula started to rise a few million years ago (Lee et al., 2006). The rapid change between north and south Taiwan may be a result of the Eurasian continent turning more sharply south of 23^{O}N. In terms of the collision boundary in northern and central Taiwan, it can best be described as a zone. The zone includes the Coastal Range on the east to the Coastal Plain on the west. The Coastal Range/Longitudinal valley undergoes the highest compressive strain, the Central Range is in dilation at the surface, and the Foothills are under little compression. With the deformation distributed across Taiwan and the broad boundary area, as shown by Ssplitting data, the tectonic processes may also be vertically distributed (Kuo-Chen et al., 2009). The Central Range stands out being a region of high resistivity, i.e., most possibly dry, but highly deformable zone, as revealed by the rapid uplift (Hu et al., 2009) and surface dilatation (Fig. 6). This zone may extend downward for a few hundreds of kilometers as implied by our S-splitting analysis (Kuo-Chen et al., 2009; Silver, 1996, etc.) This zone corresponds to the mobilized zone in our geodynamic models when erosion was introduced (see later discussion.)

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