IIWXIV

The 14th International Ichnofabric Workshop

POST-WORKSHOP
FIELD GUIDE

MAY 3–7, 2017 ROUND TAIWAN

Compiled by:

Weng-Si Chao, Sassa Chen, Steven Jyh-Jaan Huang, Pei-Chen Kuo, Andrew Tien-Shun Lin, Ludvig Löwemark, Charlie Zheng

This field guide is largely based on
Hsieh et al., 2001; Huang and Löwemark, 2017; Lin et al., 2017

Field Trip at a glance!

Start at 06:50
Bus departure from Howard Hotel

May 3rd — **PETROLEUM AND EARTHQUAKES**

CPC core repository in Miaoli – Ta-an Gorge – Earthquake Museum

May 4th — **BADLANDS & MUD VOLCANOES**

Wushanding mud volcanoes and badlands, Jiguanshan Ridge – Lichi Mélange (Taitung)

May 5th — **THE VOLCANIC ARC**

Siaoyeliu – Sanxiantai – Baxiendong – Tropic of Cancer – Shihtiping – Chichi – Fanshuliao Gorge

May 6th — **THE MARBLE GORGE**

Taroko Gorge – Chingshui Cliffs

May 7th — **LIFE ON THE CENOZOIC SHELF**

Yilan Coast & Bitoujiao Geopark

End on May 7th ~18:00
Howard Hotel / Main Gate of NTU / Taipei Main Station

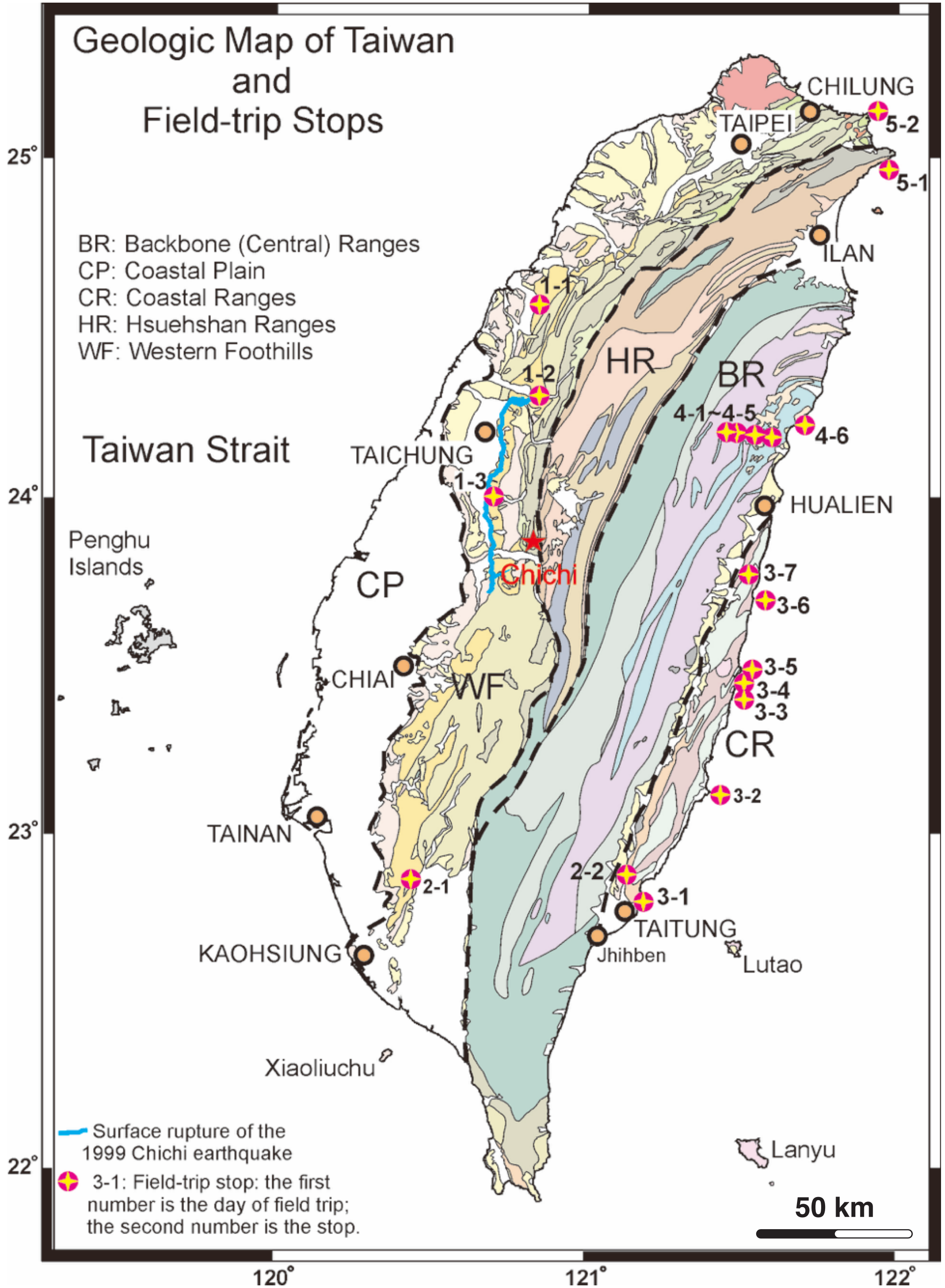


Figure 1. Geological overview of Taiwan.

Geology of Taiwan

Taiwan and its north-south trending mountain ranges contain a record of the still ongoing collision between the volcanic arc on the Philippine Sea Plate and the continental margin of the Eurasian continent (Figure 2). The Philippine Sea plate is moving northwestward with a rate of 82 mm/yr (Yu, Chen & Kuo, 1997). In the south, oceanic crust of the Eurasian plate is still being subducted under the Philippine Sea Plate, thereby providing an analogue for the early stages of the collision. In the central part of Taiwan, the Coastal Range is actively bulldozing the sedimentary and metamorphic rocks of the Central Ranges and the Western Foothills towards the NW, thereby representing the active phase of the collision. In the north, the mountains are collapsing, thereby representing a post-collisional state of the orogeny. At the same time, the subduction of the Philippine Sea Plate at the Ryukyu Arc and the westwards propagating opening of the Okinawa Trough have resulted in volcanic activities that are evident from the volcanoes of the Yangmingshan mountains north of Taipei.

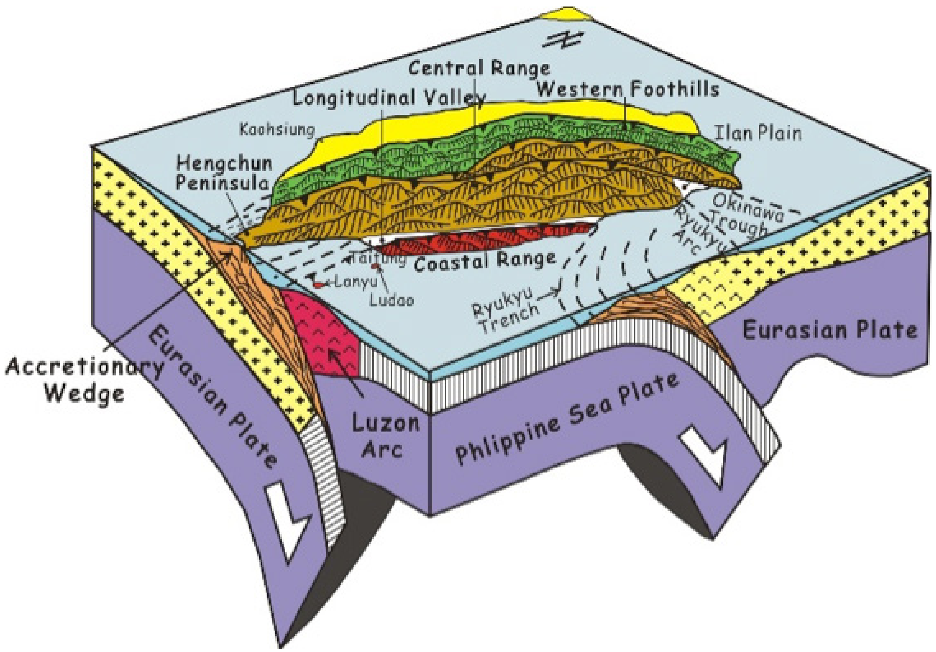


Figure 2. 3D tectonic framework of Taiwan.

The Taiwan orogenic belt comprises four geologic provinces (Ho, 1988, Fig.2-3). From east to west, they are the Coastal Range, the Central or Backbone Range, the Hsuehshan Range, and the Western Foothills. The terrains are of Eurasian plate affinity with the exception of the Coastal Range, which incorporates the accreted volcanic arc and belongs to the Philippine Sea plate. Overthrusting of the Luzon arc on the northern South China Sea margin has exhumed material that was previously located in the outer part of the rifted South China Sea margin (Figure 3).

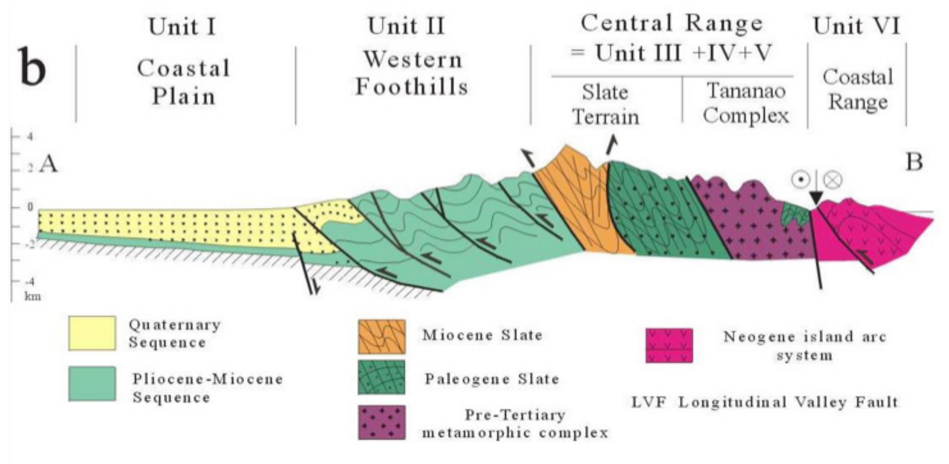


Figure 3. A transect across the central part of Taiwan. The Coastal Range acts like a bulldozer, pushing the rocks on the continental margin of the Eurasian Plate towards the NW (modified after Teng, 1990).

Day 1 – Petroleum & Earthquakes

Stop 1-1
CPC Corporation, Taiwan, core repository in Miaoli

The Chinese Petroleum Corporation (CPC) was founded in Shanghai on June 1, 1946, and relocated to Taiwan in 1949 along with the ROC government. In 2007, the name was formally changed to CPC Corporation, Taiwan. CPC is Taiwan's state-owned oil and gas company and its business areas include oil & gas exploration and production, refining, petrochemicals, lubricants, solvents and chemicals; it is also Taiwan's sole importer and supplier of natural gas. The exploratory operations cover areas in the Americas, the Asia-Pacific region and Africa (http://en.cpc.com.tw/).

At the core repository in Miaoli we will be able to look at Oligocene sections from cores drilled in the Taiwan Strait (Figure 4), and lacustrine sequences retrieved from Cretaceous rift lakes in Chad (undisclosed location).

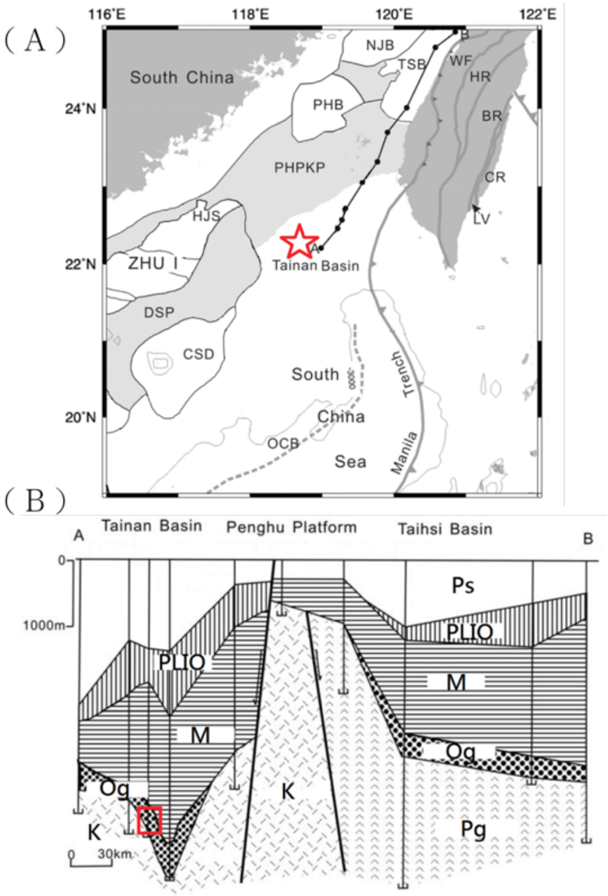


Figure 4. A) Distribution of the rifted basins to the west of the Taiwan orogeny. B) Transect (A-B) showing the stratigraphic context of the displayed cores (red rectangle).

West of the Taiwan orogen, four rifted basins separated by basement highs can be recognized from the Cenozoic sediment isopach map (Figure 4, after Lin et al., 2003). These basins, namely the Nanjihtao (NJB), Penghu (PHB), Taihsi (TSB) and Tainan basins, are Tertiary rifted basins related to the opening of the South China Sea. The displayed cores all stem from the Tainan Basin in the southern part of Taiwan Strait and show nearshore to outer shelf Oligocene sequences (Figure 5).

The evolution of the Tainan Basin can be divided into three stages: a Cretaceous rifting stage, an Oligocene graben-rifting stage, and finally a Miocene post-rifting stage when sedimentation was dominated by passive margin processes.

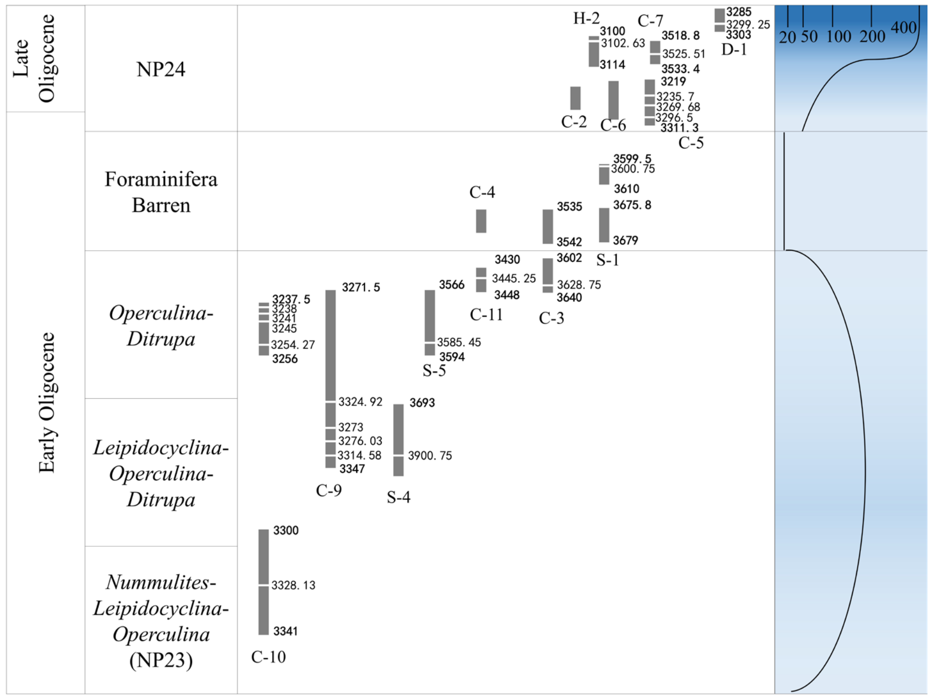


Figure 5. Chronostratigraphic chart showing age and paleowater depth for the chosen cores. White bands indicate the positions of the displayed core sections.

Stop 1-2
Ta-an Gorge: Uprising anticline and Pleistocene foreland sandstones

A large earthquake (M_w=7.6) occurred in west-central Taiwan in 1999 with its epicenter near the small town of Chichi at a focal depth of about 10 km. The Chichi rupture took place mainly along the north-south stretch of the Chelungpu Fault and cuts mainly along and within the Chinshui Shale (Figure 1). At the northern segment of Chichi rupture at Shihkang township, the rupture turns to an easterly direction and cuts stratigraphic up-section and across the strike of the Cholan Formation (Figure 6). The stop in the Cholan-Neiwan area provides an opportunity for examining the Chichi ruptures that form in a conjugate pair and helped to "push up" the Tungshih anticline (Figure 7), a décollement fold, as well as examining the coastal sediments of the Cholan Formation that were accumulated during the later stage of the foreland basin development.

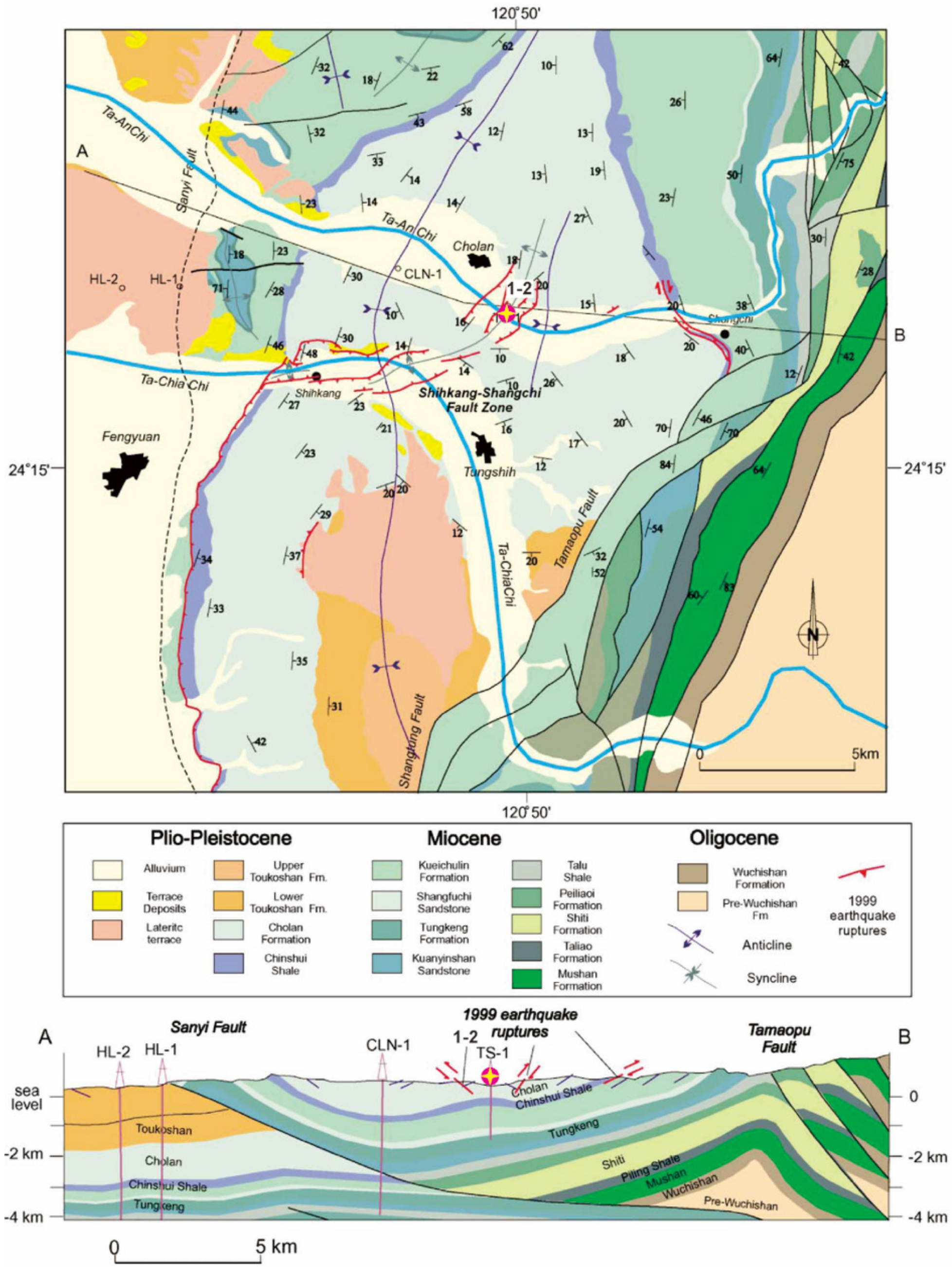


Figure 6. Map of the northern surface ruptures of the 1999 Chi-Chi earthquake in the Shihkang-Shangchi fault zone (after Lee et al., 2002). Geologic section (from C.-Y. Wang) shows that the uprising Tungshi anticline is formed by faulting and detaching along the bedding planes of the Chinshui Shale (purple-color). Note that the Tungshih anticline (at TS-1) is visible only above the detachment surface and anticline is absent beneath the detachment level (i.e., the Chinshui Shale).

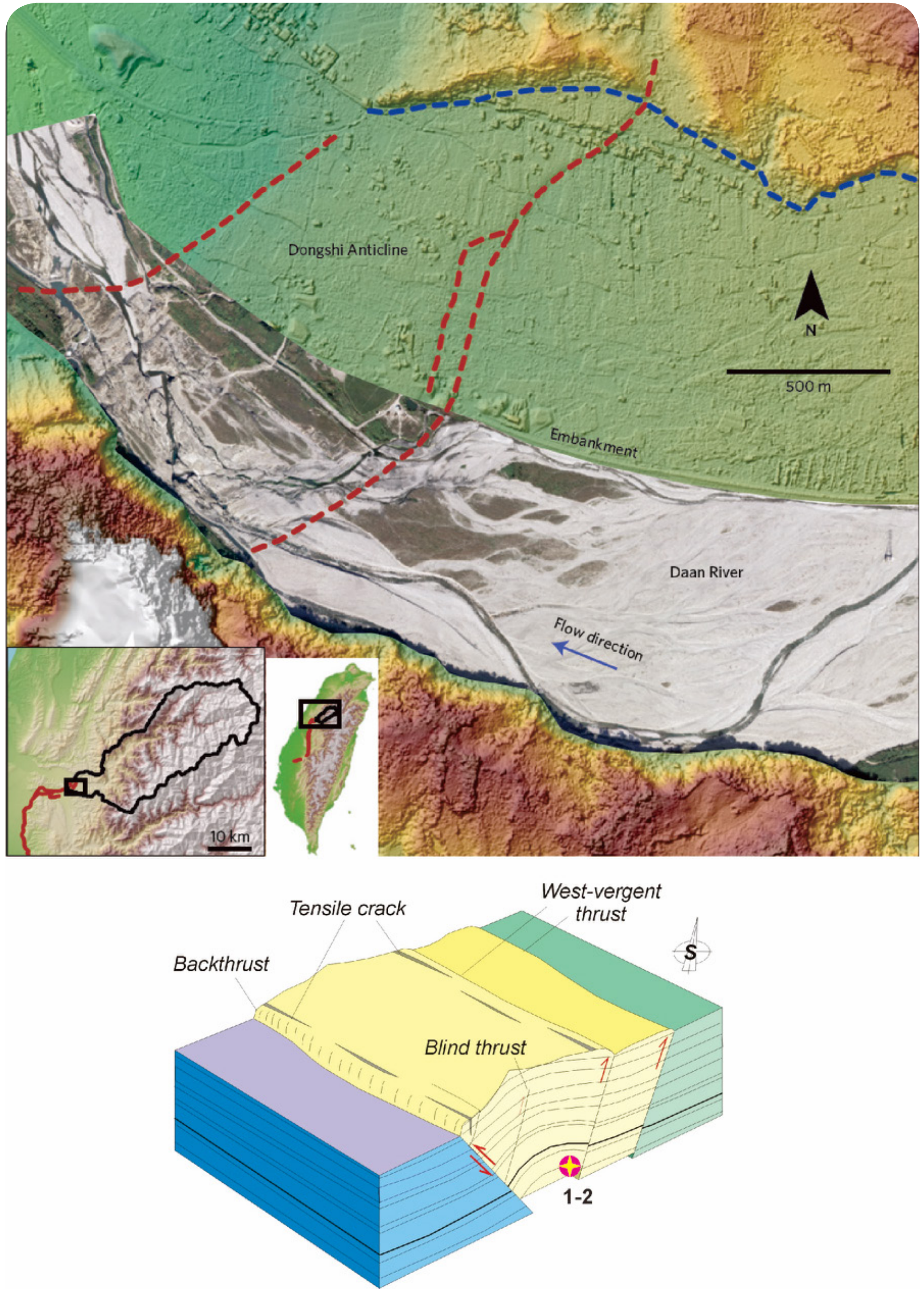


Figure 7. Aerial photograph combined with a DEM of the surrounding area (Cook et al., 2014). Ta-an River valley Pop-up structure with thrust-and-backthrust system situated on a pre-existing anticlinal fold, the Tungshih anticline, in the Diaoshenshan area near Neiwan (after Lee et al., 2002). Field stop in the gorge where the river cuts through the structure is shown as red circle.

The Cholan Formation contains a rich faunal assemblage in various horizons, including echinoids, crabs, mollusks and foraminifers. Oyster beds consisting of *Crassostrea gigas* (Thunberg) about a few tens of centimeters thick are present in the upper lower to upper parts of the Cholan Formation (Rin, 1935). The Cholan Formation sediments represent shallow marine to coastal environments that shoal upwards (Figure 8). This formation falls into biozones of NN17-18 and lower NN19 and it contains reworked Miocene nannofossils (Chen et al., 1977; Huang and Ting, 1981).

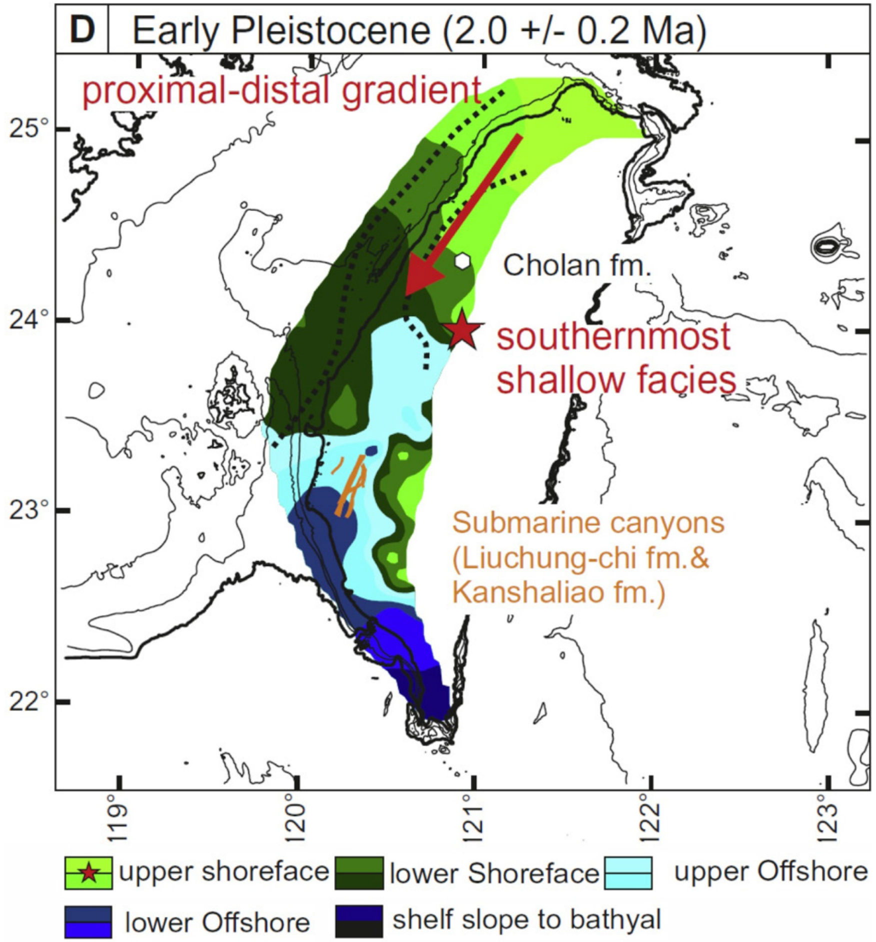


Figure 8. Paleogeographic map of the foreland basin at the time of the deposition of the Cholan Formation (modified from Nagel et al., 2013).

Stop 1-3
921 Earthquake Museum of Taiwan

Near the central portion of the 100-km stretch Chichi rupture, the fault segment cuts across the sport stadium of the Kuangfu Junior High School at Wufeng and creates a 2-3 m fault scarp (Angelier et al., 2003, Figure 9). The site has now become the earthquake museum to commemorate the loss caused by the Chichi earthquake and to witness the surface rupture brought about by the earthquake. The local fault strikes vary because the shape of the scarp was influenced by the mechanical response of the surface layers, including the stadium track cover. These local strikes do not reflect the fault geometry at depth, even at the 100 m scale considered. The average trend of the whole fault segment of the Kuangfu stadium, N141°E, is considered as the local strike of the Chelungpu fault.

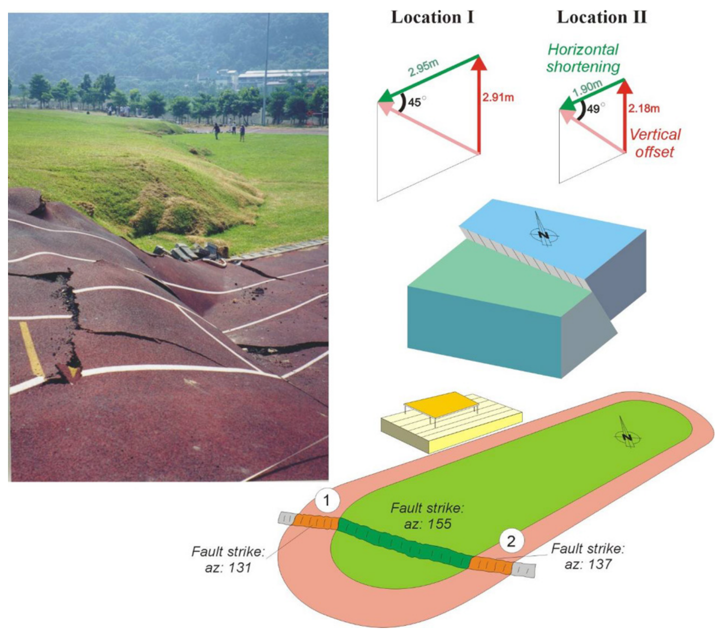


Figure 9. Kinematics analysis and reconstruction of the movement of the fault in the Kuangfu school, in Wufeng. The earthquake fault formed a 2-m high thrust scarp and cut through the sport stadium. The lines on the running tracks allow measuring the displacements of the fault in 3 dimensions. Note that the strike of the surface fault changed because of the different mechanical properties of surface materials. The reconstructed fault geometry shows a reverse fault with a fault plane dipping 45°-50° to the east.

Day 2 – Badlands & Mud volcanoes

Stop 2-1
Mud volcanoes in the Gutingkeng Formation

The Gutingkeng Formation, largely a thick (2600 m) massive mudstone sequence well known for its badland topography, is widely exposed, occupying about 750 km^2 in southwestern Taiwan. Its age ranges from late Miocene to late Pleistocene (Chen *et al.*, 1977), but the majority belongs to the Quaternary. Two facies can be recognized in the Gutingkeng sequences of the Chishan area. The shelf facies consist of medium to thick-bedded massive mudstone intercalated with thin to medium-bedded sandstone. Individual sandstone beds commonly show an erosional base and a rippled top and are characterized by parallel laminations and local hummocky cross-stratification. Bioturbation is very common, dominated by *Rhizocorallium* and *Beaconites*. Benthic foraminiferal assemblages are dominated by *Bolivina*, *Siphogenerina*, *Quinqueloculina* and *Rotalia* (Oinomikado, 1955). Both litho- and biofacies characteristics indicate a shallow-marine shelf environment for deposition.

The Gutingkeng Formation is also well known for its mud volcanoes which are aligned along the Chishan Fault (Figure 10). Three major mud volcanoes are still active: Wushanding, Shinyangnyuhu, and Yangnyhu. The Wushanding mud cones are the largest and most well-preserved mud volcanoes in Taiwan with two major vents exhibiting perfect cone shape. Muddy material with low water/sediment ratio is erupting and hence, they are able to generate beautiful cone shaped mud volcanoes. The composition of bubbling gases is CH_4-dominated (96~98%) with low helium isotopic ratios (3He/4He <0.2 Ra), which indicates a crustal source in origin. Measurements on $\delta^{13}C$ of hydrocarbon gases indicated mainly thermogenic source for mud volcanoes/pools located in the Chihshan fault zone (Chao et al., 2010; Sun et al., 2010), while mixed origins of microbial and thermogenic sources are found in other mud volcanoes in SW Taiwan.

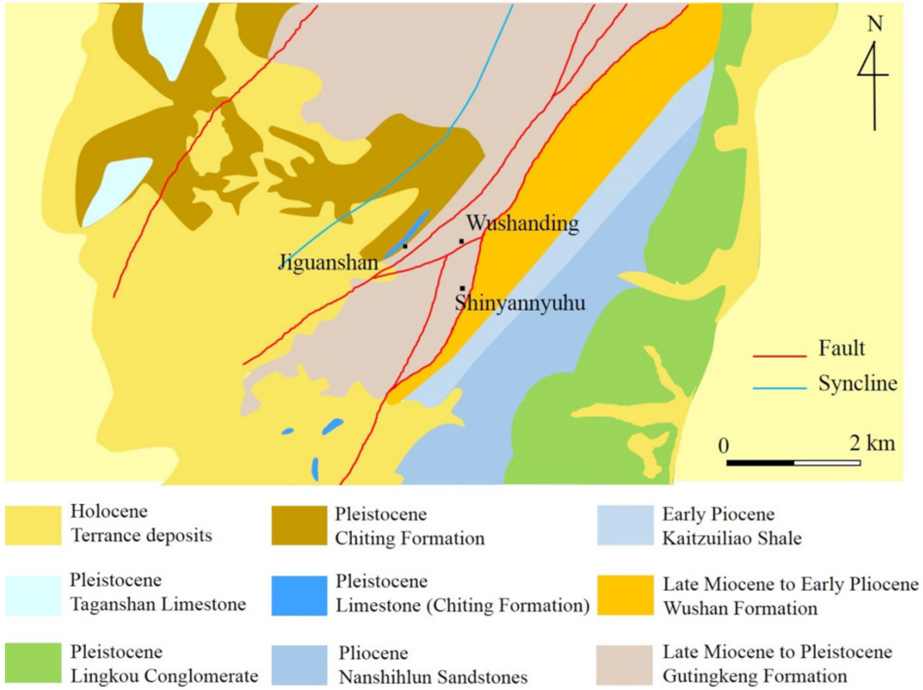


Figure 10. Geologic map showing the positions of the mud volcanoes and the steeply inclined Jiguanshan Ridge.

Mud volcanoes are mainly distributed around subduction zones and orogenic belts where lateral tectonic compressional stress is dominant. There are three general conditions controlling the formation of mud volcanoes (Figure 11):

a) Gas reservoirs appear because of magma activities or oil reservoirs evolving underground.
b) Gas reservoirs are covered by mudstone and underground water.
c) Anticline axis or faults cut through the formation causing fractures in the strata. High pressure gases pass through these fractures to erupt at the surface.

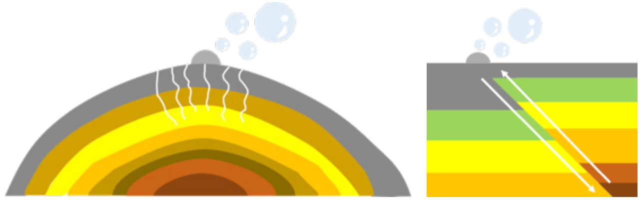


Figure 11. Mud volcanoes typically develop on anticlines or along faults.

Stop 2-2
Jiguanshan Ridge (Chicken Crown Mountain)

The Pleistocene Chiting Formation is cropping out in the form of a conspicuous ridge at Jiguanshan (Figure 10). The rocks consist of thick sandstones intercalated with shales (Sandstone: Shale=1:1) showing huge cross-bedding, planar bedding, herringbone cross-stratification and wave structures. The layers are rich in biological debris consisting of marine organisms such as bivalves, indicating that it was deposited in a shallow ocean through storms. The reason for the steep tilt angle of the layers could be related to the proximity to the Nananlao Syncline (Figure 10).

Stop 2-3
Lichi Mélange

The Lichi Mélange is widely distributed in the southern part of the Coastal Range. The type locality crops out at Lichi Village north of Taitung. The mélange is composed of thick mudstone, mixed with a variety of exotic blocks. A conspicuous badland topography is the most characteristic feature of the Lichi Mélange. According to drilling data of the CPC Corporation, the thickness of the mélange is greater than 1 km (Meng and Chiang, 1965). The exotic blocks are mostly ophiolitic fragments and sandstone. Other lithological varieties include greywacke, shale, limestone, conglomerate and andesitic agglomerate. The most distinguished exotic block is the so-called East Taiwan Ophiolite (Liou et al., 1977). The East Taiwan Ophiolite comprises all the components for a typical ophiolite sequence – peridotite, gabbro, serpentinite, diabiasic dike, plagiogranite, basalt and red clay. Paleontological studies indicate that the mélange contains microfossils of ages ranging from Oligocene to Middle Pliocene (time span of ca. 30 Ma). Based on the youngest fossils, the deposition of the Mélange is commonly assumed to begin in the Middle or Upper Pliocene (ca. 3 Ma).

The origin of the Lichi Mélange has been the subject of much controversy. Two main hypotheses are illustrated in Figure 12. Because of the intense scaly foliation and the existence of the exotic blocks, many geologists think that the Lichi Mélange is a "subduction complex" formed by tectonic processes as the South China Sea oceanic crust was

subducted (Biq, 1971; Chen, 1997; Hsu, 1988; Karig, 1973; Teng, 1981). But because of the occurrence of well bedded units in the mélange, as well as coherent turbidites, many other geologists considered the Lichi Mélange as an "olistostrome" (Barrier and Muller, 1984; Ernst, 1977; Ho, 1986; Hsu, 1956; Page and Suppe, 1981) that developed between the outer arc and a forearc basin. According to the model of subduction complex origin, the Longitudinal Valley fault is a relic of the former subduction trench and was an active major structure before and during arc-continent collision. In contrast, in the olistostrome model, the Longitudinal Valley represents a part of forearc basin, which was a relatively quiet region before the arc-continent collision.

The significance of the mélange is crucial in any reconstruction of the geological history of eastern Taiwan and especially of the Longitudinal Valley, the so-called "suture" between the Eurasian continental margin and the Luzon arc. The Lichi Mélange in the Coastal Range is therefore a key to the interpretation of the evolution of the Taiwan orogenic belt. Recent study by Chang et al. (2001) suggested that the Lichi Mélange results mainly from the shearing of lower forearc basin sequences, rather than from a subduction complex or a mere olistostrome.

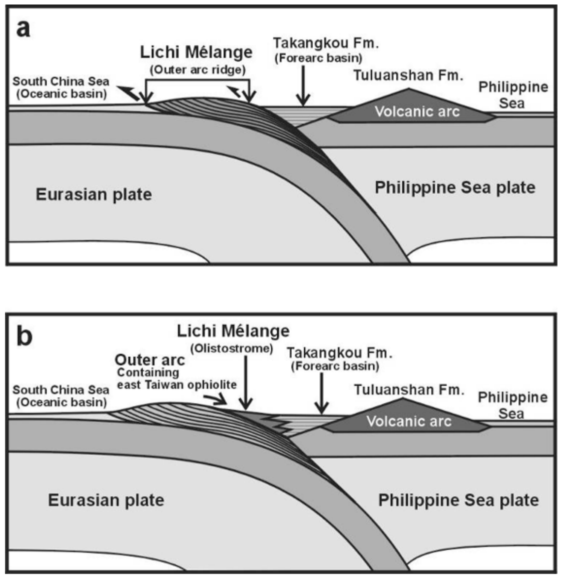


Figure 12. Comparison of two models for the origin of the Lichi Mélange (from Chang et al., 2001).

Day 3 - The Volcanic Arc

The Coastal Range (Figure 13 & 14) in eastern Taiwan is the extinct, accreted portion of the Luzon arc-trench system that sutured onto the Asian continent along the Longitudinal Valley between the Central Range and the Coastal Range (Ho, 1986). It comprises an upper Miocene arc basement (the Tuluanshan Formation) with a patchy occurrence of limestone at its top (the Kankou Limestone), overlain by a thick Plio-Pleistocene turbidite sequence (the Takangkou Formation) which is then topped by an upper Pleistocene, non-marine conglomerate unit (the Pinanshan Conglomerate).

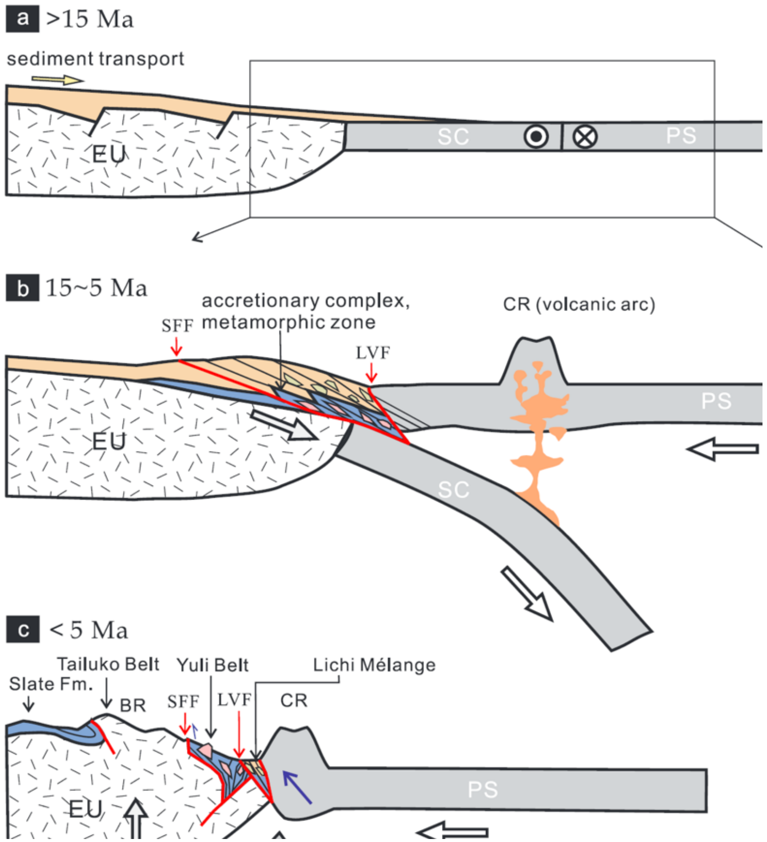


Figure 13. Evolution of the volcanic arc system (Chen et al., 2016). SC: South China Sea oceanic crust. PS: Philippine Sea Plate oceanic crust. CR: Coastal Range. EU: Eurasian Continent. BR: Backbone (Central) Range.

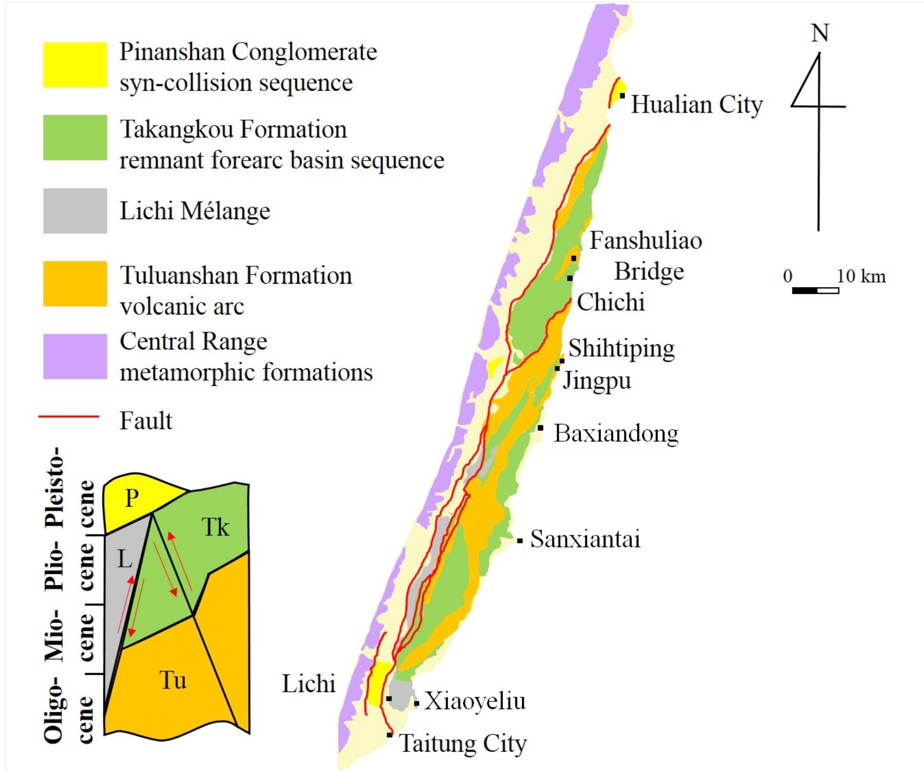


Figure 14. Geological structures and stratigraphy of the Coastal Range (modified from Chang et al., 2003 and references therein).

The sequences of the Coastal Range comprise about 6000~8000 m of marine and fluvial sedimentary and volcanic rocks of Neogene-Quaternary age. These rocks may be divided into four rock-stratigraphic units: (1) the Miocene volcanics of the Tuluanshan Formation; (2) Pliocene-Pleistocene deep-sea turbidites of the Takangkou Formation; (3) the Lichi Mélange; and (4) the Pinanshan Conglomerate (Figure 14). The Takangkou Formation is further divided into Fanshuliao Formation and Paliwan Formation (Teng, 1979).

Stop 3-1
Xiaoyehliu - An exotic sandstone block in the Lichi Mélange

A huge classical sandy turbidite block (over 1 km in dimension) is exposed along the coast north of the Fukang fishing port. The sandstone block is overturned. Its composition is similar to that of Loshui Formation exposed on the east coast of Hengchun Peninsula in southern Taiwan. Late Miocene (NN11) nannofossils have been reported from this sandstone block (Chi, 1981). This age is similar to Hengchun Peninsula turbidites, but older than the Plio-Pleistocene forearc turbidites and the muddy matrix of the Lichi Mélange (3.5-3.7 Ma) in the Coastal Range. Again, fission track analysis on zircon grains separated from the sandstone block here shows an age pattern similar to those of the Hengchun Peninsula, but differs from the forearc turbidites in the Coastal Range.

At the Hsiaoyeliu scenic area where the sandstone is polished by long-term wave actions, this sandstone block is dominated by very thick sandy turbidites deposited by high-concentration turbidity currents with abundant climbing ripples and loading/dewatering structures, such as flames, dishes and pillars, indicative of rapid deposition. Also, notice that the sandstone is capped unconformably by uplifted coral-reef complexes, which have been dated ranging from a few hundred years to 7.5 ka cal BP (Yamaguchi and Ota, 2004).

Stop 3-2
Sanxiantai - volcanic breccias

Sanxiantai, Three Saint Island, got its name from a legend stating that three Chinese saints; Lyu-Dongbin, Li-Tieguai and He-Xiangu, once set foot on the island leaving three pairs of footprints. The Sanxiantai islands consist of volcanic breccia characterized by centimeter to meter sized clasts embedded in greenish or brownish tuff. Based on their colors, these breccias were tentatively classified into "monolithologic" and "polylithologic" types. The monolithologic breccias are relatively fresh and mainly blackish, while the polylithologic breccias are characterized by varying colors, possibly representing products from different eruptive episodes. The Sanxiantai volcanic rocks contain olivine, plagioclase and two pyroxene phenocrysts without hornblende, contrasting to the occurrence of hornblende phenocrysts in the samples from the Coastal Range. The tuff, however, contains higher proportions of clay minerals, reflecting higher degrees of alteration. The outcrop occurrences and the petrography in the section where tuff and breccias intersected suggested a pyroclastic flow origin for the Sanxiantai volcanic rocks. Although Sanxiantai is adjacent to the Chengkuangao volcano, the differences in major element and trace element compositions as well as isotopic signatures between Sanxiantai and Chengkuangao samples imply distinct magmatic sources (Huang, 2015).

Stop 3-3
Baxiendong – Uplifted sea caves

More than 10 sea caves have been uplifted to elevations reaching from 20 to over 100 m above present sea level (Figure 15). The caves typically contain both beach deposits and archeological artifacts indicating that they were formed close to the sea. Charcoal in the beach sand deposits in the Chaoyin Cave have been dated to around 6.000 years BP.

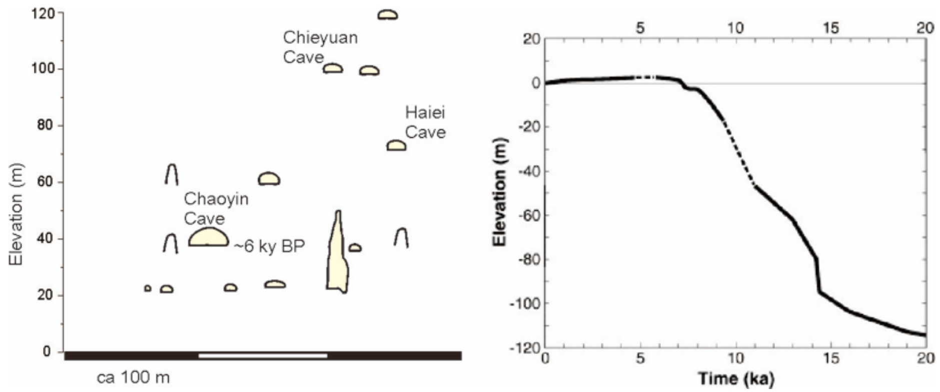


Figure 15. Vertical distribution of the sea caves at Baxiendong (left). Global sea level curve for the past 20 ky (right)(modified from Hsieh et al., 2001).

Stop 3-4
Tropic of Cancer

The Tropic of Cancer at 23°26'N is the northern boundary of the area on Earth that can receive direct overhead sunlight. At the summer solstice, the sun rises in the east and goes down in the west following the latitude. To visualize this phenomenon, the monument is designed with a slit in the middle of the structure, so that visitors can observe this phenomenon at the summer solstice (http://www.eastcoast-nsa.gov.tw/).

However, because of the slow shifting of the Earth's tilt (~14 m/year, Cronin, 1999), the monument is no longer in the exact correct position.

Stop 3-5
Shihtiping: Lava flows, ignimbrites and uplifted corals

The outcrop at Shihtiping is characterized by the presence of lava flows, white ignimbrites, agglomerates with plastic deformation, tuffs and tuffaceous sandstones and conglomerates from lower to upper sections (Figure 16). It is about 100 meters in thickness and overlies the poorly columnar-jointed lavas of the Shihmen volcanic breccias. Deposition of the Shihtiping White Tuff is later than late Miocene as indicated by the fossil age of the sediments at its base. Both glass-rich and crystal-rich tuffs have been identified. They are the products of ash-fall, surge and pyroclastic flows. The ash-fall tuffs are thinly-bedded with fine-grained glasses and crystals in alternations and are well-sorted. The volcanic surge deposits, the base surges, are represented by the coarse-grained tuffs and lapillistones with massive, planar and dune-like sedimentary structures. Many sedimentary structures such as cross bedding, parallel lamination, normal and reserve graded beddings, impacted sag blocks, plastic deformations and erosion surface can be observed in the outcrops. Optical and scanning electron microscopic studies show that they are highly vesiculated and slightly welded. White volcanic bombs are andesitic to dacitic, and consist of plastic, welded, and impacted structures in the outcrops. These deformed structures show that the pyroclastic flows were still high in temperature during transportation and deposition. This evidence suggests that these pyroclastic flows erupted and were deposited in a subaerial environment (Song and Lo, 1988). In some sections, peperite formed inside the white volcanic bombs because of the hot flow mingling with water or wet unconsolidated sediments. White volcanic bombs and pumice contain abundant vesicles with various shapes because of subaerial explosions. Lithic fragments in the ignimbrites are blackish, greenish, and reddish, and subangular to angular. The essential mineral constituents of the Shihtiping White Tuff are plagioclase, hornblende, hypersthenes, augite and magnetite listed in decreasing amount. The phenocrysts or crystal fragments are less than 50 percent, and the matrix is mainly glassy. Xenolithes of pyroxenite and hornblende gabbro can also be found at Shihtiping.

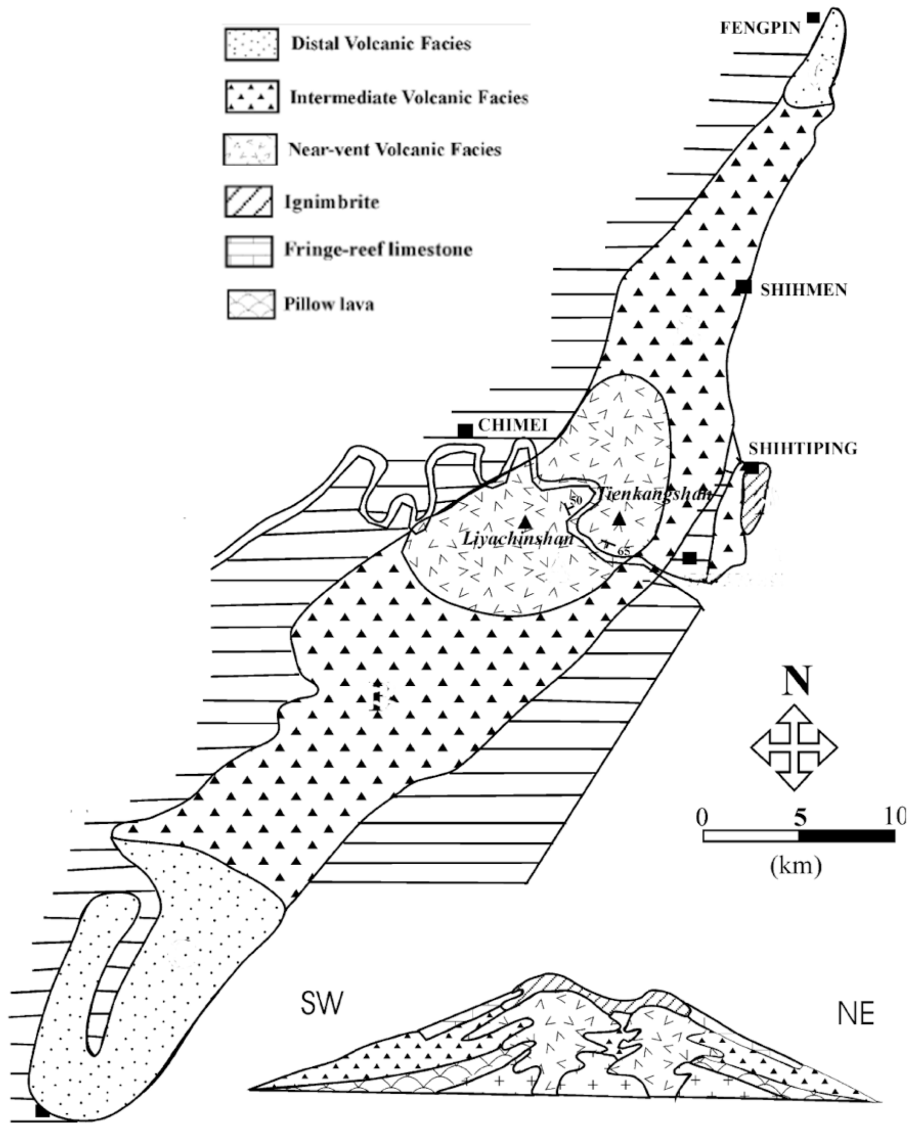


Figure 16. Lithofacies of the area around Shitiping and a reconstruction of the Chimei volcanic island (modified from Song and Lo, 1988).

Stop 3-6
Chichi (Jichi) Headland – bioeroders as uplift gauges (optional)

While the Chichi (Jichi) headland is made up of resistant volcanic rock, more easily eroded mudstones of the Takangou Formation are exposed in the Bachi Bay to the south. In this mudstone, remains of the boring bivalve *Jouannetia sp*. allows the rate of the uplift of the Coastal Range to be estimated using radiocarbon dating (Hsieh et al., 2001) (Figure 17). Dates obtained from shells now about 3 m above sea level have ages of about 900 year BP, giving an uplift rate of over 3 mm per year. This stop is of exploratory nature. The coast is very dynamic and the exact locations of the uplifted boring bivalves are hard to find.

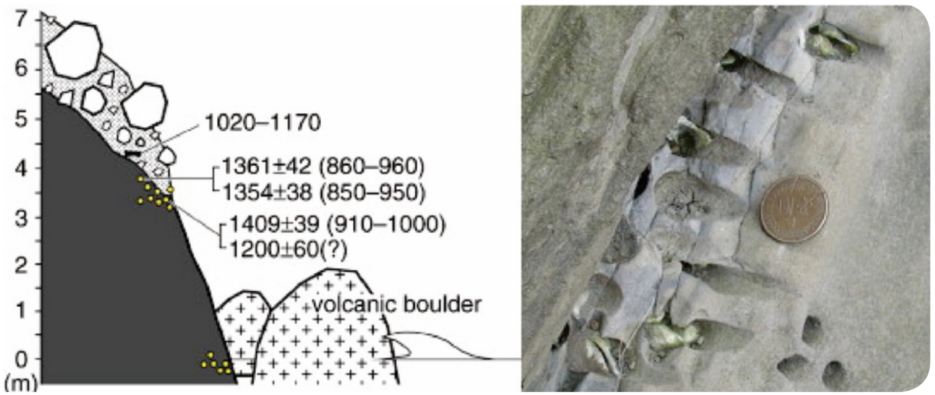


Figure 17. Uplifted and dated borings at Chichi (modified from Hsieh and Rau, 2009).

Stop 3-7
The Bridge over Fanshuliao Gorge

Apart from the nice scenery where the deep gorge cuts through the northern tip of the Coastal Range, the Fanshuliao River is also believed to be an example of an antecedent or superposed river. A river that existed before the uplift of the northern part of the Coastal Range, and river incision has since kept pace with the rising mountains, resulting in the spectacular gorge cutting through the mountain range (Hsieh et al., 2001).

Day 4 – The Marble Gorge

The Taroko Gorge formed when metamorphosed Paleozoic and Mesozoic rocks were rapidly uplifted due to the collision between the Philippine Sea Plate and the Eurasian Continent. Fossil evidence suggests that the sediments were deposited in a tropical marine environment. These sediments were then subjected to three main phases of metamorphosis in the end of the Cretaceous, the late Paleogene, and during the Plio-Pleistocene formation of Taiwan. Carbonates deposited in shallow environments then became marble, while marine sands, muds and volcanic rocks in the area were metamorphosed into schist and gneiss (Ho, 1986; Kao, 2010). Today uplift continues at an approximate rate of 5 mm/year. Together with extremely high rainfall over the mountains (>3000 mm/year) and the high shear strength of metamorphic rocks such as marble and gneiss, this has resulted in the spectacular gorge we see today.

The pre-Tertiary basement rocks (Tananao Complex) consist of schist and marble, as well as scattered gneiss and amphibolite bodies (Yen, 1954, 1960, 1967)(Figure 18). It is bounded to the east by a Mesozoic tectonic mélange with high-rank greenschist facies mineral assemblages. The geological history of the Tananao Complex can be traced back to the Paleozoic and involves multiple crustal deformations and metamorphism in the Mesozoic and Tertiary (Ernst and Jahn, 1987). Three major metamorphic stages or thermal events since late Mesozoic are recognized:

(1) late Mesozoic: A high-grade metamorphism of upper amphibolite facies coupled with granitoid intrusions occurred in the mid-late Cretaceous. This thermal event is generally correlated to the westward subduction of a paleo-Pacific plate beneath the Asian continental margin. Yen (1963) named this subduction event the Nanao Orogeny;

(2) late Paleogene: Jahn et al. (1986) and Lan et al. (1990) recognized a greenschist facies metamorphism during ~40-35 Ma. Jahn et al. (1986) correlated this event to the opening of the South China Sea. However, Lo and Onstott (1995) argued that the above K-Ar age may be merely due to the effects of mixing and/or the partial resetting of

isotopic systems by the metamorphism related to the late Cenozoic arc-continent collision;

(3) late Neogene: An up to greenschist facies metamorphism that occurred later than ~12 Ma has been widely reported in the literature (e.g., Jahn et al., 1986; Lan et al., 1990; Lo and Yui, 1996; Teng, 1990).

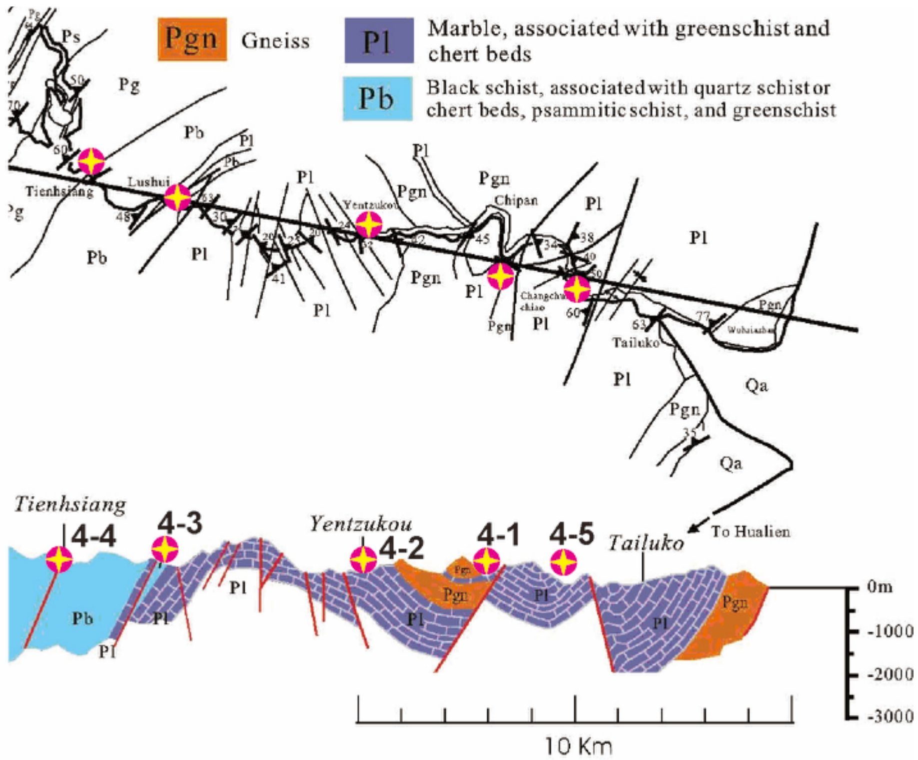
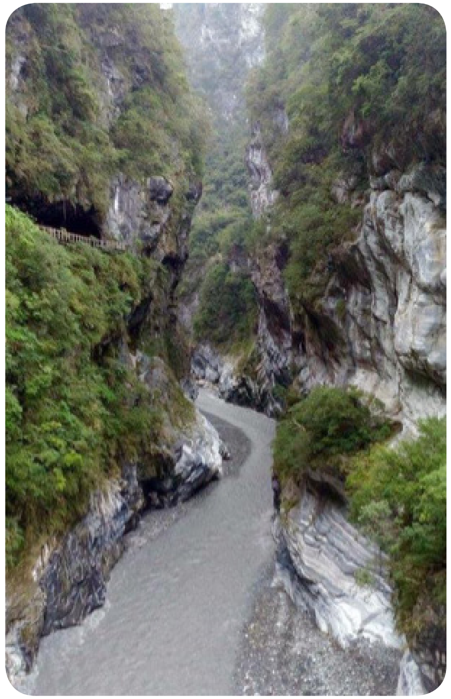


Figure 18. Geological traverse map of the eastern Central Range along the Central Cross-Island Highway (modified from Chen, 1979)

Stop 4-1
Chipan, Baisha Bridge - Contact between marble and gneiss

A contact zone between granite and marble is observed near Baisha Bridge. Rocks near the granitic intrusions may contain amphibolite facies minerals. The P-T conditions as revealed by the Chipan granitic gneiss and

Kainangang foliated gneiss indicate three episodes of metamorphism – the first stage at 2 kb and ca. 500°C, the second at 5-7 kb and 650-700°C, and the third stage at 4 kb and 450°C. Jahn et al. (1986) and Lan et al. (1996).



Stop 4-2
Yanzikou – Swallow Grotto

This older portion of the highway diverges from the new thruway that services vehicular traffic and is meant to be walked to fully appreciate this marvel of nature. The Grotto trail is interspersed with tunnels and overlooks the narrowest portion of Taroko Gorge where the river is most rapid. Be cautious of falling rocks when walking on the trail. Park authorities provide hard hats for visitors free of charge (www.rtaiwanr.com).

Figure 19. View from the Swallow Grotto trail.

Stop 4-3
Cihmu Bridge and Frog Rock

The Cihmu Bridge at Frog Rock (due to the shape of the outcrop) is the best place to observe the metamorphic transposition structure (green schist and marble contact).

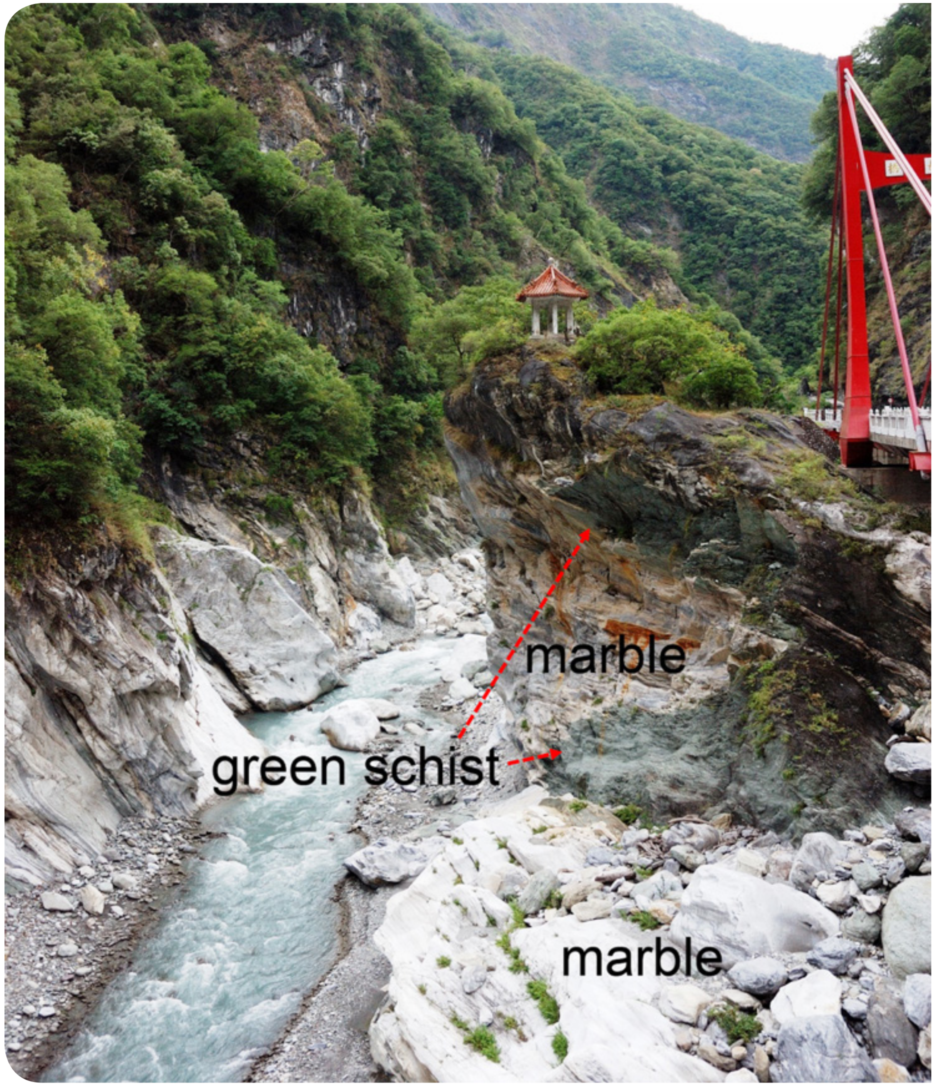


Figure 20. Frog Rock at Cihmu Bridge.

Stop 4-4
Tienhsiang - Schist of a Mesozoic metamorphosed mélange

Tienhsiang (Tienxiang), a famous recreation area within the National Taroko park, is located on a terrace at the intersection of Da-sa river and Takili river. Below the Chih-hui bridge, an outcrop of metamorphosed

mélange can be found. The metamorphosed exotic blocks here including marble, metasandstone, quartzite, metachert, and green schist are highly deformed and randomly distributed within strongly foliated quartz-mica schists. The quartz-mica schists could represent the metamorphosed mudstone and shale which usually constitute the main part of mélange. Please note that the quartz-mica schists have suffered polyphase deformation and foldings which results in multi-schistosity developed within the rocks.

Stop 4-5
Changchun Shrine (Eternal Spring Shrine)

The Changchun Shine (Eternal Spring Shrine) recognizes the personnel died during the construction of Central Cross-Island Highway. Rivers adjacent to the Changchun Shrine become the scattering falls, and the Highway Bureau named it after "Chanchun Falls" which is now the significant landmark on Central Cross-Island Highway.

Stop 4-6
Chingshui Cliffs

Chingshui Cliff is one of the most famous cliffs in the Taiwan due to the huge relief from the mountains to the seafloor (Figure 21). On the outcrop, distinct vertical normal faults with slickensides can be observed.

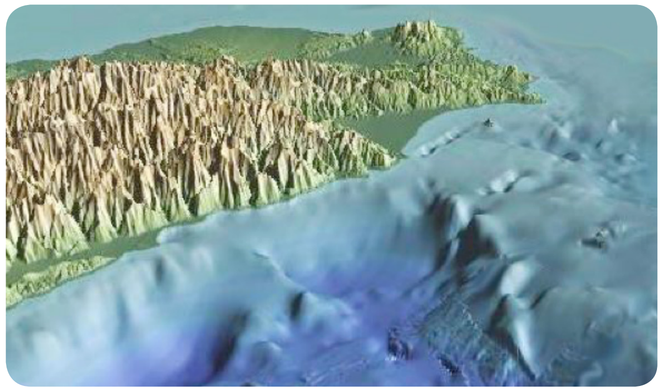


Figure 21. Digital elevation model showing the eastern coast of Taiwan. Note how the Chingshui Cliffs dive into the Hoping Basin south of the Ryukyu Arc.

Day 5 – Life on the Cenozoic Shelf

Stop 5-1
Shicheng coast - Differential erosion and the mysterious sandfingers

The Oligocene Tatungshan Formation (part of the only weakly metamorphosed Hsueshan Range) consists of argillites intercalated with thin and thick bedded sandstone beds deposited in inner offshore environment (Figure 22; 陳文山 et al., 2016). The tilted layers in combination with the strong coastal erosion results in conspicuous differential erosion of the sandy and argillaceous layers. In some layers, intriguing bioturbation in the form of ~10 cm thick plug-shaped, sandfilled burrows can be observed at the boundary between underlying muddy sediment and the overlying sandstones. In the mudstone, *Thalassinoides-like* and *Phycosiphon*-like traces are abundant.

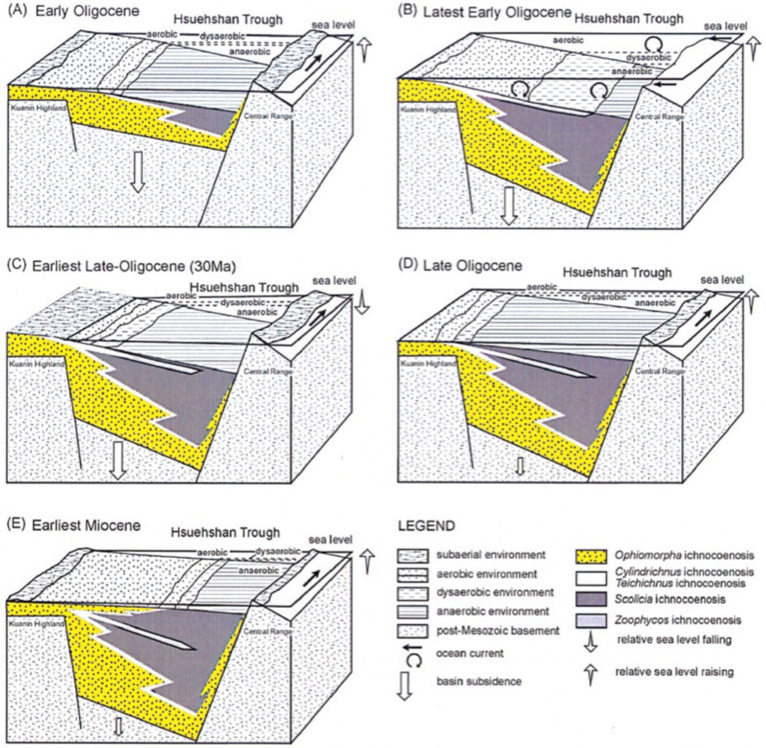


Figure 22. Evolution of the Oligocene half-graben depositional environment between the Eurasian continent in the West and the Central Range in the East (Chen, 2005).

Stop 5-2
Bitoujiao Geopark

The cliffs and the coastal platform at Bitoujaio Geopark expose argillaceous sandstones and mudstones of the late Miocene to Pliocene Kueichulin Formation (Figure 23). Herring-bone cross-bedding, flaser-bedding, wavy bedding, as well as abundant fossils and trace fossils indicate that the sediments were deposited in an intertidal to sub-tidal environment where tidal currents played an important role. Of particular interest are a large number of crab burrows, sometimes found in conjunction with exquisitely preserved crab fossils indicating a catastrophic event killing off large numbers of crabs. Possible *Zoophycos* trace fossils have also been observed, making Bitoujiao one of the youngest shallow marine occurrences of this trace fossil.

Bitoujiao is a syncline situated at the northeasternmost tip of the Western Foothills. The name means "nose cape" and derives from the nose-like shape of the tip of the cape.

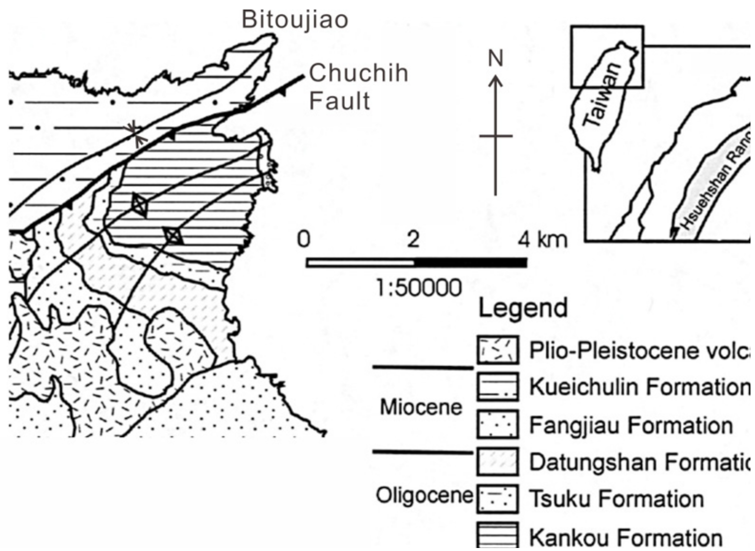


Figure 23. Geological map of the Bitoujiao and the surrounding area (modified after Chen, 2005)

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