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Was the 1999 Chi-Chi Earthquake in Taiwan a "Subduction Earthquake"?

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ABSTRACT

Based on paleo-reconstructions of tectonic evolution of Taiwan, on the style of deformation across the Taiwan mountain ranges, on global travel-time tomography beneath Taiwan and on the characteristics of the Chi-Chi earthquake, I propose that the last M7.6 earthquake is a "subduction earthquake" which has ruptured a segment of the plate interface between the Eurasia and the Philippine Sea. Considering this event as an interface thrust earthquake, I propose to guide the future investigations of the Taiwan Foothills with such view including ultra-deep drilling (about 5-8 km) through the ruptured fault, down-hole permanent monitoring, systematic paleoseismic studies across active faults and numerical modeling of elastic deformation of Taiwan coupled with GPS observations. The aim of these studies being the determination of the distribution, recurrence and magnitudes of earthquakes in the western part of Taiwan.

(Key words: Chi-Chi earthquake, Continental subduction, Drilling)

1. INTRODUCTION

Like in Japan 5 years ago after the M6.9 Kobe earthquake, the M7.6 Chi-Chi earthquake has urged the community – especially in Taiwan - to draw the conclusions from this dramatic event. Geologists and geophysicists are duty bound to analyse as well as possible the occurrence of the Chi-Chi earthquake, to make investigations on past seismic events and also to formulate suggestions in order to minimize future disasters. An open letter, written in collaboration with J. Angelier, was thus sent soon after the earthquake, in which we declare that Taiwan provides a unique opportunity to drill onland through the plate boundary between Eurasian and Philippine Sea Plates (Lallemand and Angelier 2000, in press). Depending on interpretations, the plate boundary might correspond either to a so-called "seismogenic zone" that had been ruptured during the Chi-Chi earthquake (cropping out along the Chelungpu

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Fault) or an aseismic fault known in Taiwan as the Longitudinal Valley Fault. This paper favors the first hypothesis, but a twin plate boundary could also satisfy the plates kinematics.

2. THE 9.21 CHI-CHI EARTHQUAKE

On September 21st, 1999, a wide area in the Taichung and Nantou counties was severely affected by the strongest earthquake ever recorded in Taiwan. The magnitude 7.6 (Mw) quake nucleated beneath the city of Chi-Chi at a depth of about 7-10 kilometers (sources from Central Weather Bureau of Taiwan). During the following 30 seconds, the rupture propagated in all directions along a fault plane dipping 30° eastward with a maximum calculated slip of 6 meters about 40 kilometers to the north of Chi-Chi (Yagi and Kikuchi 1999). Most damage occurred along the 80 km-long superficial fault trace (hereafter called the Chelungpu Fault, Fig. 1). Geodetic measurements using GPS were acquired a few days after the mainshock by the scientists from Academia Sinica (Yu et al. 1999). They revealed great displacements of the mountain range to the east with respect to the coastal plain to the west. The foot of the range above the fault was uplifted by 3 meters on average, whereas northwestward displacement increases from 3 meters south of Nantou to 7 meters north of Taichung. All these preliminary studies done by various teams from Taiwan were presented and debated during the Geophysical Annual Meeting held in Keelung late October (28-29, 1999).

3. TAIWAN IS UNIQUE

The island of Taiwan is located at the junction between two lithospheric plates : the Eurasian plate which is mainly continental in nature (mainland China belongs to this plate), but also oceanic in its southern part (abyssal part of the South China Sea) and the Philippine Sea plate which is mainly oceanic in nature (Fig. 2). Continental plates are thick, with a buoyant crust whose upper surface is generally exposed above sea-level. Conversely, oceanic plates are thin with a higher mean density which allows them to sink into the earth mantle when plates converge. In general, oceanic plates subduct beneath either continental or other oceanic plates. This is the case all around the Pacific ocean for example. This process is associated with an intense seismicity caused by the friction between the plates and volcanism . Taiwan represents a category which is almost unique in the world where a continental plate (supposed to be buoyant) subducts beneath an oceanic plate. Besides, the western fold-and-thrust belt exposed in Taiwan is a typical example of an accretionary wedge which in most places in the world is found only in a submarine setting. This situation has been reached because the same Eurasian plate is both continental and oceanic as explained above. To the south of Taiwan, the oceanic part of the plate is subducting beneath the Philippine Sea plate causing the formation of the Luzon volcanic arc in the Philippines and small islands (Batan, Lanyu, Lutao ; Fig. 3). This volcanic belt extends along the eastern coast of Taiwan, but volcanism here has been inactive since a few million years. As we move from south to north, the Eurasian plate becomes continental in nature. Indeed, the Taiwan strait corresponds to the Chinese continental platform. At this location, the subduction of the continental part of the Eurasian Plate is re-

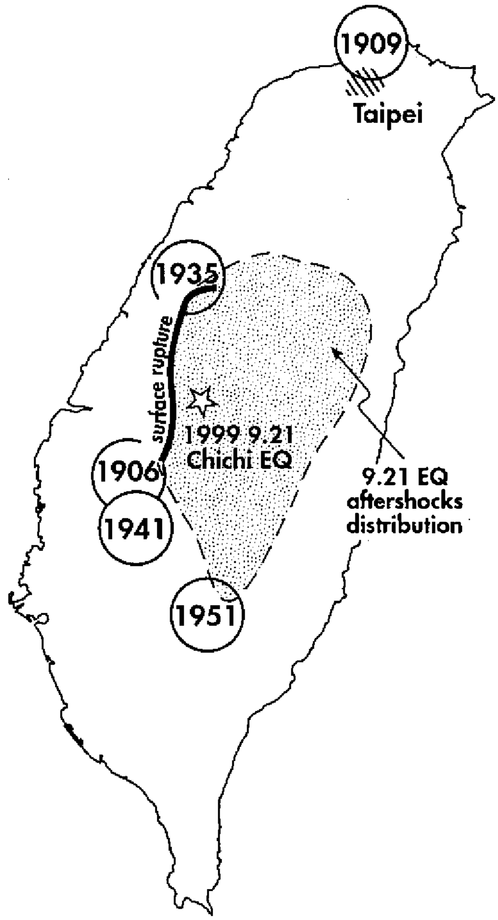

Fig. 1. Location map of historical earthquakes of magnitudes more than 7 in western Taiwan from Chang et al. (1998). The dotted area represents the distribution of aftershocks which have followed the 9.21 Chichi earthquake (open star) and the thick line corresponds to the surface rupture along the ChelungPu Fault. EQ = earthquake.

sponsible for the surrection of the Taiwan belt and its exposure above sea-level (Fig. 4).

The concept of continental subduction beneath Taiwan is not accepted by all scientists, so I will list some arguments to initiate a thinking on this matter. If we agree on the process of continental subduction, then the Chi-Chi earthquake is an excellent candidate for being an interplate thrust earthquake nucleated along the plate interface between the Eurasian and Philippine Sea plates (Fig. 4). The Chelungpu Fault which has been ruptured during the big earthquake then becomes the plate boundary, and further studies must be performed with a view of a "Subduction Earthquake" rather than a thrust earthquake along one of the faults recognized in the fold-and-thrust belt (Fig. 5).

4. WHY IS THERE A CONTINENTAL PLATE UNDERTHRUSTING THE TAIWAN RANGES ?

This concept is not new. In 1981, John Suppe from Princeton University published a now-classical paper in the Memoir of the Geological Society of China, in which he explains the

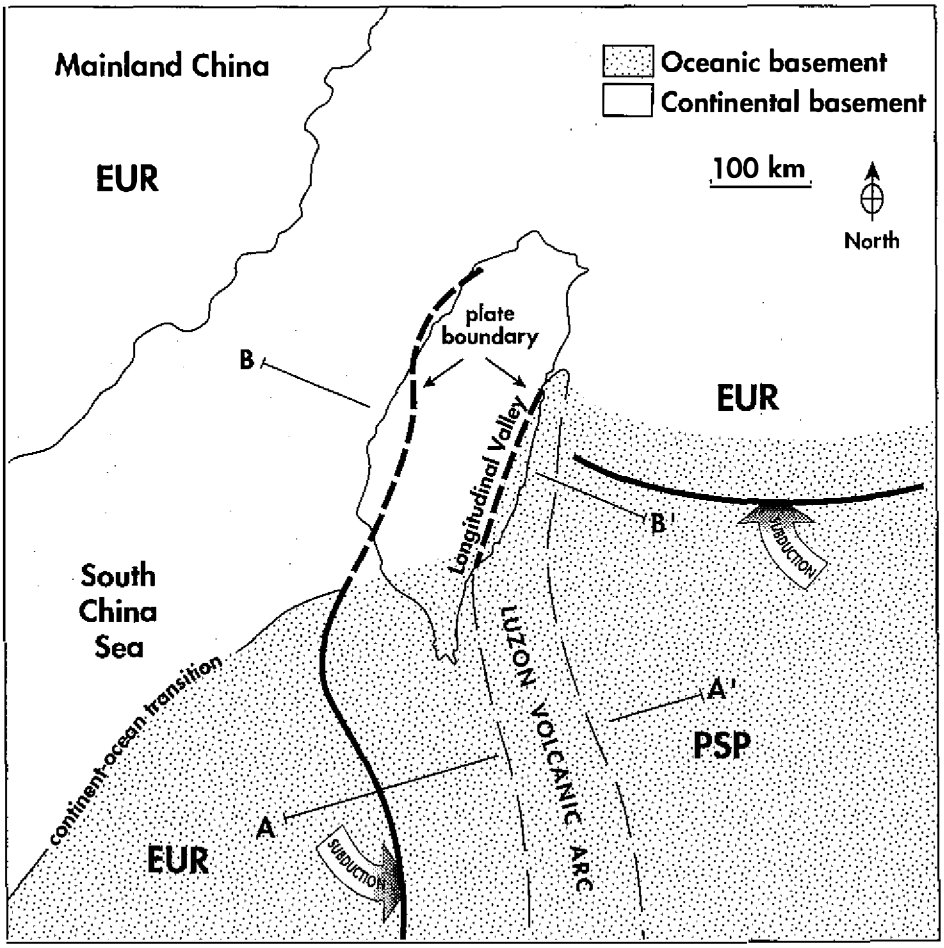

Fig. 2. Convergence between the oceanic Philippine Sea Plate (PSP) and the Eurasia Plate (EUR) – mainly continental but partly oceanic (stippled area) – near Taiwan at a rate of 7 cm/yr (70 km/Ma) along a northwest direction (Seno et al. 1993). Thick lines represent the deep-sea trenches known as plate boundaries, whereas dotted lines in Taiwan show the 2 possible (and debatable) locations of the plate boundary on each side of the mountain range. A-A' and B-B' are locations of cross-sections on Figs. 3, 4, 5 and 7.

mechanics of mountain building and metamorphism in Taiwan in terms of a wedge-shaped fold-and-thrust belt sliding above a so-called "décollement" which is the plate interface. The mountain wedge was approximated as a wedge of Coulomb material at compressive failure, analogous to a wedge of soil that develops in front of a bulldozer, which deforms until the critical stable surface slope is attained. This "Coulomb wedge" model was then applied by

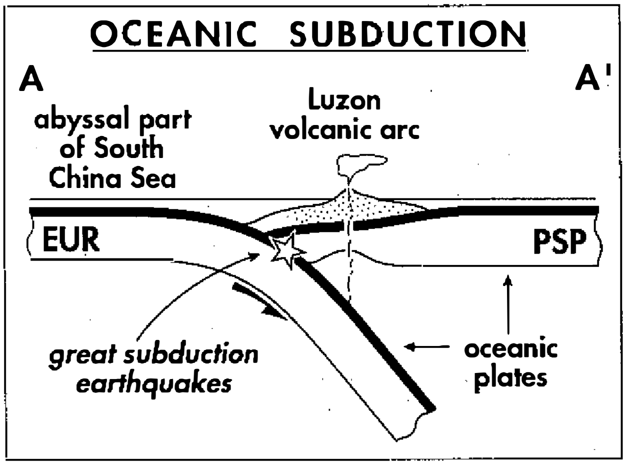

Fig. 3. Simplified section across the plate boundary (Manila Trench) south of Taiwan. See Fig. 2 for location. At this latitude, the oceanic part of the Eurasian Plate (abyssal part of the South China Sea) is subducting beneath the oceanic Philippine Sea Plate causing interplate earthquakes (open star) and volcanism (Luzon volcanic arc).

numerous scientists to all submarine accretionary wedges forming at deep trenches. Simple reconstructions of plate convergence for the past few millions of years, assuming a convergence of the PSP with respect to the Eurasia plate at 7 cm/yr (or 70 km/Ma) in a NW direction (Seno et al. 1993), show that there is necessarily a long slab of the Eurasian plate that has been subducted beneath Taiwan (e.g., Angelier et al. 1990, Teng et al. 1990, Seno 1994, Lallemand et al. 1997, Fig. 6, Chemenda et al. 1997). The subduction of this "missing part" of the Eurasia plate has produced the volcanoes (Chimei for example) and volcanoclastic material presently observed in the Coastal Range east of the Longitudinal Valley. This concept, widely accepted by geologists because required by paleo-reconstructions, was questioned by geophysicists because of the lack of geophysical evidence supporting this idea. Indeed, neither deep earthquakes nor shallow tomography attested to a subducting slab beneath Taiwan (e.g., Wu et al. 1997 ; Fig. 5).

This difficulty was recently resolved after the publication of a global travel-time tomography of the Earth mantle done by Bijwaard et al. (1998). Their model based on the inversion of seismic rays arrivals from a catalog of 82000 relocated earthquakes has provided clear images of velocity contrasts within the mantle able to image subducting slabs with a resolution of 0.6° (about 70 km). From their analyses, the Eurasian plate appears to subduct steeply beneath Taiwan up to a latitude slightly south of Ilan. On the tomographic image, the slab vanishes to the north but also at shallow depths (less than 100 km depth) suggesting a slab detachment beneath the central part of the island (Fig. 7). This explanation might account for the absence of deep seismicity and/or slab continuation from surface to depth, as well as the high heat-flow and low seismicity beneath the Central Range. In this context, the two opposite models (Figs.

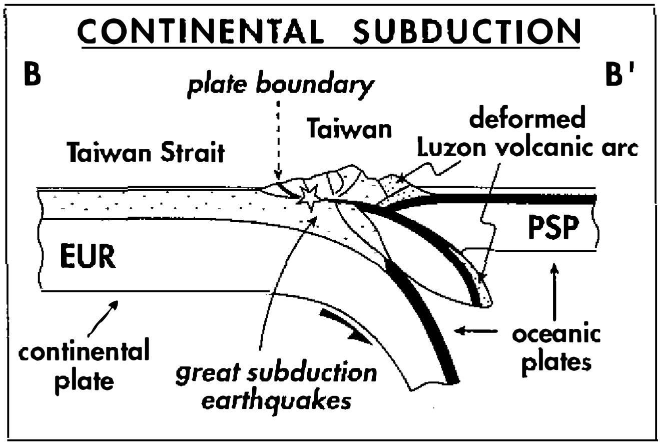

Fig. 4. Simplified section across Taiwan (see Fig. 2 for location) from Malavieille et al. (in press). At this latitude, the oceanic part of the Eurasian Plate was subducted and the continental part collided with the Luzon volcanic arc since a few millions of years. This collision is responsible for the mountain building as well as the deformation of the extinct volcanic arc. According to this model, the plate boundary crops out in the Foothills in the vicinity of the ChelungPu Fault that has been ruptured during the Chi-Chi earthquake. The open star marks the hypocenter of the Chi-Chi "subduction" earthquake.

4 and 5) could be reconciled into a new one close to those of Fig. 4 at shallow depths but including a slab detachment beneath Taiwan as suggested by the lack of subducting plate on Fig. 5. Based on analog modeling, Chemenda et al. (1997) already proposed an inversion of subduction polarity in northern Taiwan which caused the detachment of the Eurasian slab from north to south together with the birth of a new westward dipping subduction zone of the Philippine Sea beneath the Coastal Range. Their mechanical model satisfactorily explained the present GPS velocity field (Yu et al. 1997) as well as other geophysical observations but apparently failed because of the lack of evidences supporting this westward incipient subduction.

5. WHY THE CHELUNGPU FAULT IS THE BEST CANDIDATE FOR REPRESENTING A SEGMENT OF THE PLATE BOUNDARY ?

Based on field and marine observations, especially in the southern part of Taiwan, Malavieille et al. (1997, in press) have proposed a model of evolution with geological sections across the island at various latitudes. Figure 4 shows a simplified version of a section in the central part of Taiwan where the Chi-Chi earthquake occured. According to the depth and the focal mechanism of the earthquake, it is obvious that it fits perfectly with the subduction

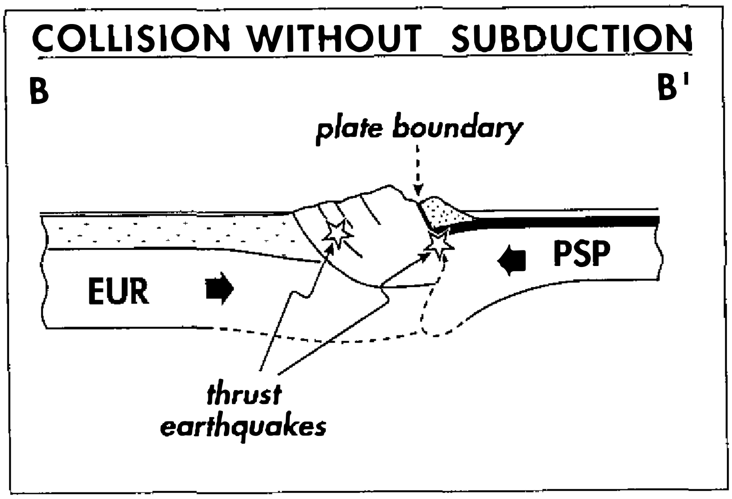

Fig. 5. Simplified section across Taiwan (see Fig. 2 for location) from Wu et al. (1997). According to these authors, seismological and geophysical data do not support the existence of a plate underthrusting Taiwan. They propose a lithospheric scale collision between both plates with the involvment of the lower crust in building the Central Range. In this model, the Chi-Chi earthquake has ruptured one of the thrust faults located in the Foothills which do not represent the plate boundary, the boundary being represented by the Longitudinal Valley Fault.

interface (plate boundary) which is gently dipping toward the east. Note that it is remarkable that this interpretation was proposed a few years prior to the Chi-Chi earthquake. Some scientists consider that the plate boundary coincides with the Longitudinal Valley Fault (Fig. 5) for 3 principal reasons : (1) there is a change in nature of rocks which compose the Coastal range (volcanics from the Philippine Sea plate) and the rest of the island including the Central Range (metamorphic and sedimentary rocks of continental affinity) ; (2) the straight valley represents a first order morphotectonic feature ; (3) both GPS and in-situ measurements across the Chishang Fault indicate a shortening of 2 to 3 cm/yr mostly accommodated by creep along a single fault in the central part of the valley (Angelier et al. 1997).

Coseismic slip along the Chelungpu Fault varied from 3 to 7 meters as indicated above from the observation of the surface rupture. The increasing slip in the northern part of the fault can not be supported by elastic deformation (strain release after accumulation). It is more probably caused by some "ductile" behavior of surface sediment which locally amplify the ground motion (see Seno's report on the web : http://www.eri.u-tokyo.ac.jp/seno). Let us suppose that the fault was locked for the last century and strain accumulated leading to elastic deformation in the vicinity of the fault, then it gives an average slip of 3 cm/yr, which is a significant part of what we need to account for the convergence between the plates. A surface rupture of such magnitude (3-7 m of slip) along a thrust fault is almost unique in the world and

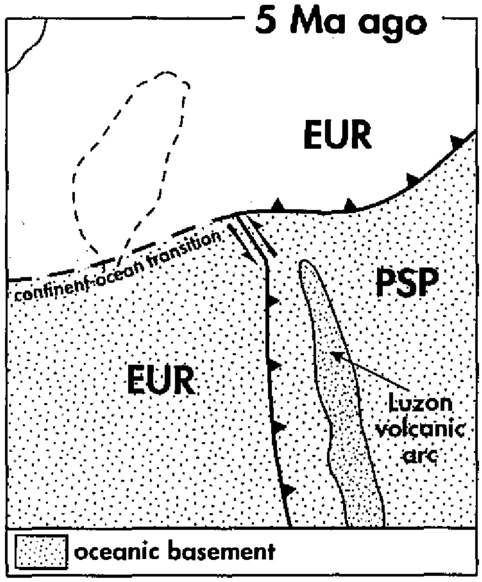

Fig. 6. Simplified sketch of plate boundaries 5 Ma ago after Lallemand et al. (1997). Taiwan did not existed at that time because only oceanic plates were subducting on each side of a presumed transform fault. It is clear from this reconstruction that the Eurasian Plate that has been subducted beneath the northern Luzon volcanic arc (now the eastern coastal range in Taiwan) at that time must be found as a slab at present beneath Taiwan.

generally observed only in submarine accretionary wedges near the emergence of subduction interface. Tetsuzo Seno and his colleagues have reached the same conclusion after surveying the surface rupture soon after the earthquake.

6. HOW TO TEST THE HYPOTHESIS OF A SUBDUCTION EARTHQUAKE AND WHAT ARE THE PERSPECTIVES ?

It is known that very often, subduction interfaces are segmented longitudinally. The idea is that the same segment is ruptured through geological times with a given time recurrence and a given magnitude (and thus slip). This concept has been illustrated nicely in Japan (Nankai Trough) but also all around the Pacific ocean. In SW Japan for examples, segments about 200 km long are ruptured every 100-150 years with magnitudes 8 or more. This process is well constrained because scientists can access to 1000 years historical records of great interplate earthquakes as well as studies from trench excavation and archeological sites (Sangawa 1992). In the case of Taiwan, we know that M>7 earthquakes have occurred during this century to the north (1909 and 1935 earthquakes) of Chi-Chi and to the south (1906, 1941 and 1951 earth-

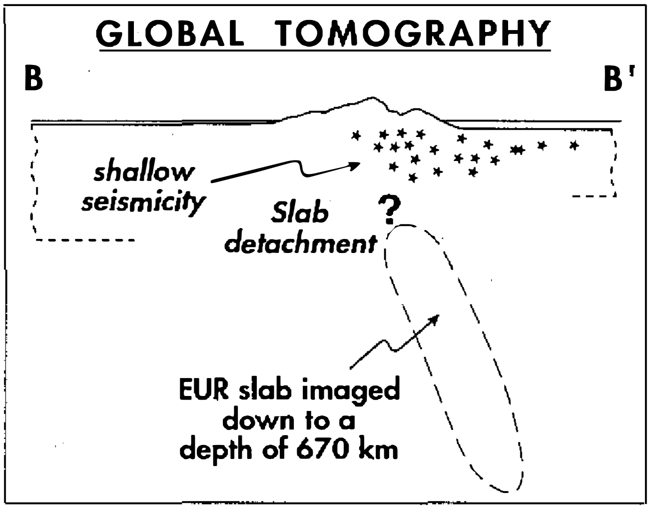

Fig. 7. Simplified sketch illustrating a tomographic image across Taiwan extracted from the global travel-time tomography model of Bijwaard et al. (1998). Seismicity is only observed at shallow depths. A slab is clearly distinguished at depths of 100 – 670 km. It is apparently not connected to the surface (Eurasian Plate).

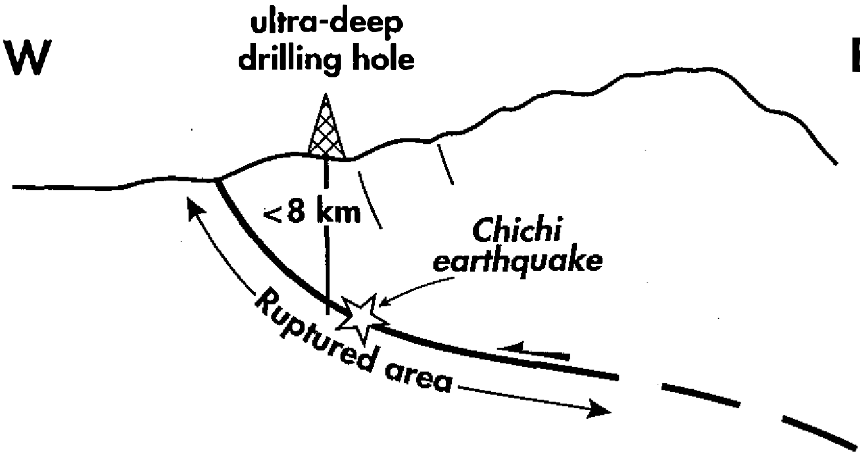

Fig. 8. Schematic illustration of ultra-deep continental drilling through the "seismogenic zone" which could represent the plate boundary between Eurasian and Philippine Sea Plates.

quakes ; Fig. 1, Chang et al. 1998). This could suggest some segmentation of the plate boundary. It is clear that systematic trenching across the active faults of the western foothills is needed in order to determine the recurrence and magnitude of paleoevents. Indeed, only the last century seismic activity is known in Taiwan. Elastic models of plate deformation involving the inversion of GPS data must be performed in order to determine the degree of locking along the interface.

Most of the world's great interplate earthquakes and tsunamis initiate in the zone of underthrusting, so-called by specialists the "seismogenic zone" of subduction zones. The study of the seismogenic zone became a priority since the June 1997 SEIZE (SEIsmogenic Zone Experiment) International Workshop in Hawaii. To understand the mechanics of interplate (subduction) earthquakes was defined as one of the major target for the beginning of 21st century by the international community of geologists and geophysicists. It has been decided to drill during the next century this frictional plate interface at selected sites where its depth is shallow enough (Costa-Rica, Cascadia, Nankai). The ship to be used, still under construction, will be the OD21 Japanese drilling ship, equipped with a riser and able to drill up to 10 km below the seafloor at depths of 2.5 km. It is useful to summarize briefly some of the questions to be answered in the future (from the internal Report of SEIZE Workshop) because it shows the present-day uncertainty we have in understanding these fundamental processes : (1) What is the physical nature of seismological asperities which undergo higher slip during earthquakes ? ; (2) What are the temporal relationships between stress, strain and pore fluid composition throughout the earthquake cycle ? ; (3) What controls the updip and downdip limits of the seismogenic zone ? ; (4) What is the nature of tsunamogenic earthquake zones ? In Taiwan, there is no need to drill offshore because the plate boundary crops out onland. The wells drilled by the Chinese Petroleum Company in the Western Foothills provide an excellent background for an ultra-deep hole (about 8 km) that could be drilled across the lastly ruptured area near Chi-Chi (Fig. 8). Such drilling across major faults have been performed in strike-slip environments (San Andreas in US, Nojima in Japan or Philippine Faults). There is a European project to drill through normal faults in the Corynth Strait (Greece), but there has never been drilling through a major reverse fault at great depths (the décollement has been drilled offshore through accretionary wedges in Barbados, Nankai and Costa-Rica, but never in the seismogenic zone). Also, a down-hole seismometer could be installed for permanent monitoring of the fault. It would allow to record high-frequency micro-earthquakes that can not be detected from seismometers at the surface.

In conclusion, Taiwan represents a unique opportunity in the world to study a seismogenic plate interface cropping out onland and reachable at shallow depths. The whole Earth Science community should be directly concerned by the fundamental observations made from a drill hole through the seismogenic fault and its permanent monitoring. Such operation coupled with paleoseismic studies (access to recurrence time and magnitudes of past earthquakes) would certainly greatly improve our knowledge on these hazardous faults.

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