

# Active tectonics of the onshore Hengchun Fault using UAS DTM combined with ALOS PS-InSAR time series (Southern Taiwan)

Benoit Deffontaines<sup>1, 2</sup>, Kuo-Jen Chang<sup>2, 3</sup>, Johann Champenois<sup>4</sup>, Kuan-Chuan Lin<sup>5</sup>, Chyi-Tyi Lee<sup>2, 6</sup>, Rou-Fei Chen<sup>2, 7</sup>, Jyr-Ching Hu<sup>2, 5</sup>, Bénédicte Fruneau<sup>2, 8</sup>

5 <sup>1</sup>LAREG Unit (IGN-UDD-IPGP-UPEM), LaSTIG (IGN-UPEM), Marne-la-Vallée, 77454, France

<sup>2</sup>Lab. Int. Assoc. D3E N°536, CNRS-MOST France-Taiwan.

<sup>3</sup>Department of Civil Engineering, National Taipei University of Technology, Taipei, 10654, Taiwan

<sup>4</sup>Laboratoire Tectonique et Mécanique de la lithosphère, IPGP, Paris, 75005, France

<sup>5</sup>Department of Geosciences, National Taiwan University, Taipei, 10617, Taiwan

10 <sup>6</sup>Department of Applied Geology, Central Taiwan University, Chungli, 32001, Taiwan

<sup>7</sup>Departement of Geology, Chinese Culture University, Taipei, 11114, Taiwan

<sup>8</sup>Université Paris Est, LaSTIG, IGN, UPEM, Marne-la-Vallée, 77454, France.

*Correspondence to:* Kuo-Jen Chang (epidote@ntut.edu.tw)

**Abstract.** Characterize active faults and quantify their activity are major concern in Taiwan, especially following the major  
15 Chichi earthquake of September 21<sup>st</sup>, 1999. Among the targets that still remain poorly known in terms of active tectonics, are  
the Hengchun and Kenting Faults (Southern Taiwan). From the geodynamic point of view, they affects the outcropping top  
of the Manila accretionary prism of the Manila subduction zone that runs from Luzon (N. Philippines) to Taiwan. In order to  
better settle the location and quantify the activity of the Hengchun Fault, we start from the existing geological maps, Chinese  
Petroleum Corporation (CPC, 1993) and Central Geological Survey (Sung, 1991) ones, which we update thanks the use 2  
20 products derived from Unmanned Aircraft System's acquisitions : 1) the very high precision (<50 cm) and resolution (<10  
cm) Digital Terrain Model (DTM), and the 2) the georeferenced aerial photograph mosaic of the studied area. Moreover, the  
superimposition of the resulting structural sketch map with new PS-InSAR results obtained from PALSAR ALOS-1 images,  
validated by GPS data, allow to characterize and quantify the surface displacements during the monitoring period (2007-  
2011). We confirm herein the geometry, the characterization and the present quantification of the active Hengchun Fault  
25 deformation that act as an active left-lateral transpressive fault. As the Hengchun ridge faces one of the last major earthquake  
of Taiwan (December 26<sup>th</sup> 2006, depth: 44 Km,  $M_L=7.0$ ), it is needed to better constrain the Hengchun Peninsula active  
tectonics in order if possible to prevent major destructions in the near future.

## 1 Introduction

The island of Taiwan is the place of the so rapid NW-SE trending oblique Eurasian versus Philippine Sea Plates convergence  
30 (e.g. Ho, 1986, 1988). A Southwest propagation of the deformation in Taiwan is proposed by Suppe (1981; 1984). It is  
confirmed for instance by the continuous GPS measurements that highlight displacements in the Southern Taiwan of about 6  
cm  $y^{-1}$  (e.g.: Yu et al., 1997). This local shortening rate is about the maximum range in the world. We focus herein in the

Southern Taiwan area (so called the Hengchun Peninsula), that is geodynamically interpreted as the Taiwan incipient collision zone (Lallemand et al., 2001, see Fig.1) which is the transition of the Manila subduction area toward onshore Taiwan collision. The Hengchun Peninsula is situated at the summit of the outcropping onshore Manila accretionary prism (Malavieille et al., 2002; Chang et al., 2003).

5 From the geological point of view, it is a complex area, as its lithology is composed of both folded turbidites as well as the "Kenting Melange" situated close to the Hengchun Fault zone (see Fig.1) and composed of highly deformed shales and large blocks of various lithologies. Evidence of this structural complexity are the five different 1/50.000 scale geological maps (Huang et al., 1997, 2006; Chang et al., 2003 and 2009; Zhang et al., 2016) that have been drawn independently and that are geologically incompatible! Two different major fault zones (Hengchun and Kenting Faults) NNW-SSE trending parallels the eastern side of the 15 km long Hengchun valley and had been recognized by previous authors as potentially active (Huang, et al., 1997, 2006; Chang, et al., 2003, 2009; among others)... As the Hengchun Peninsula is the place of sensitive industries, such as the TAIPOWER Nuclear Power Plant N°3, it is a major concern to better decipher the neotectonics and the active tectonics of the place. Consequently, we address in this paper the localization, and characterization of the deformation of the Hengchun Fault which is the southernmost onshore active fault in Taiwan.

15 Below, we first focus on the high resolution Digital Terrain Model (DTM below) and the orthorectified images of the Hengchun Fault Zone acquired from Unmanned Aircraft/Aerial System (UAS). For a terminological point of view, we used herein the UAS acronym that encompasses all the aspects of deploying those aircrafts and which is less restrictive than Unmanned Aircraft/Aerial Vehicle (UAV) that corresponds only to the platform itself. Then following the classical photo-interpretation techniques, we carefully map and interpret the morphostructures in term of geological mapping, revealing the active tectonic structures. We also benefit from PS-InSAR results derived from ALOS-1 radar images, that give us the interseismic displacement along the Line of Sight (LOS herein) of the radar through the 2007-2011 period. The latter is validated by two E-W trending precise leveling lines across the Hengchun Fault and few GPS stations. Finally, the discussion leads us to propose a simple geodynamic and tectonic model for the Hengchun Fault that fits with all the available data.

## 25 **2 High resolution Digital Terrain Model (DTM) obtained from UAS**

An Unmanned Aircraft System (UAS), commonly known as a drone, is an aircraft without human pilot on board that flies autonomously, and is now been used widely for many aspects because of its convenience, high resolution, etc. (Huang and Chang, 2014; Fernandez Galarreta et al., 2015 ; Giordan et al., 2015 ; Tokarczyk, 2015 ; Bühler et al., 2016; Deffontaines et al., 2016A). The UAS used in this study is a modified version of the already-available Skywalker X8 delta-wing aircraft reinforced by carbon fiber rods and covered partially by Kevlar fiber sheets. The drone is launched by hand, flies and takes photos autonomously, then glides back down to the ground by using a pre-programmed flight plans organized by ground control system, and controlled by the ground control station and remote controller. The autopilot system used in this study is

composed of and modified from the open source APM (Ardupilot Mega 2.6 autopilot) firmware and open source software Mission Planner, transmitted by ground-air XBee telemetry. In order to generate high resolution DTM and mosaic orthorectified images, a total of 3767 photos were gathered by Sony ILCE-QX1 camera mounted on the crafts, during 5 fly missions, for a total coverage area of 33 km<sup>2</sup> with 8cm Ground Sampling Distance (GSD). The coverage of the adjacent photos is kept at least for 85% overlap and 45% sidelap. The raw images are processed by Contextcapture and Pix4Dmapper software mutually, the data sets generated in this study are orthoimages and DTMs, with a grid spacing of 10cm. Prior to the morphotectonic analysis (Deffontaines et al., 1991, 1993, 1997, 2016A; Pubellier et al. 1994...), the quality of the data set (see whole data set on figure 2) needs to be evaluated. 18 ground control points are extracted from airborne LiDAR dataset. The comparison of the UAS DTM with airborne LiDAR data gives a root-mean-square deviation (RMSD) of 4cm with maximum error of 40cm for the open bar ground area. The Fig. 3 illustrates some case examples of the quality of both the DTM as well as the orthorectified image of the Hengchun Fault. The morphostructures analyses based on photo interpretation are conducted accordingly.

### 3 Geology of the Hengchun area

From a geologic and geodynamic point of view, the Hengchun Peninsula is interpreted as the northern tip of the Manila accretionary prism (Malavieille et al., 2002; Chang et al., 2003). It is mainly composed of several lithological formations that are described below from the older to the younger ones (see location on the cross-section of Fig. 1C).

The Mutan Formation is farther the larger outcropping formation of the Hengchun Peninsula. Middle to late Miocene in age, it is composed of classical turbidites deposits such as interbedded sandstones (channels and levees) and shales (Sung and Wang, 1986). The Mutan Formation is a very thick pile (locally several thousands of meters) and highly deformed turbidites (locally even overturned, Chang et al., 2003).

The complex Maanshan formation, late Miocene, Pliocene up to Quaternary in age, is a mix of submarine erosion and depressions fill-in of both Mutan and Kenting formations (Cheng and Haung, 1975; Page and Lan, 1983; Lin and Wang, 2001; Huang, 2006). The Maanshan formation outcrops partly in the South of the Hengchun Basin (CGS geological map (Sung, 1991), see panorama of the Hengchun Basin on Figure 4). We believe that the Maanshan formation composes partly the basement of the Hengchun Basin and the offshore Manila accretionary prism to the south (Lundberg et al., 1992 and 1997; Reed, et al., 1992).

The Kenting Mélange, which is only outcropping east of the Hengchun Basin, is known as a tectonic Mélange (Tsan, 1974A and B; Page and Lan, 1983; Huang, 1984; Pelletier and Stephan, 1986; Huang et al., 1997; Chang et al., 2003, 2009A and B; Deffontaines et al., 2016B, Zhang et al., 2016; Malavieille et al., 2016; among others...). It is interpreted as a chaotic tectonostratigraphic unit containing blocks of various origin (ophiolitic and sedimentary), size and lithology embedded in a sedimentary matrix (Malavieille et al., 2016). It is herein interpreted as a large tectonic breccia of composite ages that ranges from 1 to 10Ma (see Malavieille et al., 2016) as it mixes various sizes of different blocks and different turbiditic and shale

bodies (Page and Lan, 1983; Lin and Wang, 2001, Chang et al., 2003). To our point of view this shaly/blocky tectonic Mélange is injected (intruded) within the major fault zones south of Taiwan due to both the plate convergence and high pressure of fluids at depth (see also Deffontaines et al., 2016B). Future scientific work is needed in order to both precise the processes that creates this tectonic Melange and to reconstruct (or inverse) its evolution through time as there is still different incompatible assumptions and hypotheses (see Malavieille et al., 2016, and work in progress).

Geological mapping in the fields lead us to look for active tectonic cracks within anthropic concrete dykes. They reveal the clear transpressive and thrusting component of the Hengchun Fault (Figure 5). As the concrete dykes are manmade and very recent, it is easy to reconstruct and inverse the deformation following the Angelier's methodology settled along the Longitudinal Valley Fault (see also Lee et al., 1998, 2000, 2001, 2003, 2005, 2006).

From a structural point of view, the Hengchun Fault geological map that we propose (Fig. 6), is the result of (1) field studies (Figs. 4 and 5 taken Jan. 3rd, 2007), (2) the synthesis of previous geological mappings (CPC, 1993, the CGS-Sung, 1991, Chang et al., 2003, Chen et al., 2005, and more recently the Giletycz et al., 2015) ; and (3) a detailed photo-interpretation of both the orthorectified mosaic of the UAS aerial photograph as well as the hill-shading of the high resolution UAS derived DTM (Fig. 5). The detailed structural photo-interpretation of the Hengchun Fault area checked in the fields, takes into account the basic morphostructural principles (Deffontaines et al., 1991, 1993, 1997; Pubellier et al., 1994...) such as the geometry of the drainage pattern (bayonet tracks, curves and alignments), the alignments of small scarps present in the flat Hengchun Basin (Fig. 6, index 5) that helps to get the morphotectonic features (Fig. 6, faults that affect the topography, index 2 for instance). We also added on the Hengchun Fault geological mapping, geomorphological objects such as paleo-surfaces (index 5 on Fig.6) which are easily recognized by smooth textures and structures above the Kenting Mélange. Those paleo-surfaces are slightly tilted, folded and uplifted east of the Hengchun Fault and are witnesses of the vertical uplift of the tectonic activity of the Hengchun Fault. Unfortunately, due to the slight tilt, it remains uneasy to extract fold axes from those paleo-surfaces. It should be interesting to date these paleo-surfaces in order to get the middle to long-term activity of the deformation. We select also the chevrons from the morphostructural analysis of the high resolution UAS-DTM (index 6 on Fig. 6). Chevrons correspond to the top of harder rocks tilted structural surfaces within the Kenting Mélange East of the Hengchun Fault. They reveal opposite tilted strata, consequently the presence of folds (anticlines as well as synclines, index 7 on Fig. 6) close and parallel to the Hengchun Fault zone. Some tectonically offset and eroded mud volcanoes are also identified and mapped herein (index 3, on Fig. 6), especially in the South Hengchun Basin and close to the Taipower Nuclear Power Plant N°3. We interpret these mud volcanoes as the outcropping traces of the shale intrusions within the Hengchun Fault zone south of Taiwan very probably due to fluids overpressure at depth in relation to the intense tectonic stress (see also Deffontaines et al., 2016B).

The Hengchun Fault is recognized as active (Bonilla, 1976; Hsu and Chang, 1979; Lee, 1999; Lin et al., 2000; Deffontaines et al. 2001). Geological mapping in the field reveals many active cracks within anthropic concrete dykes. These cracks highlight the clear transpressive and thrusting component of the Hengchun Fault (Fig. 5). One may note that we cannot recognize clearly in the topography the trace of the Hengchun Fault as a unique straight line thrusting (see Fig. 6) contrasting

to the CGS geological mapping (Sung, 1991) or its sinusoidal shape on the CPC geological mapping (1993). We only highlights herein the Hengchun Fault Zone which is made of locally aligned segments of faults that affect the eastern part of the very recent Hengchun Basin deposits (cf. index 2 on Fig. 6).

5 The active Hengchun Fault appear on Figure 6 as made of several parallel small aligned straight "faults segment" with a transpressive thrusting component (see Fig. 6, index 2). This is in contrast with the rectilinear drawing of the CGS geological mapping (Sung, 1991) or its sinusoidal shape on the CPC geological mapping (1993). But remember that regional geological maps aim at both stratigraphy and structure where fault trace is putting at where maximum stratigraphic throw locates (or just approximately) which may have large differences with the active fault trace situated strictly at active lines where last rupture locates. Moreover on land, last fault rupture can only be identified by geomorphic features; not by drilling or  
10 geophysical prospecting.

From the dating of the deformation point of view, the vertical long-term slip rate has been settled from marine terraces study and estimated of  $6.3 \text{ mm y}^{-1}$  at Haikou and  $3.8\sim 6.1 \text{ mm y}^{-1}$  at Nanwan (Chen and Liu, 1993). Other marine terrace studies from WS Chen (CGS reports in Chinese) show similar long-term slip rate. Further datings ought to be undertaken in order to better characterize the ages of the terraces, paleo-surfaces and the different deposits of the Hengchun Basin in order to  
15 inverse and reconstruct the tectonic history (Liew and Lin, 1987).

#### 4 Inputs of PS-InSAR interferometry on the Hengchun Fault

In order to get the tectonic activity of the Hengchun Fault, we processed 13 radar images (ALOS-1 PALSAR images acquired in L-Band ( $\lambda = 23.6 \text{ cm}$ )) in ascending mode between January 2007 and January 2011 so providing 4 years of monitoring, through the STAMPS software (Hooper et al. 2007). A series of 12 interferograms has been generated, all with  
20 respect to a unique « Super Master » image situated in the mid-time series (Pathier et al., 2003; Fig. 7). The method identifies PS pixels (more than 20.000 PS points are available, see Fig.8A and 8B) that are characterized by their phase stability over the whole period. PS analysis leads us to extract a map of mean LOS surface velocities for each PS and also to catch their displacements through time series.

The results (Fig.8A and 8B) show an impressive density of PS (more than  $140 \text{ PS/km}^2$ ) in this area where both human  
25 activity and luxuriant vegetation prevail. The PS map reveals a clear continuous difference in LOS velocities across the Hengchun Fault (HeF below) where the Hengchun valley (western side of the HeF) is subsiding with values ranging from  $-5$  to  $-10 \text{ mm y}^{-1}$  contrasting with the westernmost Hengchun ridge which is uplifting. The eastern side of the HeF is characterized by the rapid increasing uplift of the Kenting Mélange up to a maximum that seems to parallel the Hengchun Fault. Farther east the PS LOS velocities decrease with the distance to the Hengchun Fault so the east of the Hengchun  
30 peninsula appears to be slightly tilted. We observe in the Hengchun peninsula a similar dissymmetric active vertical behaviour as in the Coastal Range (Eastern Taiwan) : the western part of the relief is highly actively uplifting and folding contrasting to the eastern part characterized by a decreasing uplifting and which is slightly tilted to the east (see also

Deffontaines et al., 2016A). We note in Fig. 9B and Fig. 10, the coherence in between the PS LOS velocities and the GPS measurements (coloured large dots that we put into the same LOS radar geometry). Consequently, those PSInSAR results offer a precise mapping of the active interseismic splays of the Hengchun Fault and allow the quantification of the tectonic displacements.

5 Dealing with the Kenting Fault, with the data used in this study we see no gradient of PS LOS velocity, nor differential noticeable displacements on the GPS stations situated around the Kenting Fault (see Figure 8A-8B and 9A-9B). Moreover from the geological mapping analysis (Chang et al. 2003), the Kenting Fault has a sinusoidal planimetric geometry that follows more or less the topographic isocontour of the relief. So the Kenting Fault is a low dipping thrust fault. Consequently, this fault may be either locked at the surface, or an inherited inactive fault, or have a tectonic activity that we do not observe  
10 on this PS-InSAR dataset.

We note a great coherence in between the PS and the available GPS measurements (colored large dots on fig. 8B) provided on 2 stations. For comparison purposes, GPS measurements have been projected on the radar LOS. We compared also these PS results with leveling data acquired during the same period of time (between March 2008 and April 2011, during 3 campaigns of measurement). As for GPS data, we converted leveling measures into LOS values. Figure 9 allows comparing  
15 the leveling data, the mean LOS velocities of PS along the leveling lines, and GPS data for the 2 stations close to the leveling lines.. One may note the agreement between all of them.

Moreover, in order to better characterize the Hengchun Fault activity, and quantify the LOS velocity variation on both sides of HeF, we computed the LOS velocity offset across the fault, using different profiles perpendicular to the fault line. This offset characterizes the slip rate of the fault. We present two specific profiles in Fig. 10 (see location Fig. 8). The two PS  
20 profiles, which run transverse to the Hengchun Fault, one north of the Hengchun valley close to the Checheng city, and the second one southward (close to Hengchun city), show LOS offset less than  $10 \pm 2.5 \text{ mm y}^{-1}$ .

Thanks to a series of more than 30 profiles perpendicular to the fault, we computed the interseismic LOS velocity offset along the fault, from North to South, with values reaching  $7 \pm 2.5 \text{ mm y}^{-1}$  that reveals the clear tectonic activity of the Hengchun Fault (Fig. 11). One may note the excellent coherence between slip rates derived from PS analysis and the GPS  
25 measurement (projected in LOS) represented by the yellow triangle, (see Fig. 11). This is a major result from this study as it demonstrates the interseismic activity of the fault, and allows obtaining the average annual interseismic LOS displacement of the Hengchun Fault, and its spatial variation along the fault.

StaMPS gives also access to time series of displacement, from 2007 to 2011. We can thus derive at each image acquisition date the displacement related to the fault (a cumulated slip value), then allowing monitoring its slip variation through time.  
30 The time series of slip values (Fig. 12) does not show any clear acceleration, it only expresses a linear behavior of the fault during this period.

## 5 Discussion: up-dated Hengchun active tectonic model

Many different tectonic models have been proposed on the active Hengchun Fault zone (thrust, left-lateral strike-slip...). But it is needed to give both structural and active tectonic arguments for the Hengchun Fault (e.g. Liew and Lin, 1987; Central Geological Survey and CPC geological mappings -1991 and 1993 respectively; Chen and Liu, 1993, 2000; Chang et al., 2003, 2009A and 9B; Chen et al. 2005...).

The simplest model that we propose herein that fits with the oblique NW trending Taiwan geodynamic convergence (Suppe, 1984), the E-W displacements measured by GPS data (Yu et al., 1997), the geological dataset and the geological mapping (CPC-1993 and CGS- Sung, 1991; Chang et al., 2003 and 2009, Giletycz et al., 2015), our detailed UAS DTM photo-interpretation (Fig. 6) and our interferometric 2009-2011 PS LOS displacements (Fig. 8A and 8B), is given for the western part of the onshore Hengchun Peninsula (Fig. 13).

From the interferometric point of view, if we generalize, the western Hengchun Peninsula is slowly uplifting toward the LOS (less than  $+1 \text{ cm y}^{-1}$ ) contrasting to the slow subsidence of the eastern part of the Hengchun Peninsula ( $-0.25 \text{ cm y}^{-1}$ ). So as the average displacements deduced from PS-InSAR across the Hengchun Fault is continuous across the fault zone, it shows the existence of a clear interseismic creeping component, with a value of  $0.8 \text{ mm y}^{-1}$  along the LOS. The variation of displacements on both sides of the Hengchun Fault zone reveals also the progressive folding of the Hengchun Fault zone: the eastern hanging wall is progressively uplifting contrasting to the progressive subsidence of the Hengchun Basin (Foot Wall - see Fig. 9 and 10). These interferometric results combined with the structural photo-interpretation (Fig. 6) show that the fault is only locally outcropping and that active folding occurs at depth, increasing progressively with time stress and strain at depth.

Consequently due to the structural geometry, the Hengchun Fault appears to act as an active left lateral transpressive strike-slip fault with an active uplifting and folding (anticline) of its eastern hanging wall, contrasting to the active subsidence of the western footwall (which corresponds to the easternmost part of the Hengchun Basin). Moreover the Hengchun Fault is not outcropping along one continuous North to South small straight line but describe a "Fault Zone" made of little active fault segments (see Fig. 6). One may note that the left lateral strike-slip motion has been deduced from the obliquity of the GPS arrows evidenced in the bibliography (e.g. Chang et al., 2003). Therefore the figure 13 shows a simple model where the Hengchun Fault acts as a transpressive left-lateral  $N160^\circ E$  trending fault zone. Its active hanging wall is overthrusting and is actively folding the topographic surface that tilts and folds the paleo-surfaces, and marine terraces. The Hengchun Basin (Hengchun Fault footwall - and west of it) under the transpression is folded as well, and is actively subsiding with a parallel to the fault syncline axis that helps for the lagoonal deposition of the Pleistocene/Holocene Hengchun Basin deposits (Chen et al., 1991).

Many faults in Taiwan (e.g. Chelungpu Fault - 921 Chichi Earthquake, September 21<sup>st</sup>, 1999) present both component of slip (left-lateral strike-slip and thrusting) such as the Hengchun Fault. Dealing with the amplitude of the Hengchun Fault deformation, the interferometric displacement toward the LOS ( $0.8 \pm 0.2 \text{ cm y}^{-1}$ ) correspond to the instantaneous

interseismic slip rate that could be a bit different than the vertical long term slip rate deduced from the marine terraces datings  $6.3 \text{ mm y}^{-1}$  at Haikou and  $3.8\text{--}6.1 \text{ mm y}^{-1}$  at Nanwan (Chen and Liu, 1993). From this slight difference in between the long term and the instantaneous slip rates, we may deduce the fact that the Hengchun Fault **may be** not only a creeping fault (work in progress).

## 5 **6 Conclusions and perspectives**

First, **dealing with the technical and methodological conclusions**, the flights of UAS **with image acquisition** lead us **capable to produce** through photogrammetry. A high resolution **DTM** of the Hengchun Fault area with a less than **7cm** ground resolution and less than 40 cm precision **is then produced for this study**. However for some places, the texture **may change rate quicker and** higher than **the image capture acquisition, like for example the lakes or water surfaces due to sunlight reflection for instance, which** causes noises in DTMs. Concerning **the DTM photo-interpretation**, especially for the active geological structures, the terrain is easily to be modified by human activity in Taiwan: cities and farmer land are **rapidly growing in** some areas **concealing** morphotectonic **structures**. Fortunately, the **ortho-mosaic** images **help** to recognize those artefacts. Overall, the autonomous UAS and well developed photogrammetry **technique allow generating conveniently** high detail topographic information, and **help** to carry on long term scale morphotectonic study. Integrating of PS-InSAR data **giving** the short term active movement of the Hengchun Fault and **High Resolution DTM structural photo-interpretation acquired from** UAS demonstrates longer term topographic deformations and anomalies, thus providing one of different tectonic deformation **to locate, characterize and quantify the** active tectonics features.

Then with these so useful high resolution topographic data, we undertook a classical geological and geomorphological photo-interpretation that lead us to up-date and refine the pre-existing CPC-1993 and CGS-1991 geological maps, especially on both side of the Hengchun Fault. The latter lead us to precise the structural geometry of the Hengchun Fault in the Peninsula (Fig. 6). Moreover, the PS-InSAR interferometric processing that we carried out over the Hengchun Peninsula from 2007 to 2011 with more than 12 coherent interferograms reveal **clear interseismic** displacements of the Hengchun Fault. Moreover, our interferometric results **are in agreement with** GPS data **and** reveal the active **section and folding** of the eastern hanging-wall of the Hengchun Fault of about  $0.8 \pm 0.2 \text{ cm y}^{-1}$  toward the LOS. Furthermore the footwall is submitted also to a **complementary** active subsidence **related** to the development of an active syncline **parallel to** the Hengchun Fault. These displacements are a cumulative vector taking into account both planimetric and **vertical** components of the deformation. Our results are fully coherent with both two leveling lines E-W trending across the Hengchun Fault and three continuous GPS stations. Moreover **PS density (more than 140 PS Km<sup>-2</sup>) offers a spatial density of measurements that is greatly higher than that the one** offered by GPS, allowing us a global and whole coverage and mapping of the active Hengchun Fault deformations.

**Moreover PS density (more than 140 PS/km<sup>2</sup>) offers a spatial density of measurements that is greatly higher than that the one offered by the GPS, allowing us a global and whole coverage and mapping of the active Hengchun Fault deformations.**



From the active tectonics conclusions, we deduce that the highly dipping Hengchun Fault acts as an inter-seismic creeping left-lateral strike-slip fault with a clear transpressive component of  $0.8 \text{ cm y}^{-1}$  in LOS that is associated with active foldings. As the PS interferogram spectrum increase continuously from W to E above the whole Hengchun Fault zone, it means that the HeF is actively folding at depth. Moreover, the lack of clear PS discontinuity across the Hengchun Fault zone proves that it is not offsetting the topography (and outcropping) during the acquisition monitoring period (2007-2011). This signs the slow continuous increase of tectonic stress at depth which is a major clue for a future earthquake in that area.

Unfortunately, the active differential displacement on both side of the Kenting Fault is much more difficult to highlight with our PS results, due (1) to the low dipping of that fault deduce from its mapping geometry, or (2) to an inherited inactive fault, or (3) a locked fault at the surface, and also maybe due to (4) the ductile rheology of the underlying formation (Mutan clay turbidites - MT). Consequently, it is needed to much better map the Kenting Fault in order to better understand its rheology and active behaviour (work under progress).

Anyway, the shallow seismicity (Deffontaines et al., 2016B) confirms the high onshore shallow tectonic activity that hits the Hengchun Peninsula. The deep offshore major Hengchun earthquake (December 26th 2006, depth: 44 Km,  $M_L=7.0$ ) also participated to the active deformation of the Peninsula.

Finally, due to the homogenous  $0.8 \text{ cm y}^{-1}$  LOS displacement toward the LOS all along the 15 Km of the Hengchun Fault studied area, it is definitely needed to better constrain the Hengchun peninsula active tectonics in order to prevent major destructions and major failure in the near future as for example for the present so sensitive energy industries (e.g. the Taiwan Nuclear Power Plant N°3 situated along the southern tip of the Hengchun Fault).

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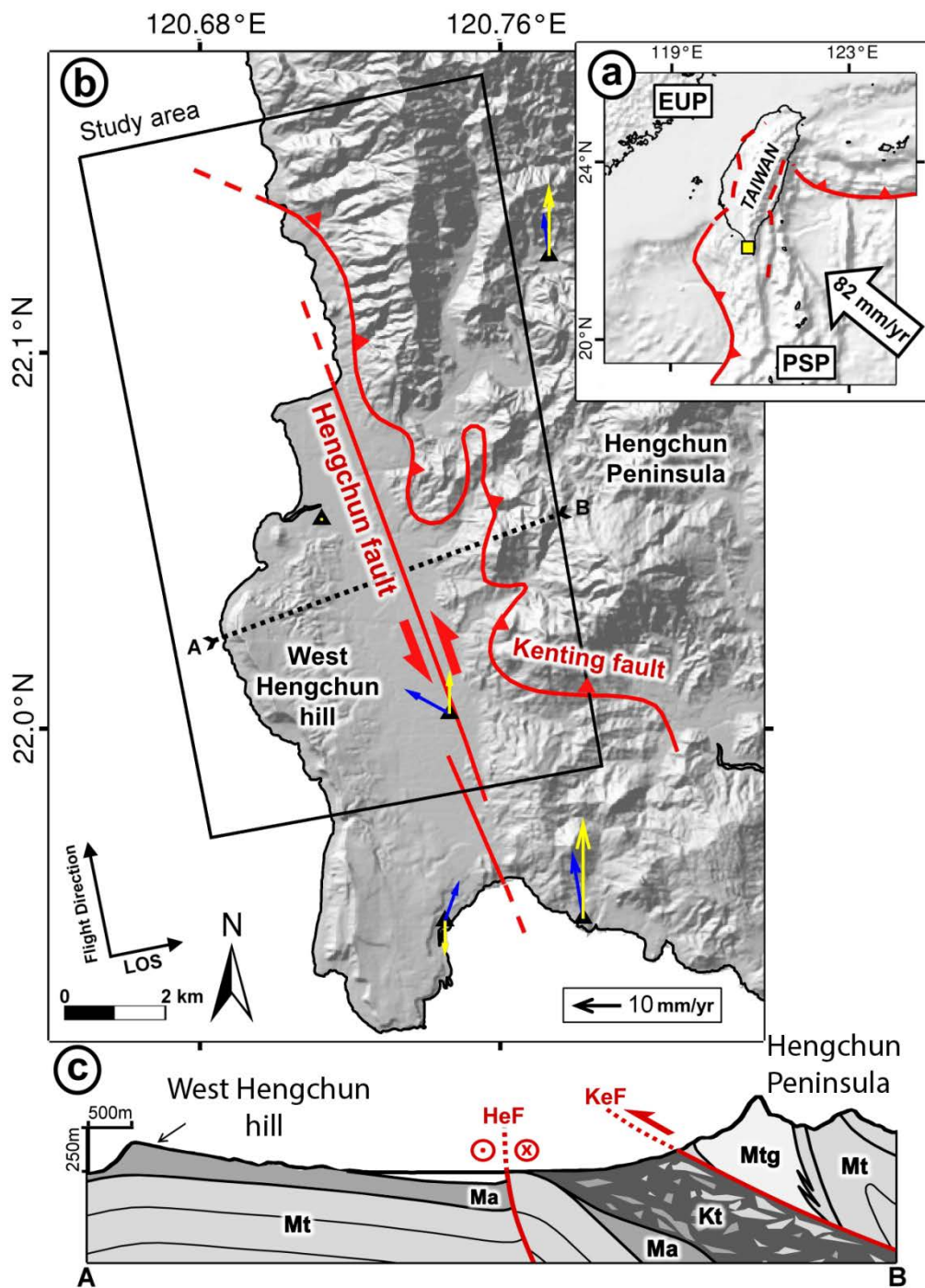
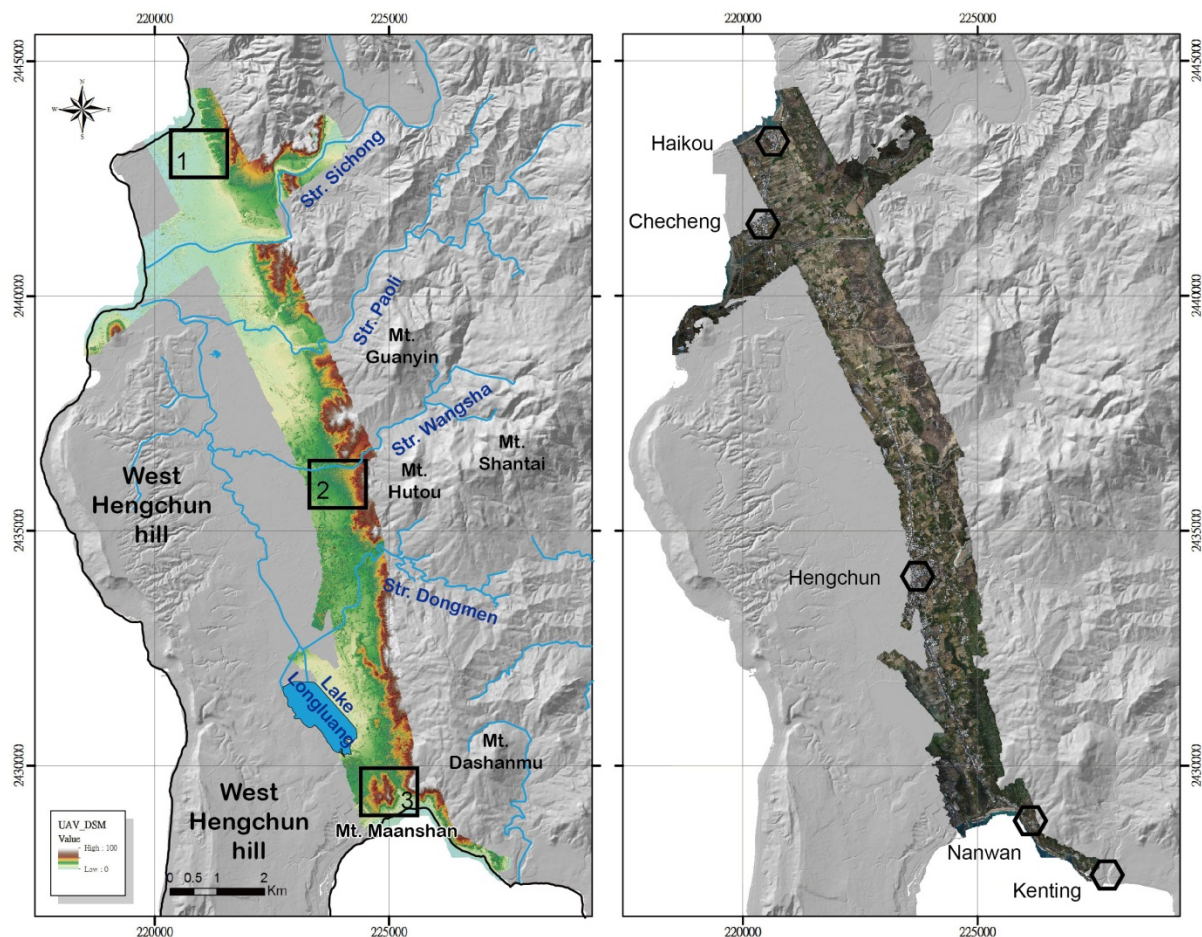


Figure 1: Location of the Hengchun and Kenting Faults within Southern Taiwan. Fig. 1a: Location of the Hengchun Peninsula (yellow quadrangle); EUP Eurasian Plate; PSP: Philippine Sea Plate.  $82 \text{ mm y}^{-1}$  is the rate convergence of the Philippine Sea Plate toward Eurasia (Yu, et al. 1997). Fig.1b: W Hengchun Peninsula hill-shade from the 40m ground resolution DTM: The heavy red lines are Hengchun and Kenting Faults. Black Triangle: used GPS stations; Blue and yellow arrows represent horizontal and

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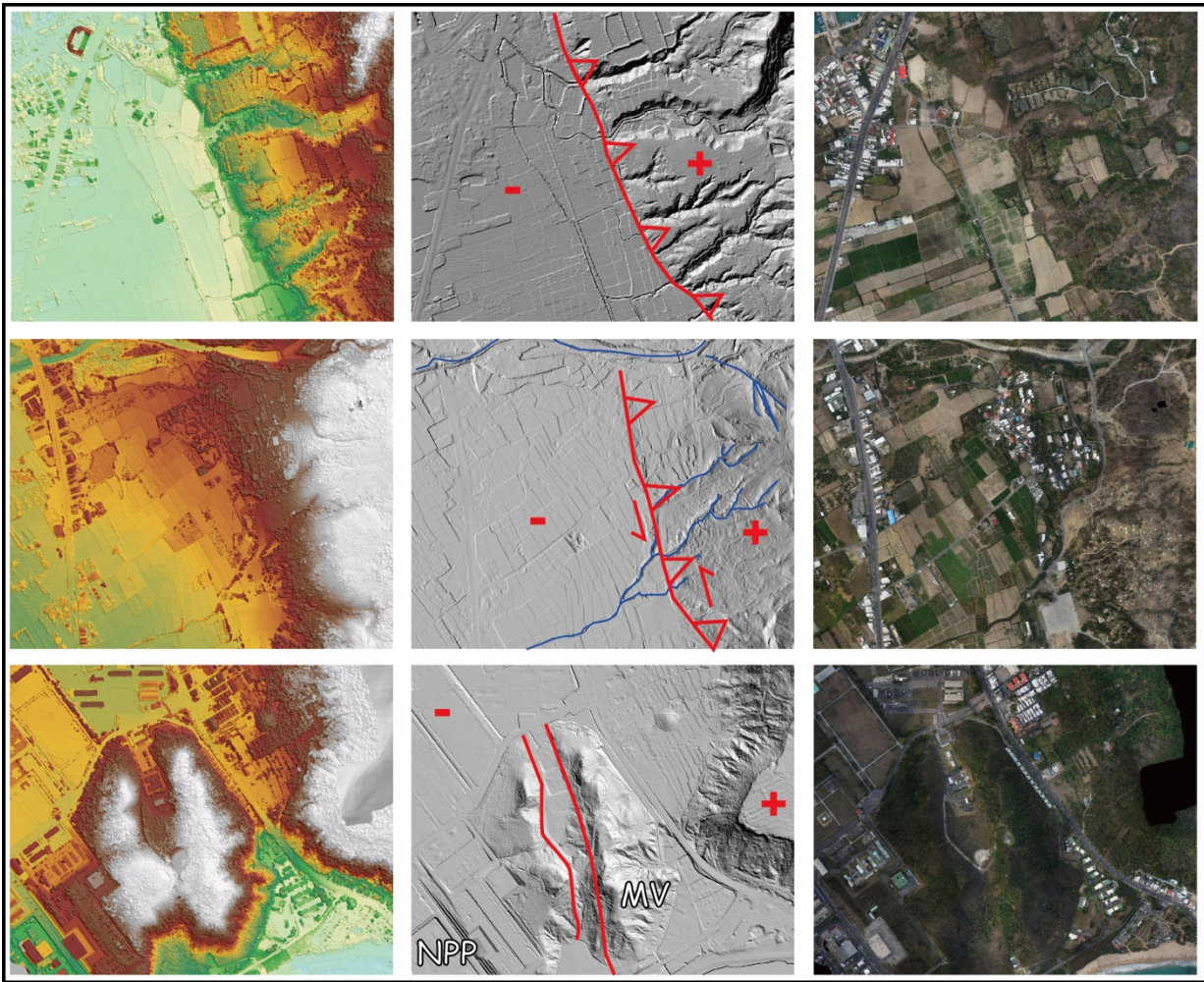
vertical GPS displacements respectively; Black quadrangle study area; A-B location of Fig.1c geological cross-section; Fig. 1c: W-E trending synthetic geological cross-section (modified from Chang et al., 2009B; and Zhang et al., 2016), Ma: Maanshan formation, Mt and Mtg: different facies of Mutan formation, Kt: Kenting Melange, HeF: Hengchun Fault, KeF: Kenting Fault.



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Figure 2: Right: in colour, the mosaic of UAV orthorectified images. The black hexagons locate cities. One may notice the contrasting relief on both sides of the Hengchun valley: its western flank is a homogenous structural surface slightly dipping east contrasting to the highly eroded eastern part. For both Fig. 2 left and right, the black and white hill-shade DTM correspond to a part of the 5m ground resolution Taiwan DTM.

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5 **Figure 3: Three case examples taken from North to South of the Hengchun UAS Digital Terrain Model (DTM). Each box cover the**  
**same area (1.3 km x 1.1 km): First column: hypsometric color images (see legend in Fig.2 left). Second column: Black and white**  
**hill-shading relief from UAS derived DTM; heavy red line corresponds to the Hengchun Fault, blue line to the drainage, NPP:**  
**Taiwan Nuclear Power Plant N°3, MV: Mud volcano. Third column: Associated orthorectified images acquired from UAS. The**  
**first line of images highlights the active tectonic scarp of the Hengchun Fault which differentiate 2 blocks: an uplifted (+) locally**  
**eroded terraces to the east and a flat lowland sedimentation area to the west. The second line of images highlights the left lateral**  
**offset geometry (red arrows) of tributaries (blue line) on a glacis which is uplifted (+) on the east of the Hengchun Fault. The third**  
 10 **line of images shows a deformed N-S trending elongated mud volcano (MV) close to the Taiwan Nuclear Power Plant N° 3 (NPP**  
**and see infrastructures on the lower left corner of the deformed mud volcano) and a flat uplifted (+) terraces (paleosurface of Fig.**  
**6) on the blue side.**



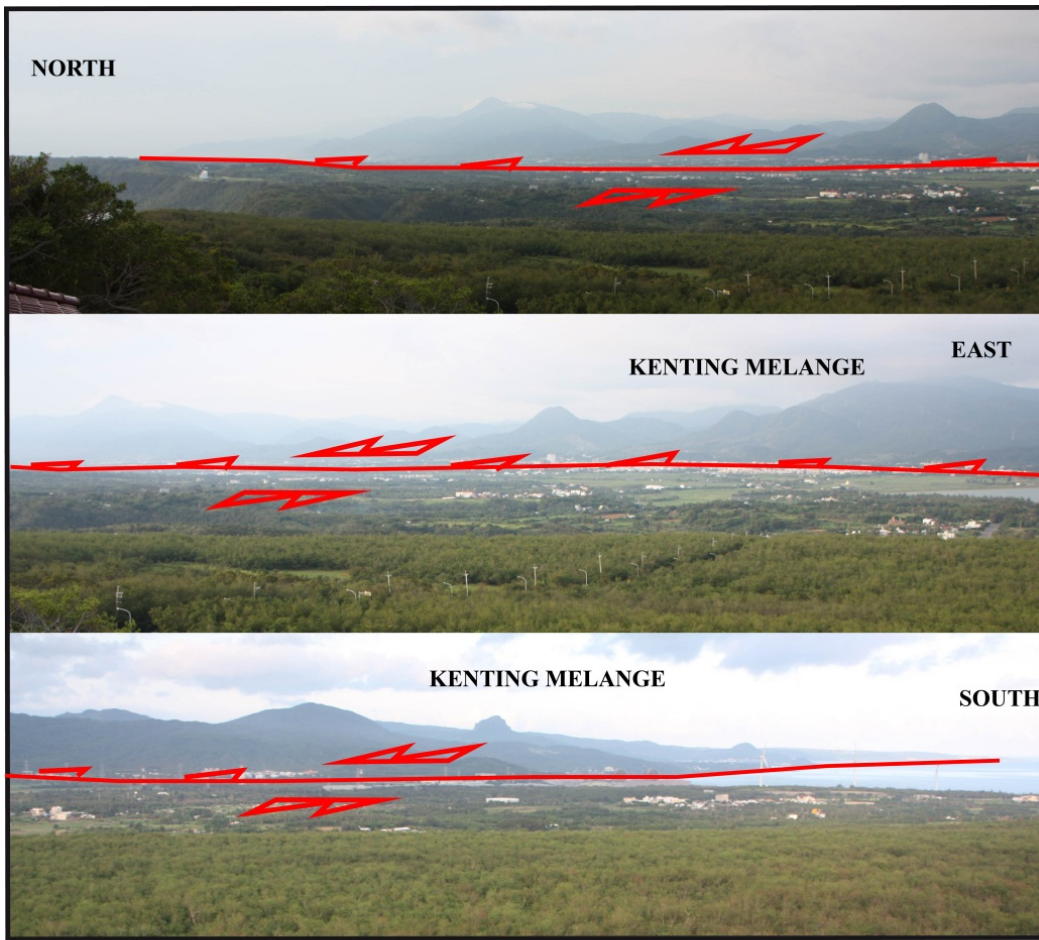


Figure 4: Panorama of the Hengchun Fault observed from the SW part of the studied area. Red lines (1) correspond to the left lateral compressive Hengchun Fault. Note the isolated summits within the Kenting Melange that is composed of highly deformed shales with various huge blocks (olistoliths?) interpreted herein as a tectonic breccia.



5 Figure 5: Field work **photograph** of compressive features affecting recent concrete dykes after the Hengchun earthquake (Dec. 26<sup>th</sup> 2006,  $M_L=7.0$ ), see location on Fig. 1 near the Fang-Shan village ( $22.26^\circ\text{N}$ ,  $120.66^\circ\text{E}$ ). The red compass **gives** the scale of the outcropping deformation (20cm). **Thrust** associated with three back-thrusts highlighting a small pop-up (below the compass). The red arrow **reveals** the thrusting component that affects the new concrete dykes

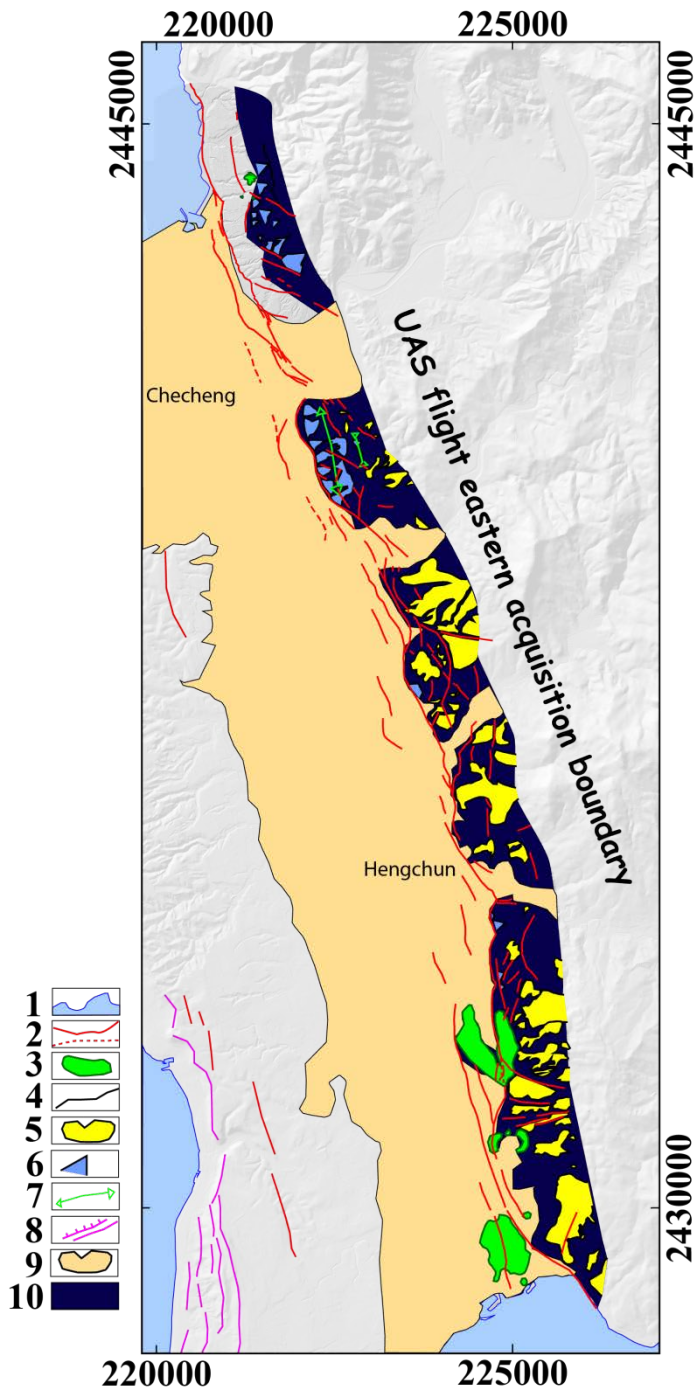
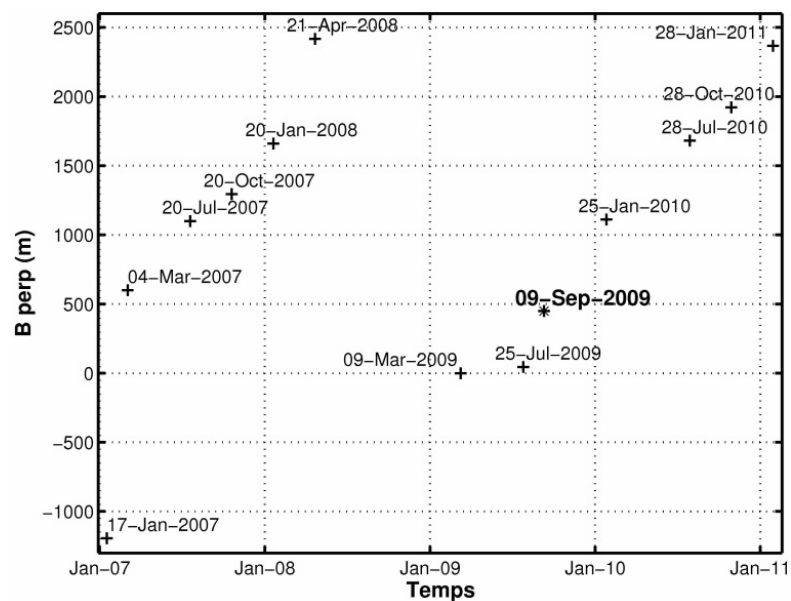


Figure 6: Morphostructural map of the Hengchun Fault : 1. Shoreline ; 2. Faults (red lines: certain faults, red dashed lines: inferred); 3: Mud-volcano ; 4: Lithological boundaries; 5: Paleo-surfaces ; 6: Chevron corresponding to tilted structural surface, 7: Fold axes; 8: Landslide and extrados faults (see Deffontaines et al., 2016B); 9: Hengchun valley alluvial and marine deposits; 10: Kenting Mélange. Note that the Hengchun Fault is made of numerous small parallel faults affecting a rather wide area of the

eastern Hengchun valley. It is associated with a N-S trending fold close to Checheng. Some folds that tilt paleosurfaces and NE-SW, E-W and NW-SE oblique faults affect the Kenting Mélange.



5 Figure 7: Available ALOS-1 SAR images and their associated perpendicular baselines. All slave images are linked to the best master image chosen in the middle of the time series that maximizes the sum correlation of all intererograms (Hooper et al., 2007).

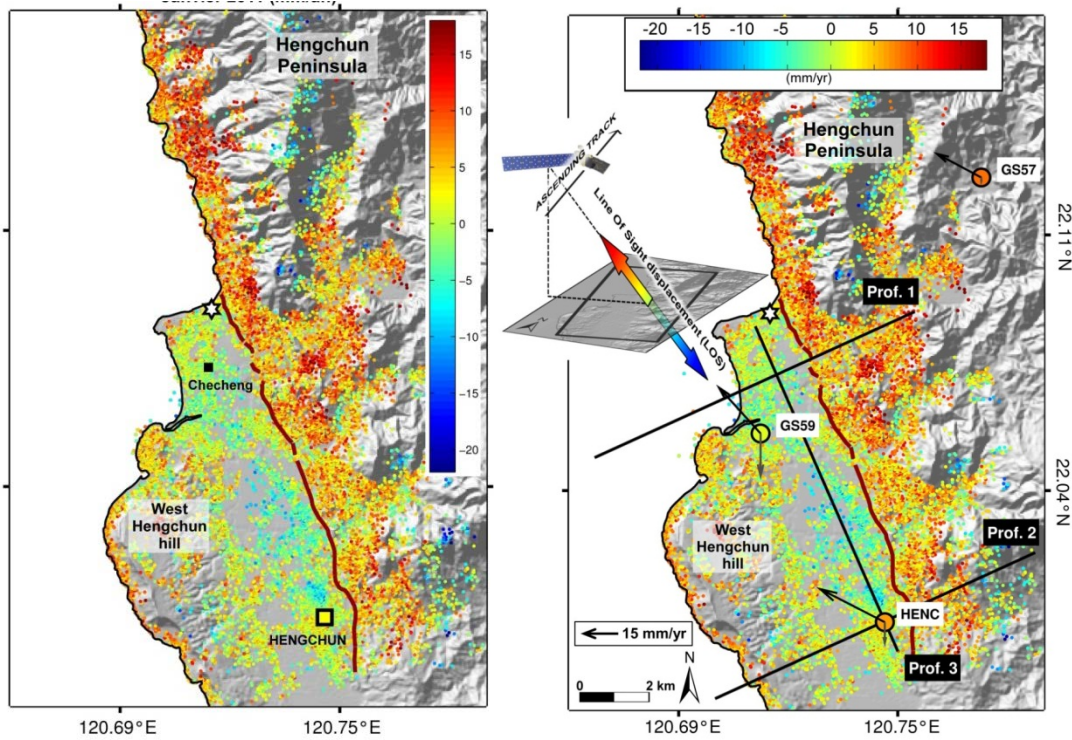


Figure 8A left, 8B right: Mean LOS velocities of PS between Jan. 2007 and Jan. 2011, superimposed to the shaded 40m ground resolution Digital Terrain Model. Right : The circles are GPS points and the color in the circles indicates their LOS velocity component. Black and grey arrows give their horizontal and vertical velocity. Red line: Hengchun Fault. Location of profiles 1 and 2 (see Fig. 10).

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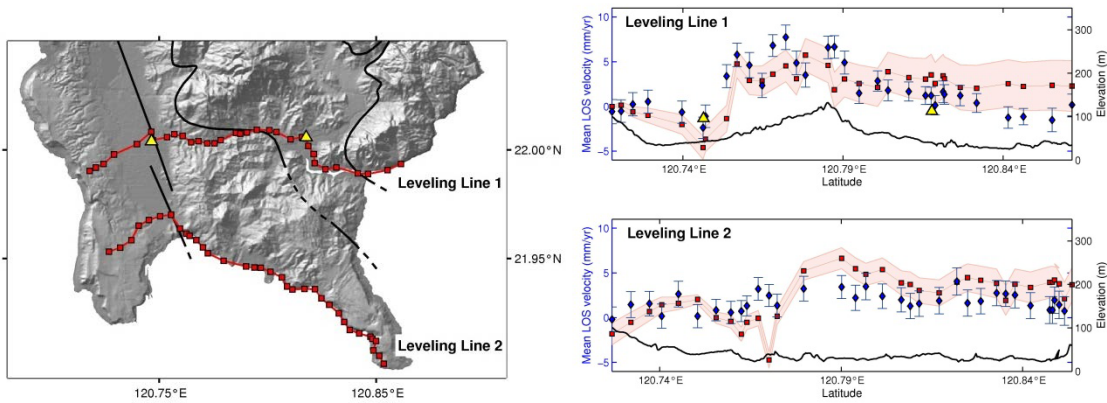


Figure 9A and 9B: A Location of the leveling lines on the Hengchun Peninsula, B associated PS mean velocity with error bars (blue dots,) leveling data (red square) and GPS stations data (yellow triangle), projected on LOS. Note the general agreement of all topographic displacement values.

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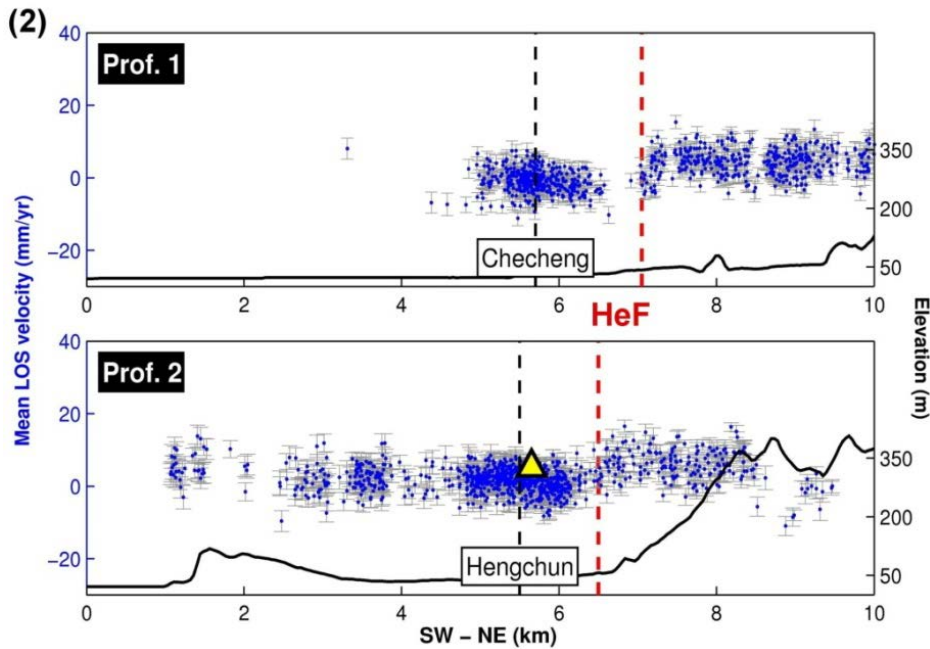


Figure 10: E-W projection of mean LOS velocity in mm/y (blue dots with error bars, E on the right) on profiles transverse to the Hengchun Valley, Black line: topography, Yellow triangle: GPS point, HeF: Hengchun Fault. Note on both profiles the LOS offsets close to  $10 \pm 2.5 \text{ mm y}^{-1}$  associated with the Kenting Mélange uplift east of the Hengchun Fault which contrast with the relatively subsiding Hengchun valley.

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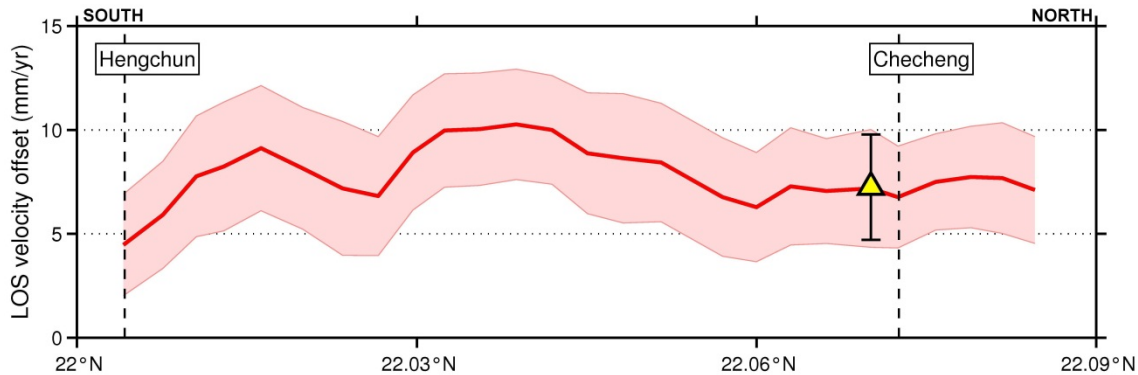


Figure 11: Hengchun Fault along strike variation of LOS velocity offset across HeF (in  $\text{mm y}^{-1}$ ) from Hengchun to Checheng cities. Note the active interseismic displacement and its northward variations which confirms that Hengchun Fault is an active Fault of Taiwan.

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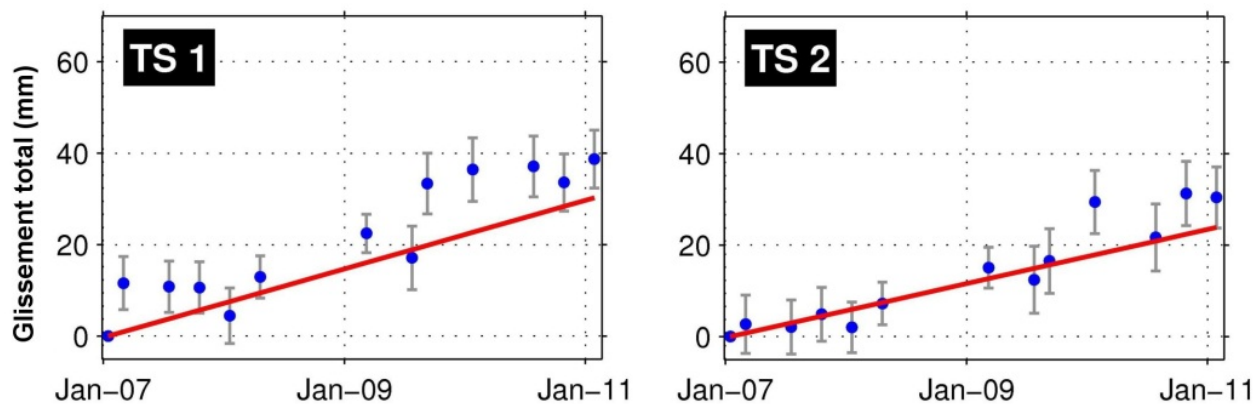
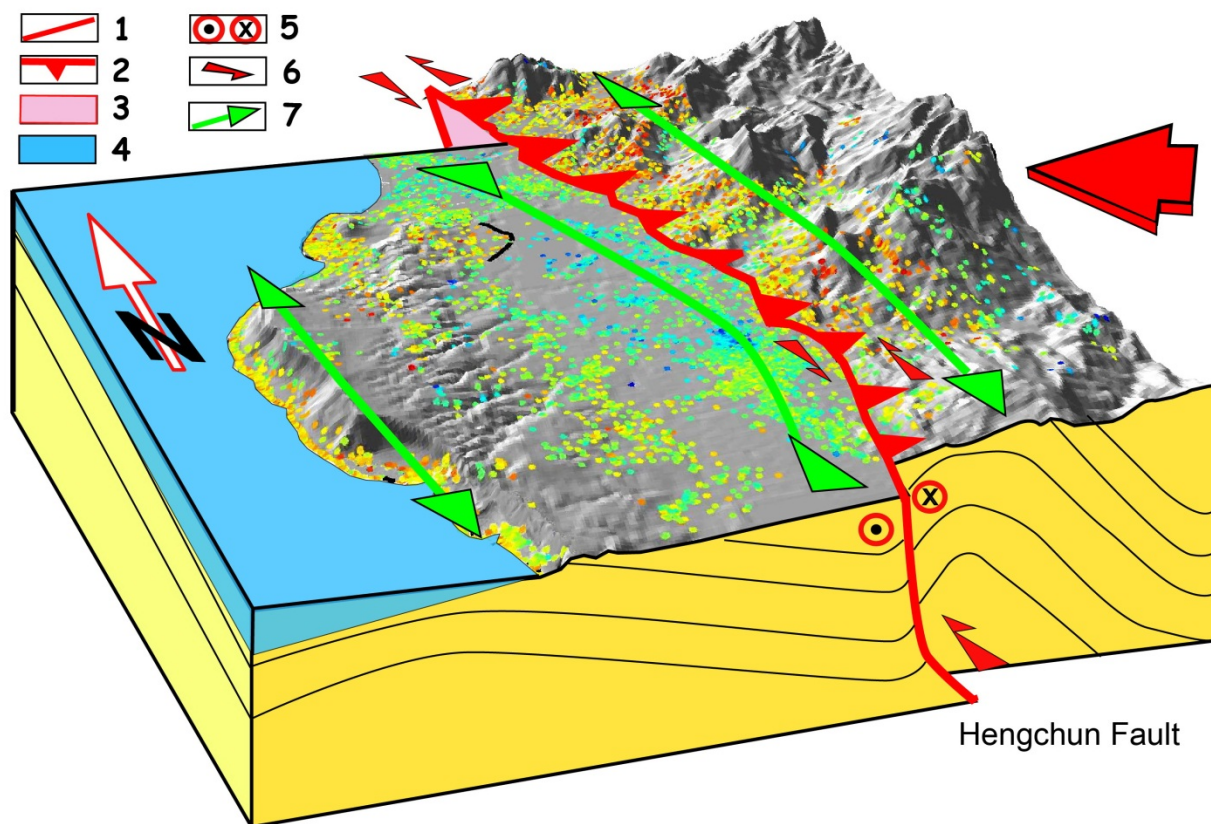


Figure 12: Time series of cumulated slip (on profiles 1 and 2) where no particular seasonal effects prevail. Further studies and PS monitoring ought to be developed in the near future to up-date and precise this aspect



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Figure 13: Simplest model of active inter-seismic tectonic deformation of the Hengchun Fault compatible with the oblique geodynamic convergence (large red arrow on the right), GPS and interferometric active displacements, and the detailed UAS DTM photo-interpretation. 1: Fault ; 2: Thrust ; 3: Fault plane ; 4: Taiwan Strait / South China Sea ; 5: Left lateral component ; 6: Transpressive left lateral component ; 7: Fold (anticline and syncline). The GPS data and PS mean LOS velocities implies that

**Hengchun Fault acts as a left-lateral transpressive strike-slip fault with an actively folding and uplifting anticline (hanging wall) contrasting with the aligned active subsidence of the syncline that trends parallel to the Hengchun Fault.**