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# Monitoring of active tectonic deformations in the Longitudinal Valley (Eastern Taiwan) using Persistent Scatterer InSAR method with ALOS PALSAR data

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#### ABSTRACT

This paper presents new observation of the interseismic deformation along the Longitudinal Valley (Eastern Taiwan) that represents a major tectonic boundary of the Taiwan collision zone. We investigate the southern part of the Valley from Rueisuei to Taitung (latitude 23.5°N-22.7°N), which is the part of the Valley where interseismic surface creep has already been observed at some points of the Longitudinal Valley Fault (LVF). A Persistent Scatterer SAR interferometry approach (StaMPS) is applied using ten L-band SAR images from ALOS satellite acquired over the period 2007-2010. Interferograms from L-Band data show a dramatic improvement of coherence in comparison to previous studies using C-Band ERS data. The density of measurement resulting from StaMPS processing is the highest achieved so far in the area (about 40–55 points per km<sup>2</sup> for a total of 77,000 points) allowing a continuous view of the deformation along the Valley and also giving information on its borders (Central Range and Coastal Range). The most striking feature of the resulting mean velocity map is a clear velocity discontinuity localized in a narrow band (0.1-1 km) along the LVF and responsible for up to 3 cm/yr velocity offset along the radar line of sight, which is attributed to shallow interseismic creep. InSAR results are in good agreement with continuous GPS measurements over the same period (0.3 cm/yr rms). The density of measurement allows us to improve fault trace map along the creeping section of the LVF (with accuracy of about 100 m) and to find new field evidences of the fault activity. In some places, our trace differs significantly (hundreds of meters) from previous published traces. The creep rate shows significant variations along the fault. At the southern end of the valley the deformation is distributed on several structures, including the Luyeh Strand, and drops significantly south of the Peinanshan. However there are discrepancies with previous studies made from ERS data over the period 1993–1999 that remain to be investigated. The mean velocity for each point of measure and the improved faults' trace are provided as Supplementary data.

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# 1. Introduction

The Longitudinal Valley is a major geological and tectonically active boundary of the Taiwan orogen. According to GPS measurements, about 3 cm/yr of horizontal shortening are accommodated across this valley (Yu and Kuo, 2001). It is considered as a collision boundary zone between the Eurasian Plate and the Luzon volcanic arc of the Philippine Sea Plate (e.g., Angelier et al., 1997; Malavieille et al., 2002), which converge at a rate of 8.2 cm/yr in the direction N306°E (Seno et al., 1993; Yu et al., 1997) (Fig. 1a). On the eastern side of this narrow valley located between the Central Range to the west and the Coastal Range to the east (Fig. 1b), the 150-km-long Longitudinal Valley Fault (LVF) accommodates a significant part of the present-day convergence (Yu and Kuo, 2001) by earthquakes up to  $M_L = 7.3$  but also by aseismic slip (interseismic creep or postseismic). Understanding the spatial and temporal variations of slip behavior, especially the part of aseismic slip, on this major fault is important for earthquake hazard assessment because it has direct implications on the seismogenic potential of the fault. Furthermore, the factors controlling the slip behavior, seismic or aseismic, are still not well understood. Such issues have already been addressed in other tectonic contexts, like strike-slip faults (e.g., Bürgmann et al., 2000b; Bakun et al., 2005) or subduction zones (e.g., Pritchard and Simons, 2006; Perfettini et al., 2010). However, the Long-itudinal Valley is a rare and valuable case-study area showing a

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Fig. 1. (a) Tectonic framework of Taiwan. Taiwan is the result of the ongoing collision between the Eurasian Plate (EUP) and the Philippine Sea Plate (PSP). The collision occurs in a double inverse subduction context: in the south-west, the EUP subducts beneath the PHP, whereas in the north-east, the PHP subducts beneath the EUP. The black arrow indicates the direction of convergence between these two plates with an estimated rate of about 82 mm/yr (Seno et al., 1993; Yu et al., 1997) (black dashed frame: location of (b)). (b) Map of Eastern Taiwan. The Longitudinal Valley, located between the Central Range and the Coastal Range, is 150 km long and maximum 7 km width. This area is the plate suture boundary between the EUP and the PSP. Red lines show major fault traces located in the Longitudinal Valley from Central Geological Survey (2006): the Longitudinal Valley Fault (LVF) with triangles pointing in dip direction, the Peinan Strand (PeS), the Luyeh Strand (LuS), the Chimei Fault (ChF) and the blind Coastal Range Fault (CRF) in dashed line. The dashed frame represents the area covered by SAR images. In background, shaded relief is extracted from the 40 m digital elevation model. On the left bottom corner, two arrows indicate the flight direction of ALOS satellite associated with ascending track, and look direction of radar (line of sight). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

well-documented active fault with a significant reverse component and where steady-state shallow creep can be observed on land.

A first important issue before interpreting spatial variations of deformation, is to know whether other faults accommodate part of the deformation across the valley. This problem is critical in the Longitudinal Valley area because several active faults are present (Fig. 1b). The Central Range Fault (CRF) is located on the western side of the valley (Shyu et al., 2006). East of the LVF, in the Coastal Range, several faults have been mapped (Wang and Chen, 1993),

amongst which the Chimei Fault seems to be a significant tectonic boundary (Chen et al., 1991); however, their present-day tectonic activity remains poorly known.

Some large instrumental earthquakes in the valley have shown that the LVF is not the only active fault. The  $M_L$  7.3 1951 sequence of earthquakes (Chen et al., 2008b) produced surface ruptures along the LVF but also along a poorly documented primarily left-lateral strike-slip fault (Yuli Fault) (Shyu et al., 2007). A few kilometers west of the east-dipping Luyeh Strand (LuS), the  $M_W$  6.1 2006 Peinan earthquake (also called Taitung earthquake) occurred at about 10-km-depth on a N–S high angle 80° west-dipping fault, which may be part of the Central Range Fault system (Wu et al., 2006; Chen et al., 2009a). Smaller earthquakes, even with precise relocation (Kuochen et al., 2004), cannot be easily attributed to known faults mapped in the valley, except for the east-dipping Chihshang segment of the LVF, especially well illuminated by the  $M_W$  6.8 Chengkung earthquake aftershocks sequence in 2003 (Wu et al., 2006; Hu et al., 2007).

Analysis of GPS data over the period 1992–1999 indicates that in the Coastal Range, north of Chihshang and east of the central and northern segments of the LVF, other faults than the LVF may accommodate the deformation during interseismic period (Yu and Kuo, 2001). At the southern end of the LVF where it splits into the Luyeh Strand and the Peinan Strand (also called Lichi Fault), there are geodetic evidences of partitioning of the interseismic deformation (Lee et al., 1998). Nonetheless, the low spatial density of the geodetic measurements does not allow identifying precisely where these faults are located and how much of the deformation they accommodate, especially during the interseismic period.

The same problem of density of measurements arises when looking at interseismic variations of slip behavior along-dip and along-strike the LVF. Along-dip, the 2003 Chengkung earthquake gave evidences (Hu et al., 2007; Hsu et al., 2009) that, at least on the Chihshang segment, the LVF shows an evolution from aseismic creep at shallow depth to stick-slip behavior at 10-25 km, where locked asperities able to produce  $M_W$  6.8 earthquake seem to coexist with creeping areas as revealed by observations of repeating earthquakes sequences (Chen et al., 2008a, 2009b). Along-strike, seismological and geodetic measurements have only been able to get the first-order variations of slip behavior along the LVF, showing a contrast between the southern Chihshang segment and the segments north of Rueisuei (Yu and Kuo, 2001; Kuochen et al., 2004; Huang et al., 2010). The shallow creep is only well-documented from the few sites instrumented by creepmeter, local geodetic network (Angelier et al., 1997, 2000; Lee et al., 2003, 2005) or repeated measurement along leveling lines (Chen et al., 2011; Ching et al., 2011). Those measurements are particularly focused on area where the deformation is localized within short distance around the fault trace (several cm/yr of shortening within a few hundreds of meters) causing damages to human made structures (e.g., at Chihshang (Mu et al., 2011) or at the Yuli Bridge (Yu and Kuo, 2001)). Away from these places, spatially continuous observations in the field are difficult due to absence of clear markers of deformation. The ground deformation can also be elastically distributed over several kilometers if the creep occurred at deeper level and if the shallower part of the fault plane is completely or partially looked. It is then necessary to have dense surface displacement measurements not only along-strike but also across-strike to catch the entire deformation signal.

Space-borne Interferometric Synthetic Aperture Radar (InSAR) techniques have the potential to dramatically improve the spatial density and continuity of surface displacement measurements, complementing GPS and ground-based measurements (e.g., Bürgmann et al., 2000a; Hooper et al., in press). Two InSAR studies on the Longitudinal Valley have already been published. A first study applied conventional Differential SAR Interferometry (DInSAR) using a stacking approach based on ERS satellites C-band data spanning the 1997-2000 period (Hsu and Bürgmann, 2006). The authors were able to confirm the first-order spatial variability of the deformation along the LVF, but only based on eight local measurements of ground displacement offset across the fault. More recently, using a larger dataset of ERS data from 1993 to 1999 through the StaMPS Persistent Scatterer Interferometry (PSI) technique (Hooper et al., 2007). Peyret et al. (2011) were able to get a more comprehensive view of the deformation in the valley with about 20,000 points of measurement. However, their density of measurement dramatically decreases in hilly areas, like in the Coastal Range on the hangingwall of the LVF fault. This makes precise mapping and interpretation of the creeping sections difficult on several parts of the fault, as well as the measurement of the ground velocity offset across the fault.

In this study, we present results from a new set of data acquired by the Advanced Land Observing Satellite (ALOS), which provide a larger density of measurement points even on hilly and vegetated area. These data, complemented by field work, allow us to address the main issues mentioned above by mapping with an unprecedented level of details the interseismic ground deformation in the Longitudinal Valley area, and by quantifying variation of creep rate along the LVF.

# 2. ALOS data and PSI method

# 2.1. Dataset

This study uses PALSAR (Phased Array type L-band Synthetic Aperture Radar) images provided by the ALOS satellite from the Japan Aerospace Exploration Agency (JAXA). A major characteristic of the PALSAR sensor is that it operates in L-band, with a wavelength ( $\lambda = 23.6$  cm) which is five times longer than the wavelength of usual C-band sensors. The PALSAR choice is justified because the previous InSAR studies in Eastern Taiwan using C-band data (Hsu and Bürgmann, 2006; Peyret et al., 2011) were limited by temporal

decorrelation notably due to a dense vegetation cover. It has been shown that ALOS L-band interferograms suffer less from temporal decorrelation even on vegetated areas than C-band ones because the longer wavelength penetrates deeper through the vegetation (Sandwell et al., 2008; Meng and Sandwell, 2010).

We considered all ALOS images available along the ascending path 445 that cover the part of the Longitudinal Valley between Rueisuei and Taitung (Fig. 1b), where the highest fault creep rates have been documented before. Images were acquired from January 2007 to February 2010 (Fig. 2) with a mean duration between each acquisition of about 3 months, with a 15 months gap in the dataset between May 2008 and August 2009 (this time gap can decrease the PS density and also the uncertainty associated to the measure of surface displacements). The chosen polarization mode for the SAR data is HH (horizontal–horizontal), which appears to provide higher performance than HV (horizontal–vertical) for InSAR studies using ALOS data (Cloude and Papathanassiou, 1998; Ge and, 2009).

#### 2.2. PSI method: StaMPS processing

Using our ALOS dataset, conventional InSAR method is able to generate differential interferograms covering 3 yrs with a high coherence not only in the Longitudinal Valley but also in the Coastal Range and the Central Range (two examples are provided in Supplementary material S1). The quality of these interferograms makes possible a precise mapping of a clear phase discontinuity that separates the Coastal Range from the Longitudinal Valley, which corresponds to the LVF activity. Nevertheless, the quantification of the deformation from such interferograms can be highly affected by atmospheric perturbations. Furthermore, only some couples of dates give such a good quality, most of the other interferograms are more affected by decorrelation effects. In order to perform a proper time series analysis of the displacements and to mitigate decorrelation and atmospheric effects, recent technigues and in particular the ones based on identification and analysis of stable radar targets, also called Persistent Scatterers (PS), have



Fig. 2. Available ascending ALOS PALSAR acquisitions. Perpendicular baselines are plotted as a function of acquisition dates. Values are given with respect to the "Super Master" image (in bold) chosen for the StaMPS processing (September 16th 2007).

.5°N

33

Range

Central ,

Fig. 5b

been developed (e.g., Ferretti et al., 2001; Hooper et al., 2007). Those techniques, relying on a set of interferograms built from SAR data acquired at different times, allow to measure displacements of specific points (presenting stable phase) at each date of SAR acquisition and over long periodof time. All interferograms are performed with a common master image with released limitations in temporal or spatial baselines, allowing in our case to use all the data even with high perpendicular baseline and large temporal difference. In PS approaches, different strategies can be used to estimate atmospheric signal and correct it, leading to higher precision of measure than with conventional InSAR. PS methods have proven to be very efficient to measure slow and small ground deformation, especially in urban environment, where density of PS is high because of the numerous man-made structures that constitute permanent and stable bright scatterers (e.g. Prati et al., 2010; Sousa et al., 2010).

In this study, the Stanford Method for Persistent Scatterers (StaMPS) developed by Hooper et al. (2007) is employed, which has proven to be reliable even in natural terrains. This method uses both information of amplitude dispersion and phase stability with time to determine which pixels can be considered as PS. Furthermore, it does not use any a priori model of deformation through time, as some PS approaches do, but it assumes that deformation and consequently the interferometric phase is spatially correlated. The StaMPS method is applied to the ALOS PALSAR dataset described previously. The main processing parameters are given in supplementary materials (S2). The image of September 16th 2007 has been chosen as the common master image of the interferograms. First, a set of nine differential interferograms was generated with this image as master reference, using ROI\_PAC (Rosen et al., 2004) and a 40 m horizontal resolution DEM. At the end of the StaMPS processing chain, we obtain a map giving for each PS its mean velocity along the radar line of sight of the (LOS velocity) over the whole period. It is also possible to reconstruct the PS time series of displacements at each acquisition date.

#### 3. Interseismic surface deformation analysis

## 3.1. PSI results

The PS mean LOS velocity map for the period 2007-2010 is shown in Fig. 3. Velocities are given with respect to the reference area which is located in the city of Yuli. A high density of measurements is obtained with more than 77,300 PS over the studied area. Two different areas can be distinguished: the southern end of the valley, near Taitung city and its surroundings, with a high PS density due to an important urbanization (more than  $\sim 55 \text{ PS per km}^2$ ), and the rest of the valley where the PS density is lower (  $\sim$  40 PS per km<sup>2</sup>) mainly due to the presence of vegetation and high topography on its borders. These density values are a real improvement compared to the Peyret et al. (2011) study using ERS data, especially in hilly areas like the Coastal Range and the Peinanshan. Regarding ground displacements, at first glance these results show clearly two blocks separated by an important discontinuity, consistent with thrusting of the Coastal Range over the Longitudinal Valley: one block with LOS velocities ranging between 10 mm/yr and 35 mm/yr toward the satellite, and a second block, with lower velocities, composed by the Longitudinal Valley and the Central Range with PS velocities between 0 mm/yr and 10 mm/yr. A more detailed analysis is given in Section 3.3.

#### 3.2. Comparison with continuous GPS data

In order to complete and validate these PSI results, a comparison with the continuous GPS (cGPS) data has been done. The island of



Fig. 5a

Fig. 3. Map of P3 mean LoS velocities (in min/y) of the southern pair of bong during Valley between January 2007 and February 2010 derived from PALSAR dataset. The velocities are relative to the mean velocity of PS pixels of the reference area represented by the white star (Yuli city). The big dots with different colors represent the cGPS stations and their LOS velocities with the same color scale as PSI results. The figure on the bottom right corner illustrates the direction of the LOS vector of displacement. The four black dashed frames indicate the location of focus presented in Figs. 5 and 6. Near Fuli, the line of sight unit vector NEU is [-0.1339, -0.6092, 0.7816]. All PS measurements and unit vectors are given as Supplementary material S3.

Taiwan is one of the most instrumented places in the world in term of cGPS monitoring. Nowadays, over its 150 km, the Longitudinal Valley is very well instrumented with 52 cGPS stations installed by different institutes (Central Weather Bureau, Academia Sinica, Ministry of Interior and National Taiwan University).

We collected data from 32 cGPS located in our study area (Figs. 3 and 4a) and we chose the IULI station as the reference in order to have a similar reference between PS and cGPS. The velocities were estimated from daily solution from 29/01/2007 to 06/02/2010. The cGPS time series were defined for each component according to equation using the least-square method as modified from Nikolaidis (2002). Based on the catalog of the Central Weather Bureau, two medium events, the 13th May 2008,  $M_W$ =5.2 inland earthquake and the 29th July 2009,  $M_W$ =5.4 Pingtung offshore earthquake occurred during the period of study, but have a limited effect on the relative displacement between our selected stations (a few mm). In the secular time series, we corrected the coseismic part of those events and got the velocities field of the period 2007-2010. Smaller seismic events that have occurred at the same period in the study area do not introduce visible offsets in the cGPS time series.

40

30

20



**Fig. 4.** Comparison between cGPS and PSI. (a) Map of location of the cGPS stations used in this study. Each station is represented by a colored circle representing the difference between cGPS and PSI velocities. Black triangle represents the reference cGPS station (located close to the PSI reference). Red lines show major fault traces presented in Fig. 1. (b) cGPS mean LOS velocities versus PS mean LOS velocities for the period January 2007–February 2010 period. The black dashed line represents the perfect correlation. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

To compare the displacements measured by PSI and cGPS, we first projected the 3D displacement vector provided by cGPS onto the line of sight (LOS) of the radar for each station. This is done using the components of the radar sensitivity vector, unit vector pointing from ground to satellite calculated by StaMPS (considering a mean azimuth angle of 12.4° and a variable incidence angle estimated at each station). As the PS density is higher than the density of cGPS stations, we estimate an average PS LOS velocity around each cGPS station by selecting all PS within a square area of 500 m by 500 m centered on each station). Uncertainty of the average LOS velocity is estimated by the standard deviation of the individual PS LOS velocities inside this area. These uncertainties range from 1 mm/yr to 3 mm/yr (Fig. 4b).

The spatial analysis of the difference between cGPS LOS velocities and PS LOS velocities showed a linear trend that is certainly due to long wavelength residual orbital errors commonly found in InSAR. We estimated the corresponding spatial trend through a least square approach, and then corrected the PSI results from it (Figs. 3 and 4b show the corrected results). This correction improved the agreement between cGPS and PS measurements decreasing the RMS difference from 8.25 mm/yr to 2.58 mm/yr, which is more consistent with the estimated individual errors on cGPS and PS measurements. The corrected PS mean LOS velocity values and their corresponding LOS vectors are given in Supplementary materials (S3).

#### 3.3. Detailed analysis along the valley

#### 3.3.1. From Rueisuei to Fuli

At the latitude of Rueisuei, north of our study area (Fig. 5a), the LOS velocity change across the LVF is distributed over 2–4 km

and do not show clear discontinuity. LOS values and the difference of cGPS velocities between the JSUI station, located on the hangingwall of the LVF, and the YULI and JULI stations located on the footwall are compatible with a thrust of the Coastal Range toward the valley and the Central Range. The smooth deformation pattern shown by the PS could be due to a distribution of slip on several small faults, branching at depth on the LVF (that could not be identified because of the too high uncertainty of the PS measurements and of the relative low density of PS west of Rueisuei). Alternatively, this could be explained by an elastic deformation related to deeper creep on the LVF occurring downdip of a shallow locked zone of the fault. Concerning the Chimei Fault, which is mapped a few kilometers east of the LVF (Fig. 1) and is only partially covered in the PS velocity map, there is no evidence of interseismic surface deformation related to it.

Southward, the LOS velocity change across the LVF increases and becomes more and more localized on the fault (Profs. 1 and 2 in Fig. 5a). North of Yuli city, close to the JULI cGPS station, deformation occurs within 200–300 m with a difference of LOS velocity higher than 25 mm/yr between the footwall and the hangingwall (Prof. 3 in Fig. 5b). In the absence of any earthquake large enough to produce such a deformation signal, it is undoubtedly related to creep occurring at least at shallow depth.

There is no evidence of interseismic surface deformation associated to the Yuli Fault that ruptures during the 1951 series of earthquakes. Its fault trace, which is roughly parallel to the LVF but located in between the CRF and the LVF, is passing through the Yuli city where evidences for a left lateral coseismic rupture exists (Shyu et al., 2007).

Between Yuli and Fuli (Fig. 5b), the spatial continuity of the deformation along that 23 km long segment of the LVF can be established. The LOS velocity offset is relatively constant at



**Fig. 5.** PS mean LOS velocity maps between north Rueisuei and north Yuli with hill-shaded DEM as background (a) and between Yuli and south Fuli (b). Big dots with different colors represent the cGPS stations and their LOS velocities with the same color scale as PSI velocities. Black and grey arrows are, respectively, the horizontal and vertical components of each cGPS stations. Black lines show update fault traces obtained with the PSI results while grey lines show fault traces from Shyu et al. (2005) (dashed where inferred) and black dots indicate the major cities. Labels F1 and F2 indicate makers of deformation found on the field and shown in Fig. 7. The black dashed lines indicate the location of the PS profiles presented below (Profs. 1–5). These profiles are perpendicular to the major segment of the Longitudinal Valley Fault (LVF) and are superimposed on the topographic profiles from a 40 m digital elevation model. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

35–40 mm/yr (Profs. 4 and 5 in Fig. 5b). Regarding cGPS measurements, the stations installed on the Coastal Range present a significant uplift and a horizontal component consistent with the direction of convergence between the Eurasian Plate and the Philippine Sea Plate. The relative velocities with the four cGPS stations on the other side of the fault indicate mainly a thrust displacement with a left lateral component.

# 3.3.2. From Fuli to Taitung

South of Fuli (Fig. 6a), in the area of Chihshang (CHIH station), shallow creep is well documented and monitored by several creepmeters installed at Tapo and Chihshang since 1998 (Lee et al., 2003). PS results show a localized deformation (Prof. 6 in Fig. 6a) that is consistent with shallow creep reaching the surface. South of Chihshang, the gradient of LOS velocity is lower across



**Fig. 6.** PS mean LOS velocity maps between south Fuli and north Luyeh with hill-shaded DEM as background (a) and between north Luyeh and the south ending of the valley (b). Big dots with different colors represent the cGPS stations and their LOS velocities with the same color scale as PSI velocities. Black and grey arrows are, respectively, the horizontal and vertical components of each cGPS stations. Black lines show update fault traces obtained with the PSI results while grey lines show fault traces from Shyu et al. (2005) (dashed where inferred) and black dots indicate the major cities. Labels F4, F5 and F6 indicate makers of deformation found on the field and shown in Fig. 7. The black dashed lines indicate the location of the PS profiles perpendicular to the major segment of the Longitudinal Valley Fault (LVF) and the Luyeh Strand (LuS) and are superimposed on the topographic profiles from a 40 m digital elevation model. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

the LVF. In some places, the total deformation appears to be accommodated not only by the LVF, but also by other structures inside the Coastal Range like around the T107 cGPS station and the T109 cGPS station (Profs. 7 and 7b in Fig. 6a). East of the T109 station, a new active fault trace is proposed. This fault may branch on the LVF and could explain the decrease in LOS velocities across the LVF close to this station. Regarding the activity of the Central Range Fault, separating the Central Range and the Longitudinal Valley, which is considered as an active but blind fault from Chihshang to the southern end of the valley (Shyu et al., 2006), there is no evidence of surface deformation in the PSI results.

In the southern end of the valley (Fig. 6b), between Luyeh and Taitung, the mean LOS velocity map reflects a more complex tectonic setting. The deformation is accommodated on several active structures surrounding the Peinanshan Mountains (Profs. 8 and 9 in Fig. 6b). The density of measurements over the Peinanshan is enough to detect that no clear discontinuity of displacement occurs inside it. Near Luyeh, the LVF seems to split into several faults. South-East of the LONT station, a clear active NE-SW structure connects the Coastal Range to the Peinanshan, crossing the valley (Prof. 8 in Fig. 6b). Further west, a significant gradient of LOS velocity appears at the eastern boundary of the Central Range that corresponds to the LuS (Profs. 8 and 9 in Fig. 6b). It may be continuous over more than 25 km extending to the south into the Taitung basin (Prof. 10 in Fig. 6b). Deformation also occurs east of the Peinanshan, on the Peinan Strand. These observations are in agreement with a partitioning of the deformation on the Luyeh and Peinan Strands proposed by Lee et al. (1998). South of the Peinanshan a slight N-S gradient of LOS velocity seems to outline the south termination of a Coastal Range block with respect to the Taitung Basin (Fig. 6b). In this transition zone, two north-south profiles (see Supplementary material S4) show a progressive decrease of mean LOS velocities over more than 5 km with no clear discontinuity as observed across the Luyeh Strand. However, changes in the horizontal component of three cGPS stations (PEIN, TTUN and TTSK) indicate a rotation to the south west with respect to the stations in the Coastal Range. This implies some extension between the Coastal Range block and the Taitung basin and indicates a distinct behavior of the Taitung basin relative to the Coastal Range.

# 3.4. Fault mapping and field evidences

One aim of this study is the precise mapping of the active tectonic structures in the valley. Several previous studies have established structural maps of the Longitudinal Valley at different scales (Lee et al., 1998; Chang et al., 1998; Shyu et al., 2005). The Central Geological Survey Taiwan (CGS) published the first edition of active fault map of the island of Taiwan in 1998 with a 1/500,000 scale (Chang et al., 1998). Since this date, the map has been regularly updated while improving the scale. A recent version of the active faults map from the CGS dates 2006 (Fig. 1b). In 2005, Shyu et al. (2005), based on field work and geomorphological analysis of shaded relief maps, drew up a new map of active faults in Eastern Taiwan (Shyu et al., 2005) improving the scale of the CGS map.

Independently of these previous studies, we combined both information derived from single differential interferograms and PSI results to map the location of shallow creeping sections of the faults. We used two differential interferograms in complement to PSI because, in several places, these interferograms (with baselines lower than 70 m) including a large surface deformation signal (integrated over 3 yrs) highlight the location of the LOS velocity discontinuity with a greater spatial accuracy than the PSI results (see Supplementary material S1). The resulting fault traces (shown in Figs. 5 and 6 and provided in Supplementary material S5) can be compared to the map of Shyu et al. (2005). The traces look very similar at a regional scale where for its major part the LVF follows the basal relief of the western side of the Coastal Range. However, several portions of our LVF trace are located up to several hundred meters further west in the valley (comparisons between the PSI fault trace with the one of Shyu et al. (2005) are given as Supplementary material S6). Since the LVF trace runs along the Hualian, Hsiukuluan, and Peinandachi rivers, its morphological signature can be eroded or hidden beneath recent fluvial deposits (Chen et al., 2007). This can lead to positioning error when only geomorphological approach is used.

Two field trips have been conducted in our study area to find new evidences of deformation near the LVF and the Luyeh Strand in order to validate PSI fault traces. Near Yuli city (Fig. 5b), two adjacent bridges are affected by the activity of the LVF as documented by Yu and Kuo (2001) from geodetic measurements. However, the fault line from Shyu et al. (2005) is located about 1 km further east at the foot of the Coastal Range. Precise location of the bridges deformation in the field (between the second and the third pillars, F1 in Fig. 7) are actually in agreement with the location of a shallow creeping section revealed by the PS results, which show at that place a clear LOS velocity offset of about 2.5 cm/yr. PS results do not show surface deformation further east (Fig. 5b).

Southward, guided by the PSI map, we found an evidence of activity along a concrete dike situated north of Fuli city (Fig. 7, F2). The dike, perpendicular to the fault, shows clear marks of compression. At this place, the LOS velocity offset is about 2.5 cm/yr. Between Chihshang and Luyeh (Fig. 6), we found another nice field evidence of the active thrust fault affecting a dike (Fig. 7, F3), that is exactly located on the fault trace mapped from PSI.

South of the valley, near Luyeh and Taitung (Fig. 6b), the PSI fault trace map shows significant differences from the previous maps. One of the most interesting active structures visible on the PSI map connects the Coastal Range to the north of the Peinanshan. Actually, it exists in the PSI map an important discontinuity (about 1.8 cm/yr) but no interpretation on the nature of this structure can be made with these results. Previously this structure was identified with uncertainty as an anticline (Shyu et al., 2008). Regarding the Luyeh Strand located west of the Peinanshan, its activity is visible on the PSI results and also in the field. Along the fault, we found three markers of deformation in recent human-made constructions (Fig. 7, F4, F5 and F6), less important than those shown close to the LVF but indicating fault activity. Concerning the Peinan Strand, the PSI results show also differences with previous maps. Its traces seem more complicated with several possible active segments, certainly one at the eastern boundary of the Peinanshan and one at the western boundary of the Coastal Range. The southern termination of the Peinan Strand is often supposed to continue within the Taitung basin (e.g., Lee et al., 1998; Shyu et al., 2008), however the PSI map suggests that the E-W gradient of LOS velocity stops against the basin and turn into a more gentle N-S gradient along the south end of the Peinanshan and of the Coastal Range (Profs. 11 and 12 in Supplementary material S4). In contrast, the Luyeh Strand may continue southward, following the eastern side of the Central Range along the western side of the Taitung basin (Prof. 10 in Fig. 6b).

### 4. Shallow creep rate estimation

First order spatial variations of shallow creep activity have been shown by other geodetic studies (especially from GPS and InSAR), with creep rates changing according to the latitude (Hsu and Bürgmann, 2006; Peyret et al., 2011). The unprecedented spatial resolution of the map of mean LOS velocities and the new derived fault trace of this study allows us estimating more accurately the spatial variations of shallow creeping activity along the LVF and the Luyeh Strand. In order to examine the spatial variation along these faults, we created a set of 58 close profiles across the fault lines. We used an N20°E axis to create these series of orthogonal profiles every 2 km from Rueisuei to Taitung. All profiles include the PS located inside a 1 km by 8 km band and projected onto the profile. A subset of ten representative profiles is presented in Figs. 5 and 6.

We choose to quantify the LOS velocity offset (LOSVO) across the fault to give information on the creep activity of the fault. All profiles have a good quality, allowing us to separate the LVF and the LuS. But, regarding the Peinan Strand, the trace is not clear

# **Longitudinal Valley Fault**



**Fig. 7.** Field evidences of tectonic activity over the Longitudinal Valley. F1, F2 and F3 are deformations connected to the Longitudinal Valley Fault (localized on Figs. 5b and 6a). F1 is the Yuli Bridge where the eastern part is uplifting contrary to the western part which is quite stable. F2 is localized north to Fuli, while F3 is localized north to Luyeh with a clear deformation affecting the dike. In this place, the deformation on the lower part of the dike shows clearly the thrust component of the fault displacement and the upper part is affected by a back thrust. F4, F5 and F6 are associated with the Luyeh Strand and present less important deformations (localized in Fig. 6b).

20 cm

enough in the PSI results to lead to a proper measurement and interpretation.

40 cm

To calculate the velocity offset between both sides of the fault, we separated the hangingwall and footwall according to the fault trace. A linear regression is first performed on each side. The LOS velocities for both sides are then computed at the fault trace and used to estimate the LOS velocity offset across the fault. We propagate the uncertainty by simply summing the two Root Mean Square values of LOS velocities estimated on the hangingwall and footwall sides.

The LOS velocity offsets are estimated on both LVF and Luyeh Strand with the use of 43 profiles and 17 profiles, respectively. These measurements are analyzed according to the latitude (Fig. 8). Concerning the LVF, LOSVO can be estimated between Rueisuei and north of Luyeh, ranging from 1 to 3.2 cm/yr. From north to south, the LOSVO increases rapidly between Rueisuei and Yuli with a quasi linear trend, followed by a stable segment until Fuli (LOSVO is about 2.6 cm/yr). The first maximum is localized south of Fuli. After this place, the LOSVO is decreasing until the south of Chihshang where we decided to estimate the total offset across both present structures (Prof. 7 in Fig. 6a). The LOSVO continues to decrease down to 1.3 cm/yr, corresponding to the place where we identify another potential active fault inside the Coastal Range (Prof. 7b in Fig. 6a). In this case, for the LOSVO estimation across the LVF, we exclude the part of the profile east of this fault. Part of the deformations is accommodated by this second fault system within the Coastal Range which is responsible for about 8-10 mm/yr of additional LOSVO. North of Luyeh, the LOSVO shows a second maximum up to 3 cm/yr. Another decrease can be observed just before the complex tectonic setting of the south end of the valley, where we decided to measure offsets on the Luyeh Strand only. The Luyeh Strand presents an increase of the LOSVO from North to South, reaching 1.4 cm/yr close to the Peinanshan over more than 5 km. The LOSVO slowly decreases along the Taitung basin and becomes stable with a rate of 0.5 cm/yr.

50 cm

In addition, velocity offsets are estimated from cGPS data in five places where appropriate pairs of cGPS stations can be found,



**Fig. 8.** Spatial evolution of LOS velocity offset (in mm/yr) across the Longitudinal Valley Fault (red line) and the Luyeh Strand (blue line). Triangles represent estimated LOS velocity offset from couple of nearby cGPS stations localized on both side of the faults. The magenta and yellow triangles are those associated with the LVF. The yellow one corresponds to a non-optimal cGPS configuration where one of the cGPS station is too close to the LVF and then do not measured the whole deformation of the hanging wall which is distributed over 2 km in that place. The blue triangle is associated with the Luyeh Strand. Profiles presented in Figs. 5 and 6 are represented by red and blue dashed lines. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

one across the Luyeh Strand and the four others across the LVF (triangles in Fig. 8). Estimation from the pair of cGPS stations T110 and LONT across the Luyeh Strand is in good agreement with PSI LOS velocity offset estimations. On the LVF, three estimations (corresponding from north to south to the pairs T105-T103, TAPE-TAPO and KUAN-T109) are also in agreement with the rates estimated from PS profiles. Offset estimated from the pair S105 and ERPN, is lower than the total velocity offset given by PSI. This can be explained by the location of the ERPN station which is too close to the fault on the hangingwall and do not encompass all the deformation.

This LOSVO profile in Fig. 8 should reflects spatial variation of fault creep rate: an increase of LOSVO can indicate a higher shallow slip rate. However, it can also mean a change of the fault slip orientation modifying the projection of the surface displacement along the radar line of sight. For example, given a fixed slip rate, an increase of the left-lateral component with a decrease of the reverse component will result in a smaller apparent LOS velocity offset (see geometry of the radar line of sight in Fig. 3). At least, the LOSVO gives a minimum shallow creep rate quantification.

### 5. Discussion

### 5.1. Spatial variation of creep

Changes of the along-dip distribution of shallow creep seem to occur along the LVF when considering the change of distance that is needed to reach the complete LOS velocity offset along our profiles. This parameter characterizes whether the deformation is diffused or localized near the fault trace. For instance, profiles 2 or 3 (Fig. 5) are showing deformation localized within a few hundreds of meters, contrasting with profile 5 where the deformation is distributed over 1-2 km, which suggests a deeper shallow creep not reaching the surface. Even in places where there are field evidences that the creep reaches the surface, splay faults branching on the LVF near the surface can cause distributed deformation, like at Chihshang where a three fault branches coupled with a 50-60-m-wide pop-up structure is observed in the hangingwall (Mu et al., 2011). This could occur at larger scale, like at the latitude of GPS station T109 (Prof. 7b in Fig. 6a) where a secondary fault located a few kilometers east of the LVF accommodates part of the deformation.

In any case, such narrow zones of deformation across the LVF (less than a few kilometers) indicate that creep occurs at least within the first kilometers of the crust and continuously from Rueisuei to the Peinanshan (Fig. 3). The velocity offsets across the LVF measured along the radar line of sight range from 1 to 3 cm/yr. They are relatively constant between Yuli and Fuli but more variable south of Fuli (Fig. 8). These variations can be explained (1) by the presence of secondary faults in the hangingwall, (2) by change of the slip rake depending of the left-lateral component of the slip, or (3) by a variation of the creep rates. It is difficult to discriminate between the last two possibilities because we only have measurement along one line of sight and because of the scarcity of the cGPS station in the area.

At its southern end, the LVF is divided into several active structures. The Luyeh Strand is passing west of the Peinanshan and have the same N20°E orientation as the LVF. Further south, the continuity of the Luyeh Strand along the eastern border of the Taitung basin may be questioned. Peyret et al. (2011) propose that the Luyeh Strand rather wraps around the south of the Peinanshan turning in E-W direction toward the sea. It is true that the Peinanshan is showing high LOS velocity values with respect to the footwall of the LVF and that the velocity decreases rapidly southward in the Taitung basin. However, this decrease is without clear discontinuity in contrast with the eastern border of the Taitung basin (see profiles 11 and 12 in S4 compared to profile 10 in Fig. 6). In any case, from a cinematic point of view, GPS and InSAR data show that the Taitung basin is a distinct unit from the Coastal Range and the Central Range. This supports the tectonic interpretation of Malavieille et al. (2002) who propose the existence of a geological major transfer zone of deformation at the latitude of Taitung delimitating the southern limit of a Coastal Range block overthrusting the Central Range to the west and backthrusting onto the Huatung Basin to the East.

At the northern end of the studied area, near Rueisuei, LOS velocity offset vanishes slowly and is more and more distributed suggesting a disappearance of the shallow creep. To explain such a change which seems to persist in the northern part of the Longitudinal Valley, some authors have proposed a correlation between shallow creep occurrence and presence of unconsolidated sediments of the Lichi mélange formation which is present along some creeping segments of the LVF (e.g., Angelier et al., 2000; Lee et al., 2006; Hsu et al., 2009). This explanation deserves further investigation, taking into account the improved fault map proposed in this study.

## 5.2. Comparison with previous InSAR studies

Comparison of ALOS interferograms with ERS ones published by Hsu and Bürgmann (2006) show the improvement of using L-band data in term of coherence. The density of measurement is also improved compared to the previous study of Peyret et al. (2011), which was also using the StaMPS software, but based on ERS data between 1993 and 1999. Density of PS is particularly increased over the Peinanshan and the Coastal Range.

Nonetheless the comparison of the spatial variation of velocity offset between our study and that of Peyret et al. (2011) shows significant differences. Comparing the LOS velocity offsets values along the LVF derived by the two studies, a major difference can be observed between Fuli and Yuli. For ascending ERS acquisition, offsets are between 0 and 1.0 cm/yr whereas the present study gives a mean offset of about 2.6 cm/yr. More generally, offsets are much lower with ERS results than with ALOS ones. The geometry of acquisition of ascending ERS data is slightly different from the ascending ALOS data used in this study, essentially by the incidence angle which is higher in ALOS data (about 38° versus 23°). However, this cannot explain more than a few millimeters of difference.

Another reason could be the different period of study. Indeed, we presented measures of deformation spanning January 2007–February 2010 period, whereas Peyret et al. used data covering the period between June 1993 and June 1996 for ascending data. No significant earthquakes occurred during both periods, but in between, important seismic events have occurred like the major  $M_W$  7.6 Chi–Chi earthquake (21st of September 1999, in the western part of Taiwan), the Ms 6.5 Chengkung earthquake (10th of December 2003) and the  $M_W$  6.1 Peinan earthquake (1st of May 2006) (Chen et al., 2009b). All these events may have affected faults activity and modified creep rates.

The 2003 Chengkung earthquake did not produce coseismic offset in creepmeters but induced a sudden increase of creep rate that decayed with time (Chang et al., 2009). This postseimic perturbation lasted up to 2006. In 2007–2009 creepmeters tend to be back to the interseismic rate (Mu et al., 2011). Noteworthy, the interseismic shortening rate of the creepmeters has also shown variation before the 2003 earthquake, slowing down from 2.7 cm/yr to about 2 cm/yr from 1993 to 2003 (Lee et al., 2005). However, the variation observed in the creepmeters between the periods 1993–1996 and 2007–2009 seems too small to explain the difference between the ERS and ALOS result, but possible temporal variations should deserve further investigations.

# 6. Conclusions

Our results show that Permanent Scatterer Interferometry using ALOS L-band data brings a significant improvement to interseismic ground displacement measurement in the Longitudinal Valley and the Coastal Range, especially in terms of point density, compared to previous studies using ERS C-band data or GPS networks.

The density of measurement allowed us to map with an unprecedented level of details the fault traces leading to the discovery of new field evidences of the LVF and Luyeh Strand present-day activities. These results should have direct implications for improving the ground-based monitoring of the creeping faults and to provide new relevant sites to augment the cGPS network.

Our results demonstrate the continuity of the shallow creep along the Longitudinal Valley Fault from Rueisuei to the Peinanshan. No evidence of shallow creep has been found on the Chimei Fault, on the Yuli Fault or on the western border of the Longitudinal Valley along the Central Range Fault. However, some secondary faults on the hangingwall of the LVF have been found to accommodates part of the interseismic deformation. PS results also show the present-day activity of a NE-SW segment connecting the Coastal Range to the Peinanshan.

The shallow creep along the LVF shows along-dip and along strike variations indicating that the mechanical behavior of the LVF is clearly not uniform. The new set of measurement provided by this study (available in Supplementary materials) should be determinant to perform a joint inversion of the slip distribution using all the available geodetic data, and useful for testing parameters controlling the slip behavior of the LVF. In this respect, the need of a temporal monitoring of the creep by InSAR overs tens of years with a better temporal sampling appears to be an important issue.

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# Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org.10.1016/j.epsl.2012.05.025.

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