# Uplift of Tainan Tableland (SW Taiwan) revealed by SAR interferometry

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**Abstract.** Interferometric processing of five SAR-ERS images reveals uplift of the Tainan Tableland (SW of Taiwan) during the period 1996-1998. The maximum measured ground motion for these two years is 2.8 cm along the radar line of sight towards the satellite, indicating for the displacement vector a vertical component of 3.2 cm, and a horizontal component of 1.6 cm towards the WSW considering additional information from GPS data. The reconstructed displacement field is consistent with the geological interpretation of the Tainan Tableland as an actively growing anticline connected to the Taiwan fold-and-thrust belt. This implies that the deformation front is located farther west than usually assumed in the Tainan area. The large Tainan city is thus located in an active deformation zone. Seismic hazard assessment is however difficult because the mechanisms and kinematics are not known in detail.

## 1. Introduction

The Tainan area belongs to the coastal plain of southwestern Taiwan. Until recently, this domain was considered as a relatively stable foreland in the front of the Taiwan fold-and-thrust belt well documented East of the Tainan Tableland [*Gong et al.*, 1995]. Some authors have however proposed that the elongated tableland on which the Tainan city was built results from recent folding and uplift [*Deffontaines et al.*, 1997; *Lacombe et al.*, 1999]. If this is correct, the Tainan Tableland belongs to the active deformation front, rather than to the stable foreland. As Synthetic Aperture Radar interferometry (InSAR) allowed successful reconstruction of earthquake deformation, volcano inflation or deflation and dyke intrusion, landsliding or subsidence [*Massonnet and Feigl*, 1998; *Amelung et al.*, 1999], we used it to determine the present-day ground deformation in the Tainan area.

## 2. Geological setting

In the Taiwan collision zone, fast convergence occurs between the Philippine Sea plate to the East and Eurasian plate to the West [8.1 cm/yr, [*Yu et al.*, 1997]] (fig. 1a). Onshore, most of the Taiwan belt is an accretionary prism resulting from plate collision since about 5 Myr [*Ho*, 1986]. The Tainan city (1.2 million inhabitants, $4^{th}$ city of Taiwan) is located in the coastal plain of SW Taiwan, between the continental shelf of South China to the West (the Taiwan Strait) and the collision belt to the East. The N070°E trending Tainan Basin extends onshore in the coastal plain where it is filled with pre-Pliocene sediments of the passive margin and overlain with siliciclastic sediments of the Pliocene and Quaternary, linked to the growth and erosion of the Taiwan belt. The recent geological evolution of SW Taiwan was controlled by the position of the advancing orogenic front. East of Tainan, the Meilin thrust was regarded as the deformation front of the SW Taiwan fold-and-thrust belt [*Lee et al.,* 1993, 1995; *Gong et al.,* 1995](fig.1b).

In the Tainan area, the coastal plain, generally flat lowland, exposes Holocene coastal deposits. At the Tainan city sandy sediments cover a structural high: the major part of the city is built on a 30 m high elongated tableland, 12.5 km long and 4 km width with a N020°E trending axis (fig. 2a). The Tainan Tableland shows a westward convex shape and an east-west asymmetry, its western part dipping gently westward, while the eastern one is being steeper. The central area shows a 2 km wide flat top. Based on analyses of aerial photographs, *Sun* [1964] described the eastern edge of the Tainan Tableland as a N020°E trending fault with the downthrown block to the East corresponding to the Tawan Lowland. Later, *Hsieh* [1972] interpreted the Tainan Tableland as an anticline above a diapir. *Lee et al.* [1993, 1995] considered this area as an uplifted block bounded by two normal faults, corresponding to an extensional feature of the offshore Tainan basin. In contrast, *Deffontaines et al.* [1997] and *Lacombe et al.* [1999] proposed to consider this tableland as the surface expression of a ramp anticline above a west-verging thrust, like a pop-up system (fig. 3b). According to this interpretation, this anticline represents part of the deformation front of the Taiwan belt, farther west than the Meilin thrust. This is consistent with the offshore location of the deformation front SW Tainan suggested by *Liu et al.* [1997] (fig. 1b).

## 3. SAR interferometry

### 3.1. Data acquisition and processing

Because of its large urban surface, Tainan area does not suffer from INSAR coherence loss, usually observed in tropical countries like Taiwan [*Fruneau and Sarti*, 2000]. We used the 2-pass InSAR approach which combines a pair of images of the same area acquired at different times (by the satellites ERS-1 and ERS-2 operating with a 56mm wavelength) with topographic information [*Massonnet and Feigl*, 1998]. The interferograms were processed by the DIAPASON© software of the French CNES (National Centre for Spatial Studies). The topographic contribution was removed using a

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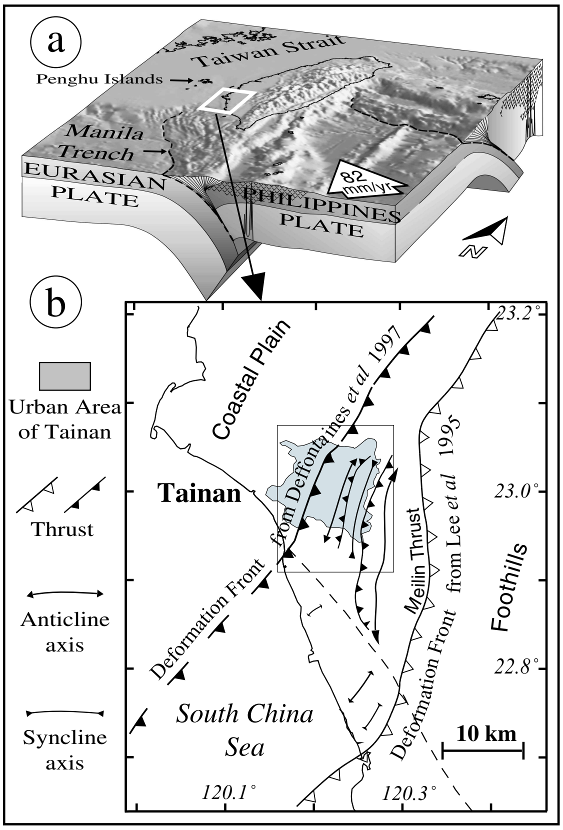


**Figure 1.** a) Taiwan geodynamical setting. b) Southwestern taiwan geological structural setting. Inferred deformation front position according to *Lee et al.* [1995] (white triangles) and according to *Deffontaines et al.* [1997] (black triangles). Box shows the extent of figure 2.

80 m x 80 m Taiwanese digital elevation model (DEM) with a 5 m average height accuracy retrieved from 1:10000 topographic maps. We selected five images (table 1), suitable for ten interferometric combinations. The time interval of 2 years (1996-1998) is sufficient to detect a deformation signal and short enough to maintain the phase coherence of the ground surface. The values of the altitude of ambiguity *(ha)*, i.e. the DEM error required to generate one interferometric fringe, range from 57 m to 14094 m.

## 3.2. Results

The six long-term interferograms (A-D, A-E, B-D, B-E, C-D and C-E) reveal the same significant fringe (i.e. one colour cycle) pattern, illustrated in figure 2b and 2c, whereas no significant signal is detected in the four short-term interferograms (A-B, A-C, B-C and D-E). The pattern of the fringe is especially highlighted by the red band which roughly follows the outline of the Tainan Tableland, except in the South West where the phase coherence is lost (fig. 2). Note that the noisy aspect of interferogram B-D is caused by atmospheric artefacts on the image D which affect every interferogram using this image. As shown by narrower colour bands, the gradient of phase difference is steeper at the periphery than on the Tainan Tableland.

A fringe corresponds to a phase variation of $2\pi$ radians that depicts displacements at sub-wavelength accuracy in the radar line of sight, unmodelled topography and possible artefacts of atmospheric origin. Topographic effect can be regarded negligible because interferograms having very different ha values show the same fringe pattern (fig. 2). Possible atmospheric effects deserve attention ; they may appear when the atmospheric conditions during the two image acquisitions differ enough to modify the propagation delay of electromagnetic waves [*Zebker et al.*, 1997]. Similarity between fringe pattern and relief, related to atmospheric

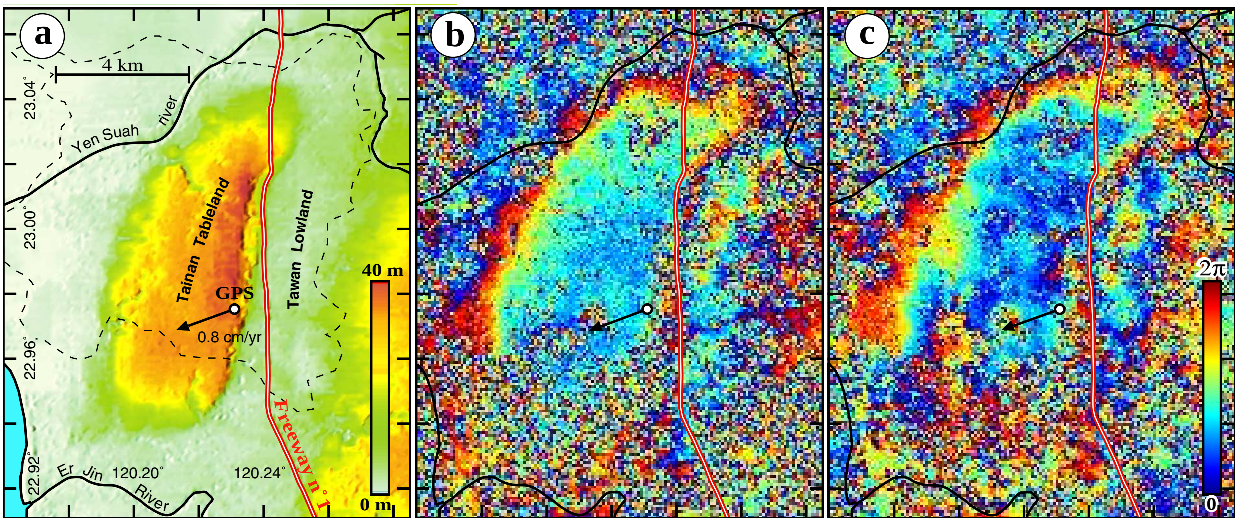


**Figure 2.** a)Topography and shaded relief of the Tainan area. b) Interferogram A-E (701 days, ha=-1141m). c) Interfergram B-D (665 days, ha=57m). Both independent interferograms AE and BD having different ambiguity altitude values show one fringe which well agrees with the outline of the tableland. The fringe indicates an uplift of the Tainan Tableland in the 2 years time interval. The noisy aspect of interferogram BD is due to atmospheric artefacts on image D. Hydrography and coastline are in black thick line, the white circle with arrow represents I004 GPS station and its displacement. Dashed line represents the outline of the urban area of Tainan.

effects, may appear where topography contrasts are strong, such as for the Etna volcano [*Beauducel et al.*, 2000]. The very low topography of the Tainan Tableland cannot produce such an atmospheric effect. Using the pair-wise logic developed by *Massonnet and Feigl* [1998], we compared independent long-term interferograms having no common images and obtained the same fringe pattern (fig. 2). The probability that a same change in atmospheric state occurs exactly between the two image acquisitions of the independent interferograms is very low; moreover, the fringe appeared only in the long-term interferograms, not in the short-term ones. We conclude that the signal represents ground deformation.

An interferogram provides only relative value of displacement along the radar line of sight. A fringe corresponds to a range change of 2.8 cm along this line between ground and satellite. Assuming a null range change for the phase-coherent zone NW of the Tainan Tableland (dark blue, upper left-hand corner of figure 2b), we found out that the Tainan Tableland was getting closer to the satellite between 1996 and 1998 passes, with a maximum range change of 2.8 cm reached at the middle of the tableland (dark blue area in the middle of figure 2b and 2c). It is reasonable to extrapolate this deformation to the southern part of the relief where coherence is lower.

### 3.3. Comparison with other sources of information

In order to estimate the vertical displacement of the Tainan Tableland, we consider additionnal information from GPS data. One station of the Taiwan GPS network (I004, triangle in figure 2) is located on the Tainan Tableland, close to our largest range change zone. At this station, the East and North velocity components are -0.76 and -0.27 cm/yr, respectively [*Yu et al.*, 1997]. These horizontal components of displacement are given relative to the Penghu Islands in the stable foreland of the Taiwan Strait (fig. 1). Considering both the range change of 2.8 cm revealed by interferometry and the unit vector from ground to satellite (east=0.28, north=-0.03, up=0.96), we computed the vertical component of displacement near the GPS station, that is 3.2 cm of two years uplift from 1996 to 1998. This implies the reasonable assumption that insignificant motion occurs between the coastal plain NW of Tainan and the Penghu Islands (the general pattern of GPS displacements indicates velocities that rapidly decrease from SE to NW).

**Table 1.** Left: SAR ERS Images (ERS-1 for A, ERS-2 for others) with orbit number and date of acquisition (local time is 2:31 AM, track 232, frame 3141). Right: Interferograms with altitude of ambiguity *(ha)* and interval of times.

| Images | | Interferogramms | | |
|---|---|---|---|---|
| Orbite | Date | | ha(m) | time(day) |
| (A) 23767 | 31-jan-96 | A-B | -89 | 1 |
| (B) 4094 | 01-feb-96 | A-C | -1241 | 71 |
| (C) 5096 | 11-apr-96 | A-D | 160 | 666 |
| | | A-E | -1141 | 701 |
| | | B-C | 96 | 70 |
| | | B-D | 57 | 695 |
| | | B-E | 97 | 700 |
| | | C-D | 142 | 595 |
| (D) 13613 | 27-nov-97 | C-E | -14097 | 630 |
| (E) 14114 | 01-jan-98 | D-E | -140 | 35 |

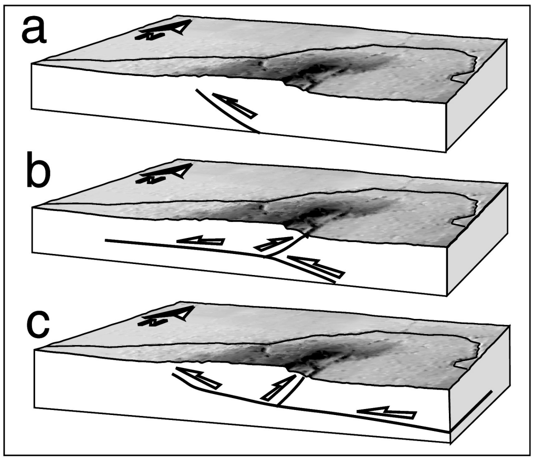


**Figure 3.** Three schematic structural models of the Tainan Tableland. a) Blind thrust model. b) Fish-tail model. c) Pop-up model.

In comparison, preliminary assessment of the vertical motion of the I004 station gives a 1.26 cm/yr uplift (S. B. Yu, personal communication, 2000). *Chen and Liu* [2000] show that their data, based on radiocarbon ages and relative sea-level curves, are consistent with an 0.5 cm/yr uplift of the Tainan Tableland since 10,000 years. Furthermore, they show a 0.1 cm/yr subsidence in the Tawan Lowland, a small depression east of the Tainan Tableland (fig. 2). This phenomenon is present on all our long term interferograms (less than one fringe with a 3 km elongated concentric pattern located on the Tawan Lowland, see fig. 2). We also collected field data in and around Tainan city, paying particular attention to cracks in buildings. Because most buildings were built later than 1950 and the deformation is spreaded out throughout Tainan city, we found few evidences for present-day deformation (west of Tainan city, North of the Tai-Pin bridge on the Yen Suah River): a concrete floor in front of a warehouse affected by tension fractures and a narrow concrete bridge which is broken are consistent with present-day tectonic compression generating uplift. All these independent results concur to indicate present-day uplift of the Tainan Tableland.

## 4. Discussion

A crucial problem deals with mechanism and kinematics of deformation revealed by our Insar analysis. *Chen and Liu* [2000], from Hsieh's hypothesis [1972], advocate for a diapir origin of the Tainan Tableland. Diapiric phenomena certainly occur offshore [*Liu et al.*, 1997] and onshore in southwestern Taiwan where thick late Cenozoic mudstone formations are present. However, these phenomena do not occur alone and they are closely related to compressive tectonics. The existence of present-day compression is evidenced by GPS-measured shortening between the Tainan station and the Penghu Island of the Taiwan Strait [*Yu and Chen*, 1998]. The N020°E trending axis of the tableland, parallel to the major structures of the collision belt, also suggests a structural control. We conclude that although diapirism cannot be excluded in the Tainan Tableland, compressive tectonics and horizontal shortening certainly control its development. Therefore, our results suggest that the Tainan Tableland belongs to the active fold-and-thrust belt, as proposed by *Deffontaines et al.* [1997] and *Liu et al.* [1997].

The uplift of the Tainan Tableland revealed by our InSar analysis cannot be of co-seismic origin because no earthquake with a local magnitude larger than 4 has occurred from 1996 to 1998 in the Tainan area (according to data of the Central Weather Bureau of Taiwan). Note that because of the concentric pattern of interferometric fringes, the deformation must be local in origin, and cannot be attributed to distant earthquakes. Coming to the interpretation in terms of interseismic deformation, the uplift could be explained by accumulation of elastic strain. According to the well-documented structural style of the SW-Taiwan Foothills [*Suppe*, 1981], a reasonable assumption is that the Tainan Tableland involves a décollement-related ramps style. Accordingly, we discuss below the three major styles of deformation front which could account for the Holocene uplift of the Tainan Tableland (fig. 3). The simplest model is a single thrust dipping to the East, the second one a fish-tail, and the third one a pop-up structure. The distribution of the InSAR deformation field shows that surface deformation remains continuous and must be local in origin. This suggests either the upper parts of the faults are locked or strain accumulation is located at the tip of creeping blind faults. The inferred single blind thrust (fig. 3a) is not consistent with the asymmetry of the Tainan Tableland (with steeper slope to the East). The latter suggests rather a west dipping backthrust upper part of a fish tail structure in agreement with the regional fold-and-thrust structure (fig. 3b). But, the stronger fringe gradient at the periphery of the tableland relative to the central area is better explained by a pop-up structure (fig. 3c). In this case, the asymmetry is attributed to the different dip angles of the thrust and backthrust.

Considering our assumption that the uplift is only due to elastic strain accumulation, it is however noteworthy how well the fringe pattern agree with the outline of the tableland. This suggests that the deformation could partly be a non-recoverable inelastic deformation absorbed by folding. Thus, the permanent cumulated uplift of the tableland would fit the pattern of the interseismic deformation field. That is why we suggest that part of the present-day deformation of the Tainan Tableland is inelastic and irreversibly absorbed by an actively growing anticline.

From the seismic hazard point of view (a major concern in Taiwan), stress and strain build up during the interseismic period of seismic cycle, and the elastic part of this deformation is released by earthquake. The size of earthquake is depending on the amount of elastic strain stored. To this respect, any definite conclusion from this work in terms of seismic hazard would be premature. This is an important issue because 1.2 million inhabitants live in Tainan city. To better investigate this essential aspect, further works, including more InSar analyses, should certainly be carried out in the near future.

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