Distribution of strain rates in the Taiwan orogenic wedge

F. Mouthereau, C. Fillon, K.-F. Ma

Institute of Geophysics, National Central University, Chungli, Taiwan
Centre de Recherches Pétrographiques et Géochimiques, Vandoeuvre-les-Nancy, France
Laboratoire de Géodynamique des Chaines Alpines, Université Joseph Fourier, Grenoble, France
Institut des Sciences de la Terre et de l’Environnement de Paris, Université Pierre et Marie Curie-Paris 6, Paris, France

A R T I C L E   I N F O
Article history:
Received 5 January 2009
Received in revised form 16 April 2009
Accepted 3 May 2009
Available online 31 May 2009
Editor: R.D. van der Hilst

Keywords:
strain rates
orogenic wedge

A B S T R A C T
To constrain the way Eurasian crust is accreted to the Taiwan orogenic wedge we investigate the present-day 3D seismogenic deformation field using the summation of 1129 seismic moment tensors of events (Mw>4) covering a period of 11 years (1995 to 2005). Based on the analysis of the principal strain-rate field, including dilatation and maximum shear rates, we distinguish four domains. Domain I comprises the Coastal Plain and the Western Foothills. It is mainly contractional in both the horizontal plane and in cross-section. Domain II comprises the eastern Western Foothills, the Hsuehshan Range and the Backbone Range. It is characterized by the highest contraction rates of 10^{-6} yr^{-1} in association with area expansion in cross-section and area contraction in the horizontal plane. Domain III corresponds to the Central Range. It is characterized by area contraction in cross-section and area expansion in the horizontal plane. The maximum contractional axis is typically low and plunges ~30°E. Extension is larger, horizontal and strikes parallel to the axis of the mountain range. Domain IV corresponding to the Coastal Range and offshore Luzon Arc shows deformation patterns similar to domain II. This seismogenic strain-rate field, which is found in good agreement with the main features of the geodetic field, supports shortening within a thick wedge whose basal décollement is relatively flat and located in the middle-to-lower crust >20 km. The east plunges of maximum strain-rate axes below the Central Range argue for the development of top-to-the-east transport of rocks resulting from the extrusion of the whole crust along west-dipping crustal-scale shear zones. The study of seismogenic strain rates argues that the initiation of subduction reversal has already started in the Taiwan collision domain.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

In Taiwan both the active and geological patterns of deformation reveal that the mountain range is built by the accretion of the Eurasian Chinese margin (Suppe, 1980; Ho, 1986; Simoes et al., 2007; Yamato et al., 2009). However, the way Eurasian materials are accreted to the Taiwan orogenic wedge is still a matter of debates. For the most popular type of models, Taiwan is interpreted as an analogue of thin-skinned oceanic accretionary wedges (Suppe, 1981; Davis et al., 1983). In this view the orogenic wedge is growing by accretion of the skinned oceanic accretionary wedges (Suppe, 1981; Davis et al., 1983). \[\text{Décollement dipping 9–10°E} \text{ at} \sim 5–10 \text{ km} \] beneath Central Taiwan whose existence has been suggested by small earthquakes distribution (Carena et al., 2002). This interpretation has been recently revisited by numerical models in order to account for the fast exhumation in the Central Range that is currently not balanced by sufficient internal shortening. This new set of models minimize the weight of frontal accretion to 0% for Simoes et al. (2007) and 50% for Fuller et al. (2006) and favour accretion by underplating of 5–10 km-thick sedimentary cover below the main décollement (Fuller et al., 2006; Simoes et al., 2007). For Simoes et al. (2007) the décollement is dipping 17°E which is much steeper than the previously proposed décollement geometry (Carena et al., 2002) and thus explicitly requires the accretion of a thicker portion of the continental crust. Other types of models argue that accretion involves the whole crust (Wu et al., 1997; Kauss et al., 2008; Yamato et al., 2009). The strain and exhumation patterns in the orogenic wedge are the consequence of the accretion of a rheologically-layered crust including the lower crust. In this latter model, the lack of surface contraction in the Central Range is interpreted as the upward extrusion of the lower crustal materials allowing passive transportation of the upper crustal materials (Yamato et al., 2009). The brief review presented here shows that the current position of the main décollement and the mechanisms of deformation are still controversial.

In order to better address the question of the mechanisms of deformation within the Taiwan wedge, the geodetic data are uneasy to use since they provide indirect and only shallow supports for more complex deeper deformation processes. On the other hand, most of the past studies on earthquakes have focused on events with low
magnitudes Ml < 4 which are inappropriate to determine the location of main faulted boundaries. It is further worth noting that recent studies on relocated micro-earthquakes have supported the existence of active vertical faults in the upper-middle crust at 15 km and even down to 30 km accommodating extrusion, rotation and exhumation in Central Taiwan (Wu et al., 2004; Gourley et al., 2007; Yamato et al., 2009). These results shed new lights on the current complex kinematic patterns within the Taiwan orogenic wedge and deserve to be investigated. Unfortunately, the driving mechanisms responsible for the displacement along these faults, which are of main interest for investigating Taiwan mountain building, remain largely unknown.

The aim of this paper is to bring new constraints on the 3D instantaneous strain field in Taiwan in order to better evaluate which type of accretion mode better applies. We focus on the orientation, magnitude and type of seismogenic strain which have not been previously investigated. The summation of seismic moment tensors of large earthquakes (Mw > 4) is adopted here to calculate the present-day strain field over the period 1995–2005. The three components of the complete strain-rate tensors are studied for different depth intervals and in cross-section. We particularly examine an E–W profile located in southern Taiwan. The results are then compared to the predicted strain rates field from a recent thermo-mechanical model and to the observed geodetic strain rates field.

2. Geological setting and geodetic constraints

The Taiwan Island is classically divided into several tectonic units (Fig. 1). The Coastal Range (CoR) to the East represents the northern Luzon Arc accreted to the collided margin. The Longitudinal Valley Fault (LVF) is the plate boundary fault between the CoR and the Central Range. The latter comprises the exhumed Paleozoic–Mesozoic metamorphic basement (Tananao Complex, TC) that is overlain by...
Fig. 2. Inter-seismic displacement field based on 1990–1995 geodetic surveys after Yu et al. (1997). Red lines correspond to major known active faults. A) Horizontal components of the geodetic velocities. A NW–SE profile of the interpolated velocities is shown (inset) together with the position of the geological units including the LVF (Longitudinal Valley Fault), the Central Range (CR) and the Western Foothills (WF). Note that displacements are nearly constant through the Central Range suggesting a lack of shortening in this region. B) Dilatation rates deduced from velocity field shown in A). Note the positive dilatation domain (extension) in the Central Range bounded by negative dilatation domains (contraction) associated with the LVF to the East and the WF to the west. C) Maximum shear strain rates calculated from the same velocity field. The large present-day shortening across the LVF and southern WF is clearly outlined. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
slates of the Backbone Range (BR) and the Hsuehshan Range (HR). The western non-metamorphic foreland fold and thrust belt, namely the Western Foothills (WF) is composed of foreland and marginal deposits accreted to the growing orogenic wedge during the Pliocene. Further west, the Coastal Plain (CP) lies at the transition between the frontal thrust units and the western foredeep (Fig. 1). Much of the currently active faults or Quaternary faults are located between the CP and the WF (Bonilla, 1977) (Fig. 2). A remarkable example that the WF are releasing seismically the current plate convergence was brought by the Chichi earthquake (MI = 7.6) which occurred on the 21st of September, 1999 in relation with activity along a deep-seated fault rupture; the Chelungpu–Sani Fault.

The Taiwan arc-continent collision results from the convergence between the downgoing Chinese continental margin belonging to the Eurasian plate and the overriding oceanic Philippine Sea plate (Fig. 1). The present-day convergence rate of the Luzon arc relative to the Chinese continental margin is estimated to be 80 mm/yr in N58°W direction (e.g. Yu et al., 1997). Inter-seismic GPS velocity field derived from 1990 to 1995 geodetic surveys (Fig. 2A) reveals that the current plate convergence is accommodated across the LVF (27–45 mm/yr) to the east and across the western frontal thrusts of the WF where geodetic velocities indicate inter-seismic shortening rates in the range of 4.6–27 mm/yr, across the frontal Chukou Fault (Yu et al., 1997). In contrast, the Central Range units (Backbone Range and Tananao Complex) show a striking deficit of shortening at surface (Fig. 2A).

3. Earthquake catalogue, data pre-processing and methodology

3.1. BATS and CWB catalogues

With the aim of examining crustal deformation within the orogenic wedge, the seismologic database must include an appropriate depth resolution and a complete solution for the seismic moment tensor. To this purpose, we adopted the BATS (Broadband Array in Taiwan for Seismology) catalogue, which contains solutions (available online http://bats.earth.sinica.edu.tw) of seismic moment tensors for events with magnitude $M_w$ larger than 3.3 since 1996 (Kao et al., 1998) (Fig. 3). Because the network is composed of broadband seismometers recording a large seismic frequency spectrum it has a poor depth resolution. Hence, we used the hypocenters determined by the short-period stations deployed by the CWB (Central Weather Bureau). This composite approach allowed us to have access to a combined data set of 1129 events distributed over a period of 11 years (1995 to 2005).

Prior to start our analysis on seismic moment tensors we must ascertain that the catalogue is complete i.e. that events reported in the studied catalogue are representative of the total seismogenic

![Fig. 3. Distribution of focal mechanisms of earthquakes used in this study. The database is composed of 1129 events reported 11 years (1995–2005) in BATS (Broadband Array in Taiwan for Seismology) catalogue. The depth of earthquakes is constrained after the CWB record (Central Weather Bureau).](image-url)
deformation over the time interval considered. On the frequency diagram (Fig. 4A) we see that earthquakes with magnitudes \( M_w \) between 3 and 5 represent 93% of all events during the 11-year record. Only one single event having a magnitude of 7 is reported in the catalogue. One can recast this analysis by calculating the magnitude of completeness \( M_c \) that is the lowest magnitude for which 100% of events are detected (Fig. 4A). \( M_c \) is estimated to be 4 in the BATS catalogue, which means that the class of earthquakes with magnitudes lower than 4 has a size lower than predicted by the theoretical distribution \( \log_{10}(N) = M_c - b \cdot M_w \) (Gutenberg and Richter, 1944). As a consequence we have removed earthquakes with magnitudes \( M_w < 4 \). The b-value in the Gutenberg–Richter relationship describes the relative occurrence of large earthquakes with respect to small ones. Some authors have suggested that b can be related to the type of tectonic regime (Schorlemmer et al., 2005). According to these authors, the b-value of 0.7 found in this study would be typical of a compressional regime in agreement with the Taiwan geodynamic context.

3.2. Focal mechanisms and hypocenter distribution of earthquakes

Most of the 1129 earthquakes studied in the collision zone are shallower than 30 km (Figs. 3 and 4B). The Moho depth beneath the Taiwan collision zone is only well constrained beneath the western foreland where it is ~30 km (Ma and Song, 1997) which means that most earthquakes are crustal events. Some of them, representing less than 20%, are found at a depth deeper than 40 km (Fig. 4B). The latter type is associated with the oceanic subduction at the Manila and Ryukyus trenches and with the thickening of the Luzon Arc crust in the Philippine Sea plate (Figs. 3 and 4B).

In order to illustrate the first-order characteristics of the seismogenic deformation we present the focal mechanisms in a ternary diagram (Frohlich, 1992) in which they are distinguished according to strike-slip, reverse or normal type of faulting (Fig. 4C). This representation reveals that the seismogenic deformation is mostly taken by reverse faulting or mixed reverse and strike-slip faulting. Fig. 3 shows that the compressive focal mechanisms are located to the east or to the west of the collision zone in association with crustal thickening in the CoR and the WF and HR, respectively. Less frequent normal faulting mechanisms (Fig. 4C) are related to extension in the Central Range in association with the exhumation of the pre-orogenic metamorphic basement and the Ryukyus arc (Fig. 3).

Several provinces with distinct seismogenic deformation patterns can be recognized (Fig. 3). One can first distinguish a seismogenic domain in the central island beneath WF, HR and part of the southern BR where earthquakes are shallower than 25 km. In eastern Taiwan, the seismogenic deformation is located below the LV and the CoR. Eastward, the depth of earthquakes is increasing to 40 km beneath the Luzon volcanic arc. In the northeast, earthquake foci are aligned along the subduction of the PSP oceanic slab beneath the Ryukyus arc trench down to a depth of 180 km. The seismogenic activity beneath the Ryukyus subduction zone is much more important than that in the subduction of the Philippines Sea plate in the Manila trench.

3.3. Summation of seismic moment tensors

To estimate the average rate of strain \( \dot{\varepsilon} \), it is common to use the following Kostrov’s (1974) formula:

\[
\dot{\varepsilon}_{ij} = \frac{1}{2\tau\mu} \sum_{k=1}^{n} M_{ik} \tau_{kij} \tag{1}
\]

which links the strain-rate tensor \( \dot{\varepsilon}_{ij} \) in the studied seismogenic volume \( V \) with the sum of the individual seismic moment tensor \( M_{ik} \) associated with faulting that occurs during the time interval \( t \) of 11 years in our case and \( \mu \) which is the shear modulus i.e. \( 3 \cdot 10^{10} \) N m\(^{-2}\). The individual moment tensor \( M_{ik} \) is defined by six independent double-couple components \( M_{ik} \) (see Table S1, Supplementary data). Theoretically, Eq. (1) is applicable only if the seismogenic deformation is quasi-continuous. In other words, faulting must be taken up on little faults distributed within a much larger seismogenic volume. However, Molnar (1983) proved that this relation remains valid for regions cut by one single fault.

Since we are interested in 3D distribution of the strain rates, we chose to study the principal strain axes (or eigenvalues) of the tensor \( \dot{\varepsilon}_{ij} \) in Eq. (1), which describes the shape and spatial orientation of strain ellipsoids. We adopt a geographical reference frame given by the coordinates axes x, y and z pointing North, East and Down, respectively. The eigenvalues \( \dot{\varepsilon}_1, \dot{\varepsilon}_2 \) and \( \dot{\varepsilon}_3 \) are arranged from most negative (shortening) to most positive (elongation) values.

Because the BATS catalogue has not been declustered for major coseismic events the reconstructed rates of deformation should be considered as only representative of the studied 11 years and hence should not be tentatively extended backward in time over geological time scale.

![Figure 4A](image_url) Distribution log_{10}(frequency)–magnitude of earthquakes which allows to constrain the magnitude of completeness \( M_c = 4 \) and b-value = 0.75 according to Gutenberg and Richter (Gutenberg and Richter, 1944) theoretical distribution of magnitudes. B) Histogram of the depth of earthquake indicating that the majority of earthquakes occur in the crust. These results have been obtained using ZMAP software. C) Ternary diagram of the studied earthquake focal mechanisms showing that most events correspond to reverse faulting, followed by strike-slip and normal faulting.
The calculation of Eq. (1) was carried out in an irregular geographic grid defined as to follow the main geological tectonic features such as plate boundaries or major tectonic contacts (Fig. 5). A total of 49 polygons were sampled. Among them, 27 onshore boxes have their vertices defined by the position of GPS permanent stations (Figs. 5 and 2) used in Yu et al. (1997). The remaining 22 boxes are located offshore. Assuming continuous strain rates in the studied area, we resampled the results for a homogeneous 1 × 1 km latitude–longitude grid in the horizontal plane and for a 1 × 1 km grid in cross-section. Interpolation algorithm refers to the continuous curvature splines in tension method provided in GMT software (Smith and Wessel, 1990). All results including the complete strain rates tensors and their eigenvalues are presented in Table S1 (Supplementary data).

3.4. Shear strain and dilatation rates

To examine the 3D deformation style we found useful to represent the strain rates by quantities that reflect the intensity and style of deformation for both vertical and horizontal planes of observation. In this aim, we estimated the maximum shear strain and dilatation rates. The maximum shear strain rate is defined by

$$\gamma = \left| \frac{\dot{e}_{\text{max}} - \dot{e}_{\text{min}}}{2} \right|$$  \hspace{1cm} (2)

with the same convention as for Eq. (2). When $\Delta$ is positive, the deformation in the cell is dominated by elongation or area expansion. On the contrary, when $\Delta$ becomes negative the deformation is mainly contractional. Finally, when elongation tends to compensate contraction $\Delta$ approaches zero. Together with the orientation of the principal strain axes these quantities fully describe the strain rates field.

4. Strain rates field in Taiwan

4.1. Crustal seismogenic strain field

The seismogenic strain distribution within the upper 30 km reveals contractional axes $\dot{e}_1$ oriented N116°E±1.5° slightly oblique to the current plate convergence (Fig. 6A). In details, the directions of contraction show deviation from this regional trend. They turn to E–W in southern Taiwan and N–S in northern Taiwan displaying a fan-shaped distribution of contraction in agreement with previous studies (e.g. Angelier et al., 1986; Hu et al., 2001; Mouchereau et al., 2002; Moutherew and Lacombe, 2006).

The maximum shear strain rates (Fig. 6C) calculated from Eq. (1) demonstrate that the seismogenic deformation is preferentially accumulating 1) in the Ryukyus subduction zone $\gamma = 2.4\times10^{-6} \text{ yr}^{-1}$, 2) in the collision zone beneath the HR and in the southern WF $\gamma = 5.5\times10^{-7} \text{ yr}^{-1}$ and 3) below the CoR $\gamma = 5.7\times10^{-7} \text{ yr}^{-1}$. It is worth noting that the strain rates detected in the WF and the CoR are related to coseismic (transient) deformation released during the Chichi event in 1999 ($M_{w} = 6.9$) and the Chengkung event in the south of the CoR in 2003 ($M_{w} = 6.8$), respectively.

The dilatation rates (Fig. 6B) reveal that the HR, WF and CoR are characterized by high rates of area reduction of $-10^{-7}$ to $-10^{-6} \text{ yr}^{-1}$. In contrast, the dilatation map shows that the Central Range (BR + TC) located in between the WF and CoR is characterized by much lower rates of contraction and larger area expansion $\Delta$ of $-10^{-10} \text{ yr}^{-1}$ that is characterized by a low but significant orogen–parallel elongation (Fig. 6A). Such an extension is likely to be permitted because of the extrusion of the Eurasian crust toward domains of lower coupling associated with the Manila and Ryukyus subduction zones. This domain is well correlated with the positive dilatation rates deduced from the geodetic displacement in the Central Range (Fig. 2B). We also notice that the south-western Taiwan displays a lack of seismogenic deformation. This contrasts with the large geodetic contraction observed in the same domain (Fig. 2C) but well correlates with the aseismic deformation observed in the Manila oceanic accretionary prism. In short, the orientation, types and relative amounts of the seismogenic strain values seem to be in fairly good agreement with the displacement field defined by the geodetic surveys (Fig. 2).

4.2. Depth distribution of strain rates

4.2.1. The Western thrust front: Coastal Plain (CP), Western Foothills (WF) and Hsuehshan Range (HR)

We first focus on the front belt domain located west of the Central Range. In this domain, the seismogenic deformation is observed down to depths of 20 km and even 25 km beneath the HR with a noticeable concentration of earthquakes in the range of 5–15 km (Fig. 7, Table S1 in the Supplementary data), which corresponds to boxes N, R, Q and to less extent B, D, G (Fig. 5). Beneath the HR, between 5 and 10 km, the Chinese crust displays the largest shear strain rates of $-10^{-6} \text{ yr}^{-1}$ (box R) related to contraction $\dot{e}_1$ oriented N115°E-plunging 12°W with an elongation $\dot{e}_3$ of $9\times10^{-7} \text{ yr}^{-1}$ being close to vertical (Table S1, Supplementary data). In the CP and the external WF, seismogenic contraction remains moderate with maximum values of $\dot{e}_1$ of $-10^{-6} \text{ yr}^{-1}$ (e.g. box D) oriented N95°E in the 5–10 km depth range in association with vertical elongation $\dot{e}_3$ of $-9\times10^{-9} \text{ yr}^{-1}$. In box Q, in between 5 and 15 km, we notice the occurrence of moderate to small contraction rates $\dot{e}_3$ from $-10^{-8} \text{ yr}^{-1}$ to $-6\times10^{-9} \text{ yr}^{-1}$ oriented N10°E–N25°E i.e. perpendicular to the regional shortening. It is associated with a horizontal larger $\dot{e}_1$ elongation of $7\times10^{-9} \text{ yr}^{-1}$ oriented N100°E (Table S1, Supplementary data) revealing an enigmatic extension (\Delta positive) in the footwall of the active Chelungpu–Sani Thrust at mid-crust. The HR, in boxes K, N and R, is characterized by the highest reported concentration of seismogenic deformation. Indeed, contraction rates $\dot{e}_1$ attain large values of $-10^{-8} \text{ yr}^{-1}$ between 5 and 10 km and even $-2\times10^{-9} \text{ yr}^{-1}$ between 15 and 20 km, which are close to the geodetic values. At a depth of 20–25 km, the HR still records contraction rates of $-2\times10^{-8} \text{ yr}^{-1}$ oriented N105°E clearly in accordance with regional contraction. This demonstrates that the lower crust can be seismogenic as suggested by earlier studies (Mouchereau and Petit, 2003). Moreover, these results suggest that most of the seismogenic deformation occur above a major decoupling located between 10 km and 20 km beneath the WF and HR.

4.2.2. Central Range (BR and TC)

With respect to the HR domain, the Central Range which includes the BR and the TC (Fig. 1) is characterized by significantly lower strain rates (boxes O, S, H, I, U) with main contraction $\dot{e}_1$ of $-10^{-9} \text{ yr}^{-1}$ and exceptionally $-10^{-8} \text{ yr}^{-1}$ in the range of 5–10 km (box I) and 10–15 km (box O) (Fig. 7 and Table S1 in the Supplementary data). The orientation of $\dot{e}_1$ is N120–140°E and is homogeneous throughout the belt over 200 km (Fig. 6A). It is interesting to further notice that $\dot{e}_1$ is plunging strongly ~30°E. But certainly the most remarkable feature, well depicted by dilatation maps, refers to the observation that the overall Central Range is undergoing extension with an elongation $\dot{e}_3$ ranging between $10^{-8}$ and $10^{-9} \text{ yr}^{-1}$ slightly larger than the contraction rate. This latter elongation is close to horizontal, i.e. 10–20° in every cell. This particular point will be discussed later in more details. At depth deeper than 15 km the less significant seismic activity
Fig. 5. Grid used to calculate the strain-rate field. The grid follows the main geological features onland and is parallel to latitudes and longitudes offshore. Red triangles refer to the permanent GPS stations reported in Fig. 2. Inset: location of domains I, II, III and IV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 6. Crustal strain rates in the 0–30 km depth range. A) Horizontal principal strain rates axes $\epsilon_{h\text{max}}$ and $\epsilon_{h\text{min}}$ are shown in terms of orientation and magnitude for each studied cell. Frequency distribution of the maximum strain rates axes is presented in inset. The present-day plate convergence deduced from geodesy is also shown (large open arrow). B) and C) are dilatation and maximum shear strain rates, respectively, calculated based on the strain-rate field determined in A) on which a cubic spline interpolation in tension in a 1 × 1 min grid has been applied. In B, the red color reveals area reduction (or 2D contraction) while the blue color indicates area expansion (or 2D extension). Red dots are the centres of sampled boxes. A mask has been applied in areas where the results are not constrained by sufficient data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 7. Dilatation and maximum shear strain rates shown as a function of depth from the surface down to 30 km and taking into account 5 km intervals. A mask has been applied to areas where the results are not constrained by sufficient data.
in the exhumed lower crust does not allow us to conclude on the style of deformation.

4.2.3. Coastal Range (CoR)

The eastern Taiwan domain includes the Coastal Range, which is part of the accreted Luzon Arc onland, the Longitudinal Valley and offshore areas belonging to the Luzon Arc (boxes V–Z in alphabetic order). Like the Western thrust front domain, this area is characterized by contraction. However, the contraction $\dot{\epsilon}_1$ is somewhat smaller especially in the upper 10 km of the arc crust. On average we estimate values in the range of $-10^{-8}$ to $-10^{-9}$ yr$^{-1}$ (Fig. 7). A noticeable increase of contraction rates is observed below 20 km depth beneath the Coastal Range where $\dot{\epsilon}_1$ attains $3 \times 10^{-8}$ yr$^{-1}$ in relation with the Chengkung earthquake. The values are hence comparable with contraction at the western thrust front HR but the depth interval of major tectonic activity is found deeper i.e. down to 40 km (Fig. 3). We hence infer based on these results that the seismogenic activity in eastern Taiwan is a consequence of the distributed shortening in the accreted arc.

4.3. Depth distribution of strain rates in southern Taiwan

Hereinafter we examine, following the same approach, the strain rates distribution along a profile striking E–W located in southern Taiwan crossing boxes B, D, G, H, X onshore and B10 box offshore (Table S1, Supplementary data). This profile is parallel to the southern cross-highland highway in order to allow for comparison with surface geology (Fig. 8). Along the profile the larger strain rates are always $\dot{\epsilon}_1$ generally striking E–W, i.e. parallel to the studied profile, and the second strain axis is either $\dot{\epsilon}_2$ or $\dot{\epsilon}_3$ (see Table S1 in the Supplementary data).

In addition to this general feature, we have calculated the strain rates for intervals of 5 km. The maximum shear strain rates show that the seismogenic deformation is accumulating preferentially at 15 ± 5 km and below the offshore Coastal Plain, the Backbone Range and at 25 ± 10 km below the Coastal Range (Fig. 8). Beneath the eastern Central Range we note a lack of deformation which is closely related to the absence of earthquakes.

It is interesting to discuss the orientation of the principal strain-rate axes and the style of deformation observed along the profile. First, we note that the large seismogenic deformation at a position x = 100 km along the profile, i.e. offshore Taiwan, is likely to be associated with the structural inversion of the Chinese margin faults. According to the definition in Mouthereau et al. (2002) this domain corresponds to the front of basement reactivation. Seismogenic deformation beneath the BR, in the depth range of 10–15 km, is characterized by contraction rates $\dot{\epsilon}_1$ of $-4.9 \times 10^{-8}$ yr$^{-1}$ (e.g. box F) plunging $-10^\circ$E whose magnitude is smaller than that below the HR. It is associated with a slightly larger elongation $\dot{\epsilon}_2$ of $5.2 \times 10^{-8}$ yr$^{-1}$ plunging $-80^\circ$W. This leads to positive dilatation meaning that extension prevails in this area.

For the same depth range, the eastern Central Range (box H) shows lower contraction rates $\dot{\epsilon}_1$ of $-8 \times 10^{-9}$ yr$^{-1}$ plunging $-30^\circ$E in association with perpendicular elongation of $10^{-10}$ yr$^{-1}$ corresponding to $\dot{\epsilon}_2$. The resulting dilatation rate is negative, which means that contraction prevails along the studied profile while extension remains prominent in the horizontal plane (Figs. 6 and 7). We found the same deformation patterns in the Central Range down to 25–30 km, i.e. above the Moho discontinuity. Finally, under the Coastal Range (box X) the contraction rates are maximum at depths of 15–20 km where $\dot{\epsilon}_1$ amounts to $-3 \times 10^{-8}$ yr$^{-1}$. This means that deformation in southern Taiwan and for the period considered is mainly taken up in eastern Taiwan. One can further notice that the contraction rates remain higher than $-10^{-9}$ yr$^{-1}$ from the surface to 35–40 km. Moreover, dilatation rates appear mainly extensional in the range of 10–20 km and 25–30 km where the largest $\dot{\epsilon}_1$ is observed.

5. Summary of main results and comparison with thermo-mechanical model

5.1. 3D deformation patterns

Based on 3D analysis of strain-rate distribution, we distinguish from west to east 1) a domain I including the outer Western Foothills and the Coastal Plain where seismogenic activity is moderate; 2) a domain II where the most significant part of the seismogenic strain is currently accumulating beneath the eastern Western Foothills, the Hsuehshan Range and/or the Backbone Range; 3) a domain III, which is characterized by very low seismogenic strains under the Central Range and 4) a domain IV beneath the Coastal Range, which is characterized by deformation patterns having strong similarities with domain II.

Domain I (boxes M, Q, D, E in Fig. 5) is mainly contractional in both the horizontal plane and in cross-section and it is characterized by a horizontal weak contraction $\dot{\epsilon}_1$ of the order of $-10^{-8}$ yr$^{-1}$ roughly oriented E–W associated with a vertical elongation $\dot{\epsilon}_2$ of the same order though and sometimes slightly larger. The intermediate contraction $\dot{\epsilon}_3$ is horizontal. Domain II (boxes K, N, R, G, F in Fig. 5) is often characterized by positive dilatation in cross-section and negative dilatation in the horizontal plane. It is associated with high contraction $\dot{\epsilon}_1$ typically between $-10^{-8}$ yr$^{-1}$ and $-10^{-6}$ yr$^{-1}$ being horizontal and associated with sometimes larger vertical elongation $\dot{\epsilon}_2$, $\dot{\epsilon}_3$ remaining generally horizontal and extensional. Domain III (boxes O, S, H, L, U) is characterized by contraction in cross-section and extension in the horizontal plane. $\dot{\epsilon}_1$ is typically lower than $-10^{-8}$ yr$^{-1}$ and often plunges toward the east more than $30^\circ$ and the strain rates distribution along a profile striking E–W associated with a vertical elongation $\dot{\epsilon}_2$ of the same order though and sometimes slightly larger than the horizontal contraction thus revealing extension in cross-section (Fig. 8).

5.2. Comparison with geodetic strain rates and possible implication

Fig. 2B and C shows the first-order characteristics of the seismogenic strain rates field derived from 1990 to 1995 geodetic velocities (Yu et al., 1997). This figure was obtained by linearly interpolating the geodetic velocity field in a grid with cells spacing of 1 × 1 min. The strain rates tensor has been easily deduced at any points of the grid for which the displacement vectors are known for 3 adjacent vertices. We derive the eigenvalues and eigenvectors in the horizontal plane and perform calculation of dilatation and maximum shear strain rates. Basically, we found that there is a fairly good agreement of the style of deformation between geodetic strain rates field and seismically-released strain rates field over the studied 11 years. For both fields, positive dilatation strain dominates in the Central Range, which is associated with horizontal elongation parallel to the orogenic trend. Strong contraction rates are observed to the east and to the west of the Central Range in correlation with the large amount of seismic events occurring within both domains (Fig. 3). Because 1) the seismogenic thickness is maximum 15 ± 5 km beneath western and central Taiwan and 2) the first-order spatial distribution of the seismogenic deformation is in good geographical correlation with the geodetic strain rates we infer that the surface displacement field outlined by the geodesy suggests that the Taiwan thrust wedge is being built above a main décollement located in the middle-to-lower Eurasian crust.

5.3. Comparison with thermo-mechanical modelling of Taiwan

Our results raise the possibility for the Taiwan mountain belt to be currently building above a décollement located in the middle-to-lower
crust. To evaluate this possibility further we compare the characteristics of the strain rates field deduced from our study (e.g., Figs. 7 and 8) with the predicted strain rates field obtained using a thermo-mechanical modelling of Taiwan (Yamato et al., 2009). In this latter model the main features of Taiwan mountain building has been reproduced by the shortening of a rheologically-layered continental crust representing the Chinese continental margin (Yamato et al., 2009). For our comparison we use the velocity field at the 200 kyr stage of the modelling (Fig. 9; which is also Fig. 9 in Yamato et al., 2009), which is assumed to represent the present-day deformation patterns in Taiwan. In this aim, we have first interpolated, in a ~5 × 5 km grid, the original velocity field obtained in the model. The strain rates tensors have then been calculated following the method used for geodetic strain rates (Fig. 2). Finally, we have derived the orientations and magnitudes of the principal strain axes as well as the dilatation and the maximum shear strain rates in the vertical plane (Fig. 9).
It is important to notice that major differences can be expected between observed and predicted patterns of deformation. These differences are due to the fact that the observed strain rates field in Fig. 8 are dependent on the number and the location of events during the 11-year record whereas earthquakes in the model are only virtually taken into account through the continuous accumulation of deformation until a plastic deformation threshold is reached. As a result, the observations show a more distributed deformation pattern (Fig. 8) than in the model in which rheological boundaries have been prescribed (Fig. 9).

The main features shown by the model (Fig. 9) are 1) a flat to west-dipping shear zone at mid-crust rheological contrast (upper décollement) at ~15 km, in the Chinese margin, which is connected eastward to a deeper shear zone (lower décollement) located at ~30 km and 2) a west-dipping shear zone at the rear of the thrust wedge.

The model predicts significant contraction rates (negative dilatation rates) in the upper 15 km above the shallow décollement at mid-crust (Fig. 9). Below, a large area dominated by area expansion (positive dilatation) is seen. These observations are in fairly good agreement with the observed deformation patterns beneath domains I and II in the same depth range and structural position (Fig. 8). According to the velocity vectors shown in Fig. 9B and C, the area expansion below the outer wedge is caused by the fastest exhumation of upper crust particles in the hanging wall of the uppermost shear zone. The predicted maximum strain-rate axes are plunging (x = 650–690 km) to the east by 20–30° E (Fig. 9). In Fig. 8, such orientations of
the maximum strain-rate axes are not clearly observed. However, we have mentioned at least one example of maximum strain-rate axis plunging 10° E below the BR (domain II, box F) at the same depth (Fig. 8). If this is confirmed by further investigations, this would indicate the possibility of the initiation of top-to-the-east shear or transport in this area.

Slightly to the east (x = 710 km) and at 15–25 km, that is in the lower Eurasian crust, the model predicts the occurrence of large contraction, which could have strong potential similarities with the large contraction observed below the HR (domain II, e.g. box R in Fig. 5) at the same depths (Fig. 8). This deformation occurs in the lower crust between the two major décollements.

In the centre of the model wedge (x = 720 km; Fig. 9), the rocks are exhumed at the same rates thus giving explanation of the observed low shear strain rates (Fig. 8). This part of the model is well correlated with the lack of seismic activity observed in the Central Range (domain III). However, the contractional strain rates observed beneath the Central Range (Fig. 8) are not clearly reproduced by the model. We suggest that in the Central Range the deformation is taken up mostly by N–S orogen-parallel elongation, which cannot be taken into account in the E–W 2D modelling (Fig. 9).

To the east, the major difference between the predicted and observed deformation patterns is due to the Luzon arc whose shortening has not been taken into account in the modelling (see Yamato et al., 2009 for more details). As a consequence, the Philippine Sea Plate, which is also taken as the stable reference frame for calculating velocities, appears undeformed. However, one can observe that domain IV is characterized by a thick seismogenic crust with deep and large earthquakes down to depths of 40 km. Yet the model predicts large shear strain rates in association with the east-dipping subduction zone at depths of 30–40 km.

Another major observation points to plunge ~30° E of the maximum strain rates below the Central Range (domain III) down to depth of 30 km (Fig. 8). In Fig. 9A, the plot of the predicted plunges of the contraction axes as a function of depth reveals that the shortening axes in the model are inclined to the east in the upper 20 km. This is interpreted to be the consequence of the top-to-the-east sense of shear and clockwise rotation about horizontal axis imposed by the kinematics of rock particles transported eastward above a west-dipping shear zone. When combined with the shortening axes inclined to west along the east-dipping subduction zone at 28 km, they outline a crustal-scale triangle zone at the rear of the wedge. We infer that the orientations of the strain axes in domain III are the consequence of this particular kinematics.

If our interpretation is correct this would indicate that the Taiwan wedge is currently accreting the Chinese margin crust above a décollement located at the base of the crust, in agreement with a thick-skinned mode of shortening. Moreover, the present-day kinematics in eastern Taiwan (Central Range) might reflect the initiation of an eastward displacement of materials originated in the deep continental crust. This further implies that the change of subduction vergence is currently ongoing in eastern Taiwan across the LVF (Fig. 10) as a response of the negative buoyancy of the Philippine Sea plate and rapid extrusion of the Central Range as already proposed (Yamato et al., 2009).

6. Conclusions

We have established that the seismogenic deformation pattern in the Taiwan collision zone is characterized by four domains (Fig. 5) below the Western Foothills (domain I), in the eastern Western foothills, the Hsuehshan Range and the Backbone Range (domain II), in the Central Range (domain III) and below the Coastal Range and offshore Luzon Arc (domain IV). Horizontal contraction is mainly accommodated within domains II and IV (Fig. 10) in agreement with geodetic constraints (Fig. 2). Within domain III, in the Central Range, horizontal extension dominates which is also in agreement with geodesy.

Though we are conscious that our data would deserve a full kinematic inversion of the strain rates, we consider our interpretations to be first-order validated by the following lines of evidence. The seismogenic strain-rate field, both in the horizontal plane and down to 15–20 km, is found in good agreement with the surface geodetic strain rate indicating that the surface deformation patterns may be related to shortening within a thick wedge whose main décollement is relatively flat and located in the middle-to-lower crust. The involvement of the lower crust beneath the Central Range as suggested by tomography data and mechanical modelling (Rau and Wu, 1995; Wu et al., 1997, 2007; Yamato et al., 2009) is supported by the eastward sense of shear beneath the Central Range. Though the geodetic and geological data, presented in the introduction, are in agreement with dominant west-vergent thrusting in the Taiwan wedge, the distribution and nature of seismogenic strain rates argue for a noticeable development of a top-to-the-east shear zone. This is particularly clear below domain III (Central Range) that is characterized by ~30° E-plunging contraction interpreted to result from the extrusion of the whole crust along a west-dipping crustal-scale shear zone. The inference of active crustal-scale vertical faults at 15 km and 30 km associated with the exhumation of the Central Range (Wu et al., 2004; Gourley et al., 2007) is supported by the deformation patterns presented in the Central Range.

We conclude that the observed seismogenic deformation pattern is controlled, to first-order, by the contrast of rheology between the upper and the lower crust. Taking into account the data presented in this study, the underplating suspected in earlier studies (e.g. Simoes et al., 2007) beneath the Central Range could be also reproduced by the differential exhumation between the upper and the lower crusts (Fig. 9) rather than by cover duplexes beneath the Central Range that are the basis of thin-skinned models.
Acknowledgments

This work has greatly benefited from the 6 months sabbatical of F. Mouthereau. Both FM and CF would like to warmly thank Prof. K.F. Ma’s team for their welcome and help in using laboratory facilities. This work has also greatly benefited from discussions with Wu Y.M. and Hu J.C. Some figures have been produced using GMT public software, ZMAP a free software for analysing earthquake catalogue and R a free software environment for statistical computing and graphics. The review by Tim Byrne has greatly improved and clarified the original manuscript. The editor Rob van der Hilst is also thanked.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.05.005.

References


