RESEARCH ARTICLE

10.1002/2017TC004475

Key Points:

- Taiwan provides insight into how a margin structure contributes to along-strike changes in a fold-and-thrust belt
- Structural inheritance of basement faults is a key component in producing along-strike changes in structure, seismicity, and topography
- These along-strike changes vary depending on which morphological part of the margin is involved in the deformation

Correspondence to:

D. Brown,
dbrown@ictja.csic.es

Citation:

Brown, D., J. Alvarez-Marron, C. Biete, H. Kuo-Chen, G. Camanni, and C.-W. Ho (2017), How the structural architecture of the Eurasian continental margin affects the structure, seismicity, and topography of the south central Taiwan fold-and-thrust belt, *Tectonics*, 36, doi:10.1002/2017TC004475.

Received 11 JAN 2017

Accepted 14 JUN 2017

Accepted article online 22 JUN 2017

How the structural architecture of the Eurasian continental margin affects the structure, seismicity, and topography of the south central Taiwan fold-and-thrust belt

Dennis Brown¹ , Joaquina Alvarez-Marron¹ , Cristina Biete¹ , Hao Kuo-Chen² , Giovanni Camanni³, and Chun-Wei Ho^{2,4}
¹Institute of Earth Sciences "Jaume Almera", ITCJA-CSIC, Barcelona, Spain, ²Department of Earth Sciences, National Central University, Jongli, Taiwan, ³Fault Analysis Group, School of Earth Sciences, University College Dublin, Dublin, Ireland,

⁴Central Weather Bureau, Taipei, Taiwan

Abstract Studies of mountain belts worldwide show that along-strike changes are common in their foreland fold-and-thrust belts. These are typically caused by processes related to fault reactivation and/or fault focusing along changes in sedimentary sequences. The study of active orogens, like Taiwan, can also provide insights into how these processes influence transient features such as seismicity and topography. In this paper, we trace regional-scale features from the Eurasian continental margin in the Taiwan Strait into the south central Taiwan fold-and-thrust belt. We then present newly mapped surface geology, *P* wave velocity maps and sections, seismicity, and topography data to test the hypothesis of whether or not these regional-scale features of the margin are contributing to along-strike changes in structural style, and the distribution of seismicity and topography in this part of the Taiwan fold-and-thrust belt. These data show that the most important along-strike change takes place at the eastward prolongation of the upper part of the margin necking zone, where there is a causal link between fault reactivation, involvement of basement in the thrusting, concentration of seismicity, and the formation of high topography. On the area correlated with the necking zone, the strike-slip reactivation of east northeast striking extensional faults is causing sigmoidal offset of structures and topography along two main zones. Here basement is not involved in the thrusting; there is weak focusing of seismicity and localized development of topography. We also show that there are important differences in structure, seismicity, and topography between the margin shelf and its necking zone.

Plain Language Summary We present newly mapped surface geology, which is integrated with *P* wave velocity maps and sections, with an accurately relocated seismicity data set, and with high-resolution topography to test the hypothesis of whether or not the regional-scale features of the margin are contributing to along-strike changes in structural style, seismicity, and topography of the south central Taiwan fold-and-thrust belt. As a corollary to this hypothesis, we also investigate whether or not there are differences in structural architecture, seismicity, and topography between the margin shelf and its necking zone.

1. Introduction

Studies of mountain belts worldwide have shown that along-strike changes in many features of their foreland fold-and-thrust belts are common [e.g., Thomas, 1985; Perez-Estaun et al., 1997; Duncan et al., 2003; Mouthereau et al., 2006; Yin, 2006; Turner et al., 2010; Arora et al., 2012]. In most cases, these along-strike changes can be related to the reactivation of preexisting faults that were inherited from the continental margins that were involved in the deformation or to changes in sedimentary thickness and facies [e.g., Jackson, 1980; Willschko and Eastman, 1983; Perez-Estaun et al., 1997; Brown et al., 1999; Kelly et al., 1999; Calamita et al., 2011; Turner et al., 2010; Butler et al., 2006; Chatzaras et al., 2013; Boutoux et al., 2014; Godin and Harris, 2014]. While along-strike changes in structural architecture and in sedimentary depositional systems of fold-and-thrust belts are well documented in fossil orogens, investigating those in active orogens can also yield important information about variations in transient features such as seismicity and topography. For example, Yin [2006], Arora et al. [2012], and Godin and Harris [2014] have shown how preexisting faults on the Indian Plate that are oriented at a high angle to the structural grain of the foreland of the Himalaya and are causing along-strike changes in the structure, seismicity, and topography of its foreland fold-and-thrust belt. Likewise,

Blanc et al. [2003], *Mouthereau et al.* [2006], and *Koyi et al.* [2016] have shown how preexisting structures in the Arabian Plate are similarly affecting various features of the Zagros fold-and-thrust belt. Investigating the role played by margin features in the development of along-strike changes is therefore not only of importance for determining structural processes, sediment pathways, and facies distribution in a fold-and-thrust belt, it is also important for understanding, and possibly mitigating, the focusing of geological hazards that are related to seismicity and topographic relief.

The area on and around the island of Taiwan provides an excellent opportunity to investigate how the structural and the morphological features of a continental margin could possibly contribute to along-strike changes in the structure, seismicity, and topography of a fold-and-thrust belt because the preexisting structural and basin architecture of the margin shelf, shelf-to-slope transition, and slope are well known [e.g., *Teng et al.*, 1991; *Yang et al.*, 1991; *Lin et al.*, 2003; *Teng and Lin*, 2004] and because there is a wealth of on-land geological, geophysical, and geodetic data that can be used to trace them into the fold-and-thrust belt [e.g., *Suppe*, 1986; *Deffontaines et al.*, 1997; *Lacombe et al.*, 1999; *Mouthereau et al.*, 2002; *Yang et al.*, 2006, 2016; *Byrne et al.*, 2011; *Alvarez-Marron et al.*, 2014; *Camanni et al.*, 2016]. In this paper, we combine the top of the Mesozoic basement map from the Taiwan Strait [*Lin et al.*, 2003] with seismic tomography to trace the regional-scale structural and morphological features of the continental margin into the south central Taiwan fold-and-thrust belt. We then present newly mapped surface geology, which is integrated with *P* wave velocity maps and sections, with an accurately relocated seismicity data set and with high-resolution topography to test the hypothesis of whether or not the regional-scale features of the margin are contributing to along-strike changes in structural style, seismicity, and topography of the south central Taiwan fold-and-thrust belt. As a corollary to this hypothesis, we also investigate whether or not there are differences in structural architecture, seismicity, and topography between the margin shelf and its necking zone.

2. Background: The Southeastern Eurasian Margin and the Taiwan Orogen

2.1. Tectonic Evolution and Structure of the Margin

The part of the continental margin of the Eurasian Plate that is currently involved in the Taiwan orogeny is thought to have evolved from a subcontinental subduction system in the Late Cretaceous [*Hall*, 2001; *Li et al.*, 2007; *Lan et al.*, 2008] to a rifting margin by the early Eocene followed, during the late early Oligocene, by seafloor spreading and, from the early Miocene to the present, the subduction of Eurasian Plate beneath the Philippine Sea Plate [*Hall*, 1996; *Lin et al.*, 2003; *Huang et al.*, 2012]. Here we define the margin's prerift Mesozoic rocks as the basement upon which the Eocene and younger sediments of the margin were deposited. The morphology of the Eurasian margin that is now entering into the collision with the Philippine Sea Plate to form the Taiwan orogen consists of a broad shelf with deep, fault-bounded Eocene age basins, a roughly northeast striking shelf slope break (the 200 m bathymetry contour), a steep, narrow slope with Miocene age basins, and a broad distal margin (Figures 1 and 2). Throughout this paper, we use the structural term necking zone [e.g., *Mohn et al.*, 2012] when referring to the area of the margin where the basement thins and slope when referring to the morphological feature where sediments were deposited on the necking zone (Figure 2). We refer to that part of the margin where the basement begins to thin as the upper part of the necking zone (Figure 2). In Taiwan, the upper part of the necking zone roughly coincides with the northern bounding-fault system of the Tainan Basin [e.g., *Lee et al.*, 1993; *Lin et al.*, 2003; *Ding et al.*, 2008]. The crustal thickness of the shelf part of the Eurasian margin has been determined from a variety of geophysical data to be about 30 ± 5 km [*Yeh et al.*, 1998; *Kim et al.*, 2004; *Kuo-Chen et al.*, 2012; *Huang et al.*, 2014; *Wu et al.*, 2014; *Chen et al.*, 2016]. Reflection and wide-angle seismic data show that the continental crust thins across the necking zone, from approximately 30 km of the shelf to approximately 18 km along the more than 300 km wide hyperextended, distal part of the margin (Figure 2) [*Chen and Yang*, 1996; *Li et al.*, 2007; *Lin et al.*, 2008; *Huang et al.*, 2012; *Yeh et al.*, 2012; *Deng et al.*, 2012; *McIntosh et al.*, 2013, 2014; *Lester et al.*, 2014]. *Yeh et al.* [2012], *McIntosh et al.* [2014], and *Lester et al.* [2014] also interpret a failed rift to occur at the base of the slope (FR in Figure 2) that projects on shore in southwestern Taiwan. The transition from continental to oceanic crust occurs to the south of the area shown in Figure 1 [e.g., *Nissen et al.*, 1995; *Zhao et al.*, 2010; *Tsai et al.*, 2004; *Deng et al.*, 2012; *Yeh et al.*, 2012; *McIntosh et al.*, 2013; *Lester et al.*, 2014].

The Eocene age synrift basins that developed on the margin shelf are oriented roughly northeast-southwest [*Lin and Watts*, 2002; *Lin et al.*, 2003; *Teng and Lin*, 2004; *Lin et al.*, 2005; *Cukur et al.*, 2011] and locally

Figure 1. Simplified geological map of the island of Taiwan (redrawn from Chen *et al.* [2000]). In the Taiwan Strait, the depth to the top of the Mesozoic basement [from Lin *et al.*, 2003]. The location of the necking zone offshore is indicated by the thick dashed lines and the shelf slope break by the thick dashed red line. The bathymetry is shown to the south and east of Taiwan. The study area on land in Taiwan is outlined by the dashed box. PH = Peikang Basement High, RS = Ryukyu subduction zone, PSP = Philippine Sea Plate, ChT = Changhua Thrust, SkF = Shuilikeng Fault, LF = Lishan Fault, ChF = Chaochou Fault, HP = Hengchun Peninsula.

accumulated up to approximately 5 km of sediments [e.g., Lin *et al.*, 2003]. Of these, the Tainan Basin is now involved in the Taiwan orogeny (Figure 1), with its eastern flank, the Hsuehshan Trough of Teng *et al.* [1991] and Teng and Lin [2004], now forming the Hsuehshan Range (Figure 1). During the late Oligocene to late Miocene, several extensional events further affected the outer shelf and necking zone areas to various degrees, resulting in an array of roughly east northeast striking extensional faults and development of the Tainan Basin [Yang *et al.*, 1991; Lee *et al.*, 1993; Lin *et al.*, 2003; Lin *et al.*, 2005; Ding *et al.*, 2008; Shi *et al.*, 2008; Tang and Zheng, 2010; Yang *et al.*, 2016]. Reactivation of the east northeast striking faults of the Tainan Basin is having a widespread, variable effect on the fold-and-thrust belt in southwestern Taiwan [e.g., Suppe, 1986; Rodriguez-Roa and Wiltschko, 2010; Alvarez-Marron *et al.*, 2014; Yang *et al.*, 2007, 2016], and it is here that we focus our investigation to test the hypothesis of along-strike changes caused by inheritance of structures from the margin.

Figure 2. A schematic cross section of the continental margin to the southwest of Taiwan that shows the terminology for the margin used in the text and a simplified structural interpretation. The location of the section is shown in Figure 1. The structure depicted in the upper crust of the shelf area is from *Lin et al.* [2003], whereas that in the slope and distal margin is simplified from *Yeh et al.* [2012] and *Lester et al.* [2014]. The Moho depth in the distal margin is from *Lester et al.* [2014], whereas that beneath the shelf and slope area is from *Tsai et al.* [2004]. The continent to ocean transition lies to the south of this diagram. YF = Yichu fault. FR = failed rift of *Yeh et al.* [2012], *Lester et al.* [2014], and *McIntosh et al.* [2014]. The vertical exaggeration is 2:1.

2.2. Tectonostratigraphy of the Taiwan Orogen

The Taiwan orogen is divided into five roughly N-S oriented tectonostratigraphic zones that are separated by major faults (Figure 1). From west to east these zones are the Coastal Plain (CP), Western Foothills (WF), the Hsuehshan Range (HR), the Central Range (CR), and the Coastal Range. In much of south central Taiwan, the boundary between the Coastal Plain and the Western Foothills is interpreted to coincide with the mostly buried tip line of the Changhua Thrust (ChT in Figure 1). In the north of the study area, the Western Foothills is in turn juxtaposed against the Hsuehshan Range across the Shuilikeng Fault (SkF). In the east, the Hsuehshan Range is juxtaposed against the Central Range across the Lishan Fault (LF). Southward, the Central Range is juxtaposed against the Western Foothills along the Chaochou Fault (ChF). Below, we give an overview of the outcropping stratigraphy and depositional environment of the Coastal Plain, the Western Foothills, the Hsuehshan Range, and the western part of the Central Range, beginning with the Mesozoic rocks that we define as basement.

Although the Central Range is outside of our study area, we give a brief description of it because the Mesozoic rocks that crop out there may make up a part of the basement in western Taiwan and in the Taiwan Strait [*Jahn et al.*, 1992]. The Mesozoic rocks in the Central Range comprise predominantly marbles and schists [*Stanley et al.*, 1981; *Ernst*, 1983; *Ho*, 1988; *Lan et al.*, 2008] whose absolute ages are not well constrained, although a number of Permian to Cretaceous isotopic ages have been determined [*Jahn et al.*, 1986; *Lo and Onstott*, 1995; *Lan et al.*, 2008; *Yui et al.*, 2009, 2012; *Wintsch et al.*, 2011]. In western Taiwan and its offshore, several boreholes intersect weakly metamorphosed continental to shallow marine siliciclastic deposits that have been interpreted to range in age from Late Permian to Cretaceous [e.g., *Jahn et al.*, 1992; *Chiu*, 1975; *Ho*, 1988; *Shaw*, 1996]. There is, however, some disagreement about the interpretations of the age of these rocks [e.g., *Chiu*, 1975; *Ho*, 1988; *Shaw*, 1996].

In the western part of the Central Range, the Mesozoic rocks are either unconformably overlain by, or in fault contact with, Eocene age siliciclastic rocks that are interpreted to have been deposited on the outer part of the margin, in an outer neritic to upper bathyal environment [e.g., *Ho*, 1988; *Teng*, 1992; *Huang et al.*, 1997]. These are unconformably overlain by predominantly middle Miocene age siliciclastic rocks that in northern to central Taiwan are interpreted to have been deposited in the upper to middle bathyal zone of the margin slope [*Chang*, 1976; *Sung and Wang*, 1985; *Huang et al.*, 1997, 2006, 2012]. Farther south, pillow lavas intercalated with middle Miocene siliciclastics are interpreted to have been erupted near the base of the slope [*Smith and Lewis*, 2007]. On the Hengchun Peninsula, in southeastern Taiwan, middle to late Miocene age turbidites are interpreted to have been deposited on the slope [*Huang et al.*, 2012; *Zhang et al.*, 2014].

The ages of the stratigraphic units of the Hsuehshan Range are poorly constrained because of a paucity of fossil assemblages that would allow a detailed stratigraphic succession to be determined [*Ho*, 1988] and because of its complex structure [e.g., *Tillman and Byrne*, 1995; *Brown et al.*, 2012]. Recently, *Chen et al.*

Figure 3. *P* wave velocity perturbation models (dVp (%)) for the island of Taiwan at various depths. The depth to the top of the Mesozoic basement in the Taiwan Strait is as in Figure 1. The location of the necking zone offshore is indicated by the thick dashed lines and the shelf slope break by the thick dashed red line. The study area on land in Taiwan is outlined by the dashed box. CP = Coastal Plain, WF = Western Foothills, HR = Hsuehshan Range, CR = Central Range. Other labels are as in Figure 1.

[2009] and Huang *et al.* [2012] reported the presence of Early to middle Eocene age foraminifera from the Hsuehshan Range. These Eocene rocks are thought to have been deposited in either a shallow marine or fluvial environment [Huang *et al.*, 2012] in what is commonly interpreted to have been the rift-related Hsuehshan Trough (or Basin) [Ho, 1988; Teng *et al.*, 1991; Lin *et al.*, 2003; Teng and Lin, 2004; Huang *et al.*, 2012]. By extrapolation from other basins of similar age to the west and north of Taiwan (Figure 1) [e.g., Lin *et al.*, 2003; Cukur *et al.*, 2011] the Eocene rocks of the Hsuehshan Trough can also be interpreted to directly overlie the Mesozoic basement. The Eocene rocks of the Hsuehshan Range are themselves unconformably overlain by late Oligocene shallow marine siliciclastic rocks [Lee, 1979; Lin *et al.*, 2003; Huang *et al.*, 2012] that are interpreted to have been deposited on the shelf to upper slope and to reflect thermal subsidence of the rifted margin following the opening of the South China Sea [Lin *et al.*, 2003; Teng and Lin, 2004].

The outcropping stratigraphy of the Western Foothills and Coastal Plain consists predominantly of Eocene through Holocene age siliciclastic rocks and unconsolidated sediments [Chiu, 1975; Covey, 1986; Ho, 1988; Teng, 1992; Shaw, 1996; Chen *et al.*, 2001; Lin *et al.*, 2003; Huang *et al.*, 2012, 2013]. The Eocene through to latest Miocene rocks are interpreted to have been deposited in shallow marine to fluvial environments [Chiu, 1975; Ho, 1988; Shaw, 1996; Huang *et al.*, 2012, 2013], whereas the latest Miocene through Holocene rocks and sediments were (and are being) predominately deposited in shallow marine and fluvial environments in the foreland basin [Covey, 1986; Teng, 1987; Chen *et al.*, 2001; Lin and Watts, 2002; Castelltort *et al.*, 2010; Nagel *et al.*, 2013]. A possible exception to this is in southwestern Taiwan where a thick mudstone unit is interpreted to have been deposited in a moderately deep water (upper slope?), open sea,

Figure 4. Geological map of the study area, with representative structural data. The locations of the cross sections in Figure 5 are shown. The transparent gray boxes, called zones A, B, and C, highlight areas where there are marked changes in the structural grain of the fold-and-thrust belt that we interpret to be due to reactivation of faults in the basement. The northernmost of these corresponds to the on-land projection of the upper part of the necking zone. The stratigraphic scheme used in the map is given in Table 1.

Figure 5. Geological cross sections through south central Taiwan. The locations are given in Figure 4. ChT = Changhua Thrust, CT = Chelungpu Thrust, SkF = Shuilikeng Fault, ST = Shuangtung Thrust, CuT = Chutochi Thrust, PT = Pingshi Thrust, CIT = Chishan Thrust, LF = Lishan Fault, ChF = Chaochou Fault, The dashed red line is the 5.2 km/s isovelocity line.

environment [Covey, 1986]. Neither the Eocene nor the Oligocene rocks are present everywhere, so in places, the lower Miocene rocks can either unconformably overlie the basement or conformably overlie the Oligocene [Chiu, 1975; Ho, 1988; Shaw, 1996]. The Miocene sequence thickens significantly southward across the on-land prolongation of the Tainan Basin and may reach as much as 6 km in thickness in southwestern Taiwan [Ho, 1988; Shaw, 1996; Lin et al., 2003]. These rocks make up a significant part of the stratigraphy involved in the thrust system in this southern part of the Western Foothills (Figure 1).

2.3. Tracing the Margin Structure Into South Central Taiwan

To aid in the correlation of regional-scale structures from the margin in the Taiwan Strait with velocity anomalies on land in Taiwan, we present three depth slices from a 3-D P wave perturbation (dV_p) model derived from the local tomography of Kuo-Chen et al. [2012] (Figure 3). The description below is confined to our study area, which is shown in Figure 3. In the northwest of the study area, at 8 km depth, the dominant negative dV_p values to the west of the Shuilikeng fault (SkF in Figure 3a) provide good correlation with the sediments of the Taihsi and foreland basins. At this depth there is also a significant increase in the relative dV_p in the Hsuehshan Range and a well-developed positive anomaly below the Alishan Range (HR and AR, respectively, in Figure 3). We interpret the increase in the relative velocity in the Hsuehshan and Alishan ranges to be caused by the presence of high-velocity basement rocks at a shallow crustal level [see Camanni et al., 2014a, 2016; Alvarez-Marron et al., 2014]. Beginning at 8 km depth, but becoming especially prominent at 12 km and 16 km depth, there is an embayment of relatively high dV_p that is associated with the high-velocity basement rocks that comprise the Peikang Basement High (PH in Figure 3) [e.g., Wu et al., 2007; Byrne et al., 2011; Kuo-Chen et al., 2012; Huang et al., 2014]. The southern flank of this area of relatively

Figure 6. Horizontal Vp maps at (a) 4 km depth, (b) 6 km depth, and (c) 8 km depth. The depth to the top of the Mesozoic basement in the Taiwan Strait is as in Figure 1. The Tainan Basement High (TBH) is interpreted to represent a fault-bounded basement high whose southern flank corresponds to the upper part of the necking zone. Zones A, B, and C are shown as transparent gray boxes marking the areas where there is a change in the structural grain of the fold-and-thrust belt. The location of the necking zone offshore is indicated by the thick dashed lines and the shelf slope break by the thick dashed red line. The locations of the velocity sections in Figure 7 are shown. TsB = Taihsi Basin. Other labels are as in Figure 1.

high dVp coincides with the on-land projection of the upper part of the necking zone, clearly indicating that it can be traced from the margin into the fold-and-thrust belt. South of this, in the Western Foothills and on the Coastal Plain, the negative dVp values reach to about 12 km depth and are interpreted to be due to thicker Miocene and foreland basin sediments that were deposited on the slope of the margin and which are now involved in the fold-and-thrust belt deformation [e.g., Wu *et al.*, 2007; Kuo-Chen *et al.*, 2012; Huang *et al.*, 2014]. By 16 km depth, the Peikang Basement High still produces a significant dVp anomaly. Below the southwestern part of the fold-and-thrust belt, there is a weak dVp high extending northeastward from a basement high on the margin.

3. The South Central Taiwan Fold-and-Thrust Belt

3.1. Data and Methodology

In this section we present the geology of south central Taiwan (Figures 4 and 5), which is integrated with the TAIGER P wave velocity model [Kuo-Chen *et al.*, 2012] (Figures 6 and 7), with earthquake hypocenter data from 1994 to 2014 (Figure 8) and with a 40 m pixel digital elevation model (Figure 9a). The geological map (Figure 4) is from our own fieldwork [see Brown *et al.*, 2012; Alvarez-Marron *et al.*, 2014]. In the map, the stratigraphy of the Miocene through Pleistocene rocks is simplified as a chronostratigraphic sequence whose north to south correlation follows that of Shea *et al.* [2003] (Table 1). We also correlate major faults from north to south in the manner of Ho [1986]. The cross sections shown in Figure 5 were drawn using the geological map, field structural data, and the standard section construction techniques [e.g., Dahlstrom, 1969; Hossack, 1979]. We refer the reader to Kuo-Chen *et al.* [2012] and its supplementary data set for the acquisition and processing parameters, the reference velocity function used for the Vp perturbation model, and the resolution testing of the TAIGER local tomography. In the velocity maps and sections presented here, we can expect a resolution of at least $20 \times 20 \times 10$ km (see the checkerboard test of Kuo-Chen *et al.* [2012]). The discretization of the 3-D velocity grid is 4×4 km horizontally and 2 km vertically to a depth of 24 km. At a depth of greater than 24 km the spatial resolution is $4 \times 4 \times 4$ km. The earthquake hypocenters have been relocated by the double-difference

Figure 7. Vp sections with the fault traces taken from the geological cross sections shown in red. Locations are shown in Figure 6. Earthquake hypocenters are projected on to the sections from 3 km either side. Fault labels are as in Figure 1.

technique [Waldhauser and Ellsworth, 2000] within the local 3-D Vp model of Kuo-Chen *et al.* [2012] using the HypoDD3D software [Waldhauser, 2001]. The relocation was carried out on all events shallower than 60 km depth that had a minimum of six readings with a reading weighting <3 (good quality). Calculations of travel time residuals of earthquakes in the Central Weather Bureau database indicate that the starting uncertainty in their locations was less than 1 km. After the HypoDD relocation the average residual was reduced, indicating that the uncertainty had improved. In the description of the structure that follows, we differentiate between the morphological features of the margin in the footwall (the shelf, the necking zone, and the slope) and those in the hanging wall of the fold-and-thrust belt (Western Foothills, Hsuehshan Range, zones A, B, and C) (Figure 4) whose structures we wish to link to those in the margin.

Finally, an important feature of the subsurface geology for the interpretations that follow is the contact between the Mesozoic basement rocks and the overlying sediments. Understanding where this contact is allows us to interpret the role played by the margin basement in the structure of the fold-and-thrust belt. In the absence of any surface data about this contact in south central Taiwan, and with a limited number of borehole data, we choose to make a seismic velocity description in which a Vp of 5.2 km/s is taken as a proxy for the velocity of the rocks near the top of the basement. We choose this velocity for two reasons:

(1) because it is in keeping with laboratory measurements of Vp carried out on clastic rocks [Christensen, 1989; Mavko *et al.*, 1998; Christensen and Stanley, 2003; Johnston and Christensen, 1992, 1993] that are similar in lithology to those described as Mesozoic in boreholes from south central Taiwan [Chiu, 1975; Shaw, 1996] and (2) because it is in keeping with the measured Vp (<5 km/s) of the late Miocene and younger sediments intersected by the Taiwan Chelungpu Fault Drilling Project borehole A [Hung *et al.*, 2009]. We stress, however, that a Vp of 5.2 km/s serves only as a proxy. It is meant to help with the interpretation of the location of these rocks at depth, but because of the uncertainties in the velocity model and in the petrophysical assumptions it may not coincide exactly with the basement-cover interface.

3.2. Structure, Seismicity, and Topography of South Central Taiwan

In the northern part of the study area (north of zone A in Figure 4), the outcropping geology of the Coastal Plain and Western Foothills comprises Pliocene to Holocene synorogenic sediments of the foreland basin with, eastward, synrift Eocene age sedimentary and minor volcanic rocks that are unconformably overlain

Figure 8. Earthquake epicenter depth slices for the study area. Events are projected 4.99 km each side of the depth slice. The depth to the top of the Mesozoic basement in the Taiwan Strait is as in Figure 1. The locations of the seismicity sections in Figure 7 are shown. The location of the necking zone offshore is indicated by the thick dashed lines and the shelf slope break by the thick dashed red line. Other labels are as in Figures 1, 3, and 6.

by Miocene sedimentary rocks (Figure 4). The Nanchuang Fm (middle to late Miocene) is absent here, and the early Miocene rocks are unconformably overlain by the late Miocene synorogenic Kueichulin Fm. The structure is that of a west verging imbricate thrust system with a roughly N-S striking structural grain (Figures 4 and 5a). Its basal thrust is interpreted to be located near the base of the low velocity (<5 km/s [Hung *et al.*, 2009]) synorogenic sediments in the Western Foothills (Figures 6 and 7a). Along the eastern flank of the Western Foothills, Eocene and Miocene rocks overthrust the Pliocene to Holocene synorogenic sediments along the Shuangtung thrust (ST in Figures 5a and 7a). Seismicity in this imbricate thrust system is scattered (Figure 8), with no clear correlation with any individual fault (Figure 7a). Beneath the imbricate thrust system, seismicity reaches to approximately 30 km depth, but there is no well-defined clustering that would suggest the location of any particular fault in the basement (Figures 7a and 8). The topography of the imbricate thrust system is dominantly subdued, with elongated hills developed in the immediate hanging walls of the frontal thrusts (Figure 9a). Only at the rear of the thrust system, where Miocene sediments crop out, do elevations reach more than 500 m.

The Shuilikeng fault is a major structural boundary across which there is an important change in the outcropping rocks and in the structure of the fold-and-thrust belt [Camanni *et al.*, 2014b] (Figures 4 and 5a). East of it, the Hsuehshan Range comprises Eocene age synrift sediments from the Hsuehshan Trough, which are unconformably overlain by late Oligocene postrift sediments. The structure of the Hsuehshan Range can be divided into two thrust sheets, the westernmost of which comprises open to tight, west verging anticlines and synclines and, from the Tili thrust (TT in Figure 5a) to the east, a set of west verging folds with a penetrative axial planar cleavage and associated thrusts that overall form an anticlinorium with a steep to overturned forelimb. The involvement of older and, at depth, higher Vp (Figures 6 and 7a) rocks in this part of the fold-and-thrust belt provides unequivocal evidence that the basal thrust ramps down to a deeper crustal level beneath the Hsuehshan Range [see Yue *et al.*, 2005; Brown *et al.*, 2012; Chuang *et al.*, 2013]. In the subsurface, the location of the ramp can be inferred from an east dipping cluster of seismicity that reaches to about 20 km depth (Figure 7a) [see Chuang *et al.*, 2013; Camanni *et al.*, 2014a, 2014b]. We interpret both the Shuangtung and Shuilikeng faults to be linked to this ramp, with the Shuangtung thrust having been cut by the Shuilikeng fault [Brown *et al.*, 2012; Chuang *et al.*, 2013]. The uplift of higher Vp rocks (>5.2 km/s) beneath the Hsuehshan Range (Figures 6 and 7a) is interpreted to indicate the involvement of Mesozoic

Figure 9. (a) Digital elevation model of the study area and (b and c) details of sigmoidal topographic features in southwestern Taiwan. The location of the necking zone offshore is indicated by the thick dashed lines and the shelf slope break by the thick dashed red line. The locations are shown by black boxes. The depth to the top of the Mesozoic basement in the Taiwan Strait is as in Figure 1. The locations of the topography sections in Figure 7 are shown. YM = Yushan Mountain, HM = Hsuehshan Mountain. Other labels are as in Figures 1, 3, and 6.

basement in the deformation. In this northern part of the study area, the Hsuehshan Range is the most seismically active part of the fold-and-thrust belt, with significant seismicity extending to over 30 km depth (Figure 8). The deepest seismicity in the Hsuehshan Range is seen in the cross section to form a steeply west dipping cluster that is interpreted to be associated with the Lishan fault (LF in Figures 7a and 8) [see Wu *et al.*, 2004; Brown *et al.*, 2012; Camanni *et al.*, 2014a, 2014b; Kuo-Chen *et al.*, 2015]. In the study area, the Hsuehshan Range has the highest elevations in the fold-and-thrust belt. The two highest mountains in Taiwan are found there: Yushan and Hsuehshan mountains, respectively (YM and HM, in Figure 9). The Puli Basin (PB in Figure 9) forms a pronounced topographic low within the Hsuehshan Range, and it is roughly centered on a marked Vp high (Figures 3 and 6).

The upper part of the necking zone marks a major change in the structure of the margin offshore western Taiwan, and across its on-land prolongation (zone A, Figure 4) there are significant along-strike changes in structure, stratigraphy, seismicity, and topography of fold-and-thrust belts (Figures 4, 6, 8, and 9a). With regard to the structure, zone A highlights a roughly north-south to northeast-southwest, en echelon

Table 1. North to South Miocene Through Pleistocene Chronostratigraphic Correlation Used in the Geological Map [From Shea *et al.*, 2003]

	Shelf		Mesozoic Shelf Break		Upper Slope	
	This Map	Nantou / Yunlin	Chiayi / Tainan	Tainan	Kaohsiung	
Pli - Ple	Toukoshan CC. ^a		Liushuang Fm. Erchungchi Fm. Kanhshialiao Fm.	Yuching Sh. ^a	Chiting Fm.	Linkou CC. Tashe Fm. (with limestone)
	Toukoshan SS. ^a					
	Cholan Fm. ^a		Liuchungchi Fm. Yunshuichi Fm.	Pelliao Sh. Chutouchi Fm.	Gutingkeng Fm. (with limestone)	Nanshihulun SS Kaizuliao Sh. Wushan Fm.
	Kueichulin Fm.	Tawo SS Shihliufeng Sh. Kuantao-shan SS	Niaotsui Fm. Chunglun Fm.	Maopu Sh. Ailiaochiao Fm. Yenshuikeng Sh. Tangenshan SS.	Wushan Fm.	
Mio	Nanchuang Fm.			Changchihkeng Fm. Hunghuatze Fm. Sanmin Sh.		
	Nankang Fm.	Fulungyuan Fm. Hourdongkeng Fm. Shihmensun Fm.	Shenkeng SS Changhukeng Sh. Shihmen Fm.			
	Takeg Fm.		Tanliaoti Sh. Shihszeku Fm.			

^aCC = conglomerate, SS = sandstone, Sh. = shale, FM. = formation.

change in the strike of thrusts that culminates with approximately 10 km westward shift of the tip line of the Changhua thrust along the dextral strike-slip Meishan fault (Figure 4). The Meishan fault is thought to link westward under the Coastal Plain with an extensional fault system that is also found offshore, along the upper part of the necking zone [e.g., Lin *et al.*, 2003; Yang *et al.*, 2016]. Immediately south of zone A, the Changhua (ChT) and Chelungpu (CT) thrusts in the western part of the fold-and-thrust belt merge into a gently east dipping basal thrust that is much shallower than to the north (compare ChT and CT in Figures 5a and 5b). Concomitant with the shallowing of the basal thrust, there is a decrease in the thickness of the Pliocene to Recent synorogenic sediments of about 5 km, and its base is uplifted by approximately 7 km in the Chelungpu thrust sheet. East of the Shuangtung thrust (ST in Figure 5b), the basal thrust is interpreted to ramp down section, and the hanging wall structure is that of an approximately 20 km wide anticlinorium. This anticlinorium includes a thicker Miocene sequence than is to the north of zone A. The southward appearance of the middle to late Miocene Nanchuang Fm at zone A (Figure 4) occurs along the northern margin of the Tainan Basin. In structural cross sections [e.g., Suppe, 1986; Rodriguez-Roa and Wiltschko, 2010; Yang *et al.*, 2007, 2016; Alvarez-Marron *et al.*, 2014], its appearance in the fold-and-thrust belt is interpreted to take place along a reactivated middle Miocene age extensional fault that coincides with the Chelungpu thrust (also known as the Tachien-shan thrust).

Through zone A, the upper crustal Vp contours have a NE strike (note in particular the trace of 5.2 km/s contour in Figure 6) that parallels the surface structural grain (Figure 4) and which continues with higher Vp values through the Alishan Ranges (AR in Figure 6), at the rear of the fold-and-thrust belt. We interpret the shallowing of the 5.2 km/s isovelocity contour across the Shuangtung thrust in the Alishan Ranges to indicate the presence of basement rocks that are involved in this part of the fold-and-thrust belt (Figures 5b and 7b) [see Alvarez-Marron *et al.*, 2014]. Zone A also marks an abrupt north to south increase in the amount of upper crustal seismicity (Figures 8a and 8b). South of zone A, seismicity is widespread in the upper 10 km across the Western Foothills and extends up to the coastline in the Coastal Plain. Events at 20 km depth are scattered, both to the north and south of zone A, while at 30 km depth seismicity occurs dominantly to the north. Beneath the Alishan Ranges, there is a good correlation between seismicity and the Shuilikeng fault (Figure 7b), although to the west seismicity clusters near the basement-cover interface, well below the interpreted location of the basal thrust. Finally, zone A marks a significant north-south increase in the topography of the fold-and-thrust belt, especially in the Western Foothills but also in the Hsuehshan Range, to the south of the Puli Basin (Figure 9a). Across zone A, the topography of the Western Foothills rises from just above sea level to form the northwest facing slope of the Alishan Ranges, which, at over 2400 m high, has the highest elevation in the Western Foothills of south central Taiwan.

Farther south, on the area that correlates with the necking zone (Figure 4), zones B and C both mark northeast striking, en echelon changes in the orientations of thrusts and curvature of fold axial traces as they take on a northeast-southwest strike. The thrust front is also interpreted to turn northeast-southwest and then continue southwestward into the offshore where it becomes the deformation front of the marine accretionary

prism that is climbing up the slope [e.g., Shyu *et al.*, 2005; Lin *et al.*, 2008]. From zone B southward, the fold-and-thrust belt widens into an imbricate thrust system that comprises wide synclines and narrow anticlines in its western part (Figures 4 and 5c). The synclines in the Chelungpu and Chutochi thrust sheets terminate northward at zone B, from where they plunge gently southward, and Miocene and younger sediments thicken. Eastward, across the Chishan thrust (CIT in Figure 5c), the broad anticlinorium of the Alishan Ranges narrows to less than half its width before terminating southward in a syncline that plunges beneath the alluvial sediments of the Pingtung Plain (Figure 4). South of zone C, which coincides with the on-land prolongation of the present shelf slope break, thrusts are almost entirely buried by the synorogenic sediments, and an active thrust top basin (the Pingtung Basin of Chiang *et al.* [2004]) is forming in the hanging wall of the Chishan thrust. The basal thrust is interpreted to comprise a series of narrow ramps and wide flats as it cuts gently down through the sedimentary section toward the east where it ramps steeply into the basement.

Zones B and C are located on the northern and southern flanks, respectively, of a roughly northeast striking *P* wave velocity high (>5.2 km/s) that extends northeastward from beneath the Coastal Plain through to the velocity high beneath the Alishan Ranges (Figure 6). We interpret this velocity high to be caused by basement rocks, and herein call it the Tainan Basement High (TBH in Figure 6). South of zone C, a pronounced velocity low suggests a deepening of the basement rocks and a concomitant increase in the thickness of the slope and foreland basin sediments. Along section C-C', the basement-cover interface ($V_p \geq 5.2$ km/s) dips gently eastward below the basal thrust (Figures 5c and 7c). There is widespread but scattered seismicity between zones B and C that roughly coincides with the Tainan Basement High (Figure 8). In the upper 10 km there is a southward decrease in seismicity across zone C in the western part of the fold-and-thrust belt, although at 20 km and 30 km depth there are events scattered throughout the southwest. The absence of any clear clustering of events makes it difficult to interpret the seismicity in terms of the structure of the fold-and-thrust belt in this area (Figure 7c). There is a very marked change in topography across zone B, from the widespread, high elevations of the Alishan Ranges to several roughly southwest-northeast oriented ridges that end southwestward (Figure 9a). At both zones B and C, these ridges undergo sharp, sigmoidal changes in strike that offset them up to several kilometers toward the west (e.g., Figures 9b and 9c). The ridges follow the trace of related thrusts and confine a set of south and southwest draining river basins. South of zone C, the topography is very subdued and only a few hills reach elevations of up to several tens of meters. In a large part of this area, the fold-and-thrust belt is buried by around 5000 m of Pliocene to Holocene sediments [see Mouthereau *et al.*, 2002; Chiang *et al.*, 2004].

4. Discussion

4.1. Along-Strike Changes Related to the Margin Structure

The necking zone of the Eurasian continental margin offshore southwestern Taiwan comprises an east north-east trending extensional fault system [Lee *et al.*, 1993; Lin *et al.*, 2003; Lin *et al.*, 2005; Ding *et al.*, 2008; Shi *et al.*, 2008; Tang and Zheng, 2010; Yang *et al.*, 1991, 2016; Yeh *et al.*, 2012; McIntosh *et al.*, 2014] that can be traced from the margin in the Taiwan Strait across the Coastal Plain [Chang, 1963, 1964; Lin *et al.*, 2003; Yang *et al.*, 2014] and into the fold-and-thrust belt where some of its faults are being reactivated [Suppe, 1986; Mouthereau *et al.*, 2001, 2002; Mouthereau and Lacombe, 2006; Yang *et al.*, 2007, 2016; Rodriguez-Roa and Wiltschko, 2010; Alvarez-Marron *et al.*, 2014; Camanni *et al.*, 2016]. In particular, the fault system along the upper part of the necking zone, the Yichu (or A), Meishan, and B faults (Figures 1 and 4), which also comprise the northern bounding faults of the Tainan Basin [Yang *et al.*, 1991; Lee *et al.*, 1993; Lin *et al.*, 2003], are of particular importance. The entire necking zone has regional-scale basement highs and lows (i.e., the Northern Depression, Central Uplift, and Southern Depression [Lin *et al.*, 2003] or the failed rift of Yeh *et al.* [2012] and McIntosh *et al.* [2014]) (Figure 2) that can be traced into the Coastal Plain (Figure 1) and, we suggest, into the fold-and-thrust belt where the Tainan Basement High correlates with the Central Uplift of the Tainan Basin [cf. Lin *et al.*, 2003; Li *et al.*, 2007; Ding *et al.*, 2008]. These basement highs and lows result in important changes in thickness of the Miocene and Pleistocene sediments [e.g., Hsiao, 1970; Shaw, 1996; Yang *et al.*, 2014]. The changes in sediment thickness from one thrust sheet to another has led to the interpretation of extensional fault reactivation in the fold-and-thrust [e.g., Suppe, 1986; Rodriguez-Roa and Wiltschko, 2010; Yang *et al.*, 2007, 2016; Alvarez-Marron *et al.*, 2014]. Furthermore, several east northeast striking faults have been historically active in the Coastal Plain area, with the 1906 Meishan and the 1946 Hsinhua earthquakes causing dextral oblique-slip surface ruptures [Bonilla, 1977; Shyu *et al.*, 2016]. We suggest, therefore, that

there is ample evidence that regional-scale east northeast striking faults that have been mapped on the necking zone of the Eurasian continental margin can be traced into the fold-and-thrust belt in southwest Taiwan where they are being reactivated, supporting our hypothesis that a number of these are causing important along-strike changes in structural architecture, seismicity, and topography of the fold-and-thrust belt in this area.

The most important along-strike change in the south central Taiwan fold-and-thrust belt takes place at zone A, which is the on-land prolongation of the upper part of the necking zone (Figures 4, 6, 8, and 9). Zone A forms the southern flank of Peikang Basement High, which has been widely recognized as an area of significant change in the structure, fault kinematics, and seismicity of the thrust belt [e.g., *Lu et al.*, 1998; *Deffontaines et al.*, 1997; *Lacombe et al.*, 1999; *Mouthereau et al.*, 2002; *Cheng et al.*, 2003; *Mouthereau and Lacombe*, 2006; *Wu et al.*, 2008, 2010; *Byrne et al.*, 2011; *Alvarez-Marron et al.*, 2014]. It has been suggested that these along-strike changes are largely due to buttressing [*Hayward and Graham*, 1989] of the thrust system by the basement high [e.g., *Lu et al.*, 1998; *Lacombe et al.*, 1999]. *Lu et al.* [1998] and *Lacombe et al.* [1999] also suggested that this basement high partially controls the tectonic escape that they interpret to take place in southwestern Taiwan. We concur with the previous authors that buttressing across the upper part of the necking zone appears to be an important deformation process. This is shown by the intensification of internal folding, back thrusting, and basement involvement in the immediate hanging wall of the Shuangtung thrust (Figure 5b). There is a significant increase in seismicity associated with the on-land projection of the upper part of the necking zone (Figure 8). Importantly, in this area, focal mechanism determinations by *Chang et al.* [2007], *Hsu et al.* [2010], *Wu et al.* [2010], *Chao et al.* [2011], and *Yang et al.* [2016] have shown that the dominant fault type to the west of the Chelungpu thrust is dextral strike-slip with lesser oblique thrusting; both of which have one roughly east northeast oriented nodal plane. To the east, these authors show a mixture of dextral strike-slip and oblique thrusting (with one nodal plane striking roughly east northeast) fault types. Likewise, modeling of GPS data [*Ching et al.*, 2011a] indicates that the deformation style in zone A is characterized by east northeast oriented, dextral strike-slip faulting. The dominance of east northeast oriented strike-slip faulting at zone A suggests a causal relationship with faults of this orientation mapped in the subsurface in the upper part of the necking zone [e.g., *Chow et al.*, 1988; *Lin et al.*, 2003; *Yang et al.*, 2014]. We suggest, therefore, that the along-strike change in structural architecture that takes place at zone A, together with the change in seismicity, are indicative of an east northeast striking lateral structure [the Choshui lateral structure of *Alvarez-Marron et al.* [2014]] that has an important component of dextral strike-slip movement. This lateral structure is forming by the reactivation of preexisting Miocene basin-bounding faults along the upper part of the necking zone, thereby accounting for the appearance and rapid increase in thickness of the middle Miocene Nanchuang Fm. In this interpretation, the abrupt southeastward increase in topography across zone A comprises the surface expression of the north dipping culmination wall that is forming above the Choshui lateral structure, with the maximum elevations reached in the basement-involved thrust sheets. While there are a number of factors that can influence topography [e.g., *Willet*, 1999; *Molnar*, 2009; *Champagnac et al.*, 2012], in south central Taiwan we agree with *Mouthereau et al.* [2002] that there appears to be a causal link between high elevations and the involvement of basement in the thrusting.

Southward, zones B and C illuminate two areas of along-strike change that are developing on the necking zone of the margin as it enters into the fold-and-thrust belt. These changes are not as pronounced as those at the upper part of the necking zone, but they are nevertheless significant features. There is an important change in the structural architecture across zone B, from the broad, basement-cored anticlinorium of the Alishan Ranges to the open synclines above a nearly horizontal basal thrust located in the Miocene and younger sediments (compare Figures 5b and 5c). En echelon, sigmoidal changes in the strike of fold axial traces, the surface trace of thrusts (Figure 4), and of topographic ridges (Figures 9b and 9c) at zones B and C all combine to suggest that these are being offset dextrally by east northeast oriented strike-slip faults. Note that in their modeled tectonic blocks *Ching et al.* [2011a] also identify two east northeast striking, dextral strike faults that roughly coincide with the locations of zones A and B. Sigmoidal offsets of structures and topography in fold-and-thrust belts are generally attributed either to reactivation of footwall basement faults or as transfer zones (tear faults) in the hanging wall that are caused by mechanical differences along the basal thrust [e.g., *Albers*, 1967; *Mugnier et al.*, 1999; *Ruh et al.*, 2014; *Koyi et al.*, 2016]. In southwestern Taiwan, the homogeneity of the hanging wall structural architecture from zone B southward seems to militate against strong mechanical differences along the basal thrust. Finally, the numerous earthquakes in the area of the

Tainan Basement High that have dextral strike-slip focal mechanisms with one roughly east northeast to northeast striking nodal plane [e.g., *Hsu et al.*, 2010; *Wu et al.*, 2010], together with the dextral east northeast striking surface rupture of the 1946 Hsinhua earthquake (Figure 4) [Bonilla, 1977], provide further support for the interpretation that the en echelon sigmoidal features observed at zones A and B are related to the dextral strike-slip reactivation of east northeast striking basement faults along the flanks of the Tainan Basement High (Figure 6).

Our proposal for east northeast striking along-strike changes in the south central Taiwan fold-and-thrust belt that are caused by the reactivation of margin structure with this orientation differs from that of other authors. For example, using various types of data, including structure, seismicity, and topography, *Deffontaines et al.* [1997], *Lacombe et al.* [1999], *Mouthereau et al.* [1999, 2002], and *Mouthereau and Lacombe* [2006] have suggested that there are a number of west northwest to northwest striking transfer zones in the western Taiwan fold-and-thrust belt. Of these, the Fengshan, Chishan, and Chiayi transfer zones are within our geological map area. Our mapping and analyses of the seismicity and topography data show no concrete evidence for the Fengshan and Chiayi transfer zones. In outcrop, the area of the Chishan transfer zone is a narrow, roughly west northwest striking fault (the Zuojhen fault (Figure 4)) developed predominantly in mudstone [see *Deffontaines et al.*, 1997]. Interpreting the regional structure of this area is complicated by the thick, monotonous mudstone lithology, several important thrusts, and what appears to be very little displacement across the Zuojhen fault. Nevertheless, more fieldwork is required to clarify the nature and importance of this fault. *Deffontaines et al.* [1997] point out that there is very little evidence for basement faults with a WNW strike, and they therefore suggest that the transfer zones are not caused by reactivation of basement faults but are newly formed in the hanging wall of the fold-and-thrust belt. *Lacombe et al.* [1999], *Mouthereau et al.* [1999, 2002], and *Mouthereau and Lacombe* [2006] do, however, suggest that basement fault reactivation is responsible for these transfer zones. In fact, *Ching et al.* [2011b] argue, on the basis of coseismic GPS displacements for sinistral displacement along the Chishan transfer fault during the 2010 Jiashian earthquake. Likewise, *Huang et al.* [2016] suggest that coseismic displacement during the 2016 Meinong earthquake took place, in part, along a NW striking fault surface, but they make no mention of the Chishan structure. Although these faults may exist in the subsurface, we do not see any evidence for them in our data. Finally, north-south oriented extensional transfer faults have been interpreted to occur on the necking zone [Yang et al., 1991], but these are at a significant angle to the Chishan and Chiayi transfer zones and roughly parallel to the Fengshan transfer.

4.2. Changes in Structure, Seismicity, and Topography From the Shelf to the Necking Zone

We furthermore suggest that the data supports the corollary to our proposed hypothesis, since it is possible to observe differences in structure, seismicity, and topography of the fold-and-thrust belt depending on whether it is the shelf or necking zone areas of the margin that are involved in the deformation. There is, for example, a very different style of basement involvement between the shelf and the necking zone. On the shelf, the roughly northeast oriented Hsuehshan Trough is inverting along almost north-south striking basin-bounding faults that penetrate deep into the crust [e.g., *Wu et al.*, 2004; *Camanni et al.*, 2014b; *Kuo-Chen et al.*, 2015], exposing deep levels of the synrift sediments that, along the eastern part of the Hsuehshan Range, have been metamorphosed to lower greenschist facies [e.g., *Clark et al.*, 1993; *Beyssac et al.*, 2007; *Simoës et al.*, 2012] and have a penetrative pressure solution cleavage [e.g., *Clark et al.*, 1993; *Tillman and Byrne*, 1995; *Fisher et al.*, 2002; *Brown et al.*, 2012]. The uplift of relatively high Vp material (Figure 7a) indicates that the Mesozoic basement rocks are involved in the thrusting. On the shelf part of the study area, seismicity is largely concentrated within the inverting Hsuehshan Trough, where it forms well-defined clusters along the basin-bounding faults (Figures 7a and 8) [e.g., *Wu et al.*, 2004; *Camanni et al.*, 2014a, 2014b; *Kuo-Chen et al.*, 2015]. We suggest that the roughly north-south oriented basin faults of the Hsuehshan Trough are ideally oriented for reactivation and the incorporation of basement rocks into the thrusting. Finally, the Hsuehshan Range has the highest elevations in the south central Taiwan fold-and-thrust belt (Figure 9), providing further evidence for the causal link between basement involvement in the thrusting and the development of high topography alluded to in section 3.1.

The upper part of the necking zone comprises a transitional area with complex structure that includes basement involvement in the thrusting, reactivation of east northeast oriented faults, widespread seismicity, and the formation of high topography. In contrast, farther down the necking zone, the basement appears to be

deforming without being incorporated into the thrust sheets. That the basement is deforming is attested to by the widespread, deep seismicity that is taking place across most of the necking zone. Seismicity is, however, dispersed and does not cluster in a way that highlights any particular fault, as it does in the Hsuehshan Range. This could imply that the basement in this area is highly fractured, with fractures optimally oriented for reactivation. It may also indicate that the seismicity data window we present (20 years) is too short to illuminate the major linked fault system that is forming the foreland thrust-and-fold belt. A further indication that basement rocks are not involved in the thrusting is the gentle eastward dip of 5.2 km/s isovelocity surface, which contrasts with what happens in the Hsuehshan Range where there is a marked shallowing of higher velocities. The Zagros [Koyi *et al.*, 2016] and the Keping Shan [Turner *et al.*, 2010] are two well-documented examples in which, as along the necking zone in southwestern Taiwan, basement faults that are at a high angle to the structural grain of a thrust belt are either bending structures into a sigmoidal geometry (Zagros) or even cut completely through the thrust belt (Keping Shan) but are not involved in the thrusting. We suggest that, in southwest Taiwan, the east northeast striking extensional faults on the necking zone of the margin [i.e., Yang *et al.*, 2014] are, like those in Zagros and Keping Shan, ideally oriented for reactivation as strike-slip faults and that they are beginning to affect the fold-and-thrust belt, causing the dextral, sigmoidal offset of thrusts, fold axes, and topography (Figures 4 and 9). Without basement involvement in the thrusting, topography on the necking zone is subdued, with no change in elevation associated with the basement faults.

5. Conclusions

Regional-scale east northeast striking faults that have been mapped on the necking zone of the Eurasian continental margin in the Taiwan Strait can be traced into the fold-and-thrust belt in southwest Taiwan where they are being reactivated, supporting our hypothesis that a number of these are causing important along-strike changes in structural architecture, seismicity, and topography of the fold-and-thrust belt in this area. The most important along-strike change takes place in the upper part of the necking zone where there is an abrupt north-south change in structure, an increase in the amount of seismicity, and an increase in topography. These changes are interpreted to be caused by the east northeast striking, dextral strike-slip Choshui lateral structure that is forming by the reactivation of preexisting faults along the upper part of the necking zone. The abrupt southeastward increase in topography across the upper part of the necking zone is the surface expression of the north dipping culmination wall of the Choshui lateral structure. Maximum elevations in this area are reached in the basement-involved thrust sheets, suggesting a causal link between basement involvement in the thrusting and high topography. Farther south, on the necking zone proper, along-strike changes are marked by en echelon, sigmoidal offsets in the strike of fold axial traces, the surface trace of thrusts, and of topographic ridges. The widespread, deep seismicity that is taking place across most of the necking zone provides evidence that the basement is involved in the deformation, but it is difficult to correlate events with individual faults. Nevertheless, basement appears to be deforming without being incorporated into the thrust sheets, and the sigmoidal offset of structures and topography is suggestive of the dextral strike-slip reactivation of east northeast striking basement faults.

It is also possible to observe differences in structure, seismicity, and topography of the fold-and-thrust belt depending on whether it is the shelf or necking zone areas of the margin that are involved in the deformation. On the shelf, the roughly northeast oriented Hsuehshan Trough is inverting along almost north-south striking basin-bounding faults that penetrate into the middle crust and have well-clustered, deep seismicity. The relationship between basement involvement in the thrusting and high topography is particularly apparent in the Hsuehshan Range. On the necking zone, east northeast oriented faults are at a high angle to the thrusting and are being reactivated as dextral strike-slip faults that are causing en echelon, sigmoidal offset of structures and topography. Seismicity is scattered, and there is no basement involvement in the thrusting.

Acknowledgments

D.B., J.A-M., and C.B. acknowledge funding provided by the Spanish Ministerio de Economía y Competitividad grant CGL2013-43877-P. H.K-C. acknowledges funding by MOST 104-2628-M-008-005-MY3. We thank two anonymous reviewers for their comments. The geophysical data are available at <http://140.115.22.221/download/data>.

References

- Albers, J. P. (1967), Belt of sigmoidal bending and right-lateral faulting in the western Great Basin, *Geol. Soc. Am. Bull.*, 78, 143–156.
- Alvarez-Marron, J., D. Brown, G. Camanni, Y.-M. Wu, and H. Kuo-Chen (2014), Structural complexities in a foreland thrust belt inherited from the shelf-slope transition: Insights from the Alishan area of Taiwan, *Tectonics*, 33, 1322–1339, doi:10.1002/2014TC003584.
- Arora, B. R., V. K. Gahalaut, and N. Kumar (2012), Structural control on along-strike variation in the seismicity of the northwest Himalaya, *J. Asian Earth Sci.*, 57, 15–24, doi:10.1002/2014TC003584.

- Beysac, O., M. Simoes, J. P. Avouac, K. A. Farley, Y.-G. Chen, Y.-C. Chan, and B. Goffé (2007), Late Cenozoic metamorphic evolution and exhumation of Taiwan, *Tectonics*, 26, TC6001, doi:10.1029/2006TC002064.
- Blanc, E. J.-P., M.B. Allen, S. Inger, and H. Hassani (2003), Structural styles in the Zagros simple folded zone, Iran, *J. Geol. Soc.*, 160, 401–412.
- Bonilla, M. G. (1977), Summary of Quaternary faulting and elevation changes in Taiwan, *Mem. Geol. Soc. China*, 2, 43–55.
- Boutoux, A., N. Bellahsen, O. Lacombe, A. Verlaque, and F. Mouthereau (2014), Inversion of pre-orogenic extensional basins in the external western Alps: Structure, microstructures and restoration, *J. Struct. Geol.*, 60, 13–29.
- Brown, D., J. Alvarez-Marron, A. Perez-Estaun, V. Puchkov, and C. Ayala (1999), Basement influence on foreland thrust and fold belt development: An example from the southern Urals, *Tectonophysics*, 308, 459–472.
- Brown, D., J. Alvarez-Marron, M. Schimmel, Y.-M. Wu, and G. Camanni (2012), The structure and kinematics of the central Taiwan mountain belt derived from geological and seismicity data, *Tectonics*, 31, TC5013, doi:10.1029/2012TC003156.
- Butler, R. W. H., E. Tavarnelli, and M. Grasso (2006), Structural inheritance in mountain belts: An Alpine–Apennine perspective, *J. Struct. Geol.*, 28, 1893–1908.
- Byrne, T., Y.-C. Chan, R.-J. Rau, C.-Y. Lu, Y.-H. Lee, and Y.-J. Wang (2011), The arc–continent collision in Taiwan, in *Arc-Continent Collision, Frontiers in Earth Sciences Series*, edited by D. Brown and P. D. Ryan, pp. 213–245, Springer, Berlin.
- Calamita, F., S. Satolli, V. Scisciani, P. Eserice, and P. Pace (2011), Contrasting styles of fault reactivation in curved orogenic belts: Examples from the central Apennines (Italy), *Geol. Soc. Am. Bull.*, 123, 1097–1111.
- Camanni, G., C.-H. Chen, D. Brown, J. Alvarez-Marron, Y.-M. Wu, H.-A. Chen, H.-H. Huang, H.-T. Chu, M.-M. Chen, and C.-H. Chang (2014a), Basin inversion in central Taiwan and its importance for seismic hazard, *Geology*, 42, 147–150.
- Camanni, G., D. Brown, J. Alvarez-Marron, Y.-M. Wu, and H.-A. Chen (2014b), The Shuilikeng fault in central Taiwan mountain belt, *J. Geol. Soc.*, 171, 117–130.
- Camanni, G., J. Alvarez-Marron, D. Brown, C. Ayala, Y.-M. Wu, and H.-H. Hsieh (2016), The deep structure of south-central Taiwan illuminated by seismic tomography and earthquake hypocentre data, *Tectonophysics*, 679, 235–245.
- Castelltort, S., S. Nagel, F. Mouthereau, A. Lin, A. Wetzel, B. Kaus, S. Willet, S.-P. Chiang, and W.-Y. Chiu (2010), Sedimentology of early Pliocene sandstones in the southwestern Taiwan foreland: Implications for basin physiography in the early stages of collision, *J. Asian Earth Sci.*, 40, 52–71.
- Champagnac, J.-D., P. Molnar, C. Sue, and F. Herman (2012), Tectonics, climate, and mountain topography, *J. Geophys. Res.*, 117, B02403, doi:10.1029/2011JB008348.
- Chang, C.-H., Y.-M. Wu, L. Zhao, and F. T. Wu (2007), Aftershocks of the 1999 Chi-Chi, Taiwan, earthquake: The first hour, *Bull. Seismol. Soc. Am.*, 97, 1245–1258.
- Chang, L. S. (1976), The Lushanian stage in the central range of Taiwan and its fauna, in *Progress in Micropaleontology, The Am. Museum of Natural History*, edited by Y. Takayanagi, and T. Saito, pp. 27–35, Micropaleontology Press, New York.
- Chang, S. L. (1963), Regional stratigraphic study of Pliocene and upper Pliocene formations in Chiayi and Hsinying area, Taiwan, *Pet. Geol. Taiwan*, 2, 65–86.
- Chang, S. L. (1964), Regional stratigraphic study of lower Pliocene and upper Miocene formations in Chiayi and Hsinying area, Taiwan, *Pet. Geol. Taiwan*, 3, 1–20.
- Chao, W.-A., L. Zhao, and Y.-M. Wu (2011), Centroid fault-plane inversion in three-dimensional velocity structure using strong-motion records, *Bull. Seismol. Soc. Am.*, 101, 1330–1340.
- Chatzaras, V., P. Xypolias, S. Kokkalas, and I. Koukouvelas (2013), Tectonic evolution of a crustal-scale oblique ramp, Hellenides thrust belt, Greece, *J. Struct. Geol.*, 57, 16–37.
- Chen, C.-H., et al. (2000), Geological map of Taiwan, scale 1:500,000, Central Geological Survey, Taipei.
- Chen, A. T., and Y.-L. Yang (1996), Lack of compressional overprint on the extensional structure in the offshore Tainan and the tectonic implications, *Terr. Atmos. Ocean. Sci.*, 7, 505–522.
- Chen, W.-S., K. D. Ridgway, C.-S. Horng, Y.-G. Chen, K.-S. Shea, and M.-G. Yeh (2001), Stratigraphic architecture, magnetostratigraphy, and incised-valley systems of the Pliocene-Pleistocene collisional marine foreland basin of Taiwan, *Geol. Soc. Am. Bull.*, 113, 1249–1271.
- Chen, M.-M., N.-T. Yu, H.-T. Chu, K.-S. Shea, and Y.-C. Hsieh (2009), Larger foraminifera in the so-called “Meichi sandstone” of Wujie area, southern Hsuehshan range, *Central Geol. Surv. Spec. Pub.*, 22, 227–242.
- Chen, K.-X., H. Kuo-Chen, D. Brown, Q. Li, Z. Ye, W.-T. Liang, C.-Y. Wang, and H. Yao (2016), Three-dimensional ambient noise tomography across the Taiwan Strait: The structure of a magma-poor rifted margin, *Tectonics*, 35, 1782–1792, doi:10.1002/2015TC004097.
- Cheng, W.-B., H.-C. Huang, C. Wang, M.-S. Wu, and T.-H. Hsuan (2003), Velocity structure, seismicity, and fault structure in the Peikang High are of western Taiwan, *Terr. Atmos. Ocean. Sci.*, 14, 63–83.
- Chiang, C.-S., H.-S. Yu, and Y.-W. Chou (2004), Characteristics of the wedge-top depozone of the southern Taiwan foreland basin system, *Basin Res.*, 16, 65–78.
- Ching, K.-E., R.-J. Rau, K. M. Johnson, J.-C. Lee, and J.-C. Hu (2011a), Present-day kinematics of active mountain building in Taiwan from GPS observations during 1995–2005, *J. Geophys. Res.*, 116, B09405, doi:10.1029/2010JB008058.
- Ching, K.-E., K. M. Johnson, R.-J. Rau, R. Y. Chuang, L.-C. Kuo, and P.-L. Leu (2011b), Inferred fault geometry and slip distribution of the 2010 Jiashian, Taiwan, earthquake is consistent with a thick-skinned deformation model, *Earth Planet. Sci. Lett.*, 301, 78–86.
- Chiu, H.-T. (1975), Miocene stratigraphy and its relation to the Palaeogene rocks in west-central Taiwan, *Pet. Geol. Taiwan*, 12, 51–80.
- Chow, J., K.-M. Yang, and H.-M. Chen (1988), Seismic interpretation of the subsurface structures in the Yichu-Chiali area, southern Taiwan, *Pet. Geol. Taiwan*, 24, 60–95.
- Christensen, N. I. (1989), Pore pressure, seismic velocities, and crustal structure, in *Geophysical Framework of the Continental United States*, vol. 172, edited by L. C. Pakiser and W. D. Mooney, pp. 783–798, Geol. Soc. Am. Mem., Boulder, Colo.
- Christensen, N. I., and D. Stanley (2003), Seismic velocities and densities of rocks, *Inter. Handbook Earthquake Eng. Seis.*, 81, 1587–1593.
- Chuang, R. Y., K. M. Johnson, Y.-M. Wu, K.-E. Ching, and L.-C. Kuo (2013), A midcrustal ramp-fault structure beneath the Taiwan tectonic wedge illuminated by the 2013 Nantou earthquake series, *Geophys. Res. Lett.*, 40, 5080–5084, doi:10.1002/grl.51005.
- Clark, M. B., D. M. Fisher, C.-Y. Lu, and C.-H. Chen (1993), Kinematic analyses of the Hsuehshan range, Taiwan: A large-scale pop-up structure, *Tectonics*, 12, 205–217.
- Covey, M. (1986), The evolution of foreland basins to steady state: Evidence from the western Taiwan foreland basin, in *Foreland Basins, Spec. Pub. 8. Int. Ass. Sed.*, edited by P. A. Allen and P. Homewood, pp. 77–90, Blackwell, Oxford, U. K.
- Cukur, D., S. Horozal, D. C. Kim, and H. C. Han (2011), Seismic stratigraphy and structural analysis of the northern East China Sea Shelf Basin interpreted from multi-channel seismic reflection data and cross-section restoration, *Mar. Pet. Geol.*, 28, 1003–1022.
- Dahlstrom, C. D. A. (1969), Balanced cross sections, *Can. J. Earth Sci.*, 6, 743–757.

- Deffontaines, B., O. Lacombe, J. Angelier, H.-T. Chu, F. Mouthereau, C.-T. Lee, J. Deramond, J.-F. Lee, M.-S. Yu, and P.-M. Liew (1997), Quaternary transfer faulting in the Taiwan Foothills: Evidence from a multisource approach, *Tectonophysics*, **274**, 61–82.
- Deng, J.-M., T.-K. Wang, B.-J. Yang, C.-S. Lee, C.-S. Liu, and S.-C. Chen (2012), Crustal velocity structure off SW Taiwan in the northernmost South China Sea imaged from TAIGER OBS and MCS data, *Mar. Geophys. Res.*, **33**, 327–349.
- Ding, W.-W., J.-B. Li, M.-B. Li, X.-L. Qiu, Y.-X. Fang, and Y. Tang (2008), A Cenozoic tectono-sedimentary model of the Tainan Basin, the South China Sea: Evidence from multi-channel seismic profile, *J. Zhejiang Uni. Sci.*, **9**, 702–713.
- Duncan, C., J. Masek, and E. Fielding (2003), How steep are the Himalaya? Characteristics and implications of along-strike topographic variations, *Geology*, **31**, 75–78.
- Ernst, W. G., (1983), Mineral paragenesis in metamorphic rocks exposed along Tailuko gorge, Central Mountain range, Taiwan, *J. Metamorph. Geol.*, **1**, 305–329.
- Fisher, D. M., C.-Y. Lu, and H.-T. Chu (2002), Taiwan slate belt: Insights into the ductile interior of an arc-continent collision, in *Geology and Geophysics of an Arc-Continent Collision, Taiwan*, vol. 358, edited by T. B. Byrne and C.-S. Liu, pp. 93–106, Geol. Soc. Am. Spec. Paper, Boulder, Colo.
- Godin, L., and L. B. Harris (2014), Tracking basement cross-strike discontinuities in the Indian crust beneath the Himalayan orogeny using gravity data—Relationship to upper crustal faults, *Geophys. J. Int.*, **198**, 198–215.
- Hall, R. (1996), Reconstructing Cenozoic SE Asia, in *Tectonic Evolution of Southeast Asia*, vol. 106, edited by R. Hall and D. Blundell, pp. 153–184, Geol. Soc. London Spec. Pub.
- Hall, R. (2001), Cenozoic reconstructions of SE Asia and the SW Pacific: Changing patterns of land and sea, in *Faunal and Floral Migrations and Evolution in SE Asia-Australasia*, edited by I. Metcalfe, et al., pp. 35–56, Swets and Zeitlinger, Lisse.
- Hayward, A. B., and R. H. Graham (1989), Some geometrical characteristics of inversion, in *Inversion Tectonics*, vol. 44, edited by M. A. Cooper and G. D. Willaims, pp. 17–39, Geol. Soc. Spec. Pub.
- Ho, C.-S. (1986), A synthesis of the geologic evolution of Taiwan, *Tectonophysics*, **125**, 1–16.
- Ho, C.-S. (1988), *An Introduction to the Geology of Taiwan: Explanatory Text of the Geological Map of Taiwan*, 192 pp., Central Geol. Sur., Taipei.
- Hossack, J. R. (1979), The use of balanced cross-sections in the calculation of orogenic contraction: A review, *J. Geol. Soc.*, **136**, 705–711.
- Hsiao, P.-T. (1970), Seismic study of the area between the Coastal Plain and the Foothills, Chiayi, Taiwan, *Pet. Geol. Taiwan*, **7**, 47–52.
- Hsu, Y.-J., L. Rivera, Y.-M. Wu, C.-H. Chang, and H. Kanamori (2010), Spatial heterogeneity of tectonic stress and friction in the crust: New evidence from earthquake focal mechanisms in Taiwan, *Geophys. J. Int.*, **182**, 329–342.
- Huang, C.-Y., W.-Y. Wu, C.-P. Chang, S. Tsao, P.-B. Yuan, C.-W. Lin, and K.-Y. Xia (1997), Tectonic evolution of accretionary prism in the arc-continent collision terrane of Taiwan, *Tectonophysics*, **281**, 31–51.
- Huang, C.-Y., P. B. Yuan, and S. J. Tsao (2006), Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis, *Geol. Soc. Am. Bull.*, **118**, 274–288.
- Huang, C.-Y., Y. Yen, Q. H. Zhao, and C.-T. Lin (2012), Cenozoic stratigraphy of Taiwan: Window into rifting, stratigraphy and paleoceanography of South China Sea, *Chin. Sci. Bull.*, **57**, 3130–3149.
- Huang, C.-Y., W.-R. Chi, Y. Yan, K.-M. Yang, P.-M. Liew, M.-S. Wu, J.-C. Wu, and C. Zhang (2013), The first record of Eocene tuff in a Paleogene rift basin near Nantou, Western Foothills, central Taiwan, *J. Asian Earth Sci.*, **69**, 3–16.
- Huang, H.-H., Y.-M. Wu, X. Song, C.-H. Chang, S.-J. Lee, T.-M. Chang, and H.-H. Hsieh (2014), Joint Vp and Vs tomography of Taiwan: Implications for subduction-collision orogeny, *Earth Planet. Sci. Lett.*, **392**, 177–191.
- Huang, M.-M., H. Tung, E. J. Fielding, H.-H. Huang, C. Liang, C. Huang, and J.-C. Hu (2016), Multiple fault slip triggered above the 2016 M_W 6.4 Meinong earthquake in Taiwan, *Geophys. Res. Lett.*, **43**, 7459–7467, doi:10.1002/2016GL069351.
- Hung, J.-H., K.-F. Ma, C.-Y. Wang, H. Ito, W. Lin, and E.-C. Yeh (2009), Subsurface structure, physical properties, fault-zone characteristics and stress state in scientific drill holes of Taiwan Chelungpu Fault Drilling Project, *Tectonophysics*, **466**, 307–321.
- Jackson, J. A. (1980), Reactivation of basement faults and crustal shortening in orogenic belts, *Nature*, **283**, 343–346.
- Jahn, B.-M., F. Martineau, J. J. Peucat, and J. Cornichet (1986), Geochronology of the Tananao schist complex, Taiwan, and its regional tectonic significance, *Tectonophysics*, **125**, 103–124.
- Jahn, B.-M., W.-R. Chi, and T.-F. Yui (1992), A Late Permian formation of Taiwan marbles from Chia-Li well no.1: Pb-Pb isochron and Sr isotopic evidence, and its regional geological significance, *J. Geol. Soc. China*, **35**, 193–218.
- Johnston, J. E., and N. I. Christensen (1992), Shear wave reflectivity, anisotropies, Poissons ratios, and densities of a southern Appalachian Paleozoic sedimentary sequence, *Tectonophysics*, **210**, 1–20.
- Johnston, J. E., and N. I. Christensen (1993), Compressional to shear velocity ratios in sedimentary rocks, *Int. J. Rock Mech. Min. Sci. Geomech. Abs.*, **30**, 751–754.
- Kelly, P. G., D. C. P. Peacock, D. J. Sanderson, and A. C. McGurk (1999), Selective reverse-reactivation of normal faults, and deformation around reverse-reactivated faults in the Mesozoic of the Somerset coast, *J. Struct. Geol.*, **21**, 493–509.
- Kim, K.-H., J.-M. Chiu, H. Kao, Q. Liu, and Y.-H. Yeh (2004), A preliminary study of crustal structure in Taiwan region using receiver function analysis, *Geophys. J. Int.*, **159**, 146–164.
- Koyi, H., F. Nilfouroushan, and K. Hessami (2016), Modelling role of basement block rotation and strike-slip faulting on structural pattern in cover units of fold-and-thrust belts, *Geol. Mag.*, **153**, 827–844.
- Kuo-Chen, H., F. T. Wu, and S. W. Roecker (2012), Three-dimensional P velocity structures of the lithosphere beneath Taiwan from the analysis of TAIGER and related seismic data sets, *J. Geophys. Res.*, **117**, B06306, doi:10.1029/2011JB009108.
- Kuo-Chen, H., F. T. Wu, W.-L. Chang, C.-Y. Chang, C.-Y. Cheng, and N. Hirata (2015), Is the Lishan fault of Taiwan active?, *Tectonophysics*, **661**, 210–214.
- Lacombe, O., F. Mouthereau, B. Deffontaines, J. Anglier, H.-T. Chu, and C.-T. Lee (1999) Geometry and Quaternary kinematics of fold-and-thrust units of southwestern Taiwan, *Tectonics*, **18**, 1198–1223.
- Lan, C.-Y., C.-S. Lee, T.-F. Yui, H.-T. Chu, and B.-M. Jahn (2008), The tectono-thermal events of Taiwan and their relationship with SE China, *Terr. Atmos. Ocean. Sci.*, **19**, 257–278.
- Lee, C.-S. (1979), Paleogene rocks of the Yushan-Shuili area, Nantou, central Taiwan, *Mem. Geol. Soc. China*, **3**, 237–247.
- Lee, T.-Y., C.-H. Tang, J.-S. Ting, and Y.-Y. Hsu (1993), Sequence stratigraphy of the Tainan Basin, offshore southwestern Taiwan, *Pet. Geol. Taiwan*, **26**, 119–158.
- Lester, R., H. J. A. Van Avendonk, K. McIntosh, L. Lavier, C.-S. Liu, T.-K. Wang, and F. Wu (2014), Rifting and magmatism in the northeastern South China Sea from wide-angle tomography and seismic reflection imaging, *J. Geophys. Res. Solid Earth*, **119**, 2305–2323, doi:10.1002/2013JB010639.
- Li, C.-F., Z. Zhou, J. Li, H. Hao, and J. Geng (2007), Structures of the northeasternmost South China Sea continental margin and ocean basin: Geophysical constraints and tectonic implications, *Mar. Geophys. Res.*, **28**, 59–79.

- Lin, A. T., and A. Watts (2002), Origin of the west Taiwan Basin by orogenic loading and flexure of a rifted continental margin, *J. Geophys. Res.*, 107(B9), 2185, doi:10.1029/2001JB000669.
- Lin, A., A. Watts, and P. Hesselbo (2003), Cenozoic stratigraphy and subsidence history of the South China Sea margin in the Taiwan region, *Basin Res.*, 15, 453–478.
- Lin, J.-Y., J.-C. Sibuet, and S.-K. Hsu (2005), Distribution of the East China Sea continental shelf basins and depths of magnetic sources, *Earth Planet. Space*, 57, 1063–1072.
- Lin, A. T., C.-S. Liu, C.-C. Lin, P. Schnurle, G.-Y. Chen, W.-Z. Liao, L. S. Teng, H.-J. Chuang, and M.-S. Wu (2008), Tectonic features associated with the overriding of an accretionary wedge on top of a rifted continental margin: An example from Taiwan, *Mar. Geol.*, 255, 186–203.
- Lo, C.-H., and T. C. Onstott (1995), Rejuvenation of K–Ar systems for minerals in the Taiwan mountain belt, *Earth Planet Sci Lett*, 131, 71–98.
- Lu, C.-Y., F.-S. Jeng, K.-J. Chang, and W. T. Jian (1998), Impact of basement high on the structure and kinematics of the western Taiwan thrust wedge: Insights from sandbox models, *Terr. Atmos. Ocean. Sci.*, 9, 533–550.
- Mavko, G., T. Mukerji, and J. Dvorkin (1998), *The Rock Physics Handbook: Tools for Seismic Analysis in Porous Media*, 329 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.
- McIntosh, K., H. Van Avendonk, L. Lavier, W. R. Lester, D. Eakin, F. Wu, C.-S. Liu, and C.-S. Lee (2013), Inversion of a hyper-extended rifted margin in the southern central range of Taiwan, *Geology*, 41, 871–874.
- McIntosh, K., L. Lavier, H. Van Avendonk, R. Lester, D. Eakin, and C.-S. Liu (2014), Crustal structure and inferred rifting processes in the northeast South China Sea, *Mar. Pet. Geol.*, 58, 612–626.
- Mohn, G., G. Manatschal, M. Beltrando, E. Masini, and N. Kusznir (2012), Necking of the continental crust in magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins, *Tectonics*, 31, TC1012, doi:10.1029/2011TC002961.
- Molnar, P. (2009), The state of interactions among tectonics, erosion, and climate: A polemic, *GSA Today*, 19, 44–45.
- Mouthereau, F., and O. Lacombe (2006), Inversion of the Paleogene Chinese continental margin and thick-skinned deformation in the western foreland of Taiwan, *J. Struct. Geol.*, 28, 1977–1993.
- Mouthereau, F., O. Lacombe, B. Deffontaines, J. Angelier, H.-T. Chu, and C.-T. Lee (1999), Quaternary transfer faulting and belt front deformation at Pakuashan (western Taiwan), *Tectonics*, 18, 215–230.
- Mouthereau, F., O. Lacombe, B. Deffontaines, J. Angelier, and S. Brusset (2001), Deformation history of the southwestern Taiwan foreland thrust belt: Insights from tectono-sedimentary analyses and balanced cross-sections, *Tectonophysics*, 333, 293–322.
- Mouthereau, F., B. Deffontaines, O. Lacombe, and J. Angelier (2002), Variations along the strike of the Taiwan thrust belt: Basement control on structural style, wedge geometry, and kinematics, in *Geology and Geophysics of an Arc-Continent Collision, Taiwan*, vol. 358, edited by T. B. Byrne and C.-S. Liu, pp. 31–54, Geol. Soc. Am. Spec. Paper, Boulder, Colo.
- Mouthereau, F., O. Lacombe, and B. Meyer (2006), The Zagros folded belt (Fars, Iran): Constraints from topography and critical wedge modeling, *Geophys. J. Int.*, 165, 336–356.
- Mugnier, J. L., P. Leturmy, G. Mascle, P. Huyghe, E. Chalaron, G. Vidal, L. Husson, and B. Delcaillau (1999), The Siwaliks of western Nepal I. Geometry and kinematics, *J. Asian Earth Sci.*, 17, 629–642.
- Nagel, S., S. Castelltort, A. Wetzel, S. D. Willett, F. Mouthereau, and A. T. Lin (2013), Sedimentology and foreland basin paleogeography during Taiwan arc continent collision, *J. Asian Earth Sci.*, 62, 180–204.
- Nissen, S. S., D. E. Hayes, P. Buhl, and J. Diebold (1995), Deep penetration seismic soundings across the northern margin of the South China Sea, *J. Geophys. Res.*, 100, 22,407–22,433.
- Perez-Estaun, A., J. Alvarez-Marron, D. Brown, V. Puchkov, Y. Gorozhanina, and V. Baryshev (1997), Along-strike structural variations in the foreland thrust and fold belt of the southern Urals, *Tectonophysics*, 276, 265–280.
- Rodriguez-Roa, F. A., and D. V. Wiltschko (2010), Thrust belt architecture of the central and southern western foothills of Taiwan, in *Hydrocarbons in Contractual Belts*, vol. 348, edited by G. P. Goffey et al., pp. 137–168, Geol. Soc. London, Spec. Pub., Boulder, Colo.
- Ruh, J. B., T. Gerya, and J.-P. Burg (2014), 3D effects of strain vs. velocity weakening on deformation patterns in accretionary wedges, *Tectonophysics*, 615–616, 122–141.
- Shaw, C.-L. (1996), Stratigraphic correlation and isopach maps of the western Taiwan Basin, *Terr. Atmos. Ocean. Sci.*, 7, 333–360.
- Shea, K.-S., H.-C. Chang, T.-Y. Huang, H.-C. Ho, W.-H. Lin, C.-W. Lin, and H.-W. Chen (2003), Geological column in Taiwan, *Central Geol. Surv. Taiwan*, Taiwan.
- Shi, X., H. Xu, X. Qiu, K. Xia, X. Yang, and Y. Li (2008), Numerical modeling on the relationship between thermal uplift and subsequent rapid subsidence: Discussion on the evolution of the Tainan Basin, *Tectonics*, 27, TC6003, doi:10.1029/2007TC002163.
- Shyu, J. B. H., K. Sieh, Y.-G. Chen, and C.-S. Liu (2005), Neotectonic architecture of Taiwan and its implications for future large earthquakes, *J. Geophys. Res.*, 110, B08402, doi:10.1029/2004JB003251.
- Shyu, J. B. H., Y.-R. Chuang, Y.-L. Chen, Y.-R. Lee, and C.-T. Cheng (2016), A new on-land seismogenic structure source database from the Taiwan earthquake model (TEM) project for seismic hazard analysis of Taiwan, *Terr. Atmos. Ocean. Sci.*, 27, 311–323.
- Simoes, M., O. Beyssac, and Y.-G. Chen (2012), Late Cenozoic metamorphism and mountain building in Taiwan: A review, *J. Asian Earth Sci.*, 46, 92–119.
- Smith, A. D., and C. Lewis (2007), Geochemistry of metabasalts and associated metasedimentary rocks from the Lushan formation of the upthrust slate belt, south-central Taiwan, *Int. Geol. Rev.*, 49, 1–13.
- Stanley, R. S., L. B. Hill, H. C. Chang, and H. N. Hu (1981), A transect through the metamorphic core of the central mountains, southern Taiwan, *Mem. Geol. Soc. China*, 4, 443–473.
- Sung, Q.-C., and Y. Wang (1985), Petrofacies of late Miocene sediments in the Hengchun Peninsula and its tectonic implication, *Proc. Geol. Soc. China*, 28, 23–44.
- Suppe, J. (1986), Reactivated normal faults in the western Taiwan fold-and-thrust belt, *Mem. Geol. Soc. China*, 7, 187–200.
- Tang, Q., and C. Zheng (2010), Seismic velocity structure and improved seismic image of the southern depression of the Tainan Basin from pre-stack depth migration, *Terr. Atmos. Ocean. Sci.*, 21, 807–816.
- Teng, L.-S. (1987), Stratigraphic records of the late Cenozoic Penglai orogeny of Taiwan, *Acta Geol. Taiwanica*, 25, 205–224.
- Teng, L.-S. (1992), Geotectonic evolution of Tertiary continental margin basins of Taiwan, *Pet. Geol. Taiwan*, 27, 1–19.
- Teng, L.-S., and A.-T. Lin (2004), Cenozoic tectonics of the China continental margin: insights from Taiwan, in *Aspects of the Tectonic Evolution of China*, vol. 226, edited by J. Malpas, C. J. N. Fletcher, J. R. Ali, and J. C. Aitchison, pp. 313–332, Geol. Soc. London Spec. Pub., London.
- Teng, L. S., Y. Wang, C.-H. Tang, C.-Y. Huang, T.-C. Huang, M.-S. Yu, and A. Ke (1991), Tectonic aspects of the Paleogene depositional basin of northern Taiwan, *Proc. Geol. Soc. China*, 34, 313–336.
- Thomas, W. A. (1985), The Appalachian-Ouachita connection: Paleozoic orogenic belt at the southern margin of North America, *Annu. Rev. Earth Planet. Sci.*, 13, 175–199.
- Tillman, K. S., and T. B. Byrne (1995), Kinematic analysis of the Taiwan Slate Belt, *Tectonics*, 14, 322–341.

- Tsai, C.-H., S.-K. Hsu, Y.-C. Yeh, C.-S. Lee, and K. Xia (2004), Crustal thinning of the northern continental margin of the South China Sea, *Mar. Geophys. Res.*, *25*, 63–78.
- Turner, S. A., J. W. Cosgrove, and J. G. Liu (2010), Controls on lateral structural variability along the Keping Shan Thrust Belt, SW Tien Shan foreland, China, in *Hydrocarbons in Contractual Belts*, vol. 348, edited by G. P. Goffey et al., 71–85, Geol. Soc. London Spec. Pub., London.
- Waldhauser, F. (2001), hypoDD: A computer program to compute double-difference hypocenter locations, *U.S. Geol. Surv. Open File Rep.*, *01–113*, 25 pp.
- Waldhauser, F., and W. L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.*, *90*, 1353–1368.
- Willet, S. D. (1999), Orogeny and orography: The effects of erosion on the structure of mountain belts, *J. Geophys. Res.*, *104*, 28,957–28,981.
- Witschko, D., and D. Eastman (1983), Role of basement warps and faults in localizing thrust fault ramps, in *Contributions to the Tectonics and Geophysics of Mountain Chains*, vol. 158, edited by R. D. Hatcher, H. Williams, and I. Zietz, pp. 177–190, Geol. Soc. Am. Mem., Boulder, Colo.
- Wintsch, R. P., H. J. Yang, X.-H. Li, and K.-A. Tung (2011), Geochronologic evidence for a cold arc–continent collision; the Taiwan orogeny, *Lithos*, *125*, 236–248.
- Wu, F.-T., C.-H. Chang, and Y.-M. Wu (2004), Precisely relocated hypocentres, focal mechanisms and active orogeny in central Taiwan, in *Aspects of the Tectonic Evolution of China*, vol. 226, edited by J. Malpas, et al., pp. 333–354, Geol. Soc. London Spec. Pub., London.
- Wu, Y.-M., C.-H. Chang, L. Zhao, J. B. H. Shyu, Y.-G. Chen, K. Sieh, and J. P. Avouac (2007), Seismic tomography of Taiwan: Improved constraints from a dense network of strong motion stations, *J. Geophys. Res.*, *112*, B08312, doi:10.1029/2007JB004983.
- Wu, Y.-M., L. Zhao, C.-H. Chang, and Y.-J. Hsu (2008), Focal-mechanism determination in Taiwan by genetic algorithm, *Bull. Seismol. Soc. Am.*, *98*, 651–661.
- Wu, Y.-M., Y.-J. Hsu, C.-H. Chang, L. S.-Y. Teng, and M. Nakamura (2010), Temporal and spatial variation of stress in Taiwan from 1991 to 2007: Insights from compressive first motion focal mechanism catalog, *Earth Planet. Sci. Lett.*, *298*, 306–316.
- Wu, F. T., H. Kuo-Chen, and K. D. McIntosh (2014), Subsurface imaging, TAIGER experiments and tectonic models of Taiwan, *J. Asian Earth Sci.*, *90*, 173–208.
- Yang, K.-M., H.-H. Ting, and J. Yuan (1991), Structural styles and tectonic modes of Neogene extensional tectonics in southwestern Taiwan: Implications for hydrocarbon exploration, *Pet. Geol. Taiwan*, *26*, 1–31.
- Yang, K.-M., S.-T. Huang, J.-C. Wu, H.-H. Ting, and W.-W. Mei (2006), Review and new insights on foreland tectonics in western Taiwan, *Int. Geol. Rev.*, *48*, 910–941.
- Yang, K.-M., S.-T. Huang, J.-C. Wu, H.-H. Ting, and W.-W. Mei, M. Lee, H.-H. Hsu, and C.-J. Lee (2007), 3D geometry of the Chelungpu thrust system in central Taiwan: Its implications for active tectonics, *Terr. Atmos. Ocean. Sci.*, *18*, 143–181.
- Yang, K.-M., J.-C. Wu, E.-W. Cheng, Y.-R. Chen, W.-C. Huang, C.-C. Tsai, J.-B. Wang, and H.-H. Ting (2014), Development of tectonostratigraphy in distal part of foreland basin in southwestern Taiwan, *J. Asian Earth Sci.*, *88*, 98–115.
- Yang, K.-M., R.-J. Rau, H.-Y. Chang, C.-Y. Hsieh, H.-H. Ting, S.-T. Huang, J.-C. Wu, and Y.-J. Tang (2016), The role of basement-involved normal faults in the recent tectonics of western Taiwan, *Geol. Mag.*, *153*, 1166–1191.
- Yeh, Y.-H., et al. (1998), Onshore/offshore wide-angle deep seismic profiling in Taiwan, *Terr. Atmos. Ocean. Sci.*, *9*, 301–316.
- Yeh, Y.-C., S.-K. Hsu, W.-B. Doo, J.-C. Sibuet, C.-S. Liu, and C.-S. Lee (2012), Crustal features of the northeastern South China Sea: Insights from seismic and magnetic interpretations, *Mar. Geophys. Res.*, *33*, 307–326.
- Yin, A. (2006), Cenozoic tectonic evolution of the Himalayan orogeny as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation, *Earth Sci. Rev.*, *76*, 1–131.
- Yue, L.-F., J. Suppe, and J.-H. Hung (2005), Structural geology of a classic thrust belt earthquake: The 1999 Chi-Chi earthquake Taiwan ($M_w = 7.6$), *J. Struct. Geol.*, *27*, 2058–2083.
- Yui, T.-F., K. Okamoto, T. Usuki, C.-Y. Lan, H.-T. Chu, and J.-G. Liou (2009), Late Triassic–Late Cretaceous accretion/subduction in the Taiwan region along the eastern margin of South China: Evidence from zircon SHRIMP dating, *Int. Geol. Rev.*, *51*, 304–328.
- Yui, T.-F., K. Maki, C.-Y. Lan, T. Hirata, H.-T. Chu, Y. Kon, T. D. Yokoyama, B.-M. Jahn, and W. G. Ernst (2012), Detrital zircons from the Tananao metamorphic complex of Taiwan: Implications for sediment provenance and Mesozoic tectonics, *Tectonophysics*, *541–543*, 31–42.
- Zhang, X., Y. Yan, C.-Y. Huang, D. Chen, Y. Shan, Q. Lan, W. Chen, and M. Yu (2014), Provenance analysis of the Miocene accretionary prism of the Hengchun Peninsula, southern Taiwan, and regional geological significance, *J. Asian Earth Sci.*, *85*, 26–39.
- Zhao, M., X. Qiu, S. Xia, H. Xu, P. Wang, T. K. Wang, C.-S. Lee, and K. Xia (2010), Seismic structure in the northeastern South China Sea: S-wave velocity and Vp/Vs ratios derived from three-component OBS data, *Tectonophysics*, *480*, 183–197.