ABSTRACT

Late Quaternary shortening along the length of the Western Foothills of Taiwan highlights the tectonic segmentation of the foreland and raises questions about the relationship between erosion and the thickness of synorogenic foreland basin fill, and their influence on thrust kinematics. We compare measurements of shortening with geodetic observations and numerical model results, and relate these to regional topography. Predictions of shortening from numerical modeling and observed strain gradients within central Taiwan are generally similar in terms of their scaling and kinematic behavior. Within this framework, the current deformation field is likely related to the inheritance of older passive-margin structures in the foreland, as well as to the easily erodible nature of the 5-km-thick sequence of synorogenic sediment accreted at the leading edge of the orogen in the last 1.1 m.y. Additionally, available constraints on the timing of recent activity of faults suggest that infilling of piggy-back or wedge-top basins there occurred rapidly, contemporaneously with the activation of the frontal thrust and a possible increase in the rate of shortening across the adjacent thrust sheet toward the center of the orogen.

INTRODUCTION

The Taiwanese orogen results from the ongoing collision of the Eurasian plate with the Philippine Sea plate, and is located between the oppositely dipping subduction zones of the Ryukyu and Manila trenches in the western Pacific Ocean (Fig. 1). Taiwan has been widely recognized as an optimal setting for studying active compressive thrust-belt behavior. The limited-size, extensively imaged foreland basin and broad deployment of dense networks of geophysical instrumentation enable high-precision observations of critical wedge mechanics and kinematics (Suppe, 1980; Carena et al., 2002; Fuller et al., 2006). Taiwan absorbs some ~82 mm/yr of oblique plate convergence (Yu et al., 1997; Chang et al., 2003) and frequent typhoon landfalls rapidly erode the surface of the orogen (Wu and Kuo, 1999; Galewsky et al., 2006), driving high rates of material flux (Willett et al., 2003). In addition, strong ground motions produced by large earthquakes trigger landslides that facilitate fluvial transport of large volumes of material in rapidly incising river networks (Galewsky et al., 2006; Lin et al., 2006; Yanites et al., 2010a).

Central western Taiwan exhibits fairly consistent topographic tapers along the length of the thrust belt (Davis et al., 1983), with one notable exception within the mature collision zone: the area surrounding Puli township, which we refer to as the Puli Topographic Embayment (PTE). The PTE has been described as representing a subcritical portion of the western Taiwanese thrust belt (Wilcox et al., 2011). It encompasses a chain of small wedge-top basins (Puli, Yuch, Sun-Moon Lake, and Toushe Basins), located within the southern part of the Hsueshan Range (Fig. 1). The region defined by these basins has been previously recognized as a unique portion of the island with respect to its structural style, history of late Quaternary strain, and thickness of Quaternary synorogenic sediments accreted in thrust sheets at the leading edge of the thrust belt directly west of Puli (Byrne and Liu, 2002; Mouthereau et al., 2002; Mueller et al., 2002; Powell, 2003; Upton et al., 2009; Yanites et al., 2010b; Wilcox et al., 2011). Relatively small wedge-top basins (~10 km across or less) within the PTE hold as much as several hundred meters of late Quaternary sediments that are currently being folded and incised as a result of active deformation and rock uplift as much as ~50 km hindward of the thrust front.

A comparison of 10 × 100 km swath topography profiles across the island (see Wilcox et al., 2011, their fig. 2) highlights the marked difference in the subaerial form of the orogen between the PTE and the adjacent Alishan Range. The linear best-fit of the average elevation values for the Alishan gives a ~3° surface slope, which is consistent with published characteristic subaerial taper angles for Taiwan from Dahlen (1990). In comparison, the ~1.5° average surface slope that extends from the frontal thrusts into the PTE is significantly lower (Fig. 4). Comparing the average elevation of Alishan topography to that of the PTE suggests the orogenic wedge is significantly thinner throughout the Puli region. We note that although the topography of the central pro-wedge varies significantly, the topography of the retro-wedge does not. The difference in average topography of the retro-wedge along strike is negligible between the northern- and southernmost swath topography transects. Additionally, the presence of a marked gravity low that coincides closely with the location of the PTE (Yeh and Yen, 1992) indicates a mass deficit in the region. Wilcox et al. (2011) assessed the taper angles of the western foreland based on measurements from 13 balanced cross sections and found that the toe of the orogenic wedge outboard of the PTE exhibits a significantly lower taper angle (α + β) than in other areas to the north and south. Based on this result the PTE was classified as a subcritical part of the wedge; however, it is important to note that this study did not take into account potential variations in rock strength within the thrust belt. The record of river channel evolution in the PTE is poorly understood prior to

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Figure 1. Tectonic setting of Taiwan (inset) and map of structural and gross stratigraphic architecture of central western Taiwan foreland and Western Foothills below 1000 m. Important faults discussed in text, from west to east along 24°N latitude, are the Changhua (1), Chelungpu (2), Shuangtung (3), and Shuilikeng (4). Locations: PTE—Puli topographic embayment (area east of Shuangtung fault, below 1000 m); SY—Sanyi overthrust. White outline shows location of Figure 3. Dotted thin black line corresponds with 1000 m elevation contour. Brown shaded regions within PTE (from north to south) outline young sediments in the Puli, Yuchi, Sun-Moon, and Toushe Basins. Focal mechanisms shown for 1935 and 1906 events. PH—Peng-Hu; CP—Coastal Plain; WFH—Western Foot Hills; AS—Alishan; HSR—Hsuehshan Range; CR—Central Range; LV—Longitudinal Valley; CoR—Coastal Range.
ca. 40 ka, when large lateritic terraces were initially abandoned. Wilcox et al. (2011) suggested that the erosive susceptibility of the 5-km-thick sequence of late Pleistocene conglomerate and gravels of foreland basin fill (i.e., the 1.1 Ma to present Toukoushan Formation) currently being accreted at the leading edge of the orogen could control wedge morphology. The key to this hypothesis is the condition where the rate of surface erosion is equal to or greater than the rate of rock uplift. Rock uplift may thus be closely linked with erosive susceptibility, resulting in locally high rates of exhumation with little or no surface uplift within weaker rocks that are highly erodible (Upton et al., 2009; Wilcox et al., 2011). The erosion-based hypothesis is different from other published models about the anomalously low topography in central Taiwan, which suggest the condition is the result of wedge propagation over a basement horst (the Peikang High) associated with earlier passive-margin extension in the Miocene (Byrne and Liu, 2002; Lu and Malavieille, 1994).

Critical wedge theory has been widely used since the early 1980s to develop a general understanding of thin-skinned orogenic development. More recently, critical wedge studies have focused primarily on changes in boundary conditions of wedge development, such as the influence of surface erosion on wedge kinematics (Moser, 1999; Konstantinovskaya and Malavieille, 2005; Hoth et al., 2006; Berger et al., 2008; Meigs et al., 2008). In the case of a steady-state critical wedge, locally intensified erosion that acts to reduce the subaerial taper and remove mass from an orogen is predicted to drive a transient internal reorganization of strain. Subcritical taper at scales less than the length of the orogen thus results in locally increased rock uplift and shortening within the zone of intensified erosion, rebuilding that region to a critical state (Davis et al., 1983).

Work identifying changes in wedge kinematics related to the effects of erosion and sedimentation has also been undertaken in numerical modeling studies and analog studies (Konstantinovskaya and Malavieille, 2005; Hoth et al., 2006; Upton et al., 2009; Malavieille, 2010), but relatively few studies have identified these specific patterns in an active thrust belt (Norris and Cooper, 1997; Wobus et al., 2003; Montgomery and Stolar, 2006). Identifying “reorganized” strain that characterizes a kinematic response to a subcritical state has generally relied on thermochronology data, as with examples from Alaska and the Himalayas (Wobus et al., 2003; Thiede et al., 2004; Berger et al., 2008; Meigs et al., 2008). Active deformation and incision of young synorogenic sediments within the PTE, some 50 km inboard of the leading edge of the thrust belt (nearly half the entire width of the orogenic wedge), thus provides insight into the kinematic impact of variations in the erosive susceptibility of the wedge in central Taiwan relative to adjacent transects of the orogen (Mueller et al., 2002, 2006; Powell, 2003; Upton et al., 2009; Wilcox et al., 2011).

In this study, topography, lithologic architecture, and shortening of adjacent regions of the active Taiwanese orogen are compared to better understand the relationships between surface erosion and critical wedge kinematics. Observations are supported by three-dimensional numerical models that explore how topography, erosion, and rheology influence shortening. Additionally, observations and model results are compared with the record of geologically determined strain and recent seismic moment release in central Taiwan (Chang et al., 2003; Mouthereau et al., 2009; Lin et al., 2010).

METHODS

Structural Restorations

Hanging-wall restorations of late Quaternary thrusts were completed for 15 balanced cross sections that extend perpendicular to strike across the Western Foothills (Wilcox et al., 2011; see locations in Fig. 1), in order to measure shortening across frontal and penultimate thrust sheets (i.e., with respect to position in the belt) that deform Pleistocene and younger synorogenic strata of the foreland basin (Figs. 2, 3). In this paper, “frontal” and “penultimate” refer to position within the wedge, with “frontal” describing the westernmost thrusts and “penultimate” describing the next thrust sheet to the east. Fault slip was determined on the sections based on the relative ages and cross-cutting relations present in the sequence of older passive-margin and synorogenic strata preserved in this region. The cross sections were first developed by the Chinese Petroleum Corporation (CPC), and are constrained by numerous seismic reflection data and borehole measurements. Restorations of the sections were based on identifiable piercing points in hanging-wall and footwall stratigraphic cutoffs to calculate shortening on thrust faults. Where hanging-wall cutoffs were not preserved (typically in penultimate thrusts) minimum shortening (i.e., “measurable shortening”) was estimated. Two of the cross sections near Taichung were modified to maintain area balancing and restorations to correspond with other published sections through the area that are based on additional seismic reflection profiles and well data (Yue et al., 2005). The sections have not been reproduced here in accordance with permissions from the CPC; however, seven representative sections have been previously published in Yang et al. (2007). Measurable shortening may not always reflect the full extent of structural segmentation due to erosion of hanging-wall ramps, precluding absolute determination of total shortening in all the sections (Fig. 2C).

Field Observations and Topographic Analysis

Field observations used in the restorations included bedding attitudes, optically stimulated luminescence (OSL) samples taken from Puli and the Peikang Valley, and shallow seismic reflection data (from Huang, 2008). OSL sample ages from sandy deposits were used to constrain a new balanced cross section through the PTE. OSL sample ages were calculated for both the moisture level measured at the time the sample was taken and for a saturated state. Topographic data derived from a 40 m digital elevation model (DEM), and OSL sample ages were used to correlate deformation of Quaternary basin sediments and incision rates along the Peikang River with individual structures and slip rates based on our cross section. Additionally, we qualitatively compare the relationship between erosive susceptibility and topography by correlating rock type distributions with geomorphic trends of topography for individual thrust sheets in the region.

Numerical Modeling

Numerical modeling was achieved using FLAC3D (version 3.1; Itasca, 2006) to examine the response of an orogenic wedge to spatially limited erosion and/or rheological differences at or near the front of the wedge. The geometry of the models consists of an elastic slab, representing the basement of Taiwan’s peripheral foreland, beneath an elasto-plastic Mohr-Coulomb wedge (Fig. 5A). These are separated by an interface along which frictional slip can occur but across which no material exchange occurs. Key conditions explored within the wedge model are spatial variations in rheology and erosion rate. Variations in rheology and erosion rate are designed to capture the behavior of a homogenous wedge as it accretes a package of weaker material with a relatively higher erosive susceptibility compared to other material along strike. The model construction and execution are identical to the models and technique discussed in Upton et al. (2009) and Wilcox et al. (2011); however, the focus here is primarily contraction and shear strain predicted by the model. Model results were then compared with DEM topography as well as published findings from GPS geodesy and seismic moment release.
RESULTS

Quaternary Shortening in the Western Foothills from Structural Restorations

We identify three generally distinct foreland and western foothill subregions, based on observed segmentation of Quaternary strain along the strike of the Western Foothills (Fig. 2C). These same three regions (Miaoli, Taichung, and Chiayi) have previously been identified based on the presence (or absence) of reactivated inherited basement structures (Mouthereau et al., 2002; Wilcox et al., 2011). Shortening across the Western Foothills is estimated to have developed over the last ~700 k.y. or less (Chen et al., 2003; Chen et al., 2007; Simoes et al., 2007a, 2007b). Our measurements of Quaternary shortening across the penultimate thrusts within the foreland/western foothills (as determined from balanced cross sections) generally mimic a pattern of shortening consistent with the trend of the southward-propagating collision between the Luzon arc and the Chinese continental margin (CCM) (e.g., decreasing shortening toward the southern part of the island; Simoes and Avouac, 2006).

While total shortening in Taiwan is generally acknowledged to decrease from north to south, slip profiles for the two youngest frontal thrusts highlight segmentation in the west-central portion of the thrust belt (Fig. 2C). Shortening across the PTE (i.e., from north to south) can be described as follows. The frontal Changhua thrust is divided into three segments with a central segment located directly astride the PTE. Two other segments of the frontal Changhua thrust have maxima centered over the northern and southern margins of the PTE, respectively, at the boundaries between the domains defined by the thickness of <1 Ma foreland basin fill (i.e., Miaoli-Taichung and Taichung-Chiayi). In addition, the penultimate Chelungpu thrust also displays a maximum at the northern edge of the PTE but has three smaller segments that decrease in amplitude from north to south, across the Taichung-Chiayi domain boundary. A more striking correlation between shortening and the PTE is apparent on a combined plot of the two frontal thrusts. This indicates that a large central segment is located squarely in the middle of the PTE (Fig. 2C). Two other maxima coincide with the northern and southern boundaries of the PTE at the previously mentioned domain boundaries (i.e., Miaoli-Taichung and Taichung-Chiayi).

Shortening within the PTE

Folded late Quaternary deposits within the Puli Basin provide evidence of young active deformation within the PTE (Fig. 3). The Puli Basin is filled with upward-coarsening unconsolidated sediments ranging from clays, silt, and peat beds (interpreted as early lake deposits) to sandstone cobble and boulder conglomerates. OSL ages of basin sediments in Puli provide important, though limited, constraints on the timing and rates of sediment accumulation within the PTE (Table 1). Seismic reflection data and borehole logs from the center of Puli indicate that the basin contains between ~350 and 500 m of sediment (Huang, 2008). OSL ages range from ca. 59 ka at an exposed basal contact of the basin sediments to ca. 41 ka at the...
top of the highest preserved basin deposits, and provide constraints on the onset and cessation of deposition within the western half of the basin (Table 1; Fig. 3). The maximum thicknesses of basin sediments lie east of the Meiyuan fault and the western limb of the Taomikang syncline, where modern sediment is still being deposited (Fig. 3). Vertical separation between the lower bedrock/cover contact and highest preserved surfaces throughout the western half of the basin is on the order of 250–300 m. These data yield an average apparent accumulation rate of 13.8–16.7 mm/yr, over a period of ~18 k.y. These rates are slightly higher than modern rates of incision (~9–11 mm/yr) measured near the Shuilikeng fault from terrace ages along the Peikang River drainage immediately north of the Puli Basin (Yanites et al., 2010b); however, the simplistic height/age calculation may overestimate actual rates of accumulation as a result of not interpreting apparent tilting of the terrace surface from north to south, in addition to back-tilting.

Direct relationships between late Pleistocene folding within the PTE and blind thrusts under the Puli Basin are difficult to identify clearly. However, short segments of axial surfaces traced
across the basin correspond to the projections of mapped thrusts where they are exposed at the edges of late Quaternary fill. When considered in light of the distribution of terrace deposits in the basin, and rapid burial by a large alluvial fan at the east side of the Puli Basin, the folds yield information on late Quaternary contraction. Surface folding may result from slip above potential duplex structures below the PTE, internal shearing within Oligocene-age shales, or displacement across the Shuilikeng or Meiyuan thrusts (Fig. 3). Minor faults, polish, and slickensides along bedding planes in shale outcrops exposed along the Peikang River drainage suggest that internal shearing is common, although these features may be ascribed to flexural slip that does not significantly contribute to surface or rock uplift. Short seismic profiles in the Puli Basin are not sufficiently resolved to image late Pleistocene growth strata; however, these data suggest the basin deposits are generally tilted eastward, similar to the surface topography of abandoned lateritic terraces.

Foreland Stratigraphy versus Topography

Quaternary subsidence based on observed thicknesses of Toukoshan (1.1 Ma) age-equivalent strata within the foreland varies markedly along strike (Chen et al., 2001; Moutheureau et al., 2002; Wilcox et al., 2011). The Toukoshan formation is generally interpreted to record subsidence in the foreland near the current leading edge of the thrust belt, whereas the Cholan Formation is a more distal, finer-grained sequence in the foreland near the current leading edge of the orogen. Exposures of Toukoshan (1.1 Ma) age are interpreted to record synorogenic strata (i.e., Cholan and Chinshui formations) (Fig. 2B). The increase in thickness of the Cholan Formation south of the CCM shelf break is a reflection of spillover of these deposits south of the arcocontinent collision before 1.1 Ma.

We note that Miocene rocks within the central Taichung domain are not exposed as far to the west as similarly aged rocks in either the Miaoli or Chiayi domains, despite an apparent relative increase in shortening along the frontal thrust of this domain (the Changhua). This is a product of the architecture of the passive margin and again highlights the importance of inheritance where Miocene strata are buried to greater depths beneath the thicker sequence of foreland basin strata that cap thrust sheets across the embayment (Fig. 3). The correlation of the along-strike terminations of thrust sheets, abrupt changes in the thickness of the foreland basin, and the topographic edges of the PTE highlight a potential link between structural kinematics in the central western foreland of Taiwan and the overall topographic form of the orogenic wedge.

Comparing the topography of the Western Foot hills belt to the map pattern of Miocene versus Pliocene–Quaternary rocks shows that younger, poorly consolidated synorogenic sediments are not present above ~750 m elevation. This relationship includes all observable exposures of similar-age synorogenic sediments throughout the western-vergent portion of the thrust belt. Comparison of east-west–oriented topographic profiles through the Western Foothills and into the PTE highlights the differences in erosional susceptibility and resulting morphology between the young Pliocene–Quaternary sediments and the Miocene rocks of the CCM (Fig. 4). Outcrops of the younger strata are deeply dissected, in particular exposures of Toukoshan formation, and have steep slopes and relatively short-wavelength ridge/valley pairs, suggesting these rocks are eroding rapidly. In contrast, areas of exposed Miocene strata contain narrow ridges reaching more than 1000 m in elevation, and display greater spacing of ridge/valley pairs and steeper regional slopes (slopes averaged over several ridge/valley pairs). These relationships are further expressed where abrupt changes in average elevation and ridge/valley spacing occur across the Shuantung thrust, at the contact between preorogenic and synorogenic strata. While a quantitative comparison of the relative strengths and erosive susceptibilities of preorogenic versus synorogenic strata is beyond the scope of our study, variation in the average elevation across the Western Foothills belt with rock age is consistent with our assertion of weaker, more efficiently eroded foreland basin strata.

Numerical Model Results

Our previous modeling of the PTE region indicated a closely coupled relationship between lower average topography and rock and surface uplift (Upton et al., 2009; Wilcox et al., 2011). Here we explore possible links between lower topography and horizontal shortening as defined in the serial cross sections (Yang et al., 2007; Wilcox et al., 2011). Three models were run and compared to a reference model that is uniform along strike both in material properties and rate of erosion (Fig. 5B). Model 1 (Fig. 5C) incorporates a zone of weaker and less dense material in the central outboard portion of the model representing the PTE, and imposes a uniform erosion rate. Model 2 (Fig. 5D) contains no material variability but imposes enhanced erosion on the central region representing the PTE. Model 3 (Fig. 5E) is a hybrid of the two preceding models, incorporating both the central zone of weaker, less dense material from model 1 and the spatially coincident enhanced erosion rate of model 2.

Modeled Topography

Weaker, less dense material (model 1, Fig. 5C) is easier to deform and produces less of a topographic load than the more dense material surrounding it. Accordingly, that less dense material is more rapidly uplifted than the surrounding material. This preferential material uplift thus occurs at the expense of material uplift in the region behind it, resulting in the expression of a high ridge at the inboard edge of the zone of weaker material and lower-than-reference topography in the region behind it. Enhanced erosion (model 2, Fig. 5D) produces

<table>
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<tr>
<th>Sample</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Dose rate (Gy/k.y.)</th>
<th>Dose rate (H2O saturated) (Gy/k.y.)</th>
<th>Paleodose (Gy)</th>
<th>Age (ka)</th>
<th>Age (H2O saturated) (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL20020714-B</td>
<td>3.25 ± 0.03</td>
<td>15.80 ± 0.09</td>
<td>2.53</td>
<td>3.8 ± 0.4</td>
<td>3.38</td>
<td>157 ± 4</td>
<td>41 ± 4</td>
<td>—</td>
</tr>
<tr>
<td>PL20020717-A</td>
<td>3.60 ± 0.04</td>
<td>17.90 ± 0.07</td>
<td>2.60</td>
<td>4.1 ± 0.4</td>
<td>3.30</td>
<td>202 ± 5</td>
<td>49 ± 5</td>
<td>60 ± 5</td>
</tr>
<tr>
<td>PL20020812-C</td>
<td>3.47 ± 0.02</td>
<td>17.28 ± 0.07</td>
<td>2.60</td>
<td>4.0 ± 0.4</td>
<td>3.50</td>
<td>192 ± 5</td>
<td>48 ± 5</td>
<td>55 ± 5</td>
</tr>
<tr>
<td>PL20020813-F</td>
<td>3.39 ± 0.01</td>
<td>16.11 ± 0.05</td>
<td>2.50</td>
<td>3.8 ± 0.4</td>
<td>3.42</td>
<td>223 ± 5</td>
<td>59 ± 6</td>
<td>65 ± 6</td>
</tr>
</tbody>
</table>
a local topographic low, which in turn reduces the ability of the wedge to buttress itself, resulting in lower-than-reference topography behind the region of increased erosion rate. Combining these two effects (model 3, Fig. 5E), produces a destructively interfering topographic signal of an intermediate elevation ridge at the inboard edge of the zone of weaker material, combined with a constructively interfering signal of lower topography behind that region of weaker and rapidly eroding material.

Modeled Horizontal Displacement
We also predict characteristic patterns of horizontal displacement from the three models. In model 1, there is a strong kinematic response to weaker material at the front of the wedge, namely a relative increase in the forward translation of that weaker material as a result of its more easily deformable nature relative to the stronger (and therefore less easily deformed) material that makes up the rest of the wedge (Fig. 5C). In contrast, the kinematic response of shortening in the wedge to heightened and
focused erosion is more complex. As material is preferentially removed from the central portion of the wedge, adjacent material from the central inboard section of the wedge moves toward the region of enhanced erosion more rapidly than in the reference model, producing increased shortening and rock uplift (Fig. 5C; note that blue colors denote movement toward the foreland). In contrast, and as a result of the reduced shortening from the rapidly eroding region as shown by the blue region in Figure 5C (horizontal displacement difference from reference model), forward translation of material outboard of the rapidly eroding region is less rapid than in the reference model (see red area in Fig. 5D). The combined case of model 3 results in a very distinct kinematic pattern, with the predicted topographic embayment being translated toward the foreland more or less as a block, and reduced shortening occurring outboard of the rapidly eroding region (Fig. 5E).

**Modeled Shear Strain**

Shear strain measured in our models gives important insight into the kinematic behaviors at the boundaries of the regions of weaker material and higher erosion rate. In model 3, we observe a complex pattern of horizontal shear strain related to the differential translation and shortening of material in the central outboard region of the wedge. Where material in the central zone is translated forward more rapidly than in the reference model, dextral shear is seen at the upper (“northern”) boundary of weaker, more rapidly eroding material and sinistral shear is present at the lower boundary (Fig. 5E). The outboard region of weaker material in model 3 that experiences less-rapid forward translation than in the reference model exhibits oppositely polarized senses of horizontal shear: sinistral at the upper (“northern”) boundary and dextral at the lower (“southern”) boundary.

Vertical displacement in our model is analogous to thrust faulting, with clockwise shear representing top-to-the-east thrusting and counterclockwise shear representing top-to-the-west thrusting, as oriented in Figure 6. The reference model exhibits focused shearing (thrusting) at the very front of the wedge along the active deformation front and at the rear of the wedge along the suture with the structural backstop. Vertical motion results for model 3 show no change in the thrust behavior of the retro-wedge along the structural backstop; however, there is marked back-stepping of thrusting within the pro-wedge relative to the reference model (Fig. 6B). This result is expected and has been shown previously in various analog and numerical models from other studies (Hoth et al., 2006, and references therein).

**DISCUSSION**

**Tectonic Segmentation and Lithologic Architecture**

Correlation in observations of the tectonic segmentation of the foreland and Western Foothills of Taiwan becomes evident when comparing patterns of structural and stratigraphic evolution against topography. The northern and southern boundaries of the PTE, as defined by topog-

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**Figure 5. FLAC3D model results.** (A) Model construction, including regions of varied material properties or enhanced erosion. (B) Reference model result. White outline is region of zoom for individual model results. (C, D, E) Individual model results and difference from reference model.
Sedimentary deposition, coincident with maxima in along-strike changes in shortening and an abrupt change in both the thickness and strike-perpendicular spacing of thrusting sheets in the Western Foothills. While there is no preserved record of infilling prior to its latest period before 59 ka, it is the greater thickness of more easily eroded Touko-shan formation capping thrust sheets that likely drove deeper incision of river channel networks and removal of material in the PTE. Measurements of shortening across the frontal thrusts indicate that the central Changhua frontal thrust segment has accommodated disproportionately more shortening than the other frontal structures to the north and south. Some of this discrepancy may be related to reactivation and inversion of normal faults underlying the thinner cover sequences in the Miaoli and Chiayi forelands. The continuing control of focused erosion on where strain in the wedge is focused has likely resulted in the current subcritical state of the PTE, the northern and southern extents of which are likely controlled by inheritance of extensional faults in the foreland basement and in turn the variable magnitude of proximal foreland subsidence.

Although we are unsure of a direct causal relationship between the observed foreland segmentation and fluvial processes currently acting within the PTE, it is worth noting that the northern and southern boundaries of the PTE additionally coincide with the current locations of the lower reaches of the Daan and Choshui river drainages, respectively (Fig. 2). Bedrock incision by powerful rivers in tectonically active regimes has been shown to have a strong effect on the evolution of topography, exhumation, and strain reorganization in critical wedges (Norris and Cooper, 1997; Wobus et al., 2003; Montgomery and Stolar, 2006). We therefore posit that these large river channel networks may have existed in their present locations for time scales comparable to the Quaternary reorganization of strain associated with the PTE.

**PTE Infilling and Kinematics**

Structural damming of the PTE and subsequent infilling of the basins can be mostly attributed to slip on the Shuilikeng thrust. If so, this likely requires an increase in slip rate on the fault around 59 ka, which could be related to a coincident change in the slip rate on other actively deforming thrusts at the same latitude. Increased or renewed rock uplift above the Shuangtung fault is perhaps a more likely candidate for having contributed to closure of the fluvial outlet of the proto-PTE, resulting from the Shuangtung thrust sheet experiencing more rapid rock uplift within the western portion above the lower termination of the Chelungpu footwall ramp (Fig. 3).

A challenge in determining high-resolution slip histories through time for some faults within the central Western Foothills and PTE is the variation in location of shortening at timescales of 10^3–10^4 years. Although age constraints for the onset of the Changhua and slip rates on the Chelungpu thrust have been determined at resolutions of 10^4–10^5 years from OSL dating (Chen et al., 2003; Chen et al., 2007; Simoes et al., 2007a, 2007b), detailed thrust behavior further into the Western Foothills and Hsue-shan Range has not been as well constrained, due largely to lack of dateable material in key areas, e.g., along the trace of the Shuangtung and Shuilikeng thrusts. Observations of out-of-sequence activity on several thrusts and active shortening as much as 50 km inboard of the active thrust front support the hypothesis that faults in central western Taiwan exhibit periodic tradeoffs in shortening across the PTE. This type of behavior is predicted by numerical and analog modeling studies of subcritical tapers within eroding critical wedges and is interpreted to be a normal process associated with eroding critically tapered thin-skin wedges (Upton et al., 2009; Hoth et al., 2006; Konstantinovskaia and Malavieille, 2005).

We also draw some parallels between the observations in Taiwan and wedge kinematics in other orogens. The strike-parallel kinematics of the Taiwanese thrust belt, dominated by structural inheritance, can be compared to wedge development across the Kazeron or the Eastern Cordilleras of the central and southern Andes, where the orogenic wedges generally exhibit changes in their morphology and surface elevation across regions of inherited structural fabrics, such as extensional normal faults (Kley et al., 1999; Authemayou et al., 2005). Additionally, we can relate the convergence-parallel kinematics of central Taiwan and the PTE to other examples of critically tapered wedges responding to focused erosion, such as examples from the Alps, Alaska, and the Himalayas, where the reorganization of internal deformation is closely coupled with surface erosion (Moser, 1999; Thiede et al., 2004; Berger et al., 2008; Meigs et al., 2008). In these examples, and in numerical models that approximate the effects of focused erosion acting on a materially consistent critical wedge, increased strain is observed within the area of heightened erosion, often along fluvial and glacial valleys. In contrast, the PTE provides a unique insight into the relationships between erosion, topography, and subcritical taper. Here, focused erosion of thicker unconsolidated sediments at the toe of the orogenic wedge has resulted in the generation of a topographic low, but not at higher elevations of the thrust belt, where precipitation and erosion rates are significantly higher (Dash et al., 2003). Instead of a subcritical taper that coincides only with the locus of more efficient erosion, the subcritical portion of the wedge extends tens of kilometers inboard, adjacent to areas of higher erosion rates north and south of the PTE.

**Geodesy**

Chang et al. (2003) and Lin et al. (2010) calculated geodetic solutions for the orogen-scale

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**Figure 6. FLAC3D model shear strain results (xz plane). (A) Reference model result. (B) Model 3 result. Note back-stepping of “west”-vergent thrusting (blue) in model 3, and thrust activity far inboard of active deformation front.**

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strain field of Taiwan, for both before and after the major 1999 Chi-Chi earthquake. These studies provided overviews of the orogeny-scale kinematics related to a large earthquake in Taiwan and considered the importance of a major event as it relates to the long-term kinematic behavior of the wedge. We relate average topography, variations in shortening, and numerical model predictions with geodetic observations from the summarized studies to investigate the likelihood of focused erosion driving the formation of the PTE. We note, however, that the geodetic strain and moment release defined in these studies records wedge growth over only one earthquake cycle and may not represent average longer-term behavior in the wedge. We include this discussion, however, because the Chi-Chi earthquake occurred on the frontal, penultimate thrust that bounds the outboard edge of the PTE and it seems inescapable that it plays an important role in the longer-term evolution of the region. Postseismic response of the orogen to an earthquake on the Chelungpu Fault is very similar to our modeled response of an orogen to a region of weaker, more rapidly eroding material within the frontal portion of the wedge (Figure 7). Assuming that the Chi-Chi event is a characteristic earthquake for the Chelungpu fault, and that the fault has experienced many earthquake cycles in its lifetime, then this pattern of postseismic deformation might also be assumed to be characteristic and recurring.

Strain field maps from Chang et al. (2003) show that the Taichung region is undergoing pure shortening further inboard from the active deformation front and across a broader area than anywhere else in the entire orogen. Associated with this observation is the recognition of roughly linear bands of transcurrent deformation that correlate well with the domain boundaries of the Miaoli, Taichung, and Chiayi regions. Additionally, their findings show a correlative reduction in shortening ahead of the Chelungpu thrust, as well as a lesser but still noticeable decrease in strain even further inboard into the wedge. These patterns of deformation type and relative intensity are predicted by our numerical model results, and are consistent with observations of active folding within the Puli Basin.

**SUMMARY**

Observations of active deformation and age dating of young sediments within the PTE help in identifying the length and time scales of the current kinematic response to a transient subcritical state within central western Taiwan, as well as providing some constraints on the mechanisms of deformation acting within the PTE.

Structural inheritance has strongly affected the recent (<1.1 Ma) distribution and magnitude of proximal foreland subsidence as a result of synorogenic sediment loading and subsequent reactivation of preexisting Miocene-age extensional faults bounding the Kuanyin and Peikang basement highs in the foreland (Wilcox et al., 2011). The thicker sequence of synorogenic foreland basin sediments outboard of the PTE have likely controlled landscape evolution in central Taiwan, relative to adjacent regions along strike, since being incorporated into the thrust belt. This unique history of landscape evolution results from both inherited structures and surficial processes initiating a topographic low as a result of more efficient erosion of thrust sheets covered by 5 km of unconsolidated, easily eroded sediment (Wilcox et al., 2011).

The current subcritical state of the PTE currently drives a reorganization of the wedge’s internal strain, with some shortening being transferred inboard of the Western Foothills. We posit that rapid removal of material from the Chelungpu thrust sheet and the current mass deficit represented by the PTE drives active deformation within the embayment, as predicted by our numerical models.

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![Figure 7. Geodetic observations of Taiwan. Difference between pre- and post-seismic (1999 Chichi) GPS observations, modified from Lin et al. (2010). Vector field result is the difference between average annual velocities for 1990–1995 and 2003–2005.](image-url)


Yeh, Y.H., and Chen, Y.G., 1999, Bouguer anomaly map of Taiwan: Taipei, Taiwan, Academia Sinica, Institute of Earth Sciences, 1 p.