Research paper

Stratigraphic modeling of the Western Taiwan foreland basin: Sediment flux from a growing mountain range and tectonic implications

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ABSTRACT

Sediment flux signals from source to sink in foreland basins preserve a record of tectonics, sea level and climate through erosion and sedimentation. However, longitudinal sediment transport often occurs in foreland basins, thus removing part of the orogenic material flux from foreland basin records. Here we use mass balance calculation and stratigraphic simulations of sediment fluxes for the Taiwan orogen to provide an order of magnitude estimate of how much orogenic material may bypass a foreland basin. Our results indicate a significant, potentially more than 50%, mismatch between sediment volume currently preserved in the basin and the amount of material presumably eroded from the orogen since the onset of collision in Taiwan. This suggests either a significant overestimation of average erosion rates over the period concerned with orogenic development of Taiwan, or it supports previous paleogeographic work suggesting that longitudinal sediment transport in the paleo-Taiwan Strait served as a major bypass conduit of importance for the establishment of a steady state orogen. We identify candidate submarine topography in the South China Sea that may preserve Taiwan's missing erosional mass.

1. Introduction

Sediment fluxes within foreland basins exert a primary control on basin architecture involving interactions between tectonics, sea level and climate through erosion and sedimentation (e.g., Allen et al., 2013; Castelltort et al., 2015; Flemings and Jordan, 1989; Posamentier and Allen, 1993). The orogenic history of many ancient basins has been reconstructed with help of sedimentary records, such as in the Alps (Garzanti et al., 2004; Lihou and Allen, 1996), Pyrenees (Puigdefàbregas et al., 1992; Vergés and Burbank, 1996), or Himalayas (Garzanti et al., 2005; White et al., 2002), but it is still not well known how much of the orogenic history is eventually preserved and how tectonics, facies and sediment supply to basins are linked (Castelltort et al., 2015; Romans et al., 2016).

The western foreland basin in Taiwan (Fig. 1A) is a particularly suitable place to study interactions between tectonics and sediment fluxes because it is very young (5–6 Ma) and still very active (modern deformation, e.g., Suppe, 1981; Covey, 1984; Lin et al., 2003) and provides an opportunity to connect tectonics and depositional processes at different stages of the basin’s evolution. The western foreland of Taiwan is the historical basin where the classical foreland filling sequence was first described by Covey (1984, 1986). Indeed, the basin evolved from an early underfilled stage with relatively deep-water sedimentation (now observable in the modern setting in the South of the orogen) to a late balanced-filled stage, where shallow marine environments persist until today (most of modern Taiwan Strait, Covey, 1984), despite the enormous amount of sediment supplied to the ocean by the rising Taiwan mountains (Milliman and Kao, 2005; Milliman and Syvitski, 1992). In that sense, Taiwan orogen is emblematic of the distinct classical evolutionary stages (underfill to overfill, flysch to molasse) that characterize many ancient foreland basin systems such as in the Molasse basin of the Alps (Allen et al., 1991), the Bradanic Trough in the Apennines (Tropeano et al., 2002), the Solomon Sea in Papua New Guinea (Silver et al., 1991) or the South-Pyrenean foreland basin (Puigdefàbregas and Souquet, 1986). As a consequence of the oblique collision, the basin records a time-transgressive south-westward oriented migration of facies belts (e.g., Covey, 1984; Chen et al., 2001a, 2001b; Nagel et al., 2013) and sediment depocenters...
similar to other oblique collisions such as in Papua New Guinea (Abbott et al., 1994; Silver et al., 1991), but the details of the geometry of the initial collision at the scale of Taiwan are still ambiguous and several models have been proposed. Whereas some models favor an arc-continent collision (Huang et al., 2006; Suppe, 1984, 1988; Teng, 1990), others suggested a two stage collision of an exotic block with the Eurasian continental margin and a second collision of Luzon volcanic arc with the passive margin (Lu and Hsi, 1992), or an arc-arc collision between Luzon volcanic arc and a paleo-Ryukyu arc system extending to the west of Taiwan (Seno and Kawanishi, 2009; Sibuet and Hsu, 1997; Sibuet et al., 1995), or even that collision may have happened synchronously along the margin at the scale of Taiwan (within a larger scale context of obliquity between EUR and PSP, Fig. 1A, Castelltort et al., 2011; Lee et al., 2015).

From an orogenic point of view, Taiwan has been proposed as a possible illustration of topographic steady state in a critical orogenic wedge because it shows an approximately constant width of 90 km (Suppe, 1981; Stolar et al., 2007) and elevations and cross-sectional area plateau in the central segment of the belt (Fig. 1B). Indeed, if it was not at steady state, the orogen should be wider in the North where collision started earlier, and progressively narrower southwards. Instead the cylindrical shape of the orogen suggests that it has reached a critical size and slope. As a consequence, Taiwan orogen has been taken as an emblematic example of a steady state orogen in which erosional processes are able to balance uplift rates. As a note of caution some authors have explained that while the idea of steady state generally applies at large-scale in Taiwan, high-frequency climate oscillations linked to orbital climate shifts may well prevent the establishment of pure steady state at all scales (e.g., Whipple, 2001). Additionally, the Western orogen is rising above 4 km, forming a mountain range collapse and recycling of the metamorphic orogenic belt (Dorsey and Lundberg, 1988; Nagel et al., 1995). In most recent studies, arc-continent collision is estimated to have initiated in late Pliocene (Nagel et al., 2013; see discussion below). This is based on observing a continuous sandstone provenance shift and increasing illite crystallinity, interpreted to represent progressive unroofing and recycling of the metamorphic orogenic belt (Dorsey and Lundberg, 1988; Nagel et al., 2013). Oblique collision between the N-S trending Luzon volcanic arc and the NE-SW trending passive margin resulted in southwest propagating collision (e.g., Nagel et al., 2013; Simoes and Avouac, 2006; Suppe, 1981; Teng, 1990), with modern collision point presently located offshore SW Taiwan (Lin et al., 2008; Yu and Huang, 2009). Today, the southernmost tip of Taiwan, which exhibits transient landscape features (Giletycz et al., 2015), represents a transition from the Okinawa Through. In the South, the orogen is still growing, has not reached steady state, hence the tapering elevation and decreasing width.

2. General setting and background

2.1. Geology and tectonics

The Taiwan mountains, rising almost 4 km above sea level, formed by collision between Philippine Sea plate and Eurasian continent shelf (Figs. 1A and 2). Arc volcanism associated with subduction below the Philippine sea plate ceased between 6 Ma and 3 Ma, when the arc resisted subduction and collided with the Asian passive margin to form an initial accretionary wedge (Huang et al., 2006; Yang et al., 1995). In most recent studies, arc-continent collision is estimated to have initiated in late Pliocene (Nagel et al., 2013; see discussion below). This is based on observing a continuous sandstone provenance shift and increasing illite crystallinity, interpreted to represent progressive unroofing and recycling of the metamorphic orogenic belt (Dorsey and Lundberg, 1988; Nagel et al., 2013). Oblique collision between the N-S trending Luzon volcanic arc and the NE-SW trending passive margin resulted in southwest propagating collision (e.g., Nagel et al., 2013; Simoes and Avouac, 2006; Suppe, 1981; Teng, 1990), with modern collision point presently located offshore SW Taiwan (Lin et al., 2008; Yu and Huang, 2009). Today, the southernmost tip of Taiwan, which exhibits transient landscape features (Giletycz et al., 2015), represents the youngest relief associated with the emerging orogen. Oceanic lithosphere in the South China Sea is currently being subducted below the Philippine sea plate along the Manila Trench (Fig. 1A) whereas the
Philippine sea plate itself is being subducted northwards below the Eurasian plate (Kao et al., 2000). This complex plate interaction manifests high active seismicity associated with a convergence rate of 70–80 km/Ma between the Philippine sea plate and the Eurasian continent (Seno et al., 1993; Wu et al., 2007, 2009; Yu et al., 1997). The current plate convergence is mainly accommodated within the Longitudinal Valley Fault (LVF, Fig. 1A) on the east coast and at the deformation front in the Western Foothills consistent with the main active faults (Yu et al., 1997).

The continental margin experienced extensive rifting and continental breakup phases due to the opening of the South China Sea in late Paleogene, which resulted in major subsidence and numerous sub-basins separated by topographic highs (Lee and Lawver, 1995; Lin et al., 2003). This pre-collisional segmentation of the margin has an influence on the current structuration of the orogen into different tectonic units (Figs. 1A and 4B) that consist of: (1) accreted volcanic arc (CR: Coastal Range) separated by suture zone (LVF: Longitudinal Valley Fault), (2) main orogenic belt (ECR: Eastern Central Range), (3) Hsuechuan Range (HR), (4) deformed and uplifted foreland basin strata which constitutes a classical foreland with a fold-and-thrust belt (Western Foreland Basin), and (5) undeformed onshore (Coastal Plain) and offshore foreland basin sediments (Ho, 1988).

As initially described by Covey (1984), the evolution of syn-collisional facies is very similar from north to south, except for distinctive grain size contrasts (Chou, 1973). The coarse fraction was trapped in a shallow continental shelf basin (Taishi Basin, TaiB on Fig. 2), which was separated from the South by the Peikang High topographic barrier (Figs. 1A and 2, Meng, 1967). Most of fine grain sizes were transported further southwards and became deposited in a deep marine basin to the South (Tainan Basin and/or South China Sea, TnB on Fig. 2).

The chronostratigraphy of the Western Foothills has been extensively studied with Neogene calcareous nannofossils (Chang and Chi, 1983; Chou, 1973; Huang, 1977; Huang and Huang, 1984) and provides ground truth for five key biostratigraphic horizons (the most recent four are on Fig. 3) that are best documented (see synthesis in Nagel et al., 2013): nannofossil zone boundaries NN5-6 (12.5 ± 1 Ma), NN11-12 (5.5 ± 0.5 Ma), NN15-16 (3.5 ± 0.5 Ma), NN18-19 (2 ± 0.2 Ma) and NN19-20 (0.5 ± 0.15 Ma). The stratigraphic succession comprises a first retrogradational series consisting of shallow marine deltaic environments, which are often tidally influenced (Fig. 3,
Kueichulin fm.). The transgression associated with the end of this formation marks the onset of orogenic loading of the shallow marine shelf environment. To the South, the formation passes progressively into deeper marine mud-dominated deposits (Fig. 3). The source of sediments during deposition of Kueichulin formation is essentially the same as during previous passive margin history of the basin, from the Eurasian continent to the southeast (Castelltort et al., 2011; Nagel et al., 2013; Shaw, 1996). It is followed by the Pliocene Chinshui Shale, a relatively deep marine mud-dominated formation, which represents the underfilled stage of the foreland basin (Covey, 1984). Reworked fossils, paleocurrent directions and facies analysis point to a main source from the East of the basin at this period, which is the growing orogenic wedge (Chang and Chi, 1983; Nagel, 2012; Nagel et al., 2013). The Cholan formation represents a large-scale progradational sequence of shallow marine wave- and tide-influenced environments, which became progressively dominated by fluvial processes upsection. This is the main foreland basin stage driven by large sediment fluxes out of Taiwan orogen and southward migration of facies belts. During late Pleistocene, increased erosion lead to deposition of large alluvial sediments, which most likely are an ancient example of braided rivers draining the orogen today (Covey, 1984).

2.2. The foreland basin unconformity

Flexural response due to loading of the Eurasian shelf by the forming orogen and its sedimentary response has been studied in detail (Castelltort et al., 2011; Chen et al., 2001a; Chiang et al., 2004; Simoes and Avouac, 2006; Tensi et al., 2006). Tensi et al. (2006) suggested that the passive margin lithosphere already experienced flexure since 12.5 Ma and interpreted the observed flexure as not being related to initial arc-continent collision, which is consistent with plate kinematic reconstructions (Hall, 1996; Sibuet and Hsu, 2004). The basal foreland unconformity is observed in the Northern basins (Taishi basin, Fig. 4) with an age estimated between 8.6 and 5.6 Ma (based on biostratigraphic data), consistent with a flexural migration of the load from east to west (Lin and Watts, 2002; Lin et al., 2003). This unconformity separates the passive margin sequence and the foreland basin sequence, which onlaps onto it. The depositional hiatus increases in duration from
the current frontal thrust towards the forebulge in the middle of Taiwan Strait (Lin et al., 2003; Yu and Chou, 2001).

2.3. Modern sediment fluxes in Taiwan: uplift, climate and erosion

East Asian monsoonal climate was most probably established since 8.5 Ma (i.e., late Miocene) with an intensification observed since 5 to 3 Ma (Liu et al., 2003; Wan et al., 2006; Zheng et al., 2004). Today the island experiences 4 to 6 typhoons per year, with maximum annual rainfall of 2000–3000 mm yr⁻¹ (Kao and Milliman, 2008). The total annual amount of sediment delivered to the ocean by Taiwanese rivers has been estimated to be up to 500 Mtyr⁻¹ with a strong asymmetry across the mountain range (Dadson et al., 2003; Liu et al., 2008). Estimates of erosion rates range between 2.2 and 8.3 mm yr⁻¹ (Dadson et al., 2003; Fuller et al., 2003) and up to 30 mm yr⁻¹ (Resentini et al., 2017) in agreement with quantitative estimates from thermochronometric constraints of 3–10 mm yr⁻¹ (Lee et al., 2006; Willett et al., 2003).

Much of the suspended sediment is delivered at hypopycnal concentrations into the Taiwan strait (Dadson et al., 2005; Milliman and Kao, 2005; Milliman et al., 2007) where it is redistributed by seasonal and tidal currents (Jan et al., 2002). The northeast directed South China Sea current (green arrow, inset Fig. 2), for example, transports warm tropical water into the Strait with a peak intensity during summer months (June to August). In contrast, the southwest directed China Coastal current (blue arrows, Fig. 2) delivers Yangtze-derived mud into the northern Taiwan Strait (Hu et al., 2010; Xu et al., 2009) during winter months (September to May).

Marine observations indicate that fine mud particles are relatively quickly transported northwards out of the Taiwan Strait (Horng and Huh, 2011; Horng et al., 2012; Hu et al., 2011; Kao et al., 2008; Liu et al., 2010; Milliman et al., 2007). For example, marine investigations in the Choshui river delta made before and after a typhoon hit the island, showed that fine-size particles are redistributed and transported northward within a month (Milliman et al., 2007). Thus, sediments eroded from the orogen possibly contained a larger amount of mud than currently found in ancient plio-pleistocene deposits, and that has been fractionated away by marine processes.

Average sedimentation rates vary greatly from 2 mm yr⁻¹ in the Western foreland basin to 3–4 mm yr⁻¹ in the Coastal Range (Chen et al., 2001a; Lin et al., 2003; Lundberg and Dorsey, 1990), with a rapid increase observed since the onset of deformation in the Western Foothills (Chang et al., 1983; Lock, 2007; Moutheroeau and Lacombe, 2006; Moutheroeau et al., 2001). These values are in accordance with erosion rates estimates of between 2 and 10 mm yr⁻¹ from modern river sediment loads and interpretation of thermochronological data (Dadson et al., 2003; Fuller et al., 2003, 2006; Liu et al., 2000a, 2001, 2000b; Siame et al., 2011; Simoes et al., 2007; Simoes and Avouac, 2006; Willett et al., 2003)(Table 1).

3. Material and methods

As explained in the introduction, the aim of this paper is to test the influence of different tectonomorphic scenarios in controlling the stratigraphic architecture of the Western Foreland Basin of Taiwan, with a focus on constraining the magnitude of sediment bypass out of the basin and its implications for understanding the underfill to overfill evolution of foreland basins.

To do this we use a stratigraphic model that requires two main input conditions: subsidence/uplift and sediment fluxes. In the following sections, we introduce the basic physical laws used in the 3D stratigraphic model Dionisos and we then review the data and processing that are behind subsidence and sediment flux patterns that we use in this work and that are based on observations reviewed in the previous geological setting section. Finally, we outline the setup of numerical experiments.

3.1. 3D stratigraphic model "Dionisos"

To evaluate the complex relationships between the stratigraphic record, tectonics (subsidence, with respect to the initial collisional geometry) and climate (erosion rates), the stratigraphic model Dionisos was used (Granjeon, 1997). Dionisos is a process-based modeling tool using a diffusion and advection law that links sediment flux to local slope (potential available energy to move sediment) and water flow (transport efficiency of the lithologies defined by a diffusion coefficient). Erosion and sedimentation at each point of the basin are defined by combining the transport equation and the law of mass conservation:

\[ Q_{sed} = -K \cdot Q_{water} \cdot \text{grad} \cdot h \]

The second basic assumption of the model is the law of mass conservation

\[ \frac{\partial h}{\partial t} = - \text{div} \cdot Q_{sed} \]

where:

- \( Q_{sed} \) = sediment transport \([m^2/s]\)
- \( Q_{water} \) = relative water flow \([-\]
- \( K \) = diffusion coefficient \([m^2/yr]\)
- \( h \) = ground elevation \([m]\)
- \( \frac{\partial h}{\partial x} \) = elevation gradient (i.e., slope)

Boundary supplies (i.e. sediment volume and sand, mud fraction), water discharge of rivers at source locations and rainfall must be defined for each sedimentary sequence. It is important to note that all the water introduced by rivers and rainfall is conserved and flows towards the lowest part of the basin (Granjeon and Joseph, 1999). The potential sediment availability is simulated by a maximum erosion rate, which depends on climate (rainfall), subsidence rate and uplift rate (topographic elevation).

The study area was set as a 500 km × 320 km rectangle in the Taiwan Strait where abundant data is available (Fig. 2). It is confined to the flexural forebulge in the West and to the Coastal Range in the East, and includes the Taishi basin in the North and the Tainan Basin in the South (Fig. 2). The input data required by Dionisos consist of tectonic subsidence for different time intervals, sediment supply and eustatic sea level fluctuations. Parameters for compaction, flexure and sediment transport are embedded within the model and can be adjusted to fit benchmark geological data. Sediment influx can be set as a boundary condition into and/or out of the study area, but can also be simulated with basement erosion.

The subsidence data is explained in the following section. Published boreholes and seismic lines offshore in the Taiwan Strait and onshore (Lin and Watts, 2002; Lin et al., 2003; Yu and Chou, 2001) together with constructed depth maps (Fig. 5) for five key stratigraphic horizons defined in an earlier study (Nagel et al., 2013) provide a solid first approximation database. Constraints on sediment fluxes are obtained from combining modern river loads, denudation data and sediment volumes and presented in sub-section 3.3.

3.2. Foreland basin subsidence

The most important basin-scale controls on accommodation include sea-level changes and flexural subsidence related to lithospheric thickening and tectonic loads. The West Taiwan basin formed by flexural bending of the Asian passive margin in front of westward migrating thrust loads of the growing accretionary wedge (Lin et al., 2003). In order to better constrain subsidence of the sedimentary basin, backstripping techniques (using Airy isostasy) were applied to 28 boreholes and 9 stratigraphic sections (Nagel et al., 2013; Watts and Ryan, 1976).

Backstripping is used to stepwise decompartment and unload a borehole
The influence of water depth and sedimentation on total subsidence are extracted in order to isolate the contribution of tectonic subsidence alone. The tectonically driven subsidence at any location in the basin is given in Allen and Allen (2009):

\[
TS = Y \left( \frac{\rho_m - \rho_w}{\rho_m - \rho_s} \right) - \Delta d \left( \frac{\rho_w}{\rho_m - \rho_w} \right) + (W_d - \Delta d)
\]

where \(W_d\) is the average water depth at which the sedimentary units were deposited, \(Y\) is the decompacted sediment thickness, and \(\rho_m, \rho_w, \) and \(\rho_s\) are densities of mantle, water and sediment, and \(\Delta d\) is the difference in sea-level height between the present and the time at which the sediments were deposited:

\[
\Delta d = \frac{\rho_m - \rho_w}{\rho_m} (h_2 - h_1)
\]

The water depth at the time of deposition for the backstripped strata was estimated using paleobathymetries from depositional models of Nagel et al. (2013). Note that since sediments in the western foreland basin were deposited on a shallow marine continental shelf, the influence of the water column (10s of metres) on the backstripped strata is small relative to the considered sediment thicknesses (100s of metres). For decompaction, sediment was assumed to be composed of two main grain size classes, sand and mud, which correspond to the modern siliciclastic river supply and is consistent with detailed lithologic analysis (Huh et al., 2011; Nagel et al., 2013). When the basin gets progressively filled with sediments, mechanical compaction introduces loss of water during sediment burial and affects depth-porosity curves for different lithologies. The trend between porosity and depth is usually approximated by:

\[
\varnothing = \varnothing_0 e^{-cy}
\]
where $\phi_0$ describes surface porosity and $c$ the coefficient of compaction (Table 2). The flexure of the basement was computed with an elastic thickness of 15 km, a Young’s modulus of 100 GPa and a Poisson’s ratio of 0.25, chosen according to published values for the Taiwan foreland basin (Lin and Watts, 2002).

Backstripping results provide a detailed record of the Asian passive margin subsidence and uplift history at the five key biostratigraphic horizons explained above (Fig. 5). Lin et al. (2003) showed that the subsidence history of the Asian passive margin is strongly influenced by its syn- and post-rift history due to extension in the South China Sea (post-breakup extension from 30 to 21 Ma, thermal subsidence from 21 to 12.5 Ma and a second post-breakup extension from 12.5 to 6.5 Ma). Increased subsidence since the early Pliocene (Figs. 5D and 6) is ascribed to growth of the Taiwan orogen as it propagates westward, introducing deformation and increasing sedimentation rates in the basin (Chang and Chi, 1983; Mouthereau et al., 2001). In addition, Tensi et al. (2006) demonstrated that the load associated with initial foreland basin has migrated rapidly westward 1 Ma ago and was stabilized at the same time as the basin was buried under large quantities of sediments (alluvial and fluviatile fans of the Toukoshan fm.).

The reconstructed subsidence pattern (Fig. 6) is consistent with sediment isopach maps shown in Fig. 5. The obtained subsidence history of each stratigraphic section can then be interpolated to the boundaries of the stratigraphic simulation project to produce subsidence maps (Fig. 7) that constitute a direct input into Dionisos. Subsidence pattern in between two key stratigraphic horizons is simply linearly interpreted between the two considered maps.

Table 2
Values used in the backstripping for the different lithologies observed in the Western Taiwan foreland basin and compaction coefficient (after Allen and Allen, 2009; Lin et al., 2003; Tensi et al., 2006).

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Surface porosity ($\phi_0$)</th>
<th>Compaction coefficient ([\text{km}^{-1}])</th>
<th>Density ([\text{kg/m}^3])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shales</td>
<td>0.63</td>
<td>0.51</td>
<td>2720</td>
</tr>
<tr>
<td>Sandstones</td>
<td>0.49</td>
<td>0.27</td>
<td>2650</td>
</tr>
<tr>
<td>Mudstones</td>
<td>0.56</td>
<td>0.39</td>
<td>2680</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
<td>1.00</td>
<td>1030</td>
</tr>
<tr>
<td>Mantle</td>
<td>3.30</td>
<td>3.30</td>
<td>3330</td>
</tr>
</tbody>
</table>

Fig. 5. Maps of decompacted sediment thickness in between the five key biostratigraphic (nannofossils) horizons of Nagel et al. (2013). White dots in map of panel D represent location of Chinese Petroleum Company drill holes.
Lin and Watts (2002) showed that topography is insufficiently high to produce the observed subsidence pattern in an isostatic flexural model driven by surface loads. Following Simpson (2014), it can be proposed that this observation is an illustration of a possible decoupling between subsidence and surface loads, especially prominent in deeply eroded mountain ranges. In his model, Simpson explains that what may have been previously attributed to “buried loads” (as in Taiwan, e.g. Lin and Watts, 2002) could be related to accumulation through time of vertical deformation due to repeated large seismic events and dragging of the foreland margin by reverse slip on the main orogenic front.

### 3.3. Sediment fluxes and basin boundaries

The volume of sediment deposited in the basin was calculated from data of published boreholes drilled by the CPC (Chinese Petroleum Corporation) in the western foreland basin (Fig. 5) (e.g., Lin et al., 2003; Shaw, 1996). For each sequence the sediment thickness is extrapolated between the present day forebulge and the Western Foothills by a triangulation algorithm to obtain four maps between early Miocene and late Pleistocene (four maps in between the five key chronostratigraphic horizons, Fig. 5).

The sediment volume accumulated within each time sequence is shown in Table 3. A total of 82'000 to 125'000 km$^3$ of sediment accumulated since 5.5 Ma in the foreland basin of Taiwan. If we assume that collision started between 5.5 Ma and 3.5 Ma, and that before 5.5 Ma

<table>
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<tr>
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<th></th>
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<tbody>
<tr>
<td>0.0-2.0</td>
<td>47'214-64'884</td>
<td>23'607-32'442</td>
<td>..</td>
<td>17'864-26'203</td>
</tr>
<tr>
<td>2.0-3.5</td>
<td>20'443-35'980</td>
<td>13'628-23'987</td>
<td>..</td>
<td>7'985-19'748</td>
</tr>
<tr>
<td>Total</td>
<td>67'657-100'864</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5-5.5</td>
<td>15'917-26'502</td>
<td>7'959-13'251</td>
<td>..</td>
<td>6'594-9'012</td>
</tr>
<tr>
<td>5.5-23.5</td>
<td>76'298-103'383</td>
<td>4'239-5'743</td>
<td>4'239-5'743</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>159'872-230'749</td>
<td></td>
<td></td>
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</tr>
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</table>
accumulated sediment thickness corresponded primarily to influx of material from Asia mainland, we interpret the increasing sediment influx from the Taiwan orogenic wedge to be in a range of 6’500 to 28’000 km³/Ma (Table 3). This sediment influx is probably overestimated since the basin also must have received material from its western border, i.e. Asia mainland. However, this contribution was probably swamped by the dramatic increase in sedimentation rates that accompanied Taiwan orogeny (Chang and Chi, 1983). In addition, some of the sediment transported into the foredeep consisted of recycled foreland basin deposits. Therefore, calculated sedimentation rates over the area of modern foreland basin are lower when compared with sedimentation rates from Western Foothills, especially during the last phase of orogenic widening, from 0 at the onset to 100 km width at the end.

Finally, initial sediment supply history imposed in the model is shown in Fig. 8. Two sources of sediment are defined along the western and northern sides of the model box (Fig. 2). It is important to note that these sources refer to general provenances located along the model boundaries and are not meant to represent individual rivers. Today, only smaller tributaries of the Minjiang and Jiulong rivers drain directly into the Taiwan Strait, collectively discharging only 1/10 of Taiwanese rivers (Table 5). Water discharge per source area was assumed to be similar to modern river discharge of Southeast Asia (Table 5). Since sediment transport in Dionisos is modeled by diffusion, a short review of published values for the diffusivity coefficient K in different depositional environments is provided here for the sake of comparison with other studies having used a similar approach (Table 6). Although these studies did not all use diffusion in exactly the same way for modeling sediment transport (for instance depending on whether water discharge is taken into consideration or not), an average value for each depositional environment was used based on the values compiled in Table 6.

Fig. 9 shows the sensitivity of different parameters (water discharge, sediment thickness, sediment volume, sedimentation rate) for 7 model runs with increasing sediment transport efficiencies (between 0.1xKinitial and 1000xKinitial, with Kinitial being the diffusion coefficient of base model). All models were run with the standard model setup described above. Parameters were measured at three different points within the basin at seismic lines #1, #2, and #5 (see Fig. 2) as well as the average value from 3.5 Ma to 0 Ma (marked with asterisk).

Simulations start at 12.5 Ma, which corresponds to the NN5-6 nannofossil boundary. This key biostratigraphic horizon has already been used in an earlier study to reconstruct the paleogeography during the arc-continent collision (Nagel et al., 2013). The study shows that sedimentation in the foreland basin during the Miocene to Pleistocene took place in a mixed storm- and tide-dominated shallow marine depositional environment. Paleobathymetry did not change significantly from 12.5 Ma to 3.5 Ma (Fig. 10), when the basin started to subside due to the approaching orogenic wedge in the east and the mud-dominated Chinshui Shale was deposited (Fig. 3). It is important to note that progradation and shallowing-upward cycles associated with the approaching orogenic wedge took place earlier in the northern parts of the

<table>
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<tr>
<th>Sediment Volumes SE Asia</th>
<th>[km³]</th>
<th>2 - 0 Ma</th>
<th>2 - 5 Ma</th>
<th>5 - 11 Ma</th>
<th>11 - 17 Ma</th>
<th>17 - 24 Ma</th>
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Table 4

Sediment volume accumulated in the Cenozoic sedimentary basins of Southeast Asia (modified from, Métivier et al., 1999).
basin and progressed southward as the basin was filling up (Nagel et al., 2013).

3.4. Experimental setup

To explore the orogen growth history and basin architecture, three different tectonic scenarios were tested (Fig. 11). Each model considers the same initial boundary supply data (Fig. 8). In these experiments, orogenic uplift begins at ∼4 Ma, which is in agreement with recent provenance studies (Nagel et al., 2013). The first orogenic growth model (Fig. 11A) considers southward propagation of the orogen at a rate of 90 km/Ma until present day length of 360 km is reached, and assumes a fixed steady state width of 90 km (Suppe, 1981). Using the time-space principle initially constructed by Suppe (1981), steady state size was reached after ca. 1.3 Ma following onset of orogeny. In a second model (Fig. 11B) it is assumed that the orogen collided with a large promontory simultaneously along the length of the modern orogen, with no (or just minor) southward propagation. This scenario is based on sedimentological studies and paleogeographic reconstruction of Castelltort et al. (2011) and tectonic-thermochronometric data of Lee et al. (2015). The third model, intermediate between both previous ones (Fig. 11C), considers a linear growth in length of the orogen with time, along with lateral displacement of the orogen area as it over-thrusts the Eurasian margin. In all three models, a continuous and constant uplift rate of 5 km/Ma was assumed. This rate covers the range of uplift rates that have been determined in Taiwan (Table 1).

4. Simulation results and discussion

4.1. Foreland basin geometry

An initial test was performed to explore the adequacy of the imposed basin subsidence to reproduce the first order geometry observed on seismic lines in the Taiwan Strait (Fig. 4). A key horizon to compare is the transition from passive margin sedimentation to foreland basin sedimentation with the flexural forebulge unconformity as described above (Lin et al., 2003). As shown in Fig. 12, the imposed timing and subsidence results in stratigraphic patterns (Fig. 12B) that correlate well with geometries observed in seismics (Fig. 12A).

4.2. Mass flux calculations

Theoretical models of mountain building have proposed that an orogen can reach a topographic steady state when rates of rock uplift and erosion are balanced (Willett and Brandon, 2002). These models predict that, once steady state is reached, sediment flux into the basin exceeds available accommodation space because no additional tectonic load is acting on subsidence, and therefore the basin becomes overfilled with time (Covey, 1986; Naylor and Sinclair, 2008). Despite observations suggesting that the subaerial part of Taiwan’s orogen has been in steady state since the Late Pliocene (Suppe, 1981, 1984), or even increased in exhumation rate in the Pleistocene (Hsu et al., 2016), the Western Foreland basin is still not overfilled. This can be explained either by a large original accommodation space (inherited from previous history) or by continuous removal of sediment from the basin, thus preventing it to fill-up.

To explore sediment dynamics within the foreland basin, mass balance calculations were done for a southward propagating orogen model. The total amount of material transported into the basin (according to tectonic scenario of Fig. 13) is compared with the amount of sediment preserved. The theoretical total amount of material, which has been eroded from the orogen since 4 Ma, is estimated by multiplying the integrated area (Fig. 13) with erosion rate (Table 1). Currently 55% of the annual fluvial sediment discharge is flowing West and 45% is drained East (Dadson et al., 2003; Liu et al., 2008). Hence the total sediment volume produced by the orogen was corrected for fluvial
discharge flowing East.

Fig. 13 shows the potential sediment flux into the foredeep coming from the Taiwan mountains as estimated by the model. Computed fluxes vary from 25’000 km³ (for a southward propagation rate of 30 km/Ma and an average erosion rate of 2 mm/yr) and up to 425’000 km³ (for a southward propagation rate of 90 km/Ma and an average erosion rate of 12 mm/yr), although this may be overestimated since it does not take into account the recycling of foredeep sediments. The current river sediment flux during typhoon season (Liu et al., 2008) was taken as an upper boundary for the maximum possible sediment influx, when extrapolated over 4 Ma (i.e., 285’000 km³).

The amount of sediment preserved in the basin is much smaller than the possible amount of sediment brought into the basin (Fig. 13) when one considers a southward propagation rate of 90 km/Ma and erosion rates in a range of 4–6 km/Ma (Table 1). Our calculations suggest that between 25’000 km³ and 115’000 km³ of material may have bypassed the foreland basin. If this is correct, it suggests that at least half the sediment eroded from the orogen may not be preserved in eventual foreland basin stratigraphic records. This material is likely longitudinally transported South, out of the basin (Nagel et al., 2013), and into the South China Sea. Observations in south-central Taiwan already indicate enhanced southward sediment transport since Late Pliocene marked by increasing amounts of submarine incisions (Fuh et al., 1997, 2003). The southward sediment transport is also observed in the migration of sediment depocenters and facies belts, mainly driven by large sediment flux from the orogen (Nagel et al., 2013; Simoes et al., 2007).

4.3. Simulated sediment fluxes

An orogen that produces a steady flux of sediments was modeled for each of the three different growth scenarios in Fig. 10 and the volume of material deposited in the basin was calculated for each scenario (Fig. 14). Steady state is established when the elevation of the mountain's top reaches a roughly constant value in less than 1 Ma. This is achieved by tuning the diffusion coefficient for continental sediment transport K, whereby an increase in K equals an increase in erosion, until a value of K is found that gives satisfactory results (mountain range elevation) for all 3 scenarios. Three different models were run, with a mean uplift rate set to 3, 5 and 12 mm/yr. Material is allowed to leave the basin to the south by diffusion. The area of the orogen at each
time step is the same for each growth model, thus with identical uplift and erosion parameters the available material at each interval is assumed to be equal. This allows to compare the three models only in terms of their different tectonic growth scenario, and in terms of their implications for sediment transport in the basin alongstrike the orogen.

The sediment volume of the foreland basin produced by each of the three models is shown in Fig. 15. The three standard models (southward, lateral, or oblique propagation) tend to overestimate the preserved sediment volume. Southward and oblique propagation achieve a better fit to observed sediment thicknesses than lateral propagation. Moreover lateral propagation did not accurately reproduce foreland basin geometries. The best fit (geometry and volume) is achieved with the oblique collision scenario. The southward propagation models suggest an excess of sediment carried into the basin of between 15',000 and 80',000 km$^3$. This amount is in agreement with the theoretical mass balance calculations (Fig. 13).

Fig. 11. Three orogen growth models tested in this study. A) Pure lengthening: southward propagation (90 km/Ma) of a steady state orogen with a fixed width of 90 km. B) Pure widening: lateral propagation, with a fixed length of 360 km. C) Lengthening and overthrusting: southsouthwestward propagation of a steady state orogen.

Fig. 12. A) Yu and Chou interpreted seismic line #1 (see location on Fig. 2). B) Cross-section at the position of seismic line #1 through simulated stratigraphy with Dionisos (this study). The input subsidence forces a dramatic change of sedimentation pattern at the transition from passive margin sedimentation to foreland sedimentation. This mimics the "flexural forebulge unconformity" documented by Yu and Chou (2001). This unconformity represents the boundary between the pre-collisional Nanchuang Fm. and the syn-collisional Kueichulin Fm. and was estimated approximately at 6.5 Ma (Lin et al., 2003).

Fig. 13. A) Orogen growth model with a steady state orogen width of 90 km and a southward propagation rate of $V_p = 30$–90 km/Ma. B) The theoretical volume eroded from the mountain was calculated by integrating the orogen area through time multiplied by the erosion rate. C) The modern river discharge was extrapolated over 3.5 Ma and taken as an upper limit for the maximum possible sediment influx into the basin system (Table 5). The theoretical sediment volume eroded from the mountains and feeding the Western Foreland Basin was corrected for the fluvial discharge flowing to the east, which is currently 45% (Dadson et al., 2003).
As observed, even though the orogen reached a steady state size as suggested by Suppe (1981), due to longitudinal transport, the basin never becomes overfilled.

Earlier observations already implied an important longitudinal sediment transport out of the basin and observations from the southwest of Taiwan seem to confirm these predictions (Covey, 1984; Yu and Hong, 2006). Longitudinal sediment transport is common in most foreland basins. A good example is the southern Pyrenees, where longitudinal sediment routing systems dominated a wedge-top depozone, with deep marine sedimentation prevailing (Mutti, 1977; Castelltort et al., 2017). It is important to note in contrast, that an averaged orogen-wide erosion rate of 3 mm/yr produces a sediment volume that is consistent with the preserved sediment volume in the western foreland basin (Fig. 15, Model C). This means that, according to our approach, either previous estimates of erosion rate based on thermochronological constraints are too high, or sediment bypass occurred at least for parts of basin history.

Because of the presence of many submarine canyons draining sediment from the Taiwan Strait to the deeper basin in the Manila trench (Damuth, 1979; Yu and Chang, 2002; Yu et al., 2009), a fundamental unknown is whether one can find there the missing sediment volume suggested by our calculations. Sparse literature data are available on the nature of the sedimentary basins in the area of the South China Sea close to Taiwan (Lee et al., 1993; Lin et al., 2008; Yu and Huang, 2009), with a main focus on the Pearl River delta and associated submarine fan deposits (Lüdmann et al., 2001; Su et al., 1989; Xiong et al., 2004) (Li et al., 2008). A topographic map of the submarine regions south of Taiwan indicates a peculiarity in the slope of the South China Sea continental margin compared to its continuation further to the South. This suggests an anomalous accumulation of sediment in this area. Topographic profiles across and along the continental margin (Fig. 16, inset) show that the ocean floor remains at a bathymetry of about −4000 m. As a first order approximation we use the isobath −3600 m and a line roughly parallel to the shelf edge to delimit the contour of this promontory of the continental margin and to compute its volume. The volume enclosed by the area drawn on Fig. 16 and using −4000 m as a base elevation represents 28′700 km³ (15′400 km³ when −3600 m is used as a base elevation for the calculation).

The volume of this submarine topography is compatible with deposits originated in the Taiwan orogeny that would have bypassed the Taiwan Strait. The outline of Tainan basin on the topographic map of Fig. 16 and its southwestward orientation visible on paleogeographic maps of Fig. 5 show that Tainan basin may have constituted a longitudinal through working as a conduit for material sourced in Taiwan orogenic wedge. In this case, a non-negligible portion of the sedimentary record of mountain building may have been preserved outside of the foreland basin itself. However this hypothesis remains to be tested with future work investigating the sedimentological nature and stratigraphy of this anomalous promontory and look for potential sediment depocenters outside of the Taiwan Strait. This finding outlines the potential complexity of interpreting provenance signals (Romans et al., 2016) in orogen-basin systems with highly dynamic topographic evolution.

5. Conclusions

The sedimentary system of the Taiwan foreland basin is governed by oblique collision between Luzon volcanic arc and the Asian passive margin. Different geometrical models of orogen growth and its influence on basin architecture were tested by means of a stratigraphic
modeling approach. By looking at sediment volumes in the foreland basin and calculating mass flux sediment budgets, we document that a significant (perhaps more than 50%) portion of the sediment eroded from the orogen is not preserved in the stratigraphic record of the immediately adjacent foreland basin. The excess sediment is most likely transported northwards into the Okinawa Trough and southwards into the South China Sea, where large submarine channel-lobe systems developed. This interpretation is consistent with an increasing amount of submarine incisions since Late Pliocene observed in southwest Taiwan.

We propose that this may explain why, despite being in front of a steady state orogen, the basin remains in an “underfilled” state. We tested three different orogenic growth scenarios with longitudinal transport. While predicted preserved sediment thicknesses exceeded observed sediment thickness, longitudinal transport was efficient enough to keep the basin from overflowing in all three scenarios. However, we find that, despite recent suggestions that collision in Taiwan may have been synchronous along its entire length (over the length of Taiwan, Castelltort et al., 2011, Lee et al., 2015), an oblique collision fits better the observed basin architecture.

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