Taiwan is considered the archetypical orogen in the development of critical wedge models of mountain building; however, the issue of how arc collision progressed along the margin remains poorly understood. To resolve this, the detrital archive of orogenesis preserved in Coastal Range rocks of eastern Taiwan was used to reconstruct the erosional response of arc collision. The spatial and temporal distribution of exhumation recorded in this detrital record is consistent with southwards progression of arc–continent collision in a punctuated rather than sequential manner with deposition confined to segmented foredeep basins. Apparent increases in sedimentation rates in Taiwan during the Pleistocene may not reflect increased erosion, but instead may be due to the collisional margin architecture.

**Supplementary materials:** Analytical details and dating results are available at www.geolsoc.org.uk/SUP18693.

Taiwan, one of the most intensively studied orogens on Earth and an archetypical orogen in the development of critical wedge models of mountain building (Suppe 1984; Willett et al. 2003; Fuller et al. 2006), grew as a consequence of accretion of Asian continental material along the WNW side of the mountain belt and collision of the Luzon arc on the eastern (retro) side (Fig. 1). Collision between the Luzon arc and the Eurasian continental margin is oblique, and southwards propagation of arc–continent collision has been estimated to occur at a rate of c. 50–90 mm a⁻¹ since c. 6 Ma (Byrne et al. 2011). To track the arc collision process during the late Cenozoic, it is crucial to know which of these models (if any) is correct, because, for example, if the density and flux of the material entering the wedge changes it has an impact on the application of critical wedge models (e.g. Hilley & Streecker 2004). As a result, current wedge models may be oversimplified and not applicable to small orogens such as Taiwan. Insights into the nature of collision can be found in the detrital thermochronometry record preserved in the retro-foredeep basin. Provided the sediment transfer process is short and direct there are two possibilities, as follows.

(1) If collision progressed smoothly then bedrock exhumation, recorded by exhumed reset (<6 Ma) grain ages from previously deeply buried (>6 km) cover rocks should young progressively southwards; that is, the occurrence of reset ages in sediments deposited at Shuilien in the north will be earlier and hence older than those recorded at Sanshien in the central Coastal Range (Fig. 1).

(2) If collision progressed in a non-steady or punctuated manner, exhumation-related reset ages would vary in occurrence along the margin with a non-linear trend in exhumation ages southwards. If punctuated collision is related to the positioning of the magmatic arc volcanic centres there should be correlation between arc location and the decrease and local rise in exhumation-related age patterns.

The goal of this study is therefore to determine which of these possibilities applies to Taiwan and reveal the potential consequences for sediment accumulation rates; in particular, whether the observed rise in Coastal Range sedimentation (Chi et al. 1981) reflects a change in exhumation rate or climate as generally suggested (e.g. Zhang et al. 2001), or whether closing of sediment transfer pathways and a reduction in sediment transport along the margins of the mountain belt significantly change the preservation potential and hence the preserved record.

**Geological setting.** The 4 km high Taiwan orogen (Fig. 1) is the result of collision between the Luzon volcanic arc and the South China margin. The region currently experiences some of the highest rock uplift rates in the world (e.g. Willett et al. 2003) and associated rock exhumation recorded by bedrock thermochronology studies in the Central Range yields generally young ages (<6 Ma) diagnostic of rapid rock uplift and erosion (Liu et al. 2000; Willett et al. 2003; Fuller et al. 2006; Lee et al. 2006; Beyssac et al. 2007). Owing to the high rates of erosion the bedrock thermochronometry data mainly represent the latest phase in orogen development. The earliest records of collision, about which little is known, have been eroded away and redeposited in surrounding basins.

The Coastal Range of eastern Taiwan (Fig. 1) offers an exceptional opportunity to examine the early evolution of mountain growth, erosion and the preserved detrital record as it includes Miocene volcanic and volcanioclastic rocks of the Luzon arc sequence unconformably overlain by kilometres of Taiwan-derived Plio-Pleistocene sediments (Dorsey 1992). The accreted Luzon arc includes two volcanic islands, Chimei and Chengkuangao, with a third volcanic island potentially represented by the Yuehmei pyroclastic deposits (Fig. 1). Volcanic activity at Chimei initiated at 15–16 Ma and ceased by c. 6 Ma,
whereas activity to the south at Chengkuangao ceased c. 3 Ma (Huang et al. 2006) consistent with overall southwards propagation of collision over time. Turbidite deposits with continental material interpreted as Taiwan-derived first appeared in the retro-foredeep basin at c. 4–5 Ma (Dorsey 1988), suggesting subaerial exposure and erosion of proto-Taiwan. In the Coastal Range detrital fission-track dating of Plio-Pleistocene sediments records early unroofing of the nascent mountain belt, revealing when the sedimentary cover was removed, when the mineral grains were exhumed from depth as a result of the Penglai orogeny, and how fast they were delivered into the basin (Liu et al. 2000; Kirstein et al. 2010). An indication is provided by an investigation of samples from the northern Coastal Range that the Central Range was rapidly exhumed in late Pliocene times (Kirstein et al. 2010), hence an objective of this study is to extend and build on these preliminary results.

Suturing of the Coastal Range to Taiwan is accommodated by major structures within the Longitudinal Valley (Fig. 1). The observed Longitudinal Valley segmentation appears to be related to the spatial distribution of the volcanic arc centres consistent with a potential lithological control on strain localization and highlighting a density contrast along the margin. Holocene marine terraces in the Coastal Range also reveal segmentation along the margin, with surface uplift of the section north of Chimei volcanic centre having occurred at a slower rate (4–7 mm a\(^{-1}\)) than in the region to the south (7–10 mm a\(^{-1}\)) (Hsieh et al. 2004). Margin segmentation is intrinsic to the punctuated evolution model and suggests that sediment sections either side of the accreted volcanic centres of the same depositional age should retain different detrital FT age signatures.

**Dating.** Zircon FT (ZFT) and U–Pb dating were applied to a set of new samples collected from two sections in the southern Coastal Range at Sanshien and Mawu. These provide temporal constraints on the thermal evolution of the margin and are critical to unravelling models of collision propagation through time. We focused on zircon for the thermochronometry work as apatite was not present in the majority of the sampled rocks. The few apatite fission-track (AFT) results that we did obtain were unavoidably restricted owing to low numbers of grain ages. The new samples span a stratigraphic interval that dates from 2 to 0.9 Ma, determined by combined magnetostratigraphy and biostratigraphy analyses (Chen 1988; Horng & Shea 1997; Fig. 2).

All new zircon fission-track and U–Pb dating results are presented in Figure 2. The ZFT data are generally overdispersed (>30% age dispersion) indicating mixed age populations. Radialplotter was used to implement a mixture modelling algorithm to identify sample age components (Vermeesch 2009) and these are shown on the radial plots in Figure 2. Of particular interest are the youngest peak age components (P1) as they reflect the most recent thermal event to have affected the source area. Zircons from Sanshien deposited between 1.95 and 1.03 Ma contain significant Late Miocene–Early Pliocene, Cretaceous and Jurassic age components (Fig. 2). The samples from Mawu deposited between 1.9 and 1.3 Ma have dominant Cretaceous, Jurassic and Permian–Silurian ZFT ages. Although similar sources are found in the youngest sample deposited in the Early Pleistocene there is also a minor Miocene (6.4 Ma) component (Fig. 2) that records exhumation of reset zircons. Double dating the same ZFT grains by the U–Pb method did not yield any concordant ages, thus ruling out volcanic sources. Double dating of the other samples yielded crystallization ages ranging from the Eocene (36 Ma) to Archaean (3 Ga), with Proterozoic ages dominating. These U–Pb ages are similar to previous results and confirm that the source of the sediments is principally from the continental margins of southeastern China, and the similarity of ages amongst all samples confirms that the source areas did not change throughout the sequence (Kirstein et al. 2010).

Reset AFT grain ages are expected to occur earlier in the stratigraphic sequence than reset zircon grains owing to greater sensitivity to thermal resetting (effective closure for AFT is c. 110 ± 10°C whereas for ZFT it is 235 ± 20°C; Liu et al. 2000; Willett et al. 2003). AFT analyses record Miocene to Pliocene age components. In the northern Coastal Range at Shuimuting (SH) (Fig. 1) the apatite grain age dispersion is low (0.2%), consistent with a single age population from the Middle Miocene (12–13 Ma). In the central Coastal Range samples deposited earlier than 2.6 Ma at Shuimuting are dominated by Miocene apatite grain ages (P1: 14–11 Ma). Samples at Hsiukuluan and Sanshien deposited between 2.58 and 1.75 Ma contain a significant proportion of reset Pliocene grains (P1: 4 Ma). In the south at Mawu, samples deposited in the Early Pleistocene record a switch from a dominant Miocene population (P1: 14 Ma) to a Pliocene population (P1: 2.8 Ma) after c. 1.6 Ma.

**Discussion.** Knowledge of the timing at which thermally reset apatite and zircon grains enter the retro-foredeep basin is important to
distinguish between different models of collision progression along the margin. In the simple southwards progression model every 55 km southwards along the margin there should be a 1 myr change in

ZFT grain ages reveal unreset sedimentary cover material preserved in the north at Shuilien (depositional age 4.1–3.8 Ma; Kirstein et al. 2010). Miocene AFT ages (14–12 Ma) also suggest that the samples have not been reset by the collision process, although the sediment petrography and the AFT results presented here suggest that the grains may have been sourced from the Luzon arc (Dorsey 1988). In the central region from Sanfu south to Sanshien (Fig. 1) sediments deposited more recently than 1.9 Ma have young (ages less than c. 6 Ma) ZFT grain ages, which indicate that removal of the sedimentary cover material had already occurred by that time. Young AFT ages measured in sediments deposited later than c. 2.5 Ma in this region yield Pliocene age components (3.5–5.5 Ma). In the southwards progression model a lag of close to 1 myr would be expected between the Sanfu and Sanshien sections, assuming direct sourcing of material from the orogen. At Mawu, 17 km further south, samples deposited between 1.9 and 1.3 Ma contain no reset ZFT ages, suggesting that the thick sediment cover material was still being removed at this time in this region. It is only post 1.2 Ma that reset ZFT ages are detected, implying wholesale removal of the overlying rock column and erosion of either deeply buried sediment cover or basement material. The AFT results from Mawu record a young apatite population (3.5 Ma) measured in sediments deposited between 1.4 and 1.3 Ma; similar AFT ages are not seen in the older sediments from this region, consistent with differential exhumation in the adjacent source area (Lee et al. 2006). The ZFT and AFT age distributions in the sediments are consistent with available bedrock fission-track data from the Central Range, which indicate that exhumation began in northern Taiwan c. 6 Ma with a proposed increase in exhumational cooling in the southern Central Range c. 2 Ma (Lee et al. 2006). Thus the timing at which thermally reset apatite and zircon grains enter the retro-foredeep basin varies from north to south along the margin, with boundaries identified based on the positioning of the volcanic arc centres. As a result of dividing the Coastal Range into regions bounded by the accreted volcanic island arc centres of Chimei and Chengkuangao, a clear structure emerges that has implications for the evolution of the margin and in particular collision progression with time.

The present northwestward direction of the Philippine Sea plate was established between 3 and 5 Ma, and local changes in the stress field are recorded in this time interval in the Coastal Range (Chi et al. 1981; Dorsey 1988). In the Pliocene, the timing of volcanic arc subsidence and arc rotation is contemporaneous and propagates southwards, starting at Chimei c. 5–3 Ma and occurring at Chengkuangao between 3 and 2 Ma (Lee et al. 1991). Transtension and rotation of the arc can result from oblique convergence as the bathymetric high of the outer arc intersects the continental margin and results in a torque on the adjacent segment. This configuration should have a profound effect on sediment transfer pathways and ultimately sediment accumulation rates in the retro-foredeep basin.

The study sites in the Coastal Range received sediment continuously from Pliocene times and there is little sedimentology evidence to suggest a major change in source during that time (e.g. Dorsey 1988; U–Pb results from this study). Palaeocurrent data indicate that during early to middle Pliocene times currents transporting the sediment into the foredeep basin were highly variable but with a dominant direction to the SSE (Chen 1988). However, directions changed in the sediments deposited in the Late Pliocene–Pleistocene in the central Coastal Range, suggesting transport from the orogen (west) direct to the basin (east). To the south of Chengkuangao palaeocurrent data indicate continued transport to the SSE. Submerged topography associated with the Luzon volcanic ridge may have formed important barriers to sediment transfer and localized deposition as collision progressed (Fig. 3). In the northern Coastal Range an increase in sedimentation rate at Chimei from 0.5 mm a−1 at 3–5 Ma to c. 3.6 mm a−1 between 2 and 1 Ma is proposed after arc rotation was completed in the north (Chi et al. 1981; Lee et al. 1991), consistent with damming of the system as the arc rotated and fragmentation of the foredeep into discrete basins, which means that increases in basin accumulation rates do not reflect an increase in crustal thickening and growth of topography but instead relate to more focused deposition, with a reduction in along-strike transport of sediment and an increase in apparent sediment accumulation rates (Fig. 3).

The topography associated with the volcanic centres influences not only sediment routing and preserved sediment volumes, but also segmentation, deformation and uplift of the island. The region most affected by continuing collision today is located in the Central Ranges south of 23°30′N (Chung et al. 2008). Here, the southernmost accreted volcanic centre of Chengkuangao (Fig. 1) separates a zone of aseismic activity to the north from a zone of deformation to the south where the majority of the vertical displacement associated with recent faults drives surface and rock uplift inland in the
southern Central Range (Chung et al. 2008). Arc deformation and associated submarine topography prevented progressive southwards propagation of the collision, and this together with the entrainment of crust with variable density has an impact on the application of critical taper models of mountain building to this small orogen. In particular, changes in accretionary flux can lead to a transient rather than steady state in mountain building and can have a direct impact on orogen width, sediment flux and internal deformation (Hilley & Streeker 2004).

Our results support the punctuated evolution model and resolve outstanding issues with respect to the timing of exhumation from in situ fission-track dating of the Central Range (Lee et al. 2006) and sedimentology in the Coastal Range (Dorsey 1992). More significantly, our study highlights the role of volcanic centres in the collision process and their significant impacts on sediment routing and margin architecture. In studies of arc collision zones and other small orogens in the geological record, researchers should be wary of interpreting rises in sediment accumulation as simply reflecting increases in erosion associated with topographic expansion and mountain building. The influence of complex margin architectures, drainage reorganization and sediment routing is rarely considered when interpreting detrital datasets; however, as shown here, there is a large potential to bias the preserved sedimentary record and hence our interpretation of the principal driving force of change in older geological environments where much of the plate-tectonic context has been lost.

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