GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G50311.1

Manuscript received 12 April 2022
Revised manuscript received 6 June 2022
Manuscript accepted 19 June 2022

Extensional mountain building along convergent plate boundary: Insights from the active Taiwan mountain belt

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ABSTRACT

Late brittle extension is a common feature in orogenic belts, and its role in mountain building processes is still the subject of debate. Its timing relationship with crustal thickening, the building of topography, basin infill, and rock exhumation are of key importance in determining whether it is a major factor in orogenic development or merely causes near-surface secondary effects. We examined this question in relation to the active arc-continent collision of Taiwan, studying its structural evolution by integrating new and critical geochronological results for tensile vein filling of hinterland metamorphic terrane with syn-collision deposition records. Acceleration of rock exhumation and molasse deposition was found to be coeval with the initiation of brittle tensile structures at ca. 1.6 Ma, which was long overdue as continental subduction started well before 6.5 Ma in central to northern Taiwan. The topographic mountain of Taiwan was thus constructed when the upper crust of the thickened orogenic prism turned extensional, as orographic elevation and relief are prerequisites for molasses production. Syn-collisional brittle extension is therefore proposed as a possible facilitator of both augmented extrusive exhumation and the formation of orography.

INTRODUCTION

Brittle extensional structures are observed in both active and ancient mountain belts, while their function in the structural and topographic development of these orogenic belts has been debated. In addition to inherited rift structures and post-orogenic normal faults that facilitate mountain collapse, syn- and late-orogenic extensional faults and shear fabrics have been well-documented in the hinterland of many orogenic belts as late overprinting structures (Malavieille, 1993; Crespi et al., 1996). Some of these are found, or thought, to have actually formed under a contractional regime as a result of dramatic footwall extrusive exhumation (Searle and Lamont, 2020), while tensile stress was considered to be responsible for others, and enabled extrusive corner flow to core complex-style exhumation of high-grade rocks in the footwall (e.g., Ratschbacher et al., 1989). A major challenge to understanding such extensional deformation is its timing in relation to the constructive phase of orogeny. Gravitational contrast due to overthickened crust (Platt et al., 2015) in regions of pronounced topographic and structural relief is often thought to be the cause (Long et al., 2015); the implication is that the normal faults are a late post-collisional feature that followed the establishment of orography and eventually led to the collapse of mountainous geomorphology (Dewey, 1988). For large-scale orogenic events, deep crustal or lithospheric reconfigurations have been proposed to cause shallow normal faulting during or even immediately before topographic rise, such as delamination of overthickened lithospheric root (Molnar et al., 1993) or lower crustal flow (Royden et al., 2008) in the formation of the Tibetan Plateau. Exact ages of these brittle extensional structures, relative to orogenic and orographic buildup, are usually unavailable due to the lack of datable mineral growths or methodological resolution. The ongoing mountain building of the Taiwan island, under a clear arc-continent collision framework (Suppe, 1981; Teng, 1990), serves as an ideal laboratory for examining the temporal relationships among normal faulting, orogenic shortening, crustal thickening, and topographic development. We analyze the deformational history of Taiwan with key geochronological constraints on a late brittle extensional system at the Hoping locality in the metamorphic hinterland, which are then integrated with regional thermochronologic and foreland sedimentation records to illuminate a direct correlation between the normal faulting and foreland molasse formation. Syn-orogenic, upper-crustal normal faulting is proposed to account for both hinterland exhumation and orographic relief buildup.

THE TAIWAN OROGENIC SYSTEM

Following total consumption of the South China Sea along the Manila Trench, the passive Chinese continental margin was incorporated into the subduction zone, causing shortening within the overriding Philippine Sea plate through forearc closure that caused the Luzon Arc to impinge on the evolving orogenic prism in the arc-continent collision (Malavieille et al., 2002). At present, the plate convergence is ~80 mm/yr in the northwest direction (e.g., Lin et al., 2010). Due to the obliquity between the northeast-trending Chinese continental margin and the near-longitudinal Manila subduction system, the Taiwan mountain building process propagates southward with a characteristic spatiotemporal correlation of orogenic development in which the southern, central, and northern parts of the island are currently in the initial-, full-, and post-collisional stages, respectively (Suppe, 1981; Shyu et al., 2005). Most of the island outcrops the bulldozed Chinese continental margin, from the frontal filled foreland basin (Coastal Plain) and fold-thrust upper margin cover series (Western Foothills) in the west, to the metamorphosed lower margin cover sequences (Slate belt) and basement (Tananao Metamorphic Complex) in the crest and eastern hinterland.

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CITATION: Chen, C.-T., et al., 2022, Extensional mountain building along convergent plate boundary: Insights from the active Taiwan mountain belt: Geology, v. XX, p. , https://doi.org/10.1130/G50311.1

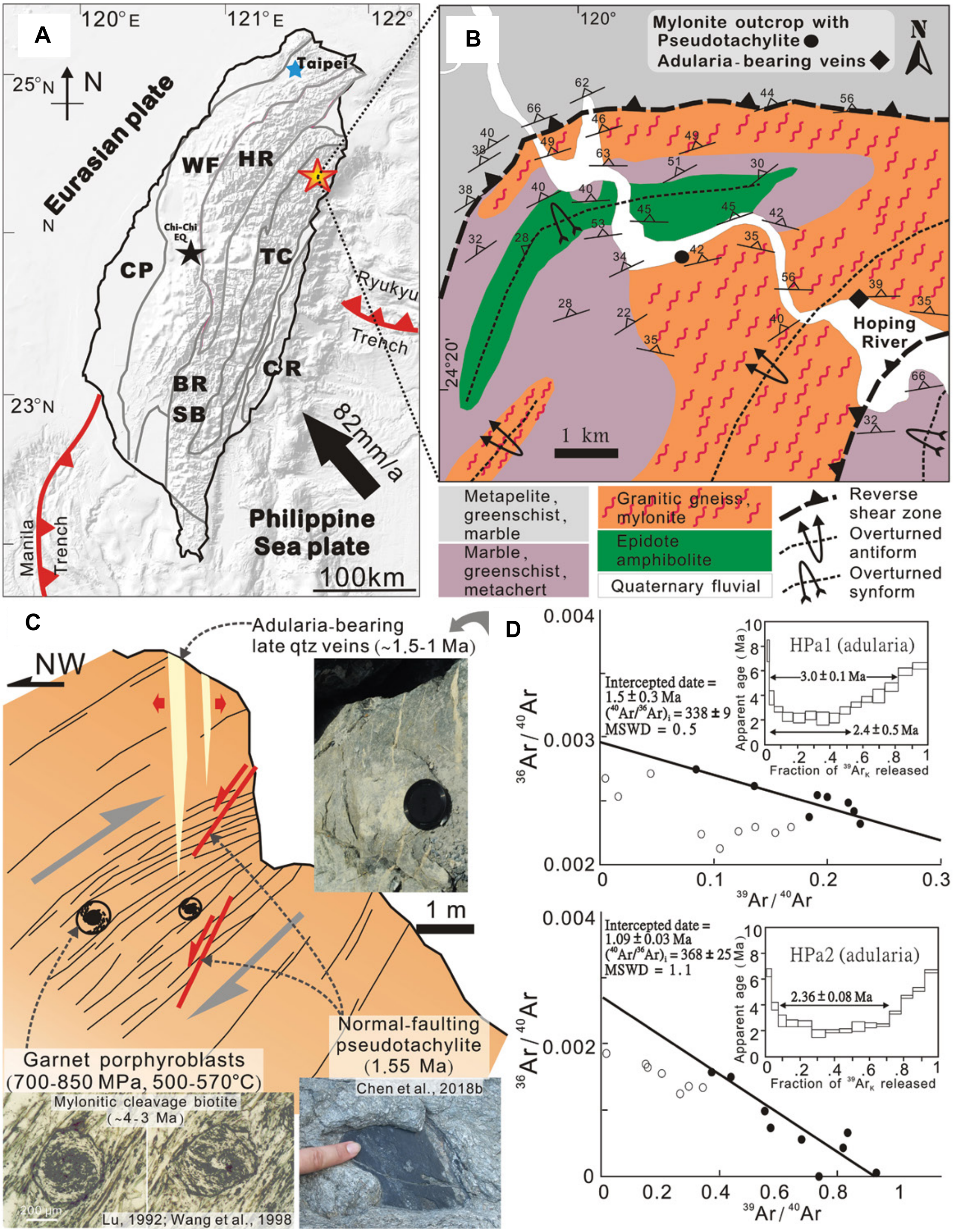

Figure 1. (A) Tectonic framework of the Taiwan mountain belt. CR—Coastal Range; TC—Tananao Complex; BRSB—Backbone Range slate belt; HR—Hsuehshan Range; WF—Western Foothills; CP—Coastal Plain. The Hoping area is marked with the red star. (B) Geological map of the Hoping area in the hinterland Tananao Metamorphic Complex. (C) Schematic structural diagram of the Hoping structural complex with field photos of the late brittle tensile vein system and normal faulting pseudotachylite and photo micrograph (plane-polarized light) of mylonite (from Lu, 1992). (D) $^{40}Ar/^{39}Ar$ step-heating results of adularia crystals deposited in the tensile veins.

Philippine Sea plate–affinity rocks of accreted Luzon Arc and forearc deposits are only found in the Coastal Range east of the Central Range along the Longitudinal Valley suture (Suppe, 1981; Teng, 1990; Fig. 1A). The incorporated continental margin basement (the Tailuko belt of the Tananao Metamorphic Complex), an active margin during Mesozoic Paleo-Pacific subduction, was metamorphosed to higher greenschist and local amphibolite facies during this Neogene mountain building (Lo and Onstott, 1995; Beyssac et al., 2007). The slates, including the Hsuehshan Range and the Backbone Range slate belts, were Cenozoic deposits. Therefore, they have only experienced the current orogeny (Beyssac et al., 2007; Chen et al., 2018a). The entire system began with subduction at the Manila Trench at ca. 15 Ma as evidenced by the earliest northern Luzon volcanism (Lai et al., 2017), and then the foreland basin appeared at ca. 6.5 Ma in central–northern western Taiwan (Lin et al., 2003), which provides evidence of tectonic loading from a significant orogenic wedge following continental underthrusting. Recent acceleration of the subsequent development of the orogenic edifice starting at ca. 2–3 Ma, including surface uplift and exhumation, has been speculated (e.g., Hsu et al., 2016; Chen et al., 2018a; Lai et al., 2022). The entire range is dominated by reverse shearing structures, which were overprinted by extensional (mostly) brittle structures in the ridge and eastern side (Crespi et al., 1996); current deformation is similarly characterized by range-front shortening (including the 1999 CE Chi-Chi earthquake) as well as contractional earthquake focal mechanisms in the mid-crust, whereas extension occurs in the uplifting apex and eastern parts of the range, and the shallow crust beneath (Lin, 2002; Lin et al., 2010). Such a deformation pattern reflects strain partitioning with substantial tectonic underplating at the wedge base, which sustains wedge growth and surface uplift (Beyssac et al., 2007; Malavieille et al., 2021). Unroofing from the surface of the growing wedge has only been recorded well behind the foreland flexure (6.5 Ma; Lin et al., 2003) at <3 Ma both in the foreland basin (Teng, 1990) and in the retrowedge forearc basin (Teng, 1987; Dorsey, 1988; Lai et al., 2022).

THE HOPING STRUCTURAL COMPLEX

The Hoping region, which hosts the late brittle extension system studied here, is situated in the northeast section of the Tailuko belt within the Tananao Schist basement complex. The Tailuko belt—as the deformed, pre-Cenozoic continental margin basement—contains upper greenschist- to amphibolite-facies, Permian to Cretaceous, schistose rocks (Yui et al., 2009). These include quartz-mica schist, meta-sandstone, and meta-conglomerate of terrigenous series protolith (Tianshiang Schist); chlorite schist, metachert, and metabasite from an oceanic stratigraphy (Changchun Formation); massive marble (Jiuqu Marble); and orthogneiss from Late Cretaceous (ca. 88 Ma) Yanshanian granitic intrusions. This tectonic collage was assembled during Mesozoic Paleo-Pacific subduction and remobilized in the current continental subduction collision, which resulted in the development of thrust contacts among the units (Yui et al., 1991). In the Hoping region (Fig. 1B), the elongated Tachoshui Gneiss bodies are juxtaposed against marble, amphibolite, and pelitic schist units along northeast-trending to east-northeast–trending shear zones and bear concordant gneissosity that becomes mylonitic toward the contacts (Chiao, 1991). Restoring the latest clockwise rotation due to lateral extrusion associated with the retreat of the Ryukyu trench (Lin et al., 2010), these shear zones were ductile backthrust that formed in the deep retrowedge (Chu et al., 2012). One such reverse mylonite has been structurally inverted into brittle normal fault with paleoseismic evidence present (Ferré et al., 2016), while throughout the region ductile contractional structures are ridden by late extensional brittle normal faults and tensile veins (Fig. 1C) as were observed in the eastern Tananao Complex further south (Crespi et al., 1996).

Detailed thermal-metamorphic and chronological constraints are available for this particular mylonitic fault zone. The meta-granites are porphyroblastic with northeast-trending to east-west–trending and moderately north-dipping foliation, and are composed of albite, quartz, biotite, muscovite with minor epidote, garnet, chlorite, K-feldspar, apatite, zircon, and iron sulfide. Analyses of zoned and syn-tectonic snowball garnet porphyroblasts with cogenetic biotite, muscovite, and plagioclase indicate prograde metamorphism up to amphibolite facies with pressures of 7–8.5 kb and temperatures of 500–570 °C for mylonitization during continental underthrusting and crustal stacking (Lu, 1992). The foliation-defining biotite grains yielded 4.14 ± 0.02 to 2.99 ± 0.02 Ma crystallization ages that mark mylonitic backthrust shearing (Wang et al., 1998). The ductile contractional structures above were cut by generally north-south–trending, thick, vertical vein systems containing large and sometimes euhedral adularia and quartz crystals with minor chlorite, epidote, and phengite (Fig. 1C). New ^{40}Ar/^{39}Ar step-heating analyses of vein adularia yield crystallization ages of ca. 1.5 Ma and ca. 1.1 Ma (Fig. 1D; detailed data are available in the Supplemental Material[1]) and chronicle the tectonic switch to prevalent brittle tensile deformation in the schist complex. Normal-faulting paleo-earthquakes recorded by pseudotachylite veins offsetting mylonitic foliation were also dated at ca. 1.55 Ma (Chen et al., 2018b). Accompanying the extension was fast and accelerating exhumation of 2–4 mm/yr to 4–8 mm/yr starting at ca. 2 Ma as determined by zircon and apatite fission-track and (U-Th)/He thermochronology (Hsu et al., 2016) as well as the reset ca. 1.6 Ma microcline ^{40}Ar/^{39}Ar plateau ages (Lo and Onstott, 1995).

The complete fate of the continental margin through the orogenic wedge is illuminated by integrating rock records with field structures (Fig. 2B). After being assembled in the frontal part of the upper plate during Cretaceous paleo-Pacific subduction (Yui et al., 2009), it was pulled into subduction between ca. 10 Ma (blueschist record of South China Sea metabasites in the Yuli belt of eastern Tananao Complex; Lo et al., 2020) and ca. 6 Ma (margin sequence subduction and foreland flexure; Lin et al., 2003; Chen et al., 2018a) and reached ~25–30 km depth (prograde garnet porphyroblastic growth) before ca. 4 Ma. The continental margin was then basally accreted and shortened in deep retrowedge along backthrusts during 3–4 Ma; rapid exhumation immediately followed, with extensional deformation, which turned brittle and seismogenic starting at least by ca. 1.6 Ma. Current extension is evidenced in shallow crustal (<20 km) earthquake focal mechanisms (Lin, 2002) and geodetic measurements (Lin et al., 2010).

TEMPORAL RELATIONSHIP WITH FORELAND SEDIMENTATION AND RELIEF BUILDUP

A significant time lag is present in the Taiwanese prowedge between foreland basin formation at 6.5 Ma for central to northern Taiwan (Lin et al., 2003) and the first arrival of detritus originating from the Taiwanese mountains later than 3 Ma (Teng, 1990). The provenance change happened around the onset of the early Pleistocene Cholan Formation and led to the rapid filling of the foreland basin and subsequent subaerial deposition as the late Pleistocene (ca. 1.5 Ma) thick, alluvial gravel beds (Huoyenshan Conglomerate of Toukoushan Formation in the Western Foothills; Teng, 1990; Fig. 2A). A similar phenomenon is found in the retrowedge side of the Luzon forearc basin, which recorded a belated but torrential influx of Taiwan-derived sediments (Dorsey, 1988) as the late Pleistocene provenance changed from the arc-derived Fanshuliao Formation to the orogen-derived Paliwan Formation in the Coastal Range (Teng, 1987), with biotite-grade detritus from Tananao Schist arriving at ca. 1.4 Ma (Dorsey, 1988). For an emerging island, rapid shedding of coarse detritus requires increases in both elevation and topographic relief, which would concur due to the humid, sub-tropical climate of Taiwan. Thus, the delay of orogenic infill to the flexure foreland and retrowedge collision basins clearly indicates that crustal thickening due to continental subduction was not caught up by the development of mountainous topography (Fig. 2C). For the northern Hsuehshan Range, where underthrust margin sequence is exposed, the Taiwanese orogenic wedge possessed low elevation without relief from 8 Ma (onset of margin subduction) through 6 Ma (reaching peak metamorphism) until ca. 2.5 Ma, when molasse Cholan deposition appeared in the foreland. This implies rising topography in tandem with the inception of fast rock exhumation (Chen et al., 2018a; Fig. 2B). Such an “orographic dormant” stage would be even longer for the Hoping region, considering the earlier subduction of up to ca. 10 Ma of the distal, rifted margin basement as the Tananao protoliths (Lo et al., 2020).

The dramatic increase of orogenic sedimentation evidenced in coarse, schist-grade detritus arrival at both foreland and forearc basins since ca. 1.5 Ma, coeval with the initiation of rapid exhumation, coincided with the strain regime change from contractional to extensional in the hinterland Hoping area. The ongoing upper-crustal tensile deformation at wedge top since at least ca. 1.6 Ma has therefore facilitated not only the acceleration of rock exhumation but also the buildup of mountainous topography while still under active plate convergence (Fig. 2C). In the geomorphic viewpoint, the mountain was built after the upper crust of the orogen turned extensional rather than through orography-driven

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[1] Supplemental Material. ^{40}Ar/^{39}Ar step-heating analysis and data. Please visit https://doi.org/10.1130/GEOL.S.20421162 to access the supplemental material, and contact editing@geosociety.org with any questions.

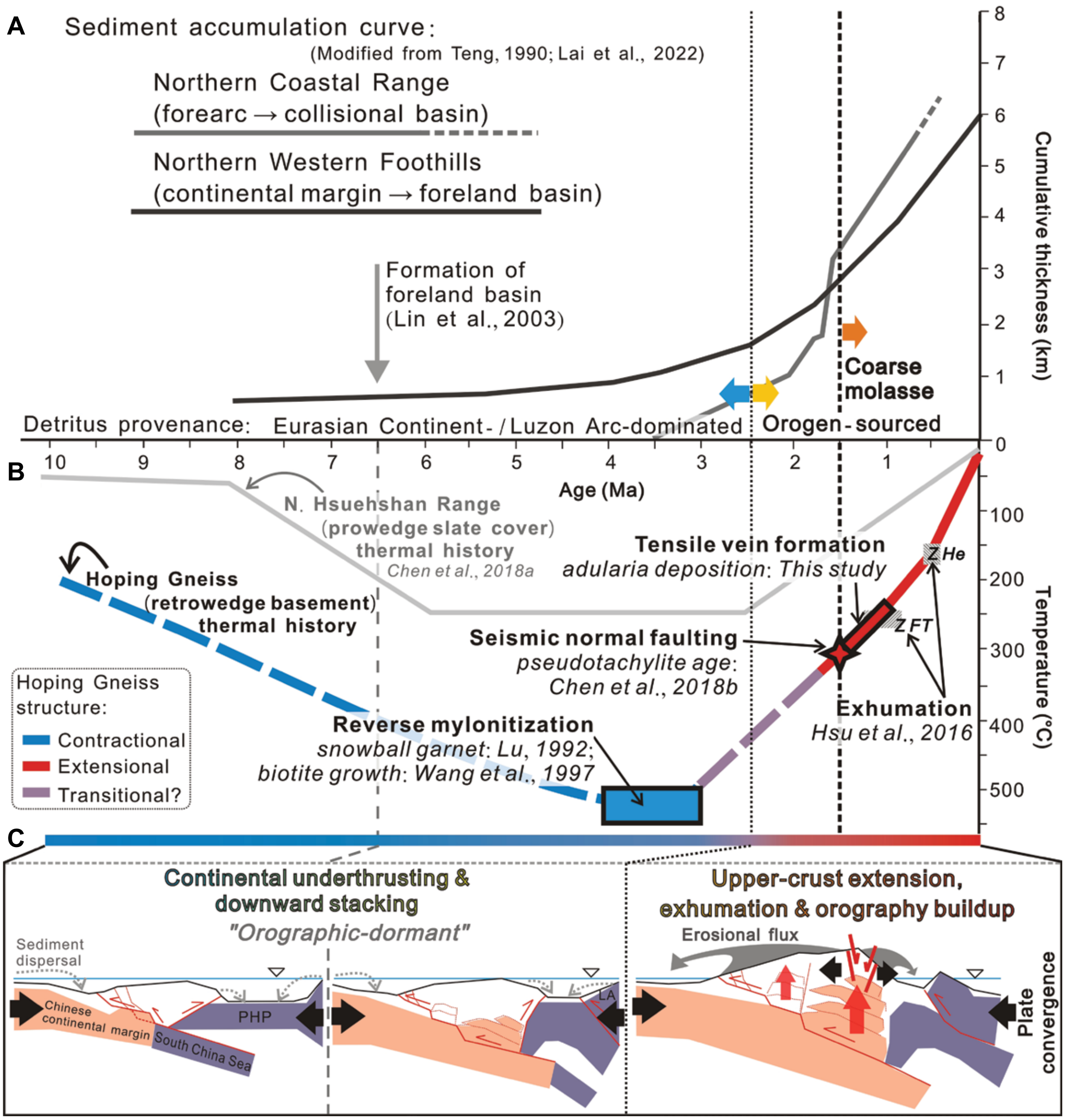

Figure 2. (A) Sediment accumulation and molasses arrival in the foreland and forearc basins (modified from Teng [1990] and Lai et al. [2022]). (B) Thermal-deformation evolution of the Hoping structural complex (refer to the text for details); Z FT—zircon fission-track ages; Z He—zircon (U-Th)/He ages. (C) Schematic profiles correspond to the proposed evolutionary stages of orogenic architecture. PHP—Philippines Sea Plate; LA—Luzon Arc.

extension. The extensional deformation has been partitioned into secondary normal faults distributed across the Taiwanese hinterland (e.g., Crespi et al., 1996) instead of being concentrated along the normal faulting detachments that are characteristic of metamorphic core complexes (Platt et al., 2015). East of the Hoping region, the mountain range immediately gives way to the deep-marine Hoping Basin and the steep Ching-Shui Cliff with apparent normal-slips marks their shared border; however, wrench deformation in the forearc of the southwestward-propagating Ryukyu subduction system seems to have also participated in the formation of the Hoping Basin (e.g., Lallemand et al., 2001; Malavieille et al., 2002), and requires further detailed analyses. Reorientation of maximum principal shortening axis from NW-SE to vertical in the later half of the orogeny under overall contractional tectonic setting might be contributed from combined effects from isostasy (Dewey, 1988) or thermal weakening (e.g., Royden et al., 2008) of thickened continental crust, upward push by stacking of underplated duplexes (Malavieille et al., 2021), and breakoff of the anchoring South China Sea slab (Lallemand et al., 2001). The capability to initiate and speed up both orographic buildup and hinterland exhumation indicates that upper-crust extension and the resultant tectonic denudation play an integral role in the construction of mountain belts.

ACKNOWLEDGMENTS

We benefited from discussions with Hao-Tsu Chu, Chia-Yu Lu, Yu-Chang Chan, Tzen-Fu Yui, Andrew T. Lin, Yi-Ching Yeh, and Timothy Byrne. Constructive comments from the reviewers and editor are deeply appreciated. This work was financially supported by grants from the Ministry of Science and Technology (MOST), Taiwan, R.O.C. (MOST 110-2116-M-008-008- and MOST 111-2116-M-008-019-), and National Central University to C.-T. Chen, and grants MOST 110-2116-M-002-029- and MOST 109-2116-M-002-013- to C.-H. Lo.

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