Acta Geochim (2017) 36(3):511–514
DOI 10.1007/s11631-017-0222-y

ORIGINAL ARTICLE

Test the topographic steady state in an active mountain belt

Kai Deng[1] · **Shouye Yang**[1,2]

Received: 13 April 2017 / Revised: 4 May 2017 / Accepted: 16 August 2017 / Published online: 29 August 2017

Abstract Landscape evolution is the window to the link between deep earth and surface processes. One of the key issues in landscape evolution is to characterize the topographic steady state of mountain belts. The Taiwan mountain belt is an extraordinary case due to its extremely high uplift and denudation rates. The uplift of Taiwan Island is caused by the oblique collision between the Luzon Arc and the East Asian continent. In this case, the mountain building process in the north always occurs earlier than that in the south, which causes the spatial distribution of steady-state regions. The East Central Range receives much research attention with the presence of river basins that mainly distribute along the trajectory of the collision propagation. Normally, based on analyses of geomorphic parameters, the whole Central Range, or at least part of it, should be at a topographic steady state. However, the balance between uplift rates and denudation rates that exist in these regions is seldomly tested. In this contribution, we make a comprehensive literature review on the uplift and denudation rates derived from various approaches, including sediment yields, in-situ cosmogenic nuclide ^{10}Be, incision of river channels, thermochronology, and GPS observations. This literature review reveals that the topographic steady state may prevail in the northern and middle parts of the East Central Range. However, an obvious inconsistency in denudation rates calculated by different methods prevents us from better constraining the topographic steady state in some regions of this mountain range.

Keywords Taiwan · Uplift · Denudation · River profile · Sediment yield · In-situ ^{10}Be

11th International Symposium on Geochemistry of the Earth's Surface.

✉ Shouye Yang
syyang@tongji.edu.cn

1 State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, People's Republic of China

2 Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, People's Republic of China

1 Introduction

Taiwan Island is famous for frequent landslides and rapid mass wasting due to active tectonics and a high typhoon frequency (Hovius and Lin 2000). In modern times, its uplift rates can reach as high as 10–15 mm/yr in the Central Range (Ching et al. 2011). Correspondingly, the modern erosion in Taiwan is quite fast, with the area-weighed mean rate of 4–7 mm/yr (Dadson et al. 2003; Kao and Milliman 2008). Under such extreme tectonic and sediment transfer conditions, how the balance is established between its erosion and uplift over different spatial and temporal scales is of particular interest and still needs to be precisely depicted. Furthermore, this balance is closely related to the achievement of the topographic steady state (Whipple 2004), which will provide guidance in applying landscape evolution models to this active mountain belt.

The Taiwan mountain belt has been formed by the oblique collision between the Luzon Arc and the Asian continental margin since the late Miocene, resulting in the southward propagation of mountain building processes and thus increased collision duration to the north (Clift et al. 2003; Huang et al. 2006). This space-for-time substitution provides an excellent opportunity to study the evolution of mountain growth, erosion, and its topographic steady state. In previous studies, the analyses of river profiles are commonly used to study the topographic steady state of Taiwan. Based on the geomorphic indexes, the whole Central Range, or at least part of it, should be at a topographic steady state (Chen and Willett 2016; Cheng et al. 2012; Stolar et al. 2007). However, in order to test the steady state of the Central Range, the balance between uplift and denudation in steady-state regions should be further discussed (Whipple 2001).

In recent decades, the erosion of Taiwan Island has been investigated in detail with multiple methods, including sediment yields, in-situ ^{10}Be, incision of river channels, and thermochronology. In addition, the uplift of Taiwan Island has been measured over timescales. In modern times, the Global Positioning System (GPS) has been widely used to measure the horizontal and vertical deformation of this active mountain belt. Ggeological uplift rates can be estimated from the uplift information of marine terraces. The abundance of literature data allows us to make comparisons between denudation rates and uplift rates in the East Central Range (the core of the mountain belt) and further test the spatial distribution of steady-state regions indicated by topographic characteristics.

2 Data compilation

We only focus on the river basins in the East Central Range because they are distributed along the trajectory of the collision propagation. Based on the variations of geomorphic indexes, the topographic state of river basins can be separated into two types: steady state (middle part) and non-steady state (northern and southern parts) (Stolar et al. 2007). Specifically, the spatial range of the steady-state region is 125–250 km north of the southern tip of the island (Stolar et al. 2007). Next, uplift rates and denudation rates in the southern (0–125 km), middle (125–250 km) and northern (>250 km) parts are separately compiled for further comparison.

Denudation rates over timescales can be calculated by various methods. The modern (10^0–10^2 yr) denudation rates are deduced from gauging-derived sediment yields, and the area-weighted average rate of the East Central Range is 5–11 mm/yr, calculated by two different methods (Dadson et al. 2003; Kao and Milliman 2008). Centurial (10^2–10^3 yr) denudation rates are quantified by in-situ ^{10}Be concentrations in river sediments, with the area-weighed mean value of $\sim$4 mm/yr in the East Central Range (Derrieux et al. 2014; Siame et al. 2011). Holocene (10^3–10^4 yr) incision rates are also used in this study, although the data can only be found in two rivers (Liwu and Hsiukuluan Rivers). Furthermore, long-term (10^5–10^6 yr) exhumation rates can be revealed by zircon and apatite fission-track data. The denudation rates have accelerated in both the northern and southern Central Range since $\sim$1 Ma, with the rate of 4–10 mm/yr (Byrne et al. 2010; Lee et al. 2006).

The modern (10^0–10^1 yr) rock uplift rates are obtained by continuous GPS observations. The high rates of 10–15 mm/yr are observed in the northern and middle Central Range, but the southern part is experiencing subsidence (Ching et al. 2011). In geologic history, the uplift of marine terraces is commonly used to indicate the Holocene uplift rates along the coast (Hsieh et al. 2004; Song et al. 2004). However, this kind of data cannot be obtained from the Central Range. Considering that the response time of fluvial landscape of the Central Range generally ranges from 0.25 to 2.5 Ma, the topographic steady state is likely to prevail in the plate tectonic timescales (Whipple 2001). Hence, the long-term uplift rates may be similar to the denudation rates derived from fission-track data.

3 Comparison between denudation rates and uplift rates along the East Central Range

Based on the dataset described above, the denudation rates can be compared with the corresponding uplift rates along the East Central Range (Fig. 1).

For the topographic steady-state regions proposed by Stolar et al. (2007), the gauging-derived erosion rates seem to be lower than GPS-derived uplift rates in modern times, which may indicate a non-steady state (Fig. 1). However, it is also noteworthy that the denudation rates over different timescales (10^0–10^4 yr) remain relatively consistent (Fig. 1). The steady denudation is a typical characteristic of the topographic steady state. The controversy between both observations is not found in previous studies. From our perspective, GPS data spanning several years might not yield uplift rates that are representative for those prevailing at geological timescales because they may be greatly influenced by short-term seismicity, e.g. seismic elastic strain accumulation or release (Ching et al. 2011). This deduction can be supported by thermochronology data to some extent because the denudation rates over different timescales (10^0–10^4 yr) are within the range of long-term uplift rates, which are also lower than the GPS-derived uplift rates (Fig. 1). Hence, the topographic steady state should be dominant in the middle part of the East Central Range.

The northern part of the East Central Range may be experiencing post-collisional collapse (Clift et al. 2008). However, the modern erosion rates and Holocene incision rates are similar to the long-term uplift rates, while the Centurial denudation rates seem to be lower (Fig. 1). Hence, it is possible that the steady state may be maintained in the northern part of the East Central Range, but

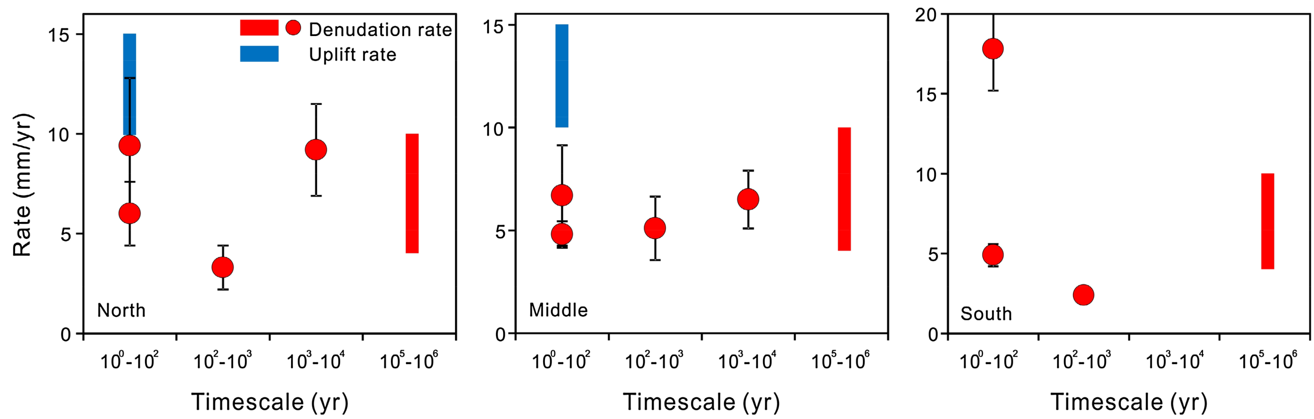

Fig. 1 Comparison between denudation rates and uplift rates over timescales along the East Central Range. The *black short lines* represent *error bars* of corresponding measurements. *Color bars* indicate the range of denudation/uplift rates over a certain timescale. The denudation rates over the timescales of 10^0–10^2, 10^2–10^3, 10^3–10^4 and 10^5–10^6 yr are sourced from sediment yields (Dadson et al. 2003; Kao and Milliman 2008), in-situ ^{10}Be (Derrieux et al. 2014; Siame et al. 2011), incision of river channels (Dadson et al. 2003), and thermochronology (Lee et al. 2006), respectively. The modern uplift rates are derived from GPS observations (Ching et al. 2011)

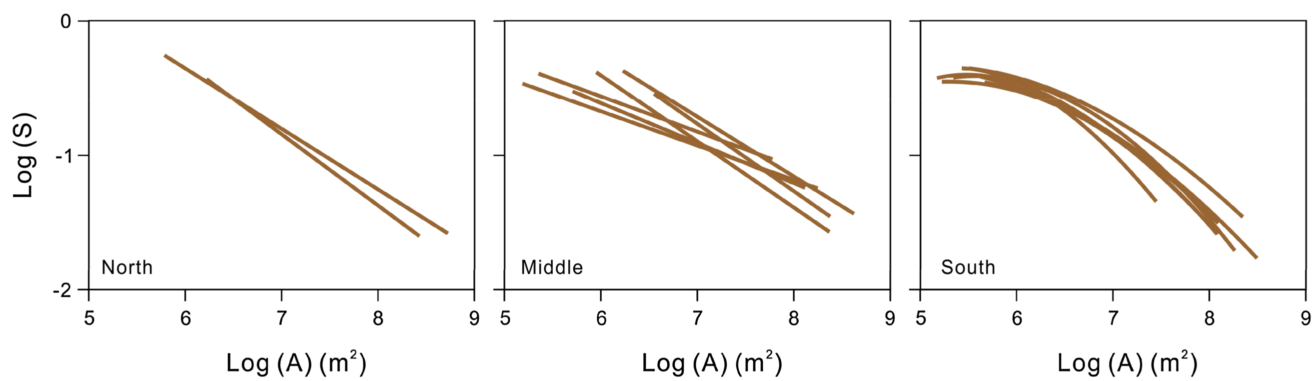

Fig. 2 The fitted correlations between bedrock channel slope (S) and drainage area (A) in the East Central Range. Each *brown line* represents one river The data are sourced from Chen et al. (2006)

whether or not the transition between steady state and non-steady state exists needs to be clarified based on more comprehensive data. In the southern part of the Central Range, a major obstacle for comparison is the huge discrepancy between two gauging-derived erosion rates calculated by different methods (Fig. 1). The erosion rate calculated by the monthly weighted average (MWA) method (Dadson et al. 2003) is much higher than that calculated by seasonal rating curves (Kao et al. 2008). One possibility is that the overrepresentation of sediment observations during flood seasons by MWA method exists in the southern part of the East Central Range (Kao et al. 2005), and thus the high denudation rate of ~18 mm/yr cannot be used. Hence, the long-term uplift rates exceed the denudation rates in the timescale of 10^0–10^3 yr, indicating the mountain growth. However, it should be kept in mind that, in the future a reliable conclusion needs to be supported by more data of representative sediment yields.

The division of the topographic steady state based on our analysis is generally consistent with other results from analyses of topographic features. Based on the stream-power incision model, the relationships between bedrock channel slope (S) and basin area (A) show different patterns along the East Central Range (Fig. 2). The S–A plots of the northern and middle parts show a liner model, corresponding to a steady-state topography (Chen et al. 2006). In comparison, the S–A plots of the southern part are in a convex form, which indicates a topographic non-steady state and the mountain growth (Chen et al. 2006). This can also be evidenced by the basin hypsometry, which shows a steady-state topography in the northern and middle parts of the East Central Range (Cheng et al. 2012).

4 Conclusions

In this contribution, the spatial distribution of steady-state regions in the East Central Range is tested by comparing the denudation rates over timescales with uplift rates. It reveals that the topographic steady state may prevail in the northern and middle parts of the East Central Range. Regarding the southern part, the obvious inconsistency in denudation rates estimated by different methods prevents us from drawing any solid conclusions on the topographic steady state. Furthermore, this study emphasizes that the comparison between proxies of uplift rates and denudation rates could be very helpful to test the representativeness of these methods when applied in various geological settings.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 41376049 and 41225020), National Programme on Global Change and Air-Sea Interaction (GASI-GEOGE-03), and by AoShan Talents Program Supported by Qingdao National Laboratory for Marine Science and Technology (No. 2015ASTP-OS11).

References

Byrne T, Chan YC, Rau RJ, Lu CY, Lee YH, Wang YJ (2010) The Arc-Continent Collision in Taiwan. Front Earth Sci 4:213–245

Chen CY, Willett SD (2016) Graphical methods of river profile analysis to unravel drainage area change, uplift and erodibility contrasts in the Central Range of Taiwan. Earth Surf Process Landf 41:2223–2238. doi:10.1002/esp.3986

Chen YC, Sung Q, Chen CN (2006) Stream-power incision model in non-steady-state mountain ranges: An empirical approach. Chin Sci Bull 51:2789. doi:10.1007/s11434-006-2194-x

Cheng KY, Hung JH, Chang HC, Tsai H, Sung QC (2012) Scale independence of basin hypsometry and steady state topography. Geomorphology 171–172:1–11. doi:10.1016/j.geomorph.2012.04.022

Ching KE, Hsieh ML, Johnson KM, Chen KH, Rau RJ, Yang M (2011) Modern vertical deformation rates and mountain building in Taiwan from precise leveling and continuous GPS observations, 2000–2008. J Geophys Res Solid Earth. doi:10.1029/2011jb008242

Clift PD, Schouten H, Draut AE (2003) A general model of arc-continent collision and subduction polarity reversal from Taiwan and the Irish Caledonides. Geol Soc Lond Spec Publ 219:81–98

Clift PD et al (2008) Post-collisional collapse in the wake of migrating arc-continent collision in the Ilan Basin, Taiwan. Spec Pap Geol Soc Am 436:257–278

Dadson SJ et al (2003) Links between erosion, runoff variability and seismicity in the Taiwan orogen. Nature 426:648–651. doi:10.1038/nature02150

Derrieux F et al (2014) How fast is the denudation of the Taiwan mountain belt? Perspectives from *in-situ* cosmogenic ^{10}Be. J Asian Earth Sci 88:230–245

Hovius N, Lin JC (2000) Supply and removal of sediment in a landslide-dominated mountain belt: central range, Taiwan. J Geol 108:73–89

Hsieh ML, Liew PM, Hsu MY (2004) Holocene tectonic uplift on the Hua-tung coast, eastern Taiwan. Quat Int 115–116:47–70. doi:10.1016/S1040-6182(03)00096-X

Huang CY, Yuan PB, Tsao SJ (2006) Temporal and spatial records of active arc-continent collision in Taiwan: a synthesis. Geol Soc Am Bull 118:274–288

Kao SJ, Milliman JD (2008) Water and sediment discharge from small mountainous rivers, Taiwan: the roles of lithology, episodic events, and human activities. J Geol 116:431–448

Kao SJ, Lee TY, Milliman JD (2005) Calculating highly fluctuated suspended sediment fluxes from mountainous rivers in Taiwan. Terr Atmos Ocean Sci 16:653–675

Kao SJ, Jan S, Hsu SC, Lee TY, Dai M, Lee TY (2008) Sediment budget in the Taiwan Strait with high fluvial sediment inputs from mountainous rivers: new observations and synthesis. Terr Atmos Ocean Sci 19:525–546

Lee YH, Chen CC, Liu TK, Ho HC, Lu HY, Wei L (2006) Mountain building mechanisms in the southern central range of the Taiwan Orogenic Belt—from accretionary wedge deformation to arc–continental collision. Earth Planet Sci Lett 252:413–422

Siame LL et al (2011) Erosion rates in an active orogen (NE-Taiwan): a confrontation of cosmogenic measurements with river suspended loads. Quat Geochronol 6:246–260

Song SR, Liu CM, Chen CH, Lo W (2004) Pumice layers in marine terraces: implications for tectonic uplift rates on the east and northeast coasts of Taiwan over the last hundreds of years. Quat Int 115–116:83–92. doi:10.1016/S1040-6182(03)00098-3

Stolar DB, Willett SD, Montgomery DR (2007) Characterization of topographic steady state in Taiwan. Earth Planet Sci Lett 261:421–431

Whipple KX (2001) Fluvial landscape response time: how plausible is steady-state denudation? Am J Sci 301:313–325

Whipple KX (2004) Bedrock rivers and the geomorphology of active orogens. Annu Rev Earth Planet Sci 32:151–185. doi:10.1146/annurev.earth.32.101802.120356