Late Cenozoic uplift of southeastern Tibet

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ABSTRACT

The age of surface uplift in southeastern Tibet is currently unknown, but the initiation of major river incision can be used as a proxy for the timing of initial uplift. The topographically high eastern plateau and gently dipping southeastern plateau margin are mantled by an elevated, low-relief relict landscape that formed at a time of slow erosion at low elevation and low tectonic uplift rates prior to uplift of the eastern Tibetan Plateau. Thermochronology from deep river gorges that are cut into the relict landscape shows slow cooling between ca. 100 and ca. 10–20 Ma and a change to rapid cooling after ca. 13 Ma with initiation of rapid river incision at 0.25–0.5 mm/yr between 9 and 13 Ma. A rapid increase in mean elevation of eastern Tibet beginning at this time supports tectonic-climate models that correlate the lateral (eastern) expansion of high topography in Tibet with the late Miocene intensification of the Indian and east Asian monsoons.

Keywords: Tibet, thermochronology, thermal modeling, tectonics, Indian monsoon, east Asian monsoon, Miocene.

INTRODUCTION

A substantial part of the high topography related to the Tibetan orogen has developed east of the main Himalayan collision zone (Fig. 1, inset) where a crustal volume of $>2 \times 10^7$ km^3 has been added in Cenozoic time. However, eastern Tibet lacks large-magnitude, late Cenozoic shortening structures commonly associated with crustal thickening (Burchfiel et al., 1995; Leloup et al., 1995; Wang and Burchfiel, 1997; Wang et al., 1998), consistent with crustal thickening by eastward flow of the deep crust without significant horizontal deformation of the surface (e.g., Royden et al., 1997; Clark and Royden, 2000). Thus, one of the few means of dating crustal thickening in eastern Tibet is through the fluvial response to an increase in mean elevation.

The regional topographic slope of the southeastern Tibetan Plateau is defined by low-relief, upland erosion surfaces which we interpret as remnants of a once-continuous, low-elevation paleolandscape (or relict landscape) prior to plateau uplift (Clark, 2003). These remnant surfaces are preserved because fluvial incision of deep river gorges, initiated on major rivers and principal tributaries, has not yet progressed through the entire fluvial network. Because remnant surfaces have not yet adjusted to modern uplift and trunk stream incision rates, they act as passive markers to vertical motion of the Earth's surface and their modern altitude provides a useful datum for measuring surface uplift and the magnitude of river incision. Therefore, the timing of accelerated erosion rates related to forming deep river canyons can be used as a proxy for the timing of plateau uplift.

Changes in erosion rate can be interpreted from the cooling history of the shallow crust by using low-temperature thermochronometers such as the apatite (U-Th)/He and fission-track (AFT) systems. Cooling ages collected on a vertical elevation transect track the thermal history of a crustal section relative to the Earth's surface. When samples cool through their closure temperatures [~40–80 °C for (U-Th)/He (Farley, 2000) and <~125 °C for apatite fission tracks (e.g., Gleadow et al., 1983; Green et al., 1986)] in response to erosional or structural exhumation, their age vs. elevation relationship can be used to determine the rate of exhumation using reasonable assumptions about the geothermal gradient (e.g., Stockli et al., 2000). The incision of major rivers into the relict landscape is manifested by a dramatic transition from slow to rapid erosion rates, producing an increase in

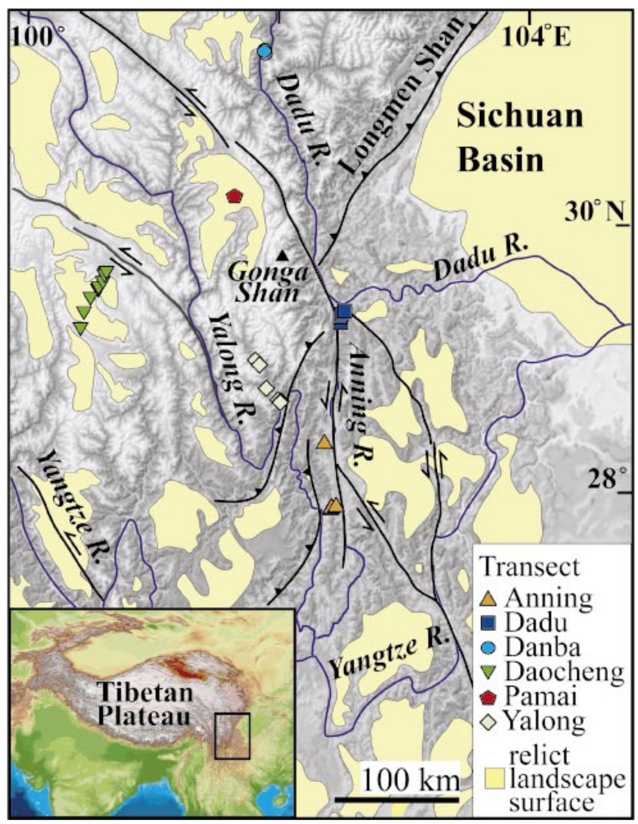

Figure 1. Sample location map and generalized Cenozoic tectonic structures (from Burchfiel et al., 1995; Wang et al., 1998). Colored symbols represent individual sample locations grouped by vertical transect location. Yellow shading outlines extent of relict landscape surface. Note that Sichuan Basin is not Cenozoic depocenter. Surface of Sichuan Basin is cut across deformed Mesozoic strata with less than few hundred meters of Cenozoic sedimentary cover.

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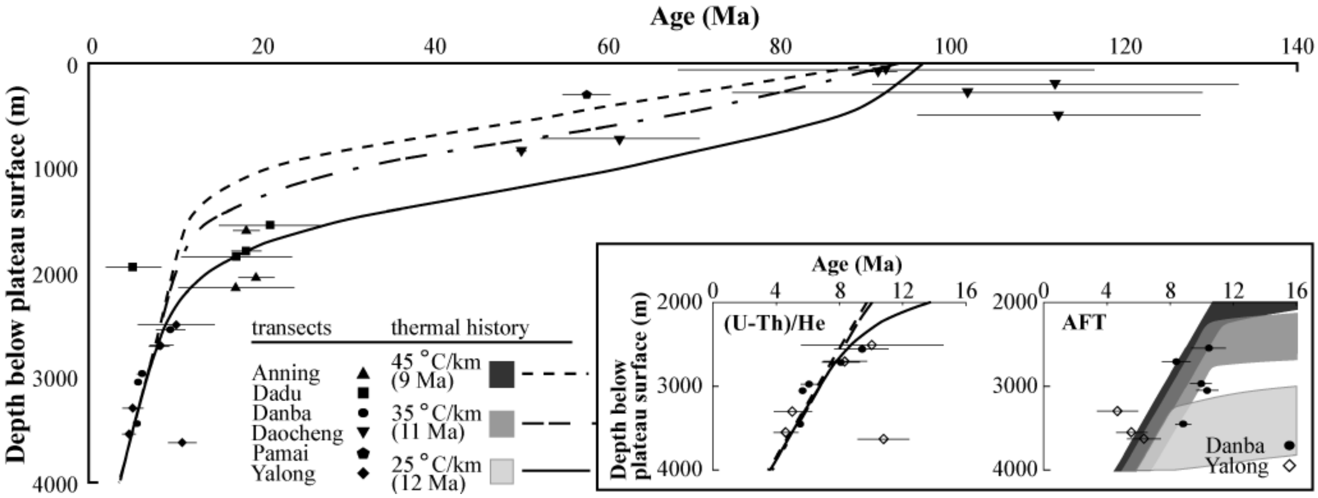

Figure 2. Depth vs. age data for all sample transects. Minimum sample depth is determined by subtracting sample's elevation from elevation of nearest remnant surface. Local erosion of plateau surface is considered for Danba and Yalong transects so that these samples are plotted 750 m lower than their minimum depth estimate. Error estimates are standard errors based on standard deviation of replicate analyses at 1σ. Inset figures show (U-Th)/He and apatite fission-track (AFT) ages for deepest sample transects. Lines represent 2-step model thermal histories of erosion at rate of 0.01 mm/yr from 100 Ma followed rate of 0.4 mm/yr beginning at 12, 11, or 9 Ma for geothermal gradients of 25, 35, or 45 °C, respectively (for grain radius = 54 μm, surface temperature = 10 °C, and He diffusion parameters from Farley, 2000). Inset box shows close-up of deepest transects (Danba and Yalong) for both (U-Th/He) and AFT ages. Model AFT ages for same three thermal histories were calculated by using range of nominal closure temperatures between 90 and 110 °C for each thermal history. Three model histories are represented by degree of gray-scale shading.

cooling rates recorded by the thermal history of the shallow crust (Appendix DR1[1]).

LOW-TEMPERATURE THERMOCHRONOLOGY

We present data from 29 granitoid samples collected for apatite (U-Th)/He thermochronology and a subset of eight samples collected for AFT thermochronology (Fig. 1; Table DR1 [see footnote 1]). Samples were collected across the relict landscape and in the river gorges along the Yangtze River and three of its major tributaries, the Yalong, Dadu, and Anning Rivers (Fig. 1; Table DR1[see footnote 1]). Rugged terrain, restricted accessibility, and limited exposure of lithologies appropriate for (U-Th)/He dating prohibited collection of a transect from the plateau surface to the bottom of the river gorge in any single locality. Consequently, we collected elevation transects covering as great an elevation range as possible in multiple localities (Table DR1; see footnote 1). We subtract each sample elevation from the average local elevation of the relict landscape in order to estimate the minimum depth for each sample. The depth of each transect beneath an originally subhorizontal surface provides a common reference frame between transects (Clark, 2003; Appendix DR1 [see footnote 1]).

The Daocheng transect and a single sample at Pamai were collected within 840 m of the elevation of the relict landscape surface (Fig. 1). Mean (U-Th)/He ages range from 50 to 112 Ma on the Daocheng transect and 58 $\pm$ 6 Ma at Pamai (Fig. 2; Tables DR2 and DR3 [see footnote 1]). The large age range within a narrow elevation interval indicates slow cooling, likely accompanied by slow erosion, between ca. 50 and 120 Ma (Appendix DR1; see footnote 1).

The Dadu and Anning transects span an intermediate depth range of between 1500 and 2150 m below the relict landscape (Fig. 1). In the vicinity of both transects, an elevation step of ~0.5–1 km in the remnant surface occurs locally across the Xianshuihe fault (Appendix DR1; see footnote 1). Mean (U-Th)/He cooling ages of 5–21 Ma from the Dadu transect exhibit a positive correlation between age and elevation with a slope of ~0.03 mm/yr (Tables DR2 and DR3; see footnote 1). The (U-Th)/He mean ages of 17–20 Ma on the Anning transect define a steep age vs. elevation gradient for a similar depth interval (Table DR2 and DR3; see footnote 1). The slopes of both transects are poorly defined owing to the narrow elevation range of each transect (300–550 m) and the large scatter in some of the ages.

The deepest samples collected beneath the plateau surface come from the Yalong and Danba transects (1800 and 2880 m depth) (Fig. 1). Mean (U-Th)/He ages are 9.4–5.5 Ma on the Danba transect and 10.8–4.6 Ma on the Yalong transect (Table DR2 and DR3; see footnote 1). Together, these ages exhibit a steep, well-defined depth vs. age trend with a slope of ~0.25 mm/yr collected over an elevation interval of nearly 1 km (Appendix DR1; see footnote 1). Pooled mean AFT ages range from 10.5 to 8.4 Ma at Danba and from 6.4 to 4.7 Ma at Yalong (Fig. 2; Table DR4 [see footnote 1]). The Danba AFT data define a steep depth vs. age trend, whereas the Yalong AFT data are scattered (Appendix DR1; see footnote 1). Long AFT track lengths on all of these samples are consistent with rapid cooling rates (Table DR4; see footnote 1) (e.g., Gleadow et al., 1986).

REGIONAL COOLING PATTERN AND FORWARD THERMAL MODELING

To a first approximation, the cooling pattern observed from the regional (U-Th)/He data is consistent with a protracted period of slow erosion or slow cooling beneath the relict landscape surface from ca. 100 to after ca. 20–10 Ma (Fig. 2). The variation in mean ages vs. depth suggests slow erosion rates ($\leq$0.02 mm/yr?) or slow cooling by conduction ($\leq$1 °C/m.y.) beneath a surface that has been subject to <2 km of total erosion since 100 Ma. These alternatives are indistinguishable on the basis of our data. Taken separately, the ages on the Anning transect suggest an early initiation of rapid cooling (ca. 20 Ma). Because large errors are associated with these samples and rapid cooling is observed over only a few data points, we prefer to use the ages on

[1]GSA Data Repository item 2005097, Appendix DR1, Tables DR1–DR4 (sample locations and age data), and Figure DR1, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301–9140, USA.

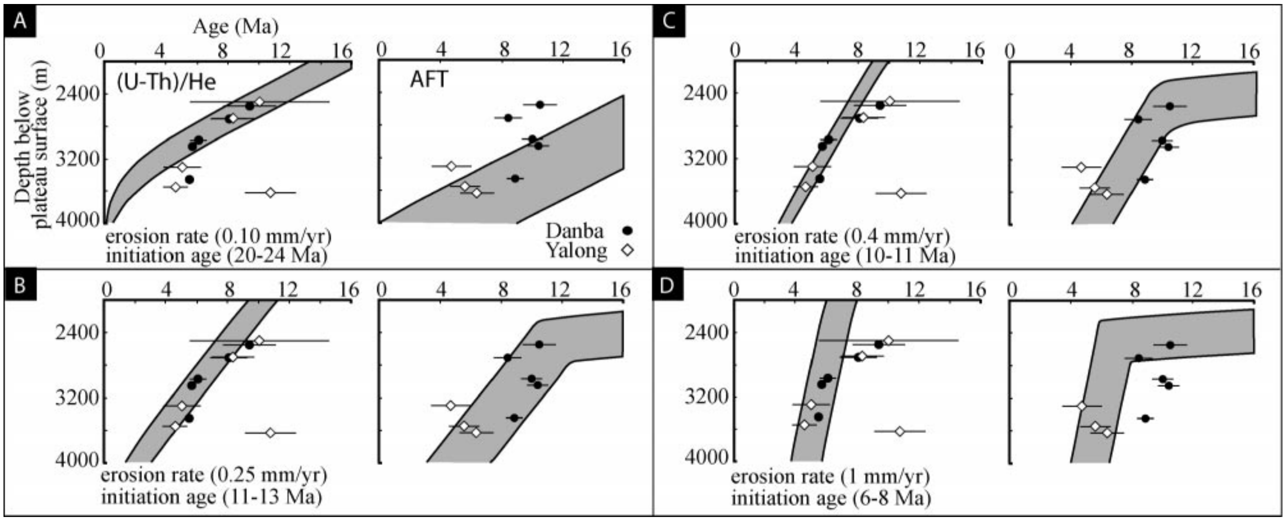

Figure 3. Apatite (U-Th)/He and fission-track (AFT) data compared with forward-modeling results. Solid lines surrounding gray field represent range of model fits to data for varying ages of initial river incision and erosion rate, assuming 35 °C/km geothermal gradient and 10 °C surface temperature. A: For erosion rates of 0.1 mm/yr and less, model fits only higher-elevation samples for He data. Model produces ages that are too young to fit lower-elevation samples for He data and ages that are too old to fit fission-track data. B and C: Example of acceptable fits to both data sets for erosion rates of 0.25 and 0.4 mm/yr, respectively. Model results simultaneously fit both data sets. D: For erosion rates of 1.0 mm/yr, model result can fit some part of age vs. depth data but cannot produce simultaneous fit to both (U-Th)/He and AFT depth vs. age curves.

the Danba and Yalong transects to define the interval of rapid cooling associated with canyon cutting.

Ages from the Danba transect provide our best constraints for estimating the timing and rate of rapid incision because of the high reproducibility of the (U-Th)/He ages and consistency with the AFT ages. The depth vs. age trend on the Danba transect is nearly identical to that of the Yalong transect (except for the lowermost sample) (Appendix DR1; see footnote 1). Young AFT ages and steep age vs. elevation gradients on the Danba transect suggest that these samples must have resided at or above the closure temperature for apatite fission tracks prior to recording of the oldest AFT age of ca. 10 Ma. If we assume no erosion of the adjacent relict landscape since 10 Ma, the minimum depth estimate of these samples suggests an initial geothermal gradient of ≥50 °C/km. However, the plateau surface near Danba and Yalong has undergone glacial erosion, which is relatively uncommon in eastern Tibet and is generally not observed on the relict landscape. If we allow for 750 m of local erosion of the relict landscape above the Danba and Yalong transects due to possible glacial erosion, we can consider lower geothermal gradients between 30 and 35 °C/km. (This estimate of erosion is the minimum amount that allows a reasonable initial geothermal gradient. Smaller erosion estimates require initial geotherms of >35 °C/km.) Local erosion of the relict landscape effectively translates the Danba and Yalong transects deeper beneath an original surface relative to the other transects.

We consider a simple two-step cooling history with a spatially uniform geothermal gradient that represents a protracted period of slow cooling and erosion followed by a change to rapid cooling representing entrenchment of river gorges (Fig. 2). We forward modeled the observed ages by using a one-dimensional thermal model with a standard finite-difference algorithm, constrained by the depth of the sample transect beneath an original relict landscape (Appendix DR1; see footnote 1). The (U-Th)/He ages were computed from this thermal history using a second finite-difference algorithm (Wolf et al., 1998; Farley, 2000). We choose a range of nominal closure temperatures, 90–110 °C, for the AFT data (e.g., Green et al., 1986, and references therein).

For initial geothermal gradients between 30 and 35 °C/km, the Danba transect can be fit with an erosion rate between 0.25 and 1 mm/yr (Figs. 3A–3D), with a significantly better fit between 0.25 and 0.5 mm/yr. The same result is obtained when the Yalong data are superimposed on the Danba data. When the Danba AFT data are included, only models with erosion rates between 0.25 and 0.5 mm/yr fit all the data simultaneously (Figs. 3B and 3C). If the erosion rate is much less than 0.25 mm/yr, the slope of the age vs. elevation data cannot be matched for either the (U-Th)/He or AFT data (Fig. 3A). Erosion rates that fit the He data but are >0.5 mm/yr produce model AFT ages that are much younger than observed (Fig. 3D). The AFT ages from the Yalong transect are consistent with these results. Considering all of the acceptable model fits, we determine an erosion rate for this part of eastern Tibet of 0.25–0.5 mm/yr and an initiation age for the rapid erosion of 9–13 Ma.

DISCUSSION

The erosion rates (0.25–0.5 mm/yr) and initiation age of rapid erosion (9–13 Ma) determined from our data are consistent with published thermochronology data obtained northwest of our study area (Xu and Kamp, 2000; Kirby et al., 2002) and short-term (10^4–10^5 yr) rates derived from stream-sediment cosmogenic nuclide exposure ages (0.015–0.022 mm/yr on the relict landscape and 0.14–0.80 mm/yr in the Dadu River gorge; Ouimet et al., 2005). Dividing the 3–3.5 km maximum depth of the major river gorges (or as much as 4.25 km if we consider an additional 750 m of erosion near Danba and Yalong) by our model initiation age of 9–13 Ma yields an average erosion rate of 0.23–0.47 mm/yr, consistent with the model rates of 0.25–0.5 mm/yr obtained for the Danba and Yalong transects. This indicates that our model results are consistent with the current depth of the river gorges beneath the plateau and that the erosion rates may have been approximately uniform during the time of rapid incision.

Because we were unable to collect a complete elevation transect in one locality, we were not able to observe the acceleration of erosion rate on any single transect. However, the fact that the age vs. depth data can be interpreted with a simple two-step erosion history of accelerated river incision into a slowly eroding landscape (Fig. 2) supports the notion of distributed regional-scale uplift, as suggested by the geomorphic observations. In particular, the similarity in the age vs. depth data on the Danba and Yalong transects suggests that both the Dadu and Yalong Rivers are responding to a regional signal. The data presented here are along strike of the highest portion of the plateau margin (i.e., perpendicular to the regional topographic gradient). If uplift or geothermal gradient were spatially variable in this region, we would expect greater age variability between transects in the deepest river gorges (i.e., Danba and Yalong) than is observed. However, we expect that future transects collected more interior to the high plateau or more distal along the plateau margin (i.e., parallel to the regional topographic gradient) will show age variation related to the lateral growth of the plateau margin.

Late Miocene initiation of major river incision is broadly contemporaneous with development of high topography near the Sichuan Basin between 12 and 5 Ma (Kirby et al., 2002) and the initiation of the modern strike-slip and normal faulting pattern in eastern Tibet at 8–4 Ma (e.g., Wang et al., 1998; Chen et al., 2000). We suggest that these major regional events that took place in eastern Tibet from ca. 13 to 5 Ma were related to the onset of crustal thickening beneath the easternmost plateau margin (east of long 100°E).

River gorges require that an increase in mean topography occurred prior to or coeval with the initiation of major river incision because elevated topography is necessary in order to create deep river canyons. It is possible that rapid incision of the major rivers lagged behind the onset of uplift, depending on climatic conditions. However, we suggest that the changes in elevation probably induced river incision at least within 1–2 m.y. of the initiation of surface uplift.

Uplift and increased precipitation may have had important synergistic effects that are responsible for the synchroneity between monsoon strengthening and the development of high topography and rapid river incision in eastern Tibet. Perturbation of wind patterns by the lateral expansion of the Tibetan Plateau are though to have led to the strong seasonality associated with the modern-day monsoonal climate observed in Southeast Asia (Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992, 1997). Uplift of eastern Tibet may have strengthened precipitation (related to regional climatic changes and orographic effects) so that increased elevation and increased precipitation acted in concert to increase river incision rates. It is significant that the ages we obtain for the initiation of rapid fluvial incision in Tibet (13–9 Ma) closely approximate the estimated timing of environmental change (8.5 Ma; e.g., Kroon et al., 1991; Prell et al., 1992; An et al., 2001) and are consistent with a strong link between the lateral (eastern) expansion of high topography in Tibet and the synchronous (or slightly later) late Miocene intensification of the east Asian monsoon.

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REFERENCES CITED

An, Z., Kutzbach, J.E., Prell, W.L., and Porter, S.C., 2001, Evolution of the Asian monsoons and phased uplift of the Himalayan-Tibetan plateau since late Miocene times: Nature, v. 411, p. 62–66.

Burchfiel, B.C., Chen, Z., Liu, Y., and Royden, L.H., 1995, Tectonics of the Longmen Shan and adjacent regions, Central China: International Geology Review, v. 37, p. 661–735.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J., and Zhang, X., 2000, GPS measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation: Journal of Geophysical Research, v. 105, p. 16,215–16,227.

Clark, M.K., 2003, Late Cenozoic uplift of southeastern Tibet [Ph.D. thesis]: Cambridge, Massachusetts, Massachusetts Institute of Technology, 236 p.

Clark, M.K., and Royden, L.H., 2000, Topographic ooze: Building the eastern margin of Tibet by lower crustal flow: Geology, v. 28, p. 703–706.

Farley, K.A., 2000, Helium diffusion from apatite; general behavior as illustrated by Durango fluorapatite: Journal of Geophysical Research, v. 105, p. 2903–2914.

Gleadow, A.J.W., Duddy, I.R., and Lovering, J.F., 1983, Fission track analysis: A new tool for the evaluation of thermal histories and hydrocarbon potential: APEA Journal, v. 23, p. 93–102.

Gleadow, A.J.W., Duddy, I.R., Green, P.F., and Lovering, J.F., 1986, Confined fission track lengths in apatite: A diagnostic tool for thermal history analysis: Contributions to Mineralogy and Petrology, v. 94, p. 405–415.

Green, P.F., Duddy, I.R., Gleadow, A.J.W., Tingate, P.R., and Laslett, G.S., 1986, Thermal annealing of fission tracks in apatite, 1. A qualitative description: Chemical Geology, v. 59, p. 237–253.

Kirby, E., Reiners, P.W., Krol, M.A., Whipple, K.X, Hodges, K.V., Farley, K.A., Tang, W., and Chen, Z., 2002, Late Cenozoic evolution of the eastern margin of the Tibetan Plateau: Inferences from $^{40}Ar/^{39}Ar$ and (U-Th)/He thermochronology: Tectonics, v. 21, doi: 10.1029/2000TC001246.

Kroon, D., Steens, T., and Troelstra, S.R., 1991, Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers, *in* Prell, W.L., Niitsuma, N. et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 117: College Station, Texas, Ocean Drilling Program, p. 257–263.

Leloup, P.H., Harrison, T.M., Ryerson, F.J., Chen, W., Li, Q., Tapponnier, P., and Lacassin, R., 1995, The Ailao Shan–Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina: Tectonophysics, v. 251, p. 3–84.

Ouimet, W., Whipple, K.X, Royden, L.H., and Granger, D., 2005, Long transient response times of rivers in eastern Tibet to regional plateau uplift: The affect of mega-landslides, European Geosciences Union Spring Meeting, Vienna, Austria.

Prell, W.L., and Kutzbach, J.E., 1992, Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution: Nature, v. 360, p. 647–652.

Prell, W.L., and Kutzbach, J.E., 1997, The impact of Tibet-Himalayan elevation on the sensitivity of the monsoon climate system to changes in solar radiation, *in* Ruddiman, W., ed., Tectonic uplift and climate change: New York, Plenum Press, p. 171–201.

Prell, W.L., Murray, D.W., Clemens, S.C., and Anderson, D.M., 1992, Evolution and variability of the Indian Ocean summer monsoon: Evidence from the western Arabian Sea drilling program, *in* Duncan, R.A., et al., eds., Synthesis of results from scientific drilling in the Indian Ocean: American Geophysical Union Geophysical Monograph 70, p. 447–469.

Royden, L.H., Burchfiel, B.C., King, R.W., Wang, E., Chen, Z., Shen, F., and Yuping, L., 1997, Surface deformation and lower crustal flow in eastern Tibet: Science, v. 276, p. 788–790.

Ruddiman, W.F., and Kutzbach, J.E., 1989, Forcing of late Cenozoic Northern Hemisphere climate by plateau uplift in southern Asia and the American West: Journal of Geophysical Research, v. 94, p. 18,409–18,427.

Stockli, D.F., Farley, K.A., and Dumitru, T.A., 2000, Calibration of the apatite (U-Th)/He thermochronometer on an exhumed fault block, White Mountains, California: Geology, v. 28, p. 983–986.

Wang, E., and Burchfiel, B.C., 1997, Interpretation of Cenozoic tectonics in the right-lateral accommodation zone between the Ailao Shan shear zone and the eastern Himalayan syntaxis: International Geology Review, v. 39, p. 191–219.

Wang, E., Burchfiel, B.C., Royden, L.H., Chen, L., Chen, J., Li, W., and Chen, Z., 1998, Late Cenozoic Xianshuihe-Xiaojiang, Red River, and Dali fault systems of southwestern Sichuan and central Yunnan, China: Geological Society of America Special Paper 327, 108 p.

Wolf, R.A., Farley, K.A., and Kass, D.M., 1998, Modeling of the temperature sensitivity of the apatite (U-Th)/He thermochronometer: Chemical Geology, v. 148, p. 105–114.

Xu, G., and Kamp, P., 2000, Tectonics and denudation adjacent to the Xianshuihe fault, eastern Tibetan Plateau: Constraints from fission-track thermochronology: Journal of Geophysical Research, v. 105, p. 19,231–19,251.

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