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Geochronology transforms our view of how Tibet's southeast margin evolved

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Staring out across the lush and unforgiving landscape of China's Yunnan and southwestern Sichuan Provinces with a geologic map in hand, one is immediately humbled by the skill of the Chinese geologists who were tasked with a seemingly impossible job. The mapping was, by and large, accurate; however, the Cenozoic chronology was based entirely on biostratigrapic and lithostratigrapic correlation (e.g., Ge and Li, 1999) with little, if any, absolute age control. With limited exposure and elusive datable horizons except for a few dikes cross-cutting stratigraphy and interbedded lava flows (e.g., Studnicki-Gizbert et al., 2008), there were few constraints on absolute time in the Cenozoic. Because the area is important for understanding the evolution of the Tibetan Plateau as a whole, the community working in the area pressed on, leaning heavily on the regional stratigraphy in building a Miocene history of how rivers re-organized and incised the Tibetan Plateau's southeast margin (e.g., Clark et al., 2004; Schoenbohm et al., 2006) in response to passive surface uplift resulting from flow of the lower crust (Clark and Royden, 2000) (Fig. 1A). This narrative was reinforced by subsequent low-temperature thermochronology that yielded a middle Miocene timing of river incision (Clark et al., 2005; Ouimet et al., 2010). Using largely the same geologic age constraints from the sedimentary basins, paleo-altimetry studies determined that the Plateau margin was already high in the Eocene (Hoke et al., 2014; Li et al., 2015; Tang et al., 2017), consistent with high elevations in southern and central Tibet (Rowley and Currie, 2006).

Over the past few years, sedimentary basins of the southeastern margin of the Tibetan Plateau have finally begun to yield absolute age constraints, including two new ages from volcanic ashes in the Lühe Basin reported in this issue of *Geology* (p. 3–6) by Linnemann et al. (2017). This spate of geochronology (Hoke et al. 2014; Gourbet et al. 2017; Linnemann et al., 2017) squarely reassigns the age of at least two basins from middle and late Miocene to the Paleogene (Fig. 1A). This reassignment of time, at a minimum, should force us to step back and assess how our interpretations of the southeast margin might change. Given their revised age for the Lühe Basin, Linnemann et al. point out that the much of the modern biodiversity was established in the early Oligocene, 20 m.y. earlier than previously thought. The past, apparently, looked very much like the present, and likely included the establishment of high elevation prior to the late Paleogene. Perhaps as important, time is much more compressed than initially envisioned. Taking the results from Gourbet et al. (2017) with those of Linnemann et al., it would appear that deposition of the Shuanghe and Xiaolongtan Formations occurred over a relatively brief window of time between 37 Ma and 32.5 Ma. These shake-ups in time will likely continue: the youngest zircon U-Pb ages (n = 12) for a tuffaceous sandstone reported by Wissink et al. (2016), in what is mapped as the Paleocene Yunlong Formation, average 36.3 Ma, making them equivalent in time with the Shuanghe Formation of the Jianchuan Basin. Keeping in mind that lithostratigraphy and biostratigraphy were the glue that bound correlations in the area, what other surprises await?

It is certainly within the realm of possibility that what we once thought was Miocene throughout the southeast margin of the Tibetan Plateau now resides in the later part of the Paleogene. This opens up the interesting possibility that these units record late Eocene to earliest Oligocene terrestrial temperatures from the region. There are a large number of plant fossil-derived temperature estimates data throughout the region from basins formerly thought to be Miocene (Xu et al., 2008; Xia et al., 2009; Sun et al., 2011; Yao et al., 2010; Jacques et al., 2011; Jacques et al., 2014), yet with a mean temperature of 17.6 ± 2.3°C over the 10° of latitude there appears to be no meaningful trend from basins that share fossil assemblages with the flora of Lühe and Jianchuan Basins (Fig. 1B). Branched glycerol dialkyl glycerol tetraether (GDGT) temperatures derived from a survey of modern soils of southeast Tibet and the southeast margin of the Tibetan Plateau yield coherent lapse rates that match weather station data (Wang et al., 2017), suggesting a potential horizon for understanding Paleogene temperatures and potentially elevation histories.

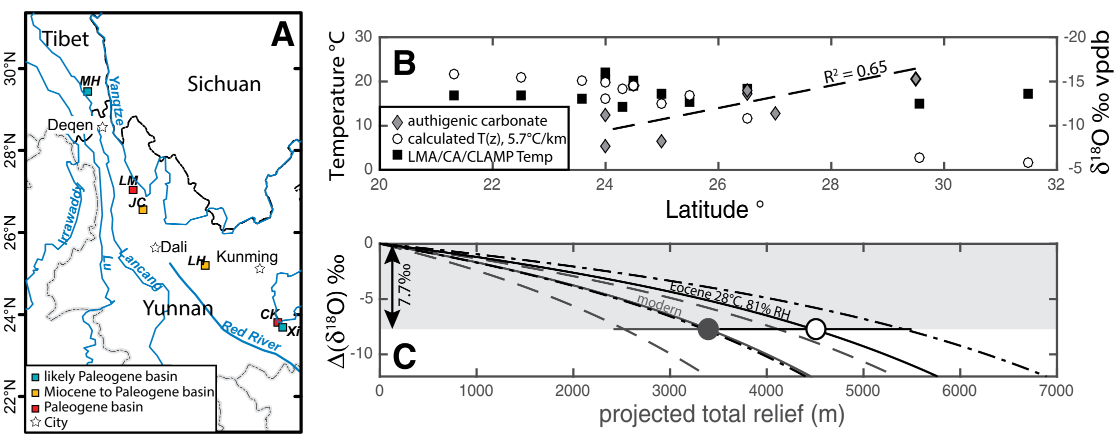

Figure 1. A: Location map highlighting Paleogene sedimentary basins. B: Plant fossil-derived temperature estimates (see references in text) plotted as reported (open symbols) and temperatures for their present-day elevations based on the lapse rate of Wang et al. (2017). Gray diamonds are $\delta^{18}O_c$ values, and dashed line is a linear regression through these data. C: Rayleigh fractionation curves for modern conditions and Eocene conditions. Dashed lines are 1σ bounds on the mean from the model (solid lines). Circles represent elevation for the 7.7‰ north-to-south difference in $\delta^{18}O_c$.

Linneman et al. and Gourbet et al. (2017) suggest that the paleo-elevation history of the southeast margin of Tibet be revisited in light of their revised ages, as they impact some of the assumptions used to calculate paleo-elevations. The most noteworthy of these are the shallower slope of the isotope-elevation gradient (Molnar, 2010) and the temperature corrections applied to pedogenic carbonates by Hoke et al. (2014). Gourbet et al.'s (2017) reanalysis of existing paleo-altimetry data applied a large continentality effect correction by assuming a mid-latitude −2.0‰ per 1000 km decrease in $\delta^{18}O$ and a total distance of 1500 km. Li et al. (2015) applied the same continentality correction over much shorter distances. The continental effect at tropical latitudes, where this part of Asia was located in the Paleocene, can be absent or much weaker than that of the mid-latitudes. In South America, for example, there is a much weaker continental effect, with little to no fractionation of Atlantic sourced moisture across thousands of kilometers until the foot of the Andes (Insel et al., 2013).

Here I attempt to draw some additional insight on the elevation history of the Paleogene basins on the southeast margin of Tibet by examining the $\delta^{18}O_c$ and $\delta^{18}O_{mw}$ values of authigenic carbonates alongside a revised isotope elevation gradient for a warmer, late Paleogene world. This simple analysis is limited to the data reported by Hoke et al. (2014) and Li et al. (2015) (Fig. 1A). Today, these basins span 5.5° of latitude along a NNW-SSE trend that reaches the edge of Tibet. If these basins were at low elevation, isotopic values would be little changed over this distance given their present and paleo-latitudes (Bowen and Wilkinson, 2002), and even with a strong continental effect, only ~1.2‰ of fraction would be observed from north to south. Instead, the $\delta^{18}O_c$ data exhibit a northward decrease in $\delta^{18}O_c$ of 7.7‰ ($R^2 = 0.65$; Fig. 1B). The $\delta^{18}O_{mw}$ values, calculated using plant fossil-derived mean annual air temperature (MAAT) plus 5 °C corrections, increase the total south-to- north decrease in $\delta^{18}O_{mw}$ to 10.4‰. It is difficult to explain such a large offset without a northward increase in elevation across the transect. A Rayleigh fractionation curve (Fig. 1C) using Rowley's (2007) model, assuming a +5 °C offset from modern temperatures and 81% relative humidity, generates a much shallower isotope elevation gradient than standard modern conditions (22 °C and 81% relative humidity). Again, in the spirit of keeping it simple and not going through the educated guesses of initial isotopic values, moisture pathways, or temperature corrections, the −7.7‰ difference in $\delta^{18}O_c$ yields an estimate of ~4.5 ± 1 km of relief from north to south (Fig. 1C). A modern isotope elevation gradient would result in a more modest 3.4 km ± 1 km of relief (Fig. 1C). These estimates are consistent with the modern topographic relief between these basins today. The assigned ages of basins of the southeast margin may change in age, but they still, almost certainly, reflect a high southeast margin of Tibet since at least the Eocene. More paleo-altimetry studies, ideally using different approaches, and continued refinement of geologic time, can test the elevation history developed to date. As the geochronology of this areas evolves, get ready for more surprises, for surely the narrative will change again.

REFERENCES CITED

Bowen, G., and Wilkinson, B., 2002, Spatial distribution of $\delta^{18}O$ in meteoric precipitation: Geology, v. 30, p. 315–318, https://doi.org/10.1130/0091-7613(2002)030<0315:SDOOIM>2.0.CO;2.

Clark, M.K., Schoenbohm, L.M., Royden, L.H., Whipple, K.X, Burchfiel, B.C., Zhang, X., Tang, W., Wang, E., and Chen, L., 2004, Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns: Tectonics, v. 23, TC1006, https://doi.org/10.1029/2002TC001402.

Clark, M., and Royden, L., 2000, Topographic ooze: Building the eastern margin of Tibet by lower crustal flow: Geology, v. 28, p. 703–706, https://doi.org/10.1130/0091-7613(2000)28<703:TOBTEM>2.0.CO;2.

Clark, M., House, M., Royden, L., Whipple, K., Burchfiel, B., Zhang, X., and Tang, W., 2005, Late Cenozoic uplift of southeastern Tibet: Geology, v. 33, p. 525–528, https://doi.org/10.1130/G21265.1.

Ge, H., and Li, D., 1999, Cenozoic coal-bearing basin and coal-farming regularity in western Yunnan: Kunming: Yunnan Science and Technology Press, p. 88.

Gourbet, L., et al., 2017, Reappraisal of the Jianchuan Cenozoic basin stratigraphy and its implications on the SE Tibetan plateau evolution: Tectonophysics, v. 700–701, p. 162–179, https://doi.org/10.1016/j.tecto.2017.02.007.

Hoke, G.D., Liu-Zeng, J., Hren, M.T., Wissink, G.K., and Garzione, C.N., 2014, Stable isotopes reveal high southeast Tibetan Plateau margin since the Paleogene: Earth and Planetary Science Letters, v. 394, p. 270–278, https://doi.org/10.1016/j.epsl.2014.03.007.

Insel, N., Poulsen, C.J., Sturm, C., and Ehlers, T.A., 2013, Climate controls on Andean precipitation $\delta^{18}O$ interannual variability: Journal of Geophysical Research: D, Atmospheres, v. 118, p. 1–22, https://doi.org/10.1002/jgrd.50619.

Jacques, F.M.B., Su, T., Spicer, R.A., Xing, Y.-W., Huang, Y.-J., and Zhou, Z.-K., 2014, Late Miocene southwestern Chinese floristic diversity shaped by the southeastern uplift of the Tibetan Plateau: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 411, p. 208–215, https://doi.org/10.1016/j.palaeo.2014.05.041.

Jacques, F., Guo, S.X., Su, T., and Xing, Y.W., 2011, Quantitative reconstruction of the Late Miocene monsoon climates of southwest China: A case study of the Lincang flora from Yunnan Province: Palaeogeography, v. 304, p. 318–327, https://doi.org/10.1016/j.palaeo.2010.04.014.

Li, S., Currie, B.S., Rowley, D.B., and Ingalls, M., 2015, Cenozoic paleoaltimetry of the SE margin of the Tibetan Plateau: Constraints on the tectonic evolution of the region: Earth and Planetary Science Letters, v. 432, p. 415–424, https://doi.org/10.1016/j.epsl.2015.09.044.

Linnemann, U., et al., 2017, New U-Pb dates show a Paleogene origin for the modern Asian biodiversity hot spots: Geology, v. 46, p. 3–6, https://doi.org/10.1130/G39693.1.

Molnar, P., 2010, Deuterium and oxygen isotopes, paleoelevations of the Sierra Nevada, and Cenozoic climate: Geological Society of America Bulletin, v. 122, p. 1106–1115, https://doi.org/10.1130/B30001.1.

Ouimet, W., Whipple, K., Royden, L., Reiners, P., Hodges, K., and Pringle, M., 2010, Regional incision of the eastern margin of the Tibetan Plateau: Lithosphere, v. 2, p. 50–63, https://doi.org/10.1130/L57.1.

Rowley, D.B., and Currie, B.S., 2006, Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet: Nature, v. 439, p. 677–681, https://doi.org/10.1038/nature04506.

Rowley, D.B., 2007, Stable isotope-based paleoaltimetry: Theory and validation: Reviews in Mineralogy and Geochemistry, v. 66, p. 23–52, https://doi.org/10.2138/rmg.2007.66.2.

Schoenbohm, L.M., Burchfiel, B.C., and Liangzhong, C., 2006, Propagation of surface uplift, lower crustal flow, and Cenozoic tectonics of the southeast margin of the Tibetan Plateau: Geology, v. 34, p. 813–816, https://doi.org/10.1130/G22679.1.

Studnicki-Gizbert, C., Burchfiel, B.C., Li, Z., and Chen, Z., 2008, Early Tertiary Gonjo basin, eastern Tibet: Sedimentary and structural record of the early history of India-Asia collision: Geosphere, v. 4, p. 713–735, https://doi.org/10.1130/GES00136.1.

Sun, B.-N., et al., 2011, Reconstructing Neogene vegetation and climates to infer tectonic uplift in western Yunnan, China: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 328–336, https://doi.org/10.1016/j.palaeo.2010.09.023.

Tang, M., et al., 2017, Paleoelevation reconstruction of the Paleocene-Eocene Gonjo basin, SE-central Tibet: Tectonophysics, v. 712–713, p. 170–181, https://doi.org/10.1016/j.tecto.2017.05.018.

Wang, C., Hren, M.T., Hoke, G.D., Liu-Zeng, J., and Garzione, C.N., 2017, Soil *n*-alkane δD and glycerol dialkyl glycerol tetraether (GDGT) distributions along an altitudinal transect from southwest China: Evaluating organic molecular proxies for paleoclimate and paleoelevation: Organic Geochemistry, v. 107, p. 21–32, https://doi.org/10.1016/j.orggeochem.2017.01.006.

Wissink, G.K., Hoke, G.D., Garzione, C.N., and Liu-Zeng, J., 2016, Temporal and spatial patterns of sediment routing across the southeast margin of the Tibetan Plateau: Insights from detrital zircon: Tectonics, v. 35, p. 2538–2563, https://doi.org/10.1002/2016TC004252.

Xia, K., Su, T., Liu, Y.-S.C., Xing, Y.-W., Jacques, F.M.B., and Zhou, Z.-K., 2009, Quantitative climate reconstructions of the late Miocene Xiaolongtan megaflora from Yunnan, southwest China: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 276, p. 80–86, https://doi.org/10.1016/j.palaeo.2009.02.024.

Xu, J.-X., Ferguson, D.K., Li, C.-S., and Wang, Y.-F., 2008, Late Miocene vegetation and climate of the Luhe region in Yunnan, southwestern China: Review of Palaeobotany and Palynology, v. 148, p. 36–59, https://doi.org/10.1016/j.revpalbo.2007.08.004.

Yao, Y., Bruch, A., and Mosbrugger, V., 2010, Quantitative reconstruction of Miocene climate patterns and evolution in Southern China based on plant fossils: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 291–307, https://doi.org/10.1016/j.palaeo.2010.04.012.

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