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New U-Pb dates show a Paleogene origin for the modern Asian biodiversity hot spots

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ABSTRACT

Yunnan, in southwestern China, straddles two of the world's most important biodiversity hot spots (i.e., a biogeographic region that is both a reservoir of biodiversity and threatened with destruction) and hosts more than 200 fossiliferous sedimentary basins documenting the evolutionary history of that biodiversity, monsoon development, and regional elevation changes. The fossil biotas appear modern and have been assumed to be mostly Miocene in age. Dating has been by cross-correlation using palynology, magnetostratigraphy, and lithostratigraphy because numerical radiometric ages are lacking. Here we report the first unequivocal early Oligocene age (33–32 Ma) of a section in the Lühe Basin (25.141627°N, 101.373840°E, 1890 m above mean sea level), central Yunnan, based on U-Pb zircon dates of unreworked volcanic ash layers in a predominantly lacustrine succession hosting abundant plant and animal fossils. This section, located in Lühe town, is correlated with an adjacent section in the Lühe coal mine previously assigned to the upper Miocene based on regional lithostratigraphic comparison. Our substantially older age for the Lühe town section calls into question previous estimates for the surface uplift and climate history of the area, and the age of all other correlative basins. The modernization of the biota ~20 m.y. earlier than previously thought overturns existing concepts of vegetation history in southwestern China, and points to Paleogene modernization of the biota in Yunnan and associated Asian biodiversity hot spots.

INTRODUCTION

Yunnan, southwestern China, is noted for its high species diversity and endemism (e.g., Chen et al., 2013) and straddles two globally important Asian biodiversity hot spots: the Indo-Burmese (extending into south China, Thailand, Laos, and Vietnam) and south-central China hot spots (Myers et al., 2000). To qualify as a hot spot there has to be high species diversity and endemism, and it has to be under threat. Species richness and endemism are often associated with topographic complexity and strong rainfall seasonality typical of Asian monsoon systems, the characteristics of which are also determined in large part by topography (Boos and Kuang, 2010; Roe et al., 2016). More than 200 small, reputedly Cenozoic, sedimentary basins (Ge and Li, 1999) provide a largely unexplored archive of the evolution of the regional biota, tectonics, and paleoclimate (e.g., Hoke et al., 2014; Li et al., 2015; Ma et al., 2005; Xu et al., 2008; Yi et al., 2003; Zhang et al., 2007). Successful interpretation of these records depends on accurate chronologies of the basin fills, yet much of the inter-basin correlation has been based on lithostratigraphy and/or paleontological comparisons, particularly those of palynofloras (Bureau of Geology and Mineral Resources of Yunnan Province, 1990; Zhang, 1996). Inevitably, the lack of well-dated tie points hampers precise age assignments through magnetostratigraphy, particularly in basins undergoing high and variable sediment accumulation rates.

Many of the Yunnan sedimentary basins are regarded as Miocene or younger because their plant fossil inventories include numerous modern genera (e.g., Zhang, 1996). Unfortunately, independent age constraints are scarce throughout the region (Lebreton-Anberrée et al., 2016), but recent U/Pb and $^{40}Ar/^{39}Ar$ dating has shown that a succession mapped as Eocene to Pliocene in the Jianchuan Basin on the southeastern margin of Tibet is no younger than 35.4 ± 0.8 Ma (Gourbet et al., 2017), thus raising concerns about other age determinations in the region.

GEOLOGICAL CONTEXT

In Lühe town (Nanhua County, south-central Yunnan; 25.141627 °N, 101.373840°E, 1890 m; Fig. 1), recent construction work exposed several volcanic ash beds within organic-rich lacustrine fossiliferous mudstones. The ash beds exhibit internal graded bedding indicative of single event deposition and contain primary magmatic zircon amenable to U-Pb geochronology. The unit to which these mudstones belong is uncertain, having been assigned to both the Shihuiba Formation (Bureau of Geology and Mineral Resources of Yunnan Province, 1990) and the Xiaolongtan Formation (Zhang, 1996). Regardless of this uncertainty, the unit is within the Lühe Basin fill, until now regarded, like those in many Yunnan basins, as late Miocene (ca. 13–5 Ma) in age. The Lühe section (Fig. 2) contains numerous well-preserved leaf, fruit, and seed fossils (Fig. 3; Table 1; Figs. DR1 and DR2 in the GSA Data Repository[1]), as well as a rich palynoflora

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[1]GSA Data Repository item 2018006, analytical methods, geology and plant fossils of the Lühe section, zircon images, U-Pb concordia diagrams, Table DR1 (U-Pb isotopes), Table DR2 (Lu-Hf isotopes), Table DR3 (main and trace elements incl. REE of tuffs), and additional references, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

Data Repository item 2018006 | https://doi.org/10.1130/G39693.1

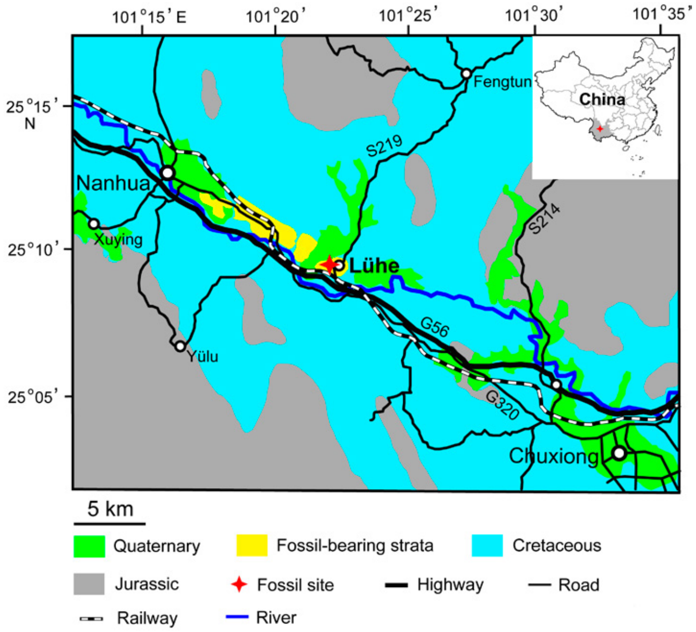

Figure 1. Geological map and location of the Lühe section (Lühe Basin, Yunnan, China).

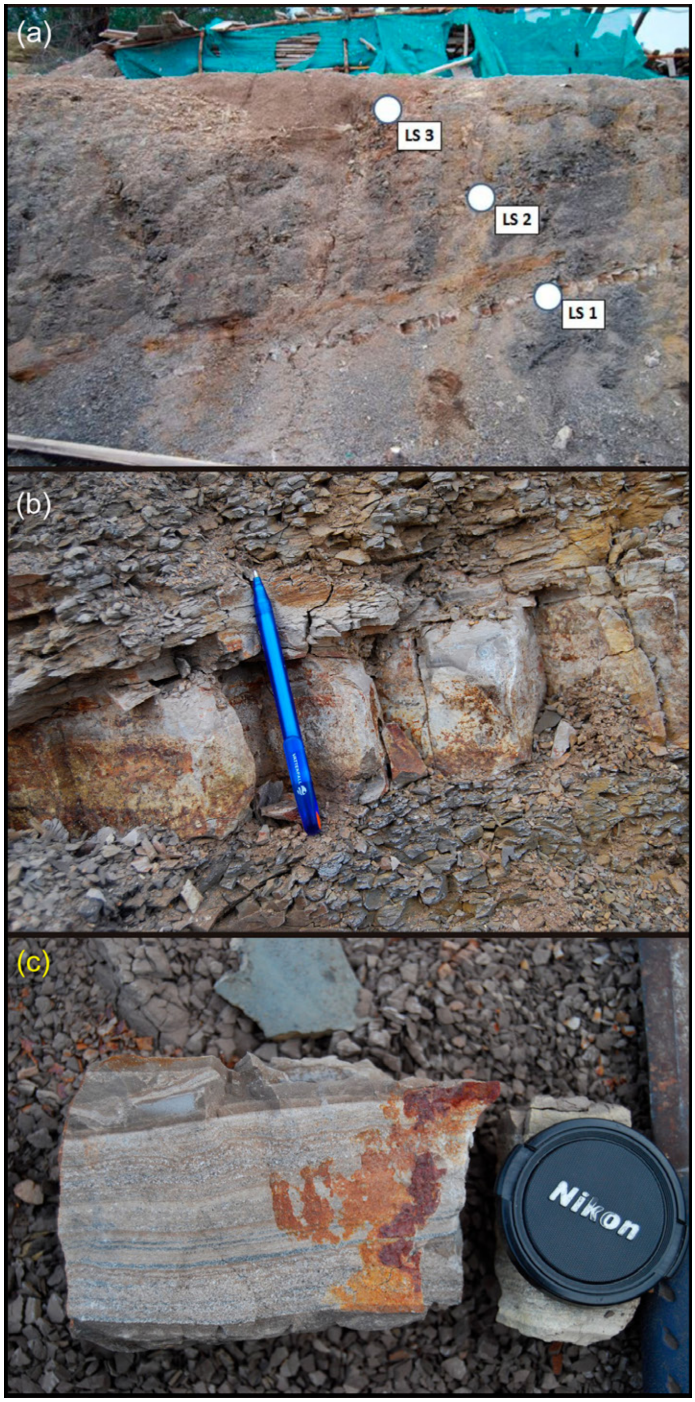

Figure 2. Images of the outcrop with the investigated tuff samples of the Lühe section, China (Xiaolongtan Formation, Lühe Basin). A: Three ash layers and the location of samples LS1, LS2, and LS3. B: Detailed image of ash layer LS1. C: Hand specimen of ash layer LS1. Note the laminated texture.

similar to many other Miocene floras reported in Yunnan, and is lithostratigraphically partly correlated with extensive sections exposed in the nearby Lühe coal mine (Zhang, 1996). The mine sections also yield numerous plant remains, including wood (Ma et al., 2005; Yi et al., 2003) and a rich subtropical mixed evergreen and deciduous broadleaved forest palynoflora (Xu et al., 2008) providing detailed insight into the ancient vegetation and climate of this region. Although regarded as a product of late Miocene deposition, the youngest and most abundant detrital zircons within tuffaceous fluvial sandstones exposed in the Lühe mine are dated as 34–32 Ma (Wissink et al., 2016). Although intriguing, such detrital zircon ages are not definitive for determining the age of deposition. Here we present U-Pb geochronological data from intercalated primary tuffs in the Lühe Basin that document an early Oligocene (33 ± 1 Ma) age of volcanic input and thus sediment deposition, making the preserved biota ~20 m.y. older than previously thought.

MATERIALS AND RESULTS

Samples of three different tuff layers were taken from the Lühe town site in A.D. 2015 (Fig. 2). The ash beds are preserved in dark gray to black lacustrine mudstones with an abundance of leaf fossils representing numerous extant genera (Table 1; Figs. DR1 and DR2). The lower ash bed (LS1; Figs. 2B and 2C) is ~10 cm thick and shows strong internal lamination resulting from aerial or hydraulic sorting (Fig. 2C; Figs. DR3a and DR3b). The ash was deposited as a single event and lacks organic content. Two other ash beds (LS2, LS3) occurring slightly higher in the section (Fig. 2A) were also sampled. The pale gray color and the occurrence of numerous magmatic zircons indicate a magmatic source of felsic to intermediate composition. Analytical details are given in the Data Repository.

All three samples (LS1–LS3) contain zircon grains that are euhedral and of magmatic origin (Fig. DR4). The pristine zircon morphology confirms the primary deposition of the ash beds and rules out posteruptive sedimentary transport and reworking. Only a small number of grains have rounded or subrounded crystal surfaces (Fig. DR5). The occurrence of such grains (sample LS2) can be easily explained by partial reworking during eruption. In cathodoluminescence mode all zircons show a clear magmatic zoning and no alteration by fluids or metamorphism. We analyzed a total of 45 zircon grains from all 3 samples (LS1: n = 10, LS2: n = 25, LS3: n = 10). Clearly magmatic zircon grains show a ^{206}Pb-^{238}U age range of 34–32 Ma (Table DR1) with a concordant age comprising 6 zircon grains (sample LS1) of 33 ± 1 Ma (Fig. DR6). In general agreement with their stratigraphic position, concordia ages for samples LS2 and LS3 are slightly younger (32 ± 1 Ma; Fig. DR6), but overlap within error with the age of LS1. The U-Pb zircon ages for all 3 investigated ash beds from the Lühe site range between 33 ± 1 and 32 ± 1 Ma, and we interpret this early Oligocene age to reflect the timing of deposition of the fossil-bearing strata of the Lühe section.

Figure 3. Illustrations of typical leaf fossils from the Lühe section (Lühe Basin, Yunnan, China). A: *Sequoia* sp. (LH3–0308). Scale bar = 1 cm. B: *Cryptomeria* sp. (LH1–0353). Scale bar = 0.5 cm. C: *Pinus* sp. (LH1–0036). Scale bar = 0.5 cm. D: *Cyclobalanopsis* sp. (LH1–0120). E: *Castanopsis* sp.(LH1–0312). F: *Ostrya* sp. (LH1–0101). G: *Betula* sp. (LH3–0270). Additional material is illustrated in Figure DR2 (see footnote 1). A: *Sequoia* sp. (LH3–0308). Scale bar = 1 cm. B: *Cryptomeria* sp. (LH1–0353). Scale bar = 0.5 cm. C: *Pinus* sp. (LH1–0036). Scale bar = 0.5 cm. D: *Cyclobalanopsis* sp. (LH1–0120).Scale bar = 1 cm. E: *Castanopsis* sp.(LH1–0312). Scale bar = 1 cm. F: *Ostrya* sp. (LH1–0252). Scale bar = 1 cm. G: *Betula* sp. (LH1–0587). Scale bar = 1 cm.

TABLE 1. COMPARISON OF THE TAXONOMIC COMPOSITION OF THE LÜHE FOSSIL FLORA WITH OCCURRENCES IN NEOGENE AND THE MODERN FLORA IN YUNNAN

Lühe flora		Present or absent during Neogene of Yunnan	Present or absent in modern Yunnan
Family	Genus		
Pinaceae	*Pinus*	present	present
Pinaceae	*Tsuga*	present	present
Pinaceae	*Picea*	present	present
Cupressaceae	*Calocedrus*	present	present
Cupressaceae	*Cryptomeria*	absent	present
Cupressaceae	*Metasequoia*	present	absent
Cupressaceae	*Sequoia*	present	absent
Aquifoliaceae	*Ilex*	present	present
Berberidaceae	*Mahonia*	present	present
Betulaceae	*Betula*	present	present
Betulaceae	*Carpinus*	present	present
Betulaceae	*Alnus*	present	present
Betulaceae	*Ostrya*	absent	present
Fagaceae	*Castanopsis*	present	present
Fagaceae	*Cyclobalanopsis*	present	present
Fagaceae	*Quercus*	present	present
Juglandaceae	*Palaeocarya*	present	absent
Lauraceae	*Machilus*	present	present
Oleaceae	*Fraxinus*	present	present
Salicaceae	*Populus*	present	present
Sapindaceae	*Acer*	present	present
Sapindaceae	*Dipteronia*	absent	present
Simaroubaceae	*Ailanthus*	present	present

Note: Neogene occurrences are after Huang et al. (2016); modern flora data are from Wu et al. (1987).

Zircons (n = 11) of sample LS2 have a rounded shape and show clear indication of sediment transport (Table DR1; Fig. DR7). All rounded or subrounded grains have significantly older U-Pb ages covering the Jurassic (155 Ma, 181 Ma, 199 Ma), the Permian (274 Ma, 292 Ma), the Carboniferous (325 Ma), the Silurian (434 Ma), the Ordovician (456 Ma), the Cambrian (514 Ma), and the Neoproterozoic (598 Ma, 612 Ma).

Analysis of the Lu-Hf isotope composition of 33–32 Ma zircons from samples LS1 to LS3 revealed ε_{Hf} values between −10.0 and −12.8, and calculated model ages are in the range of 1.47 to 1.32 Ga (Table DR2). These data are consistent with remelting of ca. 1.4–1.3 Ga crust during magma generation (Fig. DR8). The Th/U ratio of most zircon grains ranges between 0.3 and 1.8 (Table DR1), which is consistent with zircon growth in a felsic magma.

The geochemical composition of bulk-rock samples (LS1–LS3) indicates a trachyandesitic magma source (Table DR3; Fig. DR9). Furthermore, a transition from calc-alkaline to tholeiitic magma suites is indicated (Table DR3; Fig. DR10). The Y-Nd ratios of the ash samples point to derivation from a magma of within-plate character (Fig. DR11) consistent with subducted Indian plate as the magma source. Light rare earth elements are strongly enriched. An Eu anomaly is missing (Table DR3; Fig. DR12a) because of the high plagioclase content in the samples (Taylor and McLennan, 1981). Incompatible mobile elements (e.g., Rb, Ba) are enriched in contrast to depletion of compatible elements such as Cr and Ni (Table DR3; Fig DR12b). Negative zircon ε_{HfT} values (Fig. DR7; Table DR2) indicate partial recycling of cratonic crust. Collectively, the geochemical fingerprinting of ash beds LS1–LS3 points to a mixture of recycled crustal rocks and a crustal-influenced mantle. The presence of tuff layers within the Lühe Basin is suggestive of a Paleogene age because no known proximal Neogene sources exist. Possible Paleogene sources include trachyandesitic and andesitic volcanic centers of eastern Tibet (Wang et al., 2014; Zhang et al., 2005).

DISCUSSION AND CONCLUSIONS

The age congruence between the Lühe ash horizons and detrital grains (Wissink et al. 2016) supports the lithostratigraphic correlation between the Lühe town and mine sections. The previously reported late Miocene age for the Lühe section and paleobotanically correlated basins was based on the relatively modern taxonomic composition of the contained floras (Ge and Li, 1999; Xu et al., 2008; Zhang et al., 2007). Most Lühe plant taxa continued to exist in Yunnan throughout the Miocene and have survived to the present day (Huang et al., 2016) (Table 1). Our revised age shows that the modern aspect of vegetation in southwest China was established by the start of the Oligocene ~20 m.y. earlier than previously thought, changing radically our understanding of the evolution of biodiversity across the region and the origins of the Asian biodiversity hot spots.

Our new chronological data show that the Lühe town section and, by extension, the Lühe Basin, record a modernization of vegetation that must have taken place before the earliest Oligocene. Although elsewhere in southern China there is evidence of some ecological change across the Eocene-Oligocene transition (e.g., Spicer et al., 2017), many first occurrences of typical Neogene and modern taxa appear in the middle to late Eocene, coincident with the development of monsoonal climates in that area (Spicer et al., 2014, 2017; Herman et al., 2017). Until precise and accurate chronologies are developed for more basins across southern Asia, it is difficult to generalize about when and how the modernization of the biota occurred, other than it was a Paleogene phenomenon.

An early Oligocene age of deposition for the Lühe Basin also affects our understanding of the paleoelevation history of Yunnan. Our early Oligocene age questions previous elevation estimates for the area (Hoke et al., 2014) that were based on the assumption that the Lühe Basin is late Miocene in age. This is mainly because stable isotope data from the Miocene Siwalik pedogenic sediments in northern India were logically, but inappropriately, used as a low-elevation comparison (Li et al.,

2015) and Miocene, instead of Paleogene, isotopic lapse rate models were applied (Hoke et al., 2014). While previous stable isotope paleoaltimetry reconstructions (Hoke et al., 2014; Li et al., 2015) obtained a paleoelevation of ~1 km for the Lühe Basin, these estimates need to be reexamined even if the revised elevations are within the measurement uncertainty. Similar questions apply to any results obtained from sections correlated with the Lühe Basin, such as Lanping, where Lühe mean annual air paleotemperature data were used to constrain paleoaltimetric calculations (Hoke et al., 2014). Paleoelevations have been revised for the Jianchuan Basin, reducing the Eocene surface height from 3300 ± 500 m (Hoke et al., 2014) to 1200 ± 1200 m (Gourbet et al., 2017). Even if the paleoelevation estimates remain unchanged within uncertainty after they are reassessed, the revised age for the Lühe Basin means that those surface heights were attained ~20 m.y. earlier than currently envisaged; this may have implications for geodynamic models such as those invoking lower crustal flow (Clark and Royden, 2000; Li et al., 2015; Royden et al., 2008) or our understanding of the long-term evolution of landscapes and life (Mulch, 2016).

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