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Negligible surface uplift following foundering of thickened central Tibetan lower crust

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ABSTRACT

This study used clinopyroxene (cpx) compositions and zircon Hf-O isotopes of Eocene adakitic rocks (EARs) from the Qiangtang block to resolve the mechanism(s) responsible for the formation of the central Tibetan Plateau. The two leading and opposing hypotheses for the origin of these rocks are (1) partially molten foundered lower crust, and (2) partial melting of continentally subducted upper crust. The consensus is that some crustal sources within the mantle have reached eclogite facies, while evidence remains insufficient. Reverse zonation for cpx in high Mg# andesitic samples shows a low Mg# core with lower Sr and Sr/Y than the high Mg# rim, suggesting derivation of parent magma by interaction between some eclogite-derived felsic melts and mantle peridotite. Overall, the mantle-like zircon $\delta^{18}O$ (mean value of ~5.9‰) and $\varepsilon_{Hf}(t)$ (up to +6.7) values argue for a mafic source rather than buried upper-crustal rocks. Given the EARs were formed within a short time span after the end of crustal shortening, the original felsic melts were most likely derived from the foundered and eclogitized lower crust. The foundering process explains the early Eocene low-relief topography and the intermediate, eclogite-free modern crustal composition of central Tibet. Surface uplift as a response to lithosphere removal, however, was likely negligible, based on various lines of evidence, including sediment provenance, isotope paleoaltimetry, and thermochronology, perhaps because the central Tibetan crust was weak.

INTRODUCTION

The driving mechanism(s) of thickening and uplift of the Tibetan crust during Neo-Tethyan subduction termination and the subsequent India-Asia collision is(are) of great significance to our understanding of orogenesis. Studies show that, in the early stages of collision, crustal shortening and thickening were localized in the hinterland, i.e., central Tibet, far from the collision front, to form an early Paleogene protoplateau (Fig. 1; for reviews, see Wang et al. [2014] and Kapp and DeCelles [2019]). The lower modern central Tibetan crust has an intermediate-felsic average composition and is eclogite-free, as inferred from the low seismic velocities ($V_p < 6.6$ and $V_s < 4.25$ km/s; Galve et al., 2006; Yang et al., 2012), and limited crustal xenoliths in Pleistocene lavas (Hacker et al., 2000). Extensive Eocene volcanic rocks with minor intrusive equivalents formed abruptly after a magmatic lull since the Early Cretaceous in the Qiangtang block (QB), a key part of the protoplateau (Fig. 1), and they show chemical similarities with adakitic rocks (referring to intermediate-felsic high Sr/Y and La/Yb rocks; Castillo, 2012). These Eocene adakitic rocks (EARs) provide us prime access to the deep processes responsible for formation of the protoplateau.

There are two opposing hypotheses for the formation of these distinct rocks in central Tibet. The first hypothesis is that the EARs were partial melts of continentally subducted flysch-rich upper crust at mantle depth, while the southward subduction of Asian lithosphere beneath central Tibet kinetically drove protoplateau formation (Tapponnier et al., 2001; Wang et al., 2008; Replumaz et al., 2016). The opposing hypothesis is that the crust was shortened, thickened, and uplifted by plate stress from India-Asia collision, and then the thickened lower crust (presumably turned into eclogite) foundered to cause further uplift and partially melted to generate the EARs (Chen et al., 2013; Chapman et al., 2018; Kelly et al., 2020). The two hypotheses fundamentally impact our overall knowledge of India-Asia continental tectonics (see Replumaz et al.[2016] and Kelly et al. [2020], respectively).

Here, we present major- and trace-element compositions of clinopyroxene (cpx) and zircon Hf-O isotopic data for the EARs to test between the two end-member hypotheses. The compositional variation in reverse cpx and mantle-like zircon $\delta^{18}O$ values provide strong evidence for the lower-crustal foundering model, but we contend the surface uplift associated with lithosphere removal was negligible, perhaps because the crust was weak.

GEOLOGICAL SETTING

As the central part of the Himalayan-Tibetan orogen, the QB is a wide plateau with thickened continental crust of 60–70 km and high but flat topography (average >4800 m; Fig. 1; Owens and Zandt, 1997; Yang et al., 2012). It underwent two pre-Cenozoic collisional events, i.e., with Songpan-Ganzi block (SG) in the Late Triassic and with the Lhasa block in the Early Cretaceous, forming the Jinsha and Bangong sutures, respectively (Fig. 1; Kapp and DeCelles, 2019). At the northern boundary of the protoplateau

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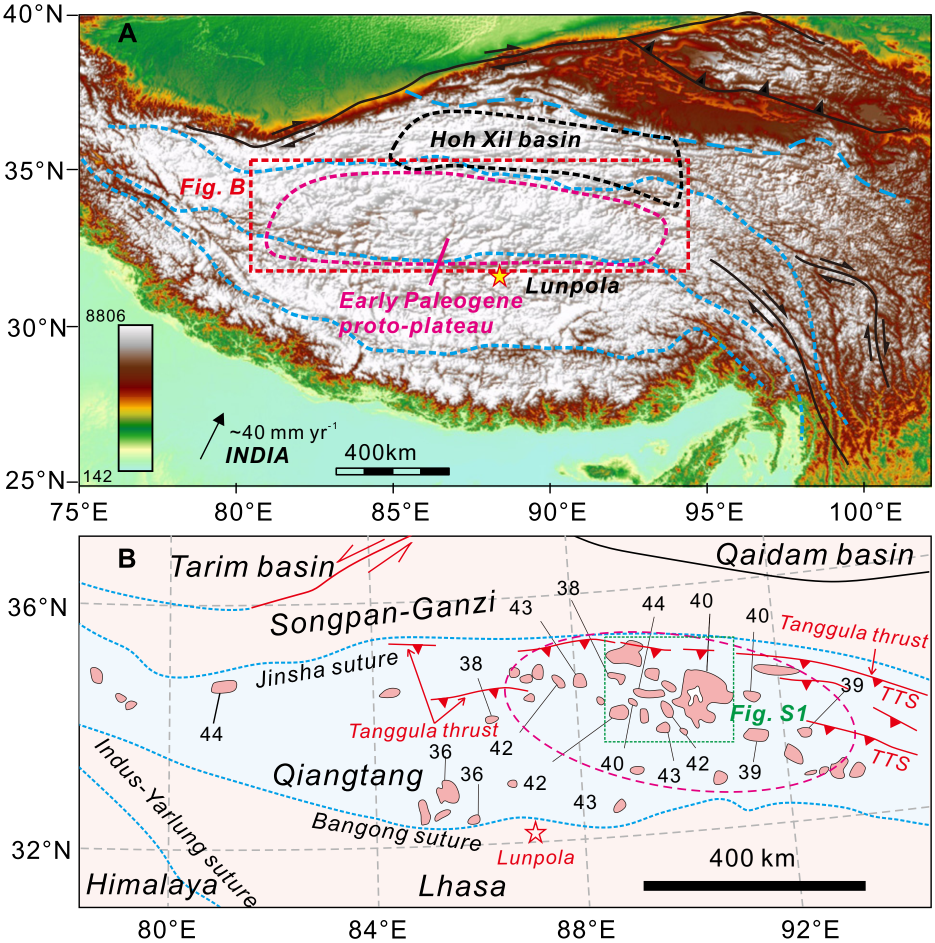

Figure 1. (A) Tectonic outline of the Himalayan-Tibetan Plateau. Spatial delineation of the protoplateau is based on Wang et al. (2014). (B) Sketch map showing distribution and magmatic age (black labels) of Eocene adakitic rocks (EARs; after Chapman et al., 2018).

(Fig. 1), Tanggula thrust belt movement has shortened the QB crust up to 50% and formed the Hoh Xil foreland basin (Staisch et al., 2014; Li et al., 2017; Kapp and DeCelles, 2019). Recent combined studies of field and structural geology, basin analyses, and stratigraphic analyses have shown that the timing of thrusting likely ended ca. 50 Ma, following a major phase of deformation and uplift of the QB crust at ca. 54 Ma (Li et al., 2017; Jin et al., 2018; Kapp and DeCelles, 2019).

Early Paleogene magmatic rocks in the QB chiefly include EARs and minor small Eocene–Oligocene mafic dikes (Chen et al., 2013). The EARs are widely distributed in the QB but are more concentratedly in the mideastern part, where they form a field covering a total area of ~9000 km^2 (Fig. 1B). The strata exposed there are composed of mainly Mesozoic shallow-marine and minor Cretaceous–Paleogene terrestrial rocks. The EARs in this region lie flat and unconformably above the strongly shortened and folded Mesozoic–Lower Paleocene strata and the weakly deformed or undeformed Lower Eocene strata (Fig. S1 in the Supplemental Material[1]; Kapp and DeCelles, 2019).

SAMPLES AND ANALYTICAL RESULTS

In total, 20 andesitic, 20 dacitic, and four rhyolitic samples from the mideastern QB (Fig. 1B; Fig. S1) were collected for geochemical analyses (see the Supplemental Material for petrography, analytical methods, and results). These samples are adakitic according to bulk-rock geochemical compositions; i.e., high SiO_2 (57.25–71.58 wt%), Sr (>415 ppm), Sr/Y (72–215), and La/Yb (18.6–100), and low Y (<15.5 ppm) and Yb (<1.72 ppm) (Fig. 2; Table S3). In addition, 22 samples from Dongyuehu, Luanqinshan, Zhuozishan, and Yuejinla (Fig. S1) present high Mg# (>60) with high Cr (69–314 ppm) and Ni (69–149 ppm) contents, resembling typical primitive andesite (Kelemen et al., 2014; this broad definition includes dacite and rhyodacite with Mg# >60, so hereafter we refer our samples with Mg# >60 as primitive EARs). Eleven samples (andesite to rhyolite) showed relatively uniform Sr-Nd isotopic values, $(^{87}Sr/^{86}Sr)_i$ = 0.7064–0.7078 and $\varepsilon_{Nd}(t)$ = −6.21 to −2.51, which are within the range of literature data (Fig. 2C).

The zircon $^{206}Pb/^{238}U$ ages of five samples were also consistent with previous results and together suggest a short life span for EAR magmatism (ca. 45–36 Ma, with a distinctive peak at ca. 40 Ma; Chen et al., 2013). The age, morphology (e.g., euhedral to subhedral, homogeneous internal structures; Fig. S3), and high Th/U ratios (0.11–1.81) of the analyzed zircon grains are indicative of a magmatic origin, and thus the measured Hf-O isotopic data represent the primary value precipitating from parent magma. These grains showed slightly variable $\delta^{18}O$ (4.7‰–7.6‰, with mostly ~5.9‰, and a mean value of 5.9‰ ± 0.2‰) and slightly negative to positive $\varepsilon_{Hf}(t)$ values (−6.1 to 4.7; Table S2).

Reverse zonation (Fe-rich cores and Mg-rich rims) was observed in some cpx grains from primitive EARs (Fig. 3; Fig. S2). The Mg-rich rims had the same compositions as normal (unzoned) grains. Although the Mg# as well as the Ni and Cr contents increased from the core to rim, the low-Mg# core showed lower Sr, Sr/Y, and Dy/Yb, but higher Y and Yb than the rim. Notably, inverse calculation by using the Fe-Mg exchange and partition coefficient between cpx and melt showed that only the melt equilibrated with the high-Mg# cpx has adakitic features (Fig. 3; Table S6).

PETROGENESIS OF THE EARS

Primitive andesites can be produced by crust-derived melts reacting with mantle peridotite or mixing with mantle-derived melts, or by ultralow-degree melting of a shallow hydrous mantle, and those with adakitic affinity require the involvement of garnet ± amphibole during partial melting and/or magmatic evolution (e.g., Xu et al., 2002; Castillo, 2012; Kelemen et al., 2014). The positive correlation between La/Yb and Dy/Yb ratios suggests that the adakitic features of EARs were controlled by garnet, although amphibole fractionation in the magmatic evolution cannot be excluded (Fig. 2E). Additionally, the lower Ba, Sr, Th, and rare earth element contents of the EARs compared with Eocene–Oligocene mafic dikes are in stark contrast with the trend of low-degree mantle melting (Fig. 2F).

The presence of reverse-zoned cpx in primitive EARs implies open-system magma evolution with involvement of two end members, and the key to distinguishing the eclogite-derived melt–mantle interaction from magma mixing models is whether the primitive end member represented by the high-Mg# rim cpx originally had adakitic features. As elaborated before,

[1]Supplemental Material. Experimental methods, Figures S1–S5, and Tables S1–S8. Please visit https://doi.org/10.1130/GEOL.S.12811868 to access the supplemental material, and contact editing@geosociety.org with any questions.

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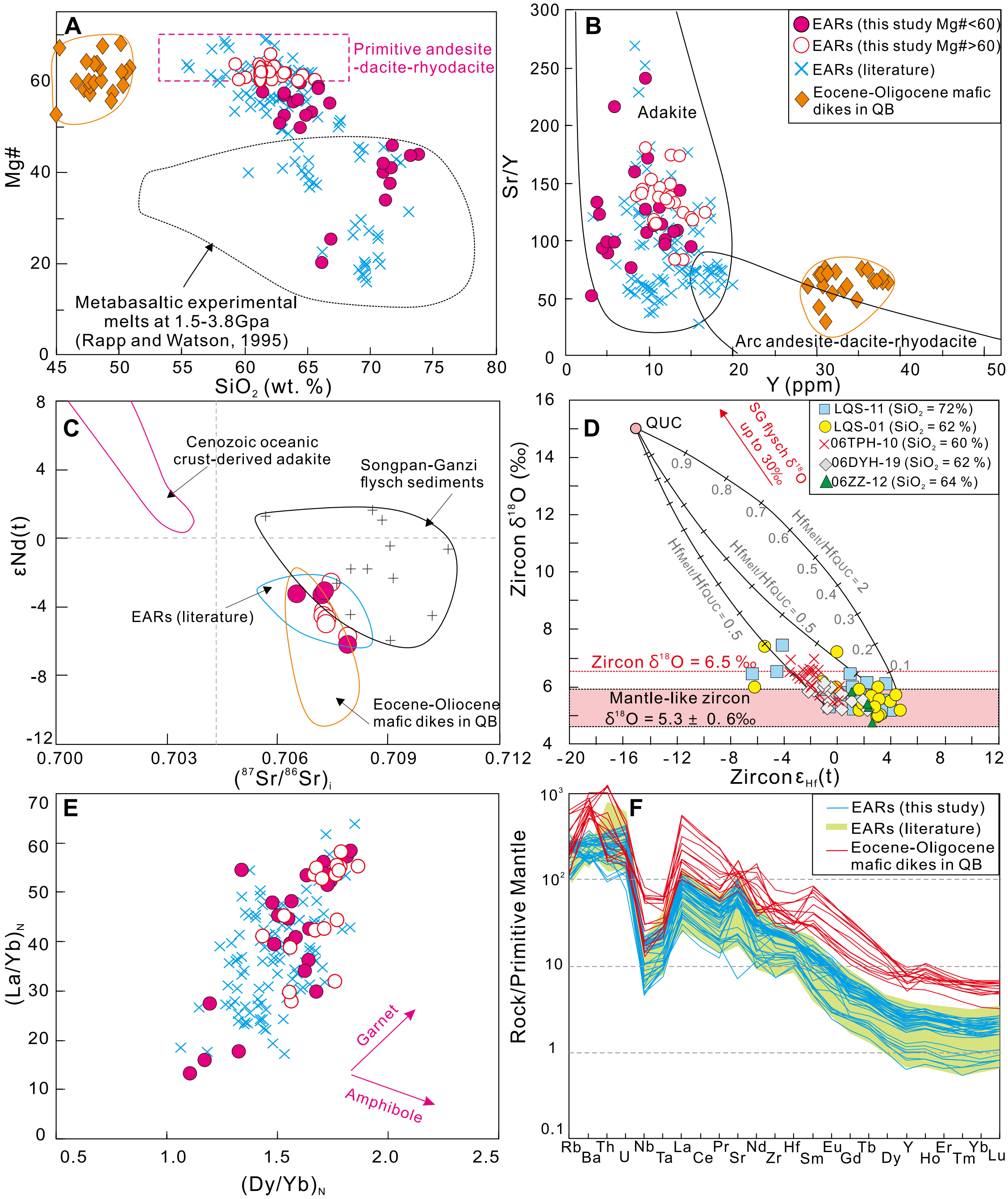

Figure 2. Geochemical diagrams of (A) Mg# versus SiO_2, (B) Sr/Y versus Y, (C) bulk-rock Sr-Nd isotopes, (D) zircon Hf-O isotopes for Eocene adakitic rocks (EARs) in central Tibet, (E) (La/Yb) versus $(Dy/Yb)_N$, and (F) trace-element distribution pattern. Published EAR data are listed in Table S7 (see footnote 1). Data sources: Mafic dikes (Chen et al., 2013), Cenozoic oceanic adakite (Castillo, 2012), and Songpan-Ganzi (SG) flysch (She et al., 2006). Because the Qiangtang upper crust (QUC) comprises mainly metagraywacke, as revealed by sedimentary xenoliths in Triassic S-type granites (Lu et al., 2017), Hf isotopic values of these xenoliths and S-type granites, and average $\delta^{18}O$ = 14.9‰ for bulk continental sediment (Spencer et al., 2014), are assumed to be the makeup of assimilated materials. QB—Qiangtang block; QUC—Qiangtang upper crust' UCC—upper continental crust.

inverse calculation indicated that the melt equilibrated with the high-Mg# rim cpx presents adakitic affinities (Fig. 3D). Meanwhile, the rare Eocene–Oligocene mafic dikes have higher Y and lower Sr/Y than the EARs (Fig. 2B). This further highlights that, if the primitive EARs were formed by anatexis of thickened lower continental crust followed by mixing with mantle-derived magma, the reverse cpx phenocrysts should have low-Mg# cores with higher Sr and Sr/Y than high-Mg# rims, opposite to the observed trend (Fig. 3). The low-Mg# core cpx may have been xenocrysts from the evolved mantle-derived magma represented by the mafic dikes. The compositional variation of the reverse-zoned cpx phenocrysts is similar to that in high-Mg adakite in modern arcs, which is interpreted to reflect interactions between silicic melt of an eclogitized slab and mantle peridotite (Yogodzinski and Kelemen, 1998). Central Tibet has been an intracontinental block since the Early Cretaceous, and the geochemical features of the EARs are distinct from oceanic adakite (Fig. 2C; Fig. S4). Thus, the most feasible petrogenetic mechanism for the primitive EARs is melt originating from eclogitized continental crust that reacted with mantle peridotite during ascent.

Zircon crystallized from magmatic rocks directly derived from mantle or remelted such rocks (i.e., mafic lower crust) has a narrow range of $\delta^{18}O$ (5.3‰ ± 0.6‰, 2σ), and this range remains nearly constant during fractional crystallization processes (Valley et al., 2005). In comparison, zircon with $\delta^{18}O$ differing from mantle-like values indicates incorporation of supracrustal materials such as sediments that have interacted with the hydrosphere (10‰–40‰) or hydrothermally altered magmatic rocks (to 20‰) (Valley et al., 2005; Spencer et al., 2014). As the SG has been covered by very thick (average ~8 km) and extensive (~3 × 10^5 km^2) Triassic flysch sediment with no magmatism since the Early Jurassic, in the intracontinental subduction model, the rhyolitic

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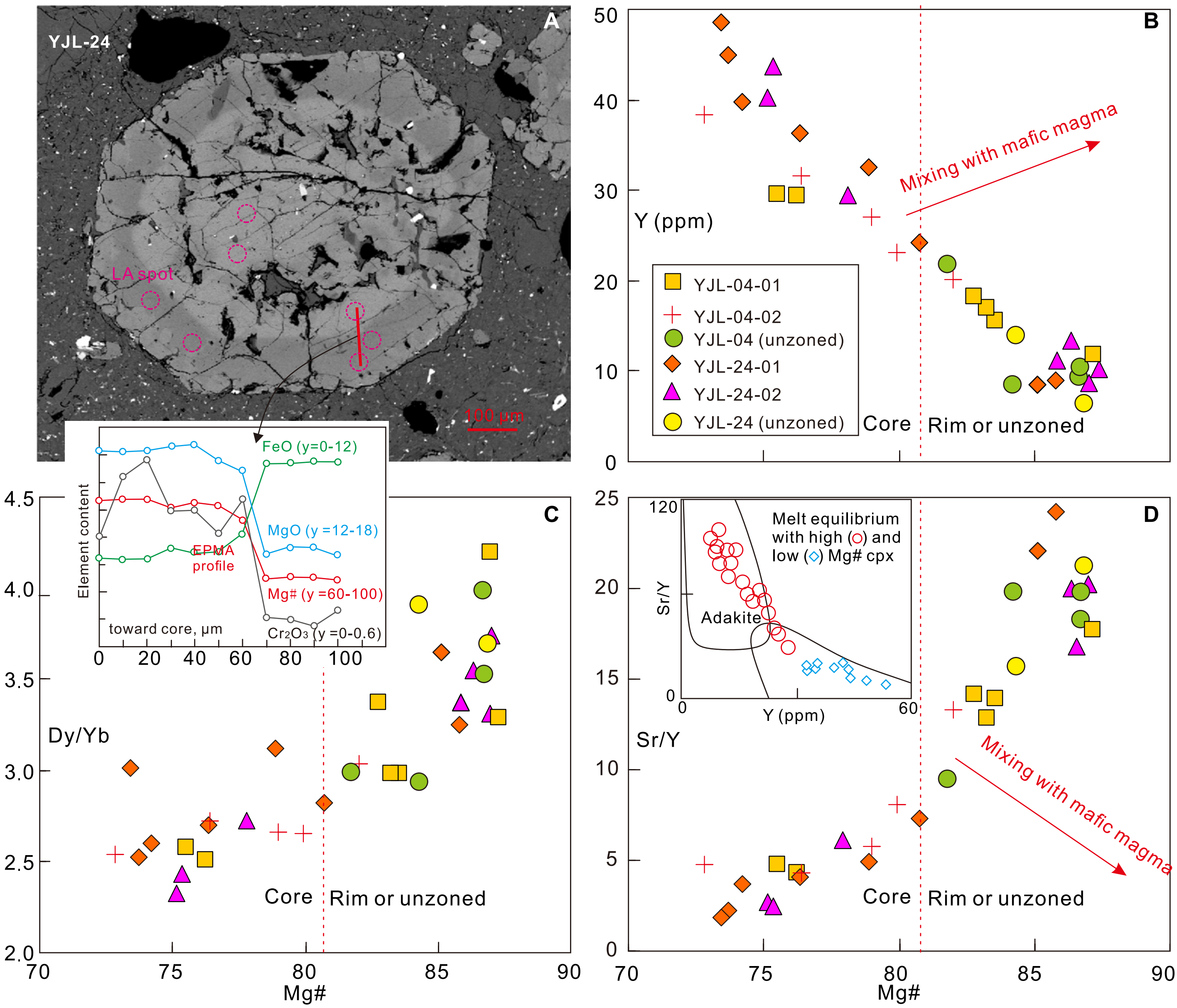

Figure 3. Representative textural (backscattered electron images; see Fig. S2 for photomicrograph [see footnote 1]) and compositional complexities of clinopyroxene (cpx) in primitive Eocene adakitic rocks (EARs). Inset shows composition profile, where values (e.g., MgO [*y* = 12–18]) refer to range of *y* axis. LA—laser ablation; EPMA—electron probe microanalysis.

EARs were proposed to be pristine melts of subducted SG flysch, with most of them reacting with mantle peridotite to form the primitive EARs (Wang et al., 2008). Despite the fact that Sr-Nd isotopes of the EARs are similar to the SG flysch (although in themselves are not really distinctive of any particular source reservoir), the overall mantle-like $\delta^{18}O$ values of zircon grains from the EARs, including those from the rhyolite, demonstrate a predominantly mantle-derived source (Fig. 2). A combination of literature data with our new results shows the EARs have similar isotope compositions, as well as good linear correlations between SiO_2 (as a proxy of evolution) and major/trace elements and the aluminum saturation index (Fig. 2; Fig. S4), implying a genetic relationship via fractional crystallization with minor assimilation of upper-crustal sediments.

Our new data support the interpretation that the source of EARs was eclogitized mafic lower-crustal materials. Their removal is necessary in order for the melts to interact with mantle peridotite along the way to the surface. The only nondynamic alternative, which is plausible but less likely, is that the crust-mantle transition beneath the Eocene QB was repeated following the earlier shortening events. There is no independent evidence for that in the geological record, but we cannot completely rule it out, as multiple Mohos have been described under other plateaus (Chapman et al., 2015). The foundering hypothesis explains the modern crustal composition of central Tibet (i.e., felsic and eclogite-free) and also concurs with a recent high-resolution–based tomographic interpretation of the nature of high-velocity bodies located within the asthenosphere beneath the QB, which are more likely to be foundered Tibetan lithosphere rather than the previously proposed continentally subducted Asian lithosphere (Chen et al., 2017b).

ROLE OF FOUNDERING IN BUILDING THE CENTRAL TIBETAN PLATEAU

The gravitational instability (i.e., eclogite) that we suspect drove the removal of lower crust to form adakitic melts could have formed by either high-pressure metamorphism during orogenic shortening or magmatic processes (e.g., Leech, 2001; Ducea, 2002, 2011). Orogenic shortening applies to the study area, as the EARs

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formed after a prolonged magmatic lull, while the QB crust had experienced up to ~50% north-south shortening prior to the postulated foundering event (Fig. 4A; Kapp and DeCelles, 2019). The low post–45 Ma erosion rates together with the flat-lying EARs and weakly deformed early Eocene strata suggest the formation of EARs coincident with the achievement of low-relief topography and shortly postdating the end of upper-crustal shortening (Fig. S1; Rohrmann et al., 2012; Li et al., 2017). This can be explained by lithosphere removal, as numerical simulation predicts that, in collisional belts, lithospheric foundering results in broad and flat plateaus (Fig. 4B; Wang et al., 2015; Li et al., 2016). However, postfoundering surface uplift and exhumation in central Tibet, as the isotropic response to removal of dense lower lithosphere, were minimal according to the following lines of observations: (1) low post–45 Ma erosion rates, as indicated by the thermochronological data (Rohrmann et al., 2012); (2) little detritus from the QB being deposited in the Hoh Xil Basin since ca. 50 Ma (Li et al., 2017); and (3) approximately the same paleo-elevation for the QB from the Eocene to middle Oligocene, based on stable-isotope paleoaltimetry (Xu et al., 2013). These observations imply that either the size of foundering blobs was small (a few kilometers; Ducea, 2011), and/or the lithosphere where the eclogite developed was rheologically weak (Wang et al., 2015). The latter seems more likely, given the EARs erupted over a large area within a short time period. The weak middle-lower crust of central Tibet is documented by geophysical data (e.g., Owens and Zandt, 1997; Yang et al., 2012) and is suggested to have already existed before the Cenozoic (Chen et al., 2017a; Kelly et al., 2020; and references therein), which provides an explanation for the localization of crustal shortening in central Tibet during the early time of India-Asia collision.

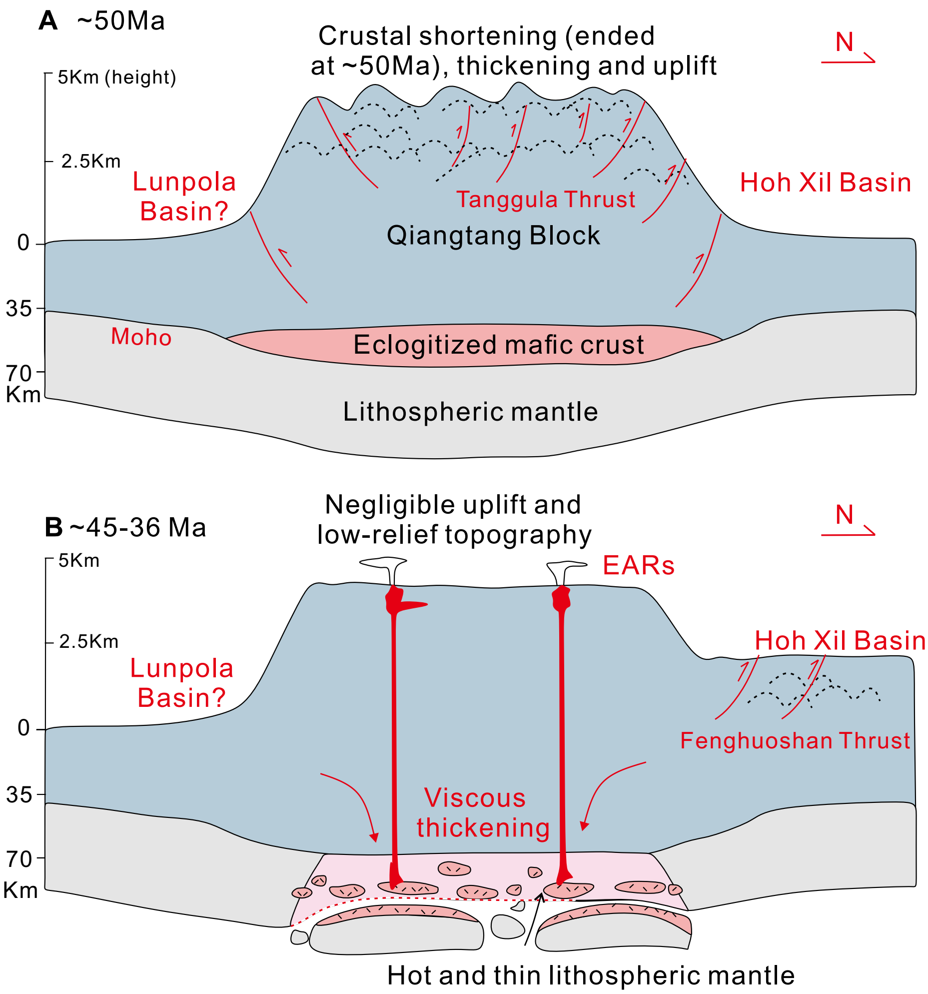

Figure 4. Cartoon illustration of early Paleogene tectono-topographic evolution of central Tibet. Paleo-elevation is based on Xu et al. (2013). EARs—Eocene adakitic rocks.

CONCLUSION

Our study has ruled out the underthrusted sediment hypothesis in an important tectonic debate that has regional specifics but global implications. We propose that the EARs in central Tibet are the manifestation of lower-crustal foundering and partial melting of the downgoing drip (Fig. 4). The lithosphere removal resulted in the establishment of a low-relief plateau surface but negligible further uplift. We emphasize the importance of searching for crustal melt signatures in the mantle in adakitic rocks in order to test for geodynamic processes. This goal can be achieved by designing spatially controlled targets (individual minerals or portions of minerals) that retain signatures otherwise mixed in the bulk rock.

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