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Plume-modified collision orogeny: The Tarim–western Tianshan example in Central Asia

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ABSTRACT

Plume-modified orogeny involves the interaction between a mantle plume and subducting oceanic lithosphere at accretionary margins. We propose that a plume can also be involved in collisional orogeny and accounts for the late Paleozoic geological relations in Central Asia. Continental collision between the Tarim and Central Tianshan–Yili blocks at the end Carboniferous resulted in an orogeny lacking continental-type (ultra)high-pressure [(U)HP] rocks and significant syncollision surface erosion and uplift, features normally characteristic of continent-continent interactions. Their absence from the Tianshan region corresponded with the arrival of a mantle plume beneath the northern Tarim. Elemental and isotopic data reveal an increasing influence of the mantle plume on magmatic petrogenesis from ca. 300 to 280 Ma, immediately after collision at 310–300 Ma. The rising mantle plume interrupted the normal succession of collisional orogenic events, destroying the deeply subducted continental crust and hence preventing slab break-off–induced continental rebound. Plume-modified continental collision thus limited continental (U)HP rock exhumation and associated surface uplift.

INTRODUCTION

Oceanic convergent zones have been shown to be impacted by mantle plumes. The resultant "plume-modified orogeny" is exemplified by ancient orogens in North America and eastern Australia (Murphy et al., 1998, 1999; Betts et al., 2012), and the present Tonga subduction zone and Samoa plume (Chang et al., 2016). Plume-slab interaction can cause prominent tectonic changes such as flattening of the subducting slab, development of a slab window or slab break-off due to plume erosion, arc- to plume-related magmatic transition, and supercontinent fragmentation (e.g., Murphy et al., 1998, 1999; Dalziel et al., 2000; Betts et al., 2012). In contrast to growing understanding of the interplay between a mantle plume and an oceanic subduction zone, the influences of a plume at a zone of continental collision have not been investigated. This study proposes such a case by providing age, geochemical, and isotopic evidence that the late Paleozoic continental collision orogeny in the western Tianshan and Tarim region in Central Asia was profoundly affected by the impingement of the Tarim mantle plume. In particular, such plume-collision interaction explains previously enigmatic features of the collisional orogen, i.e., the lack of continental-type (ultra) high-pressure [(U)HP] rock suites and the absence of significant surface uplift during collision, and it extends our understanding of plume-modified orogeny to collisional settings.

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GEOLOGICAL OVERVIEW AND KEY ISSUES

The northern margin of the Tarim craton and the adjoining Tianshan region in Central Asia are an accretionary orogen that recorded the consumption of the Paleozoic Paleo-Asian Ocean (Fig. 1; e.g., Windley et al., 2007; Cawood et al., 2009; Charvet et al., 2011; Xiao et al., 2015; Zhao et al., 2018). In the late Paleozoic, oceanic subduction and closure resulted in collision between the Tarim craton and the Central Tianshan (CTS)–Yili block, forming the South Tianshan (STS) suture zone, which contains ophiolite relics and (U)HP metamorphic rocks (Fig. 1B; e.g., Gao et al., 2011; Han et al., 2011, 2016a; Klemd et al., 2011; Xiao et al., 2013; Bayet et al., 2018; Zhang et al., 2019). A final stage, involving north-directed oceanic subduction is evidenced by Carboniferous passive-margin deposition along the STS–northern Tarim and intense arc magmatism in the CTS-Yili block. The collision time is commonly suggested at ca. 325–310 Ma, coinciding with the (U)HP metamorphism (e.g., Gao et al., 2011; Han et al., 2016b; Loury et al., 2018; Zhang et al., 2019). A large igneous province (~4×10^5 km^2) in the Tarim and STS region includes ca. 300 Ma kimberlites near Bachu, ca. 295–285 Ma flood basalts, and 285–265 Ma (ultra-)mafic intrusions and/or dikes, as well as rhyolites, granites, and syenites (Fig. 1B). These early Permian bimodal magmatic suites have been ascribed to the incubation of a mantle plume beneath the Tarim lithosphere (e.g., Zhou et al., 2009; Xu et al., 2014), as manifested by crustal uplift centered in Tarim at the Carboniferous-Permian transition (Li et al., 2014).

Current models for the Tarim and CTS-Yili collision invoke a classic Alpine-Himalayan–type belt, but this interpretation fails to reconcile the lack of continental-type (U)HP rock suites and the lack of significant upper-plate uplift in the CTS-Yili region during collision. Such collision zones are normally characterized by intense and rapid surface uplift and exhumation of continental-type (U)HP rocks, mainly induced by break-off of the lower plate around the ocean-continent boundary and prompt continental slab rebound, as the subducting dense oceanic slab fails to resist the

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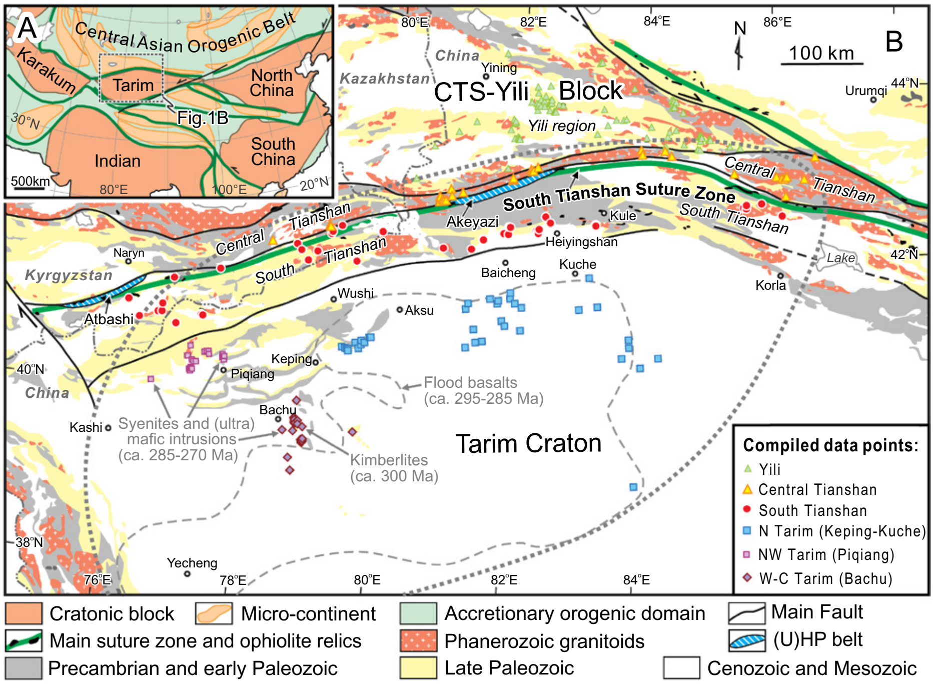

Figure 1. (A) Tectonic overview map of Asia and major continental blocks (modified after Zhao et al., 2018). (B) Simplified geological map of Tarim and western Tianshan (modified after Gao et al., 2011; Han et al., 2011; Xu et al., 2014), showing main tectonic units and sample locations of compiled age and geochemical data. Thick dotted line indicates inferred influential extent of Tarim mantle plume. CTS—Central Tianshan; N, NW, and W-C Tarim—northern, northwestern, and western-central Tarim, respectively; (U)HP—(ultra)high-pressure.

buoyancy of the continental crust (e.g., Davies and von Blanckenburg, 1995; van Hunen and Allen, 2011; Zheng and Chen, 2016). In contrast, the South Tianshan belt preserves the world's largest oceanic-type (U)HP terrane but lacks continental-type counterparts (Fig. 1B; Zhang et al., 2019). The (U)HP units along the STS suture are sandwiched between greenschist belts and dominated by blocks/lenses of eclogites, blueschists, and minor ultramafic rocks embedded in garnet-bearing pelitic schists and marbles, derived from protoliths of oceanic crust and sedimentary rocks (Gao et al., 1999; Klemd et al., 2011; Zhang et al., 2019). Evidence for negligible syncollision uplift and erosion includes (1) the accumulation of stable carbonates and fine clastic rocks in the foreland region (i.e., northern Tarim and STS) during late Carboniferous–early Permian time and the associated scarcity of coarse clastic sediments derived from an exhumed orogenic belt; and (2) the paucity of Permian postorogenic clastic detritus in the northern Tarim foreland basin from the CTS-Yili block, as revealed by rare 380–310 Ma detrital zircons, which contrasts with intense coeval magmatism in the CTS-Yili area (Han et al., 2016b). We consider these features to reflect modification of the collisional orogeny by the Tarim mantle plume (Han et al., 2016b; He et al., 2016).

METHODS

We evaluated the interaction between the Tarim plume and the collision zone by fingerprinting spatial and temporal variations in magma source characteristics, based on data from 330–260 Ma magmatic rocks in the Tarim and western Tianshan regions. This included 276 radiometric ages (Table DR1 in the GSA Data Repository[1]), 1297 major- and trace-element analyses, and 515 whole-rock $\varepsilon_{Nd}(t)$ and 100 zircon $\varepsilon_{Hf}(t)$ isotopic analyses (Table DR2), including our new analyses from Tarim and STS (Tables DR2–DR5). We utilized elemental ratios of Nb/Yb, Th/Yb, Nb/La, and Ce/Pb, and Nb anomalies as source proxies to differentiate plume-related magmatism with oceanic-island basalt (OIB) signatures and subduction-related (or subduction-inherited) magmatism with arc signatures. See the Data Repository for information on the use of relevant elemental proxies and parameters, as well as for sample information and analytical methods used in this study.

TEMPORAL RELATIONS BETWEEN CONTINENTAL COLLISION AND MANTLE PLUME

Although the main phase of continental collision between the Tarim and CTS-Yili blocks is assumed to correspond with ca. 325–310 Ma (U)HP eclogite-facies metamorphism in STS, this is at odds with the oceanic-crust origin for the (U)HP rocks outlined above. The (U)HP metamorphism indicates the persistence of oceanic-slab subduction until ca. 310 Ma (Bayet et al., 2018). We suggest continental collision at ca. 310–300 Ma, corresponding to the main exhumation stage of the (U)HP rocks (Klemd et al., 2005). This inference accords with numerical modeling that suggests that (U)HP rocks were exhumed during the transition from oceanic to continental subduction, as is the case for the western Alps, New Caledonia, and Cuba (Agard et al., 2009; Burov et al., 2014). The 310–300 Ma collision is also supported by magmatic records in the region. Compiled crystallization ages of magmatic rocks indicate a quiescence between 310 and 300 Ma along the southern part of the CTS-Yili block, particularly in the CTS region (Fig. 2A; Table DR1). Such a suppression of magmatic activity can be accounted for by the continental subduction of the Tarim cratonic margin beneath the southern CTS-Yili block. This interpretation coincides with a dramatic decrease of whole-rock $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values of magmatic rocks in the CTS domain (the upper plate), from juvenile to evolved signatures after the 310–300 Ma age interval (Fig. 2C; Table DR2). The prominent decrease of Nd-Hf isotopes implies a significant input of old continental materials into the magma source, probably inherited from the subducted lower plate, i.e., Tarim continental crust commencing at 310–300 Ma.

In the Tarim region, the first sign of mantle plume–related magmatism occurred at ca. 300 Ma, i.e., the extrusion of kimberlites in the Bachu area (Figs. 1B and 2A; Zhang et al., 2013), which was followed by extensive, bimodal magmatism at ca. 295–265 Ma (Zhou et al., 2009; Xu et al., 2014). Thus, the ascent and arrival of the Tarim mantle plume head at ca. 300 Ma immediately succeeded continental subduction and collision between the Tarim and CTS-Yili block at 310–300 Ma. The age of ca. 300 Ma represents a synchronous magmatic initiation in the CTS, STS, and Tarim areas, after the 310–300 Ma magmatic lull in the CTS (Fig. 2A), implying a petrogenetic link between these early Permian magmatic suites.

MAGMATIC-ROCK ELEMENTAL AND ISOTOPIC EVIDENCE

Source characteristics of early Permian magmatic rocks (300–280 Ma) exhibit a systematic variation with space and time, as shown by the proxies of Nb/Yb (Fig. 2B), Nb/La, and Ce/Pb ratios, and Nb anomalies (Fig. DR1). Spatially, these values are most elevated and comparable to OIBs for rocks in the Bachu area in western-central Tarim to the south, and they progressively decrease to arc-like signatures in the Yili area to the north (Fig. DR1). From plume initiation at ca. 300 to a magmatic climax at 290–280 Ma, the elemental proxies for magmatic rocks in

[1]GSA Data Repository item 2019357, compiled data (Tables DR1 and DR2), sample and method descriptions and notes for elemental proxies, and analytical results (Tables DR3–DR5), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

the CTS, STS, and Tarim areas gradually increased from arc-like to typical OIB-like features (Fig. 2B; Fig. DR1). Similar trends can be observed from magmatic rock $\varepsilon_{Nd}(t)$ values, which were mostly negative and increased from 300 to 285 Ma toward the Bachu magmatic suites, which have more elevated $\varepsilon_{Nd}(t)$ values (−1 to +6; Fig. 2C). Zircon saturation temperatures of the Permian magmatic rocks in the CTS, STS, and Tarim areas gradually increased from ca. 300 to 285 Ma, with comparably higher temperatures (mostly >800 °C) than those of rocks older than 300 Ma (Fig. 2D). Thus, the consistent variation and gradual transition in elemental ratios, Nd and Hf isotopes, and zircon saturation temperatures suggest that: (1) the Tarim mantle plume, with a center near Bachu, most likely influenced the sources and origin of Permian magmatism, not only in the Tarim, but also in the STS and CTS areas; and (2) the magnitude of the plume's influence varied temporally and spatially, increasing from ca. 300 to 280 Ma but weakening to the north.

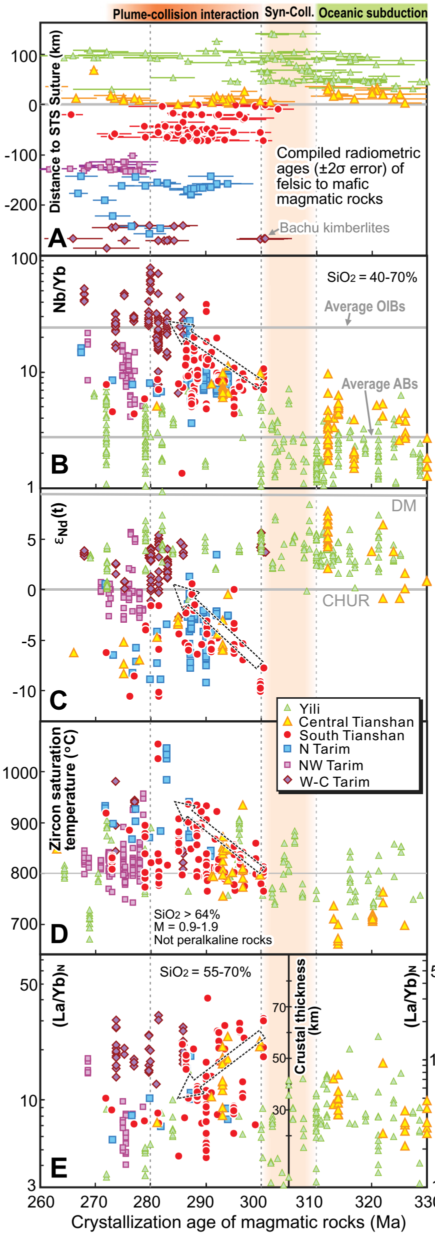

Figure 2. Plots showing (A) compiled crystallization ages with 2σ error bars (see data sources in Table DR1 [see footnote 1]), and (B–E) representative elemental-isotopic parameters versus ages (see data sources in Table DR2) for 330–260 Ma magmatic rocks in the Tarim and western Tianshan region of Central Asia. See Figure 1B for sample legend and locations. STS—South Tianshan; ABs—arc basalts; OIBs—oceanic-island basalts; Syn-Coll.—syncollision; DM—depleted mantle; CHUR—chondritic uniform reservoir.

The Nb/Yb versus Th/Yb plot (Fig. 3A) shows that the early Permian magmatism in the CTS and STS lies in the transitional field between the Bachu magmatic suites with an OIB signature and the Yili rock suites with a continental arc/crust signature. Nd-Hf isotopic decoupling is evident for Permian magmatic rocks in the CTS and STS (Fig. 3B), implying a "zircon effect" due to the addition of subducted oceanic terrigenous sedimentary rocks into magma sources (Bayon et al., 2009). These features suggest that the Permian magmatism in the CTS and STS was derived from mixed sources because of the interaction between plume-induced and post-collisional, arc-inherited magmatic processes.

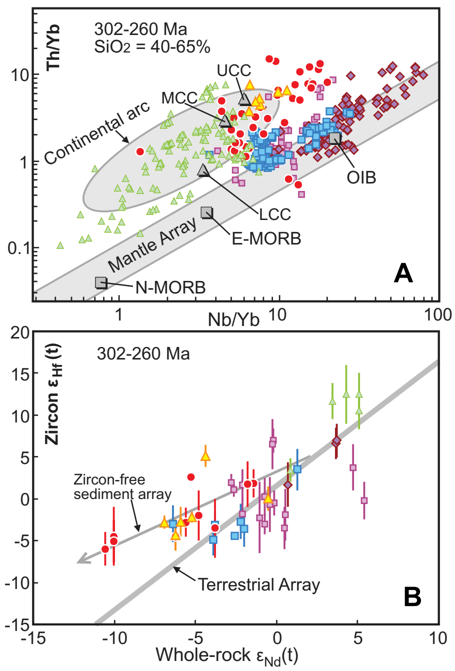

Figure 3. Plots showing (A) Nb/Yb versus Th/Yb and (B) whole-rock $\varepsilon_{Nd}(t)$ versus zircon $\varepsilon_{Hf}(t)$ for 302–260 Ma magmatic rocks in the Tarim and western Tianshan region of Central Asia. See Table DR2 (see footnote 1) for data sources, and Figure 1B for sample legend and locations. UCC, MCC, and LCC—upper, middle, and lower continental crust, respectively; OIB—oceanic-island basalt; E-MORB—enriched mid-oceanic ridge basalt; N-MORB—normal mid-oceanic ridge basalt.

The $(La/Yb)_N$ ratios (Fig. 2E; where N denotes chondrite-normalized values, SiO_2 = 55–70 wt%), which can constrain the depth of partial melting and crustal thickness (Profeta et al., 2015; Hu et al., 2017), suggest a normal crust (~30–40 km thick) in the CTS-Yili area in the Carboniferous but a thicker crust (~50–60 km) for the CTS domain in the earliest Permian. Such crustal thickening of the upper plate likely resulted from the continental collision between the Tarim craton and the CTS-Yili block at 310–300 Ma. Magmatic rocks in the CTS and STS have their highest $(La/Yb)_N$ ratios at ca. 300 Ma and decrease at 290–280 Ma, implying crustal thinning (Fig. 2E). This is compatible with the plume incubation model of Xu et al. (2014), which suggests an early-stage plume incubation at deeper levels and late-stage adiabatic decompression melting during the plume upwelling.

THE NEW MODEL

The temporal, spatial, and petrogenetic relations of late Paleozoic magmatism in Tarim and western Tianshan enable us to link the continental collision orogeny with the arrival of the mantle plume head at the end of the Carboniferous (Fig. 4). At 310–300 Ma, collision

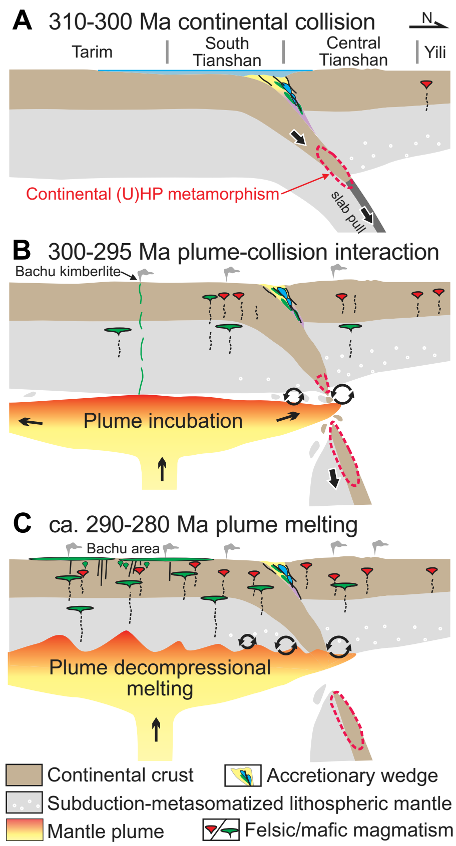

Figure 4. Tectonic model showing plume-modified continental collision orogeny in the Tarim and southwestern Tianshan of Central Asia. Scenario of plume incubation is modified after Xu et al. (2014). (U)HP—(ultra) high-pressure.

between the Tarim and CTS-Yili blocks closed the STS ocean, leading to the subduction of the Tarim continental margin (Fig. 4A). In normal collisional zones, the buoyancy contrast between continental and oceanic crust results in slab break-off at the lithospheric transition, enabling rapid rebound of buoyant continental lithosphere, and causing exhumation of continental-type (U)HP rocks and intense surface uplift, such as recorded in the western Alps, Himalaya, and Dabie-Sulu (e.g., Davies and von Blanckenburg, 1995; Zheng and Chen, 2016). Numerical modeling suggests an ~10–25 m.y. interval between initial continental collision and later slab break-off for a normal oceanic slab (van Hunen and Allen, 2011). However, for the northern Tarim craton, we infer that continental subduction and collision along the STS suture at 310–300 Ma were interrupted, prior to slab break-off, by the ascending Tarim mantle plume at ca. 300 Ma. During the plume incubation stage (Fig. 4B), the thermal-chemical-mechanical erosion/incision by the rising plume likely destroyed or possibly broke the deeply subducting continental crust, preventing the exhumation of the continental-type (U)HP rocks. Recent seismic data have revealed discontinuous high-density-velocity bodies at 100–200 km depth beneath northern Tarim and STS (see Deng et al., 2017, their figure 6A), possibly representing the detached Tarim lithosphere. The lack of rebound of the subducting continental crust resulted in no significant surface uplift.

The model of "plume-modified orogeny" was proposed to primarily depict the interaction between a mantle plume and an oceanic subduction zone along accretionary orogens (e.g., Murphy et al., 1998, 1999; Dalziel et al., 2000; Betts et al., 2012; Chang et al., 2016). The relatively short duration of continent-continent collision compared with the long history of convergent plate margins and accretionary orogens results in the infrequent encounter of a mantle plume with an active continental collision zone. The proposed scenario in Tarim and western Tianshan may provide a new example of plume-modified continental collision orogeny. Recently, Faure et al. (2018) proposed that the interaction of the late Permian Emeishan mantle plume near the boundary of the South China and Indochina blocks could account for the (ultra)high-temperature rock suites in central Vietnam due to plume-induced slab break-off during continental collision. The influence of a mantle plume on an active continental collisional orogen will fundamentally change the course of orogenesis and its tectonomagmatic expression, and hence it provides further insight into the spectrum of features recorded within these dynamic zones of lithospheric interaction.

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