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Discussion

Reply to comment by P.J. O'Brien on: "The onset of India–Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya" by Mary L. Leech, S. Singh, A.K. Jain, Simon L. Klemperer and R.M. Manickavasagam, Earth Planetary Science Letters 234 (2005) 83–97

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1. Comment

We thank O'Brien for directing our attention to his recent publication on modeling of diffusion in garnets, including one garnet from the Tso Morari Complex [1], and allowing us to show how our data and existing interpretation are consistent with his model. It seems O'Brien wants the timing of ultrahigh-pressure metamorphism (UHPM) in the Tso Morari Complex to be the same as the well-established 46 Ma UHPM event in Kaghan over 500 km to the northwest (e.g., [2]), and is attempting to reinterpret our U–Pb zircon dating from the Tso Morari Complex to fit his notion. But rather than fight the age data, why not develop a model that fits the data? Guillot et al. [3] describe a warped geometry of the Indian subduction plane that places the Tso Morari Complex and Kaghan at different depths based on their ages of UHPM; this model allows for a 55–54 Ma UHP event in the Tso Morari Complex and a 46 Ma event in Kaghan [4].

In his numerous previous publications [5–8], O'Brien has reiterated the intuitively obvious requirement for steep subduction in order to achieve high-*P*, low-*T* eclogite-facies metamorphic conditions. In fact, in our paper [9] we cited multiple publications from the many workers who have discussed a variety of evidence for an earlier steep subduction period in the India–Asia collision [7,10–14]. But our subduction model [9] goes beyond simply describing early subduction as steep—in order to reconcile the short period of time available for Tso Morari protolith to enter the subduction zone and then to metamorphose at UHP conditions at 53.3 ± 0.5 Ma, subduction must ultimately be vertical. The subduction model we present quantifies the timing and angle of subduction, and considers the geometry of a subduction zone accounting for the strength of

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continental lithosphere; further, we use our model to calculate and revise the timing of the initial collision between continental India and Asia from 55 Ma to 57 Ma.

The main result of the new model [1] for diffusion in garnet as it pertains to the Tso Morari Complex is to limit the period from UHP to amphibolite-facies metamorphism to no more than 3 Ma, ending with garnets cooling below about 450 °C ("where measurable diffusion in garnet no longer occurs" [15]). O'Brien states that the results of dating from the multiple intermediate- to high-temperature geochronometers given by de Sigoyer et al. [16] all fit, within error, a 3 Ma period from 48 to 45 Ma that brackets the age of

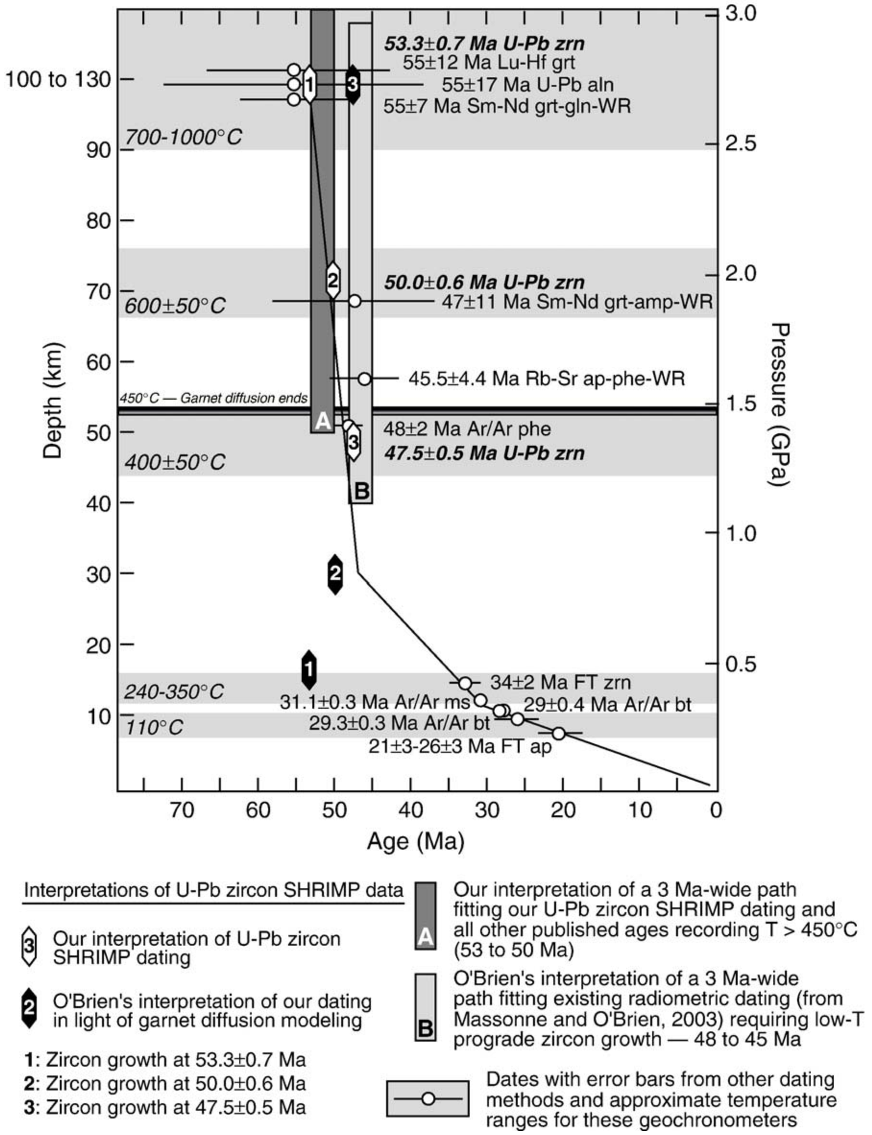

Fig. 1. Depth/pressure vs. time graph showing results of various radiometric dating methods [9,16,17] plotted in appropriate temperature ranges for those methods (modified after Fig. 17 in [8]). The exhumation *P–T–t* path shown is modified from de Sigoyer et al. [16] to account for the more recent discovery of coesite and other mineralogical evidence for UHP metamorphism [18,19]. Two 3-Ma-wide paths are shown following the garnet diffusion modeling of Konrad-Schmolke et al. [1]; one path fits our interpretation of U–Pb zircon SHRIMP dating from Leech et al. [9] and the other path shows O'Brien's interpretation of our dating based on diffusion modeling in garnet [15]. Note that O'Brien's preferred exhumation path for UHP to retrograde metamorphism between 48 and 45 Ma (1) requires all reported ages from high-temperature geochronometers to be half to one standard error younger than the original author's interpretation; (2) requires low-temperature prograde zircon growth; and (3) incorrectly presumes that $^{40}Ar/^{39}Ar$ phengite dates cooling >450 °C, his stated closure temperature for his garnet diffusion model. Abbreviations: aln, allanite; amp, amphibole; ap, apatite; bt, biotite; FT, fission-track; gln, glaucophane; grt, garnet; phe, phengite; WR, whole rock; zrn, zircon.

UHPM in Kaghan. Because our U–Pb zircon SHRIMP dates of 50.0±0.6 Ma and 53.3±0.7 Ma precede this 3 Ma period, O'Brien insists our zircons must record low temperature prograde zircon growth (Fig. 1, black symbols) and ignores de Sigoyer's [16] c. 55 Ma dates from eclogite.

It is widely accepted by those working in UHP terranes that the host rocks to eclogites which contain UHP index minerals such as coesite and diamond experienced the same *P–T–t* path as the eclogite (e.g., [20–23]); the presence of coesite in quartzofeldspathic host rocks to eclogite testifies to this fact [24]. To imply that the gneisses we dated did not experience UHPM because they lack coesite is misleading. It is always difficult to assess metamorphic *P–T* conditions in quartzofeldspathic gneisses as they typically do not contain the appropriate mineral assemblages to make thermobarometric calculations. We did not report detailed petrology of the dated samples because the main purpose of our recent paper [9] was to apply new U–Pb dating of zircons from Tso Morari gneisses to the tectonics of continental collision; additional details of the petrology and U–Pb dating are presented in Leech et al. [25].

The U–Pb, Lu–Hf and Sm–Nd ages in de Sigoyer et al. [16] correspond to *P–T* conditions above the closure of diffusion in garnet (≥450 °C); we interpret their c. 55 Ma ages to be in agreement with our new data and show that the rapid exhumation period occurred 53–50 Ma (Fig. 1, white symbols). O'Brien focuses on his preconceived 48–45 Ma exhumation period which also encompasses the $^{40}Ar/^{39}Ar$ phengite ages at 48±2 Ma [16]; in fact, $^{40}Ar/^{39}Ar$ in phengite records a well-established closure temperature of 400±50 °C [26] tracking cooling after the cessation of diffusion in garnet (Fig. 1).

The 3 Ma period that O'Brien chooses (48 to 45 Ma) for UHP to amphibolite-facies metamorphism in the Tso Morari Complex spans the time for UHPM in Kaghan (46 Ma). In order to fit the chronometric data between 48 and 45 Ma, O'Brien must use an extreme interpretation of de Sigoyer's dating: that 55±17 Ma ($U–Pb_{aln}$), 55±12 Ma (Lu–Hf), 55±7 Ma (Sm–Nd), 48±2 Ma (Ar/Ar_{phe}), 47±11 Ma (Sm–Nd), and 45±4 Ma (Rb–Sr) all fall within the same 3-Ma-long period (Fig. 1). Though technically permissible, O'Brien's interpretation requires large errors on all three c. 55 Ma ages (previously interpreted to record peak metamorphism) and ignores the significance of those ages (e.g., closure temperatures in three different radiometric systems).

The most extensively dated UHP terrane is the Dabie–Sulu belt in eastern China. In the Sulu region, coesite-bearing zircon domains (cores and mantles) unquestionably yield the timing for UHPM while younger quartz-bearing zircon rims record retrograde zircon growth [27]; in these UHP rocks, no prograde zircon growth is seen. Leech et al. [28] demonstrate that U–Pb ages on different zircons from the same area, but lacking coesite inclusions, record the same span of ages for peak and retrograde zircon growth as described by Liu et al. [27] and $^{40}Ar/^{39}Ar$ dating recording retrograde metamorphism in the same rocks [29].

Although existing data are not yet sufficient to refute O'Brien's unconventional interpretation of prograde zircon growth, our reading of the geochronologic data satisfies (with a higher probability) all published ages as well as O'Brien's garnet diffusion model. Our interpretation places the rapid exhumation period between 53 and 50 Ma, followed by continued cooling below the closure of diffusion in garnet (at ca. 450 °C) to yield the reliable $^{40}Ar/^{39}Ar$ phengite age at 48±2 Ma and $^{40}Ar/^{39}Ar$ biotite and muscovite ages at ca. 30 Ma (Fig. 1). Not only does our model satisfy all published radiometric dating for the Tso Morari Complex, it also avoids the implication of O'Brien's model that U–Pb zircon dating interpreted to record peak metamorphism in all UHP terranes is wrong. Zircon is extraordinarily useful in interpreting long crustal histories [30] and is widely used to date peak metamorphism in UHP terranes.

We are continuing to work to link the petrology and the geochronology of these rocks; interpretations will always remain somewhat speculative until multiple zircon growth domains in the same grains are dated and/or indisputable index mineral inclusions are found within dated zircon domains.

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