Source of Detrital Chrome-Rich Spinels with Melt Inclusions from the Cretaceous Greywackes of the Eastern Tethyan Himalayas: Hotspot Volcanics, not Ophiolites

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Bin Zhu[1](zhub@atmos.albany.edu), William S.F. Kidd[1] (wkidd@atmos.albany.edu),
David B. Rowley[2] (rowley@geosci.uchicago.edu),
Brian S. Currie[3] (curriebs@muohio.edu)
1. Earth & Atmospheric Sciences, University at Albany, Albany, NY 12222
2. Geophysical Sciences, University of Chicago, Chicago, IL 60637
3. Department of Geology, Miami University, Oxford, OH 45056

Introduction

Melt inclusions (figure 1) found in mineral grains as tiny droplets trapped during crystal growth offer a unique way of catching instantaneous melt composition as magma cools due to their effective isolation from the influence of later processes, and thus they can reveal the melt evolution that may not be recorded in bulk-rock data (Watson, 1976; Roeder and Poustovetov, 2001). Given the low chromium solubility in basaltic melts (Roeder and Reynolds, 1991) and thus no significant crystallization of the Cr-rich spinel on the walls of inclusions, the compositions of the melt inclusions in Cr-spinels would be a better approximation of the original magma than those hosted in silicate minerals (Kamenetsky, et al. 1998; Kamenetsky, et al. 2001; Sigurdsson, et al. 2000). The unusual chemical durability and the lack of cleavage and high degree of hardness make the Cr-spinels resistant to lower grade alteration and mechanical breakdown, and they may be enriched in some sedimentary rocks (Cookenboo, et al. 1997; Dewey and Mange, 1999). Therefore the studies of Cr-spinel with melt inclusions in ancient sediments may provide key information on the provenance areas and tectonic evolution in a complex orogenic system (Kamenetsky, 1996).

There is a significant amount of Cr-spinels with melt inclusions in the heavy mineral assemblage from the Cretaceous Tianba Flysch at the northern end of Nieru Valley (Tianba-Jiabula area), southern Tibet (figure 2). The compositional data of chrome rich spinels associated with melt inclusions have the potential to provide a direct constraint on the tectonic setting in the source area, especially with respect to the type of basalt, and therefore can both strengthen provenance studies based on detrital mode, heavy mineral analysis, and geochemistry of sandstones.

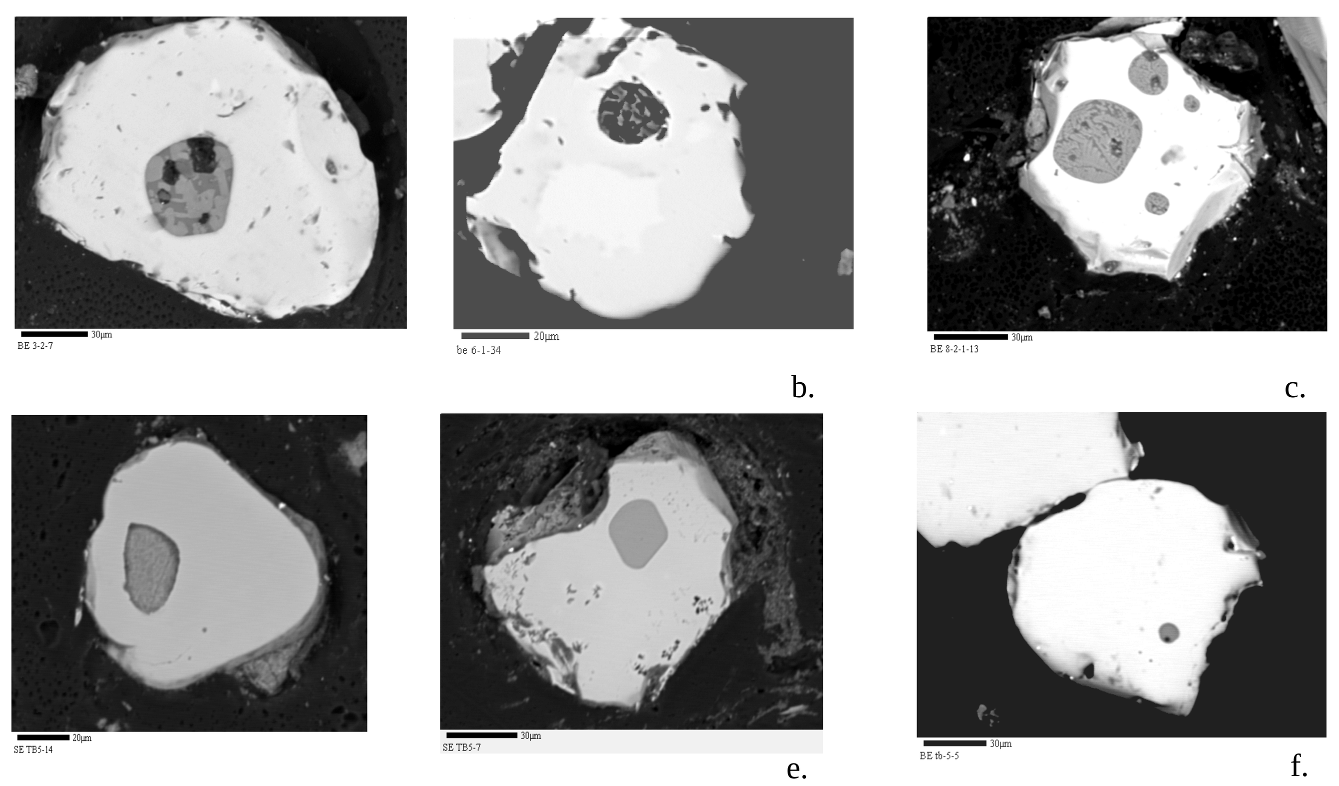

Figure 1. Back-scattered electron image of melt inclusions (grey) in Cr spinels (white) from Tianba Flysch
(a) Melt inclusion consists of pyroxene blebs (bright), residual glass (dark grey), shrinkage vapor bubbles and minor sulfide droplets. Four pyroxene compositions show that they have significantly different contents in the major oxides, as expected from closed-system crystallization.
(b) Melt inclusion includes pyroxene (bright) and residual glass (black).
(c) Melt inclusion contains spinifex-like texture, defined by acicular clinopyroxene crystals.
(d) Melt inclusion contains some partially crystallized minerals. Line scans on this spinel show that there is a significant composition change of the spinel at the melt/spinel interface where Al_2O_3 increases from 18.04% to 29.17% while Cr_2O_3 decreases from 36.24% to 26.11%. This is good evidence that crystallization of Cr-rich spinel continued on the inclusion walls post-entrapment of melt inclusion.
(e) Homogenised melt inclusion heated 96 hours at 1250 C.
(f) Homogenised melt inclusion heated 96 hours at 1200 C.

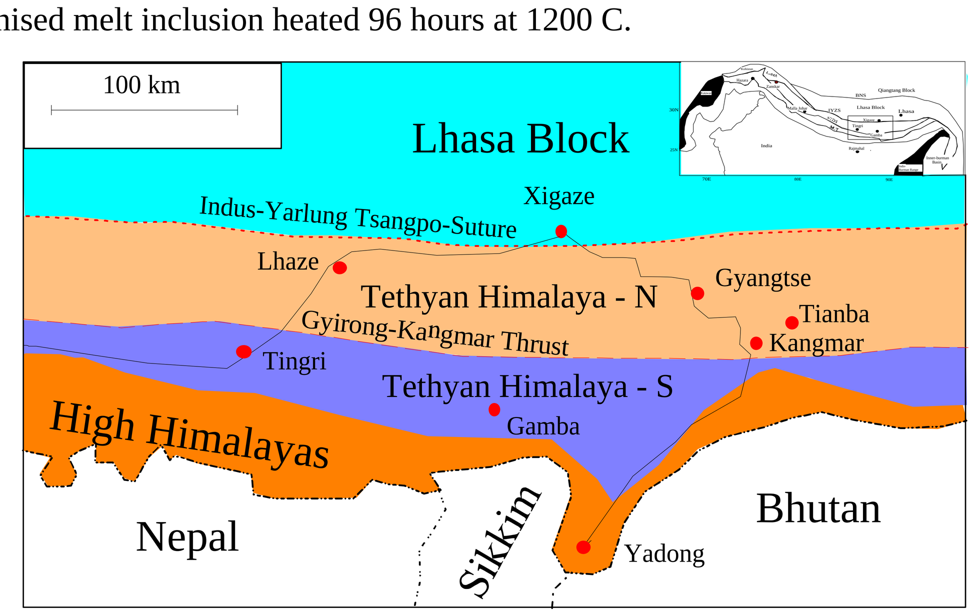

Figure 2. Sketch geologic map of Gyangtse-Tingri area, southern Tibet. The insert map shows this area located in the Himalaya system.

Cr-rich spinels in Tianba Flysch

The detrital spinels from Tianba Flysch can be characterized as a complex solid solution of the oxides of chromium, magnesium, aluminum, iron and titanium with 15-26 wt% Al_2O_3, 36-45 wt% Cr_2O_3, 10-12 wt% MgO, 20-30 wt% FeO^t, and 1.5-2.0 wt% TiO_2. Most spinel-peridotites have spinels with low or negligible TiO_2 contents (except spinel in plagioclase-peridotite), while volcanic spinels with TiO_2 <0.2 are uncommon (some suites of low-Ti MORB, arc tholeiites and boninites). The detrital spinels from Tianba Flysch therefore were derived from volcanic rocks, consistent with the observation of melt inclusions in spinel grains.

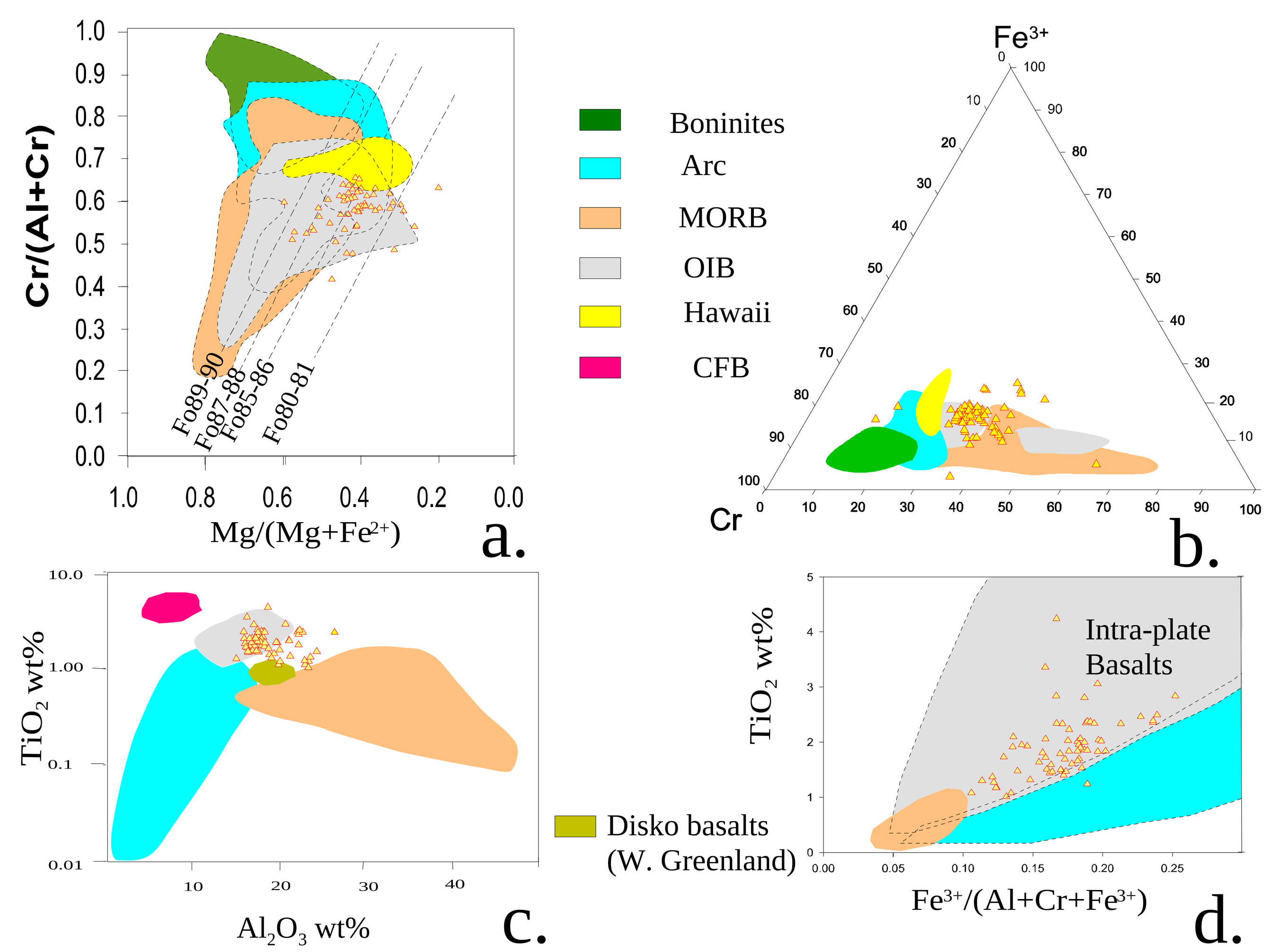

Figure 3. Major element contents of spinels and tectonic setting discriminant plot: Cr-rich spinels from different origin and tectonic settings can be discriminated by plotting major element concentrations (Irvine, 1967; Dick and Bullen, 1984; Kamenetsky et al, 2001; Barnes and Roeder, 2001). Because of possible overlaps among various tectonic environments on the binary or ternary plot of individual elements, all major elements should be considered to determine the possible parental magma of the studied spinels.
a. Cr/(Cr+Al) vs. $Fe^{2+}/(Mg+Fe^{2+})$ after Barnes and Roeder, 2001; Isopleths of olivine Fo (dashed lines) from Kamenetsky et al, 2001. There is a negative correlation between Cr# (Cr/(Al+Cr) and Mg# (Mg/(Mg+Fe^{2+}), and the Mg# values are significantly scattered along the higher Cr# (close to 0.6). This may be a possible path of spinel crystallization with olivine, plagioclase (Roeder, 1994). Comparison of our data with those coexisting with olivine in modern volcanics (Kamenetesky et al, 2001) indicates that these spinels were most likely sourced from primitive basalts with olivine phenocrysts at least as Mg-rich as Fo^{80-86}. The spinels plot in the fields of oceanic island basalts (OIB) and MORB.
b. Cr-Al-Fe^{3+} tenary plot. Most detrital spinels plot in the OIB field with a few in MORB.
c. TiO_2 vs. Al_2O_3 after Kamenetsky et al, 2001. Studies of spinel compositions from different tectonic settings show that TiO_2 and Al_2O_3 contents of spinel form a linear trend for those from Continental Flood Basalts (CFB), OIB and MORB. Our data plot in the middle of this trend, mainly in the OIB field.
d. TiO_2 vs. $Fe^{3+}/(Al+Cr+Fe^{3+})$ after Arai, 1992. All spinels but one plot in the field of intra-plate basalt and there are no spinels from MORB source.

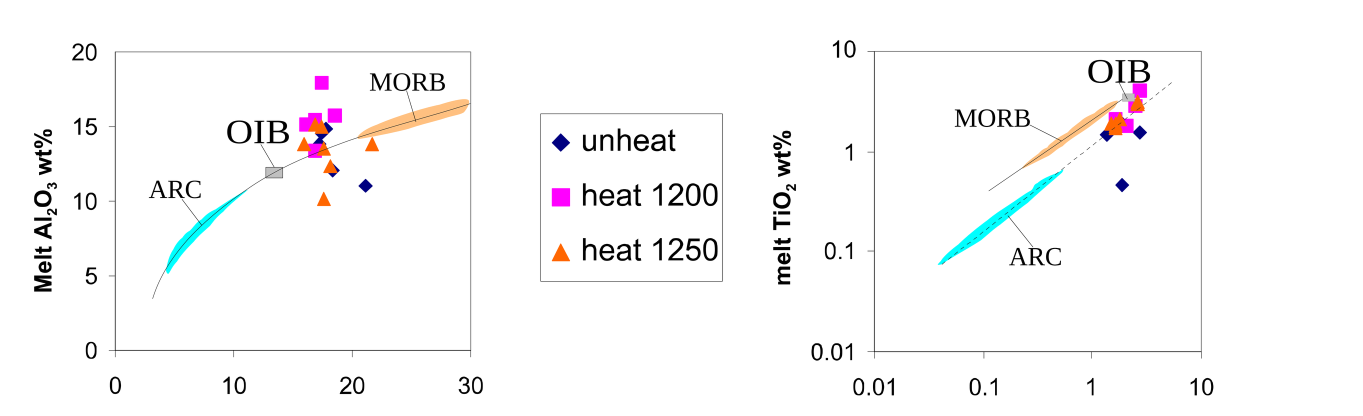

Figure 6. Positive correlation between Al_2O_3 and TiO_2 contents in melt inclusions and hosted spinels (the best fit lines and fields are from Kamenetsky, et al. 2001). Continuous line in **a**. is a power law best fit through published data; Continuous and dashed lines in **b**. are best fit through the high-Al (Al_2O_3 in melt>14 wt%) and low Al (Al_2O_3 in melt<14 wt%) data respectively. Our data are very close or aligned with their best fit lines, and the relatively narrow range of our data and proximity to the OIB point suggest a single source for these detrital spinels.

Melt inclusions in Cr-rich spinels

To obtain the original composition of partially crystallized melt inclusions, high-temperature experiments on about 400 spinel grains were performed with a one atmosphere furnace. The sample loader was suspended on a Fe-doped Pt-wire in the center of the furnace and the oxygen fugacity at the FMQ buffer was controlled by a CO+CO_2 gas flow during heating. Spinels were heated in two experiments, at 1200 C, and 1250 C, for 96 hours, to obtain homogenised melt inclusions (figure 4). Each experiment was terminated by electrically cutting the Pt-wire causing the samples to fall into water and quench.

For comparison, unheated melt inclusions were probed using broad beam analysis (a beam diameter of 10 microns). The major oxide compositions of the melt inclusions are shown in figure 5. There is no clear correlation of sample batch and melt compositions, except for Mg content. The higher temperature experiment run (1250C) yields higher MgO (>8%) than 1200C experiments (<8%).

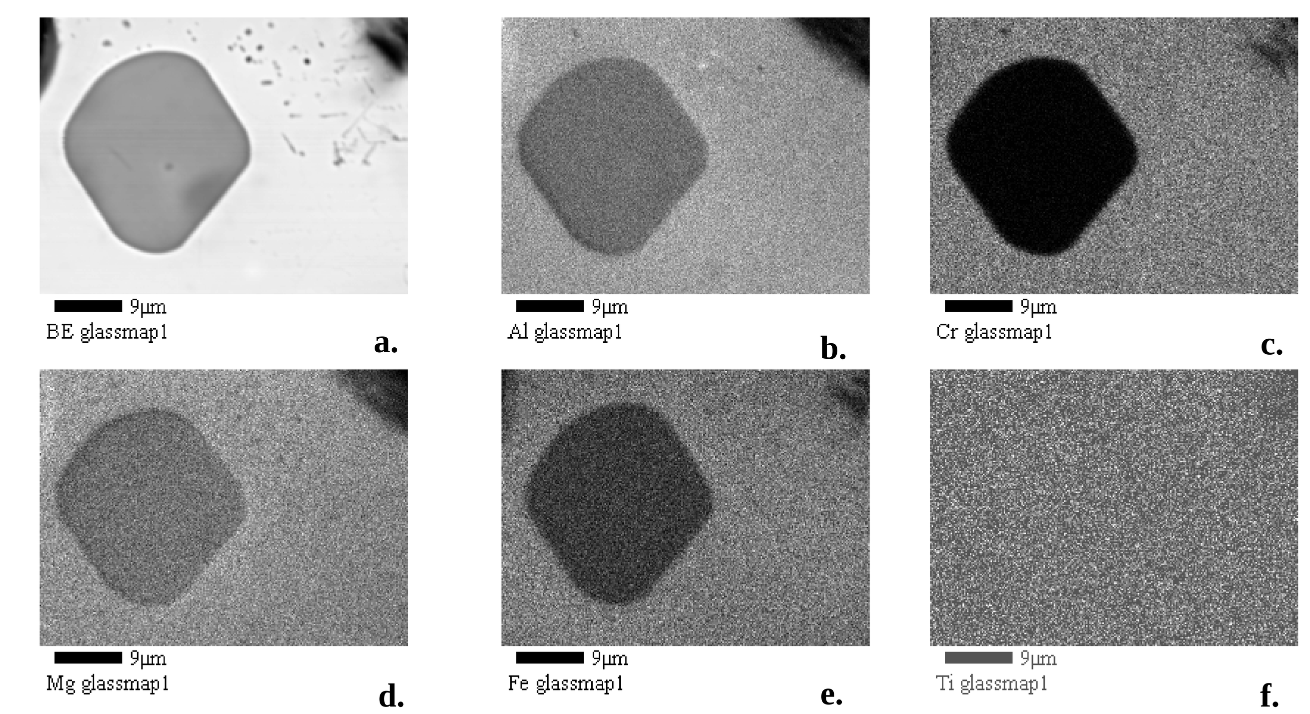

Figure 4. Elemental maps of a melt inclusion quenched from 1250C, showing the homogenised melt inclusion.
a. Backscatter image of the melt inclusion; **b.** X-ray image of Al distribution;
c. X-ray image of Cr distribution; **d.** X-ray image of Mg distribution;
e. X-ray image of Fe distribution; **f.** X-ray image of Ti distribution.

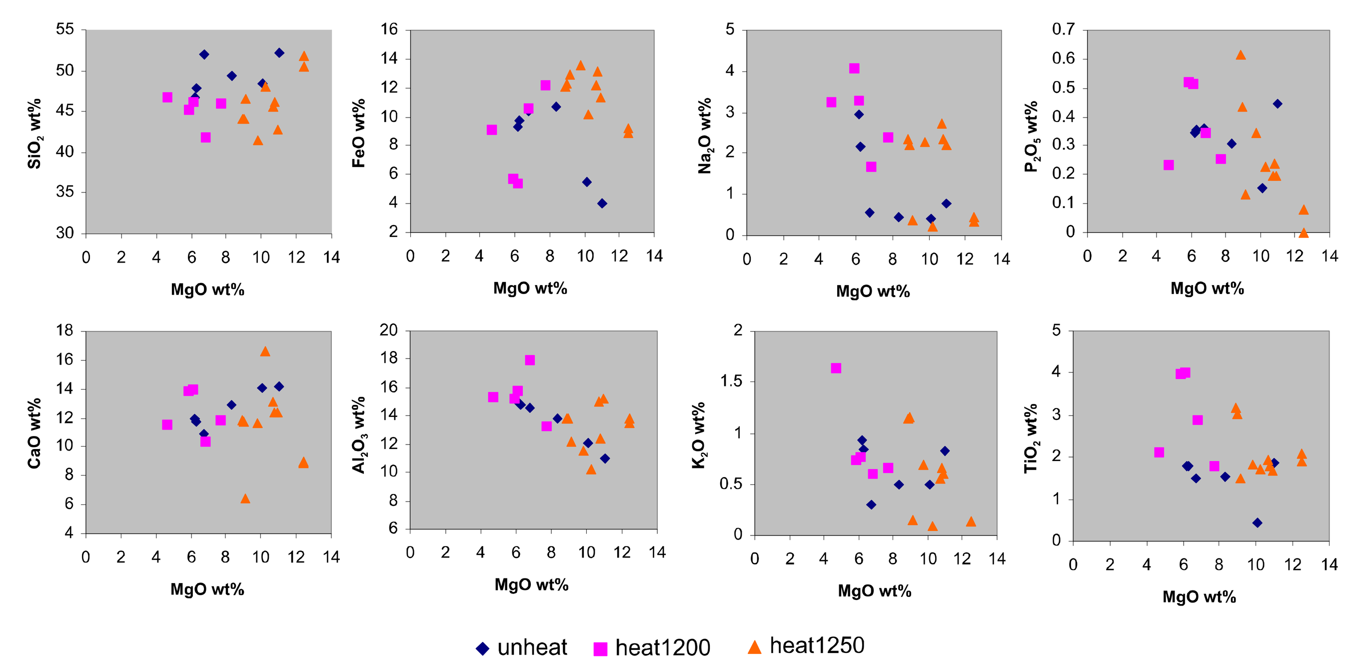

Figure 5. Major-element compositions of melt inclusions in the detrital spinels from Tianba Flysch. Note K, Ti, Al, P, and Na are increasing while Mg decreases, showing relative enrichment of incompatible elements during the crystallization of olivine and spinel.

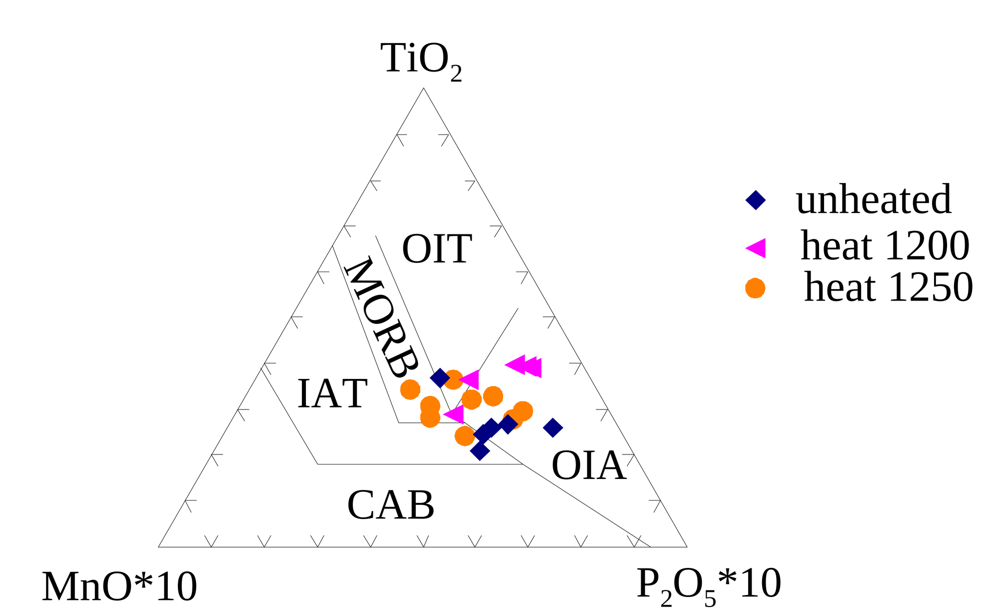

Figure 7. TiO_2-MnO-P_2O_5 plot (after Mullen, 1983). CAB: Calc-Alkaline basalts; IAT: Island Arc Tholeiites; OIA: Ocean Island Alkali basalt or Seamount Alkali Basalt; OIT: Ocean Island Tholeiites. 13 of data plot in OIA field with three in MORB, two in OIT, and two in IAT. Therefore the melt of the spinel melt inclusions was most like oceanic island basalt.

Discussion

1. Given that abyssal ocean crust may be finally transported to a subduction zone, a wide variation in the chemical compositions would commonly be expected for the spinels derived from arc complexes. TiO_2 content in arc spinels is generally below 1 wt %. Our detrital spinels have a narrow range of chemical compositions; most of them have TiO_2 content around 2 wt %, and they consistently plot in the discriminant fields of OIB or intra-plate basalts. No significant contribution of spinels to the Tianba flysch from arc-trench complexes has been detected.

2. Clastic wedges correlative with the Tianba flysch are deposited all along the Himalayas (figure 2), from the Trans-Indus Salt Range, to the Malla Johar and Thakkhola regions. In particular, the geochemical composition of a basaltic pebble fragment found in the Valanginian to Aptian volcaniclastic sandstones in the Thakkhola region (Durr and Gibling, 1994) indicates a source of alkali basalts of within-plate affinity. All basins of the East India coast are characterized by Hauterivian to Aptian sandstones, pointing to rejuvenation of the craton ascribed to lithospheric doming (Garzanti, 1993). A large flood-basalt event (Figure 8), linked to the activity of the Kerguelen mantle plume, started at 117 Ma (Baksi, 1995; Kent, 1997), as recorded in the Rajmahal-Sylhet-Bengal Trap Province of northeast India (Kent, 1991), and this provided volcanic clastics to Cretaceous turbiditic sandstones along the north Indian passive margin, now locally preserved in the Tethyan Himalaya sedimentary sections.

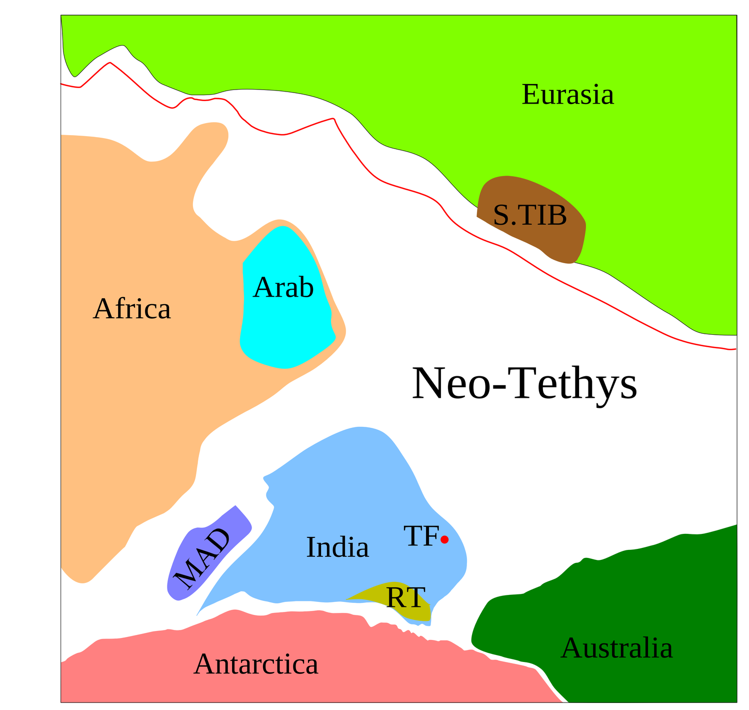

Figure 8. Reconstruction map at about 117 Ma (modified after Besse and Courtillot, 1988). MAD, Madagascar block; S.TIB, southern Tibet; RT, Rajmahal Traps; TF, Tianba Flysch. The red line is the major subduction zone.

Conclusions

Cr-rich spinel is a significant detrital component in turbidites from the well-exposed, mid-late Cretaceous Tianba Flysch sequence in the Nieru Valley, southern Tibet. About 5% of the spinels contain melt inclusions of 5-60 µm diameter, glassy or partly crystallized. The compositions of melt inclusions correlate well with the compositions of hosted spinels, and both show a possible cocrystallization of olivine and spinel in the parental magma. Based on palaeo-tectonic reconstruction, presence of mid-late Cretaceous fossils in the strata, and the chemical compositions of spinels and associated melt inclusions, we conclude that volcanics of the Rajmahal, which are associated spatially and temporally with Kerguelen hotspot activity on India about 117 Ma ago, were the source for these Cr-rich spinels. Although the Tianba Flysch looks in the field like a typical collisional product, and the presence of Cr-rich spinels might suggest an ophiolitic source and a Cretaceous ophiolite-obduction on the northern Indian continental margin, our detailed work shows clearly that the Tianba Flysch is neither ophiolite-derived, nor related to the start of the India-Asia collision.

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