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Himalayan detrital chromian spinels and timing of Indus-Yarlung ophiolite erosion

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ABSTRACT

The geochemistry of detrital chromian spinels is commonly used to discriminate provenance from different tectonic settings of mafic and ultramafic igneous rocks. Detrital spinels in Cenozoic foreland-basin successions fed from the Himalaya Orogen were assertively interpreted as sourced from the ophiolitic rocks of the Indus-Yarlung suture zone. This study compares the geochemistry of detrital Cr-spinels from the Tethys Himalaya passive margin and Cretaceous Xigaze forearc successions with those from the Indus-Yarlung ophiolites. Cr-spinels in the Indus-Yarlung ophiolites have low TiO_2 (mostly <0.2%) and high Al_2O_3 (10–48%). Detrital Cr-spinels from the Tethyan Himalaya have instead high TiO_2 (mostly >0.2%) and low Al_2O_3 (mainly 6–23%), indicating a rift-related basaltic origin. Detrital Cr-spinels from the Xigaze forearc basin have either low TiO_2 (mostly <0.2%) and low Al_2O_3 (4–34%), suggesting provenance from a supra-subduction-zone peridotite, or high TiO_2 (>1.0%), indicating intra-plate basaltic origin. Compositional fingerprints of detrital Cr-spinels from Lower Eocene foreland-basin strata in the central-eastern Himalaya indicate provenance from the Lhasa Block without input from the Indus-Yarlung ophiolites. Only Cr-spinels from the Lower Eocene foreland-basin strata in the north-western Himalaya and the Upper Eocene–Lower Miocene remnant-ocean turbidites of the Bengal basin are mostly ophiolite-derived. The Indus-Yarlung ophiolites were thus emplaced and exposed to erosion since the Early Eocene (>50 Ma) in the NW Himalaya, but only subsequently (50–38 Ma) in the eastern Himalaya.

1. Introduction

Provenance analysis is a powerful tool to reconstruct the tectonic evolution of adjacent orogenic belts (e.g., Critelli and Garzanti, 1994), and data on stable accessory minerals found in sedimentary rocks are being applied with increasing frequency in paleotectonic reconstructions (e.g., von Eynatten and Dunkl, 2012; Zhu et al., 2011). Heavy minerals resistant to diagenetic dissolution such as zircon and chromian-rich spinel are faithful indicators of the petrological characteristics of parent felsic/intermediate and mafic/ultramafic magmatic rocks, respectively (e.g., Dick and Bullen, 1984; Kamenetsky et al., 2001). Detrital Cr-spinel is generally less employed than zircon, in spite of its usefulness in discriminating among potential mafic and ultramafic sources.

In the Himalayan region, detrital spinels are widely found in foreland-basin strata (e.g., Ding et al., 2005; Garzanti et al., 1987; Najman and Garzanti, 2000), and generally inferred to have been mostly derived from ophiolites of the Indus-Yarlung suture zone. However, detrital spinels are also found in the Tethyan Himalayan strata (Hu et al., 2010; Sciunnach and Garzanti, 1997; Zhu et al., 2004) as well as in the Xigaze forearc basin (Dürr, 1996). The geochemistry and provenance discrimination of detrital Cr-spinels derived from different sources within the Himalayan Orogen can help us solve one of most hotly debated topics in Himalayan geology, i.e. the timing of emplacement and onset of erosion of ophiolite allochthons. It has long been suggested that the Indus-Yarlung ophiolites were obducted onto the Indian passive margin during the Late Cretaceous, well before the onset of the India–Asia collision (e.g., Ding et al., 2005; Searle, 1986). This interpretation, however, has been repeatedly challenged (e.g., Cai et al., 2012; Garzanti and Hu, in review; Garzanti et al., 2005; Guillot et al., 2003). Other geologists have suggested instead that the ophiolites were thrusted as part of the Asian subduction complex during the earliest Paleocene–Eocene stages of the Himalayan Orogeny (e.g., Einsele et al., 1994; Garzanti et al., 1987).

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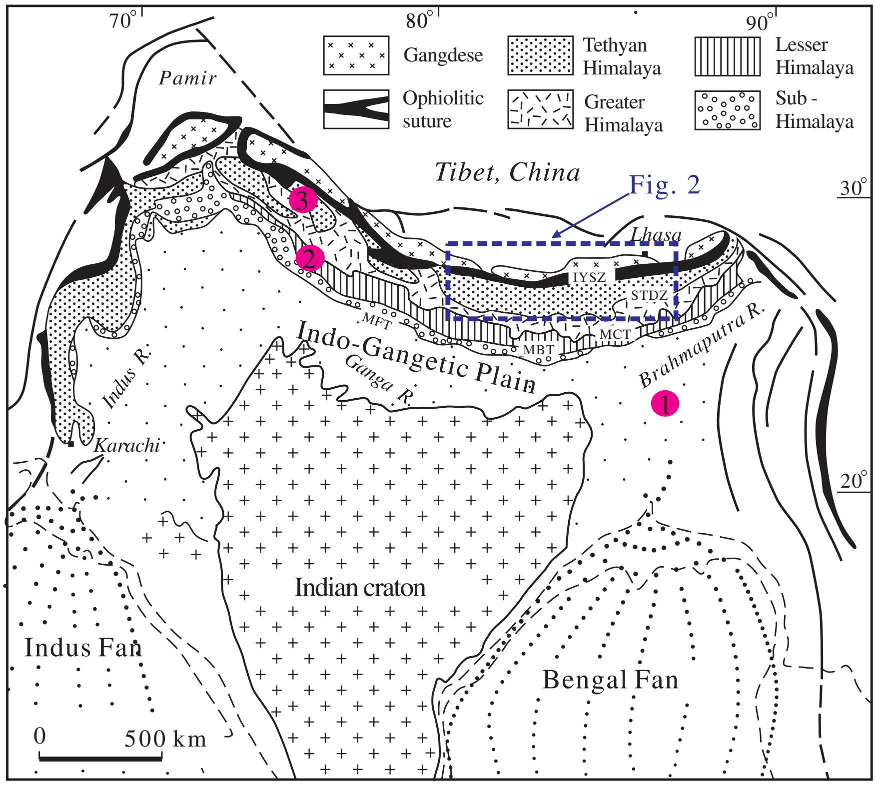

Fig. 1. Simplified geological map of the Himalayan region (revised from Critelli and Garzanti, 1994), showing locations related to this study. 1—Bengal basin; 2—Subathu basin; 3—Chulung La, Ladakh; boxed area is shown in greater detail in Fig. 2. IYSZ–Indus–Yarlung suture zone; MFT—main frontal thrust; MBT—main boundary thrust; MCT—main central thrust; STDZ—South Tibet detachment zone.

This article compares the geochemistry of Cr-spinels found in the Tethyan Himalaya passive-margin and Xigaze forearc-basin successions with those of the Indus-Yarlung ophiolites and syn-collisional basins in order to evaluate their potential sources.

2. Geological background

The Indus-Yarlung suture zone (Fig. 1), represented by discontinuous ophiolite bodies and serpentinite-matrix mélange, delineates the east–west trending contact between the Indian and Asian Plates for over 2500 km (e.g., Dai et al., 2013; Gansser, 1980; Hébert et al., 2012).

The Xigaze forearc basin (Fig. 2) is considered to be the forearc to the southern active margin of the Asian plate. Basaltic basement is overlain by a shallowing-upward megasequence including abyssal sediments at the base (Chongdui Formation), deep-sea turbidites (Ngamring Formation), and shelfal and deltaic facies at the top (Padana Formation) (An et al., in review; Dürr, 1996; Einsele et al., 1994; Wang et al., 2012).

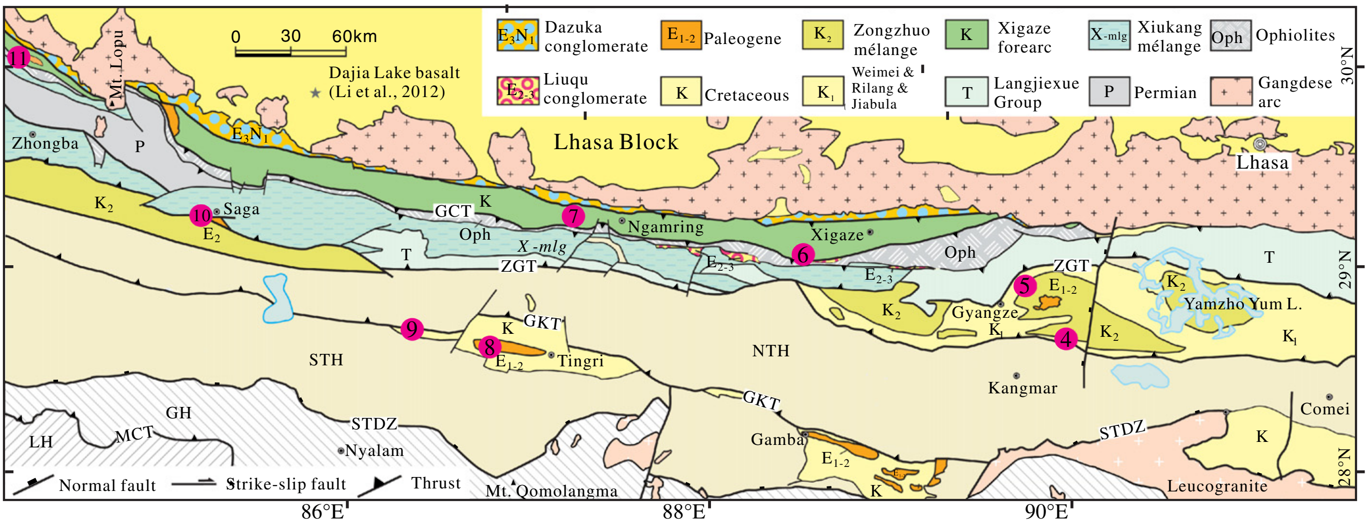

Fig. 2. Simplified geological map of southern Tibet. LH: Lesser Himalaya; GH: Greater Himalaya; STH: Southern Tethyan Himalaya; NTH: Northern Tethyan Himalaya; GCT: great counter thrust; ZGT: Zhongba–Gyangze thrust; GKT: Gyirong-Kangmar thrust; STDZ: South Tibet detachment zone; MCT: main central thrust; Locations: 4—Tianba, Kangmar; 5—Chuangde, Gyangze; 6—Naxia, Xigaze; 7—Sangsang, Angren; 8—Qumiba, Tingri; 9—Gucuo, Tingri; 10—Sangdanlin, Saga; 11—Cuojiangding, Zhongba.

Table 1
Data source of Himalayan Cr-spinels.

Stratigraphic unit		Place	Formation	Age	Sample	Grain no.	Longitude	Latitude	References
Pre-collisional basins	Xigaze forearc basin	Cuojiangding, Zhongba	Padana	Late Cretaceous	09CJD03	27	N29°56′47.1″	E84°20′37.0″	This study
		Padana, Sangsang	Padana	Late Cretaceous	09PDN01	33	N29°21′29.5″	E86°44′14.4″	This study
		North to Xigaze	Ngamring	Early Late Cretaceous	10AR06	22	N29°14′57.0″	E88°56′38.5″	This study
		North to Xigaze	Ngamring	Early Late Cretaceous	10AR14	33	N29°13′27.9″	E88°48′46.8″	This study
		South to Anreng	Ngamring	Late Early cretaceous	10AR-A11	52	N29°20′54.8″	E87°17′47.6″	This study
		Naxia, Xigaze	Ngamring	Late Early cretaceous	09NX09 & 09NX15	120	N 29°08′7.3″	E88°26′38.9″	This study
	Tethyan Himalaya	Gucuo, Tingri	Guocuo Quartzarenite and Wölong Volcaniclastics	Early Cretaceous	–	133	N 28°48′55.8″	E86°19′12.9″	This study; Hu et al. (2010)
		Chuangde, Gyangze	Weimei and Rilang	Early Cretaceous	–	96	N 28°58′00″	E89°44′05″	This study
		Sangdanlin, Saga	Denggang	Late Cretaceous	–	16	–	–	Wang et al. (2011)
		Tianba, Kangma	Tianba	Early Cretaceous	–	30	–	–	Zhu et al. (2004)
		India, Nepal, Tibet	–	Carboniferous–Permian	–	27	–	–	Sciunnach and Garzanti (1997)
Syn-collisional basins	Tibet Himalaya	Qumiba, Tingri	Enba	Early Eocene	06QMB08	48	N28°41′27.1″	E86°43′37.7″	This study
		Qumiba, Tingri	Enba and Zhaguo	Early Eocene	–	18	–	–	Zhu et al. (2005)
		Sangdanlin, Saga	Sangdanlin and Zheya	Early Eocene	–	128	–	–	Ding et al. (2005); Wang et al. (2011)
		Cuojiangding, Zhongba	Quxia and Jialazi	Paleogene	–	139	–	–	Hu et al. (submitted for publication)
	Ladakh Himalaya	Marpo and Dibling, Ladakh	Chulung La	Early Eocene	–	30	–	–	K. Honegger in Garzanti et al. (1987)
	Subathu	Subathu, India	Subathu	Early Eocene	–	27	–	–	Najman and Garzanti (2000)
	Bengal basin	Assam and Bengal basin	Disang, Barail, Tipam	Oligocene to Pliocene	–	16	–	–	Rahman (2008)
		Surma basin	Kopili, Barail	Eocene to early Miocene	–	8	–	–	Najman et al. (2008)
		Sylhet trough	Barail, Surma	Oligocene to Pliocene	–	9	–	–	Mandal (2009)
Yarlung Zangbo suture zone		Saga & Sangsang	–	Early Cretaceous	–	245	–	–	Bédard et al. (2009)
		Xiugugabu	–	Early Cretaceous	–	63	–	–	Bezard et al. (2011)
		Diding, Dazhuqu, Qunrang, Jinlu, Zedang	–	Early Cretaceous	–	257	–	–	Dubois-Coté et al. (2005)
		Zisong, Jinlu	–	Early Cretaceous	–	89	–	–	Dupuis et al. (2005)
		Zhongba	–	Early Cretaceous	–	53	–		Dai et al. (2011)
		Yungbwa	–	Early Cretaceous	–	55	–	–	Liu et al. (2010)
		Yungbwa	–	Early Cretaceous	–	24	–	–	Xu et al. (2011)

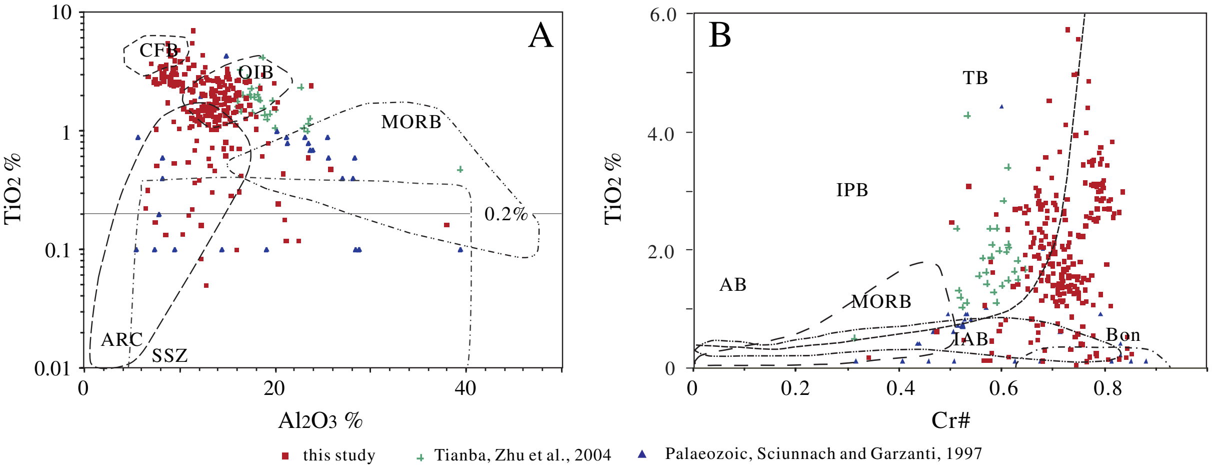

Fig. 3. TiO_2–Al_2O_3 plot (Kamenetsky et al., 2001) and TiO_2-Cr# plot (Arai, 1992) of Cr-spinels from Tethyan Himalayan strata. Data sources refer to Table 1. Abbreviation: MORB—mid-ocean ridge basalt; CFB—continental flood basalt; OIB—oceanic island basalt; ARC—arc; SSZ—supra-subduction-zone; AP—abyssal peridotite. IPB—intra-plate basalt; TB—tholeiitic basalt; AB—alkaline basalt; IAB—island arc basalt; Bon—boninite.

North of the Xigaze forearc basin and located in the southern part of the Lhasa Block (Fig. 2), the Gangdese Arc is composed of Jurassic to Cretaceous granitoids and Cretaceous to Cenozoic terrigenous and volcanic rocks (Chung et al., 2005; Mo et al., 2008; Zhu et al., 2011). Geochronological studies suggest that plutonic rocks formed in discrete magmatic events at 205–152 Ma, 109–80 Ma, 65–41 Ma, and 33–13 Ma (Chung et al., 2005; Zhu et al., 2011).

South of the Indus-Yarlung suture zone, rocks once belonging to the northern margin of India are traditionally subdivided in the Tethyan, Greater, and Lesser Himalayas (Fig. 1). The Tibetan Tethyan Himalaya comprises a southern and a northern zone, separated by the Gyirong-Kangmar thrust (Ratschbacher et al., 1994; Fig. 2). The southern Tethys Himalaya includes platform carbonates and diverse terrigenous units of the Paleozoic to Eocene age (Hu et al., 2012; Jadoul et al., 1998; Willems et al., 1996), whereas the Northern Tethyan Himalaya is dominated by the Mesozoic to Paleogene outer shelf, continental slope and rise deposits (Hu et al., 2008).

South of the Tethyan Himalaya, separated by the South Tibetan detachment zone, lies the Greater Himalaya, comprising medium to locally high-grade metasediments and Cambro-Ordovician orthogneisses. The Lesser Himalaya includes Precambrian to Eocene sedimentary rocks metamorphosed up to lower-amphibolite facies. Cenozoic foreland-basin strata are preserved on top of the Lesser Himalaya in Nepal (DeCelles et al., 1998) and in NW India (Najman and Garzanti, 2000) (Fig. 1). The Bengal Fan developed on the remnant-ocean floor since the Paleogene onset of the India–Asia collision (Fig. 1; Najman et al., 2008).

During the earliest Cretaceous, the northern margin of India was situated at middle latitudes in the southern hemisphere (Patzelt et al., 1996), while the Lhasa Block was in low latitudes of the northern hemisphere. India rifted from Gondwana in the Early Cretaceous and drifted northward (e.g., Hu et al., 2010; Zhu et al., 2009; and references therein), to collide with the Lhasa Block (Asian Plate) around the Paleocene/Eocene boundary (Hu et al., 2012; Najman et al., 2010; Zhu et al., 2005).

3. Samples and methods

Over 30 sandstone samples were collected from the pre-collisional Tethyan Himalaya passive-margin and Xigaze forearc-basin successions. The Southern Tethyan Himalaya samples are from the uppermost Jurassic–Lower Cretaceous Gucuo Quartzarenite and Wölong Volcaniclastics near Tingri (Hu et al., 2010; Fig. 2). The samples from the Northern Tethyan Himalaya are from the Upper Jurassic to

Table 2
Summary of geochemical data of Cr-spinels from different Himalayan stratigraphic units.

Stratigraphic unit			Number	TiO_2	Al_2O_3	Cr_2O_3	MgO	Cr#[a]	Mg#[b]	Source rocks	Tectonic setting
Pre-collisional basin	Tethyan Himalaya	Group 1	n = 42	0.05–0.84	6.45–28.8	29.18–63.96	0.27–22.59	0.34–0.85	0.03–0.75	Basaltic	Rifting
		Group 2	n = 203	1.01–7.11	6.76–23.72	32.27–54.67	0.3–17.63	0.5–0.84	0.03–0.81	Basaltic	Intra-plate
	Xigaze forearc basin	Group 1	n = 225	0–0.9	4.26–34.06	26.82–62.95	0.81–19.75	0.35–0.9	0.04–0.85	Peridotite	Supra-subduction zone
		Group 2	n = 56	1.1–3.01	9.53–20.34	36.53–50.66	1.05–16.77	0.58–0.8	0.06–0.76	Basaltic	Intra-plate
	Yarlung Zangbo ophiolites		n = 620	0–0.67	10.59–48.08	20.06–57.72	2.07–20.67	0.22–0.95	0.12–0.93	–	Forearc

Stratigraphic unit		Number	TiO_2	Al_2O_3	Cr_2O_3	MgO	Cr#[a]	Mg#[b]	Interpreted source
Syn-collisional basin	Cuojiangding Group, Zhongba	n = 139	0–2.75	0.35–33.77	16.44–71.18	0.81–15.57	0.42–0.97	0.1–0.69	Southern Lhasa
	Enba and Zhaguo Fms, Tingri	n = 66	0–4.57	2.45–28.89	28.2–66.6	0.18–16.83	0.42–0.95	0.01–0.75	Southern Lhasa
	Sangdanlin and Zheya Fms, Saga	n = 128	0–0.51	1.59–33.33	29.3–71.0	2.96–18.89	0.34–0.97	0.18–0.85	Southern Lhasa
	Chulung La Fm, Ladakh, India	n = 30	0.02–0.47	8.83–45.66	20.84–55.87	4.83–17.10	0.23–0.8	0.29–0.72	Indus-Yarlung ophiolite
	Subathu Fm, NW India	n = 27	0.05–0.28	9.9–46.8	18.2–60.46	8.88–16.83	0.21–0.8	0.45–0.7	Indus-Yarlung ophiolite
	Bengal Basin	n = 33	0.02–0.41	9.13–51.49	16.07–56.67	4.59–19.02	0.17–0.8	0.35–0.59	Indus-Yarlung ophiolite

All Fe was expressed as FeO, and ferric iron content was calculated following Barnes and Roeder (2001).

[a] Cr = Cr/(Cr + Al).

[b] Mg = Mg/(Mg + Fe^{2+}).

Table 3
Summary of Himalayan syn-collisional basin stratigraphy.

	Formation/Group	Age	Tectonic unit	Place
N	Chulung La	Early Eocene	Tethyan Himalaya	Ladakh, NW India
S	Subuthu	Early to middle Eocene	Lesser Himalaya	NW India
N	Cuojiangding	latest Paleocene	southern Lhasa	Zhongba, Southern Tibet
	Sangdanlin and Zheya	Early Eocene	Tethyan Himalaya	Saga, Southern Tibet
	Enba and Zhaguo	Early Eocene	Tethyan Himalaya	Tingri, Southern Tibet
S	Kopili and Barail	Late Eocene-Early Miocene	Bengal Basin	Eastern India and Bangladesh

References as in Table 1; N = north; S = south.

Lower Cretaceous Weimei and Rilang Formations near Gyangze (Hu et al., 2008; Fig. 2). The samples from the Xigaze forearc basin are from the Albian–Campanian Ngamring and Padana Formations near Xigaze, Ngamring and Zhongba (Wang et al., 2012; Fig. 2). One sample is from the syn-collisional Lower Eocene Enba Formation near Tingri (Hu et al., 2012; Fig. 2). Further information on analyzed samples is contained in Table 1.

Sandstone samples were powdered into <260 μm size. Heavy minerals were separated by elutriation methods, and Cr-spinels were selected by hand-picking, mounted in epoxy, and polished for analyses. Cr-spinel geochemical composition was determined at the State Key Laboratory for Mineral Deposits Research, Nanjing University using a JEOL JXA-8100M electron microprobe following the method described by Hu et al. (2010). In order to get reliable compositions of detrital Cr-spinels, points for analysis were selected: (1) close to grain cores; (2) away from microveins or altered zones after checking in black-scattered light. Geochemical data are listed in Appendix A. Supplementary data.

4. Cr-spinels in pre-collisional basins and ophiolites

Cr-spinels from different source rocks and different tectonic settings can be differentiated by their chemical composition using discrimination plots, such as binary plots of TiO_2 versus Al_2O_3, and TiO_2 versus Cr# [Cr / (Cr + Al)] (e.g., Arai, 1992; Dick and Bullen, 1984). Most spinels from residual mantle peridotites tend to have lower TiO_2 (<0.2%) than spinels from volcanic rocks (Kamenetsky et al., 2001).

Out of the 245 analyzed Cr-spinels from the Mesozoic Tethys Himalaya strata, 95% have TiO_2 >0.2% (Fig. 3A), suggesting basaltic origin. Cr-spinels can be divided into two groups according to TiO_2 concentration (Fig. 3A and B; Table 2). Group 1 (n = 203, 83%) has relatively high TiO_2 (1.0–7.1%); Al_2O_3, Cr_2O_3 and Cr# are 6.9–23.7%, 32.3–54.7%, and 0.50–0.84, respectively. Group 1 spinels (Fig. 3A and B) are similar to those from the mid-Cretaceous Tianba Formation near Kangmar (Fig. 1; Zhu et al., 2004), where 97% Cr-spinels have >1.0% TiO_2. Group 2 spinels (n = 42, 17%) have low TiO_2 (≤0.9%, but mainly >0.2%); Al_2O_3, Cr_2O_3 and Cr# are 6.4–38.0%, 29.2–64.0%, and 0.34–0.85, respectively. Group 2 spinels are similar to those from the Carboniferous–Early Permian strata in the Tethyan Himalaya (89% of which have <0.9% TiO_2; Sciunnach and Garzanti, 1997; Fig. 3A and B). (See Table 3.)

The 281 analyzed Cr-spinels from Xigaze forearc-basin strata are also divided into two groups according to their TiO_2 content (Fig. 4; Table 2). Group A spinels (n = 225, 80%) have low TiO_2 (<0.9%; 61% of grains < 0.2%); Al_2O_3, Cr_2O_3 and Cr# are 4.3–34.1%, 26.8–64.5%, and 0.35–0.90, respectively, suggesting their origin from mantle peridotites. Group B spinels (n = 56, 20%) have relatively high TiO_2 (1.1–3.0%); Al_2O_3, Cr_2O_3 and Cr# are 9.5–20.3%, 36.5–50.7%, and 0.58–0.80, respectively, indicating basaltic origin.

Finally, we have compiled the available geochemical data from 786 spinels in Indus-Yarlung ultramafic rocks (see Table 1), 620 of which have Al_2O_3 >10% and Cr_2O_3 >20%. The TiO_2, Al_2O_3, Cr_2O_3 and Cr# are 0.01–1.06%, 10.6–48.1%, 20.1–57.7%, and 0.22–0.95, respectively.

5. Cr-spinels in syn-collisional basins

A foreland basin system began to develop since 55–50 Ma, soon after India collided with the Lhasa Block (e.g., Ding et al., 2005; Garzanti et al., 1987; Hu et al., 2012; Wang et al., 2011). Abundant detrital Cr-spinels occur in Paleogene syn-collisional basins from southern Tibet (Ding

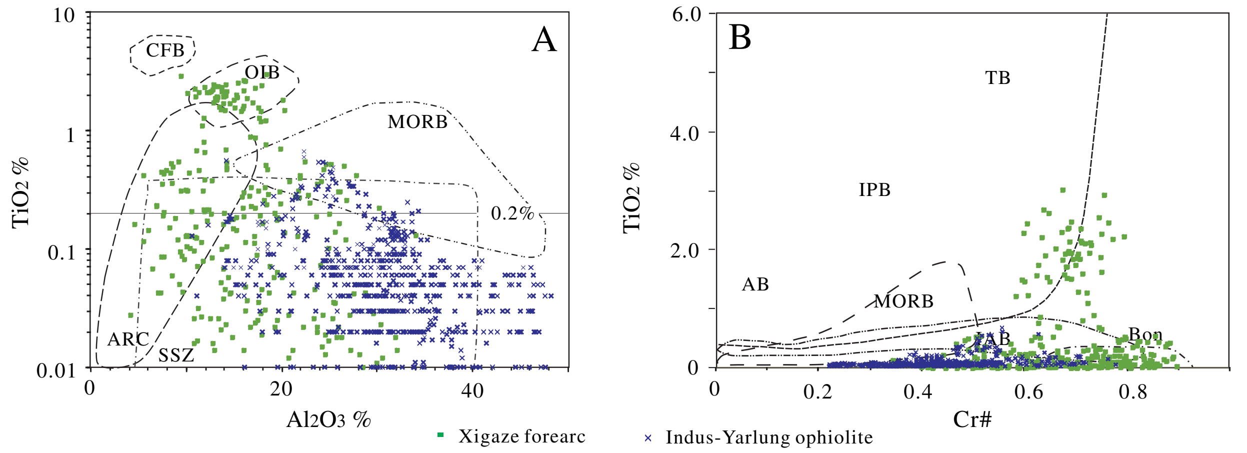

Fig. 4. TiO_2–Al_2O_3 plot (Kamenetsky et al., 2001) and TiO_2-Cr# plot (Arai, 1992) of Cr-spinels from different Himalayan units. Data sources refer to Table 1. Abbreviations as in Fig. 3.

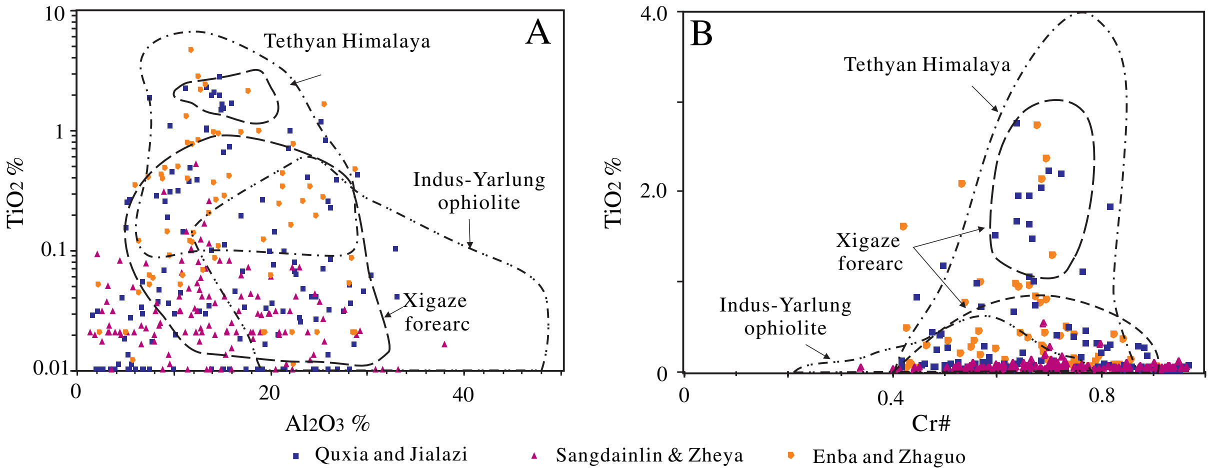

Fig. 5. TiO_2–Al_2O_3 plot (Kamenetsky et al., 2001) and TiO_2-Cr# plot (Arai, 1992) of detrital Cr-spinels from Himalayan syn-collisional basins in south Tibet. Data sources refer to Table 1.

et al., 2005; Wang et al., 2011; Zhu et al., 2005) to the NW Himalaya (Garzanti et al., 1987; Najman and Garzanti, 2000) (Table 3). Cr-spinels from the Lower Eocene Sangdanlin and Zheya Formations near Saga (Fig. 1) have very low TiO_2 (≤0.5%, 98% of which <0.2%) and Cr# 0.34–0.97. On tectonic-discrimination diagrams they plot in the "supra-subduction-zone peridotite" field, largely overlapping Group B spinels from the Xigaze forearc basin (Fig. 4).

Detrital Cr-spinels in the Paleocene Cuojiangding Group (Quxia and Jialazi Formations) near Zhongba, which unconformably overlie the Xigaze forearc-basin succession (Hu et al., submitted for publication) have TiO_2 ≤2.75% and Cr# 0.42–0.97, and are indistinguishable from those of the Sangdanlin and Zheya Formations. Similar compositions are found in the Eocene Enba and Zhaguo Formations near Tingri (TiO_2 ≤4.6%, Cr# 0.42–0.95). Cr-spinels from the Sangdanlin, Zheya, Enba and Zhaguo Formations are similar to those in the Xigaze forearc strata (Fig. 5), but distinct from those in the Indus-Yarlung ophiolites (Fig. 5).

Detrital Cr-spinels from the Lower Eocene Chulung La Formation in Ladakh (data provided by K. Honegger in Garzanti et al., 1987; Fig. 1) have low TiO_2 (0.02–0.47%, 67% of which <0.2%) and Cr# 0.23–0.80. Detrital Cr-spinels from the Lower to Middle Eocene Subathu Formation in NW India (Fig. 1; Najman and Garzanti, 2000) have similarly very low TiO_2 (0.05–0.28, 85% of which <0.2%) and Cr# 0.21–0.80, indicating their origin from mantle peridotites.

Cr-spinels with geochemical compositions similar to Chulung La and Subathu spinels are found in the Upper Eocene to Lower Miocene Kopili and Barail Formations of the Bengal basin (Fig. 1) (TiO_2 0.02–0.41%, 67% of which < 0.2% and Cr# 0.17–0.80; Table 2, Najman et al., 2008). Detrital Cr-spinels from the Chulung La, Subathu, Kopili and Barail units compare well with those of the Indus-Yarlung suture (Fig. 6), but are markedly different from those of the Xigaze forearc-basin and Tethys Himalaya strata.

6. Potential sources of detrital Cr-spinels

Group 1 detrital spinels from the Tethyan Himalaya strata have > 1.0 TiO_2, and in TiO_2 versus Al_2O_3 (Fig. 3A) and TiO_2 versus Cr# diagrams (Fig. 3B) most closely match spinels from the oceanic-island or intraplate basalts. These detrital spinels were thus most probably sourced from Lower Cretaceous basalts once widespread in northern India, as suggested by provenance studies on Lower Cretaceous volcaniclastic sandstones deposited all along the Tethyan Himalaya (Garzanti, 1993; Hu et al., 2010; Zhu et al., 2004 and references therein). Group 2 detrital spinels from the Tethyan Himalayan strata (≤0.9%, but mainly > 0.2% of TiO_2) were probably derived from the rift-related Upper Paleozoic basalts in northern India, as suggested by provenance studies on the Carboniferous–Permian Tethyan Himalayan strata (Sciunnach and Garzanti, 1997).

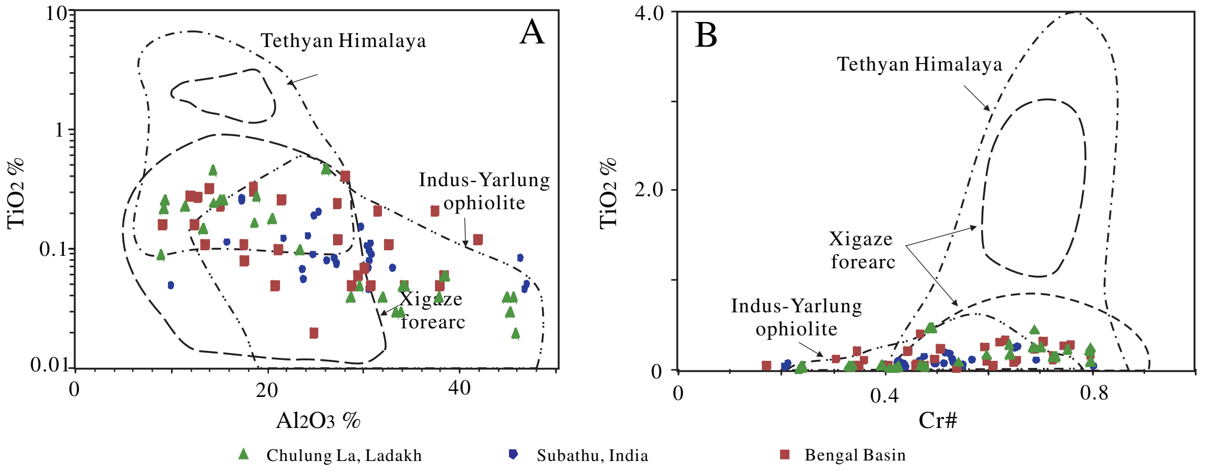

Fig. 6. TiO_2–Al_2O_3 plot (Kamenetsky et al., 2001) and TiO_2-Cr# plot (Arai, 1992) of detrital Cr-spinels from Himalayan syn-collisional basins in India and Bengal basin. Data sources refer to Table 1.

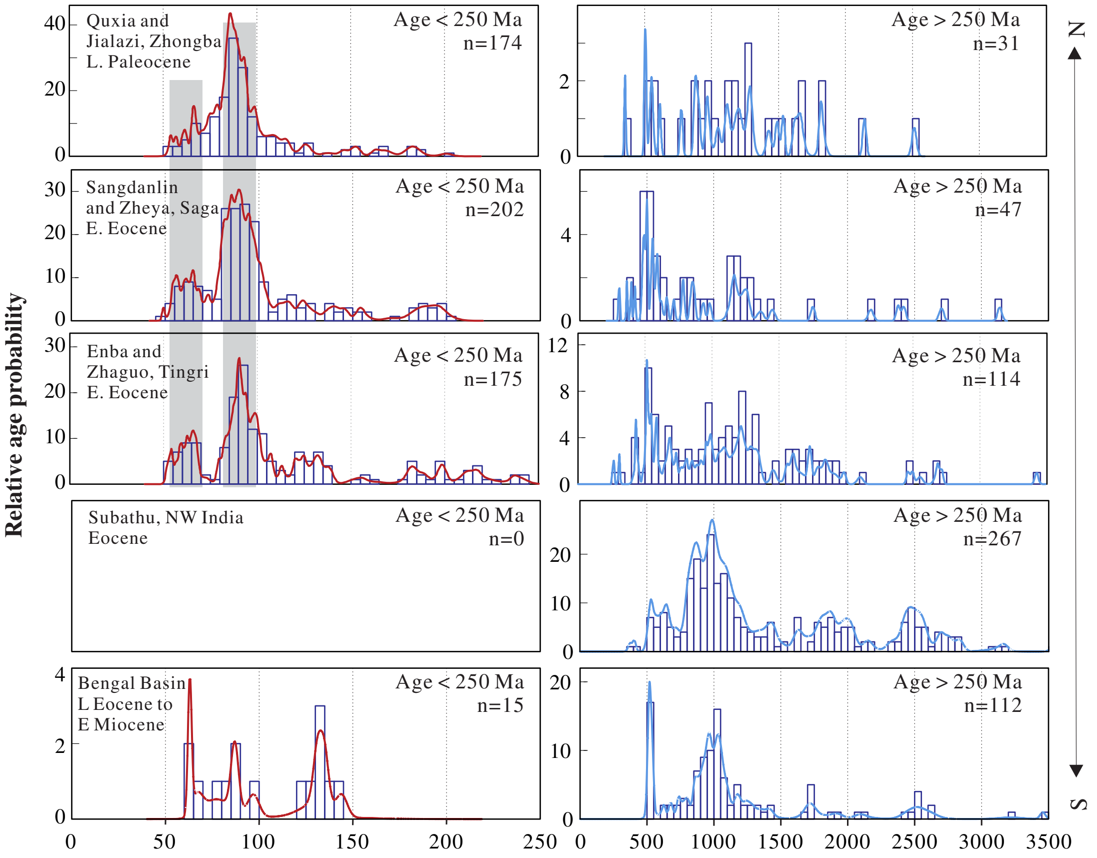

Fig. 7. Comparison of relative U–Pb age probability of detrital zircons.
Data sources: Enba and Zhaguo Formations in Tingri (Hu et al., 2012); Quxia and Jialazi Formations in Cuojiangding area (Hu et al., submitted for publication); Sangdanlin and Zheya Formations in Saga (Wang et al., 2011); Subathu Formation (Ravikant et al., 2011); Bengal basin (Najman et al., 2008).

In TiO_2 versus Al_2O_3 (Fig. 4A) and TiO_2 versus Cr# diagrams (Fig. 4B), Group A detrital spinels in Xigaze forearc strata plot in the "supra-subduction-zone peridotite" field, and were possibly derived from a paleo-ophiolitic suite within the Gangdese region (southern Lhasa). Potential Cr-spinel sources in the Gangdese region include: 1) the Xietongmen ultramafic and mafic rock suites of debated origin found 10 km north of the Xigaze forearc basin (Gao et al., 2003; Hou et al., 2001; Li et al., 2003); 2) the E/W trending and ≥60 km long Sumdo ultramafic eclogite belt of Permian age exposed in the eastern part of the Lhasa Block and interpreted as a dismembered ophiolite (Chen et al., 2009; Yang et al., 2009). Group B detrital spinels in the Xigaze forearc strata plot instead in the "oceanic-island basalts" or "intra-plate basalts" fields (Fig. 4), suggesting that such a source also probably existed within the southern Lhasa Block. Permian intra-plate basalts ~263 Ma in age were recently discovered ~35 km north of the Xigaze forearc basin near Dajia Lake area in the southern Lhasa Block (Li et al., 2012, Fig. 2).

7. Timing of Indus-Yarlung ophiolite erosion

Earlier studies considered the Indus-Yarlung ophiolite as formed at a slow-spreading ridge (e.g., Girardeau and Mercier, 1988), whereas based on geochemical evidence a supra-subduction-zone setting was proposed later on (e.g., Hébert et al., 2012). Most recently, Dai et al. (2013) proposed that the Indus-Yarlung ophiolite near Xigaze was formed in a forearc environment, which is conclusively documented by field evidence (An et al., in review). Radiolarian chert, siliceous shale and finally turbiditic sandstones of the Xigaze forearc-basin lie in direct, conformable stratigraphic contact onto pillow lavas, which represents the typical oceanic-crust stratigraphy (Kusky et al., 2013).

Cr-spinels from the Lower Eocene Sangdanlin and Zheya Formations near Saga (52–50 Ma, Wang et al., 2011) and Enba and Zhaguo Formations near Tingri (~50 Ma, Hu et al., 2012; Najman et al., 2010; Zhu et al., 2005) are similar to those in Xigaze forearc strata (Fig. 5), but distinct from those in Indus-Yarlung ophiolites (Fig. 5). This indicates provenance of Lower Eocene foreland-basin sediments in southern Tibet from the Lhasa Block, as strongly supported by detrital zircon U–Pb age populations (Hu et al., 2012; Wang et al., 2011; Fig. 7). Detrital zircons from the Subathu Formation of NW India (Ravikant et al., 2011) compare well with the Tethyan Himalayan strata (Hu et al., 2010), whereas those from the Kopili and Barail Formations show a mixed provenance from the Tethyan Himalaya and Gangdese Arc (Najman et al., 2008; Fig. 7). Cr-spinels in the Chulung La, Subathu and Kopili–Barail Formations unambiguously suggest provenance from the Indus-Yarlung ophiolitic rocks (Fig. 6). Based on such evidence, we suggest that in the Early Eocene (55–50 Ma) the Indus-Yarlung ophiolites were not yet exposed to erosion in the eastern Himalaya, whereas they were already exposed and eroded in the NW Himalaya (Garzanti et al., 1987; Najman and Garzanti, 2000). Thus, our data do not support the application in the Himalayas of Oman model of ophiolite obduction and subsequently erosion (e.g., Ding et al., 2005; Searle, 1986), before the India–Asia collision.

8. Conclusion

Our results show that the geochemistry of the detrital Cr-spinels can be used profitably to trace specific mafic and ultramafic sources of clastic wedges derived from collisional orogens. Moreover, it helps us to constrain effectively the timing of exposure and erosion of ophiolitic nappes within the orogenic belt. The methods used here to unravel the tectonic and erosional evolution of the Himalayan region could well prove to be useful in other similar geodynamic settings worldwide.

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Appendix A. Supplementary data

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