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Testing the validity of Nd isotopes as a provenance tool in southern Tibet for constraining the initial India–Asia collision

Xiumian Hu *

State Key Laboratory of Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, China

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ABSTRACT

Sm–Nd isotopic systematics has been proven to be a powerful tool for investigating the source provenance and tectonic significance of sedimentary rocks. Here, I report the Nd isotopic compositions of Mesozoic to Paleogene siliciclastic sediments from southern Tibet in an attempt to determine the temporal variations in their provenance. The data reveal a shift in $\varepsilon_{Nd}(0)$ values of Mesozoic strata in the Tethyan Himalaya, varying from −16.3 to −12.7 in the Jurassic to −8.1 to −3.7 in the Cretaceous. The less negative $\varepsilon_{Nd}(0)$ values of the Cretaceous siliciclastic rocks indicate increasing input of a juvenile mantle component from the source region. Such a shift can be attributed to the Early Cretaceous mantle-derived magmatism that was predominant in northern Greater India. This study indicates that there is a significant overlap in the $\varepsilon_{Nd}(0)$ values of rocks from the Tethyan Himalaya and Lhasa block, implying that Nd isotopes may not be a good provenance proxy to constrain the initiation of the India–Asia collision. Such an inference is also evidenced by similar Nd isotopic compositions between rocks from the Bhainskati Formation in the Nepalese foreland basin, sourced from the Tethyan Himalaya, and the Enba and Zhaguo formations in southern Tibet, sourced from the Lhasa block.

1. Introduction

In recent years, Sm–Nd isotopic systematics has been proved to be a powerful tool for investigating the provenance and tectonic significance of sedimentary rocks (e.g., Murphy and Nance, 2002), and it has been applied to bulk-rock analyses of various Himalayan sedimentary units (Parrish and Hodges, 1996; Ahmad et al., 2000; Najman et al., 2000; Robinson et al., 2001; Richards et al., 2005). The existing Nd isotopic data suggest that the Higher Himalaya has $\varepsilon_{Nd}(0)$ values of approximately −19 to −11, with a few samples up to −5, while the Lesser Himalaya typically has more negative $\varepsilon_{Nd}(0)$ values of approximately −32 to −10, indicating a much older crust as its source (e.g., Ahmad et al., 2000; Robinson et al., 2001; Martin et al., 2005; Richards et al., 2005). Moreover, these isotopic distinctions are largely consistent along strike in the entire Himalayan orogen (e.g., Richards et al., 2005). The Tethyan Himalaya has Nd compositions similar to the Higher Himalaya (e.g., Miller et al., 2001; Robinson et al., 2001; Richards et al., 2005), but fewer samples have been analyzed from the Tethyan Himalaya than from the Higher Himalaya and Lesser Himalaya units. Thirty-three among 43 samples of the Tethyan Himalaya were from the Paleozoic strata, with only ten samples from the Mesozoic strata. Based on the different Nd compositions of Himalayan lithic-tectonic units, Nd isotopes from the Himalayan foreland sediments were successfully used to document the erosional history of the Tethyan Himalaya, the Indus-Yarlung suture zone, the Higher Himalaya, and the Lesser Himalaya (e.g., Clift et al., 2001; Robinson et al., 2001; DeCelles et al., 2004).

A variety of indicators have been used to constrain the timing of the initial India–Asia continental collision, but the actual age of the collision remains disputed, with estimated ages varying from 70 to 34 Ma (e.g., Yin and Harrison, 2000; Aitchison et al., 2007; Najman et al., 2010). Sedimentary indicators, such as the first arrival of material derived from the Asian plate onto the Indian margin or the earliest strata to contain mixed India- and Asia-sourced detritus, have been used to provide minimum constraints on the timing of the initial collision (e.g., Najman, 2006). Nd isotopes have been used to constrain the timing of the collision through the recognition of orogenic material within the Himalayan foreland sediments in northwest India (the Subathu, Dagshai, Kasauli, and Siwalik formations, Najman et al., 2000) and in central Nepal (the Bhainskati Formation, Dumri Formation, and Siwalik Group, Robinson et al., 2001; DeCelles et al., 2004). Recently, Henderson et al. (2010) documented the Nd isotopic characteristics of detrital apatite from modern river sediments originating from the Indian and Asian plates. They applied this approach to Tertiary Indus Molasses in an attempt to better determine the timing of the India–Asia collision. However, their samples of modern river sands from each plate are limited both in place and in quantity. In addition, the modern sands may not correctly reflect the sedimentary provenance at the time when the sediments during the early India–Asia

* Tel.: +86 25 8359 3002; fax: +86 25 8368 6016.
E-mail address: huxm@nju.edu.cn

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collision were deposited, considering the significant exhumation and erosion in the Himalaya during the Cenozoic.

In this study, Nd isotopic data from Mesozoic–Paleogene siliciclastic sediments, both in the Tethyan Himalaya (Indian block) and in the Lhasa block, were analyzed in an attempt to determine variations in their provenance over time and, hence, their tectonic history and to confirm the validity of Nd isotopes as a provenance tool for constraining the initial India–Asia collision.

2. Geological setting

The Himalayan orogenic belt consists of a series of lithotectonic units (Fig. 1). The Indus-Yarlung suture zone in southern Tibet defines the contact between the Indian and Asian continents (Fig. 1) (e.g., Hodges, 2000; Wang et al., 2000), and it consists of ophiolites, ophiolite-bearing accretionary complexes (Ziabrev et al., 2004), and post-Early Eocene molasse-type sediments (e.g., Wang et al., 2010). North of the suture zone is the Lhasa block, an Andean-type northern margin of Tethys formed by Jurassic to Paleogene calc-alkaline plutons intruding into the Lhasa continental crust (e.g., Schärer et al., 1984; Chung et al., 2005), and Paleogene Linzizong volcanic successions (~65–40 Ma, e.g., Mo et al., 2007). The Xigaze forearc basin forms the southern active margin of the Lhasa plate and comprises mainly Cretaceous (Aptian–Santonian) clastic deep-water turbidites (Einsele et al., 1994; Wu et al., 2010) (Fig. 1). A retroarc foreland basin filled with shallow marine to continental sediments of mid- to Late Cretaceous age (Takena and Shexing formations) is developed in the Linzhou basin near Lhasa (Leier et al., 2007a).

South of the Indus-Yarlung suture zone, the lithotectonic units now present on the Indian plate are Tethyan, Higher and Lesser Himalaya (Fig. 1a). The South Tibetan Detachment System separates the Tethyan Himalaya from the Higher Himalaya to the south. The latter is composed of Proterozoic–Cambrian rocks that experienced high-grade metamorphism (Parrish and Hodges, 1996). The Main Central Thrust separates the Higher Himalaya from the Lesser Himalaya to the south, which consists of low-grade metamorphic crustal rocks of the Indian continent that are mainly Precambrian in age (e.g., Hodges, 2000). The sub-Himalaya, containing the Himalayan foreland basin sedimentary rocks (DeCelles et al., 2004; Najman et al., 2005), lies to the south of the Lesser Himalaya, with the Main Boundary Thrust separating the two terranes.

The Tethyan Himalaya in southern Tibet is generally subdivided into southern and northern zones along the Gyirong-Kangmar thrust (Ratschbacher et al., 1994). The southern zone (Tingri-Gamba areas) is characterized by the presence of shallow-water (shelf) calcareous and terrigenous sedimentary rocks of Paleozoic to Eocene age deposited on the Indian passive margin basin (Willems et al., 1996; Garzanti, 1999). These rocks were overlain by Eocene Enba and Zhaguo siliciclastic rocks that have been interpreted as

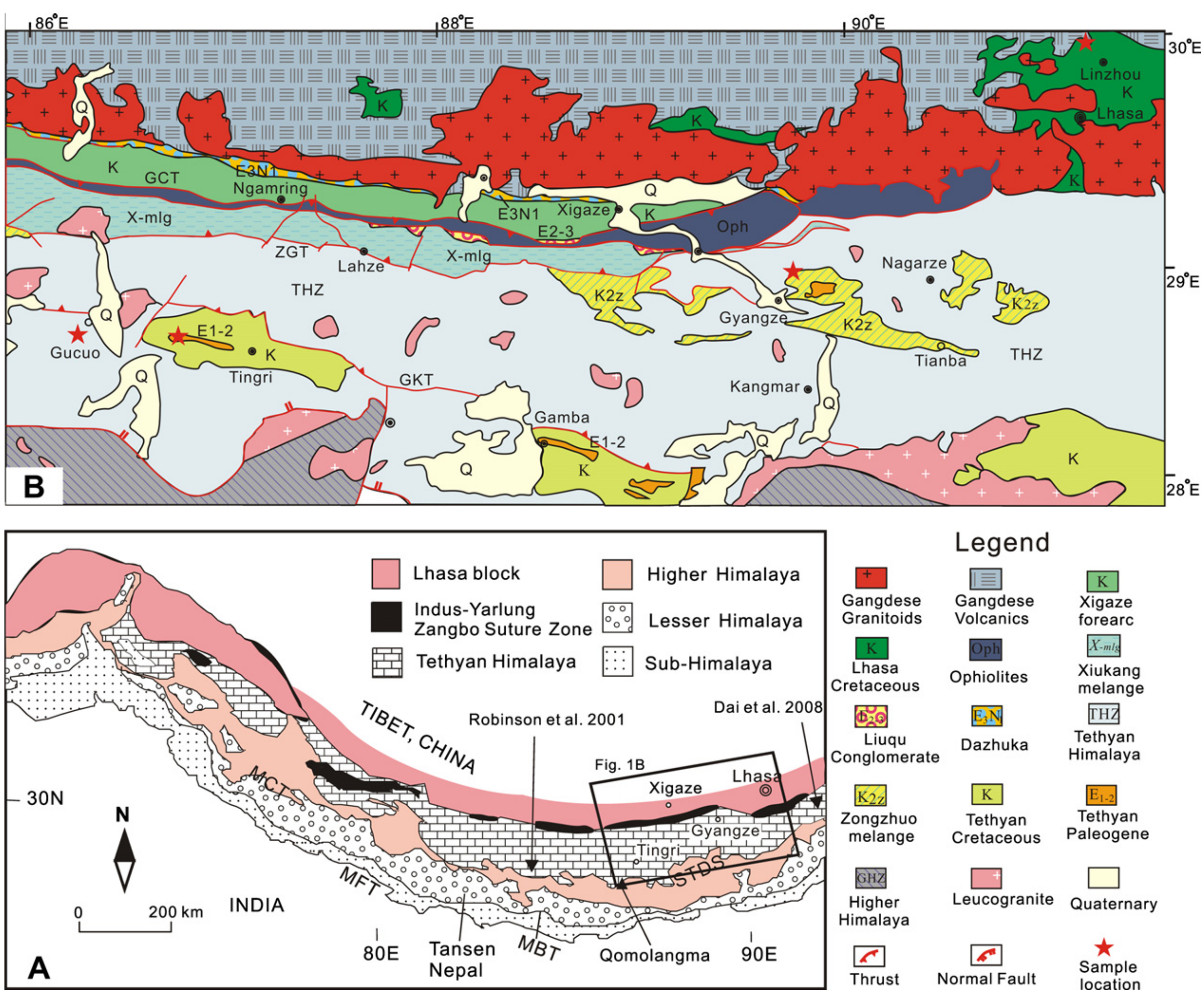

Fig. 1. (A) Geologic sketch map of the Himalayas, modified from Gansser (1964). Locations where Mesozoic Sm–Nd data are available are indicated; (B) simplified geologic map of southern Tibet revised from Pan et al. (2004), showing the sample locations as stars. GCT – Great Counter Thrust; ZGT – Zhongba-Gyangze Thrust; GKT – Gyirong-Kangmar Thrust; STDS – South Tibet Detachment System; MCT – Main Central Thrust.

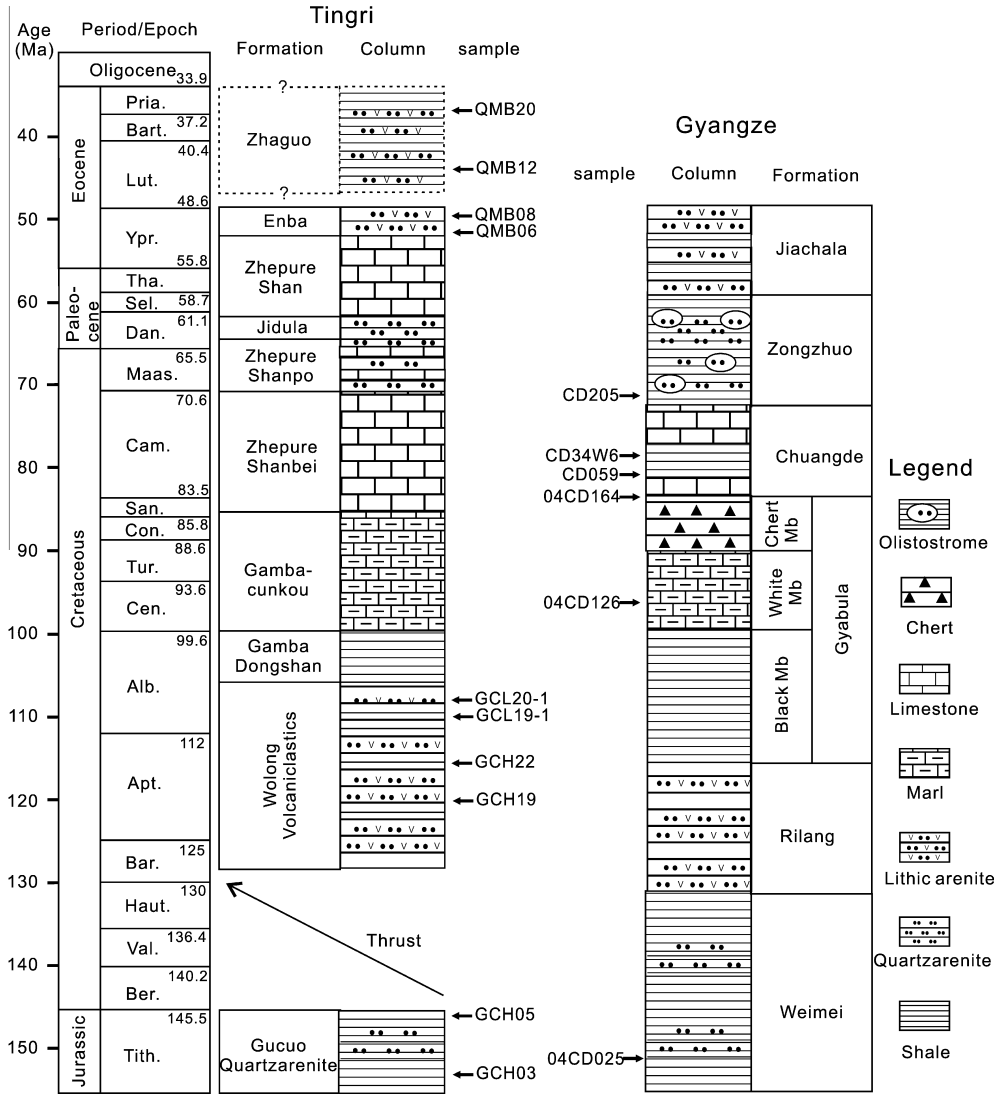

Fig. 2. Composite stratigraphic log of the Upper Jurassic–Paleogene strata in the Tingri and Gyangze areas, showing Nd isotopic sample locations. The stratigraphy in the Tingri area is from Wang et al. (2002), Zhu et al. (2005), and Hu et al. (2010). The stratigraphy in the Gyangze area is from Li et al. (2005) and Hu et al. (2008).

syncollisional deposits (Wang et al., 2002; Zhu et al., 2005; Najman et al., 2010) (Fig. 2). The northern zone (Gyangze-Saga areas) is mainly dominated by Mesozoic to Paleogene deep-water sedimentary deposits of the outer shelf, continental slope, and rise (Hu et al., 2008).

During the Jurassic–Early Cretaceous, the northern margin of Greater India was situated at high-to-mediate latitudes in the southern hemisphere (Gradstein et al., 1991; Patzelt et al., 1996), while the Lhasa block was at a low latitude in northern hemisphere (Achache et al., 1984). The Neo-Tethyan ocean separated Greater India from the Lhasa block, which should have been at least thousands of kilometers in width at that time (see review by Ali and Aitchison (2008)). Greater India rifted from the Australian-Antarctic Continent in the Early Cretaceous (see Zhu et al., 2009a) and started to drift northward in the late Early Cretaceous (see Hu et al., 2010); it then collided with the Lhasa block (Asian plate) in the latest Cretaceous–Paleogene.

3. Samples and methods

Samples for Sm–Nd isotopic analysis were selected from fine siliciclastic rocks from three sections in the Tethyan Himalaya, including the following: (1) the Qumiba section, Tingri (GPS N28°41′9.6″, E86°43′52.4″), following the biostratigraphy of Wang et al. (2002) and Zhu et al. (2005) (Fig. 2); (2) the Gucuo section, Tingri (GPS N28°46′56″, E86°19′13″), following the stratigraphy of Hu et al. (2008, 2010) (Fig. 2); and (3) the Chuangde section (GPS N28°57′56″, E89°44′20″), following the stratigraphy of Li et al. (2005) and Hu et al. (2008) (Fig. 2). For comparison, samples from the Upper Cretaceous Shexing Formation in the Dianzhong section, Linzhou, Lhasa block (Leier et al., 2007b), were analyzed. The biostratigraphic studies in these sections allow to assume the approximate absolute ages for these samples. The strata in the Tethyan Himalaya examined in this study were derived from the northern Indian margin as supported by the available provenance data, including detrital zircon U–Pb ages in the Gucuo area by Hu et al. (2010), in the Gyangze area by Cai et al. (2011), and in the Tingri area by Zhu et al. (2005) and Najman et al. (2010).

Approximately 100 mg of powder from each sample was dissolved in a mixture of HF and HNO_3 in Teflon beakers. Sm and Nd were then separated and purified by conventional cation-exchange techniques. The isotopic measurements of the purified Sm and Nd solutions were performed on a Finnigan Triton TI thermal ionization mass spectrometer (TIMS) at the State Key Laboratory of Mineral Deposits Research, Nanjing University. The mass

Table 1
Analyzed Nd isotopic data of Mesozoic siliciclastic rocks from southern Tibet.

Section	Sample	Formation	Rock type	T (Ma)	Sm (ppm)	Nd (ppm)	$\frac{^{147}Sm}{^{144}Nd}$	$\frac{^{143}Nd}{^{144}Nd}$	±2σ	$\varepsilon_{Nd}(0)$	$\varepsilon_{Nd}(T)$	T_{DM}(Ga)
Qumiba, Tingri	QMB12	Zhaguo	Shale	40	6.7	32.4	0.125	0.512298	3	−6.6	−6.3	1.3
	QMB20	Zhaguo	Shale	40	6.6	29.4	0.136	0.512269	7	−7.2	−6.9	1.5
	QMB06	Enba	Shale	50	7.0	34.5	0.123	0.512256	10	−7.5	−7.0	1.3
	QMB08	Enba	Shale	50	6.9	33.1	0.126	0.512308	5	−6.4	−6.0	1.3
Gucuo, Tingri	GCL19-1	Wolong Volcaniclastics	Shale	110	15.0	94.3	0.096	0.512374	7	−5.1	−3.7	0.9
	GCL20-1	Wolong Volcaniclastics	Shale	110	15.5	82.8	0.113	0.512272	7	−7.1	−6.0	1.2
	GCH19	Wolong Volcaniclastics	Shale	120	8.2	36.0	0.138	0.512306	17	−6.5	−5.6	1.5
	GCH22	Wolong Volcaniclastics	Shale	120	9.9	43.8	0.137	0.512256	2	−7.5	−6.5	1.6
	GCH03	Cucuo Quartzarenite	Shale	150	10.5	59.4	0.107	0.511713	5	−18.0	−16.3	1.9
	GCH05	Cucuo Quartzarenite	Shale	150	11.4	62.6	0.111	0.511900	8	−14.4	−12.8	1.7
Chuangde, Gyangze	CD205	Zongzhuo	Shale	75	3.9	21.2	0.111	0.512355	7	−5.5	−4.7	1.0
	CD34W6	Chuangde	Shale	80	22.6	111.1	0.123	0.512283	13	−6.9	−6.2	1.3
	CD059	Chuangde	Shale	80	24.9	123.3	0.122	0.512182	4	−8.9	−8.1	1.4
	04CD164	Gyabula	Shale	85	7.4	37.4	0.119	0.512232	8	−7.9	−7.1	1.3
	04CD126	Gyabula	Shale	95	9.4	48.9	0.116	0.512239	16	−7.8	−6.8	1.2
	04CD025	Weimei	Shale	150	8.1	44.1	0.111	0.511927	7	−13.9	−12.2	1.7
Dianzhong, Linzhou	DZ-01	Shexing	Siltstone	85	5.2	23.8	0.132	0.512319	3	−6.2	−5.5	1.4
	DZ-11	Shexing	Shale	85	6.9	35.7	0.117	0.512182	5	−8.9	−8.0	1.4
	DZ-07	Shexing	Andesite	85	5.8	35.7	0.097	0.512539	4	−1.9	−0.9	0.7

fractionation correction for the Nd isotopic ratios was $^{146}Nd/^{144}Nd = 0.7219$. The blanks for Sm and Nd were 5×10^{-11} g. Depleted mantle model ages were calculated based on the model of DePaolo (1981). The results of the Sm–Nd isotopic analysis of the bulk rocks are summarized in Table 1.

4. Results

In general, the Mesozoic samples from the Tethyan Himalaya can be divided into two groups in terms of Nd isotopic compositions: the Pre-Cretaceous group and the Cretaceous group. The samples from the Cretaceous group have much less negative $\varepsilon_{Nd}(0)$ values and younger Nd model ages than those of the Pre-Cretaceous group.

Three samples of the Pre-Cretaceous group in the Tethyan Himalaya have $\varepsilon_{Nd}(0)$ values of −18.0 to −13.9, with an average of −15.4 (Table 1). These values are comparable with previous published $\varepsilon_{Nd}(0)$ values of −16.7 to −18.0 (five samples) from Mesozoic strata in the Lhakang area, southeastern Tibet (Dai et al., 2008) (Fig. 1a), and with $\varepsilon_{Nd}(0)$ values of −18.8 to −16.2 (two samples) from Mesozoic strata in Nepal (Robinson et al., 2001) (Fig. 1a). The values are also comparable to those of Paleozoic samples in the Tethyan Himalaya, with $\varepsilon_{Nd}(0)$ values of −20.1 to −11.7 (23 samples) (Ahmad et al., 2000; Robinson et al., 2001; Miller et al., 2001; Richards et al., 2005) (Fig. 3).

Nine samples of Cretaceous strata in the Tethyan Himalaya have $\varepsilon_{Nd}(0)$ values of −8.9 to −5.1, with an average of −7.0 (Table 1). Robinson et al. (2001) reported one sample from Lower Cretaceous rocks in Nepal with an $\varepsilon_{Nd}(0)$ value of −6.2. Dai et al. (2008) also reported one sample from Mesozoic rocks in SE Tibet with an $\varepsilon_{Nd}(0)$ value of −8.0. Those two samples are comparable with the values obtained from the Cretaceous samples in this study (Fig. 3).

Two samples from the Enba Formation have $\varepsilon_{Nd}(0)$ values of −7.5 and −6.4 (Table 1). The Nd isotopic compositions of two samples from the Zhaguo Formation are very similar to those from the Enba Formation, with $\varepsilon_{Nd}(0)$ values of −7.2 and −6.6 (Table 1).

Two samples of siliciclastic rocks from the Sexing Formation in the Lhasa block yield $\varepsilon_{Nd}(0)$ values of −8.9 and −6.2 (Table 1). These values are similar to those of Lower Cretaceous siliciclastic samples from Cuoqin, central Lhasa, reported by Zhang et al. (2007), which have $\varepsilon_{Nd}(0)$ values of −10.9 to −6.4. One andesitic sample from the upper part of the Shexing Formation yielded an $\varepsilon_{Nd}(0)$ value of −1.9 (Table 1), which is slightly less than those of the coeval Gangdese batholith, with $\varepsilon_{Nd}(0)$ values of 0 to +2.1 (Wen et al., 2008).

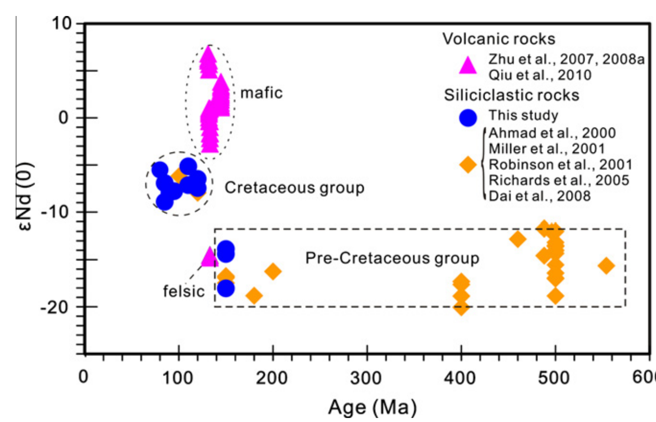

Fig. 3. Variation of $\varepsilon_{Nd}(0)$ values with sediment ages for samples from the Tethyan Himalaya. Data for the siliciclastic rocks are from Ahmad et al. (2000), Robinson et al. (2001), Miller et al. (2001), Richards et al. (2005), Dai et al. (2008), and from this study. Data for the Cretaceous volcanic rocks in the Tethyan Himalaya are from Zhu et al. (2007, 2008a) and Qiu et al. (2010).

5. Discussion

5.1. A significant shift of $\varepsilon_{Nd}(0)$ values of the Mesozoic strata in the Tethyan Himalaya

In the Tethyan Himalaya, less negative Nd isotopic values were found in the Early Cretaceous Wölong Volcaniclastics and the Rilang Formation (Fig. 3). The $\varepsilon_{Nd}(0)$ values varied from an average of approximately −15.4 in the Jurassic strata to an average of approximately −7.0 in the Cretaceous strata. The less negative $\varepsilon_{Nd}(0)$ values of the Cretaceous siliciclastic rocks reveal the input of a juvenile mantle-derived component in the source area.

What was the source of the juvenile mantle-derived material in northern Greater India? An Early Cretaceous volcanic event has been documented in northern Greater India from widely distributed volcaniclastic rocks in southern Tibet, including the Wölong Volcaniclastics in Tingri (Jadoul et al., 1998; Hu et al., 2010), the

Rilang Formation in Gyangze (Hu et al., 2008), and the Tianba Flysch near Kangmar (Zhu et al., 2004). Similar Lower Cretaceous volcaniclastic rocks have been documented widely in the western Himalaya, including Zanskar and Kumaon in India (Garzanti, 1991) and the Thakkhola Graben in northern Nepal (e.g., Garzanti, 1999). Early Cretaceous (~132 Ma) igneous rocks are present in the eastern Himalaya, where they are interbedded with or intrude deep-water Tethyan Himalayan sedimentary strata (e.g., Zhu et al., 2007, 2008a, 2009a; Qiu et al., 2010). The $\varepsilon_{Nd}(0)$ values of those Early Cretaceous mafic rocks (basalts and diabase) are –2.8 to +6.8 ($n = 34$), and they were interpreted as an Oceanic-Island-Basalt-type mantle source (Fig. 3, Zhu et al., 2007, 2008a; Qiu et al., 2010), while the felsic dacites have more negative $\varepsilon_{Nd}(0)$ values of approximately −14.6 ($n = 3$) (Fig. 3, Zhu et al., 2007).

The significant shift of $\varepsilon_{Nd}(0)$ values between the Jurassic and the Cretaceous siliciclastic rocks is coeval with the occurrence of Early Cretaceous magmatic activity in the Tethyan Himalaya. Such a temporal and spatial connection enables the enhanced $\varepsilon_{Nd}(t)$ values recorded by the Cretaceous siliciclastic rocks in the Tethyan Himalaya to be attributed to the presence of Early Cretaceous magmatic activity being widely developed in northern Greater India.

5.2. Implication for provenance interpretation for Eocene Nepalese foreland sediments

The Eocene foreland sediments (Bhainskati Formation) in the Tansen area of Nepal (Fig. 1a) are mainly composed of quartzarenites and black shales that are considered to be of orogenic provenance (DeCelles et al., 2004; Najman et al., 2005). Based on detrital zircons, Nd isotopic composition, and the presence of Cr-spinel, DeCelles et al. (2004) suggested that there are three sources of the Bhainskati Formation, including the Tethyan sedimentary rocks, the Cretaceous igneous rocks in the Indus-Yarlung suture zone, and the forearc. Evidence for the source of the Cretaceous igneous rocks in the Indus-Yarlung suture zone comes from a few Early Cretaceous detrital zircons found in the Bhainskati Formation. Considering the presence of an Early Cretaceous volcanic event in northern India and abundant Early Cretaceous detrital zircons (approximately 140 to 120 Ma) in the Wölong Volcaniclastics (e.g., Hu et al., 2010), which are different from those from the Xigaze forearc and the Lhasa block (Leier et al., 2007b; Wen et al., 2008; Wu et al., 2010), the Early Cretaceous detrital zircons are probably sourced from Cretaceous sediments in the Tethyan Himalaya instead of the Indus-Yarlung suture zone. Due to the presence of Cr-spinels, the Bhainskati Formation was also regarded as a diagnostic signal from the Indus-Yarlung suture zone. However, abundant detrital Cr-spinels have been found in the Mesozoic sediments in the Tethyan Himalaya (e.g., Zhu et al., 2004; Hu et al., 2010; Wang et al., 2011). The Xigaze forearc and the Lhasa block cannot be the source for the Bhainskati Formation because both the Xigaze forearc and the Lhasa block contained abundant Mesozoic zircons (Leier et al., 2007b; Wen et al., 2008; Wu et al., 2010), which were not observed in the Bhainskati Formation.

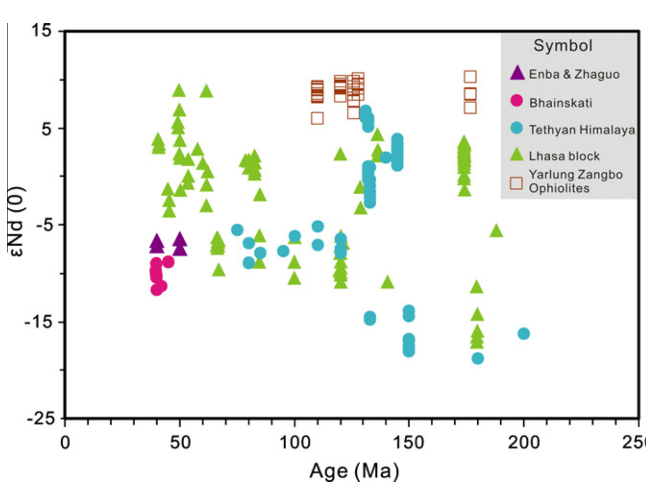

Fig. 4. Diagram of $\varepsilon_{Nd}(0)$ values vs. sediment ages for the samples from the Tethyan Himalaya, the Lhasa block, and the Himalayan foreland basin in Tingri (this study) and in Nepal (Robinson et al., 2001; DeCelles et al., 2004). Data for the Tethyan Himalaya are as in Fig. 3.

The Bhainskati Formation has $\varepsilon_{Nd}(0)$ values of –11.5 to –8.6 (Robinson et al., 2001; DeCelles et al., 2004) (Fig. 4). These Nd isotopic compositions are comparable with the Cretaceous sediments in the Tethyan Himalaya, with $\varepsilon_{Nd}(0)$ values of –8.9 to –5.1. Therefore, we suggest that the sediments of the Bhainskati Formation were most probably sourced from the Tethyan Himalaya sediments.

5.3. Testing Nd isotopes as a provenance tool for constraining the India–Asia collision

5.3.1. Nd isotopic compositions in the Tethyan Himalayan and the Lhasa block

To determine the origin of detrital material eroded from the Himalayan orogens, a thorough characterization of potential sources, including the Tethyan Himalaya, the Indus-Yarlung suture zone and Lhasa block, is needed in terms of Nd isotopic composition.

The Indus-Yarlung suture zone ophiolites ($n = 40$, Appendix; Mahoney et al., 1998; Zhou et al., 2002; Xu and Castillo, 2004; Niu et al., 2006; Xu et al., 2008) have much more positive $\varepsilon_{Nd}(0)$ values of +6 to +10 (Fig. 5).

In general, the 81 samples of sedimentary and igneous rocks from the Tethyan Himalaya (Appendix, Ahmad et al., 2000; Miller et al., 2001; Robinson et al., 2001; Richards et al., 2005; Zhu et al., 2007, 2008a; Dai et al., 2008; Qiu et al., 2010) can be divided into three groups according to their $\varepsilon_{Nd}(0)$ values (Fig. 5): (1) the Pre-Cretaceous sediments and felsic volcanic rocks have $\varepsilon_{Nd}(0)$ values of approximately −20 to −11 ($n = 36$), very similar to those of the Higher Himalaya (Robinson et al., 2001; Martin et al., 2005; Richards et al., 2005); (2) the Cretaceous sediments ($n = 11$) have $\varepsilon_{Nd}(0)$ values of −8.9 to −5.2; and (3) the Cretaceous mafic volcanic rocks ($n = 34$) have more positive $\varepsilon_{Nd}(0)$ values ranging from −3 to +6.

Collectively, the 103 sedimentary and igneous rocks of Mesozoic to Paleogene age (250–40 Ma) from the Lhasa block (Appendix, Allegre and Othman, 1980; Debon et al., 1986; Harris et al., 1988; Jiang et al., 1999; Chu et al., 2006; Mo et al., 2007; Zhang et al., 2007; Dong et al., 2008; Wen et al., 2008; Zhu et al., 2008b, 2009b; Yu et al., 2010) showed a wide range of $\varepsilon_{Nd}(0)$ values, from −17.1 to +8.8 (Fig. 5). The $\varepsilon_{Nd}(0)$ values of the igneous and siliciclastic rocks from the Lhasa block range from −11.1 to +8.8 and −17.1 to −6.2, respectively, values that are similar to those of the Tethyan Himalaya (Fig. 5). It follows that the Nd isotopic composition cannot be considered as an effective provenance tool to constrain source variations from one plate to another.

In a diagram of $^{147}Sm/^{144}Nd$ vs. ε_{Nd} values, the Sm–Nd isotopic data of whole rocks from both the Lhasa block and the Tethyan Himalaya largely overlap (Fig. 6). These data did not plot in the Eurasian vs. Indian provenance fields, respectively, as defined by detrital apatites from modern sands by Henderson et al. (2010).

5.3.2. Nd isotopic compositions from the Himalayan foreland basin

In principle, if Nd isotopic data can be used to distinguish provenance material from the Indian or Asian side, Himalayan foreland sediments with known provenances would be expected to show different isotopic patterns.

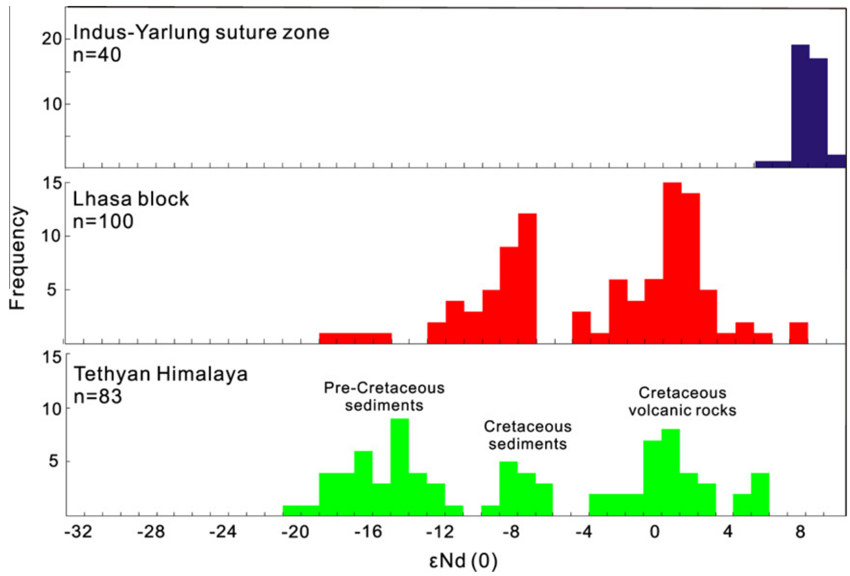

Fig. 5. Histogram showing the range of $\varepsilon_{Nd}(0)$ values for the Tethyan Himalaya, the Lhasa block, and the Indus-Yarlung suture zone ophiolites. Data for the Lhasa block are from Allegre and Othman (1980), Debon et al. (1986), Harris et al. (1988), Jiang et al. (1999), Chu et al. (2006), Mo et al. (2007, Zhang et al. (2007), Dong et al. (2008), Wen et al. (2008), Zhu et al. (2008b, 2009a,b), and Yu et al. (2010). Data for the Indus-Yarlung suture zone are from Mahoney et al. (1998), Zhou et al. (2002), Xu and Castillo (2004), Niu et al. (2006), and Xu et al. (2008). Data for the Tethyan Himalaya are as in Fig. 3.

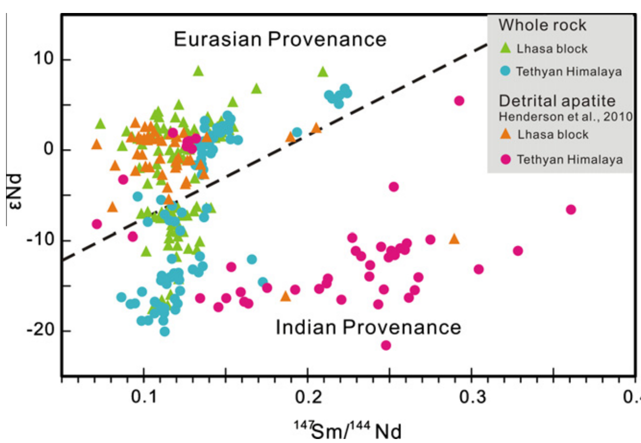

Fig. 6. Sm–Nd isotopic results of whole rocks and detrital apatites (modern sands) from the Lhasa block and the Tethyan Himalaya. Indian vs. Eurasian provenance fields of Henderson et al. (2010) are shown for comparison. Whole rock data are as in Fig. 3 for the Tethyan Himalaya and in Fig. 4 for the Lhasa block. The detrital apatite data are from Henderson et al. (2010).

The Early Eocene Enba and Zhaguo formations have materials derived mainly from the Lhasa block according to previous provenance data ($\varepsilon_{Nd}(0) = -7.5$ to -6.4; Zhu et al., 2005; Najman et al., 2010; unpublished data) (Fig. 4). The Eocene Bhainskati Formation in Nepal, which has a source from the Tethyan Himalaya (Section 5.2), has $\varepsilon_{Nd}(0)$ values of −11.6 to −8.5 (DeCelles et al., 2004), which are slightly more negative than those of the Enba and Zhaguo formations (Fig. 4).

Therefore, we conclude that it is difficult to distinguish the source of the Lhasa block or the Tethyan Himalayan sediments in terms of Nd isotopic composition, especially when the Cretaceous sediments of the Tethyan Himalaya were exposed at the surface during the early stages of the India–Asia collision.

6. Conclusion

I began this study with one question: are there differences in the Nd isotopic signatures of the Tethyan Himalaya and the Lhasa block that will constrain the timing of the India–Asia collision? To answer this question, samples from the Mesozoic–Paleogene siliciclastic sediments in southern Tibet were analyzed, which led to the following conclusions.

(1) Values of $\varepsilon_{Nd}(0)$ showed a shift toward less negative values from −18.0 to −13.9 in the Jurassic to −8.9 to −5.1 in the Cretaceous. The enhanced $\varepsilon_{Nd}(0)$ values of Cretaceous siliciclastic rocks reveal significant input of a juvenile mantle-derived component in the source area, which I attribute to the presence of the detritus from Early Cretaceous volcanic rocks in the northern Greater India margin recorded in the coeval volcaniclastic rocks of the Wölong Volcaniclastics and equivalent strata.
(2) This study, combined with published data, indicates that the range of $\varepsilon_{Nd}(0)$ values in the Tethyan Himalaya is very similar to those of the Lhasa block. Thus, Nd isotopes cannot be used as a powerful provenance tool to constrain changes in sediment source from one plate to another.
(3) According to the Nd isotopic compositions, sediments of the Eocene Bhainskati Formation in the Nepalese foreland basin were most probably sourced only from the Tethyan Himalaya sediments. The similar Nd isotopic composition of the Bhainskati Formation to those of the Enba and Zhaguo formations, which were sourced mainly from the Asian side, is further evidence that it is difficult to distinguish the source either from the Tethyan Himalaya or from the Lhasa block based on Nd isotopic compositions.

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Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jseaes.2011.09.023.

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