

Provenance and drainage system of the Early Cretaceous volcanic detritus in the Himalaya as constrained by detrital zircon geochronology

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Abstract The age range of the major intra-plate volcanic event that affected the northern Indian margin in the Early Cretaceous is here defined precisely by detrital zircon geochronology. U–Pb ages of Early Cretaceous detrital zircons found in the Cretaceous to the Paleocene sandstones cluster mainly between 142 Ma and 123 Ma in the northern Tethys Himalayan unit, and between 140 Ma and 116 Ma in the southern Tethys Himalayan unit. The youngest and oldest detrital zircons within this group indicate that volcanism in the source areas started in the latest Jurassic and ended by the early Albian. Stratigraphic data indicate that volcanoclastic sedimentation began significantly earlier in southern Tibet (Tithonian) than in Nepal (Valanginian), and considerably later in Spiti and Zaskar (Aptian/Albian) to the west. This apparent westward migration of magmatism was explained with progressive westward propagation of extensional/transensional tectonic activity and development of fractures cutting deeply across the Indian continental margin crust. However, detrital zircon geochronology provides no indication of heterochrony in magmatic activity in the source areas from east to west, and thus lends little support to such a scenario. Westward migration of volcanoclastic sedimentation may thus reflect instead the westward progradation of major drainage systems supplying volcanic detritus sourced from the same volcanic centers in the east. Development of multiple radial drainage away from the domal surface uplift associated with magmatic upwelling, as observed for most large igneous provinces around the world, may also explain why U–Pb ages of detrital zircons tend to cluster around 133–132 Ma (the age of the Comei igneous province) in Tethys Himalayan units, but around 118–117 Ma (the age of the Rajmahal igneous province) in Lesser Himalayan units.

Key words northern Indian margin, Cretaceous Himalayan Orogen, volcanoclastic detritus, drainage system, zircon geochronology, palaeogeography

1 Introduction

In the Early Cretaceous, a major intra-plate volcanic

event affected the entire northern India passive margin facing Neotethys, as long documented by studies of volcanic and volcanoclastic rocks exposed in various regions of the Himalayan orogeny (Figure 1). Lower Cretaceous volcanoclastic sandstones have been deposited all along the Tethys Himalayan domain, from the Zaskar Range

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(Baud *et al.*, 1984; Garzanti, 1991, 1993a) to Spiti, Nepal (Bordet *et al.*, 1971; Garzanti and Pagni Frette, 1991; Gibling *et al.*, 1994; Garzanti, 1999) and southern Tibet (Jadoul *et al.*, 1998; Hu *et al.*, 2008, 2010; Figure 2). Geochemical analyses of basaltic grains and detrital Cr-spinels from these sandstones point to the alkaline character of the volcanism, consistent with a “within-plate” tectonic setting (Dürr and Gibling, 1994; Zhu *et al.*, 2004; Hu *et al.*, 2010, 2014). Lower Cretaceous volcanic rocks have never been reported so far in the western Himalaya, but are well known to occur in the Lesser Himalaya of Nepal (Aulis

Trachyte; Sakai, 1983; Sakai *et al.*, 1992) and in the Tethys Himalaya of southeastern Tibet (Sangxiu Formation; Zhu *et al.*, 2009; Qiu *et al.*, 2010; Xia *et al.*, 2014). Mafic protoliths of late Early Cretaceous age have been recognized even in Lesser Himalayan eclogites of Nepal (Groppo *et al.*, 2007). All of these volcanic rocks are generally considered as belonging to the Rajmahal-Sylhet flood-basalt igneous province of the northeastern Indian subcontinent (Baksi, 1995; Kent *et al.*, 2002) and/or to the Comei large igneous province (Zhu *et al.*, 2009).

This article provides new U–Pb ages of zircon grains

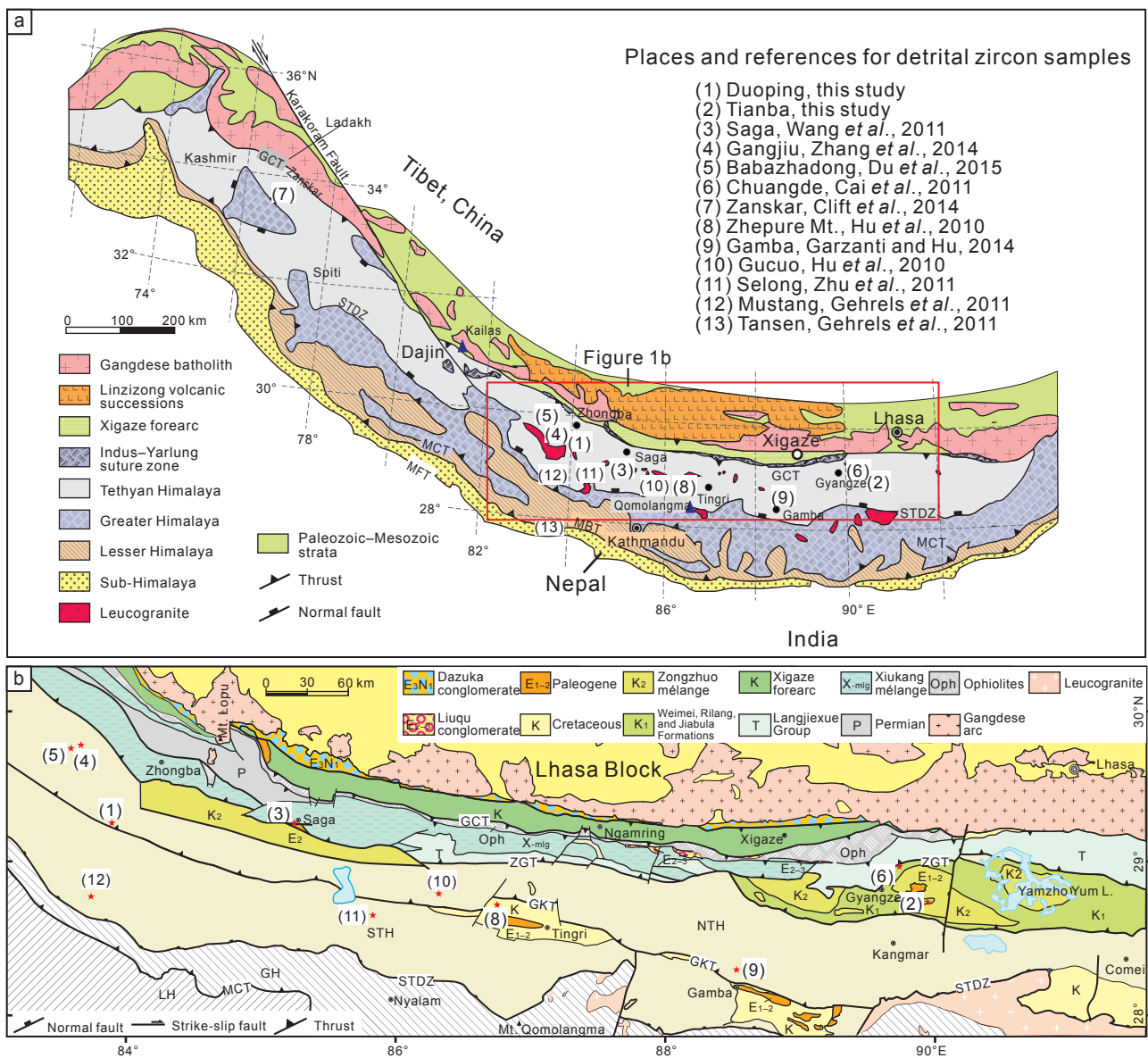


Figure 1 a—Geological map of the Himalayan belt; b—Simplified geological map of the southeastern Tibet. Locations of sandstone samples considered for detrital-zircon geochronology are shown. GCT = Great Counter Thrust; ZGT = Zhongba–Gyangze Thrust; GKT = Gyirong–Kangmar Thrust; STDZ = South Tibetan Detachment Zone; MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust; NTH = Northern Tethyan Himalaya; STH = Southern Tethyan Himalaya; GH = Greater Himalaya; LH = Lesser Himalaya.

from Lower Cretaceous volcanoclastic sandstones of the northern Tethyan Himalaya in southern Tibet, and a compilation of the available geochronological and isotopic data on detrital zircons from Cretaceous–Paleocene sandstones of the northern Indian margin, including the Lesser and Tethys Himalaya. Based on the abundant and precise radiometric ages available for detrital zircons ultimately produced during the Early Cretaceous magmatic event, the age range of volcanic activity can be accurately constrained. We also discuss the palaeogeographic significance of the Early Cretaceous volcanism, and the differences observed in the age distribution of detrital zircons in different regions and tectonic domains of the Himalayan belt. The standardized time scale and web of correlation between relative biostratigraphic and absolute radiometric ages is after Ogg *et al.* (2012).

2 Geological setting

During the Jurassic, the northern passive margin of India was situated at intermediate latitudes in the southern hemisphere, separated from Asia in the north by a several thousand km-wide Neotethys Ocean (Klootwijk, 1984; Patzelt *et al.*, 1996; van Hinsbergen *et al.*, 2011). In the Cretaceous, India rifted away from the rest of Gondwana (Norton and Sclater, 1979; Zhu *et al.*, 2009), and drifted rapidly northwards until it collided with the Lhasa Block in the Paleogene to form the Himalayan Orogen (Guillot *et*

al., 2003; Najman *et al.*, 2010; Hu *et al.*, 2012).

The Himalayan belt, south of the Indus-Yarlung suture zone, is traditionally subdivided into the Tethyan, Greater and Lesser Himalayan domains (Figure 1; Gansser, 1964). In southern Tibet, the Tethyan Himalaya is divided into a northern zone and a southern zone, separated by the Gyirong–Kangmar Thrust (Ratschbacher *et al.*, 1994). The northern zone (Gyangze–Saga areas) represents the continental slope and rise, chiefly consisting of deep-water sediments of the Mesozoic (Hu *et al.*, 2008). The southern zone (Tingri–Gamba areas) represents a more proximal part of the Indian passive margin, mostly characterized by shelfal carbonates and terrigenous sedimentary rocks of the Paleozoic to the Paleogene (Willems *et al.*, 1996; Hu *et al.*, 2012; Sciunnach and Garzanti, 2012).

The Greater Himalaya, south of the southern Tibetan Detachment Zone, largely consists of Proterozoic meta-sedimentary protoliths intruded by crustal melts during the Cambrian to the Ordovician (DeCelles *et al.*, 2000). Deformed at medium- to high-grade metamorphism as a consequence of collision, these rocks were thrust onto the Lesser Himalaya along the Main Central Thrust in the earliest Miocene (Hodges, 2000; Yin, 2006). The Lesser Himalaya includes a high-grade metamorphic basement and a 8–10 km-thick low-grade metasedimentary succession of the Upper Paleoproterozoic to the upper Lower Cambrian, dominated by siliciclastic protoliths in the lower part and containing carbonates in the upper part; the Upper Paleo-

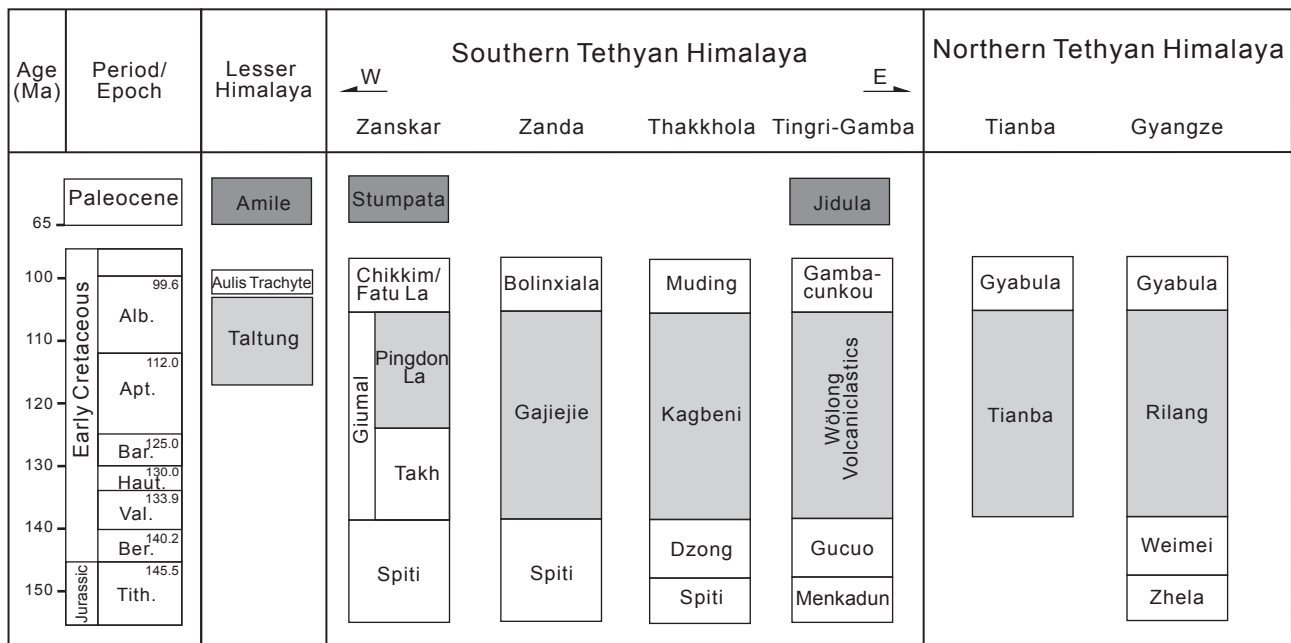


Figure 2 Stratigraphic correlation of the latest Jurassic to the Early Cretaceous in Himalayas. See references in the text. Tith. = Tithonian; Ber. = Berriasian; Val. = Valanginian; Haut. = Hauterivian; Bar. = Barremian; Apt. = Aptian; Alb. = Albanian.

zoic to Cenozoic strata unconformably follow (DeCelles *et al.*, 2001; Myrow *et al.*, 2003; McKenzie *et al.*, 2011).

2.1 U–Pb detrital zircon ages of different Himalayan domains

The Cambrian to Jurassic sandstones in both Tethyan Himalayan and Lesser Himalayan domains contain detrital zircons with U–Pb ages clustering at about 570–480 Ma, 1200–750 Ma, and 2560–2430 Ma (Gehrels *et al.*, 2011). The Cretaceous and lower Paleocene sandstones show a prominent additional cluster of Early Cretaceous (Figures 3, 4; Hu *et al.*, 2010; Clift *et al.*, 2014). Greater Himalayan paragneisses yielded detrital zircons with ages of 1200–800 Ma, 1900–1600 Ma, and 2700–2400 Ma, with a small Neoproterozoic cluster at 750–540 Ma (Gehrels *et al.*, 2011). The lower Lesser Himalayan units contain zircon grains older than 1.4 Ga, inferred to have been largely derived from a Paleoproterozoic arc (Kohn *et al.*, 2010). U–Pb ages group mostly between 2.0 Ga and 1.7 Ga, and subordinately between 2.8 Ga and 2.4 Ga (Gehrels *et al.*, 2011).

2.2 Lower Cretaceous lavas and volcanics in the Lesser Himalaya

The Taltung Formation of the Tansen area (Nepal), dated at the Early Cretaceous by plant fossils, rests unconformably over the Upper Carboniferous–Permian glacial and fluvial sediments of the Sisne Formation (Sakai, 1989). The unit, 250 m-thick, comprises gravelly to sandy braided-river deposits overlain by sandy to silty meandering-river deposits. The <20 m-thick basal conglomerate with scoured disconformable base contains basalt and quartzite pebbles exclusively (Charchare Conglomerate). Intercalated in the lower part of the Taltung Formation is the Aulis Trachyte, a 30 m- to 200 m-thick volcanic unit mainly consisting of trachytic lavas with sparse anorthoclase and sanidine (Sakai, 1989; Sakai *et al.*, 1992). A Rb–Sr biotite-feldspar age of 96.7 ± 2.8 Ma was obtained from a gravel of phonotephrite by Sakai *et al.* (1992). The disconformably overlying Amile Formation includes mainly quartzose sandstones; siltstones and carbonates yielding corals and echinoids are intercalated in the middle part. In the lack of age control, an Early Paleocene age may be suggested by its stratigraphic position. Palaeocurrent analyses indicate that detritus was derived from the south and south-east throughout the Cretaceous–Paleocene (Sakai, 1983).

2.3 Lower Cretaceous lavas and volcanics in the Tethyan Himalaya

Lower Cretaceous volcanoclastic sediments deposited

in deltaic to shelfal environments are widely exposed in the southern Tethyan Himalaya, from southern Tibet (Wolong Volcaniclastics; Jadoul *et al.*, 1998; Hu *et al.*, 2010), to Nepal (Kagbeni and Dzung Formations; Garzanti, 1999 and references therein) and the Zaskar–Spiti Synclorium (Baud *et al.*, 1984; Garzanti, 1991, 1993a) (Figure 1). In the northern Tethyan Himalaya of southern Tibet, Lower Cretaceous volcanoclastic rocks were deposited in deep-water environments, and are exposed in the Gyangze, Saga, and Zhongba areas (Tianba Formation; Zhu *et al.*, 2004; and Rilang Formation; Hu *et al.*, 2008) (Figure 1).

The volcanic rocks of the Sangxiu Formation in southern Tibet range in thickness from several meters to 614 m and consist of alkali basalts, diabase, gabbroic diabase and more felsic volcanic rocks (dacite) interbedded with deep-water sediments (Wan *et al.*, 2011; Liu *et al.*, 2013). Basalt geochemistry indicates an intra-plate source with contributions from the subcontinental lithospheric mantle (Zhu *et al.*, 2007, 2009). SHRIMP U–Pb analyses of zircons yielded ages of 144.7 ± 2.4 Ma and 131.1 ± 6.1 Ma for diabase, and 133 ± 3.0 Ma for dacite (Zhu *et al.*, 2005, 2008).

3 Samples and methods

Three Lower Cretaceous sandstone samples from the northern Tethyan Himalaya in southern Tibet were selected for detrital-zircon U–Pb dating, *i.e.*, two samples (06TB11 and 06TB28) are from the Tianba section near Kangmar, and one (09DP07) from the Duoping section near Zhongba (Figures 1b, 5).

Sample 06TB11 from the lower Tianba Formation is a medium-grained litho-quartzose sandstone (Q:F:L = 76:2:22); lithic grains are largely metamorphic, with a few felsic volcanic and sedimentary types. Sample 06TB28 from the upper Tianba Formation is a medium-grained litho-quartzose sandstone (Q:F:L = 63:1:36); mafic and felsic volcanic lithos prevail over metamorphic and sedimentary types. Sample 09DP07 from the lower part of the Duoping section is also litho-quartzose (Q:F:L = 63:2:35) with dominantly sedimentary (mainly siltstone) and minor volcanic lithic grains.

Heavy minerals were separated from sandstone samples by elutriation and magnetic methods. Zircon grains were handpicked randomly, mounted in epoxy resin and polished for analyses. U–Pb dating of detrital zircons was carried out by laser ablation-inductively coupled plasma-mass spectrometry (LA–ICP–MS), following Jackson *et al.* (2004). Various beam diameters (18–35 μm) were

used depending on the size of zircon grains. We obtained a weighted $^{206}\text{Pb}/^{238}\text{U}$ age of 724.4 ± 8.0 Ma (2σ , $n = 29$) from Mud Tank Zircon, in agreement with the recommended value (TIMS age = 732 ± 5 Ma; Black and Gulson, 1978). GLITTER 4.4 was used for calculations of analytical results and relevant isotopic rates. Age calculations and plotting of concordia diagrams were performed by Isoplot 3.75 (Ludwig, 2012). Zircon ages older than 200 Ma with discordance less than 10% and ages less than 200 Ma with discordance less than 20% were used. Zircon-age statistics was carried out using the Age Pick program of the University of Arizona (<http://www.geo.arizona.edu/alt/Analysis%20Tools.htm>). Because $^{206}\text{Pb}/^{238}\text{U}$ ages are more precise for younger zircons, whereas $^{207}\text{Pb}/^{206}\text{Pb}$ ages are more precise for older zircons, we based our interpretations on $^{206}\text{Pb}/^{238}\text{U}$ ages for grains younger than 1000 Ma and on $^{207}\text{Pb}/^{206}\text{Pb}$ ages for grains older than 1000 Ma.

We have also compiled U–Pb literature data on detrital zircons contained in the Tethyan and Lesser Himalayan sandstones ranging in ages from Devonian to Paleocene (sample list provided in Table 1). Lesser Himalayan sandstones belong to the Carboniferous Sisne Formation, the Cretaceous Taltung Formation and Charchare Conglomerate, and the ?Lower Paleocene Amile Formation from the Tansen region of Nepal (DeCelles *et al.*, 2004; Gehrels *et al.*, 2011). Sandstones from the southern Tethyan Himalaya are mainly from the Nyalam–Tingri area of southern Tibet, and belong to Permian (Selong section; Zhu *et al.*, 2011), uppermost Jurassic–Lower Cretaceous (Gucuo section; Hu *et al.*, 2010), and Lower Paleocene units (Tingri and Gamba areas; Hu *et al.*, 2012; Garzanti and Hu, 2014). Samples belonging to Triassic–Lower Cretaceous units exposed in the Thakkhola area of Nepal are also included (Gehrels *et al.*, 2011). Samples from the northern Tethyan Himalaya belong to the Upper Jurassic to Cretaceous exposed in the Chuangde and Tianba sections near Gyangze, in the Sangdanlin section near Saga, and in the Zhongba area (Cai *et al.*, 2011; Wang *et al.*, 2011; Zhang *et al.*, 2014; Du *et al.*, 2015).

4 Zircon ages

Sample 06TB11 from the lower Tianba Formation yielded 70 acceptable ages with clusters at 537–483 Ma (10 grains), 646–564 Ma (6 grains), 1108–743 Ma (22 grains), 2424–2332 Ma (7 grains), 2725–2535 Ma (6 grains), and 3131–3072 Ma (3 grains). One zircon yielded a young age of 231 ± 5 Ma. Sample 06TB28 from the upper Tianba Formation yielded 69 acceptable ages with clusters

at 140–131 Ma (3 grains), 539–501 Ma (7 grains), 642–563 Ma (7 grains), 1155–770 Ma (35 grains), 2777–2547 Ma (7 grains), and 3436–3105 Ma (4 grains). Sample 09DP07 from the Duoping section yielded 56 acceptable ages with clusters at 142–123 Ma (12 grains), 592–471 Ma (17 grains), and 967–825 Ma (11 grains). Results are illustrated in Figure 6.

5 Early Cretaceous detrital zircons in Himalaya

Cretaceous–Paleocene sandstones all along the southern Tethyan Himalaya yielded zircon grains with U–Pb ages clustering between 140–116 Ma ($n = 88$); the two youngest grains from the Jidula Formation in Tingri and the Stumpata Formation in Zanskar are dated at 109 Ma (Figures 3, 4). Stumpata sandstones yielded two grains with Late Jurassic ages of 161 Ma and 147 Ma (Clift *et al.*, 2014). In the northern Tethyan Himalaya of southern Tibet, zircon ages cluster between 142 Ma and 123 Ma ($n = 35$; Figures 3, 4), with one younger grain at 117 Ma and two latest Jurassic grains at 148–147 Ma. These data suggest that the volcanic event began quite close to the Jurassic/Cretaceous boundary (possibly as early as 148–147 Ma) and ended in the early Albian by ~110 Ma. This time window coincides well with volcanoclastic sedimentation in southern Tibet, which is confined between the Tithonian and the Aptian (Jadoul *et al.*, 1998).

Moving westwards, however, sedimentation of coarser quartzo-lithic to quartzo-feldspatho-lithic volcanoclastic sandstones becomes progressively younger. In the Thakkhola Graben of Nepal, it is confined between the Valanginian and the Albian (Garzanti and Pagni Frette, 1991; Nagy *et al.*, 1995; Garzanti, 1999). The Spiti succession, yielding ammonoids of early Valanginian–late Berrisian in the lower part (*Giumaliceris* assemblage) and of late Aptian–early Albian in the upper part (*Cleoniceras* assemblage; Lukeneder *et al.*, 2013), contains commonly glaucony-rich quartzose to feldspatho-quartzose sandstones, with volcanic arenites confined to the upper part only (our own data). Finally, the succession of the Zanskar Range is characterized by feldspatho-quartzose sandstones of inferred Valanginian–Aptian age (Takh Formation), and by dominant finer-grained feldspatho-quartzo-lithic volcanoclastic sandstones, locally interbedded with bars of coarser quartz arenite, in the overlying Pingdon La Formation of ?late Aptian–Albian (Garzanti, 1991, 1993a). In spite of such a robust evidence of progressive westward delay in the onset of volcanoclastic sedimentation, detrital-zircon

Table 1 List of sandstone samples analyzed for detrital-zircon geochronology. Samples from the northern Tethyan Himalaya, southern Tethyan Himalaya and Lesser Himalaya range in ages from Devonian to Paleocene

Depositional age	Place	Formation	Sample	Rock type	Latitude	Longitude	Reference
Northern Tethyan Himalaya							
Late Cretaceous	Sangdanlin, Saga; Tibet	Denggang	SDL03, 08, 10	Medium-grained quartz arenite	29°15'17.0"N	85°14'52.4"E	Wang <i>et al.</i> , 2011
	Duoping, Zhongba; Tibet	Rilang	09DP07	Coarse-grained volcanic-rich sandstone	29°44'33.6"N	83°53'47.4"E	This study
		Upper Tianba Flysch	06TB28	Coarse-grained volcanic-rich sandstone	28°43'45.1"N	89°56'42.8"E	
	Early Cretaceous	Tianba, Kangmar; Tibet	Lower Tianba Flysch	06TB11	Coarse-grained volcanic-rich sandstone	28°43'45.0"N	89°56'43.0"E
Rilang			T113	Coarse-grained volcanic-rich sandstone	—	—	
Gangjiu, Zhongba; Tibet		Rilang	S11-08U1	Coarse-grained volcanic-rich sandstone	29°56'39.2"N	83°35'46.8"E	Zhang <i>et al.</i> , 2014
Latest Jurassic	Babazhadong, Zhongba; Tibet	Rilang	S49-02U	Coarse-grained volcanic-rich sandstone	29°45'12.4"N	83°35'36.0"E	Du <i>et al.</i> , 2015
	Babazhadong, Zhongba; Tibet	Weimei	S49-01U	Medium-grained quartz arenite	29°45'12.4"N	83°35'36.0"E	
	Chuangde, Gyangze; Tibet	Weimei	T04	Medium-grained quartz arenite	—	—	Cai <i>et al.</i> , 2011
		Chuangde, Gyangze; Tibet	Weimei	T04	Medium-grained quartz arenite	—	
Southern Tethyan Himalaya							
Early Danian	Tingri; Tibet	Jidula	GZ-H5	Medium-grained quartz arenite	28°42'36.8"N	86°45'09.4"E	Hu <i>et al.</i> , 2012
	Gamba; Tibet	Jidula	13GB10	Medium-grained quartz arenite	28°16'43.0"N	88°31'40.9"E	Garzanti and Hu, 2014
	Zanskar; India	Stumpata	12072102; 12072103	Medium-grained quartz arenite	33°54'06.6"N	76°50'41.6"E	Clift <i>et al.</i> , 2014
Early Cretaceous	Gucuo; Tibet	Wolong Volcanic-clastics	GCL11, GC10, GC09, GC-H7	Coarse-grained volcanic-rich sandstone	28°46'56.0"N	86°19'13.0"E	Hu <i>et al.</i> , 2010
		Kagbeni	—	Coarse-grained volcanic-rich arkosic sandstone	28°50'16.9"N	83°46'57.2"E	Gehrels <i>et al.</i> , 2011
Latest Jurassic	Gucuo; Tibet	Chukh	—	Medium-grained sandstone	28°48'53.3"N	83°51'29.5"E	
		Dangarzhong	—	Medium-grained quartz arenite	28°50'14.2"N	83°46'54.1"E	
	Gucuo; Tibet	Gucuo Quartzite	GCQ	Medium-grained quartz arenite	28°47'03.8"N	86°19'12.6"E	Hu <i>et al.</i> , 2010

Table 1, continued

Depositional age	Place	Formation	Sample	Rock type	Latitude	Longitude	Reference
Jurassic	Mustang, Nepal	Laptal	—	Fine-grained calcareous sandstone	28°48'57.7"N	83°46'08.9"E	Gehrels <i>et al.</i> , 2011
		Formation du Quartzite	FDQ #2	Medium-grained micaceous arkosic sandstone	28°46'34.3"N	83°44'41.4"E	
Triassic		Formation du Quartzite	FDQ #1	Fine-grained sandstone	28°47'27.8"N	83°45'35.9"E	
Early Permian	Selong; Tibet	Jilong	SL5-1	Medium-grained quartz arenite	28°38'32.3"N	85°49'52.1"E	Zhu <i>et al.</i> , 2011
Carboniferous	Mustang, Nepal	—	ThimiChu#1	Pebbly arkosic sandstone	28°45'55.1"N	83°44'31.2"E	Gehrels <i>et al.</i> , 2011
		—	ThimiChu#2	Medium-grained sandstone	28°46'05.1"N	83°44'30.8"E	
Devonian		—	TilichoPass1	Coarse micaceous arkose	28°35'40.5"N	84°07'11.2"E	Gehrels <i>et al.</i> , 2011
		—	TilichoPass2	Coarse micaceous arkose	28°45'02.0"N	83°41'31.9"E	
Lesser Himalaya							
Late Cretaceous– ?Paleocene		Amile 2#	db-02-21ex-1	Quartz arenite	—	—	DeCelles <i>et al.</i> , 2004
		Amile 1#	—	Quartz arenite	—	—	
Early Cretaceous	Tansen; Nepal	Charchare 2#	db-02-21LX	Pebbly volcanic-rich sandstone	27°47'40.8"N	83°31'54.1"E	Gehrels <i>et al.</i> , 2011
		Charchare 1#	—	Pebbly volcanic-rich sandstone	27°47'40.8"N	83°31'54.1"E	
		Taltung	—	Volcanic-rich sandstone	27°47'41.7"N	83°31'54.9"E	
		Lower Sisne	—	Pebbly greenish medium-grained arkosic sandstone	27°47'24.9"N	83°32'33.8"E	
Carboniferous		Middle Sisne	—	Pebbly greenish coarse-grained arkosic sandstone	27°47'34.5"N	83°32'34.7"E	Gehrels <i>et al.</i> , 2011
		Upper Sisne	—	Pebbly greenish medium-grained arkosic sandstone	27°47'38.0"N	83°32'40.1"E	

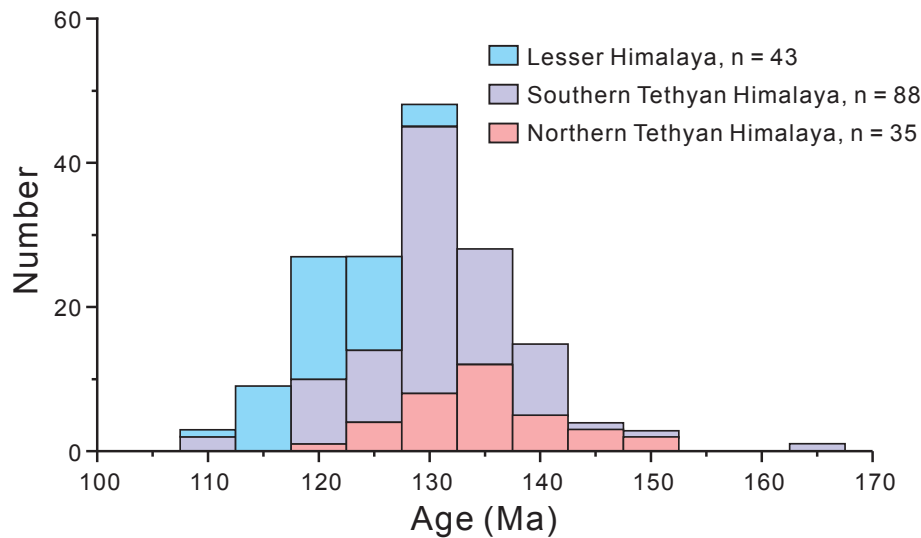


Figure 3 Comparison of Early Cretaceous detrital zircons from the northern Himalaya, southern Tethyan Himalaya, and Lesser Himalaya. Zircon ages cluster between 127–110 Ma in the Lesser Himalaya, and are thus younger than those found in both southern and northern Tethyan Himalaya (148–116 Ma). Data sources provided in Table 1.

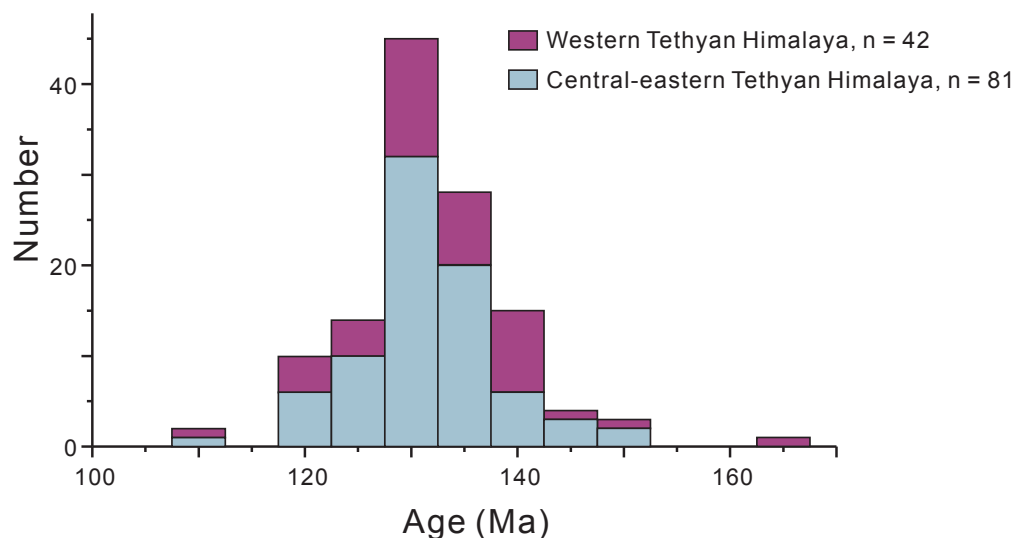


Figure 4 Comparison of Early Cretaceous detrital zircons from the central-eastern and western Tethyan Himalayas. Data sources provided in Table 1.

geochronology provides no indication of heterochrony in magmatic activity in the source areas from east to west. Cretaceous–Paleogene sandstones in the Lesser Himalaya yielded zircon grains in a narrow age range 127–110 Ma ($n = 43$; Figures 3, 4), pointing to volcanism limited chiefly to the Aptian in the source area. The absence of zircons with ages younger than 109 Ma indicates that zircon-bearing magmatic rocks were not produced later than the early Albian, which is at odds with the 96.7 ± 2.8 Ma age obtained on Aulis Trachyte by Sakai *et al.* (1992). This radiometric age is inconsistent also with the stratigraphic record. Vol-

caniclastic sedimentation ceased in fact synchronously in the late Albian (*Subticinensis* Zone; 107–104 Ma; Premoli Silva *et al.*, 1991), after the end of the magmatic event.

6 Early Cretaceous palaeogeography: Provenance and drainage system

Palaeocurrent data show that Lower Cretaceous volcanoclastic sediments were all fed from the south or south-east (Sakai, 1989; Dürr and Gibling, 1994; Gibling *et al.*, 1994; Garzanti, 1999; Hu *et al.*, 2010). Sandstone petro-

raphy and detrital-zircon geochronology indicate that detritus from penecontemporaneous volcanic rocks mixed with sediment recycled from older siliciclastic units and/or basement rocks. The source area was thus represented by northern India, including the proximal part of the continental margin and the Pan-African Orogen (Garzanti *et al.*, 1986; Cawood *et al.*, 2007; Myrow *et al.*, 2010), rejuvenated and dynamically uplifted at the onset of the magmatic event.

Hu *et al.* (2010) suggested that the Early Cretaceous volcanic activity in the northern Indian margin took place along deep-seated leaky extensional faults generated during unzipping of India from Australia/Antarctica, accompanied by minor counter-clockwise rotation (Ali and Aitchison, 2008). This final stage in the break-up of Gondwana caused a change in the direction of the regional stress field along the northeastern Indian margin (Powell *et al.*, 1988). Deep-seated fractures cutting across the continental crust allowed decompression melting and the rise of mantle-derived basaltic magma, which mixed in later stages with partial melts of continental crust, as suggested by the Hf isotopic signatures of Early Cretaceous detrital zircons [$\epsilon_{Hf}(t) = -0.2 - -7.2$; $n = 31$] (Hu *et al.*, 2010, 2012). The Tansen Basin, situated in an extensional continental setting and fed from a southern rift-shoulder consisting of Lesser Himalayan rocks, formed above a deep-seated fault along which alkalic basalts, trachytes and trachyandesites were erupted. Sandstone petrography and detrital geochronology suggest that there were possibly distinct volcanic centers supplying volcanoclastic detritus to the Indian margin. The existence of a significant eastern center as old as the Tithonian, documented poorly so far in outcrops (*e.g.*, Zhu *et al.*, 2008), is indicated by the Tithonian of basal Wölong volcanoclastic sandstones and by the latest Jurassic age of a few detrital zircons. Other centers are more clearly identified as the Comei igneous province of the southeastern Tibet, active around 132 Ma (Zhu *et al.*, 2009), and the Rajmahal-Silhet igneous province of northeastern India, active around 117 Ma (Ghatak and Basu, 2011). Lower Cretaceous volcanic rocks are unknown west of Nepal, but abundant volcanoclastic detritus in the Pingdon La Formation of the Zaskar-Spiti region implies either the existence of a yet undocumented Aptian volcanic center in the west, or the development of a large westward drainage system conveying detritus along the Indian margin from volcanic centers in the east.

This latter hypothesis suggests in turn that massive eruptions of continental-flood basalts during subsequent stages of the Early Cretaceous in southeastern Tibet and

northeastern India (Comei and Rajmahal large igneous provinces) were probably associated with domal uplift, with consequent development of a radial centrifugal drainage system and sediment dispersal, as observed for most large igneous provinces around the world (Cox, 1989; Moore and Blenkinsop, 2002). This scenario may also explain why U–Pb ages of detrital zircons tend to cluster in younger groups from north to south across the central-eastern Himalaya (Figure 3). A greater contribution from the older Comei igneous province is indicated for Tethys Himalayan units. Instead, younger zircon-ages clustering between 127–110 Ma in Lesser Himalayan units reveal supply mostly from the Rajmahal region, via a distinct southern river possibly flowing along a failed arm of the associated rift system (Sakai, 1989, his Figure 5A).

Volcanism ceased everywhere by ~110 Ma. Clastic sedimentation was followed by synchronous drowning of terrigenous shelves all along the Tethys Himalaya in the late Albian *Subticinensis* (*Breggiensis*) Zone, during a period of major starvation that lasted throughout the Cenomanian in the Zaskar Range (107–94 Ma; Garzanti *et al.*, 1989). Tethys Himalayan volcanoclastic to quartzose sediments were slowly buried by foraminiferal oozes deposited in deepening pelagic environments since the close

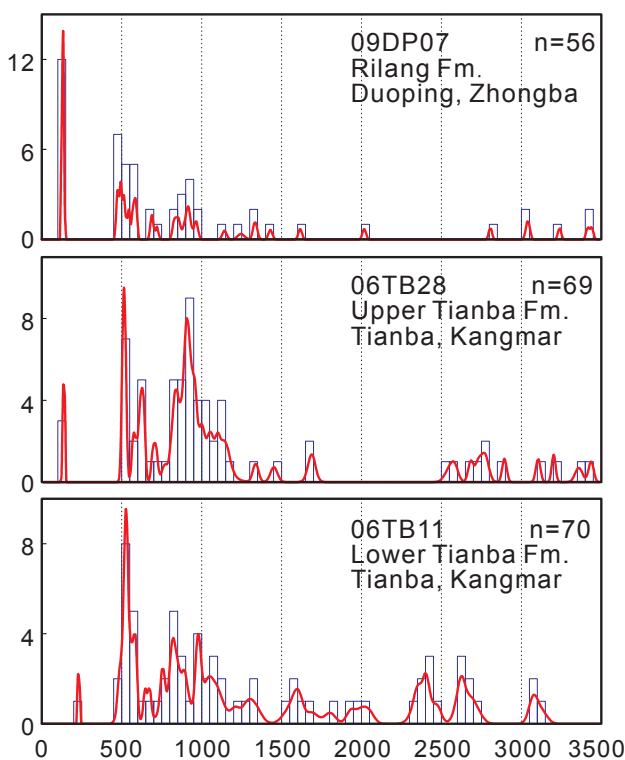


Figure 5 U–Pb age distributions of detrital zircons in the three samples from the Lower Cretaceous units of the northern Tethyan Himalaya. Data sources provided in Table 1. Fm. = Formation.

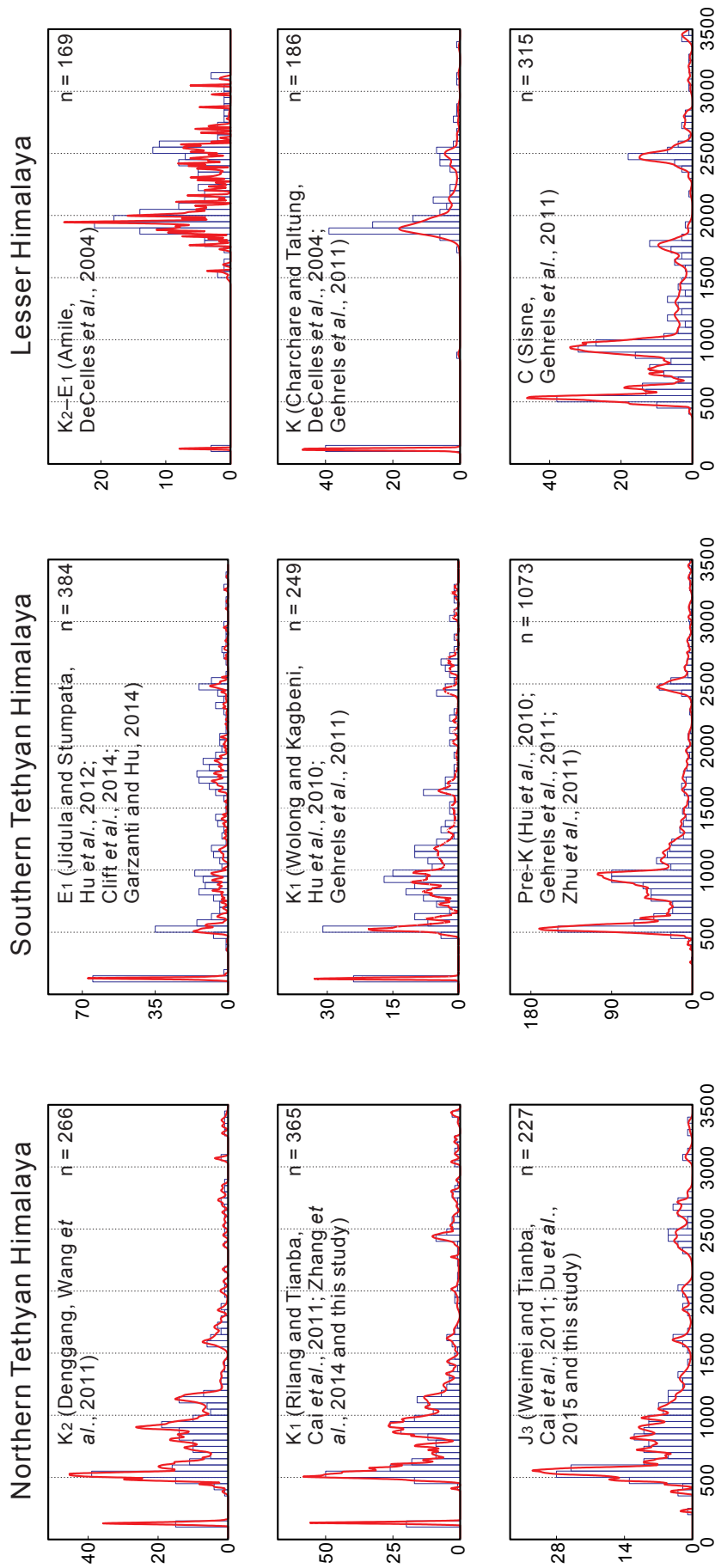


Figure 6 Comparison of detrital zircons from the northern Tethyan Himalaya (top), southern Tethyan Himalaya (middle), and Lesser Himalaya (bottom). Pre-Cretaceous units are represented in the three lower panels, Lower Cretaceous units in central panels, and Upper Cretaceous–Paleocene units in upper panels. Data sources provided in Table 1.

of the Albian (*Ticinensis* to *Appenninica* zones; 103–101 Ma; Premoli Silva *et al.*, 1991; Hu *et al.*, 2008). These units include the Chikkim and Fatu La Formations of the Spiti-Zaskar Synclinorium (Garzanti, 1993a; Bertle and Suttner, 2005), the Bolinxiala Formation of southwestern Tibet (Zanda area; Li *et al.*, 2009), the Muding Formation of Nepal (Gibling *et al.*, 1994; Garzanti, 1999), and the Gambacunkou Formation of southern Tibet (Willems *et al.*, 1996). Drowning of the Indian passive continental margin is ascribed to waning sediment supply, cooling of the crust and thermal subsidence at the end of the magmatic event (Garzanti, 1993a, 1993b).

7 Conclusions

This study provides new U–Pb ages of detrital zircons obtained from three Lower Cretaceous sandstones of the northern Tethyan Himalaya, integrated with a comprehensive compilation of previously published data from other Cretaceous to Paleocene Himalayan sandstone units. Early Cretaceous ages of detrital zircons cluster mainly between 142–123 Ma in the northern Tethyan Himalaya (with two grains at 148–147 Ma, and one at 117 Ma), and between 140–116 Ma in the southern Tethyan Himalaya (with one grain at 161 Ma, one at 147 Ma, and two at 109 Ma). These data indicate that the Early Cretaceous magmatic event which affected the passive continental margin of northern India began close to the Jurassic/Cretaceous boundary around 148–147 Ma, and ended in the early Albian by ~110 Ma. This time window coincides well with volcanoclastic sedimentation in southern Tibet, which is confined between the Tithonian and the Aptian (Jadoul *et al.*, 1998).

Stratigraphic data document the progressive westward migration of volcanoclastic sedimentation, which started as early as the latest Jurassic in southern Tibet but did not begin until the late Aptian/early Albian in the Zaskar-Spiti region of the western Himalaya. An equivalent heterochrony in magmatic activity, which would have suggested the progressive westward propagation of deep-seated leaky extensional faults generated during unzipping of India from Australia/Antarctica (as proposed by Hu *et al.*, 2010), is not supported by the age distributions of detrital zircons, which do not show remarkable differences from east to west. Alternatively, we suggest here that a major drainage system progressively prograding westwards may have conveyed volcanic detritus along the Indian margin from the same volcanic centers in the east. This provenance interpretation is supported by the fact that Early

Cretaceous volcanic rocks were only found in the eastern part of the northern Indian margin so far, and are unknown in western Nepal. Development of radial drainage and sediment dispersal away from the domal uplift caused by magmatic upwelling is observed for most large igneous provinces around the world (Cox, 1989) and might have developed also for the Early Cretaceous Comei–Rajmahal–Sylhet igneous provinces of southeastern Tibet and northeastern India.

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