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# Latest Cretaceous Himalayan tectonics: Obduction, collision or Deccan-related uplift?

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ABSTRACT

Diverging interpretations and incompatible scenarios have been proposed for the early stages of Himalayan history. Numerous researchers have postulated that northern India was involved in ophiolite obduction, arc–continent, or continent–continent collision during the Late Cretaceous or Early Paleocene, but firm geological evidence was never produced. In this article we argue against orogenic events predating the Late Paleocene, when the Neotethys Ocean was still open. The Tethys Himalayan sedimentary record testifies to anorogenic evolution, primarily controlled by dynamic uplift of the passive margin prior to the massive outburst of Deccan lavas and eventually followed by thermal subsidence. Major stratigraphic gaps in pelagic sediments suggest that such tectono-magmatic episode started to affect the base of the Indian Plate in the Campanian or possibly even in the Santonian, 10 to 20 Ma before the climax of Deccan flood-basalt eruptions. The abrupt increase in siliciclastic supply and accumulation rates recorded in sedimentary basins all around the Indian subcontinent during the Maastrichtian was followed by progradation of coastal quartzarenites along the northern Indian margin in the Early Paleocene. Sandstones derived from the rejuvenated craton and uplifted inner continental margin in the south are dominantly but not exclusively quartzose. Felsitic volcanic rock fragments and Cr-spinels, many of which with the same geochemical fingerprint as Deccan spinels and newly found throughout the Maastrichtian to Danian succession, resisted the combined effect of subequatorial weathering and subsequent diagenesis, and testify that detritus from Deccan basalts reached the Indian passive margin as far as South Tibet. At the close of the Early Paleocene India drifted away from the Seychelles block, and thermal subsidence led to widespread carbonate deposition along the Tethys Himalaya. This article illustrates how mega-events of magmatic upwelling followed by lithospheric cooling may control passive-margin sedimentation and stratigraphic patterns, as occurred in northern India first in the Early Cretaceous and next in the latest Cretaceous/Paleocene.


"*Whenever possible, substitute constructions out of known entities for inferences to unknown entities.*"
[Bertrand Russell, Logical Atomism, 1924.]

## 1. Introduction

The Late Cretaceous sedimentary evolution of the Indian continental margin facing Neotethys (Tethys Himalaya) has long been suspected to record a major tectonic event (Fig. 1; Searle et al., 1987; Yin and Harrison, 2000; Murphy and Yin, 2003). The idea that Oman-type ophiolites were emplaced onto northern India at that time has been reiterated in a number of articles (e.g., Searle, 1986; Searle et al., 1997; Pedersen et al., 2001; Corfield et al., 2005; Green et al., 2008; Searle and Treloar, 2010), even though the support for such scenario has been disputed repeatedly (Kelemen et al., 1988; Guillot et al., 2003; Garzanti et al., 2005). Other authors have favored an early collision between India and Asia, based on the supposed Eurasian character of Cretaceous/Tertiary boundary terrestrial faunas in India (Jaeger et al., 1989), detrital geochronology (Cai et al., 2011), or paleomagnetic data (Yi et al., 2011). Alternatively, and without postulating any extraneous hypothetical entity, the Tethys Himalaya succession may have simply recorded the major anorogenic event that affected the Indian subcontinent at the close of the Cretaceous (Gaetani and Garzanti, 1991; "Model 1" of Hu et al., 2012).

In this article we present first a concise description of the Cretaceous to Paleocene Tethys Himalayan stratigraphic record (Fig. 2). We discuss next why such record and other arguments: i) preclude ophiolite obduction onto the passive margin of India before collision with the

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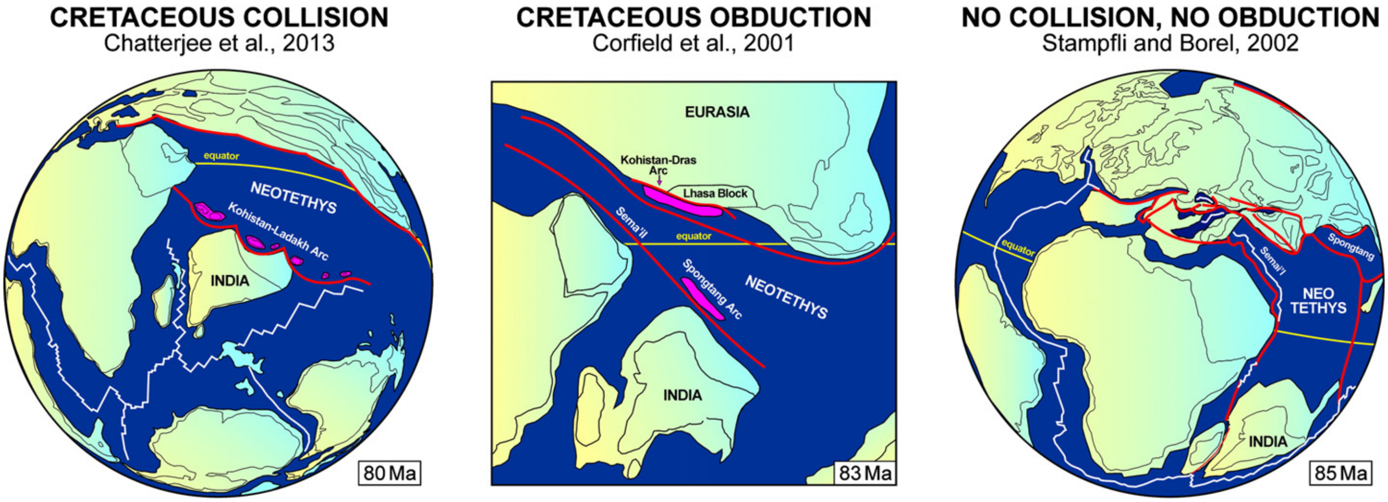


**Fig. 1.** Numerous articles envisaged orogenic evolution of northern India in the Late Cretaceous, by either arc–continent collision (e.g., Chatterjee et al., 2013) or ophiolite obduction (e.g., Corfield et al., 2001). Continuing passive-margin evolution (Stampfli and Borel, 2002) is a simpler alternative scenario that avoids inferences to unknown entities.

active margin of Asia; and, ii) certify that the India/Asia collision began well after the Early Paleocene. Finally, we show how the evidence of subsidence analysis, sandstone petrography, detrital-zircon geochronology and Cr-spinel geochemistry indicates that passive-margin sedimentation was primarily anorogenic and controlled by dynamic uplift, which we relate to Deccan magmatic upwelling and consequent cratonic rejuvenation during the latest Cretaceous to Early Paleocene.

## 2. The Tethys Himalayan record

Upper Cretaceous to Eocene strata deposited originally along the passive continental margin of northern India are exposed continuously in the Zanskar Range in the west and in South Tibet in the east (Fig. 3). In Spiti (Bhargava, 2008), southwestern Tibet (Li et al., 2009) and Kumaon (Heim and Gansser, 1939; Juyal et al., 2002), the uppermost part of

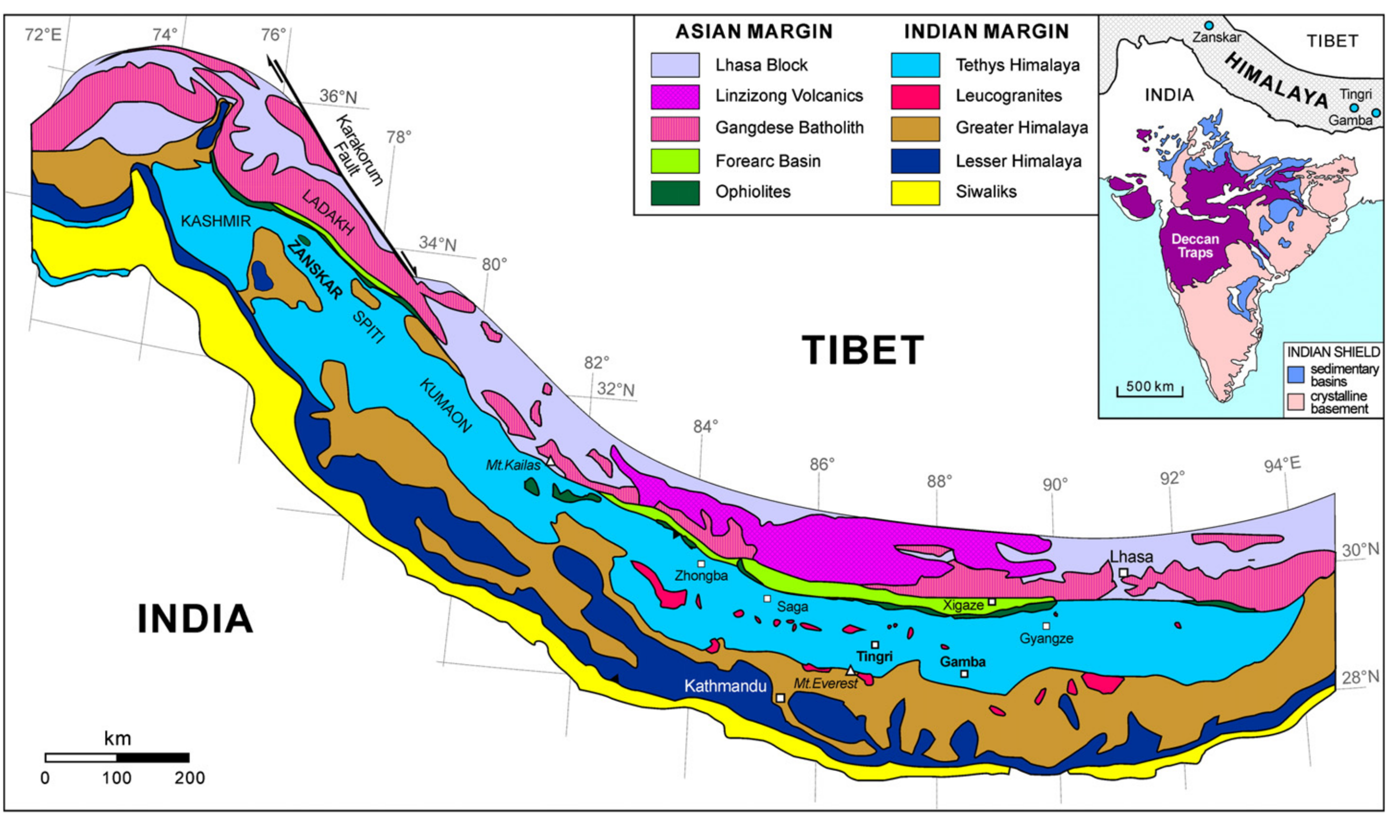


**Fig. 2.** Geological sketch map of the Himalayan Range, with localities studied in South Tibet (Tingri, Gamba) and Zanskar. The inset shows the areal distribution of the Deccan volcanic province in cratonic India.

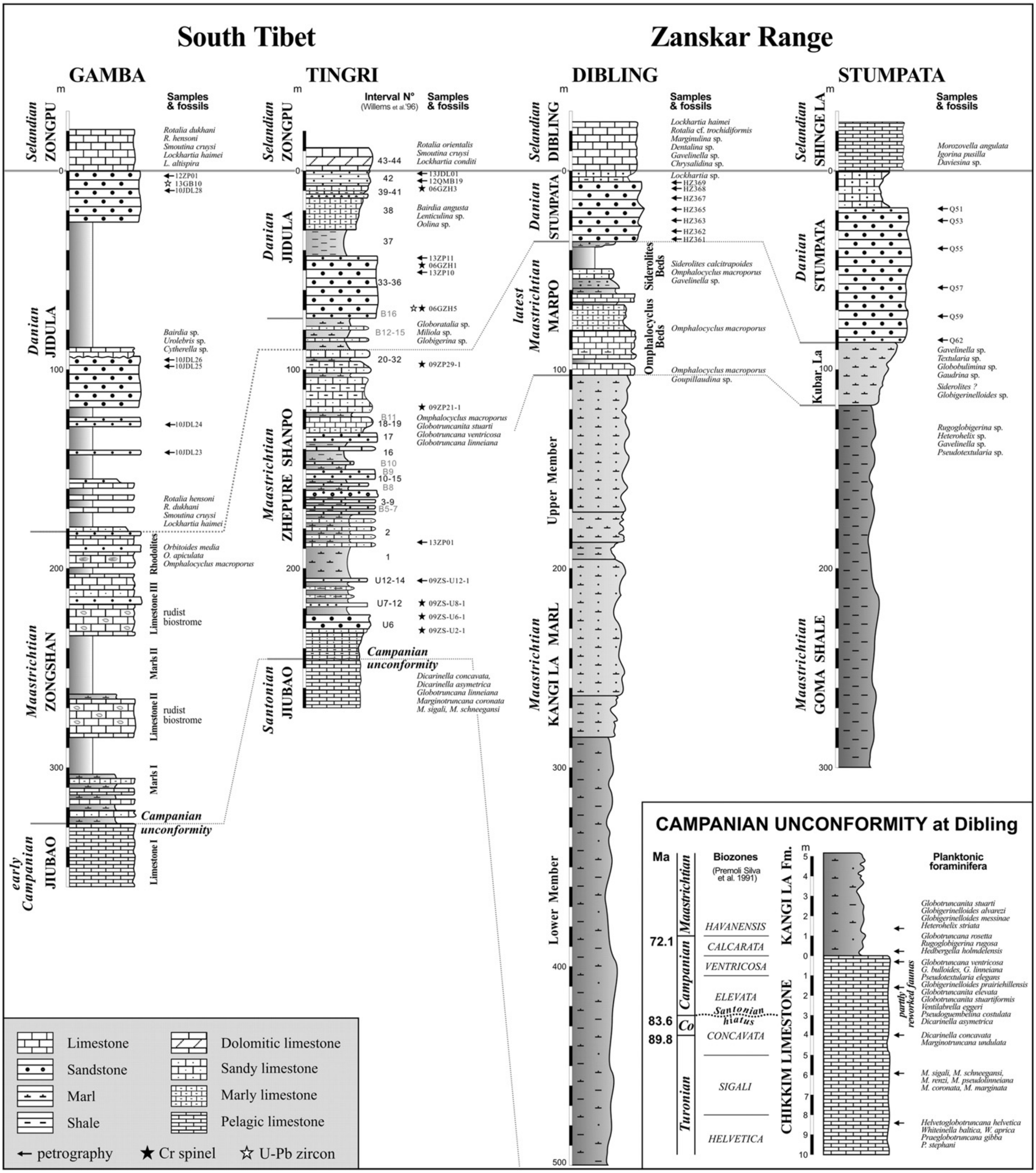


**Fig. 3.** Upper Cretaceous/Lower Paleocene stratigraphy of the Tethys Himalaya in South Tibet (Willems et al., 1996; Wan et al., 2002; Wu et al., 2011; Hu et al., 2012) and Zanskar (Gaetani et al., 1986; Garzanti et al., 1987; Nicora et al., 1987; Premoli Silva et al., 1991). Position of samples analyzed for sandstone petrography, spinel geochemistry and U–Pb zircon geochronology is indicated. Ubiquitous unconformities and extensive faunal reworking all along the northern Indian margin suggest that subsidence ceased and was probably inverted since Campanian (80–75 Ma) or even Santonian times (~85 Ma).

the succession has been eroded away. Only Lower Cretaceous strata are preserved in Nepal, and only in the Thakkhola Graben (Garzanti, 1999). In the following section we will focus on the most complete sections exposed in Zanskar and South Tibet, where the Tethys Himalaya is traditionally subdivided into a southern proximal subzone (including the Gamba and Tingri localities) and a northern distal subzone dominated by deep-water sediments and turbidites. Throughout the article, correlation between biostratigraphic and absolute ages is according to the timescale of Gradstein et al. (2012).

In the Lower Cretaceous, feldspatho–quartzose to quartzo-feldspatho–lithic volcaniclastic sandstones and interbedded mudrocks document uplift associated with volcanic eruptions south of the Tethys Himalaya (Garzanti, 1993a,b; Hu et al., 2010). At the end of magmatism, quasi-synchronous drowning of the clastic shelf is marked by condensed glauco-phosphorites overlain by pelagic limestones (Garzanti et al., 1989; Li et al., 2012). Besides variations in lithology related to the location of river mouths and climatic zonation (progressively higher southern-hemisphere paleolatitudes from west to east), Upper Cretaceous

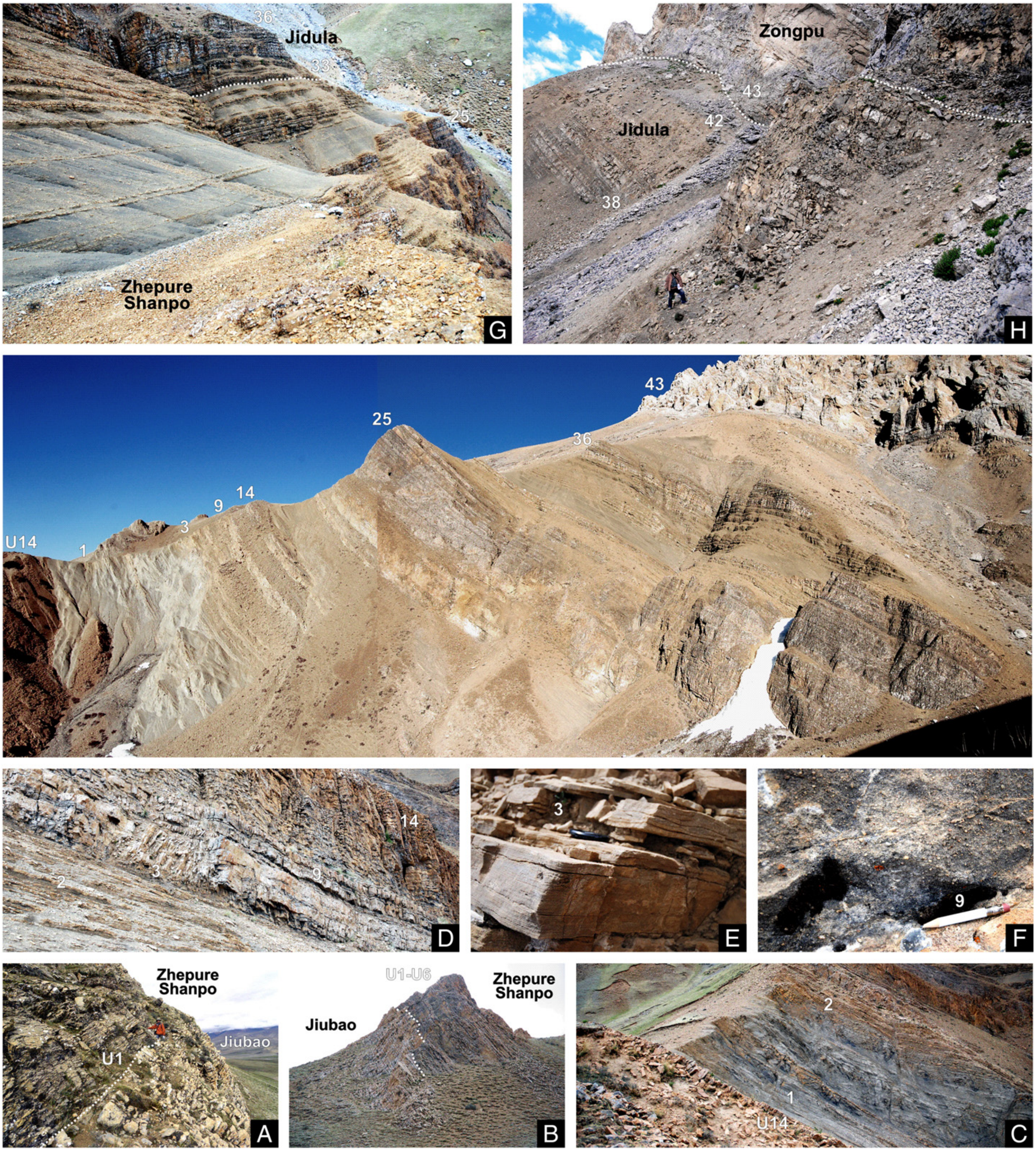


**Fig. 4.** The classic Upper Cretaceous/Lower Paleocene succession of the Zhepure Mountains. A: Campanian unconformity; B: marly limestones of the basal Zhepure Shanpo Fm.; C: marls of the lower Zhepure Shanpo Fm.; D: quartzarenites of the middle Zhepure Shanpo Fm. (E: storm-surge turbidites and wave-reworked beds, lenscap for scale; F: the coarsest-grained sandstone bed, pencil for scale); G: boundary between Zhepure Shanpo and Jidula Fms.; H: boundary between Jidula Fm. and Zongpu carbonates. Stratigraphic intervals numbered as in Fig. 3.

successions compare closely from Zanskar to South Tibet. Differences are largely apparent, due to inconsistent stratigraphic nomenclature used in different parts of the Himalaya or by different research groups.

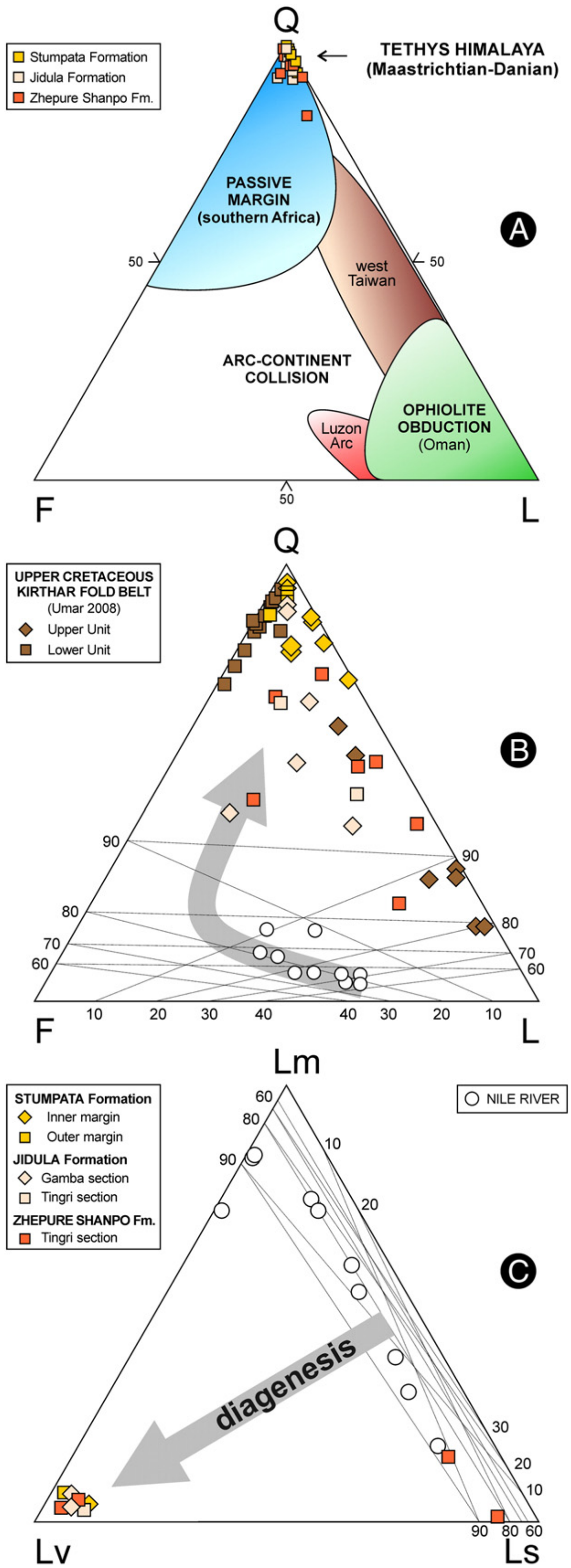


**Fig. 5.** Petrography of Maastrichtian to Paleocene sandstones from Tibet to Pakistan (Umar, 2008) indicates anorogenic setting and rejects both ophiolite-obduction and arc–continent-collision scenarios. A: Quartzose Tethys Himalayan sandstones (39 samples point-counted by the Gazzi–Dickinson method; dataset provided in Appendix Table A1) differ sharply from sands shed by the Oman ophiolites or Taiwan orogen, and compare instead with sands of African passive margins (compositional fields after Garzanti et al., 2002, 2014a,b). B, C: Detritus derived from Precambrian India and Deccan basalts was enriched in quartz and felsitic volcanic rock fragments due to recycling and both pre- and post-depositional breakdown of less durable grains (diagenetic dissolution trends outlined by gray arrows are derived from own data on Nile Delta sediments; Garzanti et al., 2006, 2008). Data are centered to allow better visualization (von Eynatten et al., 2002; www.compositionaldata.com). Q = quartz; F = feldspars; L = lithic grains (Lv = volcanic; Lm = metamorphic; Ls = sedimentary).

### 2.1. Zanskar

Gray to multicolored foraminiferal oozes were deposited at upper bathyal depths during the latest Albian to Campanian times (Chikkim and Fatu La Formations). Stratigraphic thickness increases from 56 m in the inner margin to ≥200 m oceanward, indicating average accumulation rates ranging from only 2 m/Ma to 7 m/Ma offshore. Sedimentation was remarkably discontinuous. Frequent hiatuses up to several Ma-long and repeated intervals of faunal mixing and reworking were ascribed to habitual resuspension and removal of pelagic sediment on the upper slope caused by strong oceanic currents (Premoli Silva et al., 1991). Hiatuses are most common in the Cenomanian (100–94 Ma), whereas rapid accumulation below the mudline took place in the early Turonian. Hiatuses and marked variation in thickness of diverse foraminiferal zones also characterize Coniacian/Santonian strata (90–84 Ma), where the occurrence of benthic foraminifers and macrofossils (belemnites, inoceramids, echinoderms) suggests the beginning of a shallowing trend. The top of both Chikkim and Fatu La Formations documents particularly extensive reworking of planktonic foraminifers, with index species of all three Campanian (*Globotruncanita elevata*, *Globotruncana ventricosa*, *Globotruncanita calcarata*) and early Maastrichtian zones (*Globotruncanella havanensis*) found locally mixed in the same sample (Fig. 3; Premoli Silva et al., 1991; Bertle and Suttner, 2005).

The sharp upward transition to the Kangi La Formation testifies to a turning point in passive-margin evolution around the Campanian/Maastrichtian boundary (~72 Ma), with a very pronounced increase in terrigenous supply and accumulation rates (~100 m/Ma). The unit, 500–600 m thick (Gaetani et al., 1986), is progressively replaced in the outer margin by the several hundred m-thick Goma Shale, capped by 30–35 m of silty marls with phosphatic nodules (Kubar La Fm.; Fig. 3). The lower member of the Kangi La Formation (~350 m) consists of marls and silty marls with intercalated thin mudstone/wackestone beds. The base is still rich in deeper-dwelling planktonic foraminifers, whereas inoceramids and phosphate nodules rarely encasing turrilitid ammonoids occur upward. The upper member (~180 m) is more calcareous and arenaceous, with better defined bedding and diversified burrows (*Zoophycus*, *Rhizocorallium*) indicating better oxygenation. Fragments of corals, gastropods and bryozoans occur. Lithofacies and fossil distribution document a shallowing-upward trend from upper-bathyal to outer-shelf depositional environments. In the proximal margin, the unit is capped by a prograding carbonate ramp, reaching a maximum thickness of 140 m (Marpo Limestone; Nicora et al., 1987). Rich faunas (benthic foraminifers, algae, corals, echinoderms, ostracods) indicate open shallow-marine deposition at the close of the Maastrichtian.

Above the Cretaceous/Tertiary boundary (~66 Ma), a quartzarenite marker horizon increasing in thickness from 6 m to 67 m offshore is interpreted as an aggrading mesotidal shoreline complex (Stumpata Quartzarenite; Nicora et al., 1987). The upper part of the unit is a fining-upward sequence of burrowed and locally bioclastic sandstones, capped by a condensed glauco-phosphorite yielding planktonic foraminifers of the latest Danian *Praemurica uncinata* P2 zone (~62 Ma). This major transgressive event was followed in the Selandian–Thanetian by deposition of lagoonal limestones onto the proximal

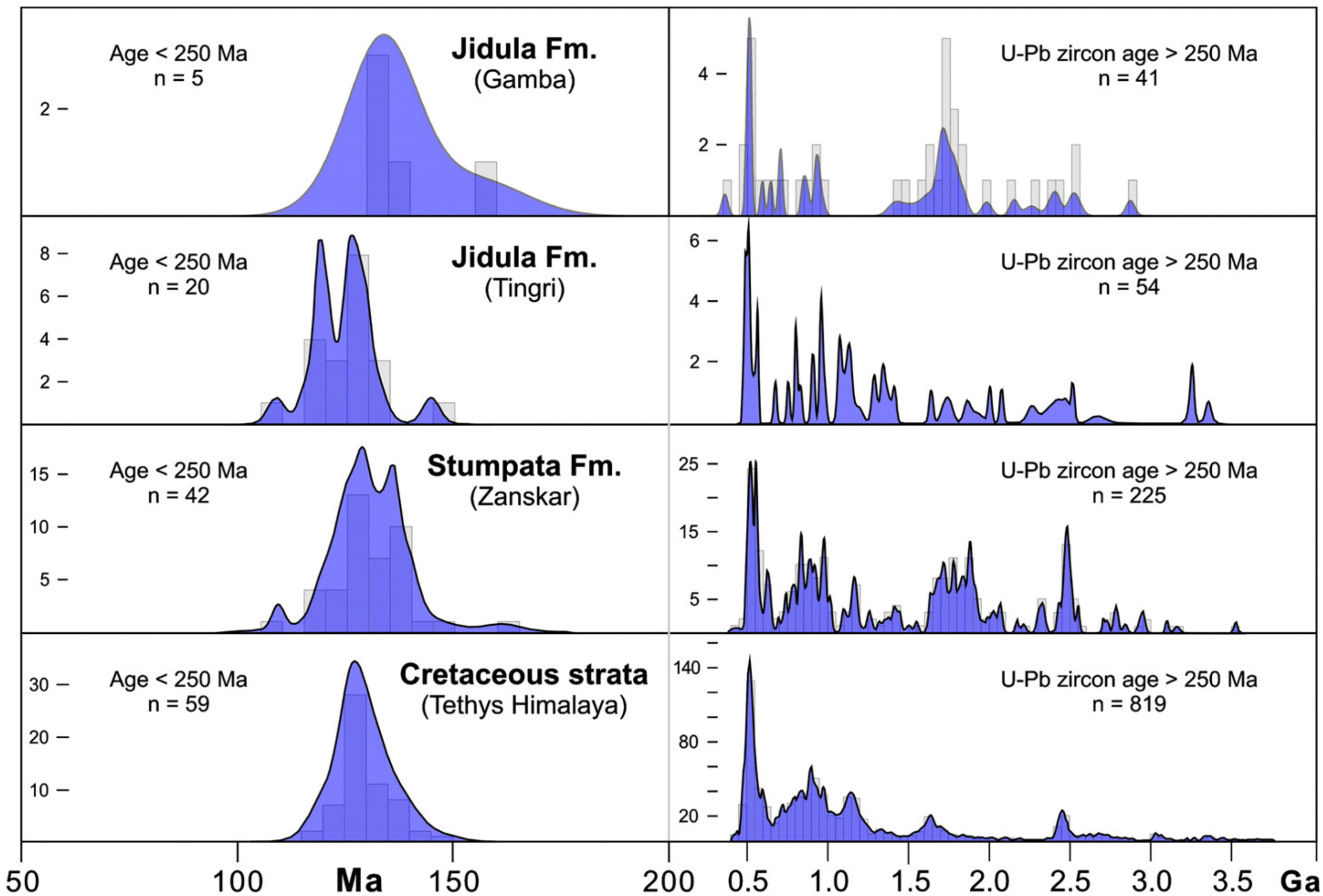


**Fig. 6.** U–Pb ages of detrital zircons in the Jidula and Stumpata Formations (data after Hu et al., 2012; Clift et al., 2014; dataset provided in Appendix Table A2) compare closely with spectra obtained from older Tethys Himalayan sandstones (data after Hu et al., 2010; Wang et al., 2011; Gehrels et al., 2011), indicating provenance from the Indian subcontinent in the south. More prominent 1.6–1.9 and ~2.5 Ga age clusters for Stumpata zircons suggest significant contributions from the Aravalli Range (Fig. 10; Kaur et al., 2011).

margin, and of locally cherty pelagic limestones and marls offshore (Garzanti et al., 1987).

### 2.2. South Tibet (Tingri)

In the classic Zhepure Mountain section of the Tingri area (Fig. 4; Willems et al., 1996), ~600 m of gray marls and marly limestones with planktonic foraminifers of the late Albian–early Coniacian age (Gangbacunkou Formation) are followed by ~80 m of marly limestones yielding planktonic foraminifers of the early Coniacian/latest Santonian age (Jiubao Formation). The paraconformable top of the unit conceals a conspicuous hiatus corresponding to most of the Campanian (Fig. 3; Wu et al., 2011; Hu et al., 2012). The overlying Zhepure Shanpo Formation contains calcareous interbeds yielding reworked planktonic foraminifers of the latest Campanian to early Maastrichtian age at the base (Fig. 4A, B). This 190 m-thick unit is a shallowing-upward sequence including marly limestones and marls in the lower part (Fig. 4C), overlain by up to very-coarse-grained channelized sandstones representing hyperpycnal flows or storm-surge turbidites with wave-reworked tops (Fig. 4D, E, F). Next, thinly interbedded marls and sandstones are followed by another quartzarenite interval overlain by fossiliferous marls. According to Wan et al. (2002), the top of the unit consists of 3.7 m-thick calcareous sandstones with gastropods, ostracods and benthic foraminifers, followed by sandstones, sandy limestones and marls yielding planktonic foraminifers of Danian age. The overlying 75 m-thick Jidula Formation consists of sandstones and calcareous sandstones with a shale interval in the middle and interbedded with marly nodular limestones with ferruginous nodules at the top, indicating deposition in deltaic to shallow-marine environments (Fig. 4G, H). The fauna includes gastropods, ostracods and a few foraminifers suggesting an early Danian age (Fig. 3; Wan et al., 2002). The sharp transgressive upper boundary is overlain by thick shallow-marine carbonates of the Zongpu Formation, yielding in the lower part foraminifers of the latest Danian age (~62 Ma; Willems, 1993; Wan et al., 2002).

### 2.3. South Tibet (Gamba)

In the Gamba area, 424 m of dark gray marls and marly limestones increasing at the top were deposited in the late Albian to Santonian times (Lengqingre and Gambacunkou Formations; Willems et al., 1996). The overlying Jiubao Formation (Limestone I of the Zongshan Fm. in Willems and Zhang, 1993) consists of ~40 m of bedded limestones yielding planktonic foraminifers of Campanian age. A paraconformity at the top, best observed in the Gamba Castle section, is followed by the ~170 m-thick Zongshan Formation of Maastrichtian age. Marls and nodular marly limestones with reworked fossils intercalated with storm-surge turbidites in the lower 50 m are overlain by limestones yielding calcareous algae and benthic foraminifers interbedded with rudist biostromes and subordinate marls (Fig. 3). The overlying ~180 m-thick Jidula Formation mainly consists of quartzose sandstones, intercalated with black limestones in the middle part. A 2–5 cm-thick mudrock near the base of the unit yielded foraminifers of the early Danian age (Wan et al., 2002). The Zongshan and Jidula Formations record an overall shallowing-upward trend from mixed siliciclastic–carbonate rocks deposited in offshore environments to shallow-marine carbonates and coastal sandstones. The overlying transgressive shallow-marine carbonates of the Zongpu Formation are dated in the lower part at the latest Danian (~62 Ma; Willems, 1993; Wan et al., 2002).

## 3. Evidence against the Late Cretaceous obduction

Arguments against the hypothesis that ophiolites of the Indus-Yarlung Suture were emplaced onto the northern Indian margin in the Late Cretaceous include:

1) patterns of magnetic anomalies in the Indian Ocean. Reconstructed plate motions indicate rapid sea-floor spreading and India–Asia convergence between ≥84 and 55–50 Ma (Patriat and Achache, 1984; Copley et al., 2010). No slowdown is observed, as might be expected if the northern margin of the Indian Plate had been involved in compressive events such as ophiolite obduction, arc–continent, or continent–continent collision. Rather, convergence rates accelerated at ~67 Ma by several cm/a, which was ascribed to weakening of the Indian continental lithosphere–asthenosphere coupling caused by magmatic upwelling (Cande and Stegman, 2011; van Hinsbergen et al., 2011);
2) Upper Cretaceous to Paleocene units of the Tethys Himalaya do not contain ophiolitic detritus. Siltstones and sandstones are invariably quartzose, indicating cratonic provenance from the south rather than ophiolitic provenance from the north (Fig. 5; Garzanti et al., 1987; Zhu et al., 2005; Hu et al., 2012);
3) the finding of Cr-spinels of ophiolitic affinity in Paleocene units of the Northern Tethys Himalaya by Ding et al. (2005) and Cai et al. (2011) is not confirmed by more recent results (Wang et al., 2011; Hu et al., 2014). Cr-spinel geochemistry indicates that the Yarlung–Tsangpo ophiolites were not exposed to erosion until after the Early Eocene (Hu et al., 2014);
4) U–Pb age spectra of detrital zircons in the Jidula and Stumpata quartzarenites indicate provenance from India in the south (Fig. 6), and preclude erosion of supposedly obducted ophiolites prior to 61 Ma (Hu et al., 2012; Clift et al., 2014);
5) because of uncertain paleo-bathymetric assessments, subsidence analysis of the Zanskar section (Corfield et al., 2005) failed to document the postulated ophiolite obduction (Garzanti et al., 2005; Sciunnach and Garzanti, 2012);
6) the obduction hypothesis was based on erroneous earlier descriptions of the Maastrichtian Kangi La Formation, interpreted as a "*flysch*" (Fuchs, 1977; Brookfield and Andrews-Speed, 1984) supposedly indicating "*a notable deepening event*" and the "*collapse of the stable Mesozoic shelf*" (Searle et al., 1987, p. 679, 695). The Kangi La Formation documents instead a shallowing-upward succession from upper bathyal limestones to shelfal silty marls eventually capped by shallow-water biocalcarenites (Nicora et al., 1987);
7) field observations made by several independent research teams and finding of faunas of the Early Eocene age in the mélange at the base of the ophiolitic klippe (Reuber et al., 1987) indicate that obduction could not have taken place before the Eocene (Kelemen et al., 1988 p. 129).

As a further argument, the supra-subduction origin of most Himalayan ophiolites is indicated by petrological and geochemical evidence (Hébert et al., 2012), as well as by stratigraphic continuity of the upper Barremian/Aptian succession at the top of the ophiolite, including pillow basalts and cherts overlain by thick turbidites of the Xigaze forearc basin (Wang et al., 2012; An et al., in press). As part of forearc basement, the Xigaze Ophiolite belonged by definition to the northern active margin of Neotethys, and its obduction onto the Tethys Himalayan passive margin could not have occurred before the intervening ocean closed and the two margins began to collide.

Ophiolite obduction did take place around the Cretaceous/Paleocene boundary along the western transform margin of the Indian Plate (Gnos et al., 1998; Beck et al., 1996; Khan and Clyde, 2013), but this well documented event does not automatically imply that ophiolites were obducted at the same time onto the northern Indian margin as well (Rowley, 1996 p. 5). Amphiboles in ophiolitic mélange of South Tibet yielded $^{40}Ar/^{39}Ar$ ages of 128–124 Ma (Guilmette et al., 2009), 90–80 Ma (Malpas et al., 2003), and 63 Ma (Ding et al., 2005). Rather than obduction or early collision processes, these diverse ages may reflect successive accretionary episodes since the beginning of subduction beneath the northern active margin of Neotethys.

## 4. Evidence against the Late Cretaceous collision

Arguments against the hypothesis that India collided with Asia in the Late Cretaceous include several of those discussed in the previous section:

1) no slowdown is observed in the convergence between India and Asia. Actually, convergence rates accelerated markedly at ~67 Ma (Copley et al., 2010; Cande and Stegman, 2011; van Hinsbergen et al., 2011);
2) Upper Cretaceous to Paleocene units of the Tethys Himalaya do not contain any orogenic detritus. Quartzose sands were supplied all along the Indian margin from rivers draining India in the south, and not derived from hypothetical Asian or arc sources in the north (Fig. 5; Garzanti et al., 1987; Zhu et al., 2005; Umar et al., 2011; Hu et al., 2012);
3) U–Pb dating of zircon grains from Jidula and Stumpata quartzarenites indicate provenance from India in the south (Fig. 6),

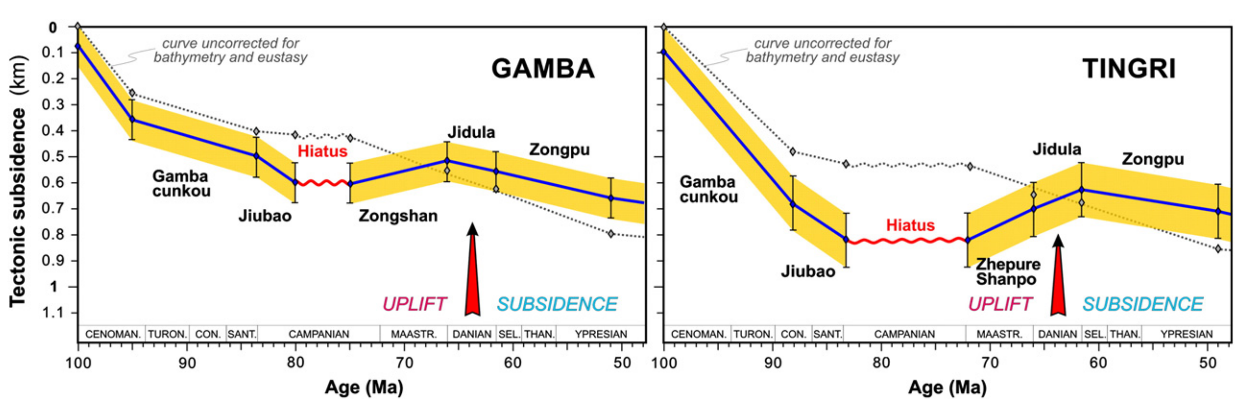


**Fig. 7.** Subsidence analysis. The widespread Campanian hiatus, documented by extensive sediment and faunal reworking all along the Tethys Himalaya, suggests inversion from basin subsidence to dynamic uplift 10–15 Ma earlier than the massive outburst of Deccan lavas.

and preclude collision with either Asia or an intervening arc before 61 Ma (Hu et al., 2012; Clift et al., 2014);

4) independent subsidence analyses, failing to provide evidence of subsidence acceleration, do not support such postulated Late Cretaceous collision (Rowley, 1998; Hu et al., 2012; Sciunnach and Garzanti, 2012);
5) earlier descriptions of the Kangi La Formation as "*consisting of more than 1000 m of deep-water shale and olistostromes*" interpreted as "*syn-emplacement flysch deposits accumulating in the foredeep of the Indian Plate margin*" (Searle, 1986 p. 927–928) have been very misleading. The unit is a shallowing-upward shelfal succession capped by shallow-water biocalcarenites (Gaetani and Garzanti, 1991 their fig. 10).

Also the Zhepure Shanpo Formation of South Tibet, which is a similar shallowing-upward shelfal succession, was formerly thought to represent submarine-fan deposits documenting the onset of the India–Asia collision (Willems et al., 1996; Zhang et al., 2012 p. 177). This interpretation has been subsequently emended by the same authors, who finally recognized that the lowermost Paleocene Jidula sandstones are passive-margin sediments consisting of Indian-derived detritus, and that the India/Asia collision took place only much later at ~56 Ma (Zhang et al., 2012 p. 186–187). Closure of Neotethys in the Late Cretaceous is in fact hardly compatible with stable carbonate-platform deposition all along the Indian margin during the whole of the Paleocene (Willems, 1993; Rowley, 1996; Zhang et al., 2012 p. 183).

Cai et al. (2011) have favored Maastrichtian collision onset based on an influx of zircon grains with Cretaceous ages in the Zongzhuo Mélange of the northern Tethys Himalaya. Further investigations, however, have demonstrated that zircon grains in the same mélange have U–Pb ages as young as 56 Ma (Sun et al., 2011). Asian-sourced detritus was thus being deposited in deep waters onto the distal Indian margin around the Paleocene/Eocene boundary, when Neotethys was about to close.

Recent studies have documented transition from endemic to cosmopolitan terrestrial faunas not earlier than the Early Eocene, consistent with India–Asia collision close to the Paleocene–Eocene boundary (Clyde et al., 2003; Chatterjee and Scotese, 2010; Clementz et al., 2011).

## 5. Evidence for anorogenic evolution

### 5.1. Subsidence analysis

Subsidence analysis was carried out from the base of the Gambacunkou Formation (~100 Ma) to the top of the Zongpu Formation (~50 Ma) using the MATLAB code provided by Allen and Allen (2005). Each formation was decompacted, sequentially recompacted during progressive burial, and finally backstripped to remove the effect of sediment load assuming local compensation and Airy isostatic correction. Values for initial porosity, exponents describing porosity loss during burial and sediment densities were taken from comparable lithologies listed in Allen and Allen (2005). Average values and uncertainties for the eustatic correction were derived from the different curves discussed in Kominz et al. (2008). Paleowater-depth estimates and associated uncertainties were based on paleontological and sedimentological analysis.

The curve obtained for the Tingri section suggests steady subsidence until Santonian times (Fig. 7). Notably reduced subsidence during the major Campanian hiatus was seemingly followed by tectonic uplift of 300 ± 200 m during deposition of the Zhepure Shanpo and Jidula Formations (Hu et al., 2012). Ceased and possibly inverted subsidence remains indicated even if the shallowest values are conservatively assumed for the top of the Jiubao Formation, a pattern that cannot be ascribed entirely to waning thermal subsidence ~30 Ma after the end of the Early Cretaceous volcanic event (Zhu et al., 2008). However, the curves obtained by Rowley (1998) based on the data from Willems et al. (1996) do not show any uplift, and the results for this part of the succession are not robust. Whether tectonic uplift was associated with the Campanian turning point in sedimentary evolution is even more difficult to establish for the Zanskar succession, where Maastrichtian deposits are much thicker (Fig. 3). Much depends on Santonian–Campanian water depths, which imply uplift if assumed to be >300 m but subsidence if assumed to be <200 m (Garzanti et al., 2005).

### 5.2. The Maastrichtian siliciclastic pulse

A multifold increase of clastic supply during the Maastrichtian is testified not only by the Tethys Himalayan succession from Zanskar to South Tibet, but around most of the Indian subcontinent as well (Saunders et al., 2007; Sahu et al., 2013). A three- to five-fold increase in sediment flux during the late Campanian–early Maastrichtian times is recorded in sedimentary basins of southeastern India, and ascribed to an increase in topography in catchment areas to the northwest (Halkett et al., 2001; Lakshminarayana, 2002). Uplift, erosion and increased sediment fluxes across northwestern India are documented by fluvial sandstones inferred to have been derived from the rejuvenated Aravalli highlands (Gombos et al., 1995; Roy, 2003). The lack of substantial sedimentation in southern India and missing Paleocene deposits in the Mahanadi and Godavari valleys of eastern and western central India are consistent with widespread erosion and sediment bypassing during the terminal Cretaceous crustal up-warp, possibly recorded in regions as far away as eastern Africa (Bosellini, 1989).

In the Kirthar and Suleiman Ranges of western Pakistan, at the western end of the Himalayan belt, upper bathyal to shelfal limestones of Turonian–Campanian age are overlain by a shallowing and coarsening-upward Maastrichtian succession including shelfal to fluvio-deltaic sandstones and pebbly sandstones (Mughal Kot and Pab Formations; Eschard et al., 2004). Such an abrupt influx of terrigenous detritus from the southeast, as indicated by facies distribution and paleocurrents, is ascribed to uplift of the Indian Craton as it passed over the Réunion "hotspot" (Smewing et al., 2002; Umar et al., 2011). From the Nepal Lesser Himalaya to the stable shelf province of the Bengal Basin, Lower

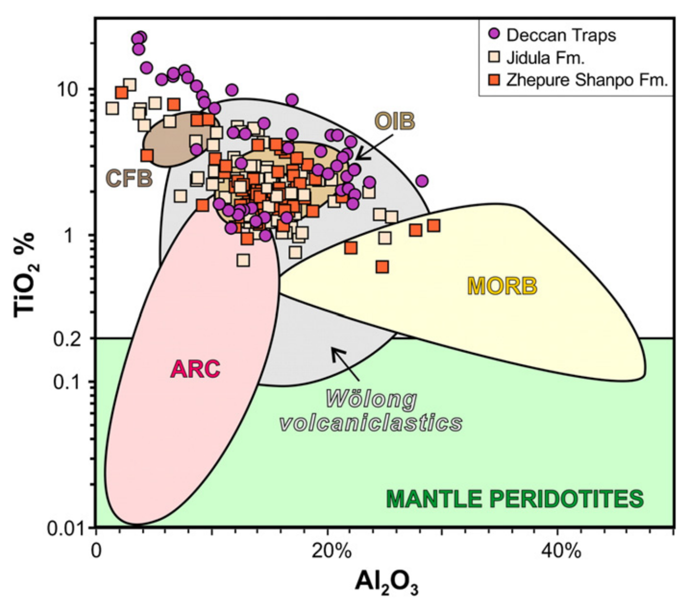


**Fig. 8.** Cr-spinel geochemistry. High-Ti detrital spinels in Maastrichtian to Danian sandstones of the Tethys Himalaya (dataset provided in Appendix Table A3) are virtually identical to spinels in Deccan basalts (data from Melluso et al., 2010), but markedly different from spinels in residual mantle peridotites or arc-related volcanic rocks. This confirms provenance from subcontinental India, and rules out erosion of ophiolites supposedly obducted onto the Indian margin in the Late Cretaceous. Fields in the $TiO_2$–$Al_2O_3$ plot after Kamenetsky et al. (2001): ARC = arc-related basalts; CFB = continental flood basalts; MORB = mid-ocean ridge basalts; OIB = oceanic island basalts. Field for Lower Cretaceous Tethys Himalayan Wōlong volcaniclastics after Hu et al. (2014).

Cretaceous basalts and volcaniclastic sandstones are overlain unconformably by Paleocene quartzarenites, indicating non-deposition or erosion during the Late Cretaceous (Sakai, 1989; Alam et al., 2003).

### 5.3. Clastic petrography

The Kangi La Formation exposed in the Zanskar-Spiti Synclinorium lacks sandstones. The terrigenous fraction increases in size and abundance in the upper part, where coarse silt represents up to 50% of the sediment. Silt-sized detritus consists dominantly of monocrystalline quartz, but includes subhedral plagioclase grains and biotite flakes altered in chlorite/vermiculite possibly derived from volcanic centers. Very fine to medium-grained Stumpata sandstones consist dominantly of monocrystalline quartz, with a few felsitic volcanic rock fragments, rare weathered feldspars, and durable heavy minerals including commonly rounded tourmaline, zircon and rutile. Etched subrounded quartz grains and ironstones at the top of the unit indicate intense subequatorial weathering (Nicora et al., 1987).

Very fine to very coarse-grained sandstones of South Tibet range from litho-quartzose volcaniclastic in the lowermost Zhepure Shanpo Formation to dominantly quartzose above and in the Jidula Formation (dataset provided in Appendix Table A1). Dominantly monocrystalline quartz is associated with felsitic volcanic rock fragments, chalcedony, a few weathered feldspars (K-feldspar, chessboard albite, minor plagioclase), sporadic phyllite grains or muscovite, and poor heavy-mineral suites including zircon, tourmaline, rutile, epidote and Cr-spinel. Carbonate clasts and bioclasts (mollusks, benthic or planktonic forams) are locally found in the Zhepure Shanpo Formation, whereas limonitized glaucony or illite–silica peloids are most common at the top of the Jidula Formation. Coarser sandstones are quartz-cemented and well to moderately-well sorted, whereas finer-grained sandstones also contain abundant interstitial phyllosilicates and pseudomatrix. Authigenic carbonates (calcite, Fe-dolomite) and Fe-oxides (limonite, hematite) occur locally. Such composition, influenced strongly by both subequatorial weathering and diagenesis, indicates mixed Continental Block, Volcanic Rift and Recycled Clastic Provenance, similar to passive-margin sediments supplied by rivers draining large flood-basalt provinces, such as the Nile, Orange or Zambezi (Fig. 5A; Garzanti et al., 2006, 2014a).

Maastrichtian sandstones exposed in the Kirthar and Suleiman Ranges are quartzose with weathered feldspars (mostly K-feldspar including microcline). Mafic volcanic rock fragments, inferred to have been derived from the erosion of Deccan lavas, increase upward, reaching 30% of detritus in the south (Fig. 5B; Fitzsimmons et al., 2005; Umar, 2008). Chemical indices point to strong weathering in humid climate, while India was passing across subequatorial latitudes (van Hinsbergen et al., 2011; Yi et al., 2011).

### 5.4. Zircon geochronology

The U–Pb ages of detrital zircons determined previously from a quartzarenite bed in the lower Jidula Formation of the Tingri section (Hu et al., 2012) are integrated here by new data obtained with the same method from a quartzarenite in the uppermost Jidula Formation of the Gamba section (Fig. 3; dataset provided in Appendix Table A2). The U–Pb age distribution of the Tingri sample shows two major Early Cretaceous (109–145 Ma; 28% of 72 analyzed grains) and Cambrian/late Ediacaran clusters (482–572 Ma; 15%). Precambrian ages fall in the 679–985 Ma (15%), 1075–1417 Ma (18%), 1644–2081 Ma (10%), 2268–2672 Ma (10%) and 3254–3362 Ma (4%) ranges. The Gamba sample shows the same Early Cretaceous (130–135 Ma) and Cambrian/late Ediacaran clusters (496–592 Ma); Precambrian ages fall mainly between 643 and 953 Ma and between 1627 and 1836 Ma, with an oldest age of 2861 Ma (Fig. 6). Spectra displaying virtually the same age clusters at 109–147 Ma (15% of 267 analyzed grains), 497–569 Ma (14%), 763–1018 Ma (18%), 1095–1445 Ma (8%), 1632–2071 Ma (23%), and 2307–2553 Ma (8%), with a few older ages scattered between 2708 and 3527 Ma, were recently obtained from two samples of Stumpata Quartzarenite in Zanskar (Clift et al., 2014). Early Cretaceous and Cambrian peaks are typical of zircon-age spectra from Tethys Himalayan sandstones (Gehrels et al., 2011), confirming Indian provenance from the south (Fig. 6). Specifically, Early Cretaceous zircon ages, more abundant in South Tibet but common in Zanskar as well, reflect the mega-volcanic event documented throughout northern India at that time (Sakai, 1989; Garzanti, 1993a,b; Hu et al., 2010), whereas Cambrian zircon ages reflect widespread felsic intrusions during the Pan-African orogeny (Garzanti et al., 1986; Gehrels et al., 2003; Cawood et al., 2007). Older zircons were ultimately derived from Precambrian rocks exposed in the Indian subcontinent farther to the south, including the Neoproterozoic Malani felsic volcanics and Erinpura granites, magmatic or metamorphic rocks of the Mesoproterozoic Delhi and Paleoproterozoic Aravalli orogenic cycles, and subordinately from the Archean craton stabilized by 2.5 Ma (Mondal et al., 2002; Malone et al., 2008; Kaur et al., 2011; Mishra and Ravi Kumar, 2014).

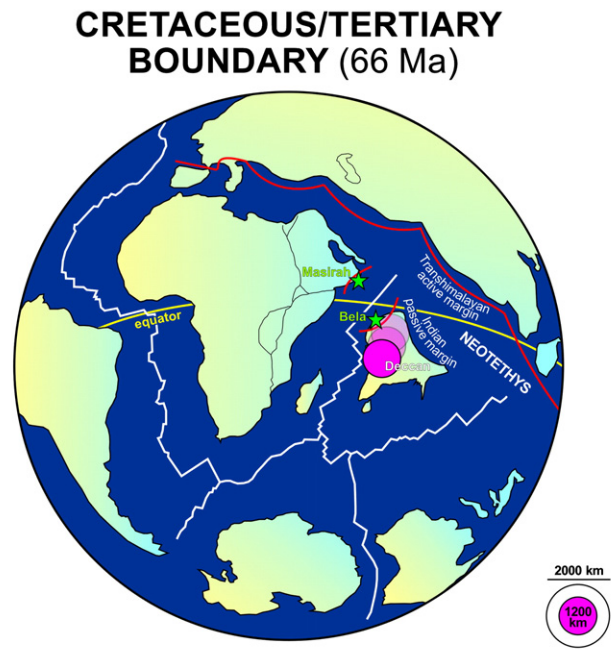


**Fig. 9.** The simple anorogenic scenario for the Tethys Himalaya in the latest Cretaceous/earliest Paleocene (reconstruction adapted from Cande and Stegman, 2011). Passive-margin evolution of northern India is indicated by stratigraphic and mineralogical data, while ophiolite obduction was taking place along the western transpressive boundary of the Indian plate, from Oman (Masirah) to western Pakistan (Bela, Muslim Bagh, Waziristan; Beck et al., 1996; Gnos et al., 1997).

### 5.5. Spinel geochemistry

Cr-spinel is the only common mineral hosted in mafic and ultramafic rocks that is chemically durable at the low temperatures of the Earth's surface. Having the best chances to survive weathering and diagenesis (Mange and Morton, 2007), it generally represents the sole tool available to detect mafic/ultramafic provenance in ancient sandstones. Its varied geochemical fingerprints reflect faithfully the origin of parent rocks (Dick and Bullen, 1984; Kamenetsky et al., 2001), and thus allow us to identify specific sources of detritus (Hu et al., 2014).

In the search for mafic volcanic or ultramafic ophiolite sources, several samples of Zhepure Shanpo and Jidula sandstones were crushed, and heavy minerals separated by elutriation methods. Cr-spinels were selected by hand-picking, mounted in epoxy, polished, and analyzed using a JEOL JXA-8100M electron microprobe at Nanjing University (method described in Hu et al., 2010; dataset provided in Appendix Table A3). Detrital Cr-spinels were found throughout the Maastrichtian

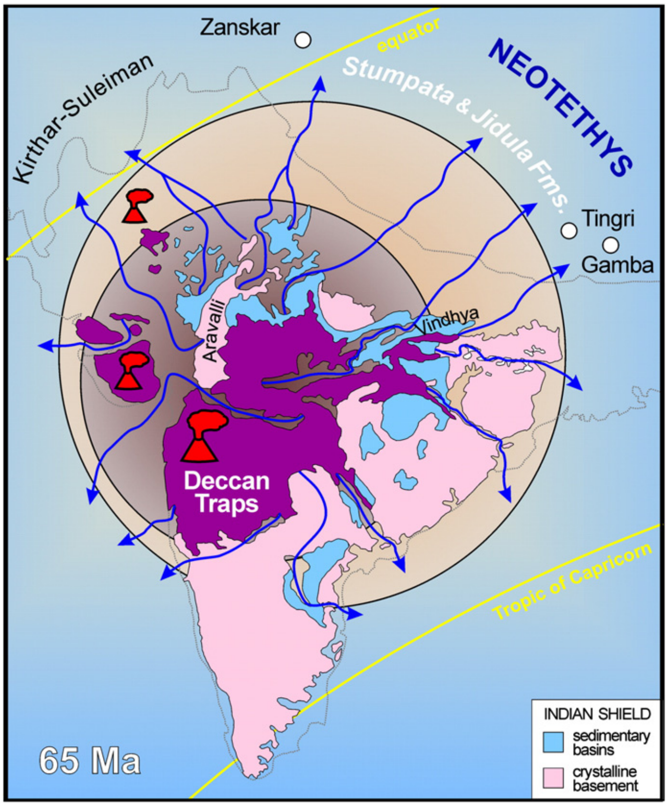


**Fig. 10.** Envisaged earliest Paleocene drainage pattern. Rivers sourced from newly erupted Deccan basalts and rejuvenated Precambrian Aravalli and Vindhya Ranges supplied quartzose sediments with volcanic rock fragments and Cr-spinel to the subequatorial shores of the Indian passive margin facing Neotethys.

to Danian succession, from the lower Zhepure Shanpo Formation to the top of the Jidula Formation (Fig. 3). Out of 170 grains, 163 have >1% $TiO_2$ and 9 have extremely high $TiO_2$ (5.7–11.0%), low $Al_2O_3$ (1.2–6.2%), and high $Cr_2O_3$ (34.8–51.7%; Cr# 0.79–0.96), a fingerprint that matches well that of Cr-spinels in Deccan flood basalts and not Ti-poor Cr-spinels derived from obducted ophiolites (Fig. 8). Discriminant analysis conducted with rigorous statistical methods (full methodological details and results provided in the Appendix) points to provenance from Deccan-related lavas for most Cr-spinels in the Zhepure Shanpo Formation. Many Cr-spinels in the Jidula Formation show closer affinities to Cr-spinels in Lower Cretaceous volcaniclastic rocks of the Tethys Himalaya (Wölong Formation; Jadoul et al., 1998; Hu et al., 2010, 2014), but several are still identified as Deccan-derived. Along with the common occurrence of detrital zircons with Lower Cretaceous ages, this indicates recycling of Mesozoic cover strata of the Indian margin, increasing progressively with time during deposition of the upper Zhepure Shanpo and Jidula Formations.

## 6. Too far? Too early?

After several hundred kilometers of orogenic shortening, Tethys Himalayan sedimentary rocks lie today between 1000 and 1500 km from the center of Deccan activity and ~500 km from the northernmost volcanic centers known, and paleomagnetic analyses indicate a latitudinal separation corresponding to an original distance possibly reaching 2000 km or more (van Hinsbergen et al., 2011, 2012). Could Indian-margin sedimentation have recorded geological events taking place so far away? Could tectonic uplift associated with magmatic upwelling have affected the northern Indian margin directly? And could this have taken place several Ma before the onset of volcanism?

Because our understanding of mantle processes is poor, opinions diverge widely as whether the causes of massive volcanic outbursts have to be found as deep as the core–mantle boundary (White and McKenzie, 1989) or at much shallower depth, associated with thermal or chemical heterogeneities in the asthenosphere (Anderson, 2011). Debating such controversial issue is far beyond the scope of this article, which is primarily concerned with the surface effects associated with the Deccan mega-volcanic event. According to plume theory (or 'myth'? Anderson, 2013), plume heads have a diameter of 2000–2500 km. Domal uplift of ~1 km starts when the plume touches the bottom of the upper mantle, and reaches maximum when the top of the head is at a depth of 250 km. For a further ~1 Ma uplift continues towards the margin of the head, while minor subsidence occurs at the plume axis (Campbell, 2007). Only minor alkaline eruptions accompany the maximum uplift stage, and initial surface swelling may precede the main phase of voluminous volcanism by as much as 20 Ma (Sahu et al., 2013). Because lithospheric plates move relative to the underlying mantle, thermal and dynamic effects are expected to be relatively short-lived at the site of initial impact, which is soon decoupled from the plume head (Saunders et al., 2007). Surface doming in the Deccan province has been considered as a classical example of plume-related uplift by advocates of mantle plumes, but challenged by skeptics, who emphasized post-eruption uplift of the basalt pile (Sheth, 2007). Timing and magnitude of denudation inferred from modeling of fission-track data are largely dependent on the assumptions adopted (Gunnell et al., 2003), and facies changes or unconformities may be ascribed alternatively to diverse autocyclic or allocyclic controls, including drainage diversions, climate changes, sea-level fluctuations or local tectonic activity (Sharma, 2007).

### 6.1. Too far?

Geological processes associated with the massive outburst of flood basalts affect large regions typically 2000 km in diameter (White and McKenzie, 1989; Rainbird and Ernst, 2001). The Tethys Himalayan passive margin thus lay at the margin of the area potentially uplifted by the Deccan event (Fig. 9). Subsidence analysis of the Gamba and Tingri sections suggests uplift of the sea floor since Campanian times (Fig. 7; Hu et al., 2012). The widespread Campanian hiatus associated with extensive reworking by oceanic currents and faunal mixing (Fig. 3) represents circumstantial evidence of inverted subsidence in Zanskar as well, but insufficiently precise assessment of paleobathymetry prevented us to conclusively establish whether tectonic uplift did affect the northwestern Indian margin directly (Sciunnach and Garzanti, 2012). This hypothesis is consistent with the reconstruction in Mahoney et al. (2002 their fig. 1), where the "hot-spot" trace is seen to pass quite close to the Zanskar Himalaya precisely at the base of the Campanian (83.5 Ma).

The good third of zircon grains in the Jidula and Stumpata sandstones clustering in the 105–145 Ma and 480–590 Ma age ranges were not derived from Precambrian India. Along with the upward-increasing abundance of Cr-spinels displaying chemical affinity with Lower Cretaceous magmatic rocks, they indicate erosion and recycling of Mesozoic sedimentary and volcanic cover strata of the inner Indian margin (e.g., Lesser Himalaya) and rejuvenation of the Pan African Orogen. Because such sources lay not far south of the presently exposed Tethys Himalaya, this represents further evidence of dynamic uplift of the Indian passive margin at the close of the Cretaceous.

Whereas surface uplift may be difficult to prove conclusively, erosion is certainly not. And the multifold increase of terrigenous supply recorded around the Indian subcontinent in the Maastrichtian, just before the outburst of Deccan lavas, speaks loudly in favor of uplift associated with magmatic upwelling. Sudden arrival along the Tethys Himalayan margin of large volumes of terrigenous detritus from India, including up to very-coarse-grained sand (Fig. 4F), testifies to rejuvenation of the subcontinent with consequent major effect on stratigraphic patterns. The quartzose composition of Maastrichtian/Danian siltstones and sandstones is ascribed to the combined effect of recycling, intense weathering in humid subequatorial climate, and subsequent diagenetic dissolution leading to selective breakdown of less durable grains (Fig. 5B, C; Garzanti et al., 2013). But common felsitic volcanic rock fragments and Cr-spinel, found recurrently in Maastrichtian to Danian sandstones, remain as faithful witnesses of continuous volcaniclastic supply. Geochemical fingerprints virtually identical to Deccan spinels (Fig. 8) are conclusive evidence that detritus from Deccan basalts was delivered via several fluvio-deltaic systems to the northern Indian passive margin, from western Pakistan (Umar et al., 2011) to Zanskar and South Tibet (Fig. 10). The radial drainage pattern originated by topographic doming during the Deccan megaevent still characterizes peninsular India today (Cox, 1989).

### 6.2. Too early?

The first traces of magmatic activity are found in western Pakistan, where submarine basalts and mafic alkalic sills chemically and isotopically similar to modern Réunion lavas have an age of ~70 Ma. Upwelling magmas postulated to represent the earliest manifestations of the Réunion "plume" thus reached the base of the Indian lithosphere first in the north, several Ma before the main phase of Deccan volcanism (Mahoney et al., 2002; Kerr et al., 2010). Consistent with relative northward motion of Indian lithosphere at ~15 cm/a over the nascent "hotspot", volcanism moved progressively southward. Isolated alkalic complexes ~600 km north of the main Deccan province are dated at 68.5 Ma (Basu et al., 1993). The earliest tholeiitic lavas were erupted at 67 Ma in the north of the Deccan province, whereas the most voluminous eruptions correspond broadly in time with the Cretaceous/Paleocene boundary at 66 Ma (Hofmann et al., 2000; Chenet et al., 2007; Keller et al., 2011). The thick lava pile shows southward overstepping by progressively younger units, and magmatism was younger by some 1–2 Ma in the southwest (Jerram and Widdowson, 2005). Mafic and felsic activity was renewed at 64–63 Ma, and the last phases took place at 63–61 Ma, associated with foundering of the newly formed volcanic rifted margin during final separation between India and the Seychelles–Mascarene plateau (Ganerød et al., 2011; Sheth and Pande, 2014).

If we compare such a succession of geological events with the Tethys Himalayan stratigraphic record, then we cannot fail to notice that siliciclastic deposition all along the northern Indian margin took place precisely between the onset of magmatism in western Pakistan (~70 Ma) and final drowning and separation of India from the Seychelles block (~62 Ma; Collier et al., 2008). Multifold increase in clastic supply from continental India during the Maastrichtian has no more plausible cause than enhanced erosion promoted by tectonic uplift associated with upwelling magmas. Equally evident is the perfect coincidence in time between the ubiquitous latest Danian transgression along the Tethys Himalaya and the onset of rapid thermal subsidence while India drifted away from the Seychelles block and Deccan magmatism eventually ceased.

Although the results of subsidence analysis remain partly ambiguous, extensive faunal reworking and widespread hiatuses point to generalized uplift of the sea floor during the Campanian (Fig. 7). Hardgrounds and appearance of macrofossils in Santonian pelagic limestones of Zanskar and Spiti suggest that surface swelling might have started here as early as ~85 Ma, almost 20 Ma before the climax of Deccan volcanism. Alternatively, this Santonian event may reflect an earlier distinct episode of dynamic uplift, associated with the separation of the India–Seychelles block from Madagascar and onset of spreading and volcanism in the Mascarene Basin (Bernard and Munschy, 2000; Torsvik et al., 2000; Calvès et al., 2011).

## 7. Conclusion

The Cretaceous to Lower Paleocene succession of the Tethys Himalaya records an entirely anorogenic evolution that both began and ended with flood-basaltic eruptions. Uplift associated with emplacement of the Rajmahal Traps (Garzanti, 1993b; Zhu et al., 2008) was followed by thermal subsidence and quasi-synchronous shelf drowning at the end of the Early Cretaceous. Widespread deposition of upper-bathyal foraminiferal oozes ensued. A similar cycle was repeated at the end of the Late Cretaceous. The widespread Campanian hiatus associated with resuspension and faunal reworking was followed by a major pulse of terrigenous supply and drastic increase in accumulation rates. This major erosional event recorded across the Indian subcontinent is ascribed to magmatic upwelling at the base of the Indian lithosphere, begun around 80–75 Ma or even some Ma earlier. The shallowing-upward Maastrichtian succession of the Tethys Himalaya is capped by Lower Paleocene coastal quartzarenites testifying to rejuvenation of the Indian subcontinent in the south. Volcanic rock fragments and Cr-spinels virtually identical geochemically to Deccan spinels resisted the coupled effect of strong weathering at subequatorial latitudes and subsequent diagenetic dissolution, and are preserved throughout the Maastrichtian to Danian succession. This "smoking-gun" evidence proves that detritus from Deccan lavas reached the passive margin of northern India (Fig. 10). At the close of the Danian (~62 Ma), transgression of marine carbonates documents a synchronous drowning event all along the Tethys Himalaya. Thermal subsidence took place at the same time as India moved away from the magma source and Deccan volcanism eventually ceased. The sedimentary record of the northern Indian margin excludes any postulated orogenic event associated with ophiolite obduction, arc–continent or continent–continent collision in the Late Cretaceous, and indicates that Neotethys remained open until the end of the Paleocene.

Supplementary data to this article, found online at http://dx.doi.org/10.1016/j.gr.2014.03.010, include the complete datasets on sandstone petrography (Table A1), zircon geochronology (Table A2) and spinel geochemistry (Table A3), along with the Appendix "*Provenance of Cr-spinels in the Zhepure Shanpo and Jidula Formations*: *a rigorous statistical approach*".

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