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Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian–Ordovician

Paul M. Myrow[1,*], Nigel C. Hughes[2,†], John W. Goodge[3], C. Mark Fanning[4], Ian S. Williams[4], Shanchi Peng[5], Om N. Bhargava[6], Suraj K. Parcha[7], and Kevin R. Pogue[8]

[1]*Department of Geology, Colorado College, Colorado Springs, Colorado 80903, USA*
[2]*Department of Earth Sciences, University of California, Riverside, California 92521, USA*
[3]*Department of Geological Sciences, University of Minnesota–Duluth, Duluth, Minnesota 55812, USA*
[4]*Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia*
[5]*State Key Laboratory on Paleobiology and Stratigraphy, Nanjing Institute of Geology and Paleontology, Nanjing 210008, China*
[6]*103 Sector 7, Panchkula, Harayana 160020, India*
[7]*Wadia Institute of Himalayan Geology, Dehra Dun, Uttranchal 248001, India*
[8]*Department of Geology, Whitman College, Walla Walla, Washington 99362, USA*

ABSTRACT

Detrital zircon samples from Cambrian and Lower to Middle Ordovician strata were taken across and along the strike of the Himalaya from Pakistan to Bhutan (~2000 km). By sampling rocks from one time interval for nearly the entire length of an orogen, and by covering a range of lithotectonic units, we minimize time as a significant source of variance in detrital age spectra, and thus obtain direct assessment of the spatial variability in sediment provenance. This approach was applied to the Tethyan margin of the Himalaya, which during the Cambrian occupied a central depositional position between two major mountain belts that formed during the amalgamation of Gondwana, the internal East African orogen and the external Ross-Delamerian orogen of East Gondwana. Detrital age spectra from our Lesser and Tethyan Himalayan samples show that well-mixed sediment was dispersed across at least 2000 km of the northern Indian margin. The detrital zircon age spectra for our samples are consistent with sources for most grains from areas outside the Indian craton that record Pan-African events, such as the Ross-Delamerian orogen; East African orogen, including the juvenile Arabian-Nubian Shield; and Kuunga-Pinjarra orogen. The great distances of sediment transport and high degree of mixing of detrital zircon ages are extraordinary, and they may be attributed to a combination of widespread orogenesis associated with the assembly of Gondwana, the equatorial position of continents, potent chemical weathering, and sediment dispersal across a nonvegetated landscape.

INTRODUCTION

Detrital zircon age spectra have been used as a means of reconstructing many aspects of Gondwana paleogeography, including provenance, patterns of sediment dispersal, and timing of orogenic uplift (e.g., DeCelles et al., 1998, 2004; Clift et al., 2001; Goodge et al., 2004b; Najman, 2006; Squire et al., 2006). Age spectra of detrital zircons provide a wealth of information, in part because they act as a census of the ages of (1) crystalline rocks exposed across a continental region at the time of sediment transport, and (2) zircons inherited from older sedimentary rocks. The relative proportions of zircon ages reflect the inputs of various sources, as controlled by the areal extent of different types of exposed bedrock, variability in bedrock zircon proportions, and differential erosion rates of the source rocks (Amidon et al., 2005; Dickinson, 2008). In addition, transport distance and cumulative input by erosion integrated along the transport path affect the final detrital age population. Certain age components may be particularly significant as an indicator of a specific provenance.

Detrital zircon age spectra for Cambrian samples of the Himalaya are of particular interest because the Cambrian Period witnessed the final amalgamation of core Gondwana (Meert and Van der Voo, 1997; Cawood and Buchan, 2007). In addition, Cambrian strata are found all along the strike of the Himalayan orogen from Pakistan to Bhutan (Fig. 1), reflecting widespread deposition across the northern Tethyan continental margin. They are also the only rocks of Phanerozoic age known to occur in all three of the northernmost lithotectonic zones of the Himalaya (Fig. 2), comprising sedimentary strata in the Lesser Himalaya to the south and the Tethyan Himalaya to the north, as well as protolith for part of the high-grade metamorphic assemblage of the intervening Greater Himalaya (Myrow et al., 2003). Much has been written about the sedimentary record of orogenic and active-margin processes in East and West Gondwana, particularly the East African, Ross-Delamerian, Cape, and Pampean orogenies that coincide with the base of the Phanerozoic (Rapela et al., 1988; Goodge, 1997; Veevers et al., 1997, 2006; Ireland et al., 1998; Dickerson, 2004; Goodge et al., 2002, 2004a, 2004b; Cawood, 2005; Squire et al., 2006). Together, this group of fold belts exhibits the interplay of tectonism and sedimentation over remarkable distances of the broader Terra Australis orogenic system (Cawood, 2005). By comparison, the ancient Tethyan margin of northern India is poorly understood. This is due in part to the strong overprint of Cenozoic deformation during the early history of the Himalayan orogen, incomplete biostratigraphic data, and limited study of Cambrian deposits in the Himalaya because of difficult access.

We present detrital zircon U-Pb age data for 11 Cambrian and Ordovician sandstone samples taken across the Himalaya in Bhutan, Tibet, northern India, and Pakistan (Figs. 1 and 2).

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[*]E-mail: pmyrow@coloradocollege.edu
[†]E-mail: nigel.hughes@ucr.edu

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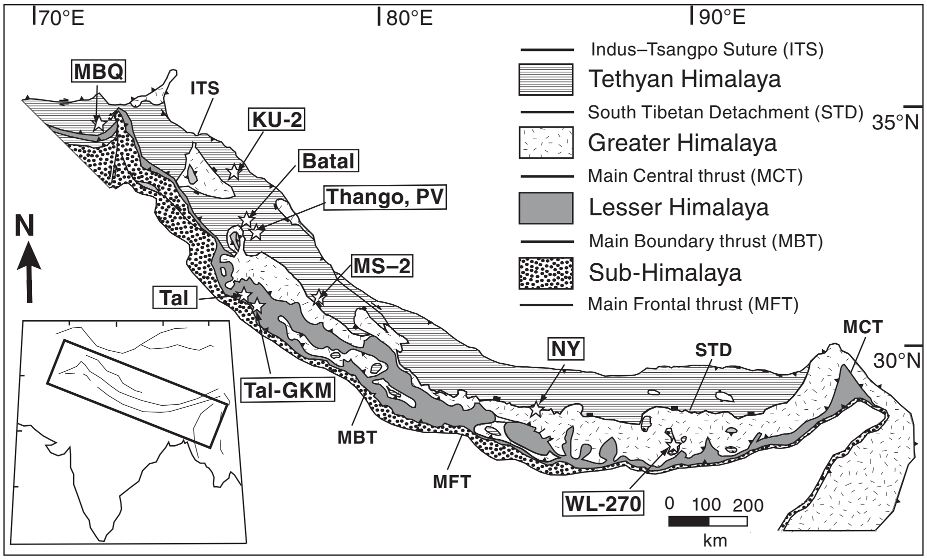

Figure 1. Lithotectonic zones, bounding faults, and locations of detrital zircon samples (in boxes).

By sampling from biostratigraphically well-constrained strata that accumulated during the last stages of Gondwanan assembly, we can evaluate the nature of sediment dispersal over a broad region of the northern margin of East Gondwana at that time. The provenance of various age components identified in these samples is interpreted with respect to specific potential sources based on the known present-day distribution of Precambrian crystalline rocks in the East Gondwanan cratons. Our results point to continental-scale distances of sediment transport, and an extraordinary degree and scale of terrigenous sediment mixing and homogenization.

HIMALAYAN REGIONAL GEOLOGY

Sedimentary and metasedimentary rocks of the northern three lithotectonic zones of the Himalaya (Fig. 1) consist of, from south to north, Proterozoic to Cambrian strata of the Lesser Himalaya (locally with overlying Permian rift deposits), high-grade metamorphic rocks of the Greater Himalaya, and Neoproterozoic through Cenozoic strata of the Tethyan Himalaya (Figs. 1 and 2). The geologic affinities of these lithotectonic zones, which have been structurally juxtaposed due to faulting associated with the Cenozoic collision of India and Asia, have been the subject of much recent debate (DeCelles et al., 2000; Myrow et al., 2003; Richards et al., 2005). Myrow et al. (2003) presented detrital zircon data from two samples (PV and Tal-GKM [which were labeled KL and GKM, respectively, in Myrow et al., 2003]) that demonstrated a similarity in age spectra between these Lower Paleozoic samples from the Lesser Himalaya and Tethyan Himalaya, with grain ages that span from Archean to Cambrian in both. The data help refute the claim that pre-Permian deposits of the Lesser Himalaya contain only Mesoproterozoic and older detritus (Parrish and Hodges, 1996; DeCelles et al., 2000, 2004; Martin et al., 2005; Richards et al., 2005), and instead support the hypothesis that the Lesser Himalaya, Greater Himalaya, and Tethyan Himalaya were part of a continuous northern passive margin of the Indian craton from the Neoproterozoic through the Cambrian (Brookfield, 1993; Corfield and Searle, 2000; Searle, 1996). Continuity of the three zones is also supported by Cambrian stratigraphy, paleocurrent data, and sedimentary facies relationships (Myrow et al., 2003, 2009; Hughes et al., 2005). This question of Himalayan stratal architecture is therefore of critical importance not only to our understanding of Himalayan orogen evolution, but also for earlier supercontinent paleogeography. In the present study, a larger suite of Lesser Himalaya and Tethyan Himalaya samples from along the length of the Himalaya was analyzed to determine the provenance and large-scale patterns of sediment dispersal within the Gondwanan supercontinent shortly after amalgamation.

DETRITAL ZIRCON ANALYSIS

We determined detrital zircon U-Pb age spectra for 11 samples collected from the Himalaya (Figs. 1 and 3; Table 1), two of which were taken from the Indian Lesser Himalaya, and nine of which were from across the Tethyan Himalaya. Zircons were prepared in polished grain mounts and analyzed by sensitive high-resolution ion microprobe (SHRIMP) at the Research School of Earth Sciences, Australian National University, following procedures given in Williams (1998, and references therein). Reflected and transmitted light photomicrographs were prepared for all zircon grains, as were cathodoluminescence (CL) scanning electron microscope (SEM) images. The CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~20 µm SHRIMP spots were wholly within the youngest single age component (i.e., the rims) within the sectioned grains. Analyses of 60–67 grains were completed for each sample (see GSA Data Repository[1]), with the exception of KU2, for which only 50 grains could be analyzed. The data were processed using the SQUID Excel macro of Ludwig (Ludwig, 2001). U/Pb ratios were normalized relative to a value of 0.0668 for the Temora reference zircon, equivalent to an age of 417 Ma (Black et al., 2003), except for sample Tal GKM, where the U/Pb ratios were normalized relative to a value of 0.01859 for the FC1 reference zircon, equivalent to an age of 1099 Ma (Paces and Miller, 1993). Uncertainties given for individual analyses (ratios and ages) are at the 1σ level (see GSA Data Repository [see footnote 1]). Correction for common Pb was either made using the measured $^{204}\mathrm{Pb}/^{206}\mathrm{Pb}$ ratio in the normal manner, or for grains younger than ca. 800 Ma (or those low in U and thus radiogenic Pb), the $^{207}\mathrm{Pb}$ correction method was used (Williams, 1998). When the $^{207}\mathrm{Pb}$ correction is applied, it is not possible to determine radiogenic $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ ratios or ages. In general, for grains younger than ca. 800 Ma, the radiogenic $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ age was used for the relative probability plots; the $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ age is also used for grains that are notably low in U, and therefore radiogenic Pb. The $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ age is used for grains older than ca. 800 Ma, or for those enriched in U. For these older grains, those >15% discordant have not been included in the relative probability plots.

The biostratigraphically constrained depositional ages of the strata sampled in this study range from terminal Early Cambrian to Ordovician. Sample Batal was collected at a locality close to the contact between the Tethyan Himalaya and Greater Himalaya in the Spiti Valley of northern India, within the Batal Formation, and is thus thought to represent the oldest Tethyan Himalaya sample of this study. The formation,

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[1] GSA Data Repository item 2010099, SHRIMP U-Pb data for zircon grains, Tera-Wasserburg and Wetherill Concordia plots, and comments on each sample, is available at http://www.geosociety.org/pubs/ft2010.htm or by request to editing@geosociety.org.

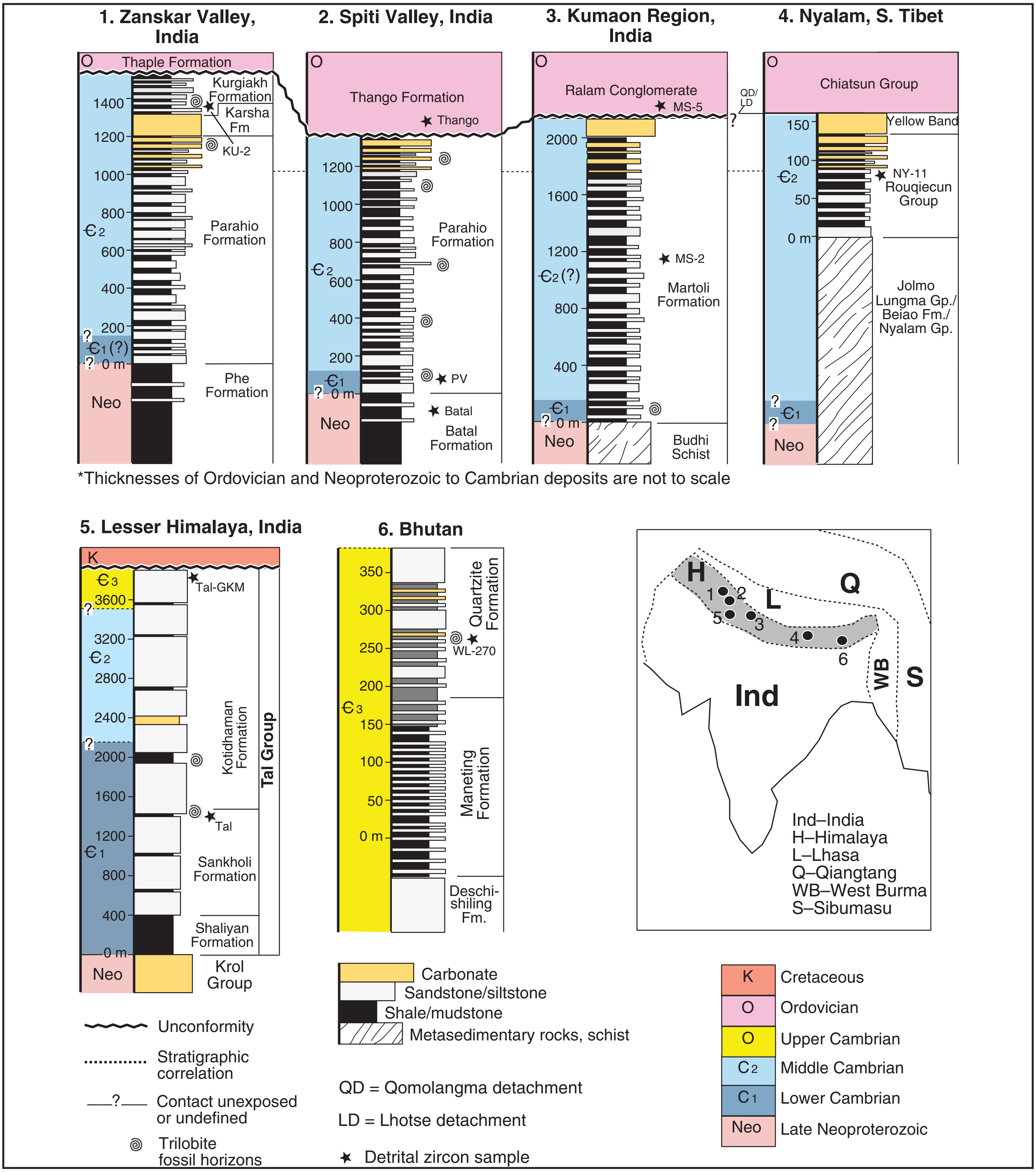

Figure 2. Cambrian stratigraphic sections with ages of strata and positions of trilobite fossil recovery. Data source: 1—Garzanti et al. (1986), Myrow et al. (2006a); 2—Brookfield (1993), Myrow et al. (2006b); 3—Kumar et al. (1984), Brookfield (1993); 4—Zhang (1988), Myrow et al. (2009); 5—Bhargava et al. (1984, 1998), Hughes et al. (2005); 6—Hughes et al. (2010). Inset map shows position of sections and adjacent tectonic zones. A stratigraphic section for sample MBQ is not shown.

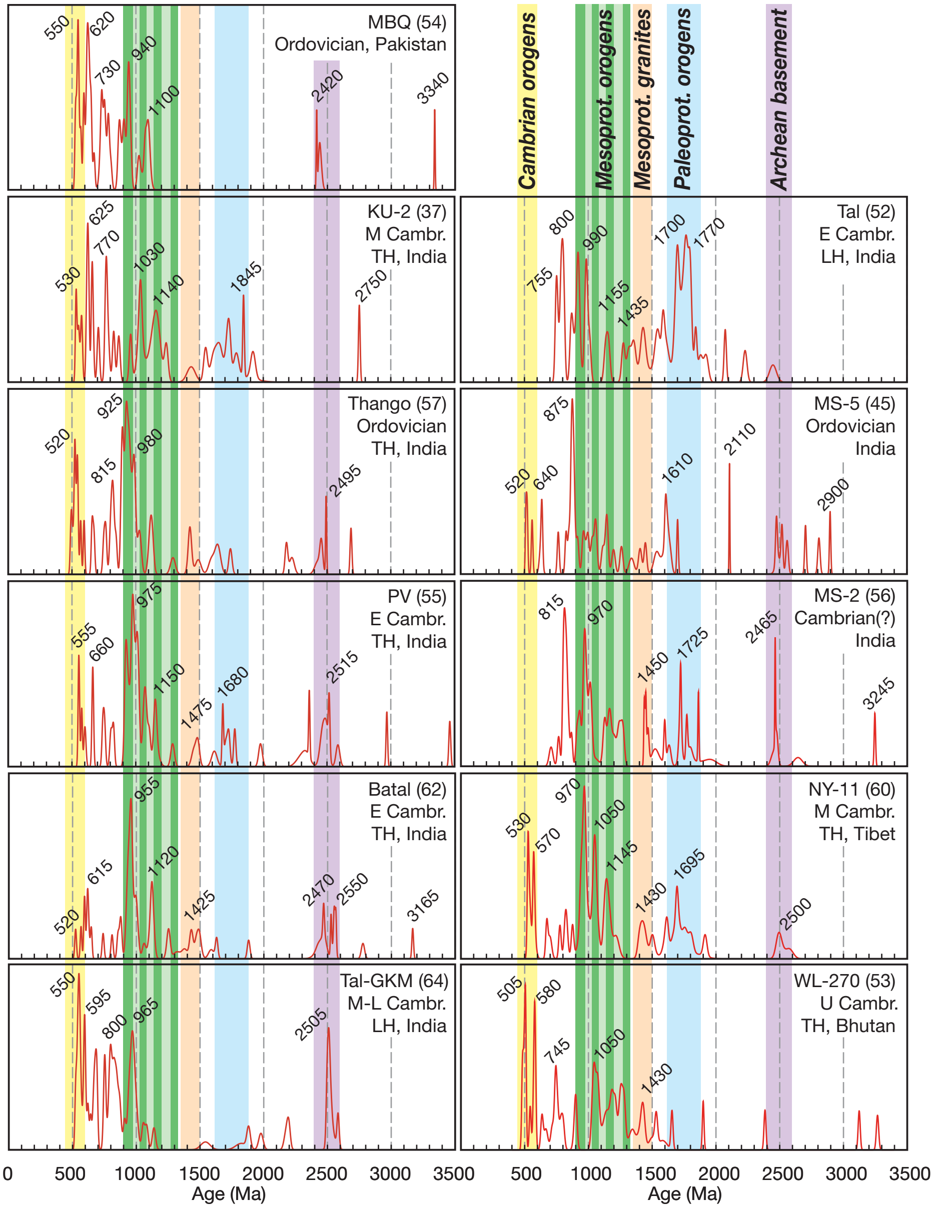

Figure 3. Detrital zircon age spectra from Cambrian and Ordovician strata across the Himalaya. Depositional ages, tectonic zones, and locations are given for each sample; see text for details. Number of grains analyzed is given in parentheses. Ages of prominent peaks are given to nearest 5 m.y. Tectonic zones: LH—Lesser Himalaya, GH—Greater Himalaya, and TH—Tethyan Himalaya. One grain in Tal-GKM yielded an age of 3526 ± 7 Ma, as listed in the GSA Data Repository (see text footnote 1), but it is not shown here.

which underlies the Early to Middle Cambrian Parahio Formation in this area, has generally been considered to be of Neoproterozoic age. However, one grain from this study (524 ± 7 Ma; see GSA Data Repository [see footnote 1]) contradicts this age estimate and indicates that the Batal is probably Cambrian. Sample MS-2 was taken from the Martoli Formation, which is exposed near Milam in the Kumaon region of northern India and from which an Early Cambrian trilobite has been reported (Kacker and Srivastava, 1996). Our sample was taken in the middle part of the formation, and the stratigraphic position of the recovered trilobite is unknown. Sample Tal from the Lesser Himalaya of northern India is from the *Drepanuroides* zone (Hughes et al., 2005) and is ~517 m.y. old (Peng and Babcock, 2008). Sample PV from the Tethyan Himalaya of the Spiti Valley is from the *Haydenaspis parvatya* level and is ~511 m.y. old (Peng et al., 2009). Sample Tal-GKM is younger than late Early Cambrian age and, based on inferred relationships with the Tethyan Himalaya, could be Late Cambrian in age or younger (Hughes et al., 2005). Detailed stratigraphic correlations with sections in northern India indicate that sample NY-11 from the Nyalam region of Tibet is from the middle Cambrian *Sudanomocarina sinindica* zone (Myrow et al., 2009; Peng et al., 2009), and likely has an age of ca. 507 Ma. Sample WL-270 was taken from the Quartzite Formation of the Wachi La region of the Black Mountains in Bhutan. It comes from a bed that contains the middle Late Cambrian trilobite *Kaolishania granulosa* and is ~493 m.y. old (Hughes et al., 2002, 2010). Sample KU-2 was taken from the *Lejopyge armata* zone in the Zanskar Valley of northern India (Myrow et al., 2006a) and is ~502 m.y. old (Peng et al., 2009). Sample MBQ is from the lower Misri Banda Quartzite, a few kilometers northeast of Nowshera, Pakistan, on the north bank of the Kabul River (Fig. 1; Pogue et al., 1992). These interbedded quartzite and argillite strata contain a specific form of the trace fossil *Cruziana* that dates the rocks as Ordovician in age (A. Seilacher, 2006, personal commun.). We did not measure a stratigraphic section at this locality. Sample Thango was collected from the Thango Formation of the Spiti Valley in rocks known to be of Ordovician age (Bhargava and Bassi, 1998; Suttner, 2007). This particular unit is a syntectonic molasse that records an enigmatic and controversial uplift event of Late Cambrian to Early Ordovician age (Srikantia, 1981; Miller et al., 2001; Gehrels et al., 2003; Myrow et al., 2006a, 2006b; Cawood et al., 2007; Paulsen et al., 2007). Finally, sample MS-5 comes from the Ralam Conglomerate, a correlative Ordovician red bed unit that unconformably overlies the Cambrian Martoli Formation in the Kumaon area of northern India (Bhargava, 1995; Hughes, 2002).

RESULTS

The samples in this study yield detrital U-Pb zircon ages that range from Archean (ca. 3500 Ma) to Ordovician (Fig. 3). Ten of the eleven samples contain minor Archean grains, a few with common peaks (e.g., ca. 3150 Ma). Many of the samples contain a prominent group of latest Archean to earliest Paleoproterozoic (ca. 2.5 Ga) zircons. Eight of the eleven samples contain a Mesoproterozoic subpopulation of ca. 1.4 Ga zircons (1.5–1.4 Ga), which make up ~3.5% to ~8.0% of the individual sample grain populations (Table 1).

All 11 samples have a large proportion of zircons between 700 and 1200 Ma, most with

TABLE 1. STRATIGRAPHIC AGE, AGE OF THE YOUNGEST DETRITAL ZIRCON GRAIN, AND PERCENTAGE OF 1.4–1.5 Ga GRAINS FOR EACH OF THE 11 SAMPLES IN THIS STUDY

Sample name	Stratigraphic age	Youngest grain (Ma)	% of 1.4–1.5 Ga grains
Batal	Early Cambrian	524 ± 7	~8.0
MS-2	Cambrian	707 ± 15	~5.4
Tal	Early Cambrian	747 ± 9	~5.8
PV	Early Cambrian	552 ± 5	~3.6
Tal-GKM	Middle-Late Cambrian	524 ± 7	0
NY-11	Middle Cambrian	526 ± 7	~6.7
WL-270	Late Cambrian	474 ± 12	~5.0
KU-2	Middle Cambrian	532 ± 6	0
MBQ	Ordovician	525 ± 5	0
MS-5	Ordovician	512 ± 5	~4.3
Thango	Ordovician	493 ± 7	~5.3

Note: Early Cambrian 542–513 Ma; Middle Cambrian 513–501 Ma; Late Cambrian 501–488 Ma; Ordovician 488–444 (Gradstein et al., 2004).

subpopulations of ca. 800, 950, 1000, and 1150 Ma. Of the 11 samples analyzed, only MS-2 and the Lesser Himalaya sample Tal lack a relatively large subpopulation of grains younger than 650 Ma. Tal-GKM, also from the Lesser Himalaya, contains ~23% zircons grains younger than 650 Ma. Finally, two of the three known Ordovician samples (Thango and MS-5) contain grains of reliable Ordovician age.

A few grains have dates that are younger than the known depositional age (GSA Data Repository [see footnote 1]). Two grains from sample KU-2 record Ordovician dates (424 ± 5 Ma and 484 ± 6 Ma), despite the biostratigraphically controlled Middle Cambrian age of the strata. The areas analyzed on these grains are enriched in common Pb, and since they are isolated analyses, they are interpreted to reflect areas that have lost radiogenic Pb. Thus, these grains are excluded from our relative probability plots. An age of ca. 300 Ma for one grain in sample MS-5 clearly reflects radiogenic Pb loss, given that the rock is Ordovician in age. Finally, two young grains in the Ordovician sample Thango at ca. 405 and 415 Ma are also interpreted to contain analyzed areas that have lost radiogenic Pb. These analyses have not been included in the relative probability plots (Fig. 3).

Statistical Analysis

We performed a statistical analysis of the data from all 11 samples to test our contention that the age distributions of these samples are remarkably similar. We ran a Kolmogorov-Smirnov (K-S) test, a nonparametric statistical analysis, to determine the degree to which each pair of samples is likely to have been derived from the same population of source grains (Table 2). For these data, all probabilities (p values) > 0.05 indicate a 95% level of confidence that the samples cannot be distinguished as coming from separate populations (Press et al., 1986; Berry et al., 2001; DeGraaff-Surpless et al., 2003).

Eight of the eleven samples show very high p values of paired comparisons. The p values range up to 0.976, and average at a high value of 0.418 (Table 2). These very high p values do not indicate statistically significant differences among the samples, and they strongly suggest that the samples were derived from a common underlying population. Although larger numbers of grains per sample might enable more subtle differences to be detected, the similarities in the peaks of the eight spectra are so striking that it is highly unlikely that their similarity is an artifact of sample size. The statistical analysis strongly supports the assertion of Myrow et al. (2009) concerning the detailed correlation of Cambrian strata across the Himalaya to unfossiliferous, relatively high-grade rocks on the slopes of Mount Everest and adjacent regions.

Three samples show distinctly less similarity, namely, Tal, Tal-GKM, and MBQ. Of these three, the Lesser Himalayan sample Tal-GKM is statistically indistinguishable from the Tethyan Ordovician Pakistani sample MBQ (p = 0.360) and from the Tethyan Ordovician sample Thango (p = 0.123). The Tal-GKM sample was taken from near the top of the Tal Formation within a thick unfossiliferous member, 1500 m above latest Early Cambrian strata. Hughes et al. (2005) and Myrow et al. (2003) considered the top of the upper member to be Middle or Late Cambrian in age based on lithologic correlations with Tethyan strata, but the similarity of the Tal-GKM distribution to that of our younger Tethyan Himalaya samples (Table 2) suggests that it may be Ordovician in age.

The sample Tal, which is the oldest of the precisely dated samples, does not contain any grains younger than ca. 682 Ma, most likely because such grains in our samples were provided by uplift and erosion of younger plutonic bodies associated with the final assembly of Gondwana. Sample Tal was apparently deposited just prior to these events, and thus did not receive these younger zircons. The presence of these grains, including a large peak at ca. 500 Ma, in the other samples diluted the proportion of older grains sampled. To explore this idea, we removed the youngest grains, arbitrarily chosen as <600 Ma, from all samples and reran the K-S test, which revealed that five of the remaining ten samples could not be distinguished from the Tal sample, as opposed to one sample with the complete data set. A similar change was obtained for Tal-GKM (five versus one samples) when grains <600 Ma were excluded. Finally,

TABLE 2. RESULTS OF KOLMOGOROV-SMIRNOV (K-S) TEST RUN ON THE DATA FROM ALL 11 SAMPLES IN THE STUDY

	Batal	KU-2	PV	MS2	Tal-GKM	Tal	WL-270	MBQ	MS5	NY-11	Thango
Batal		**0.367**	**0.976**	**0.727**	0.001	0.026	**0.117**	0.000	**0.798**	**0.579**	**0.089**
KU-2	**0.367**		**0.340**	**0.069**	0.035	0.035	**0.541**	0.002	**0.439**	**0.590**	**0.118**
PV	**0.976**	**0.340**		**0.855**	0.001	0.032	**0.135**	0.000	**0.628**	**0.428**	0.034
MS-2	**0.727**	**0.069**	**0.855**		0.001	0.033	0.008	0.000	**0.914**	**0.654**	0.029
Tal-GKM	0.001	0.035	0.001	0.001		0.000	0.013	**0.360**	0.006	0.002	**0.123**
Tal	0.026	0.035	0.032	0.033	0.000		0.001	0.000	**0.183**	0.014	0.000
WL-270	**0.117**	**0.541**	**0.135**	0.008	0.013	0.001		0.001	**0.124**	**0.206**	**0.054**
MBQ	0.000	0.002	0.000	0.000	**0.360**	0.000	0.001		0.000	0.000	0.006
MS-5	**0.798**	**0.439**	**0.628**	**0.914**	0.006	**0.183**	**0.124**	0.000		**0.795**	**0.085**
NY-11	**0.579**	**0.590**	**0.428**	**0.654**	0.002	0.014	**0.206**	0.000	**0.795**		0.037
Thango	**0.089**	**0.118**	0.034	0.029	**0.123**	0.000	**0.054**	0.006	**0.085**	0.037	

Note: These results reflect the input of both the determined ages and the errors for each grain. All probabilities (p values) > 0.05 indicate that the confidence that the pair of samples can be statistically distinguished is less than 95%. Note that three samples (Tal-GKM, Tal, and MBQ) are generally different from each other and from the other samples. The other eight have very high p values, reflecting very weak basis for their discrimination and thus a strong likelihood that they shared the same source.

the unusual nature of sample MBQ is supported by no change in the statistical distinctiveness of this sample with the reduced data set. However, as removing of grains decreases the chances of finding a statistically significant difference, these results should be viewed with some caution.

Sample MS-2 is the only other sample besides Tal that lacks grains younger than ca. 650 Ma (youngest grain 707 ± 15 Ma), yet it is still statistically indistinguishable from five of the ten other samples. With all grains <600 Ma removed from the full data set, the K-S test shows that MS-2 cannot be distinguished from eight of the other ten samples.

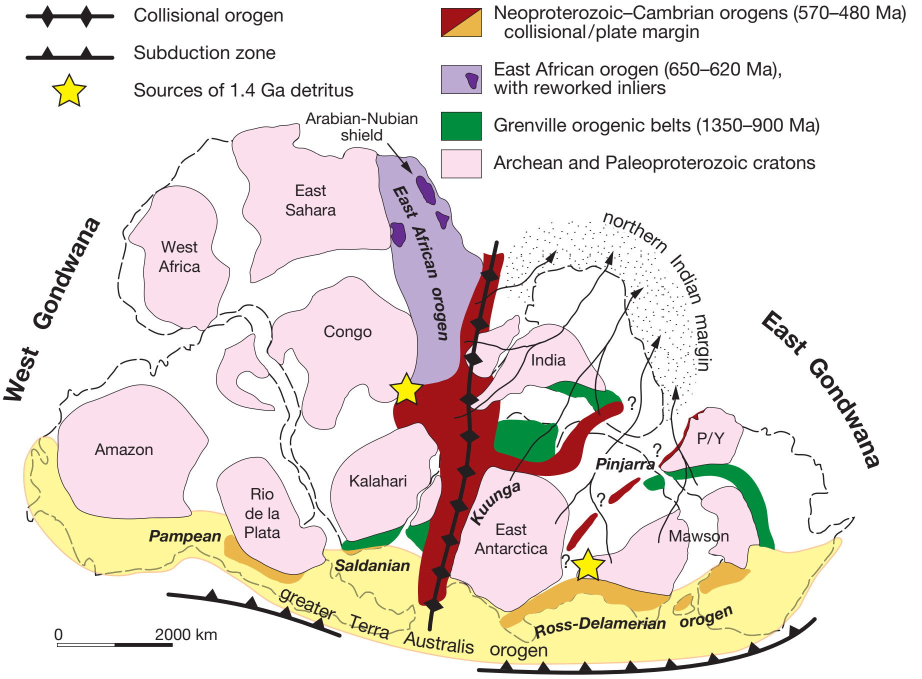

Figure 4. Reconstruction of Gondwana at ca. 500 Ma (modified from Boger and Miller, 2004; Cawood and Buchan, 2007). P/Y—Pilbara/Yilgarn cratons. The greater Terra Australis orogen of Cawood (2005) here includes the individual Pampean, Saldanian, and Ross-Delamerian orogens, active during late Neoproterozoic–Cambrian plate-margin convergence. The Mawson craton here includes the Gawler craton in southern Australia. Sediment transport paths are diagrammatic only and were likely more complex depending on the physiography at that time. Stars indicate potential sources of distinctive ca. 1.4 Ga igneous detritus (Goodge et al., 2004b, 2008; Kokonyangi et al., 2007).

INTERPRETATION

The late Neoproterozoic collision of East Gondwana (India, East Antarctica, Australia) with eastern Africa wedged the Indian craton between the East Antarctic and African cratons (Fig. 4). The northern passive margin of India was thus in a paleogeographic position to receive sediment shed from prominent, albeit distant, mountain belts developed during and immediately after Gondwanan assembly (Squire et al., 2006; Cawood et al., 2007). These include the internal East African orogen, including the juvenile Arabian-Nubian Shield; Kuunga-Pinjarra orogen; and the external Ross-Delamerian orogen, the latter of which spanned the region from the present-day Transantarctic Mountains to eastern Australia. The collisional East African orogen was active from ca. 680 to 500 Ma. Convergent-margin activity along the Ross-Delamerian orogen was likely diachronous, but Ross magmatic-arc activity had commenced by ca. 580 Ma (Cawood, 2005; Goodge et al., 2004a), and the onset of tectonic uplift and erosion in the central Transantarctic Mountains has been dated at ca. 515 Ma (Myrow et al., 2002; Goodge et al., 2004b). Final suturing of East and West Gondwana along the East African orogen, and onset of the Gondwana-margin Ross-Delamerian orogeny, may have been dynamically linked as internal Gondwana collision triggered external plate-margin convergence, perhaps associated with global reorganization of plate motions (Goodge, 1997; Boger and Miller, 2004; Cawood and Buchan, 2007).

Topographic relief created by various orogens at this time must have coincided with erosion and transport of sediment across various parts of Gondwana (Squire et al., 2006; Cawood et al., 2007), and one or more of these are the likely sources for the bulk of the widespread and voluminous deposits spread across the northern Indian margin. Some Neoproterozoic grains may have been derived relatively locally, as indicated by the presence of granite in the Lesser Himalaya dated at 823 ± 5 Ma (Singh et al., 2002). The grains that define the age peak between 500 and 560 Ma were most likely derived from widespread granite intrusions that occur throughout the Himalaya, including India, and in many regions around Gondwana (Debon et al., 1986; LeFort et al., 1986). Detrital zircons between 1.5 and 1.4 Ga may have also been derived from Indian sources, although most previous reports of rocks of this age have large geochronological uncertainties in the range of tens of millions of years; these include both K-Ar ages (e.g., 1474 ± 53; Murty et al., 1987) and Rb-Sr ages (1480 ± 40 Ma *in* Gopalan et al., 1979; 1404 ± 89 Ma *in* Sarkar et al., 1981; 1446 ± 67 Ma *in* Rathore et al., 2004). One well-dated Mesoproterozoic igneous unit from the suture zone between the Bandara craton and Eastern Ghats Province (Upadhyay et al., 2006) is a potential source area, although it is unlikely that the areal extent of these rocks, and their position within India, could explain the distribution of 1.4 Ga grains across the entire Indian margin.

East Antarctica–Australia

The small number of Archean grains found in our samples, including the subpopulation at 3.1–3.2 Ga, is compatible with sources within East Antarctica and Australia. These include the Lambert Rift area (southern Prince Charles Mountains) of East Antarctica, which was adjacent to eastern India within Gondwana (Fig. 4), and which contains a prominent suite of granitoids that were emplaced between 3.19 and 3.16 Ga (Boger et al., 2006). The Rayner Province of East Antarctica also contains abundant Archean rocks in the Napier complex and Ruker terrane, which are also a potential source for grains of this age (Harley and Kelly, 2007). The abundant ca. 2.5 Ga grains in our samples may have originated from the Diamantina craton, which consists of the combined north and south Australia cratons (Cawood and Korsch, 2008).

The significant populations of late Mesoproterozoic zircons, which record Mesoproterozoic to earliest Neoproterozoic (ca. 1300–900 Ma) continental accretion associated with the assembly of Rodinia (Rivers, 1997; Cawood and Buchan, 2007), may have been derived from Grenville-age rocks of the Kuunga orogen of East Gondwana. Older Grenville-age zircons could derive from the Albany-Fraser and Wilkes terranes of western Australia (Fitzsimons, 2000a, 2000b), which record two pulses of metamorphism and magmatism at 1330–1280 and 1200–1130 Ma. Our data from the Himalaya include grains of the latter age, but very few (≤2 grains per sample) in the range 1330–1280 Ma, and thus we consider this to be an unlikely source of sediment.

The Rayner, Rauer, and Maud Provinces of East Antarctica also contain abundant Mesoproterozoic and Neoproterozoic basement rocks (Boger et al., 2000; Fitzsimons, 2000b; Harley and Kelly, 2007), and thus could be possible sources for many of the grains dated between ca. 1500 and 800 Ma in our samples. The Rauer Province exposes basement rocks 1080–990 Ma in age, and the Maud Province exposes units with ages of 1180–1130 Ma and 1080–1030 Ma. The Grenville-age suture zone between the Rayner Province of East Antarctica and the Eastern Ghats Province of the Indian Shield is a very likely source for 990–900 Ma grains. The Rayner Province itself contains significant 1000–960 and 930–920 Ma sources, and rocks associated with this belt in Sri Lanka–South India and Lutzow–Holm Bay, Antarctica, are ca. 1040–1000 Ma in age (Fitzsimons, 2000a, 2000b).

There are no known exposed 1.4 Ga igneous rocks within either Antarctica or Australia (Wade et al., 2005; Goodge and Vervoort, 2006). However, abundant detrital zircons of this age exist in late Neoproterozoic and Early Cambrian autochthonous rift-margin sandstone deposits of Antarctica (Goodge et al., 2004b), which were shed outboard from presently ice-covered sources in the East Antarctic craton (Myrow et al., 2002). Recent discoveries of a large, isotopically distinctive 1.44 Ga granitic clast in glacial till from the central Transantarctic Mountains, and Hf isotope compositions for 1.4 Ga detrital grains in the Antarctic Neoproterozoic-Cambrian strata (Goodge and Vervoort, 2006; Goodge et al., 2008) indicate that a primary 1.4 Ga igneous source terrane exists beneath the ice cap of East Antarctica. This terrane represents a potential source for the 1.4 Ga Himalayan detrital grains described herein.

Our Himalayan detrital zircon data are consistent with sources from East Antarctic and Australian sources. Yoshida and Upreti (2006) suggested that the sources of Greater Himalayan samples were also most likely derived from the so-called Circum–East Antarctic orogen (= Kuunga orogen). The paucity of 3.4–3.6 Ga grains, and the abundance of 1.4 Ga grains, makes links with the cratons of Australia less likely (Veevers, 2000).

Dharwar Craton India-Madagascar

A potential Indian source for zircons between 3.4 and 2.9 Ga is the Dharwar region of southern India (Nutman et al., 1992, 1996; Peucat et al., 1995; Mojzsis et al., 2003; Jayananda et al., 2008) and its continuation into Madagascar. The prominent population of latest Archean to earliest Paleoproterozoic (ca. 2.5 Ga) zircons in our samples is consistent with an episode of metamorphism and granite intrusion of this age recorded in the southern Dharwar craton of southern India and Madagascar (igneous ages of 2.53–2.51 Ga) (Nutman et al., 1992; Peucat et al., 1995; Mojzsis et al., 2003; Cox et al., 2004).

East African Orogen

The mobile belt associated with the present-day Namaqua-Natal region of South Africa and adjacent Maud Province of East Antarctica was approximately equally distant from the northern Indian margin during the Cambrian. This Grenvillian province contains source rocks with ages between 1090 and 1030 Ma, and thus represents a potential source region for our Himalayan detrital samples. In particular, the Kibaran belt of Burundi and Rwanda in south-central Africa, adjacent to the Mozambique belt of southeast Africa (Kröner et al., 2003), contains granites that are 1100–900 Ma in age (Cahen et al., 1984). The Mesoproterozoic Nzilo Group of the Kibaran belt, situated in present-day southeast Africa at the juncture between the Congo craton and the Tanzania–Bangweulu block, is also a possible source area for our 1.4 Ga detrital grains. This belt of metasedimentary rocks contains a population of ca. 1500–1330 detrital grains (Kokonyangi et al., 2007), including a large subpopulation of ca. 1380 Ma grains, as well as abundant 1450–1400 Ma grains, thought to be derived from the Mitwabi Orthogneiss within the Kibaran belt (Kokonyangi et al., 2007). Late Neoproterozoic sedimentary rocks of the Molo Group of central Madagascar, which is placed in Rodinian reconstructions to the northeast of the Tanzania craton, also contain a small number of 1.4 Ga detrital zircons, as well as a large population of 600–1200 Ma zircons, and these were likely derived from African sources (Cox et al., 2004).

Younger grains in our Himalayan samples could also have been derived from the Pan-African Mozambique orogenic belt. The history of this orogen is quite complex and appears to record a series of events that range from ca. 700 Ma to 530 Ma. Early events include collision of the Tanzania-Congo cratons and Madagascar with the Maud Province–Kalahari craton (De Waele et al., 2003; Cox et al., 2004). Extensive high-grade metamorphism took place in southern Madagascar at ca. 560 Ma (Cox et al., 2004) and between 630 and 650 Ma in Tanzania (Kröner et al., 2003). Younger orogenic activity took place between 570 and 530 Ma (Meert, 2003), as recorded by regional metamorphism in Madagascar (Nédélec et al., 2000; Collins et al., 2003). This event, which represents the final assembly of core Gondwana, affected the Dharwar craton of India (Collins and Windley, 2002).

DeCelles et al. (2000) suggested that Himalayan detrital zircon spectra indicate sources in the Arabian–Nubian Shield, a northern extension of the East African orogen. Avigad et al. (2003) reported detrital zircon data from a Cambrian sample from that area, which yielded subpopulations with ages of 0.55–0.65, 0.9–1.1, 1.65–1.85, and 2.45–2.7 Ga (Avigad et al., 2003). The youngest subpopulation is consistent with a source directly from the Arabian–Nubian Shield. The older two subpopulations were attributed to the Saharan metacontinent and Saudi Arabian sources (Avigad et al., 2003). The nearest known source for the 0.9–1.1 Ga grains is the Kibaran belt, although the authors argue that ~3000 km transport of this detritus is unlikely based on textural characteristics of the deposit. Yoshida and Upreti (2006) consider the Arabian–Nubian Shield to be a less likely source for Himalayan deposits because of the overwhelming abundance of young (550–850 Ma) rocks and detrital grains in that region, and the likelihood that older sources there, which are exposed over small areas today, would have been very poorly exposed or unexposed in the Neoproterozoic to early Paleozoic.

DISCUSSION

The samples analyzed in this study were taken in order to determine the variability in detrital zircon ages along the length of the Himalayan orogen at a specific time interval, namely, the Early Cambrian to Early Ordovician, a period that records the final amalgamation of Gondwana. By choosing a suite of samples from a narrow time interval, controls on variation in age distributions are limited to spatial patterns of source terranes and sediment erosion and transport network, whereas temporal changes are of limited effect. Given the myriad ways in which a sedimentary deposit might have acquired different detrital zircon age patterns relative to exposed metamorphic and igneous rocks in the source region, the uniformity of the age spectra from the northern Indian margin is remarkable.

This is particularly true given the broad geographic range of our samples from Pakistan to Bhutan, a distance of more than 2000 km. This similarity is recorded in the presence and absence of particular detrital grain ages, and in many cases, it is also defined in terms of the relative proportions of specific age populations.

A simplified network of potential terrestrial sediment pathways that explains the available detrital zircon age data in the context of an open, north-facing Indian cratonic margin shows that the heads of these drainage networks lie generally in the upland areas of the orogens active at this time (Fig. 4). Erosion and fluvial transport of sediment across one or more parts of the intermontane system would capture and mix sediment from Pan African–age, Grenville-age, and older cratonic basement, in order of general abundance in the detrital records. Rivers traversing the remains of older orogens would also have had the potential to pick up the signature of earlier events. The broad arc of mountain belts framing the Indian craton may have focused sediment dispersal toward the northern Indian margin, where it became well mixed and relatively uniform in both its detrital age signature and, therefore, its apparent provenance. In detail, any particular drainage path depicted in Figure 4 was likely more complicated, owing in part to the uncertain existence of smaller mountain belts; for example, rocks underlying the present-day East Antarctic ice sheet (e.g., extension of the Pinjarra orogen into central East Antarctica, as speculated by Fitzsimons [2003]). Given the limits of our knowledge about the specific geomorphologic nature of mountains and rivers systems within orogens of this age, sediment transport paths may have been tortuous and included a considerable orogen-parallel component.

Nonetheless, it is clear that Gondwana assembly resulted in a broad and extensive set of mountain ranges (see Cawood and Buchan, 2007) that provided the sources, potential energy, and geographic controls on sediment dispersal that led to remarkably uniform provenance signatures during Cambrian–Ordovician deposition. Details, including relatively precise geometries of past orogens, and the nature and scale of distributary systems, are simply not possible given (1) the general absence of coeval fluvial strata for these marine rocks, and (2) the lack of exposure of rocks of this age over vast areas of west Gondwana.

Regionally, paleocurrent data from Cambrian and Ordovician strata of northern India, in both the Lesser and Tethyan Himalaya, indicate flow roughly from south/southwest to north/northeast (Ganesan, 1975; Bagati et al., 1991; Bhargava and Bassi, 1998; Myrow et al., 2006a, 2006b). Lesser Himalayan stratigraphy indicates a north- to northwest-facing passive margin setting from the Neoproterozoic through the Early Cambrian, including an extensive Neoproterozoic carbonate platform of the Krol Formation (Jiang et al., 2003). To the north, Tethyan Himalayan strata also record passive-margin deposition prior to the Cambrian–Ordovician boundary. At that time, there was an enigmatic tectonic event (Gehrels et al., 2003; Myrow et al., 2006a; Paulsen et al., 2007) that Srikantia (1981) referred to as the Kurgiakh orogeny, but that Cawood et al. (2007) named the Bhimphedian orogeny. The cause of this event is unknown, and workers have attributed the event to terrane accretion (DeCelles et al., 2000), fold-and-thrust belt tectonism (Gaetani and Garzanti, 1991; Shankar et al., 1999; DeCelles et al., 2000; Gehrels et al., 2003, 2006), and rifting (Murphy and Nance, 1991; Hughes and Jell, 1999; Wyss, 1999; Miller et al., 2001; Wiesmayr and Grasemann, 2002) along the Tethyan continental margin of northern Indian. In northern India, this event resulted in deposition of a coarse red-bed succession, from which our Thango, MS-5, and MBQ samples were taken (Myrow et al., 2006b). There are minor structural effects in the Tethyan of India for this event (Fuchs, 1982; Wiesmayr and Grasemann, 2002; Draganits et al., 2004; Myrow et al., 2006b; Paulsen et al., 2007), and there are little or no documented structural effects of this orogeny in the Indian Lesser Himalaya. Along strike in Nepal, there is evidence for regional deformation, melting of crust, and the emplacement of granite bodies at this time (ca. 490 Ma) (Gehrels et al., 2003; Cawood et al., 2007).

Even if some uplift and erosion of new source rocks took place in India at this time, eight of the eleven samples were taken from older Cambrian strata (i.e., older than 490 Ma), and, because no other tectonic events are recorded in rocks south of the present-day Himalaya and within India, it is unlikely that there were any geomorphic barriers to sediment transport across the Indian craton from distal sources at that time. It is also worth noting that Indian Ordovician samples (Thango, MS-5) show a similar detrital pattern to Cambrian samples, suggesting that no new inputs of sediment emerged in northern India at that time, except for grains younger than 500 Ma.

The sources outlined for the different populations evident in the detrital spectra indicate significant transport distances. Transport distances of 1000–2000 km within Laurentia were suggested for detrital zircons collected from Permian and Jurassic eolian sandstone samples taken from the Colorado Plateau (Dickinson and Gehrels, 2003). In this case, grain age populations indicate fluvial transport of sediment from Grenville, Pan African, and Paleozoic bedrock sources from the Appalachian orogen to the present-day Rocky Mountain region (Dickinson and Gehrels, 2003). Transport distances across the Laurentian craton of at least 3000 km are suggested for Neoproterozoic deposits in the Northwest Territories of Canada (Rainbird et al., 1992; Young, 1979). The transport distances suggested by the grain populations in our Himalayan study are of similar or greater magnitude. Previous authors have linked Himalayan zircons to distant sources, including the composite East African orogen and Arabian-Nubian Shield (DeCelles et al., 2000); Kuunga-Pinjarra orogen or circum–East Antarctic mobile belt (Squire et al., 2006; Yoshida and Upreti, 2006); and multiple sources, including Australia (Cawood et al., 2007). Our results are consistent with derivation from one or more of these distant sources. An East African orogen source, including the Arabian-Nubian Shield, would require a minimum of 2000–3000 km of transport, particularly for our eastern sites, and more than 5000 km if the 1.4 Ga grains were derived from the Kibaran belt. Kuunga orogen sources would also require a minimum of 2000 km, and more than 5000 km if 1.4 Ga grains were derived from sources in the East Antarctic craton.

In any case, by examining samples within a small window of well-constrained depositional ages from across the length of the Himalayan range, our data not only indicate extraordinary transport distances, but a high degree of sediment mixing and homogenization. Statistical analyses of modern river sediment samples along an ~250 km stretch of the Himalayan front indicate that very similar detrital zircons populations can be produced over large but proximal parts of a single orogen (Amidon et al., 2005). The relative proportions of the zircon ages in our Cambrian samples from the Himalaya are somewhat variable, as one might expect, given that they cover a distance of ~2000 km along the modern Himalayan orogen. Despite this, some samples separated by as much as ~1300 km do in fact have remarkably similar spectra, e.g., NY-11 and KU-2 (Fig. 3). Thus, not withstanding many factors that can produce variability in heavy mineral populations (Morton and Hallsworth, 1999; Garzanti et al., 2004), including zircons (Amidon et al., 2005), the great distances of sediment transport within the Gondwanan supercontinent resulted in similar age populations of detrital zircon grains along the entire northern Indian margin. This does not rule out the possibility that some of the detrital grains were derived more proximally from lower-relief source rocks within the Indian Shield, but such sources cannot explain the lateral consistency of our age spectra.

The large distances of transport and degree of sediment mixing that we illustrate for the Himalaya likely apply to much, if not the whole of Gondwana (Squire et al., 2006). In this regard, both transport distances and sediment mixing within early Gondwana are extraordinary for the geologic record. The causes of such a pattern might be unique to time and place, and may include a combination of (1) lack of continental vegetation, (2) clustering of continents near the equator, (3) increased continental weathering rates, (4) widespread uplift and erosion associated with regionally extensive and relatively synchronous orogenesis recording supercontinental amalgamation, and (5) production of significant relief, providing stream power for large-scale river systems.

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