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Documenting basin scale, geometry and provenance through detrital geochemical data: Lessons from the Neoproterozoic to Ordovician Lesser, Greater, and Tethyan Himalayan strata of Bhutan

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ABSTRACT

Detrital zircon (DZ) ages, augmented with εNd(0) and $\delta^{13}C$ isotopic values from 18 new and 22 published samples collected from Lesser Himalayan (LH), Greater Himalayan (GH) and Tethyan Himalayan (TH) rocks in Bhutan, support deposition of >7 km of sedimentary rock in late Cambrian–Ordovician time and provide a stratigraphic framework for the pre-collisional Indian margin. Youngest GH DZ grains become younger upsection from 900 Ma to 477 Ma. Youngest DZ grains in TH samples are ~490–460 Ma. Both the LH Jaishidanda Formation (Fm), and the LH Baxa Group overlie Paleoproterozoic LH rocks. The Jaishidanda Fm exhibits distinct populations of youngest DZ peaks, 475–550 Ma, and 800–1000 Ma. The Baxa Group (Manas, Pangsari, and Phuntsholing formations) contains youngest DZ peaks at both 500–525 Ma and 0.9–1.0 Ga. However, most samples from the Baxa Group in western Bhutan contain no grains younger than 1.8 Ga. Samples from the LH Paro Fm, which sits directly under the MCT in western Bhutan, have youngest DZ peaks at 0.5, 0.8, 1.0, 1.7, 1.8 Ga. εNd values generally match DZ spectra, with samples that contain old, youngest grain populations corresponding to more negative εNd signatures. The Paro Fm is an exception where εNd (0) values from quartzite samples are quite negative (−19 to −24) whereas the εNd (0) values from interbedded schist contain younger detritus (−12 to −17). $\delta^{13}C$ values from the Jaishidanda, Paro and Manas formations have $\delta^{13}C$ values (−1.8 to +6) suggestive of deposition over late Neoproterozoic to Ordovician time. $\delta^{13}C$ values from the Pangsari Fm vary from −2.8 to +1.8, compatible with deposition in the early- to middle Neoproterozoic. The young, latest Cambrian–Ordovician grains preserved in TH, GH and LH rocks suggest that the late Cambrian–Ordovician orogeny, documented in GH rocks throughout the orogen, served as a significant sediment source in Bhutan.

1. Introduction

In orogenic belts such as the Himalaya, where much of the original sedimentary package has been significantly metamorphosed, deriving the original stratigraphy and geometry of the pre-collisional sedimentary basin is challenging, but fundamentally important. Although subject to uncertainties in depositional age, source area and basin extent, the task of documenting the original stratigraphic architecture of an orogen is critical because the geometry, thickness and lateral continuity of sedimentary basins exert a first-order control on fold-thrust belt structures and deformation geometry (e.g., Mitra, 1994; McQuarrie, 2004; Mitra et al., 2010; Long et al., 2011a, 2011b). The vertical distribution of rock types exerts the strongest control on the locations of weak decollement horizons, which fundamentally control the large-scale dimensions of an orogenic belt (i.e., critical taper) (Davis et al., 1983; Dahlen and Suppe, 1988; Dahlen, 1990). Lateral variations in basin geometry (and therefore, initial taper) as well as lateral variations in strength and distribution of weak stratigraphic horizons may result in different thrust offset magnitude, different thrust geometries, and distinct structural styles both along and across strike in a thrust belt (Mitra, 1994; McQuarrie, 2004). Correlations of stratigraphy and structures along-strike are interrelated and critical in this process. An understanding of the stratigraphy, geometry, and spatial variations of pre-deformational basins can also result in definition of overlap sequences that can greatly aid in differentiating deformation timing and extent in polymetamorphic rocks. Thus, correctly identifying these basin parameters is essential to understanding an orogen at both local and regional scales.

In the Himalayan orogen, documenting the location and distribution of Neoproterozoic through Ordovician deposits can provide insight into the extent, nature and magnitude of pre-Himalayan deformation, the potential for significant lateral variations within the original margin

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architecture, and the control regional basins exerted on the location and deformation path of modern Himalayan structures. In this manuscript we present detrital zircon (DZ) ages augmented with both whole-rock Nd and $\delta^{13}C$ isotopic values from 18 new and 22 published samples collected from LH, GH and TH rocks in the eastern Himalayan kingdom of Bhutan. From this data we can argue for Neoproterozoic through Ordovician deposition in rocks interpreted as belonging to the LH, GH and TH zones. Although our data show that all three tectonostratigraphic zones experienced deposition over this time window, there is significant variation in provenance expressed as DZ spectra and εNd values. We suggest that this variation is a function of proximity to source regions, locations of major rivers, and basin scale geometry. This provides insight into larger, margin-wide deposition over this time window that is critical for constructing pre-Himalayan stratigraphic architecture.

2. Himalayan background

The ongoing collision between India and Asia, which began ca. 60–55 Ma (LeFort, 1975; Klootwijk et al., 1992; Rowley, 1996; Hodges, 2000; Guillot et al., 2003; DeCelles et al., 2004; Leech et al., 2005), has deformed the original sedimentary cover that blanketed the northern Indian craton, thereby constructing the Himalayan orogenic belt. Throughout Cenozoic time, India has moved northward with respect to Asia, and as a result, large, south-vergent thrust sheets have buried, metamorphosed and then displaced the original basin stratigraphy. Since they are now deformed and translated to the south along their entire east–west length, many questions remain regarding the spatial and temporal architecture of the original, composite sedimentary basin (e.g., Brookfield, 1993; Valdiya, 1995; Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003; Myrow et al., 2003; Yin, 2006; Myrow et al., 2010). The problem is further compounded because the Himalayan tectonostratigraphic packages were originally defined by the relationships of rocks to orogen-scale structures such as the Main Central thrust, which is recognized along the full length of the orogen (Gansser, 1964; LeFort, 1975; Hodges, 2000; Yin, 2006). These major structures were originally identified based on significant changes in metamorphic grade, such as abrupt juxtaposition of higher-grade rocks over lower-grade rocks (Heim and Gansser, 1939; Gansser, 1964; LeFort, 1975). From south to north, the classic tectonostratigraphic subdivisions and major bounding faults are the Indo-Gangetic foreland basin, the Main Frontal thrust, the Subhimalayan zone, the Main Boundary thrust (MBT), the Lesser Himalayan (LH) zone, the Main Central thrust (MCT), the Greater Himalayan (GH) zone, the South Tibetan detachment system (STDS), the Tethyan Himalayan (TH) zone, and the Indus-Yalu suture zone, which marks the northern limit of rocks associated with India (Fig. 1).

Geochemical signatures from DZ and/or εNd of LH, GH, and TH strata have been used to define stratigraphic horizons, help identify important geologic structures, and determine unroofing histories (e.g., Parrish and Hodges, 1996; Robinson et al., 2001; DeCelles et al., 2004; Martin et al., 2005; Richards et al., 2005, 2006; Imayama and Arita, 2008; McQuarrie et al., 2008; Myrow et al., 2009, 2010; Tobgay et al., 2010; Long et al., 2011a; Webb et al., 2011; Spencer et al., 2012). These lithotectonic units record the pre-collisional geologic history of the greater Indian margin, and the geochemical datasets mentioned above, combined with stratigraphic and structural relationships observed in the field, allow us to reconstruct their original basin architecture.

3. Bhutan tectonostratigraphy

We highlight the critical data on lithologic characteristics, DZ ages, εNd(0) values and $\delta^{13}C$ isotopic ratios for major formations in the Bhutan Himalaya in Table 1. The formations are organized with respect to their main tectonostratigraphic zones (TH, GH, LH) from north to south (Fig. 2). Studies in the Bhutan Himalaya have highlighted important variations to the simplified Himalayan tectonostratigraphy outlined in Section 2. The most critical of these is the definition of the TH. While in many places the TH is separated from the GH by a large top-to the north shear zone (Burchfiel et al., 1992; Grujic et al., 2002; Webb et al., 2007), Long and McQuarrie (2010) argued that in Central Bhutan, that shear zone is either missing, or broadly distributed through a 10 km section of both GH and TH rocks. Because of the lack of a distinct bounding structure, they defined the GH–TH contact at the base of the clean, cliff forming quartzite of the Chekha Formation (Gansser, 1983; Long and McQuarrie, 2010) that is typically in the immediate hanging wall of mapped portions of the STDS through Bhutan (Grujic et al., 2002) and we follow that definition in this paper. Also unique to Bhutan is the occurrence of GH rocks over a significant portion of the Bhutan landscape. Grujic et al. (2002) divided the Bhutan GH section into a lower structural level above the MCT and below a younger, out-of-sequence structure, the Kakhtang thrust (KT), and a higher structural level above the KT (Fig. 1). The higher structural section contains the bulk of leucogranite exposed in Bhutan (Gansser, 1983; Swapp and Hollister, 1991; Davidson et al., 1997). Our discussion of GH rocks is completely focused on the lower structural level between the MCT and the KT. Following Gehrels et al. (2011), the LH strata above the MBT and below the MCT are divided into a lower LH section composed of Paleoproterozoic age strata while Neoproterozoic and younger LH strata are grouped in an upper LH section (Table 1).

4. Methods

4.1. U–Pb geochronology

U–Pb geochronologic analyses were conducted on individual grains using laser-ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the University of Arizona LaserChron Center (Gehrels et al., 2006b, 2008) (Appendix 1). Approximately 100 grains were dated per sample, although for samples that did not contain 100 dateable grains, all available zircons were analyzed. Low zircon yields were common for Baxa Group rocks in western Bhutan (BU10-93, BU10-73, and BU10-64). We analyzed two TH samples, seven samples from the GH section (Fig. 1) and nine samples from the LH Baxa Group (Fig. 3, Tables 1, 2). The seven GH samples were selected so that when combined with previously published samples, the data cover a broad geographical area as well as provide data from the base to the top of the section. The TH samples were collected from Chekha Formation quartzite immediately above the STDS. For the LH samples, we focused our sampling in western Bhutan to complement published data from eastern Bhutan (McQuarrie et al., 2008; Long et al., 2011a). In particular, we sampled the coarsest quartzite beds in the Pangsari and Phuentsholing formations, as well as a range of beds in the Manas/Jainti Formation.

Reported uncertainties for individual analyses are at the 1σ level (Appendix 1). In general, $206Pb^*/238U$ ratios were used for ages younger than 1.0 Ga, and $207Pb^*/206Pb^*$ ratios were used for ages older than 1.0 Ga (asterisk denotes correction for common Pb; all ages described in the text have had this correction). Other possible sources of error, in addition to instrument errors (Appendix 1), include uncertainties in U decay constants, common Pb composition, and calibration to the zircon standard used. These errors could shift the age-probability peaks by up to ~3% (2σ). These external uncertainties provide a minimum uncertainty on sets of ages (e.g., a peak on an age-distribution diagram). Analyses that are >30% discordant (by comparison of 206Pb/238U and 206Pb/207Pb ages) or >5% reverse discordant were not considered further. Acceptance of analyses with up to 30% discordance allows us to include most of the age information from each sample, and therefore yields a more complete and accurate description of provenance components. After a general 30% discordancy filter was applied, a few GH samples displayed a population of young ages that are pulled off of concordia and project to an