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Geologic Map of Bhutan

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Abstract

We present a new, 1:500,000-scale geologic map of the kingdom of Bhutan, and surrounding areas of India and southern Tibet. The map is a compilation of the most complete and most recent mapping datasets available, and presents an unprecedented amount of structural data when compared to previous published geologic maps of Bhutan. The map is a combination of: 1) new data presented in this study; 2) compilation of small-scale, published geologic maps of specific areas of Bhutan, Tibet, and parts of India; and 3) compilation of specific areas of published, country-scale geologic maps of Bhutan. Mapping detail is focused primarily on Subhimalayan, Lesser Himalayan, and Greater Himalayan rocks, with a lower level of detail on Tethyan Himalayan rocks. We present new 3-part stratigraphic divisions for the Siwalik Group and the structurally-lower Greater Himalayan section, and compile detailed stratigraphic divisions and structural geometries for the Lesser Himalayan section and Paro Formation. We also compile detailed mapping of the Yadong cross-structure and other structurally-complex areas of southern Tibet, and present new locations for the South Tibetan detachment. Our map compilation also highlights specific areas in Bhutan that would benefit from future geologic mapping. It is our hope that this map will be a valuable tool to be utilized by Bhutanese geologists, future researchers visiting Bhutan, and travelers and trekkers as well. We also hope that this map will serve as a new starting point for future mapping in Bhutan and throughout the Himalayan orogen.

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1. Introduction

Despite being the world's type locality for active continent-continent collision, and being the highest, most scenic, and most well-known mountain range, the Himalayan-Tibetan system remains one of the more incompletely mapped, and thus least understood, orogenic belts. The primary reason for this is that access to many Himalayan countries for the purpose of scientific research has only come in the last 20-30 years. This is particularly true for the eastern quarter of the Himalayan range, which occupies, from west to east, the state of Sikkim, India, the kingdom of Bhutan, and the state of Arunachal Pradesh, India.

In the kingdom of Bhutan, which is the focus of this study, access for geological research was limited primarily to geologists from the Geological Survey of India, until pioneering efforts by Swiss (ETH) professor Augusto Gansser in the 1960's, Princeton University professor Lincoln Hollister since the 1980's, and Dalhousie University professor Djordje Grujic since the 1990's, helped form collaborations with the Bhutanese government that paved the way for more outside researchers. In this study, our collaboration with Bhutan's Department of Geology and Mines has provided us with the opportunity to collect map data over virtually the entire country.

In this study, we present a new, 1:500,000-scale map of the country of Bhutan, and surrounding areas in Tibet, Sikkim, and Arunachal Pradesh. On it we present an extensive amount of map data from our own field work, which was performed between 2006 and 2010, some of which has been published in detailed maps accompanying journal articles (McQuarrie et al., 2008; Long and McQuarrie, 2010; Long et al., 2011a;b; Tobgay et al., 2010), and some of which is new data presented for the first time in this study. We also compile map data in specific locations from published country-scale geologic maps of Bhutan, primarily from Gansser (1983), and from published mapping in specific areas of northern Bhutan and southern Tibet (Chakungal et al., 2010; Edwards et al., 1999; Wu et al., 1998). The map is digitized, in color, georeferenced (WGS 1984), and gridded every 15 minutes of latitude and longitude, with major roads, passes, and rivers located, and large towns and high peaks labeled. This map is a compilation of the most complete and most recent mapping datasets available from Bhutan, and it is our hope that it will be utilized not just by future researchers, but by travelers as well.

2. Previous Work

Prior to this study, two 1:500,000-scale geologic maps of the country of Bhutan, which accompany books (Bhargava, 1995; Gansser, 1983), were available. The map of Gansser

(1983) presents detailed, high-quality mapping along several transects, primarily in Greater Himalayan (GH) and Tethyan Himalayan (TH) rocks. However, Gansser does not present a significant amount of structural data in Lesser Himalayan (LH) rocks, and makes only general LH unit divisions (e.g. Long et al., 2011b; McQuarrie et al., 2008). Gansser's map is hand-colored, not available in a digital version, very difficult to georeference when scanned, and presents dip values in ranges of 20°-30°, making structural symbology difficult to interpret in many areas. Also, the book and map are currently out of print. We compile data from Gansser's map in many areas of Bhutan, particularly in TH rocks and in the structurally-higher GH section (see Data Sources inset on map).

The geologic map of the Geological Survey of India, which is presented in Bhargava (1995), is digitized and easy to read. However, the map presents very little strike and dip data, and many structural and stratigraphic contacts as drafted on this map are incompatible with the rugged topography of the region. The level of stratigraphic division of LH units on Bhargava (1995) is greater than that of Gansser (1983). However, the level of detailed mapping and unit division of GH rocks, which cover the majority of Bhutan, is very basic compared to Gansser (1983). Also, like the Gansser (1983) map, the Bhargava (1995) map is very difficult to georeference when scanned. We compile only a minor amount of data from the Bhargava (1995) map (see Data Sources inset on map).

Detailed geologic maps of parts of Bhutan recently published by our own Princeton research group provide approximately half of the map data compiled in this study. Long et al. (2011a) presented a 1:250,000-scale map of eastern and central Bhutan, which is a comprehensive map that compiled mapping published in Long and McQuarrie (2010); Long et al. (2011b); McQuarrie et al. (2008). The Long et al. (2011a) map is the largest single component of our compilation. Tobgay et al. (2010) presented a detailed geologic map of part of western Bhutan, focused on the Paro window area, which is also a significant addition to our compiled map.

Other compiled geologic maps include: 1) Chakungal et al. (2010), which covers part of northwest Bhutan near the town of Laya; 2) Wu et al. (1998), which covers the northwest corner of Bhutan and surrounding areas in southern Tibet, and focuses on the northeast-striking Yadong cross-structure; 3) Edwards et al. (1999), which covers part of north-central Bhutan and surrounding areas in southern Tibet; 4) the map of western Arunachal Pradesh published in Yin et al. (2010), which was used to locate the Lum La window; 5) Warren et al. (2011), which was used to locate the Laya thrust in northwest Bhutan; and 6) unpublished data from a newly-updated version of Djordje Grujic's simplified geologic map of Bhutan (see previous versions in Grujic et al. (2002); Hollister and Grujic (2006); Kellett et al. (2009)), which was used to locate the South Tibetan detachment and Kakhtang thrust in northeast Bhutan and westernmost Arunachal Pradesh.

Unit divisions, structure and stratigraphic contact locations, and rock unit descriptions on our map benefit greatly from recent studies that describe the structural geometry, metamorphic grade, and deformation history of GH rocks in Bhutan (Chakungal et al., 2010; Daniel et al., 2003; Davidson et al., 1997; Gansser, 1983; Grujic et al., 1996; Hollister and Grujic, 2006; Kellett et al., 2009; 2010; Long and McQuarrie, 2010; Long et al., 2011a; Swapp and Hollister, 1991; Warren et al., 2011). Recent studies that present new detrital geochronology data (Long and McQuarrie, 2010; Richards et al., 2006) provide valuable constraints on the age range of deposition of sedimentary protoliths of GH rocks and the age of intrusive rocks within the GH section. Finally, our map benefits greatly from recent studies focused on defining the structural geometry, stratigraphy, and deposition age ranges of map units within the Bhutan LH section(Long et al., 2011a;b; McQuarrie et al., 2008) and Paro Formation (Tobgay et al., 2010).

3. Methods

Geologic mapping was performed in the field on 1:50,000-scale topographic base maps, which were a combination of the Survey of India black-and-white series published in 1963 and the Bhutan Department of Survey and Land Records color series, which were published between 1991 and 2006. Our map data were collected primarily in across-strike (north-south) transects, combined with a few along-strike transects, most notably across Bhutan's main east-west road. We obtained GPS locations at each field stop.

To make the geologic map, each 1:50,000-scale topographic map that falls within Bhutan's borders was georeferenced in ESRI ArcGIS, using the WGS 1984 geographic coordinate system. Tables of GPS latitude and longitude locations for each field stop were compiled, and projected as labeled points into ArcGIS. The lines representing the locations of stratigraphic contacts and structures were then digitized over georeferenced topography, and were constrained by our field stop locations. Solid lines indicate precisely-located contacts (within ca. 50 m when not directly exposed) within our traverses. Dashed lines indicate approximately-located contacts or structures within our traverses, or interpolated positions of contacts or structures between our traverses.

Published geologic maps included in our compilation were taken directly out of figures in source publications, imported into ArcGIS, and georeferenced. The scanned maps of Gansser (1983) and Bhargava (1995), which were very difficult to georeference at the scale of the entire map, were georeferenced in specific locations by matching the traces of rivers. Since georeferencing of compiled maps introduces uncertainty in location, all contacts from these georeferenced maps are shown as dashed. In addition, since no topographic maps or stream locations were available outside of Bhutan, georeferencing of map data from areas in Tibet, Arunachal Pradesh, and Sikkim may not be as accurate, and all structures and contacts are shown as dashed.

Structure and contact lines drafted in ArcGIS were imported into Adobe Illustrator, where all remaining drafting was completed. This final drafting included colored polygons, line symbology, and structural symbols over georeferenced field stops. The locations of latitude and longitude lines, towns, roads, and rivers were drafted in ArcGIS from the georeferenced 1:50,000-scale topographic maps, and were then imported to Adobe Illustrator.

The map is designed as an interactive PDF that allows the user to examine layers of specific spatial datasets (e.g. polgyons, stratigraphic contacts, structural contacts, structural symbols, topography, etc.) individually. To see the list of available layers, click on the 'layers' tab in the left-hand table of contents in the PDF viewer. Layers of interest can be turned on and off by clicking on the eye symbol to the left of the name of the appropriate layer. This layered PDF design allows for specific combinations of any of the layers to be shown, which will be beneficial for future studies that seek to generate figures by modifying smaller areas of this map.

4. Areas for Future Mapping

Issues raised in the compilation of our map highlight several locations in Bhutan that would benefit from future geologic mapping. The first area is in the LH zone in the southeastern corner of Bhutan. Gansser (1983) and Bhargava (1995) map orthogneiss bodies interleaved within LH map units there, and Yin et al. (2010) show these orthogneiss bodies continuing into Arunachal Pradesh at the base of several thrust sheets. Yin et al. (2010) interpreted the orthogneiss bodies as Indian crystalline basement that sits beneath rocks of the lower Rupa Group, which is correlative to the Daling Formation in Bhutan. These orthogneiss bodies and Daling-equivalent rocks are mapped directly along-strike of multiple thrust sheets of the Manas Formation below the Shumar thrust, which we observe on our easternmost mapped transect north of Samdrup Jongkhar (Long et al., 2011a). In order to be compatible with the interpretations of Yin et al. (2010), a significant along-strike change in the map units carried in LH thrust sheets must occur in easternmost Bhutan. To accommodate for this change, we compiled the locations of the three orthogneiss bodies shown on the Gansser (1983) map, and interpreted their bases as the locations of thrust faults. We then interpreted Daling Formation rocks stratigraphically on top of the orthogneiss bodies, with queried upper stratigraphic contacts with the Manas Formation toward the west. Since these Manas-Daling contacts have not been directly observed in the field, and since this area is the site of such a dramatic along-strike change in the LH zone, an additional north-south mapping transect in southeastern Bhutan would be very valuable.

The relationship between GH and TH rocks in central Bhutan is another area of ongoing research (e.g. Hughes et al., 2011; Kellett et al., 2009; 2010; Long and McQuarrie, 2010). Areas that could benefit the most from detailed mapping include the Dang Chu klippe and Black Mountain region, as well as the area north of the Ura klippe. In the Ura area, further work distinguishing between metasedimentary rocks of the GH section and TH strata would be beneficial. For example, note that significant differences exist in the map pattern of the Ura klippe between maps in Long and McQuarrie (2010) and Kellett et al. (2009; 2010). Kellett et al. (2009; 2010) interpreted a lower structural position for the South Tibetan detachment than Long and McQuarrie (2010), and mapped a large area of rocks as TH that Long and McQuarrie (2010) interpreted as GH metasedimentary rocks. Further to the west, results from recent studies, including U-Pb zircon detrital geochronology from the Shemgang region that show that GH and TH strata must be as young as Ordovician (Long and McQuarrie, 2010), and biostratigraphic age control on TH units in the structurally-overlying Dang Chu klippe which show Cambrian deposition ages (Hughes et al., 2011), raise new questions about TH stratigraphy and the level of structural complexity in central Bhutan. We suggest that the isolated exposures of TH rocks in central Bhutan are critical areas for future detailed geologic mapping, geochronology, and biostratigraphy.

Finally, the region west and northwest of Haa in westernmost Bhutan is another area that would benefit greatly from additional mapping. This includes a very large area of GH rocks where no map data exist, and very few map data are shown for leucogranite bodies, TH units, and the location of the South Tibetan detachment on the maps of Gansser (1983) and Wu et al. (1998). An additional mapped transect, perhaps along the Amo Chu, would be very valuable for locating contacts and structures in western Bhutan.

5. Conclusions

The 1:500,000-scale geologic map of Bhutan presented here is a combination of new data and compilation of geologic maps that have only recently become available. As a result, it is now the most complete and detailed geologic map available for the country. In addition to presenting new map unit divisions, including the 3-part stratigraphy of the Siwalik Group and structurally-lower Greater Himalayan section, our map is greatly improved by the results of recent studies that define the stratigraphy, structural geometry, and deposition age ranges of the Paro Formation, and the Subhimalayan, Lesser

Himalayan, and Greater Himalayan zones. Finally, issues raised in our map compilation highlight several areas in Bhutan that would benefit from future geologic mapping.

Software

Tables of latitude and longitude points for locations of map symbols were compiled in Microsoft Excel 2007, and then exported to ESRI ArcGIS. Text for map unit descriptions was typed in Microsoft Word 2007, and then exported to Adobe Illustrator. All geographically-registered lines were drawn on ESRI ArcGIS 9.3.1. These lines were then exported to Adobe Illustrator. Line and polygon digitizing, symbology, and text were completed using Adobe Illustrator CS 11.

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