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Geology of the Dhaulagiri-Annapurna-Manaslu Himalaya, Western Region, Nepal. 1:200,000

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SCIENCE

Geology of the Dhaulagiri-Annapurna-Manaslu Himalaya, Western Region, Nepal. 1:200,000

Andrew J. Parsons^{a*} , Richard D. Law^b , Michael P. Searle^c, Richard J. Phillips^a and Geoffrey E. Lloyd^a

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Geological mapping of mountains belts is fundamental to understanding their structure and evolution. Here, a 1:200,000 scale geological map of the central Himalaya of Western Region, Nepal is presented. This map represents a compilation of previously published maps, integrated with new geological field data. The wide spatial coverage of the map and the accompanying cross sections reveal the detailed structure of the Dhaulagiri-Annapurna-Manaslu Himalaya. The addition of modern topographic and infrastructure data makes this map suitable for navigation through the region.

Keywords: geology; Annapurna; Dhaulagiri; Manaslu; Nepal; cross sections

1. Introduction

Geological mapping of mountain belts forms a vital part of the research needed to understand the geological structure and evolution of continental collision zones. We present an updated 1:200,000 scale geological map of the Dhaulagiri-Annapurna-Manaslu Himalaya, Western Region, Nepal (see [Figure 1](#) for map location) with accompanying cross sections, based on previously published geological maps and new geological field mapping (see [Main Map](#)). The first comprehensive geological map to cover much of this region was produced by [Colchen, Le Fort, and Pêcher \(1981\)](#). With the use of cartographic software, our new map geospatially intergrates new geological field mapping data with previously published geological maps and satellite imagery produced since and before the work of [Colchen et al. \(1981\)](#) (e.g. [Bollinger et al., 2004](#); [Bordet et al., 1971](#); [Catlos et al., 2001](#); [Coleman, 1996](#); [Coleman & Hodges, 1998](#); [Colchen, Le Fort, & Pêcher, 1986](#); [Corrie & Kohn, 2011](#); [Gleeson & Godin, 2006](#); [Godin, 2003](#); [Godin, Gleeson, Searle, Ullrich, & Parrish, 2006a](#); [Hodges, Parrish, & Searle, 1996](#); [Larson, Godin, Davis, & Davis, 2010](#); [Larson & Godin, 2009](#); [Le Fort, 1975](#); [Martin, Ganguly, & Decelles, 2010](#); [Paudel & Arita, 2000](#); [Paudel & Arita, 2006a, 2006b](#); [Searle, 2010](#); [Searle & Godin, 2003](#); [Stöcklin, 1980](#); [Vannay & Hodges, 1996](#)). By combining this work with modern topographic and infrastructure data, we have produced

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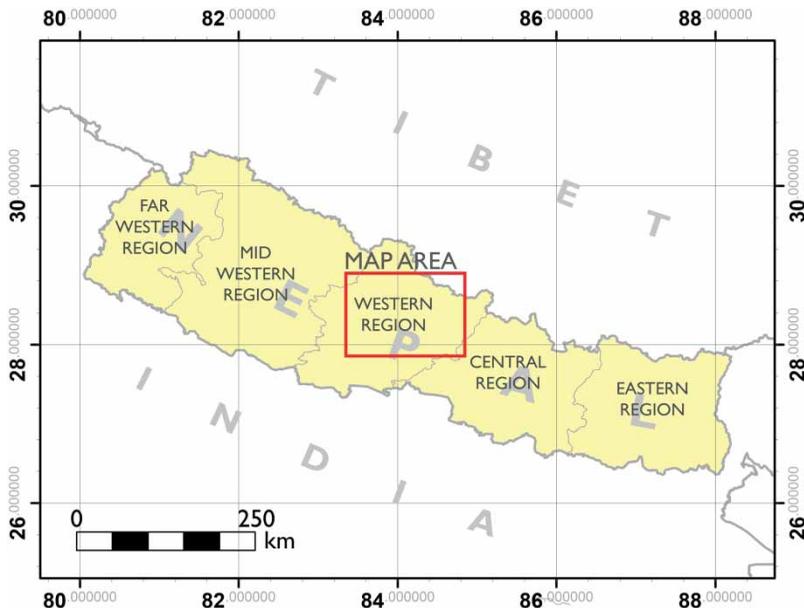


Figure 1. Regional map of Nepal. Map shows the international administrative boundaries of Nepal, India and Tibet, plus the boundaries of the five administrative districts of Nepal (data provided by ESRI Inc.). The red square indicates the location of the 1:200,000 geological map of the Dhaulagiri-Annapurna-Manaslu Himalaya.

a map plotted at a high level of geospatial precision and accuracy that should aid and encourage future geological research in the region.

2. Map and cross section construction

The geological map was composed from geological field mapping data, and interpretations of ASTER and Landsat satellite imagery (United States Geological Survey) and digital elevation models (DEMs) (De Ferranti, 2012; Jarvis, Reuter, Nelson, & Guevara, 2008), integrated with previously published geological maps from the region (Figure 2) (Bollinger et al., 2004; Catlos et al., 2001; Colchen et al., 1981; Coleman, 1996; Coleman & Hodges, 1998; Gleeson & Godin, 2006; Godin, 2003; Godin, Gleeson, et al., 2006; Paudel & Arita, 2000; Paudel & Arita, 2006a, 2006b; Larson & Godin, 2009; Larson et al., 2010; Martin et al., 2010; Searle, 2010; Vannay & Hodges, 1996). Topographic contours were produced from Shuttle Radar Topography Mission (SRTM) DEMs with a 90 m resolution, originally supplied by NASA and modified by De Ferranti (2012) and Jarvis et al. (2008) who removed most no-data voids. Infrastructure data such as roads, paths, rivers, conurbations and administrative boundaries were redrafted from open source base maps and Landsat images supplied by Esri Inc. World Geodetic System 1984 (WGS 1984) was used as the reference system and geodetic datum for map projection (National Imagery & Mapping Agency, 2000). Structural data collected during field mapping were positioned on the map using global positioning system (GPS) receiver waypoints recorded in the field. The initial positions of geological boundaries were based on digital scans of published geological maps, geospatially referenced using second- and third-order polynomial transformations and mosaicked into a single map. Three classes of boundary are used to reflect the accuracy and precision of geological boundary definition. In regions 1 and 2 (Figure 2), geological

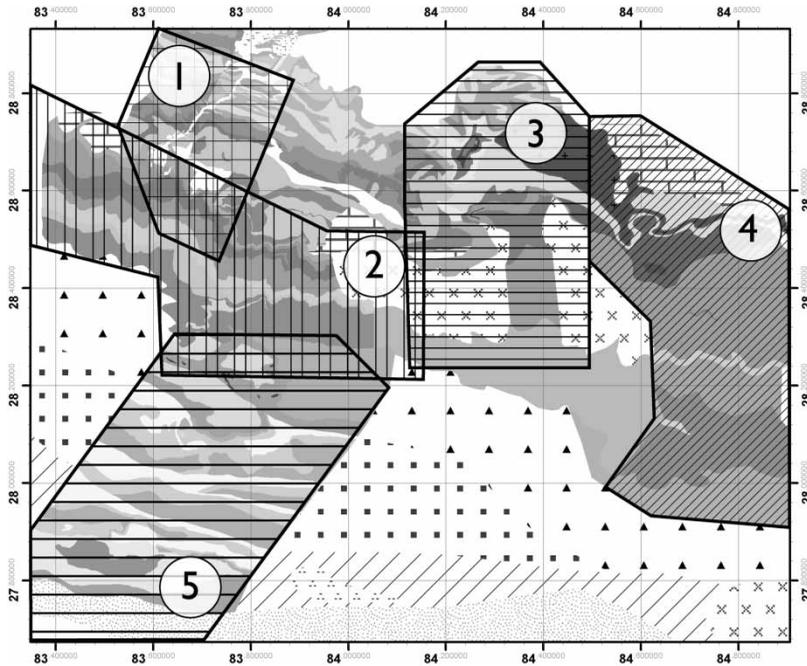


Figure 2. Sources of geological data. Greyscale version of the 1:200,000 geological map overlaid with hatched polygons to define the regions where field mapping data and previously published geological maps have been used to construct the final map. Fieldwork was conducted in regions 1 and 2 during 2012 and 2013. Geological maps used are as follows: Region 1 – [Godin \(2003\)](#); Region 2 – [Larson and Godin \(2009\)](#), [Martin et al. \(2010\)](#), [Searle \(2010\)](#); Region 3 – [Coleman \(1996\)](#), [Catlos et al. \(2001\)](#), [Gleeson and Godin \(2006\)](#), [Godin, Gleeson, et al. \(2006\)](#); Region 4 – [Larson et al. \(2010\)](#); Region 5 – [Paudel and Arita \(2000, 2006a, 2006b\)](#); Rest of map – [Colchen et al. \(1981\)](#), [Paudel and Arita \(2000\)](#), [Bollinger et al. \(2004\)](#).

boundaries relocated and re-orientated in accordance with data collected during recent field mapping are classified as ‘observed’ boundaries and carry the highest accuracy. Where possible, geological boundaries were extrapolated from known locations across the map with a high level of precision using the structure contour boundary projection method (e.g. [Bennison, Olver, & Moseley, 2013](#)), aided by interpretation of satellite imagery and local topography. These are classified as ‘constrained’ boundaries. In regions where no field mapping has been conducted by the authors, the geological boundaries from previously published maps are redrafted, with appropriate modifications based on interpretation of satellite imagery and local topography. Depending on the degree of accuracy at which these were defined on the previously published maps, these boundaries are classified as either ‘constrained’ (higher accuracy) or ‘inferred’ (lower accuracy) boundaries. Previously published structural data were also transferred directly from pre-existing maps to the new map sheet in the same manner. Where possible, previously published foliation readings were assigned to a particular generation of foliation (i.e. S1, S2, S3, etc.) that correlates with the new structural data collected by the authors. Where information is not available to make such correlations, the previously published foliation data is assigned the class of ‘unknown foliation’.

Cross sections are redrafted from previous publications. Cross section A-A’ is based on three sections produced by [Paudel and Arita \(2000, 2006a, 2006b\)](#). Cross sections B-B’ and C-C’ are based on sections produced by [Searle \(2010\)](#). Redrafted cross sections are modified to match the

colour scheme and stratigraphy displayed on the map. The structure displayed in these cross sections has not been modified from the original versions and may display minor discrepancies with respect to the location and orientation of newly mapped boundaries and structural data on the map. As such these cross sections should be treated as approximations of the cross sectional structure displayed on the new map. For balanced and restorable cross sections through the Kali Gandaki Valley and an alternative interpretation of some of the structures in the Tethyan Himalayan Sequence, the reader is referred to [Godin \(2003\)](#).

3. Geography

The central Himalaya in north Western Region, Nepal is dominated by the peaks of Dhaulagiri (8167 m), Annapurna I (8091 m) and Manaslu (8156 m) which form part of a high mountain massif. Rivers flow between these peaks along steep-sided valleys that run approximately NE-SW. The most significant of these rivers are the Kali Gandaki, Marsyandi, Modi Khola and Bhudi Gandaki. The Kali Gandaki Valley is one of the largest valleys in the Himalaya and one of only a few southwards-draining river systems that originate north of the Himalayan range. Roads and trekking routes along these valleys allow for access to much of this elevated region and are indicated on the geological map.

South Western Region is characterised by low elevation (<2000 m) foothills, separated by both NE-SW and NW-SE trending valleys. To the very south of Western Region, the edge of the Himalayan foothills bounds the flat plains of the Himalayan foreland with an elevation of <200 m. Access through these foothills is gained via numerous roads and highways, also indicated on the map.

4. Geology

The Himalayan orogen initiated at *ca.* 50 Ma ([Najman et al., 2010](#)) due to collision between the Indian and Asian continents. The Himalaya belt has been under a continuous state of convergence since that time, resulting in uplift and erosion of the world's largest mountain peaks ([Searle, Elliott, Phillips, & Chung, 2011](#)). The Himalaya can be divided into four tectonic units, separated by orogen parallel faults and shear zones ([Figure 3](#)). From SW to NE these units are the Sub-Himalayan Zone (SHZ), the Lesser Himalayan Sequence (LHS), the Greater Himalayan Sequence (GHS) and the Tethyan Himalayan Sequence (THS) ([Le Fort, 1975](#)). The stratigraphy and structures that define these units are displayed on the map sheet and are briefly described below. The stratigraphic framework is based on previously published work unless otherwise stated. Planar deformation fabrics plotted on the map are grouped into five distinct deformation fabrics (S1–S5) as defined by [Godin \(2003\)](#). Whilst [Godin \(2003\)](#) used these classifications to describe structures in the THS and Upper GHS, where possible, we have extrapolated their use to the whole of the GHS to show the relative sequence of fabric development. For a detailed review of the kinematic evolution of the Himalayan orogen, the reader is referred to [Hodges \(2000\)](#), [Yin \(2006\)](#), and [Searle et al. \(2011\)](#).

4.1. The Sub-Himalayan Zone

The Sub-Himalayan zone represents a ~6000 m thick unmetamorphosed sequence of mid Miocene-Pleistocene synorogenic sedimentary rocks belonging to the Siwaliks Group ([Decelles, Gehrels, Quade, & Ojha, 1998](#); [Paudel & Arita, 2000](#); [Upreti, 1999](#)). The Siwaliks Group contains fluvial mudstones, siltstones, shales, and subordinate sandstones and conglomerates, deposited in the wedge-top basin foredeep system of the Himalayan foreland ([Decelles et al., 1998](#); [Upreti, 1999](#)).

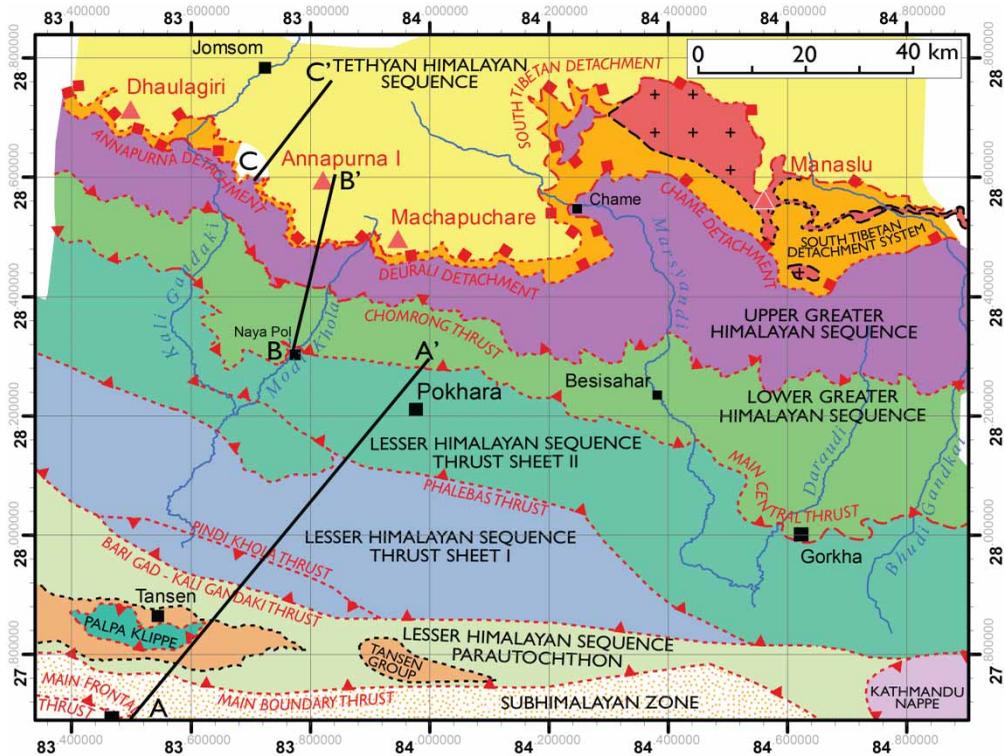


Figure 3. Simplified tectono-stratigraphic map of Western Region, Nepal. Major tectonic units and bounding faults and shear zones are labelled. The locations of cross sections are also given.

The Siwaliks Group is bound below by the Main Frontal Thrust (MFT) and above by the Main Boundary Thrust (MBT) which both dip approximately NE (Upreti, 1999). Following deposition, the Siwaliks Group was deformed into a number of south-verging thrust-fold structures (Upreti, 1999).

4.2. The Lesser Himalayan Sequence

The Lesser Himalayan Sequence lies above the Sub-Himalayan Zone in the low-level foothills of Western Region, Nepal. The LHS comprises Mid Proterozoic to Early Palaeozoic sedimentary rocks derived from the Indian continent that collectively form the Nawakot Complex (Parrish & Hodges, 1996; Stöcklin, 1980). This complex is unconformably overlain by a succession of Upper Carboniferous to Early Miocene sedimentary rocks belonging to the Tansen Group (Sakai, 1983). The allochthonous Palpa Klippe of Lower Nawakot Group strata, has been tectonically emplaced over the Tansen Group.

The Nawakot Complex (Stöcklin, 1980) is the equivalent to the Midland Formation of Le Fort (1975). It is divided by an erosional unconformity into the Lower and Upper Nawakot Groups (Stöcklin, 1980).

The Lower Nawakot Group in Western Region, Nepal consists of the Kuncha, Fagfog, Dandagaon, Nourpul and Dhading formations, listed from oldest to youngest (Stöcklin, 1980). These formations comprise a mix of phyllites, quartzites, slates, sandstones, and carbonates, with minor conglomerates and amphibolites (Paudel & Arita, 2000; Stöcklin, 1980). Fossil algal and

stromatolite horizons within the Dhading Formation are Early Palaeozoic in age (probably Cambrian, [Stöcklin, 1980](#)). The Lower Nawakot Group has a minimum thickness of 4300–6800 m as its base is not exposed in Nepal ([Stöcklin, 1980](#); [Paudel & Arita, 2000](#)).

The Upper Nawakot Group unconformably overlies the Lower Nawakot Group with an erosional basal contact ([Stöcklin, 1980](#); [Paudel & Arita, 2000](#)). In Western Region, Nepal, this group consists of the Benighat (older) and the Malekhu (younger) formations. These contain slates, phyllites, limestones, dolomites and quartzite boulder beds ([Stöcklin, 1980](#)). The Upper Nawakot Group has a thickness of 4300–6000 m ([Stöcklin, 1980](#); [Paudel & Arita, 2000](#)).

The Tansen Group is found in the southernmost exposure of the LHS, unconformably overlying the Nawakot Complex ([Paudel & Arita, 2000](#); [Sakai, 1983](#)). It consists of a 3000 m thick succession of Late Carboniferous to Early Miocene sedimentary rocks comprising diamictites, conglomerates, sandstones, basalts, quartzites and shales unconformably overlain by shales and sandstones ([Paudel & Arita, 2000, 2006a](#); [Upreti, 1999](#)). Sedimentary rocks above the unconformity represent the first foreland basin sediments of the Himalayan orogen, deposited between the Eocene to Mid Miocene during initial uplift and erosion of the High Himalaya ([Najman, Enkin, Johnson, Robertson, & Baker 1994](#); [Paudel & Arita, 2000](#); [Sakai, 1983](#)).

The LHS is bound to the south by the MBT and to the north by the Main Central Thrust (MCT), which both strike approximately NW-SE and dip towards the NE, approximately orthogonal to the length of the mountain belt ([Colchen et al., 1986](#); [Le Fort, 1975](#); [Searle et al., 2008](#)). Internally the LHS is divided into several thrust sheets that form the Lesser Himalayan Duplex ([Paudel & Arita, 2000, 2006a, 2006b](#)). The MBT and MCT form the floor and roof thrusts, respectively, of this duplex. The Lesser Himalayan Duplex comprises the Parautochthon and Thrust Sheets I and II ([Paudel & Arita, 2000](#)). The structural arrangement of these thrust sheets is displayed in cross section A-A' ([Paudel & Arita, 2000, 2006a, 2006b](#)). Bedding measured within the LHS exposed in the Modi Khola Valley close to the MCT strikes approximately NW-SE with a variable dip that frequently changes direction from NE to SW due to small-scale folding. The LHS increases in metamorphic grade from SW to NE from the diagenetic zone through anchizone and epizone rocks to chlorite grade ([Paudel & Arita, 2000, 2006a, 2006b](#)).

4.3. *The Greater Himalayan Sequence*

The Greater Himalayan Sequence (GHS) lies above the LHS and represents the metamorphic core of the Himalayan orogen. In Western Region, Nepal, the GHS outcrops on the south facing slopes of the High Himalaya and consists of Mesoproterozoic to Early Palaeozoic medium to high-grade metasedimentary rocks and crustal melts derived from the Indian continent ([Parrish & Hodges, 1996](#)). The GHS of the Dhaulagiri-Annapurna-Manaslu Himalaya can be divided into the Lower and Upper GHS and the South Tibetan Detachment System (STDS). The GHS is bound by brittle-ductile shear zones, with the MCT at its base and the South Tibetan Detachment (STD) at its top ([Le Fort, 1975](#); [Searle, 2010](#); [Searle et al., 2008](#)). Metamorphism and anatexis of the GHS associated with extrusion and exhumation occurred during the Himalayan orogeny between Oligocene and Miocene times ([Corrie & Kohn, 2011](#); [Hodges et al., 1996](#)).

The Lower GHS has an approximate structural thickness of 4800–6000 m and consists of medium- to high-grade metasedimentary rocks with protoliths equivalent to the Nawakot Complex of the LHS ([Larson & Godin, 2009](#); [Stöcklin, 1980](#)). The lower portion of the Lower GHS comprises quartzites, semipelites and phyllites and an augen-orthogneiss layer ([Bouchez & Pêcher, 1981](#); [Colchen et al., 1986](#); [Hodges et al., 1996](#); [Larson & Godin, 2009](#); [Le Fort, 1975](#)). The upper portion of the Lower GHS contains massive quartzites, marbles, dolomitic marbles, metacarbonates and schists ([Colchen et al., 1986](#); [Hodges et al., 1996](#); [Larson & Godin, 2009](#); [Le Fort, 1975](#)). Metamorphic grade increases structurally upwards from chlorite grade – lower

greenschist facies to garnet grade – upper greenschist facies (Larson & Godin, 2009; Hodges et al., 1996).

The Upper GHS has an approximate structural thickness of 6500–7200 m in the Kali Gandaki and Modi Khola valleys and 8500–9000 m in the Marsyandi Valley (Searle & Godin, 2003) and consists of kyanite- to sillimanite-grade mid-crustal metasedimentary rocks, migmatites and leucogranites (Colchen et al., 1986; Hodges et al., 1996; Le Fort, 1975). The Upper GHS of the Dhaulagiri-Annapurna-Manaslu Himalaya is divided into three units described from bottom to top as; Unit I, consisting of kyanite to sillimanite-grade schists, paragneisses and migmatites; Unit II, consisting of diopside-scapolite-grade calc-silicate gneisses and pelitic gneisses and Unit III, consisting of sillimanite-grade orthogneisses, schists and migmatites (Colchen et al., 1986; Hodges et al., 1996; Le Fort, 1975). Leucogranite dykes and sills are found throughout the Upper GHS, some of which are concordant with local foliation and deformed, whilst others are discordant to the local foliation and occasionally underformed (Gleeson & Godin, 2006; Hodges et al., 1996; Larson & Godin, 2009).

The South Tibetan Detachment System (STDS) is defined as the portion of stratigraphy that forms the hangingwall of the normal-sense ductile shear zone, locally named as the Annapurna Detachment (Kali Gandaki Valley), Deurali Detachment (Modi Khola Valley) and Chame Detachment (Marsyandi Valley) and forms the footwall of the brittle-ductile normal sense South Tibetan Detachment (STD) (*see below*). The STDS has an approximate structural thickness of 2200 m in the Kali Gandaki Valley, ~1200 m in the Modi Khola Valley and ~4000 m in the Manaslu region (Searle & Godin, 2003). The STDS consists of diopside-scapolite grade to biotite-grade calc-silicate gneisses, metacarbonates and marbles (Colchen et al., 1986; Hodges et al., 1996; Larson & Godin, 2009; Le Fort, 1975). In the Marsyandi Valley the Manaslu Leucogranite forms a 3–4 km thick leucogranite pluton at the top of the STDS (Searle & Godin, 2003). Metapelitic rocks and orthogneiss are also recognised within the STDS surrounding the Manaslu Leucogranite (Gleeson & Godin, 2006; Larson et al., 2010). Previously defined units within the STDS include the Larjung Unit in the Kali Gandaki Valley (Larson & Godin, 2009), the Annapurna Yellow Formation in the Modi Khola Valley (Hodges et al., 1996) and Unit IV and Unit V in the Nar Valley in the Marsyandi region (Gleeson & Godin, 2006). Additionally, new mapping of the STD in the Kali Gandaki Valley north of its previously mapped position now incorporates parts of the Annapurna Yellow Formation, Sanctuary Formation and Nilgiri Formation into the STDS. Elsewhere, the Annapurna Yellow Formation, Sanctuary Formation and Nilgiri Formation can be found structurally above the STD and, in such cases, these strata belong to the THS. However, the parts of these formations in the Kali Gandaki Valley that are re-mapped into the footwall of the STD are now considered to be part of the GHS. In order to differentiate rocks from the same formation that can be found in both the footwall (i.e. GHS) and hangingwall (i.e. THS) of the STD, and to amalgamate the different stratigraphic units found in different regions of mapped STDS, the strata within the STDS are collectively redefined as STDS metacarbonates, which includes marbles and subordinate metapelitic layers, STDS metapelitic rocks and STDS orthogneiss.

The base of the GHS is bound by the top-to-the-SW Main Central Thrust (MCT), which represents the basal thrust of the brittle-ductile Main Central Thrust Zone (MCTZ) (Searle et al., 2008). In the Modi Khola Valley, the MCT strikes approximately WNW-ESE with a dip of 30–40° to NNE. The top of the GHS is bound by the STD, which forms a top-down-to-the-NE low-angle normal fault at the top of the STDS (Searle, 2010). The STD strikes approximately WNW-ESE, dipping ~30° towards the NNE in the Modi Khola Valley and ~15–20° towards the NNE in the Kali Gandaki Valley. The STDS forms a brittle-ductile normal-sense detachment horizon, with a ductile shear zone at its base. This ductile shear zone is identified as the Annapurna Detachment in the Kali Gandaki Valley (Godin, Brown, & Hanmer, 1999), the Deurali

Detachment in the Modi Khola Valley (Hodges et al., 1996) and the Chame Detachment in the Marsyandi Valley (Coleman, 1996). Shear sense indicators from the Upper GHS and overlying THS in the Kali Gandaki suggest that normal-sense shearing on the STDS was followed by a phase of reverse-sense shearing (Godin, 2003).

These bounding shear zones are recognised in the field and from microstructures and metamorphic mineral assemblages observed in thin sections. Rocks in the footwall of the MCT contain original sedimentary structures (e.g. cross bedding, ripples) and are metamorphosed to chlorite grade or lower. Rocks in the hangingwall contain a pervasive MCT-parallel foliation and S-C shear fabrics, with a significant amount of dynamic recrystallisation textures developed at chlorite grade or higher conditions (Bouchez & Pêcher, 1981; Searle et al., 2008). Rocks in the footwall of the STD are dynamically recrystallised and dominated by a pervasive STD-parallel foliation produced at biotite grade or higher conditions; they do not contain foliations that formed before the STD-parallel foliation (Larson et al., 2010; Searle et al., 2008). Rocks in the hangingwall of the STD contain foliations that pre-date the STD-parallel foliation and are only weakly metamorphosed to lower than biotite grade (Godin, 2003; Searle, 2010). The MCTZ and STDS were coevally active during the Early to Mid Miocene, facilitating extrusion and exhumation of the GHS (Godin, Grujic, Law, & Searle, 2006b).

The Upper GHS and Lower GHS are separated by a thrust fault identified in the Modi Khola Valley as the Chomrong Thrust (Hodges et al., 1996). In Kali Gandaki Valley the Kalopani Shear Zone (KSZ) forms a ductile reverse-sense shear zone within Unit III (Vannay & Hodges, 1996).

A strong, pervasive foliation is observed throughout the GHS, striking between NW-SE and WNW-ESE and dipping $\sim 20\text{--}40^\circ$ towards NNE-NE. This foliation predates a number of foliations in the overlying THS and is defined as the S3 foliation on the map (See section 4.4. for a description of S1–S2, which are observed in the THS). Elongation mineral lineations associated with S3 are commonly observed in the GHS, plunging towards the NE and ENE. A later foliation (S4) related to reverse-sense shearing on the STDS and KSZ is commonly recorded by Godin (2003). The youngest fabric (S5) in the GHS is commonly observed as a distinct set of N-S striking sub-vertical joints, related to late-stage E-W extensional faulting in the Tethyan Himalayan Sequence (Coleman & Hodges, 1995; Godin, 2003).

4.4. *The Tethyan Himalayan Sequence*

The THS lies above the GHS. In Western Region, Nepal, the THS forms the tops of many of the highest peaks in the region, including Annapurna I and Dhaulagiri, and in outcrop continues north beyond the border with southern Tibet. The THS in the Dhaulagiri-Annapurna-Manaslu Himal contains an almost continuous sequence of Cambro-Ordovician to Cretaceous marine sedimentary rocks that represent a large carbonate shelf sequence formed along the northern passive margin of the Indian plate (Bordet et al., 1971; Garzanti, 1999; Gradstein et al., 1992; Godin, 2003). From bottom to top (and oldest to youngest), the THS is divided into the Sanctuary, Annapurna Yellow, Nilgiri and Sombre formations, the Thini Chu & Lake Tilicho formations (mapped as a single unit) and the Jomsom, Bagung, and Lupra formations. Above these, lies the Chuku Group that is composed of the Chuku, Kagbeni and Muding units (Godin, 2003). The sequence consists of massive limestones, calcareous shales and pelites with localised dolomitic and sandy horizons (Godin, 2003). Cross section restoration of the THS indicates that the undeformed sequence has a stratigraphic thickness of 11 km (Godin, 2003). The THS is only weakly metamorphosed near its base and does not contain any leucogranites.

The THS is bound by the STD below and the Indus-Yarlung Suture Zone (IYSZ) above (Searle, 2010). The IYSZ is exposed in southern Tibet, north of the mapped area. Internally,

the THS is deformed into km-scale folds. These folds in the southernmost exposures of the THS are overturned and verge northwards with south dipping axial planes that are folded into parallelism with the STD (see cross sections B-B' and C-C' on the map) (Godin, 2003; Searle, 2010). North of this point, fold vergence progressively rotates, becoming upright in exposures close to Jomsom (Kali Gandaki Valley) and south-verging, north of Jomsom (Godin 2003; Searle 2010). These large folds are related to crustal thickening prior to extrusion and exhumation of the GHS (Godin, 2003; Godin, Yakymchuk, & Harris, 2011). There are also a large number of NE-SW striking normal faults within the THS of the Kali Gandaki Valley. These relate to late Miocene and Plio-Pleistocene extension of the Thakkhola graben, located in the upper reaches of the Kali Gandaki Valley (Hurtado, Hodges, & Whipple, 2001).

Within the THS of the Kali Gandaki Valley, Godin (2003) has documented the presence of five distinct deformation fabrics (S1–S5). These are described as: (1) a bedding sub-parallel foliation (S1) with associated isoclinal folding; (2) an overprinting crenulation cleavage (S2) related to the km-scale folds observed in the valley; (3) an STD-parallel foliation (S3) related to extrusion and exhumation of the GHS; (4) a post-peak metamorphic foliation (S4) related to reverse-sense shearing on the STDS and KSZ, sub-parallel to the STDS and (5) a late-stage N-S striking sub-vertical fabric (S5) related to extensional faulting along the Thakkhola graben (Godin, 2003). S1–S5 are all represented on the map.

4.5. Recent deposits

Within the Kali Gandaki Valley, basin fill and glacial deposits are commonly observed and are related to syn- and post-tectonic sedimentation within the Thakkhola graben (Fort, Freydet, & Colchen, 1982; Godin, 2003; Hurtado et al., 2001).

5. Conclusions

The geological map presented herein, represents a culmination of several decades of geological research of Western Region, Nepal that builds upon the original compilation map of Colchen et al. (1981). The use of professional cartographic software has facilitated integration of field mapping data, satellite imagery, topographic data and previously published maps, resulting in the creation of an updated map that is geospatially referenced to a higher degree of accuracy than previously available. The combination of previously published maps and new field mapping data reveals the detailed structure of LHS, GHS and THS on a single map. Furthermore, the detailed topographic and infrastructure information provides readers with a useful map to aid and encourage future research in the region.

Software

The geological map was originally constructed using Esri ArcGIS 10. The final draft was composed using Adobe Illustrator CS6.

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