Forward modeling the kinematic sequence of the central Himalayan thrust belt, western Nepal

Delores M. Robinson*
Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama 35487-0338, USA

ABSTRACT

The Himalayan thrust belt is often cited as an example of a thrust system that propagated from hinterland to foreland; however, this kinematic sequence is not well documented, and the process of formation of the thrust belt has not been well supported. This study uses forward modeling and timing data to reveal a detailed view of the evolution of the central Himalayan thrust belt from the footwall of the South Tibetan detachment system southward to the Main Frontal thrust. By using a reasonable configuration of undeformed stratigraphy, the surface deformation in western Nepal can be dynamically reproduced, confirming that the cross sections from which the undeformed sections were derived are viable and propagated from hinterland to foreland. In addition, this study yields detailed step-by-step reconstructions of three cross sections and is the first of its kind in any thrust belt system. These detailed views are useful for understanding and bracketing erosion data, the basin sediments, and geodynamic models. Modeling shortening estimates are between 495 and 733 km from the Main Frontal thrust to the South Tibetan detachment system, and are within the range predicted for shortening in western Nepal obtained from balanced cross sections (485–743 km). Thus, the Himalayan thrust belt in western Nepal is essentially a forward-propagating thrust belt from hinterland to foreland, with minor out-of-sequence (<5 km) thrust and normal faults. The data and the forward modeling support a conventional wedge model for the development of the central Himalayan thrust belt.

INTRODUCTION

Before India collided with Asia, a Greater Indian passive margin sequence extended northward from India. It consisted of Lesser Himalayan sequence Proterozoic rock, adjacent Late Proterozoic–Ordovician Greater Himalayan rock, and Precambrian (?)–Paleocene Tethyan sedimentary sequence rock. Tethyan sedimentary sequence rock was deposited on Greater Himalayan rock (e.g., Robinson et al., 2001) and in some locations along the Himalayan arc possibly on Lesser Himalayan sequence rock as well (e.g., western India; Myrow et al., 2003). These Greater Indian rocks were then telescoped, forming the Himalayan thrust belt. The thrust belt is thought to consist of dominantly south-verging, southward-propagating thrust faults that formed and are presently forming in response to ongoing subduction of the Indian plate beneath the Asia plate (Gansser, 1964; Powell and Conaghan, 1973; Coward and Butler, 1985; Mattauer, 1986; Dewey et al., 1988; Searle, 1991; Molnar, 1993; Srivastava and Mitra, 1994; Hodges, 2000; Yin and Harrison, 2000). Thus, much of the deformation between the colliding continents is preserved in the Himalayan thrust belt, which consists of the Tibetan part of the thrust belt north of the South Tibetan detachment system and the southern part of the thrust belt south of the detachment system. The remaining questions within the thrust belt are how much deformation was accommodated in the Himalayan thrust belt, what was the kinematic sequence of deformation, and did the thrust belt propagate southward.

Three balanced cross sections in western Nepal yielded total minimum horizontal shortening between 485 and 743 km from the Main Frontal thrust to the immediate footwall of the South Tibetan detachment system (Robinson et al., 2006). Adding shortening from the Tethyan thrust belt and Indus-Yalu suture zone (Murphy and Yin, 2003) to this total yields a shortening estimate of 635–918 km. Paleomagnetic data from the Himalayan-Tibetan orogenic system suggest a total of 2600 ± 900 km of postcollisional convergence, with 1700 ± 610 km of this total accommodated by north-south shortening in the Tibetan Plateau and lateral tectonic escape (Patriat and Achache, 1984; Klootwijk et al., 1985; Besse and Courtillot, 1988; Patzelt et al., 1996). Granting that these values have large uncertainties, the difference between the average values equals 900 km that may be accommodated in the Himalayan thrust belt (LePichon et al., 1992). Other paleomagnetic data suggest shortening of up to 1500 km (Patzelt et al., 1996). Thus, the range of potential shortening available to be accommodated in the Himalayan thrust belt is from 900 to 1500 km. Work by Robinson et al. (2006) yielded 635–918 km of horizontal shortening in western Nepal, which falls at the lower end of this range of potential shortening; yet, these estimates are minima because penetrative strain, small-scale folds and faults throughout the entire thrust belt and ductile deformation within the Greater Himalayan rocks were not incorporated. However, the 635–918 km horizontal shortening estimate is the first estimate to attain the shortening values predicted by paleomagnetic data. These data support the hypothesis that at least in western Nepal, no more major structures exist that accommodate large amounts of shortening.

Producing a cross section involves integrating the available stratigraphic, structural, and subsurface data into a two-dimensional interpretation of the data. The process of balancing an interpreted cross section inherently implies that the cross section is admissible and that the kinematic sequence is viable. However, it is difficult to prove that the kinematic sequence works when presenting only a cross section and restored section. In order to insure that the kinematic sequence does not violate any thrust belt rules (Dahlstrom, 1969; Boyer and Elliot, 1982; Davis et al., 1983), the restoration should be forward modeled using a reconstruction program. This step-by-step reconstruction moves each fault consecutively until a resulting cross section is produced. The cross section can then be compared to the original interpreted cross section.

The goal of this paper is to determine the viability of three cross sections and associated restorations and thus, the quality of the balanced cross
sections, through the central Himalayan thrust belt. This process yields insight into the deformation sequence of the thrust belt. Many researchers assume that thrust belt systems propagate toward the foreland, but only a few studies document this hinterland to foreland sequence (cf. Horton, 1999; DeCelles, 2004 and reference therein). Modeling cross sections in reconstruction programs also ensures that the suggested kinematic sequence is plausible. The detailed nature of these reconstructions provides an unprecedented view of how the Himalayan thrust belt evolved. In fact, this is the first study of its kind to be published in any thrust belt system in a fault-by-fault fashion. Such studies will prove useful in all building and collapsing mountain belts for integrating data from geochronology, thermochronology, uplift and exhumation data, and data from the synorogenic sediments. In addition, the robustness of the horizontal shortening estimates as stated by Robinson et al. (2006) is tested through forward modeling of the restored sections.

GEOLOGIC SETTING

Nepal is located in the central part of the Himalayan arc, which extends along strike ~2400 km between Namche Barwa at the eastern syntaxis to Hazara at the western syntaxis (Fig. 1A). The Himalayan thrust belt extends across strike from the Indus-Yalu suture zone in the north (in Tibet) to the Main Frontal thrust in the south (Fig. 1B). West Nepal is situated in the apex of the Himalayan arc and records the greatest amount of horizontal shortening found in the Himalaya (Robinson et al., 2006). Figure 2 illustrates the tectonostratigraphy and structure in western Nepal, and shows the location of the three balanced cross section lines referred to in this study. The westernmost line is the Api cross section (A); the central line is the Chainpur cross section (C); and the easternmost line is the Simikot cross section (S). Major structures and stratigraphy found in western Nepal have correlative counterparts in central and eastern Nepal (Upreti, 1990, 1996; DeCelles et al., 2001; Robinson et al., 2001, 2003, 2006; Martin et al., 2005; Pearson and DeCelles, 2005).

Gansser (1964) divided the Himalayan arc into four zones, yielding a tectonostratigraphy that from north to south consists of the Tibetan (or Tethyan) Himalaya, Greater Himalaya (or High Himalayan crystallines), Lesser Himalaya, and Subhimalaya. Generally, this tectonostratigraphy is present across the arc, and has subsequently been subdivided into formations in each of the tectonostratigraphic zones. This paper only briefly outlines the stratigraphy in western Nepal as needed for understanding the forward modeling (for more information, see DeCelles et al., 2001; Robinson et al., 2006). Additionally, each tectonostratigraphic zone is separated from another by a major fault, each of which is addressed in the following paragraphs.

In western Nepal, the farthest north tectonostratigraphic unit is the Tibetan Himalaya (Fig. 2). Deposition of the rocks within the Tibetan...
Himalaya began in Precambrian to Cambrian time (Brookfield, 1993) as a passive margin sequence off the north margin of India (Gondwanaland). As India began to collide with Asia at ca. 55 Ma (see review in Najman, 2006; section 6), these rock units began to deform and presently comprise the Tibetan part of the Himalayan thrust belt. The Tibetan Himalaya is bound by the Indus-Yalu suture zone to the north in Tibet and by the South Tibetan detachment system to the south in Nepal. In western Nepal, Tibetan Himalaya rocks are present (Fig. 2), but not enough research has been accomplished in this remote region to determine the stratigraphy and structural history. Without an understanding of the deformation sequence, the formation of the Tibetan part of the thrust belt cannot be included in the model. Thus, discussion of the Tibetan Himalaya and the associated South Tibetan detachment system is not included in this study.

The Greater Himalaya is located between the South Tibetan detachment system and the Main Central thrust. The commonly applied tripartite system of the Greater Himalayan Units I, II, and III developed in central Nepal (LeFort, 1975, 1994; Colchen et al., 1986; Searle and Godin, 2003) can be applied to western Nepal. However, along the central Chainpur cross section (Fig. 2), only Units I and III are present. Unit I rocks are kyanite-bearing pelitic gneiss, migmatite, and metaquartzite with an estimated thickness of ~3 km (Robinson et al., 2006). Unit III rocks are latest Cambrian to Ordovician (Parrish and Hodges, 1996; DeCelles et al., 2000, 2001; Catlos et al., 2001; Godin et al., 2001; Gehrels et al., 2003; Martin et al., 2005) orthogneiss with a thickness of >2.6 km (Robinson et al., 2006). In the westernmost Api cross section (Fig. 2), Greater Himalayan rocks are present but were not investigated; thus, an estimated thickness of ~23 km was taken from Heim and Gansser (1939) and Gansser (1964). In the easternmost Simikot cross section (Fig. 2), only Unit I was observed for an estimated distance of 21 km northward, at which point the investigation did not proceed farther north. This yields a true thickness of ~13.5 km; however, the sequence does contain folds and possible repetitions. Greater Himalayan rock has been mapped northward to the Tibetan border (Amatya and Jnawal, 1994; Murphy and Copeland, 2005). South of the Main Central thrust within a wide zone of Lesser Himalayan rocks, there are units related to Greater Himalayan rocks, the so-called Lesser Himalayan crystalline nappes (Upreti and Lefort, 1999). In western Nepal, the Dadeldhura klippe (and associated Karnali klippe) have εNd isotopic signatures (~12 to ~7; Robinson et al., 2001) and concordant U-Pb zircon ages (464–498 Ma; Einfall et al., 1993; DeCelles et al., 1998a) that fall within the range found in Greater Himalayan rocks. Thus, the Dadeldhura thrust, which transported the rock within the Dadeldhura klippe, may have been connected to the Main Central thrust before erosion stranded the klippe.

The Main Central thrust separates Greater Himalayan rock to the north (also called the Main Central thrust sheet) from Lesser Himalayan rocks to the south. In Nepal, major unconformities separate the Lesser Himalayan rocks into three stratigraphic successions that include the Lesser Himalayan sequence, rocks that are entirely Proterozoic in age in Nepal (DeCelles et al., 2000; Martin et al., 2005), the Late Cretaceous–Paleocene Gondwana sequence, and the Eocene–lower Miocene foreland basin sequence. The Lesser Himalayan sequence from oldest to youngest includes the ca. 1.85 Ga (DeCelles et al., 2000; Martin et al., 2005) Kushma Formation quartzite, the Ranimata Formation phyllite, the 1.83 Ga (DeCelles et al., 2000) Ulleri augen gneiss, the ca. 1.68 Ga (DeCelles et al., 2000) Sangram Formation, the Galyang Formation phyllite and slate, the Syangiga Formation with a variety of phyllite, quartzite, and limestone, and the Lakharpata Group, which consists of a lower limestone and dolostone unit, a middle black shale-slate unit, and an upper limestone and dolostone unit. Robinson et al. (2006) estimate the Lesser Himalayan rock to western Nepal to be 7.1 to 9.3 km thick, but structural complexity hampers an accurate estimate. Total thickness of the Lesser Himalayan sequence may be similar to that found in central Nepal, 10–13 km (Sakai, 1983, 1985; Upreti, 1996, 1999; Pearson, 2002).

In far-western Nepal, the several-hundred-meter-thick Gondwana sequence rests unconformably on top of the Lakharpata Group. Rocks within the Gondwana sequence include quartzose sandstone, black shale, coal, lignite, and quartz pebble conglomerate in a thin (<300 m) package of Jurassic–Paleocene age (DeCelles et al., 2001; Robinson et al., 2006). The Gondwana sequence is separated by an unconformity from the overlying Tertiary foreland basin sequence, which is composed of the middle to upper Eocene (Sakai, 1989) Bhaniskati Formation (DeCelles et al., 1998b, 2004; Najman and

Figure 2. Generalized tectonostratigraphic regional map of western Nepal with cross section lines indicated (A—Api, C—Chainpur, S—Simikot). Colors of tectonostratigraphic zones are the same as in Figure 1. Location in western Nepal indicated on Figure 1. Geochronologic ages mentioned in text indicated by stars. Abbreviations are defined in the text.
Garzanti, 2000), and the lower Miocene Dumri Formation (Sakai, 1983; DeCelles et al., 1998b). The Bhaimenski Formation is ~100 m thick and consists of black mudstone, dark quartzose sandstone, and fossiliferous limestone. The Dumri Formation is ~1200 m thick and consists of sandstone, siltstone, and rare pebble-cobble conglomerate. Between the Dumri and Bhaimenski Formations is a molasse olistolith representing ca. 18 m.y. (DeCelles et al., 1998b).

Beginning in the north, major structures within the Lesser Himalayan rocks include the Ramgarh thrust, the Lesser Himalayan duplex, the Dadeldhura thrust, the Lesser Himalayan imbricate zone, and the Main Boundary thrust (Fig. 2). The Ramgarh thrust (Valdiya, 1980; Srivastava and Mitra, 1994; DeCelles et al., 2001; Pearson and DeCelles, 2005; Robinson et al., 2006) carries Kushma and Ranamata Formations >120 km to the south in far-western Nepal (DeCelles et al., 2001) and ~193 km in the Kathmandu region of central Nepal (Pearson, 2002). The northernmost exposure is in the footwall of the Main Central thrust, and the southernmost exposure is south of the Dadeldhura klippe within the Lesser Himalayan imbricate zone in the hanging wall of the Main Boundary thrust (Fig. 2). The Lesser Himalayan duplex is a hinterland–antiformal-dipping duplex between the Ramgarh thrust and the Dadeldhura klippe (Robinson et al., 2003). These synformal klippe are structurally on top of Lesser Himalayan rocks, and are carried by the Dadeldhura thrust. South of the Dadeldhura thrust lies the Lesser Himalayan imbricate zone, a sequence of complexly deformed Lesser Himalayan rocks in the frontal part of the thrust belt of which the southernmost fault is the Main Boundary thrust (Fig. 2).

South of the Main Boundary thrust, the synorogenic Siwalik Group strata, shed from the growing thrust belt beginning ca. 14–13 Ma (Ojha et al., 2000), is deformed by the Subhimalayan thrust system. The Siwalik Group consists of three informal units—lower, middle, and upper members (Tokuoka et al., 1986; Harrison et al., 1993; Quade et al., 1995; DeCelles et al., 1998a). The Subhimalayan thrust system is separated from the Quaternary to modern sediments of the Indus-Gangetic plain by the active Main Frontal thrust.

Timing data in the Central Himalaya

Forward modeling takes a retrodeformed cross section and tries to simulate the balanced cross section by successively moving thrust sheets as prescribed by the user. Thus, the models presented in this study are based on the balanced cross sections and retrodeformed sections of Robinson et al. (2006). The timing data available are presented in the following paragraph from central and western Nepal.

Thrusting and crustal thickening that buried Greater Himalayan rocks and caused peak metamorphic pressures and garnet growth (Hodges and Silverburg, 1988; Hodges et al., 1994; Ratschbacher et al., 1994; Harrison et al., 1998; Carls et al., 2001; Godin et al., 2001; Kohn et al., 2004, 2005) occurred in the Tibetan Himalaya from ca. 55 Ma to ca. 25 Ma (Ratschbacher et al., 1994; Leech et al., 2005; Ding et al., 2005). In western Nepal, the southern extension of the Greater Himalayan rock, the rock in the Dadeldhura klippe (see section below regarding simplifications), passed through the muscovite Ar closure temperature at 21 Ma (SR40; DeCelles et al., 2001; Fig. 2). Greater Himalayan rock in the immediate hanging wall of the Main Central thrust passed through the closure temperature for muscovite at ca. 25 Ma (SR124; Robinson et al., 2006; Fig. 2). In the eastern Dadeldhura klippe, Sakai et al. (1999) reported an Ar plateau age of 25 Ma from biotite in a gneiss sample (Fig. 2).

Thus, emplacement of the Main Central thrust sheet occurred from 25 to 21 Ma along a regional flat of Lesser Himalayan rock (the Ramgarh thrust sheet) in the footwall in a flat-on-flat relationship causing burial, metamorphism, garnet growth, and shear strain of the future Ramgarh thrust sheet (Robinson et al., 2003).

Ramgarh thrust motion initiated at ca. 15 Ma (DeCelles et al., 2001), which emplaced this sheet over future Lesser Himalayan duplex rocks causing burial, metamorphism, garnet growth, and shear strain in those rocks (Robinson et al., 2003). A Lesser Himalayan rock sample from the Ramgarh thrust sheet in the footwall of the Main Central thrust that has an age spectrum from 17 to 7 Ma (SR123; Fig. 2) is interpreted to represent the timing of slip. Another sample from the Ramgarh thrust sheet has an age of 12 Ma (SR103a; Fig. 2), which represents postmetamorphic cooling through the closure interval of Ar in muscovite as it is cooled as a result of uplift and exhumation (Robinson et al., 2006). Samples from the Ramgarh thrust sheet near the Simikot cross section reveal an Ar-Ar hornblende age of ca. 13 Ma and a Th/Pb monazite age of 9–11 Ma (Bollinger and Jansots, 2006; Fig. 2), which can also be interpreted as the result of uplift and exhumation. Development of the Lesser Himalayan duplex primarily occurred after the main phase of motion on the Ramgarh thrust at ca. 12–10 Ma (Robinson et al., 2006). The Lesser Himalayan duplex began to grow ca. 10–11 Ma (Quade et al., 1997; DeCelles et al., 1998a; Robinson et al., 2001) passively northward tilting the overlying Ramgarh thrust and Main Central thrust sheets (Robinson et al., 2003) and folding the northern Dadeldhura thrust sheet. Beyssac et al. (2004) reported that Lesser Himalayan temperatures decrease from 540º C in the footwall of the Main Central thrust to 330º C in the middle of the Lesser Himalayan duplex. This is the result of differential loading through time from the overlying Tibetan, Greater and Lesser Himalayan rocks. In Early Pliocene time, the Lesser Himalayan imbricate zone formed including the southernmost thrust in the system, the Main Boundary thrust (ca. 5 Ma; DeCelles et al., 1998a), which folded the southern Dadeldhura thrust sheet and completed the syncline. Slip was fed southward into the Siwalik Group, and the Subhimalayan thrust sheet was formed, including the Main Frontal thrust. The Subhimalayan thrust sheet system was active from Mid Pliocene–Holocene time (Wesnousky et al., 1999; Lave and Avouac, 2000).

Parameters and Simplifications of Forward Models

The reconstruction program, 2D Move, is a user-dictated program. A reasonable configuration of Lesser, Greater, and Subhimalayan rock extending from Greater India was deformed in sequence. The sequence does not have to be forward propagating; however, in these cross sections, the balanced cross sections are achieved through no out-of-sequence faulting, except for small displacements detailed in this section. The user dictates the placement and the amount of positive or negative displacement on each fault. However, the deformation of the rock hinterlandward of each fault is not controlled by the user. Thus, the use of 2D Move is an iterative process to obtain the most correct geometries of the rock at the topographic surface as revealed by field work.

In this study, the forward models start ca. 25 Ma with the emplacement of Greater Himalayan rocks over the Ramgarh thrust sheet along the Main Central thrust. Although this is a logical place to begin the models, it is also burdened by assumptions. These models assume that the Greater Himalayan rocks in the hanging wall of the Main Central thrust are continuous with the crystalline rock in the synformal klippen in order to simplify the model (Main Central thrust = Dadeldhura thrust). However, these klippen, commonly known as the “Lesser Himalayan crystalline nappes,” including the Almora, Dadeldhura, Jajarkot, and Kathmandu klippen, may have a different origin. Recent geochronological and Nd isotope studies suggest rocks from these two regions both have Greater Himalayan affinity (Robinson et al., 2001; Gehrels et al., 2003). This one-thrust hypothesis states that the klippen are part of the
Main Central thrust sheet (Johnson et al., 2001; Johnson 2005; Pearson and DeCelles, 2005). Some researchers suggest that these crystalline synformal klippen are separate thrust sheets (two-thrust hypothesis). The Main Central thrust sheet either extended structurally over the top of the synformal klippen (Räi et al., 1998; Upreti, 1999; Upreti and Lefort, 1999) or the klippen extended from a structurally higher thrust sheet (e.g., Langtang thrust; Kohn et al., 2004). This two-thrust hypothesis increases the amount of shortening. However, to maintain simplicity, these forward models use the one-thrust hypothesis.

Because of significant rock-type variability within the Greater Himalayan rocks, the models in this study treat the Greater Himalayan rock as one unit with no structural complexity or stratigraphic variation. Although Greater Himalayan rocks are ductile and contain intraformational thrusts and folds, the shortening in these microscale to mesoscale features is not addressed in these models. Although the author recognizes this as a gross simplification, the treatment as one slab allows for balancing so that Greater Himalayan rocks can be included in the forward modeling. Another simplification is the location of the ramp, which places Greater Himalayan rock over the top of the Ramgarh thrust sheet in a flat-on-flat relationship along the Main Central thrust. The Paleozoic contact between the Lesser Himalayan and Greater Himalayan rocks may either be a suture (DeCelles et al., 2000; Gehrels et al., 2003) or a stratigraphic contact (Parrish and Hodges, 1996; Myrow et al., 2003); thus, these models simplify this paleogeographic unknown and place Greater Himalayan rocks at the northern terminus of the Ramgarh thrust sheet.

In the restored cross sections of Robinson et al. (2006), deformation is successively restored from the foreland to the hinterland. As the Ramgarh thrust sheet was restored, the southernmost exposed part of the thrust sheet in the thrust belt, south of the Dädeldhura klippe, was placed directly beside the thrust sheets in the Lesser Himalayan duplex toward the hinterland. However, the southernmost exposed part of the Ramgarh thrust in the thrust belt is not the southern cutoff of this thrust sheet because the cutoff has been eroded. However, these models treat the southernmost exposed section as a cutoff to simplify the restoration and subsequent forward modeling; it is unknown how far south the Ramgarh thrust sheet traveled and thus, how much has been eroded. The northernmost cutoff of this thrust sheet is also unknown. The restoration was based on a simplification in the cross section that terminates the Ramgarh thrust sheet in the footwall of the Main Central thrust, which gives a minimum amount of offset. It is important to note that the Ramgarh thrust sheet could extend northward for an undetermined distance. Recent evidence presented by Murphy (2007) states that rocks of Lesser Himalayan affinity are being exhumed to the surface in the Gurla Mandata metamorphic core complex which is 50–60 km north of the root zone of the Ramgarh thrust sheet. Thus, these forward models simplify this unknown and terminate the Ramgarh thrust sheet in the footwall of the Main Central thrust, when, in fact, it may extend much farther to the north, which would add shortening.

In the forward models, Greater Himalayan rock is moved along the Main Central thrust enough to completely cover the Lesser Himalayan rock in the Ramgarh thrust sheet. This simplification leads to a minimum shortening estimate for the Main Central thrust sheet because the uncertainty of how far southward the Main Central thrust was emplaced. However, peak temperatures of 500°–550°C were attained in the northermost exposure of the Ramgarh thrust sheet, which suggests burial by the overlying Greater Himalayan rock (Bollinger et al., 2004). In addition, 40Ar/39Ar cooling data suggest an age of ca. 12 Ma in the Ramgarh thrust sheet, which indicates burial deep enough to reequilibrate the muscovite.

The last major simplification in these models deals with small offset thrust and normal faults (usually <5 km) in the thrust belt. These faults were found by geologic mapping and are present in the cross sections (Robinson et al., 2006); thus, these faults must be reproduced in the forward models. These faults cannot be added in a forward-propagating manner for two reasons: (1) when a fault is added to the thrust belt in the modeling program, it influences the hinterlandward rock and changes the configuration of the rocks to such a degree that anticipating how the rocks will change as a consequence is impossible; and (2) the faults are likely late faults due to the readjustment of critical tapers in the thrust belt, and thus, the sequence of the adjustments by the smaller faults is unknown. However, for simplification purposes, after the end of the major deformation sequence, the smaller faults are added one by one from the foreland to the hinterland. This simplification allowed the user to assess the effects and complications produced by each fault after it is created so adjustments can be addressed in the next hinterlandward fault, thus, mitigating any outstanding outcomes.

MODEL CONSTRUCTION

The reconstruction software 2D Move was used to construct each model. Reconstructed cross sections were scanned, scaled, and retraced within the 2D Move program. Basement is a loosely used term in the models (Figs. 3–5). Underneath the Lesser Himalayan rocks, basement is Indian margin granites and metamorphic rocks. While within the Greater Himalaya rocks, basement refers to Greater Himalayan rocks. However, the author acknowledges that Greater Himalayan rock is not Indian basement (e.g., Robinson et al., 2001). Each model is subject to the simplifications stated in the previous section.

Because the initial horizontal scale of each cross section is between 700 and 1000 km, the Api (Fig. 3) and Chainpur sections (Fig. 4) are vertically exaggerated, with vertical exaggeration (VE) expressed on each successive panel. The Simikot section (Fig. 5) contains no vertical exaggeration. In addition, the scale changes in all of the cross sections until stated that the scale stops changing (Figs. 3E, 4H, and 5E). In each model step, the fault that is in motion and the amount of displacement on each fault is stated. Erosion is not addressed in Figures 3–5 (see discussion for explanation).

RESULTS OF MODELS

Api Cross Section—Figure 3*

The position of southward emplacement of the Main Central thrust sheet is unknown; however, to reset the Ar muscovite ages in the Ramgarh thrust sheet, the Main Central thrust sheet is placed entirely over the Ramgarh thrust sheet (Fig. 3B). This cross section has an imbricate of the Ramgarh thrust sheet (Fig. 3C) and a main Ramgarh thrust sheet (Fig. 3D). The Lesser Himalayan duplex forms with the emplacement of the first Lesser Himalayan thrust slice (Fig. 3E) and continues through the emplacement of the sixth Lesser Himalayan thrust slice (Figs. 3F–3J) which also marks the location of the Main Boundary thrust. Note that emplacement of the Lesser Himalayan duplex successively tilts the Ramgarh thrust and Main Central thrust sheets northward into the present northward-dipping position. The Subhimalayan thrust system is developed with emplacement of three Siwalik Group thrust slices (Figs. 3K–3M). Note that the Dadeldhura thrust sheet is folded

---

*If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GE00163.S1 (Supplemental File 1) or the full-text article on www.gsjournals.org to view Supplemental File 1, a PowerPoint presentation of the sequential movements of faults in the Api cross section as reconstructed in 2D Move.
Figure 3 (continued on next page). 2D Move kinematic sequence of the Api reconstruction. Tops of each unit are delineated by the following: basement—hot pink; Kushma Formation—peach; Ranimata Formation—green, Sangram Formation—purple; Galyang Formation—brown; Syangia Formation—light pink; Lakharpata Group—turquoise; Bhainskati Formation (if present)—light gray; Dumri Formation—orange; lower Siwalik Group—olive; middle Siwalik Group—dark brown; upper Siwalik Group—tan. Active fault is bold red. Inactive faults in the forward-propagating sequence are blue. Inactive faults in the hinterlandward-breaking sequence are green. Normal faults have negative displacement; thrust faults have positive displacement. Horizontal and vertical scales are in kilometers. Abbreviations: MCT—Main Central thrust; RT—Ramgarh thrust; LH—Lesser Himalayan; VE—vertical exaggeration.
Figure 3 (continued).
Figure 4 (continued on next pages). 2D Move kinematic sequence of the Chainpur reconstruction. Colors and abbreviations the same as in Figure 3. Horizontal and vertical scales are in kilometers.
Chainpur 9: 2nd LH thrust slice moves = 26.7 km

Chainpur 10: 3rd LH thrust slice moves = 12.8 km

Chainpur 11: 4th LH thrust slice moves = 12.8 km

Chainpur 12: 5th LH thrust slice moves = 12.8 km  VE = 1.07

Chainpur 13: 6th LH thrust slice moves via FPF = 2.1 km  VE = 1.07

Chainpur 14: 7th LH thrust slice moves = 22.9 km  VE = 1.07

Chainpur 15: 1st Siwaliks thrust slice moves = 10.7 km  VE = 1.07

Chainpur 16: 2nd Siwaliks thrust slice moves = 10.7 km  VE = 1.07

Chainpur 17: normal fault = -1.6 km  VE = 1.07

Figure 4 (continued).
into a syncline as the Lesser Himalayan duplex and the Subhimalayan thrust system developed. The hinterlandward-breaking late faults begin with motion on three normal faults within the Lesser Himalayan imbricate zone (LHIZ; Figs. 3N–3P), south of the Dadeldhura thrust. North of the Dadeldhura thrust sheet, the Arnakoli thrust (Fig. 3Q) and two more late faults (Figs. 3R–3S) are emplaced.

Chainpur Cross Section—Figure 4

The Main Central thrust sheet is emplaced entirely over the Ramgarh thrust sheet but not over other Kushma Formation or Ranimata Formation thrust slices to reset the Ar muscovite ages but minimize shortening (Fig. 4B). The Ramgarh thrust sheet in this cross section is broken into several thrust slices (Figs. 4C–4E) to achieve the observed structural geology in the field. Individual thrust slices from the Kushma and Ranimata Formations are emplaced after the Ramgarh thrust sheet (Figs. 4F–4H). These thrust slices are part of the Lesser Himalayan duplex along with thrust slices that contain the entire Lesser Himalayan sequence (Figs. 4I–4O), with the last thrust forming the Main Boundary thrust (Fig. 4O). The emplacement of these seven Lesser Himalayan thrust slices and emplacement of the Subhimalayan thrust system (Figs. 4P–4Q) cause the Dadeldhura thrust sheet to deform into a syncline. Late-breaking normal and thrust faults form the Lesser Himalayan imbricate zone (Figs. 4R–4U). Just north of the Dadeldhura thrust, a break-through thrust fault called the Arnakoli thrust is present (Fig. 4V). A normal fault is present just south of Chainpur (Fig. 4W) as dictated by field mapping. However, Figure 4X contains a thrust fault that was not recognized while mapping, but the modeling program dictates the presence of a fault in order to move the rock units in the hanging wall.

---

If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00163.S2 (Supplemental File 2) or the full-text article on www.gsjournals.org to view Supplemental File 2, a PowerPoint presentation of the sequential movements of faults in the Chainpur cross section as reconstructed in 2D Move.
Figure 5 (continued on next page). 2D Move kinematic sequence of the Simikot reconstruction. Colors and abbreviations the same as in Figure 3. Horizontal and vertical scales are in kilometers.
Simikot 9: 3rd LH thrust slice moves = 15.7 km

Simikot 10: 4th LH thrust slice moves = 17.8 km

Simikot 11: 5th LH thrust slice moves = 13.6 km

Simikot 12: 6th LH thrust slice & 1st Siwaliks thrust slice move = 24.1 km

Simikot 13: 2nd Siwaliks thrust slice moves = 14.7 km

Simikot 14: 3rd Siwaliks thrust slice moves = 18.8 km

Simikot 15: 4th Siwaliks thrust slice moves over foreland = 10.5 km

Simikot 16: thrust fault = 2.1 km

Simikot 17: thrust fault = 5.2 km

Simikot 18: (new fault) thrust fault = 6.3 km

Figure 5 (continued).
of that fault closer to the topographic surface. The presence and/or absence of this fault cannot be verified, but further field work in western Nepal would clarify this issue. Two other late faults are present northward of the new fault (Figs. 4Y–4Z).

Simikot Cross Section—Figure 5

The Main Central thrust sheet completely covers the Ramgarh thrust sheet (Fig. 5B). This cross section also contains a Ramgarh thrust imbricate (Fig. 5C) and a main Ramgarh thrust sheet (Fig. 5D). After emplacement of the Ramgarh thrust sheet, the development of the Lesser Himalayan duplex starts with emplacement of three Raminita Formation thrust slices (Figs. 5E–5G). Lesser Himalayan duplex development continues with emplacement of the Lesser Himalayan thrust slices (Figs. 5H–5M). Emplacement of the Lesser Himalayan duplex folds the overlying Dadeldhura thrust sheet (also called the Karnali klippe). The first Subhimalayan thrust slice is emplaced along with the last Lesser Himalayan duplex thrust slice (Fig. 5M), which delineates the Main Boundary thrust. Emplacement of the Subhimalayan thrust system continues with more Siwalik Group thrust slices (Figs. 5N–5P), of which the southernmost thrust slice marks the Main Frontal thrust. The late-breaking faults include only one thrust fault in the Lesser Himalayan imbricate zone (Fig. 5Q) and two thrust faults north of the Dadeldhura thrust (Figs. 5R–5S). The active fault in Figure 5S was not recognized in the field but was dictated by the reconstruction program in order to move rocks in the hanging wall closer to the topographic surface.

DISCUSSION

Comparison of the Cross Sections with the Reconstruction Program

Comparing the forward modeling results with the balanced cross sections tests the robustness and viability of the balanced cross sections. Figure 6 is a visual comparison of these two methods. Each set of cross sections (Figs. 6A–6B; 6C–6D; 6E–6F) is pinned in the foreland, and then Figures 6B, 6D, and 6F are arbitrarily aligned along the Main Central thrust for comparison. Two other reference lines in each cross section are aligned south of the Dadeldhura thrust and north of the Dadeldhura thrust. In order to compare the Api cross section (Figs. 6A–6B), the vertical exaggeration was removed, which distorted the figure. In the Api section, the location of the Main Central thrust is not well predicted using 2D Move when the cross sections are pinned together in the foreland, which could manually be changed by adding another late thrust in the footwall of the Ramgarh thrust sheet to move the Main Central thrust sheet southward. If done, this would be another fault not seen in the field but predicted by 2D Move; however, this is not a satisfactory solution because the thrust would have to dip at a much shallower angle than the other faults. Location of the Ramgarh thrust sheet on top of the Lesser Himalayan duplex is well predicted as well as the location of the north limb of the Dadeldhura thrust sheet. The south limb of the Dadeldhura thrust sheet is not well predicted but could be changed by having less displacement on the normal fault south of the Dadeldhura thrust sheet, which would bring the Ramgarh thrust sheet closer to the topographic surface.

The location of the Main Central thrust sheet is well predicted in the Chainpur cross section (Figs. 6C–6D) as well as the structure of the Lesser Himalayan duplex. The north and south limbs of the Dadeldhura thrust sheet as well as the structure of the Lesser Himalayan duplex are well predicted using the 2D Move program. In the Simikot cross section (Figs. 6E–6F), the Main Central thrust sheet is well predicted along with the structure within the Lesser Himalayan duplex. However, the northern part of the Lesser Himalayan duplex remains buried at the erosion surface. The northermost late thrust fault was a fault not seen when mapping but predicted by the modeling program. In order to move the northern Lesser Himalayan duplex closer to the topographic surface, more displacement is needed on the northernmost late fault. However, more displacement would force the faults northward to be tilted beyond vertical, which is not reasonable. Thus, the Raminita Formation thrust slices were left buried at depth. The north limb of the Dadeldhura thrust sheet is too far below the ground surface but could be changed by putting more displacement on the thrust sheets in the subsurface below the north limb of the Dadeldhura thrust sheet. The south limb of the Dadeldhura thrust is well predicted along with the structure of the Lesser Himalayan imbricate zone. Overall, the reconstruction program Chainpur cross section can be replicated using the faults and structural architecture identified in the balanced cross sections, and the 2D Move Simikot section shows that the gross architecture is similar. The reconstruction program Api cross section predicts the overall structure well but is not quite accurate. The 2D Move cross sections probably do not match the balanced cross sections exactly because of the iterative process of creating the reconstruction program cross sections. Most likely, not enough positive displacement may have been added to the previous faults. If this error is made early in the building of the cross section, the error is propagated through the reconstructions, and the effects are difficult to mitigate. Uncertainties in these cross sections include the assumptions of the modeling (as detailed earlier), the along-strike correlation of stratigraphy and structure, and the geometry of the faults as depth (although reasonable assumptions are built into the balanced cross sections).

Table 1 is a comparison of the overall shortening between that found in the cross sections (Robinson et al., 2006) and the shortening predicted by the reconstruction program. The total in the Api cross section predicted by 2D Move is 511 km compared with shortening from the cross sections at 541–604 km. Shortening is underpredicted by the reconstruction program, which suggests that either the cross section may be incorrectly reconstructed or that motions on the faults in 2D Move may not have sufficient displacements. Insufficient positive displacement on faults may explain why the location of the Main Central thrust is predicted too far north (Fig. 6A) in 2D Move. Total shortening in the Chainpur cross section is 485–543 km, and the 2D Move falls within that estimate at 495 km. Total shortening in the Simikot cross section is 667–743 km, and 2D move predicts 733 km of shortening. The reconstruction program accurately predicts the amount of shortening in the cross sections in the Chainpur and Simikot cross sections but underpredicts shortening in the Api cross section.

Lessons Learned from Forward Modeling

When constructing the cross section for balancing, a sequence of thrusting is established, but the cross sections are not animated in a forward modeling program. By placing the reconstruction into a modeling program and requiring the reconstruction to work seamlessly from one stage to the next stage, insights into the building of the Himalayan thrust belt can be gained. By using the forward modeling program in combination with the timing data, this study shows that deformation within the Himalayan thrust belt essentially propagated southward, at least in western Nepal; however, minor out-of-sequence thrust and normal faults exist which are termed the late-breaking faults in this study. For reasons already detailed, these faults were initiated in a
Figure 6. Comparison of the cross sections produced using 2D Move in A, C, and E to those produced by Robinson et al. (2006) in B, D, and F. Each set of cross sections (Api [A–B]; Chainpur [C–D]; Simikot [E–F]) is aligned along the foreland pin line. Subsequently, B, D, and F are aligned along the Main Central thrust to compare the results of A, C, and E. Two more comparison lines each on B, D, and F mark the north and south limbs of the Dadeldhura thrust sheet and how the associated 2D Move cross section is aligned with those cross sections. Colors are the same as in Figure 1. Abbreviations: DT—Dadeldhura thrust; LHD—Lesser Himalayan duplex; LHIZ—Lesser Himalayan imbricate zone; MCT—Main Central thrust; RT—Ramgarh thrust; SHTS—Subhimalayan thrust system.
hinterlandward-breaking sequence from the Main Frontal thrust northward to the South Tibetan detachment system. However, this sequence is artificial; the actual sequence is impossible to determine without dating the timing of motion on these faults. Displacement on these faults is typically <5 km; thus, they do not contribute greatly to the overall shortening of the thrust belt. Table 1 illustrates that the total shortening gained when summing the displacements on these thrust and normal faults is between 6.8 and 10.6 km.

The location of the Lesser Himalayan sequence ramp over which thrust sheets in the Lesser Himalayan duplex move is determined by how far the Subhimalayan thrust system extends into the hinterland when the Siwalik Group is reconstructed (see Figs. 3A, 4A, and 5A). Movement over this ramp occurs as the Lesser Himalayan imbricate zone and Subhimalayan thrust system are forming (see Figs. 3J–3M, 4O–4Q, and 5L–5P). The reconstruction program illustrates that motion over the Lesser Himalayan ramp occurred in multiple stages as displacement occurred on multiple faults.

The data support a conventional, forward-propagating, orogenic wedge model albeit with a major component of ductile deformation in Greater Himalayan rocks. Thus, these models support a critical taper model at least from the Main Frontal thrust to the South Tibetan detachment system. The complex pattern of out-of-sequence thrust and normal faulting (the late faults) in western Nepal is consistent with an explanation that the adjustments are needed for the wedge mechanics. Erosion in the models (Figs. 3–5) is not taken into account. As the thrust sheets and slices were emplaced and huge culminations formed, erosion was attacking the exposed thrust sheets. These synorogenic sediments were deposited into the Dumri Formation (21–16 Ma) and into the Siwalik Group only to be reincorporated into the thrust belt as the thrust belt propagated southward. Figure 6 compares the present erosional surface in the cross section to where that same erosional surface would be located into the thrust belt as predicted by forward modeling. However, the program does not address erosion as the formation of the thrust belt occurred. In order to address erosion, a detailed basin history is needed from the synorogenic sediments. Clearly, critical taper would be affected by where erosion was occurring intensely. More erosion causes the wedge to become subcritical and leads to more faults being formed to maintain a critical angle (cf. Horton, 1999).

### Implications across the Himalayan-Tibetan Orogen

Channel flow models for the Himalayan-Tibetan orogenic system propose a link between channel flow and ductile extrusion of Greater Himalayan rocks driven by focused denudation at the Himalayan topographic front (Beaumont et al., 2001). This study treats the Main Central thrust sheet and the crystalline rocks in the klippe (Dadeldhura klippen and Kathmandu klippe) as riding on one fault. Robinson and Pearson (2006) point to several lines of evidence in the Kathmandu klippe, such as bedded stratigraphy in klippe rocks and the lack of an upper bounding shear zone, to suggest that channel flow could not have occurred in the klippe (sensu Beaumont et al., 2001, 2004; Jamieson et al., 2004). In order for channel flow to occur, the two-thrust hypothesis must be correct, which would dramatically increase shortening estimates. According to the models in this study and the kinematic model of Robinson et al. (2003), Greater Himalayan rocks were emplaced prior to the onset of motion along the Ramgarh thrust in middle Miocene time. Channel flow and subsequent extrusion and/or exhumation within the exposed Greater Himalayan rocks must have ended by middle Miocene time before slip in the system was transferred to the south. The numerical models show extrusion beginning in middle Miocene and continuing to the present day (e.g., Jamieson et al., 2004). In addition, ductile fabrics are not present after ca. 17 Ma (Searle et al., 2003), which suggests that channel flow could not have been active after this time. The forward models presented in this study suggest a relatively conventional wedge model system for the development of the Himalayan thrust belt. This study does not rule out that channel flow might have occurred; however, it does suggest that the timing and mechanics of channel flow need to be altered to accommodate the surface data from the thrust belt.

This study confirms that shortening estimates of 485–743 km from the footwall of the South Tibetan detachment system to the Main Frontal thrust derived from balanced cross sections in western Nepal (Robinson et al., 2006) are robust because the shortening obtained from 2D Move ranges from 495 to 733 km. In addition, Srivastava and Mitra (1994) obtained similar shortening estimates in northern India (354–421 km) crossing the same structural boundaries. Shortening from the Tibetan thrust belt north of west Nepal is 176 km (Murphy and Yin, 2003), yielding total shortening between ~700 and 1000 km in the Himalayan thrust belt.

DeCelles et al. (2002) proposed that the length of shortening of the Greater India sequence in the thrust belt should equal the distance from the Indus-Yalu suture zone to the northern edge of the plateau because Greater Indian lower crust was stripped of its supracrustal cover during the Cenozoic collision and underthrust beneath the Tibetan Plateau. The results of this study support the idea that Greater India lower crust may be underneath the Tibetan Plateau helping the plateau attain its present crustal thickness.

### Table 1. Shortening Estimates in Western Nepal

<table>
<thead>
<tr>
<th>Location</th>
<th>Cross sections (km)</th>
<th>2D Move (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>API (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subhimalaya and Lesser Himalaya</td>
<td>393</td>
<td>321.7</td>
</tr>
<tr>
<td>Greater Himalaya + klippe</td>
<td>146–211*</td>
<td>182.5†</td>
</tr>
<tr>
<td>Subtotal</td>
<td>541–604</td>
<td>504.2</td>
</tr>
<tr>
<td>Late faults</td>
<td>N.A.</td>
<td>6.8</td>
</tr>
<tr>
<td>Total</td>
<td>541–604</td>
<td>511</td>
</tr>
<tr>
<td>CHAINPUR (C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subhimalaya and Lesser Himalaya</td>
<td>374</td>
<td>327.2</td>
</tr>
<tr>
<td>Greater Himalaya + klippe</td>
<td>111–169*</td>
<td>156.8†</td>
</tr>
<tr>
<td>Subtotal</td>
<td>485–543</td>
<td>484</td>
</tr>
<tr>
<td>Late faults</td>
<td>N.A.</td>
<td>10.6</td>
</tr>
<tr>
<td>Total</td>
<td>485–543</td>
<td>495</td>
</tr>
<tr>
<td>SIMIKOT (S)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subhimalaya and Lesser Himalaya</td>
<td>522</td>
<td>480</td>
</tr>
<tr>
<td>Greater Himalaya + klippe</td>
<td>145–221*</td>
<td>245†</td>
</tr>
<tr>
<td>Subtotal</td>
<td>667–743</td>
<td>725</td>
</tr>
<tr>
<td>Late faults</td>
<td>N.A.</td>
<td>8.4</td>
</tr>
<tr>
<td>Total</td>
<td>667–743</td>
<td>733</td>
</tr>
</tbody>
</table>

*Minimum, if DK is southern continuation of Greater Himalaya (GH); maximum, if DK and GH are separate thrust sheets and overlying GH extends to middle of klippe (Upreti and LeFort, 1999).
†Calculated assuming Main Central thrust (MCT) sheet completely covered Ramgarh thrust sheet, and Dadeldhura thrust and MCT are the same.
§Not applicable; when balancing cross sections, the late faults are included in the total shortening.
Applicability to Other Thrust Belt Systems

Reconstruction programs have been used to show that, in general, a kinematic sequence is plausible (e.g., McQuarrie, 2002; DeCelles and Coogan, 2006). However, this study uses a reconstruction program to provide step-by-step details of the evolution of a thrust belt system. Not only does this study provide an unprecedented view of the evolution of a thrust belt system, specifically the Himalaya, but the future possibilities of integrating these data and other similar studies with geochronologic, thermochronologic, and sedimentary basin studies will provide a powerful view of the kinematic evolution of thrust systems. This method of reconstruction can be applied in regions where balanced cross sections currently exist (e.g., the Andes and Appalachian Mountains) and other regions across the Himalaya including Pakistan (Coward and Butler, 1985), northern India (Srivastava and Mitra, 1994), and Bhutan (McQuarrie et al., 2008).

CONCLUSIONS

Forward modeling of a thrust belt allows the user to reconstruct the thrust belt in order to prove that a proposed kinematic sequence is a viable option. In this study, three reconstructions of balanced cross sections are forward modeled in an effort to reproduce existing balanced cross sections. This study has the following conclusions:

1. Using reasonable motions on thrust faults and thrust slices and timing data from previous studies, the present surface geometry of rocks in the Himalayan thrust belt in western Nepal from the footwall of the South Tibetan detachment system southward to the Main Frontal thrust can be reproduced.

2. Because the deformation can be reproduced, this confirms that the cross sections (Robinson et al. 2006) are viable and that the kinematic sequence is plausible.

3. In addition, the detailed step-by-step forward modeling of the Greater Indian passive margin provides an unprecedented view of the evolution of the central Himalayan thrust belt. These step-by-step reconstructions can be integrated with other data to produce detailed timing of the kinematic sequence.

4. The displacement needed to reproduce the cross section in 2D Move and the amount predicted by the restoration of the cross sections are very similar. Thus, shortening estimates in 2D Move (495–733 km) are within the range predicted for shortening in western Nepal obtained from the balanced cross sections (485–743 km).

5. The sequential motion of each fault allows a visualization of the deformation sequence and shows that the Himalayan thrust belt in western Nepal is essentially a forward-propagating thrust belt from hinterland to foreland, with minor out-of-sequence (<5 km) thrust and normal faults. Thus, a conventional wedge model is sufficient to explain the data.

ACKNOWLEDGMENTS


REFERENCES CITED

Hodges, K.V., Hames, W.E., Olszewski, W., Burchfiel, B.C., Royden, L.H., and Chen, Z., 1994, Thermalbarometric...


