Chapter 2. A new kinematic evolutionary model for the growth of a duplex – an example from the Rangit duplex, Sikkim Himalaya, India

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ABSTRACT

Thrust duplexes are integral components of fold-thrust belts (FTB) and provide efficient mechanism for slip transfer during the evolution of any FTB. The Lesser Himalayan duplexes, reported all along the Himalayan arc, provide critical information on the evolution of the Himalayan fold-thrust belt. The roof thrust of the Lesser Himalayan duplex has translated the overlying Greater Himalayan crystallines farther southward to form the Greater Himalayan klippen, exposed within the Lesser Himalaya, all along the length of the Himalayan FTB.

In the Darjeeling-Sikkim Himalaya the Lesser Himalayan sequence (LHS) is repeated several times to form the Lesser Himalayan duplex; part of this duplex is exposed in the Rangit window, lying north of the Greater Himalayan Darjeeling klippe, as the Rangit duplex. The upper LHS is repeated along nine horses to form the Rangit duplex. The geometry of the Rangit duplex is significantly different and more complicated than the other Lesser Himalayan duplexes. The Ramgarh thrust is the roof thrust of the Rangit duplex and the floor thrust is interpreted to be the Main Himalayan Sole thrust (MHT). We have incorporated surface geology together with geologic constraints (e.g. return to regional dip and excess area arguments, and stratigraphic thicknesses) and geophysical data (e.g. microseismic data) to construct a balanced cross-section across the Rangit window, parallel to the N-S transport direction. The depth to detachment below the Rangit duplex is ~10 km and has a regional dip of ~3.5° N.

The Rangit duplex varies in geometry from a hinterland-dipping duplex in the north, to an antiformal stack in the middle and to a foreland-dipping duplex in the
south. Existing kinematic models are inadequate to explain the kinematic evolution of the Rangit duplex and the complex geometry requires a new kinematic model for its evolution. We propose that two different faults became the major roof thrusts during the evolution of the Rangit duplex. The Rangit duplex initiated as a foreland-dipping duplex with the early Ramgarh thrust (RT 1), as the roof thrust, and the Ramgarh thrust as the floor thrust; this was followed by a combination of footwall imbrication and reactivation of the Ramgarh thrust. The Ramgarh thrust acted as the roof thrust during the evolution of the later forming hinterland-dipping component and the antiformal stack of the Rangit duplex. The leading part of the Ramgarh thrust was deactivated and the trailing part was reactivated after every stage of footwall imbrication. The Rangit duplex accommodated a minimum shortening of ~125 km. The foreland-dipping component of the duplex along with the reactivation of the Ramgarh thrust can explain the large translation of the overlying MCT sheets that are exposed within the Darjeeling klippe of the Darjeeling – Sikkim Himalaya.

The restoration of the balanced cross section across the Rangit duplex suggests that the Gondwana basin extended for ~142 km northward of its present northernmost exposures in the Rangit duplex of the Darjeeling – Sikkim Himalaya.

2.1. INTRODUCTION

Thrust duplexes are an integral part of fold-thrust belts (FTBs) and have been described from most major orogens (e.g. Dahlstrom, 1970, Elliott and Johnson 1980, Boyer and Elliott, 1982, Butler, 1982, Coward, 1984, Diegel 1986, Mitra, 1986, Fermor and Price, 1987, Geiser, 1988, Srivastava and Mitra, 1994, DeCelles and Mitra, 1995, DeCelles et al., 1998, McQuarrie and DeCelles, 2001, McQuarrie et al., 2008). They are generally found in the internal portions of FTBs where a longer deformation history and the consequent higher connectivity between faults can lead to the formation of duplexes (Boyer and Elliott, 1982) in both crystalline basement rocks and sedimentary cover rocks. They accommodate a large fraction of the total shortening in most FTBs, and provide an efficient mechanism for transferring slip upward from the basal
decollement into the FTB wedge and for transporting roof thrust sheets over long
distances. In addition, continued reactivation of hinterland duplexes may provide the
necessary thickening in the back of an orogenic wedge to maintain critical taper and
allow continued thrusting onto the foreland (DeCelles and Mitra, 1995). Because of
their critical role in various aspects of FTB shortening, understanding the kinematic
evolution of duplexes can provide many clues to evaluating the growth of an orogen as
a whole.

In the Himalayan FTB (Fig. 2.1), the growth of the Lesser Himalayan duplex
plays a prominent role in the overall evolution of the FTB. The Lesser Himalayan
duplex has been described all along the length of the Himalayan arc, from Kumaon
(Srivastava and Mitra, 1994), through Nepal (DeCelles et al., 1998) and Sikkim
(Bhattacharyya et al., 2006, 2008), to Bhutan (McQuarrie et al., 2008). In most places
along this belt the duplex accommodates a significant fraction of the total shortening of
the Himalayan FTB, ranging from less than ~25% of the total minimum shortening in
the western Himalaya (Kumaon and Nepal) to as much as ~50% of the total minimum
shortening in the eastern Himalaya (Sikkim and Bhutan) (Mitra et al., 2009). In
addition, the roof thrust of the Lesser Himalayan duplex has translated Greater
Himalayan crystalline thrust sheets southward over long distances resulting in the
formation of the Greater Himalayan klippen, which are exposed in the Lesser
Himalaya; examples include the Almora kipple in Kumaon (Srivastava and Mitra,
1994), the Dadeldhura Klippe in western Nepal (DeCelles et al., 1998), and the
Darjeeling kipple in the eastern Himalaya. Clearly, deciphering the kinematics of the
Lesser Himalayan duplex is critical to understanding the overall evolution of the
Himalayan FTB at different locations along the Himalayan arc.

In the Darjeeling – Sikkim Himalaya (Figs. 2.1, 2.2) the Lesser Himalayan
Sequence, made up of a 6-8 km thick sequence of Proterozoic – Paleozoic Daling, Buxa
and Gondwana rocks, is repeated several times along horses forming the Lesser
Himalayan duplex. Part of this repetition is exposed in the Rangit window (Fig. 2.2)
(Ghosh, 1956, Raina, 1976, Gangopadhyay and Ray, 1980) as the Rangit duplex (Fig.
Figure 2.1. Regional map of the Himalaya (Sorkhari & Macfarlane, 1999) showing the major longitudinal lithotectonic subdivisions separated by major faults. In the Darjeeling-Sikkim Himalaya (rectangle outline), the MCT translates the GHS much farther southward than in other parts of the Himalaya.
Figure 2.2. Regional map of the Darjeeling – Sikkim Himalaya. In this region, both the MCT 1 and MCT 2 sheets are translated southward to within 5 km of the Himalayan mountain front and are exposed in the Darjeeling (DK) and the Labha semi-klippen (LK). The Rangit window (RW) lies north of the Darjeeling semi-klippe. The main faults are labeled.

MCT1 – Main Central thrust 1; MCT2 – Main Central thrust 2; DT1 – Daling thrust 1; DT2 – Daling thrust 2; RT – Ramgarh thrust; MBT – Main Boundary thrust; NKT – North Kalijhora thrust; MFT – Main Frontal thrust

Towns shown are: C - Chungthang; D - Darjeeling; Di – Dikchu; G - Gangtok; J – Jorethang; Ks - Kurseong; M - Mangan; Ma – Martam; My – Mayangchu; P-Pankhabari; Pe - Pelling ; S - Sevok; TB - Teesta Bazaar; Y - Yuksom
2.3; Bhattacharyyya et al., 2006). Unlike the Kumaon, Nepal and Bhutan Himalaya where the Lesser Himalayan duplex generally has an overall hinterland-dipping geometry (Srivastava and Mitra 1994, DeCelles et al. 1998, McQuarrie et al., 2008), the geometry of the duplex in the Darjeeling – Sikkim Himalaya is significantly different and more complicated.

Existing kinematic models for the evolution of duplexes are inadequate for explaining the kinematics of the complex geometry observed in the Rangit duplex. The generally accepted Boyer-style duplexing model with hinterland-to-foreland progression of thrusting (Boyer and Elliott, 1982), or a model calling on duplexing by forming connecting splays joining two preexisting thrusts (Mitra and Sussman, 1997), both result in simpler duplex geometries. A model incorporating hinterland-to-foreland progression together with imbricate reactivation (Boyer, 1992) provides a basis for evaluating a kinematic history for the Rangit duplex, but the Rangit duplex differs in detail because it never develops out-of-sequence imbricates in the hanging wall of the roof thrust. In this paper we describe in detail the geometry of the Rangit duplex and propose a new kinematic model to explain its structural evolution. Retrodeformation along this kinematic path yields a well constrained palinspastic restoration of the Buxa-Gondwana basin that defines the original northern extent of this basin in Peninsular India. We also discuss the implication of the Rangit duplex for the evolution of the Darjeeling – Sikkim Himalaya as a whole.

2.2. BACKGROUND

2.2.1 Regional Geology

The Himalayan orogen is considered to have formed at the northern margin of East Gondwanaland (Valdiya, 1997, Yoshida and Upreti, 2006). The growth of the Himalayan orogen is related to the collision of the Indian lithosphere against the Eurasian lithosphere that started with initial impingement at ~52 Ma (Rowley, 1996) and is continuing to the present. The shortening in the Himalayan fold-thrust belt (FTB) accounts for a significant portion of this convergence, and is dominantly
accommodated by a system of south-vergent thrust faults, where early large
displacement faults are often folded by continuing deformation (Medlicott, 1864, Heim
and DeCelles, 2005). From north to south the major thrust systems are the Main Central
thrust (MCT 1 & 2), the Ramgarh thrust, the Lesser Himalayan duplex, the Main
Boundary thrust (MBT) and the Main Frontal thrust (MFT). Traditionally the MCT and
the MBT have been used to mark the boundaries between the Greater- and Lesser-
Himalayan, and the Lesser- and Sub-Himalayan sequences respectively (Fig. 2.1).

The Darjeeling – Sikkim Himalaya lies between longitudes 88°05’E and
88°47’E in the eastern Himalaya, bounded by the Nepal Himalaya in the west and the
Bhutan Himalaya in the east (Figs. 2.1, 2.2). There are two major north-south trending
river systems in the Darjeeling – Sikkim Himalaya, the Teesta and the Rangit (Fig. 2.2).
Erosion by these rivers has formed the Teesta half window (Schwan, 1980), that is
almost entirely bounded by the MCT 2 (Fig. 2.2), but the fault is eroded through at the
southern end so that the window does not have a closed outcrop pattern. The MCT 2
carries the amphibolite grade Paro-Lingste gneiss on top of the greenschist grade
Daling Formation of the lower Lesser Himalayan sequence (LHS). Tectonically above
the MCT 2 is the MCT 1 that carries the granulite grade Kanchenjunga Gneiss in its
hanging wall. Both the MCT 1 and MCT 2 sheets are translated much farther southward
than anywhere else along the length of the Himalayan arc, and are exposed in the
Darjeeling and Labha klippen (Fig. 2.2).

Similar to elsewhere in the Himalaya, the structure in the sub-MCT, within the
Teesta half-window, is dominated by a prominent duplex that repeats the Lesser
Himalayan sequence (LHS). North of the Darjeeling klippe, and within the Teesta half-
window lies an inner window, the Rangit window (Fig. 2.2, Raina, 1976,
Gangopadhyay and Ray, 1980). The Rangit window is bounded on all sides by the
Ramgarh thrust and exposes the Rangit duplex (Fig. 2.3, Bhattacharyya et al., 2006)
that repeats the upper part of the LHS made up of the Gondwana, Buxa and upper
Figure 2.3. Map of the Rangit window showing the thrust slices constituting the Rangit duplex. The upper LHS is repeated along horses at least eight times within the duplex. The Ramgarh thrust is the roof thrust. The four northern horses form a hinterland-dipping component, the Namchi horse is the exposed part of an antiformal stack, and the three horses in the southern part of the window form a foreland-dipping component. Towns are B - Banzyang, C - Chamchey, Ch - Chiyadaara, G - Gelling, J - Jorethang, K - Kamling, Ki – Kitam, KS - Khani Sabang, N - Namchi; O - Omchu, Pk - Pakzer, PN - Purana Namchi, R - Reshi, RN – Rangitnagar power station, S - Singrep, Sa – Samdong, So – Sorok, T - Tinkitam. Small streams shown are Rak: Rathong Khola, DK: Dong Khola. AB represents the line of cross section.
Daling units.

In the foothills, south of the Darjeeling klippe, the leading part of the Ramgarh thrust is exposed near Setijhora in the Teesta valley, and places the Daling quartzites over the Gondwana sandstones; this fault was previously mapped as the North Kalijhora thrust (Mukul, 2000). South of the frontal Ramgarh thrust, the Main Boundary thrust (MBT) carries the Gondwana Group on top of the synorogenic Cenozoic Siwalik Formation (Acharyya, 1994). Here, the MBT has been folded by footwall imbrication (South Kalijhora thrust of Mukul, 2000). The Main Frontal thrust (MFT), the youngest and the southernmost thrust, brings the Siwalik Formation over the Quaternary deposits exposed at the Himalayan mountain front.

2.2.2 Stratigraphy

The details of regional stratigraphy are presented elsewhere (Mallet 1875, Ray, 1947, Ghosh, 1956, Acharyya, 1971, Acharyya and Ray, 1977, Raina 1976, Gangopadhyay and Ray, 1980, DeCelles et al., 2001, Robinson et al., 2006, McQuarrie et al., 2008) and will not be described here. The basic outline of the stratigraphic sequence exposed within the Rangit window is presented in Table 2.1.

For the purposes of deciphering the detailed structural patterns within the Rangit window we used the stratigraphic units of the upper Lesser Himalayan sequence; their salient characteristics and thicknesses are described here.

2.2.2.1 Daling Formation

The Daling Formation constitutes the upper part of the Daling Group, the oldest Paleoproterozoic group of the Lesser Himalayan sequence. The Daling Formation is dominantly a meta-pelitic sequence with a few quartzite bands. It is underlain by a greenish white to tan colored quartzite rich unit, the Reyang Formation; together they form the Daling Group. The Daling Formation of Sikkim (Acharyya, 1971) and Bhutan (Jangpani, 1976, McQuarrie et al., 2008) can be lithologically correlated with the Ranimata Formation of the Nepal Himalaya (DeCelles et al., 1998, 2001). The Reyang
Table 2.1. Stratigraphic column of the Upper Lesser Himalayan Sequence as exposed within the Rangit window (modified after Raina, 1976).
<table>
<thead>
<tr>
<th>Lesser Himalayan Sequence (LHS)</th>
<th>Gondwana Group (Permian)</th>
<th>Buxa Formation (Latest Proterozoic-early Cambrian)</th>
<th>Daling Formation (Precambrian)</th>
</tr>
</thead>
</table>

Formation can be correlated with the Kushma Formation of the Nepal Himalaya.
(DeCelles et al., 1998, 2001) and the Shumar Formation of the Bhutan Himalaya (McQuarrie et al., 2008). Detrital zircon ages from the Kushma and Ranimata Formations of western Nepal suggest a depositional age between ~1.86 and ~1.83 Ga (DeCelles et al., 2001). McQuarrie et al. (2008) report a pronounced peak at ~1.8 Ma in the detrital zircon spectra from the Daling-Shumar group of the Bhutan Himalaya.

In the Darjeeling – Sikkim Himalaya, the Daling Group is ~5 km thick and the Rangit window exposes the upper ~1.2 km of the Daling Formation as a dominantly greenish grey chloritic slate that is locally variegated in shades of purple, black and grey. Locally, Daling chloritic schists are also exposed within the duplex. The thickness of the individual beds is ~ 1-2 cm. The Daling Formation is exposed in the Sikkip horse and in the three southernmost horses of the Rangit duplex (Fig. 2.3).

2.2.2.2 Buxa Formation

The Buxa Formation overlies the Daling Formation. It is dominantly a carbonate rich unit that grades from bright green to bright pink to yellowish white colored calcareous slates and intraformational conglomerate bands at the bottom of the sequence to bluish grey stromatolitic dolomites at the top (Fig. 2.4a). The bright colored slates are generally intercalated with pink and yellowish white limestones. The Buxa variegated slates are distinguished from the Daling slates by their brighter color, local carbonate intercalations and lesser fissility (Fig. 2.4b). Locally, the upper Buxa dolomites are intercalated with grey quartzites (as seen in the Tatapani horse). The Buxa Formation is lithologically similar to the Syngia Formation-Lakarpata Group of the Nepal Himalaya; based on the presence of stromatolites, Sakai (1985) suggests a Proterozoic age for the Lakarpata Formation of the Nepal Himalaya. Recent studies of microfossils from the cherty dolomites of the Rangit window suggests a latest Proterozoic to earliest Cambrian age for these rocks (Schopf et al., 2008). However, based on detrital zircon geochronometry, McQuarrie et al. (2008) suggest a Cambrian
Figure 2.4(a) Buxa dolomite from the Sikkim horse with stromatolites showing that the bed is upward facing; pencil for scale. (b) Buxa slates from the Sikkim horse showing steeper cleavage than bedding, both dipping towards the north. The horse is upward facing, and is part of the hinterland-dipping component of the duplex; pen for scale. (c) Gondwana sandstone from the Dong horse showing cross-bedding suggesting that the bed is upward facing; hammer head in the lower left corner for scale. (d) Carbonate mylonites of the Ramgarh thrust zone as exposed near Tinkitam village in the northeastern part of the duplex; hammer for scale. (e) Gondwana coaliferous sandstone from the Jorethang horse (looking E) showing that the bedding is steeper than the cleavage, both dipping towards the south (foreland). Here a continuous Buxa-Gondwana section indicates that the top of the section is to the right (south). This horse is part of the foreland-dipping component of the duplex. (f) “S” fold (looking W) within the Gondwana Group of the Jorethang horse suggesting top to the south (forelandward) shear; hammer for scale.
maximum depositional age for the Buxa group in the Bhutan Himalaya.

The Buxa Formation is ~1.2 km thick and is best exposed in the Tatapani horse. This formation is entirely absent in the southernmost two horses of the Rangit duplex (Fig. 2.3). The thicknesses of the individual Buxa units vary with its lithology; the calcareous slates have beds that are ~2 cm thick, the limestone beds are ~3-5 cm thick while the dolomite beds have an average thickness of ~10 cm.

### 2.2.2.3 Gondwana Group

This is the youngest unit of the LHS in the Darjeeling – Sikkim Himalaya and unconformably overlies the Buxa Formation. It is predominantly a fining upwards sequence that grades from a basal conglomeratic horizon, the Rangit pebble slate (Ghosh, 1956, Acharyya 1971), to medium-grained bluish grey gritty sandstone and orthoquartzites in the middle, to black coal-bearing slates at the top of the sequence. The Gondwana sandstones are the dominant cliff-forming horizons within the window. Presence of plant fossils such as Glossopteris sp, Gangamopteris sp, and Vertebraria sp suggest a Permian age for the Gondwana Group (Acharyya, 1971).

The Gondwana Group exposed in all the horses of the duplex and is ~1 km thick. The Rangit pebble slate unit is best exposed along the southwestern boundary of the window. Beds of the Gondwana Group have variable thicknesses with an average ~20 cm for the sandstone unit and ~1-2 cm for the coal-bearing slates. Locally, the Gondwana sandstone preserves primary structures like cross-bedding (Fig. 2.4c) and graded bedding.

### 2.2.3 Method

The Rangit window exposes repeated slices of all or part of the upper Lesser Himalayan Daling-Buxa-Gondwana sequence that constitute the Rangit duplex. We used structural mapping at 1:50,000 scale, bedding-cleavage relationships, and sedimentary structures to define the successive horses of the duplex and to study the geometry of individual horses within the duplex. In addition to the surface data, we
incorporated the template constraint and seismic data (Nath et al., 2005) to construct a N-S balanced cross section across the duplex (as described later in the paper).

2.3. GEOMETRY OF THE RANGIT DUPLEX

2.3.1 Map Patterns

The Rangit window extends for ~15 km in the N-S direction from Rangitnagar to Jorethang and ~13 km in the E-W direction from Gelling to Bhanzyang and lies directly north of the Darjeeling klippe (Figs. 2.2, 2.3). Erosion through the folded Ramgarh thrust has exposed the footwall upper LHS rocks, thereby forming the Rangit window. The Ramgarh thrust, the bounding fault of the Rangit window, can be traced around the entire window. The fault is best exposed along the northeastern margin of the window, ~2 km east of the village of Tinkitam, as a ~27 m thick carbonate mylonite zone (Fig. 2.4d); there the fault was mapped earlier locally as the Tendong thrust (Raina, 1976). Our mapping has significantly modified the location of the Ramgarh thrust in the northern part of the window, where the northern margin is now placed ~0.5 km north of the Rangitnagar power station; there the fault is defined by a ~30 m thick poorly exposed contact between the greenish grey Daling slates of the hanging wall and the bright green calacareous slates of the Buxa Formation of the footwall (Fig. 2.3).

The southwestern corner of the Rangit window is defined by a ~10 m thick SW dipping mylonite zone that places the green Daling slates on top of the Gondwana coaliferous sandstone; the fault zone is exposed ~5 km west of Jorethang near Singrep village (Fig. 2.3). The southern margin of the Rangit window is generally bounded by a steeply S-dipping folded thrust fault, which we interpret to be the early Ramgarh thrust (RT 1); in many places the RT 1 is folded past the vertical to an overturned orientation and dips steeply towards the NNW. The fault separates the Gondwana sandstones (to the north) in its footwall from the steeply dipping to overturned Daling schists (to the south) in its hanging wall (Fig. 2.3). The RT 1 was mapped earlier as a north-dipping strike slip fault, the Great Rangit fault (Raina, 1976).

Along the western boundary of the window, near the village of Khani Sabong
(Fig. 2.3), deformed purple and greenish grey chloritic slates of the Daling Formation are exposed in the hanging wall of the Ramgarh thrust. Along the east-northeastern boundary of the window, the deformed footwall rocks, carbonate slates of the Buxa Formation in the proximal footwall of the Ramgarh thrust, are preserved near Chiyadaara (Fig. 2.3). Along the eastern boundary of the window, near Bhanzyang (Fig. 2.3), deformed Buxa limestones are exposed in the footwall of the Ramgarh thrust; these are overlain by the grayish green Daling slates of the hanging wall.

Within the Rangit window, the upper Daling, Buxa and Gondwana Groups are repeated at least eight times. The northern part of the window was previously interpreted as a refolded recumbent fold (Raina, 1976, Gangopadhyay and Ray, 1980). However, our mapping suggests that the repetition of the LHS is asymmetric, with each of the exposed sequences being separated from the next by a fault zone that brings the older Buxa/Daling Formation on top of the younger Gondwana Group. These individual thrust fault traces run approximately parallel to each other and the faults merge upsection into the Ramgarh thrust (Fig. 2.3). The primary structures and bedding-cleavage relationships within the imbricate slices corroborate the interpretation that the observed asymmetric repetition is not due to folding.

The LHS is repeated in horses all along the Lesser Himalayan FTB forming the Lesser Himalayan Duplex (Srivastava and Mitra, 1994, DeCelles et al., 1998, Robinson et al., 2006, McQuarrie et al., 2008). Results of seismic hazard studies in the Sikkim Himalaya (Nath et al., 2005) reveal the presence of a number of earthquake foci within the Rangit window; their focal depths vary from 7-10 km. We interpret these seismic data as additional evidence for the presence of imbricate faults in the Rangit window. Based on both map pattern and structural continuity throughout the Himalaya, we interpret the repeated LHS in the Rangit window as defining a series of individual horses. These horses are carried by imbricate faults that branch from a floor thrust and join a roof thrust, the Ramgarh thrust, forming the Rangit duplex. The floor thrust is not exposed but is interpreted to be the Main Himalayan Sole thrust (MHT) at a depth of ~10 km below the Rangit window (see section 2.3.3). At the present erosion level, most
of the exposed rocks within the Rangit window are the inflection regions of the horses where the bedding approximately parallels the attitude of the imbricate faults. Stereograms showing the bedding and cleavage orientations within individual horses are shown in Figure 2.5.

2.3.1.1 Tatapani Horse

The Ramgarh thrust, exposed poorly near Rangitnagar power station, ~15 km north of Jorethang, defines the northern boundary of the northernmost horse, the Tatapani horse; the horse is underlain by the Tatapani thrust which is exposed ~1.5 km north of Reshi (Fig. 2.3). The horse exposes a ~2 km thick section of the Buxa and Gondwana Groups, the contact between the two units being exposed near Tatapani. The exposed Buxa Formation is ~1.1 km thick and consists of a pink carbonate slaty horizon overlain by the uppermost bluish grey dolomite unit of the Buxa Formation. Preserved stromatolites within the Buxa dolomite indicate that the beds are upward facing (Fig. 2.4a) The beds dip dominantly towards the NNE (i.e., towards the hinterland); cleavage also dips towards the NNE, and is steeper than bedding (Figs. 2.4b, 2.5a), indicating that the horse is structurally upward facing and forward facing (Boyer and Elliott, 1982). The Gondwana sequence is ~800 m thick and starts with the medium grained sandstone in the south and grades to the uppermost unit, coal-bearing black slate, in the north.

Immediately north of the Tatapani thrust, the pink carbonate slates of the Buxa Formation have cleavage that is more gently dipping than bedding, both dipping towards the hinterland; these dips define the overturned southern limb of the leading anticline within the Tatapani horse. The Gondwana is not exposed anywhere in the overturned limb.
Figure 2.5. Contoured equal area stereograms of bedding poles and cleavage poles from the exposed horses of the Rangit duplex. (a) Tatapani horse: Bedding generally dips towards the NNE but is broadly folded with fold axis (FA) 30, 019. Cleavage is steeper than bedding; FA 45, 012. (b) Sikkip horse: Bedding generally dips towards north but is broadly folded; FA 32, 003. Cleavage is steeper than bedding; FA 46, 008. (c) Dong horse: Bedding generally dips towards NNW but is broadly folded; FA 30, 347. Cleavage is steeper than bedding; FA 32, 349. (d) Namchi horse: Bedding data shows a doubly plunging anticline with fold axes plunging 28,107 and 25, 264. Cleavage data from the Namchi horse showing scatter related to fanning of cleavage during folding. (e) Jorethang horse: Bedding dips steeply towards south with a mean dip of 72,178. Cleavage shows gentler dips than bedding, with a mean dip of 42, 167. (f) Sorok horse: Bedding data shows that the beds dip towards south; mean 44, 166. Cleavage dips are generally gentler than bedding with a mean dip of 41, 157. (g) Kitam horse: Bedding data from the overturned part of the horse shows beds generally dip towards NW with a mean dip of 56, 333. Cleavage is steeper than bedding with a mean dip of 62, 310. (h) Sikkip horse: Bedding data from east of the Rangit river shows that the plunge culmination lies east of the Rangit river (see text for details).
2.3.1.2 Sikkip Horse

South of the Tatapani thrust lies the Sikkip horse, underlain by the Sikkip thrust; parts of the Sikkip thrust had been previously mapped (Raina, 1976). The Sikkip horse exposes an anticline cored by the Daling Formation which is exposed from near Omchu village in the north to south of Pakzer village in the south. North of Omchu are outcrops of the Buxa Formation in the north limb of the anticline; immediately south of Reshi khola and south-west of Reshi, the uppermost grayish blue dolomites of the Buxa Formation are well exposed. The Gondwana Group of the northern limb of the anticline is ~ 900m thick and extends from the town of Reshi northward to the Tatapani thrust. Similar to the Tatapani horse, the Gondwana Group starts with the medium grained sandstone in the south near Reshi and grades northward to the uppermost unit, coal-bearing slate. The sandstones define the prominent cliffs on the S side of the ridge extending E from Reshi. Excellent exposures of the the Gondwana sandstone are also found near Chamchey along the eastern margin of the window.

The Gondwana sandstones of the south limb of the anticline are exposed on the west side of the Rangit river, north of Kamling village (Fig. 2.3). On the east side of the Rangit river, near Pakzer village, the south limb of the anticline is defined by the pink carbonate slates and dolomites of the Buxa Formation and the Gondwana Group is not exposed, indicating that the Sikkip thrust climbs section across the window from E to W (Fig. 2.3). The bedding and cleavage data (Figs. 2.4b, 2.5b) show that the cleavage is generally steeper than bedding, indicating that the Sikkip horse is hinterland-dipping and structurally upward facing and forward facing.

2.3.1.3 Ranguthang Horse

This is a small horse underlain by a footwall imbricate of the Sikkip thrust, the Ranguthang thrust, and is exposed along the eastern boundary of the Rangit window (Fig. 2.3). The Ranguthang horse exposes ~ 340 m of purplish green Daling slates at the base of the horse. The Daling Formation is overlain by ~ 250 m thick variegated carbonate slates and dolomites. The uppermost unit of the horse is the Gondwana
sandstones that form a prominent ridge near Chiyanadara village.

2.3.1.4 Dong Horse

The next major horse south of the Sikkim horse is the Dong horse underlain by the Dong thrust; the Dong thrust trace runs along Rathong khola in the west and Dong Khola in the east joining the Ramgarh (roof) thrust at the tops of each of these steep valleys (Fig. 2.3). The Dong horse exposes a ~950 m thick section of medium grained sandstone and carbonaceous slate of the Gondwana Group within it. The Dong thrust has been identified on the west side of the Rangit river as a repetition of the Gondwana Group, with the thrust juxtaposing the medium grained Gondwana sandstone of the Dong horse against the uppermost black coal-bearing slate of the next horse, the Namchi horse. The Gondwana sandstone locally shows cross bedding (Fig. 2.4c) indicating the beds to be upward facing. The beds dip towards the hinterland with a steeper cleavage than bedding (Fig. 2.5c), indicating that the horse is upward facing and forward facing. Thus, the four northerly horses of the RD are all dipping towards the hinterland (NNW) with a steeper cleavage than bedding and are upward facing (Fig. 2.5a-c). These four northern horses form a hinterland-dipping component of the Rangit duplex whose roof thrust is the Ramgarh thrust.

2.3.1.5 Namchi Horse

Along the northern part of Namchi ridge lies the Namchi horse, bounded by the Dong thrust in the north and the Jorethang thrust on the south; we interpret that it is carried by the underlying Namchi thrust which is not exposed anywhere at the surface. This horse primarily exposes the medium grained sandstones and coal-bearing shale of the Gondwana Group. In the eastern part of the window (E of Namchi), dolomites and calcareous shale of the Buxa Formation (that underlie the Gondwana) are exposed around the villages of Salebong and Banzyang on the east side of a steep transport-parallel fault; this fault may be the surface expression of a ~N-S lateral ramp that defines the eastern edge of the Rangit window. The bedding data suggest that the Namchi horse forms a doubly plunging broad anticline (Fig. 2.5d) and the crest of the
anticline runs approximately parallel to the major imbricate fault traces of the duplex (Fig. 2.3). The distribution of cleavage poles suggests that cleavage formed early and was reoriented by the folding. Cleavage is north-dipping and steeper than bedding on the N limb of the fold, and gently dipping to the N or S in the S limb where the beds dip to the south; the cleavage – bedding intersection relationships suggest that the structure is upward facing and forward facing. We interpret the Namchi horse to be the uppermost horse of an antiformal stack that occupies the middle of the Rangit duplex; balancing criteria require at least two other horses under it that lie above the floor thrust and form the core of the antiformal stack (see section 2.3.3).

2.3.1.6 Jorethang Horse

South of the Namchi horse lies the Jorethang horse, a small steeply south-dipping horse, underlain by the Jorethang thrust on its north side. The Jorethang horse is exposed along Jorethang ridge and consists of a very thin layer of green slates of the Daling Formation, variegated calcareous shales of the Buxa Formation (~275 m) and the Gondwana coaliferous sandstone (~ 430 m). Cross bedding in the Gondwana sandstones indicate that the beds are generally upward facing. The beds are significantly thinner than the northern horses and may either have been tectonically thinned or derived from the northern tapered distal edge of the Gondwana basin. Structurally this horse is different from the northern horses of the Rangit duplex; bedding and cleavage both dip towards the foreland (SSE), with steeper bedding than cleavage so that structures within this horse are forward facing and downward facing (Figs. 2.4e, 2.5e).

2.3.1.7 Sorok Horse

South of the Jorethang horse, on the southern slope of Purana Namchi ridge, there is another small steeply south-dipping horse, the Sorok horse, underlain by the Sorok thrust. The fault was previously mapped as a strike slip fault, the Ramman fault (Raina 1976). This horse exposes the green Daling slates (~1 km), immediately
overlain by the Gondwana coal-bearing black slates (~220m) with the Buxa Formation absent. The stratigraphic sequence suggests that the beds are upward facing. As in the Jorethang horse, the beds are significantly thinner than in the N-dipping horses, and this may represent structural thinning or the rocks could have been derived from the distal edge of the Gondwana basin (see Section 3.2, 4); the absence of any unit of the Buxa Formation supports the latter interpretation. Structures within this horse dip steeply towards the foreland (SSE), with steeper bedding than cleavage indicating that the horse is forward facing and downward facing similar to the Jorethang horse (Fig. 2.5f).

2.3.1.8 Kitam Horse

The Kitam horse is the southernmost horse of the Rangit duplex; it is carried by the Kitam thrust which marks its northern boundary. The southern boundary of the horse is the early Ramgarh thrust (RT 1), the roof thrust of the duplex that defines the southern boundary of the Rangit window. Similar to the Sorok horse, it carries the green slates of the Daling Formation (~300 m) in immediate contact with the coal-bearing sandstones of the Gondwana Group (~240 m) with the Buxa Formation absent. The beds generally dip steeply toward the NNW; graded bedding in the sandstones indicates that the beds are downward facing. Hence the exposed part of the Kitam horse represents parts of an overturned horse. The Gondwana sandstones exposed SE of Jorethang show a steeper cleavage than bedding, both dipping towards the NNW indicating the horse to be downward facing and hindward facing (Fig. 2.5g).

From the map patterns it is clear that the three southernmost horses of the Rangit duplex are structurally different from the northern horses. They generally dip steeply towards the foreland, and cleavage-bedding relations indicate that they are downward facing but forward facing. In addition, the presence of s-folds (looking W) within the Jorethang and Sorok horse (Fig. 2.4f) indicate that these horses have top to the foreland vergence and form a foreland-dipping component of the Rangit duplex. The Kitam horse has undergone some additional horizontal axis rotation so that it is overturned and hindward facing, but its overall structural patterns are similar to the
other two foreland-dipping horses. Their presence provides critical constraints on the kinematics of the Rangit duplex which will be discussed in more detail in the next section (section 2.4).

2.3.2 Other data

The stratigraphic sections in the three southernmost horses are significantly thinner than in the northern horses of the Rangit duplex. In addition, the Buxa section is missing in two of the horses; where present (in the Jorethang horse) it only represents the lowest part of the Buxa section. As suggested earlier, the thinner sections in these horses could be interpreted to be the result of structural thinning in the foreland-dipping horses. Measurements of strain from the transport-parallel XZ section in the Gondwana sandstones, using the modified Fry technique (McNaught, 1994), yields very low strain axial ratios (<1.2) (Table 2.2). Additionally, strains in the foreland-dipping horses (1.1-1.2) are similar to those in the hinterland-dipping horses and the antiformal stack, indicating that the foreland-dipping horses have not undergone any additional stretching and thinning. This suggests that the thickness changes are more likely controlled by stratigraphic variations. We interpret the foreland-dipping horses to have been derived from the distal (northern) tapered edge of the Buxa-Gondwana basin, so that they are the farthest traveled horses in the duplex.

In addition to the surface data, we have used the template constraint of hanging wall and footwall cutoff angles to define complementary cutoff geometries (Woodward et al., 1989). We have also incorporated seismic data (Nath et al., 2005) that are available from the Rangit window to help define the subsurface location of the imbricate faults. Using the surface and subsurface data and balancing constraints we have constructed a N-S trending cross section of the Rangit duplex (Fig. 2.6a). The imbricate faults of the hinterland-dipping component and the antiformal stack of the Rangit duplex merge upward into the Ramgarh thrust. The floor thrust of the duplex is not exposed but is interpreted to be the basal detachment that lies at a depth of ~10 km, based on balancing constraints (as described below). Additionally, earthquake data
<table>
<thead>
<tr>
<th>Name of Horse</th>
<th>x-z strain axial ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatapani</td>
<td>1.16</td>
</tr>
<tr>
<td>Sikkip</td>
<td>1.19</td>
</tr>
<tr>
<td>Dong</td>
<td>-</td>
</tr>
<tr>
<td>Namchi</td>
<td>1.12 1.09</td>
</tr>
<tr>
<td>Jorethang</td>
<td>1.11 1.09</td>
</tr>
<tr>
<td>Sorok</td>
<td>-</td>
</tr>
<tr>
<td>Kitam</td>
<td>1.16 1.19 1.18</td>
</tr>
</tbody>
</table>

Table 2.2. Distribution of x-z strain axial ratios from the horses of the Rangit duplex.
Figure 2.6a. Balanced cross section of the Rangit duplex along AB. The floor thrust of the duplex is the Main Himalayan thrust (MHT).

Figure 2.6b. Restored section of the Rangit duplex showing a total shortening of ~125 km.
from the Rangit window show a focal depth of ~10 km (Fig. 2.6a; Nath et al., 2005); this further strengthens our argument for the presence of the basal detachment at that depth. Below the duplex, this detachment (floor thrust) is interpreted to be the Main Himalayan Sole thrust (MHT) and it has a regional dip of ~3.5° towards the north.

2.3.3 Cross Section

The surface geology presented above, together with information on basal detachment depth, can be used to construct a balanced cross-section across the Rangit window parallel to the N-S transport direction (Fig. 2.6a). The basal detachment depth is estimated using a variety of geologic constraints (e.g. return to regional dip and excess area arguments, and stratigraphic thicknesses) and geophysical data as described below.

The Darjeeling klippe, exposed south of the Rangit window, is in the form of a synform; its hinge zone provides an area where the bedding dips are at sub-horizontal regional dip. The return to regional dip of the MCT sheets and the underlying Ramgarh sheet in the synform, together with thicknesses of the MCT sheets and the Daling Formation (Ramgarh sheet) yields a depth to detachment of ~7 km in the foreland part of the cross section. Similarly, variations in bedding/foliation dips from north of the duplex suggest that dips return to regional sub-horizontal dips ~52 km N of the northern end of the Rangit window before steepening again farther to the N. This, together with the exposed width of outcrop of the Daling Formation and the crystalline MCT 2 sheet, suggests a detachment depth of ~14 km at the basement – cover contact N of the Rangit duplex. Since, the thickness of the Daling Formation increases north of the duplex to ~5 km and only the upper ~1.2 km of the Daling Formation is repeated within the Rangit duplex, we interpret the presence of a ramp or the steepening of the initial sedimentary basin floor at the N end of the duplex and place the basal detachment at a depth of ~10 km under much of the hindward portion of the duplex. The detachment climbs to a depth of ~7 km under the antiformal stack portion of the duplex with the stack developing as a result of fault bend folding of successive horses.
over a ramp. In addition, seismic data (Nath et al., 2005) from within the window show that most earthquake focal depths vary from 7-10 km (Fig. 2.6a). These data are consistent with the structural and geometric arguments for the depth to detachment presented above.

The cross section shows that there are three horses in the north, the Tinkitam, Sikkip and Dong horses, that form the hinterland-dipping component of the duplex. The hanging wall cutoffs of the Gondwana units are not completely preserved so that the structural elevation of the roof thrust has to be estimated on the basis of the elevation of the Ramgarh thrust along the edge of the window and the plunge culmination of the antiformal stack. South of the hinterland dipping component, balancing constraints suggest that the space beneath the antiformally folded Namchi horse should be filled with two additional horses; these three horses together form an antiformal stack with only the uppermost horse, the Namchi horse, being exposed. Each of the higher horses of the antiformal stack is folded over the horse below it with the lowest horse being folded over a ramp of the MBT. The southernmost component of the duplex consists of three small horses, the Jorethang, Sorok and Kitam horses, that are foreland-dipping. These form a foreland dipping component of the duplex with a roof thrust that is the early Ramgarh thrust (RT 1) and floor thrust that is the Jorethang thrust which represents late-stage movement on the Ramgarh thrust. Hence, the geometry of the Rangit duplex varies from hinterland-dipping in the north, to antiformal stack in the middle, to foreland-dipping in the south.

Since the hanging wall cutoffs of the Gondwana Group and the Buxa Formation and the trailing branch lines of the foreland-dipping duplex are not completely preserved within the window, the geometry of the Rangit duplex could also be alternatively interpreted by modifying the branching and rejoining patterns in the eroded portion of the duplex (Fig. 2.7).

2.4. KINEMATICS OF THE RANGIT DUPLEX

Proper restoration of the Rangit duplex cross section requires a viable
Figure 2.7. Alternative interpretation of the geometry of the Rangit duplex. The Dong-Ramgarh thrust acts as the roof thrust of the foreland-dipping component of the duplex. This configuration is used for kinematic model 1 (see text for details). The floor thrust is the Main Himalayan thrust (MHT).
kinematic model that can suggest a suitable retrodeformation path (McNaught and Mitra, 1996). In this section we propose four different kinematic models for the evolution of the Rangit duplex and discuss their viabilities for the evolution of the duplex. The first three kinematic models are based on the Boyer and Elliott (1982) model of hinterland-to-foreland progression of thrusting while the fourth one incorporates reactivation of faults in a duplex (Boyer, 1992). We propose that the fourth model is the most viable kinematic model for reasons described in section 4.4.

2.4.1 Model 1

The first kinematic model is based on the cross section shown in Fig. 2.7. The Rangit duplex evolves in three stages. After the Ramgarh thrust brings the hanging wall Daling rocks over the northernmost part of the Gondwana basin, the duplexing is initiated by the formation of three hinterland-dipping horses, the Tatapani horse, the Sikkip and the Dong horse forming a hinterland-dipping duplex (Figs. 2.8A-C). Each of these horses carries the Daling, Buxa Formations and the Gondwana Group. The roof thrust of the hinterland-dipping duplex is the Ramgarh thrust and the floor thrust is the MHT.

At the next stage of footwall imbrication, three smaller, foreland-dipping horses (Kitam, Sorok, and Jorethang) form in that order (Figs. 2.8D,E). The first two horses carry the Daling Formation and the Gondwana Group; the Buxa Formation is absent. The Jorethang horse carries all three upper LHS units but they are thinner than the earlier formed hinterland-dipping horses; the Daling and Gondwana are fault bounded and may therefore represent only a partial section, but the Buxa Formation is also thinner.

Continued deformation is marked by the formation of the Namchi horse along with two underlying horses forming an antiformal stack (Fig. 2.8F). Based on the depth to detachment below the antiformal stack and assuming a constant thickness variation of the upper LHS units, balancing constraints suggest that each of the horses of the antiformal stack carries all the three units of the LHS (upper units of Daling, Buxa and
Figure 2.8. Schematic diagram showing the kinematic evolution of the Rangit duplex in three stages (Kinematic Model 1). North is to the right of the page. A-C: Formation of the hinterland-dipping component of the duplex, roof thrust – Ramgarh thrust, floor thrust – MHT; D-E: Formation of foreland-dipping horses; F: Growth of the antiformal stack of the Rangit duplex, roof thrust – Dong-Ramgarh thrust, floor thrust – MHT. Note the change in thicknesses of the Buxa Formation and the Gondwana Group in the footwall from stages B-F (see text for details).
Gondwana). There is thus a continuous transition from a foreland-dipping duplex to an antiformal stack similar to that observed in the southern Mountain City window in Tennesse (Diegel, 1986). The roof thrust of the foreland-dipping duplex – antiformal stack complex is the Dong-Ramgarh thrust and the floor thrust is the Main Himalayan Sole thrust (MHT) (Fig 7, 8F).

However, the absence of the Buxa Formation from the two horses of the foreland-dipping duplex (Kitam and Sorok) can not be explained by this kinematic model as it results in an inviable restored section where the Buxa is missing from the middle of the restored basin (explained later in section 4.5). In addition, the Gondwana beds are thinner and shalier (upper part of the Gondwana Group) in the foreland-dipping duplex than the earlier formed hinterland-dipping horses and the later formed antiformal stack suggesting that the Jorethang thrust has cut down section. The thinner beds in the foreland-dipping component can not be explained as due to structural thinning (section 3.2) as the internal strain in these horses are similar to those in the other horses of the Rangit duplex.

Therefore, although the cross section (Fig. 2.7) is one possible interpretation of the exposed geometry of the Rangit duplex, this reconstruction of the roof thrust of the foreland-dipping duplex is not kinematically viable. Hence, the alternative cross section (Fig. 2.6a) provides a better framework to represent the geometry and to analyze the kinematic evolution of the Rangit duplex.

We present three different kinematic models based on the cross section shown in Fig. 2.6a. All three of these models are based on the assumption that the Gondwana Group and the Buxa Formation of the Darjeeling – Sikkim Himalaya represent the distal northward extent of the main Buxa and Gondwana basin that existed along the northern margin of the Indian cratonic crust. The northward tapered basin geometry of the Gondwana-Buxa basin implies that the thicknesses of these two units would decrease northward away from main part of the basin. The thinner Buxa Formation in the lowermost horse of the foreland-dipping component of the Rangit duplex and the absence of the Buxa Formation from the southernmost two horses of the foreland-
dipping component suggest that these horses were translated from the northern extremity of the basin where the Buxa Formation pinched out northward. The thinner and shale-rich Gondwana sandstone in these slices also suggest that these rocks were derived from the tapered distal northern edge of the Gondwana basin. These lines of evidence suggest that the three southernmost horses of the Rangit duplex are the farthest traveled, and were carried over the top of the northern horses which were derived from farther inboard within the basin.

2.4.2 Model 2a

The Rangit duplex evolves in three stages. After the early Ramgarh thrust (RT 1) brings the hanging wall Daling rocks over the northernmost part of the Gondwana basin, duplexing is initiated by the formation of the hinterland-dipping Kitam horse (Fig. 2.9A), which carries the Daling and the northernmost Gondwana Group. With progressive footwall imbrication, the first three horses (Kitam, Sorok and Jorethang) form with the Jorethang horse carrying the northernmost Buxa Formation, together with the Daling Formation and the Gondwana Group. The three horses form a hinterland-dipping duplex with the RT 1 as the roof thrust and the MHT as the floor thrust (Figs. 2.9A-C).

At the next stage of deformation, large translation along the Ramgarh thrust is transferred entirely to the Jorethang thrust, and the existing three horses (Kitam, Sorok and Jorethang) are translated and rotated along the Jorethang-Ramgarh thrust (RT) (Fig. 2.9D); RT 1 becomes passive at this stage. With progressive footwall imbrication (Fig. 2.9E), three large hinterland-dipping horses (Tatapani, Sikkip and Dong) develop forming the hinterland-dipping component of the Rangit duplex (Fig. 2.9F). The roof thrust of the hinterland-dipping duplex is the RT and the floor thrust is the Main Himalayan sole thrust (MHT).

Finally, an antiformal stack forms, comprising of three horses (the Namchi horse and two underlying horses) (Fig. 2.9G). The total displacement of the antiformal stack is transferred to the roof thrust, the Ramgarh thrust.
Figure 2.9. Schematic diagram showing the kinematic evolution of the Rangit duplex in three stages (Kinematic Model 2a). North is to the right of the page. A-C: Formation of the hinterland-dipping component of the duplex, roof thrust – RT1, floor thrust – MHT; D: Large translation on the Ramgarh thrust; E-F: Growth of the hinterland-dipping component, roof thrust - Ramgarh thrust, floor thrust – MHT; G: Resulting geometry of the Rangit duplex.
The total displacement associated with the three initial hinterland-dipping horses (Kitam, Sorok and Jorethang horse) is not sufficient, however, to bring these earliest formed horses to their present position in the southernmost part of the window, and additional translation on the Ramgarh thrust is required (Fig. 2.9G). In addition, the rotation of the early formed hinterland-dipping component, during the event of large translation on the Ramgarh thrust, does not produce the deformed state geometry of the foreland-dipping component (Fig. 2.9G). Also, the mesoscopic structures (e.g. small folds, cleavage/bedding relationships) preserved within the foreland-dipping component do not support their origin through tilting and reorientation of hinterland-dipping horses. Therefore, this model is not geometrically and kinematically viable for the evolution of the Rangit duplex.

2.4.3 Model 2b

The first stage of deformation in this model is similar to Model 2a, placing Daling rocks over the Gondwana basin along the early Ramgarh thrust (RT 1). At the next stage, three foreland-dipping horses (Kitam, Sorok and Jorethang) develop in the northern part of the Gondwana basin forming a foreland-dipping component within the Rangit duplex (Figs. 2.10A-C). The three trailing branch lines of these foreland-dipping horses move up from the floor thrust along the imbricate faults to lie on the roof thrust, the RT 1, while the leading branch lines lie along the floor thrust, the Ramgarh - Jorethang Thrust (RT) (Fig. 2.10C).

With progressive footwall imbrication, the Tatapani, Sikkip, and Dong horses are emplaced as hinterland-dipping horses, and form the hinterland-dipping component of the Rangit duplex; the RT 1 is passive at this stage. The roof thrust of the hinterland-dipping component is the Ramgarh – Jorethang thrust (RT) and the MHT is the floor thrust (Fig. 2.10E). Finally, an antiformal stack forms involving the Namchi horse and two underlying horses (Fig. 2.10F).

The total displacement of the earliest formed horses generated in this model is greater than Model 2a (Figs. 2.9G, 2.10F), but, it is still not sufficient to bring the
Figure 2.10. Schematic diagram showing the kinematic evolution of the Rangit duplex in three stages (Kinematic Model 2b). North is to the right of the page. A-C: Formation of the foreland-dipping component of the duplex, roof thrust - RT 1, floor thrust - Ramgarh thrust; D-E: Growth of the hinterland-dipping component, roof thrust - Ramgarh thrust, floor thrust - MHT; F: Deformed state geometry of the Rangit duplex.
foreland-dipping component to its present position along the southern margin of the window (Fig. 2.10F). This model requires an additional ~24 km slip on the Ramgarh thrust (Fig. 2.10F) in order to generate the present geometry of the Rangit duplex. Because of the absence of any evidence for late stage large-scale movement by reactivation of the Ramgarh thrust, this is also not a geometrically viable kinematic model for the Rangit duplex.

2.4.4 Model 3

In this model the duplex evolves as a complex combination of footwall imbrication and reactivation of the imbricates. After the Daling is placed over the northern edge of the Gondwana basin along the early Ramgarh thrust (RT 1), the Rangit duplex initiates as a foreland-dipping duplex in the northernmost part of the Gondwana basin. The foreland-dipping duplex consists of three small horses (the Kitam, the Sorok and the Jorethang horse), similar to Model 2b (Figs. 2.11A-C). The roof thrust of the foreland-dipping duplex is the RT 1 and the floor thrust is the Ramgarh – Jorethang thrust (RT), with the trailing branch lines of the three foreland-dipping horses lying on the roof thrust (Fig. 2.11C).

At the next stage of footwall imbrication, the hinterland dipping Tatapani horse is emplaced with the Ramgarh thrust as its roof thrust and the MHT as its floor thrust (Fig. 2.11D). This is concurrent with reactivation of the Ramgarh thrust and translation of the foreland-dipping component farther towards the south; this obviates the need for additional work against gravity to lift the foreland-dipping component to a higher structural elevation (Fig. 2.11E). In this model, we propose that for every subsequent stage of footwall imbrication, the Ramgarh thrust is reactivated generating an additional displacement that translates the foreland-dipping component farther southward. In other words, the Ramgarh thrust remains active throughout the growth of the Rangit duplex. The reactivation on the Ramgarh thrust is required in order to attain a more stable gravitational state for the overlying foreland-dipping component.
Figure 2.11. Schematic diagram showing the sequential kinematic evolution of the Rangit duplex in three stages along with reactivation of the Jorethang-Ramgarh thrust (Ramgarh thrust) (Kinematic Model 3). A-C: Formation of the foreland-dipping component of the duplex, roof thrust - RT 1, floor thrust - Ramgarh thrust; D-G - Growth of the hinterland-dipping component, roof thrust - Ramgarh thrust, floor thrust - MHT; H-J: Formation of the antiformal stack of the Rangit duplex (see text for details).
Stages D and E show the initiation of growth of the hinterland-dipping duplex and reactivation of the Ramgarh thrust. There are two possible paths that may be followed. The first involves uplift of the foreland-dipping component during emplacement of the hinterland-dipping horse followed by reactivation of the Ramgarh thrust (Fig. 2.11, stage D followed by stage E). The second path has concurrent emplacement of the hinterland-dipping horse and reactivation of the Ramgarh thrust (Fig. 2.11, stages D and E simultaneous) so that the foreland-dipping component is never raised above the structural elevation shown in stage E. We can calculate the total energy required for horse emplacement along either path (Mitra and Boyer, 1986). Most of the work terms (Mitra and Boyer, 1986) involved in the two cases are the same. The fault sliding terms may be somewhat different in the two cases but are an order of magnitude smaller than the gravitational work term. Thus, the work done against gravity in raising the foreland-dipping component is critical in defining the most likely path.

The work done against the gravity in stage D ($W_{gD}$) for a unit width of the horse can be estimated as,

$$W_{gD} = \rho A_D g h_D \times 1000 \text{ J.}$$

where, the cross-sectional area of the rock mass (foreland-dipping component) moved against gravity ($A_D$) is $54.71 \times 10^6 \text{ m}^2$, $h_D$ ($6 \times 10^3 \text{ m}$) is the elevation through which the rock mass has been raised (Fig. 2.8 D), $\rho$ is $2.44 \times 10^3 \text{ gm m}^{-3}$ and $g$ is $9.8 \text{ ms}^{-2}$. This gives

$$W_{gD} = 7.85 \times 10^{18} \text{ J.}$$

On the other hand, the work done against gravity if stages D and E are concurrent ($W_{gE}$) is estimated as,

$$W_{gE} = \rho A_E g h_E \times 1000 \text{ J.}$$

where, $h_E = 4.16 \times 10^3 \text{ m}$ and gives,

$$W_{gE} = 5.44 \times 10^{18} \text{ J}$$
Clearly, the work done against gravity along the second path is significantly less, suggesting that the continuous reactivation of the Ramgarh thrust is necessary to maintain a lower energy path for the overlying foreland-dipping component and should be energetically favored at every stage of footwall imbrication.

This prolonged reactivation model can be compared with the earlier model that incorporates foreland-dipping horses (Model 2b). Model 2b required an additional ~24 km slip on the Ramgarh thrust in order to generate the deformed state geometry of the Rangit duplex. The absence of any field evidence for prominent late stage reactivation along the Ramgarh thrust suggests that it is unlikely that this entire additional amount of slip (~24 km) is accommodated in a single displacement event. Therefore, in this model, we propose that the Ramgarh thrust was continuously reactivated resulting in an additional cumulative slip of ~24 km along it to generate the deformed state geometry of the duplex. The amount of reactivation on the Ramgarh thrust at each stage was variable depending on the elevation of the structure and the length of the fault. The earlier formed RT 1 and imbricate faults within the foreland-dipping component remain passive during these succeeding stages of footwall imbrication and Ramgarh thrust reactivation. Formation of the three hinterland-dipping horses (Tatapani, Sikkip, and Dong) give rise to the hinterland-dipping component whose roof thrust is the Ramgarh thrust and floor thrust is the MHT (Figs. 2.11D-G); we note that the Ramgarh thrust is also the floor thrust of the foreland-dipping component.

The reactivation of the Ramgarh thrust continues during the formation of the last component of the duplex, the antiformal stack (Figs. 2.11H-J). Three horses, the Namchi, and two underlying horses, are emplaced to form the antiformal stack; the total displacement of the antiformal stack is transferred to the roof thrust, the Ramgarh thrust.

In this model the total displacement generated as a result of duplex growth and reactivation of the Ramgarh thrust during every stage of footwall imbrication starting with Tatapani horse emplacement, is sufficient to arrive at the deformed state geometry of the Rangit duplex exposed in the Rangit window. Therefore, the model is both
geometrically and kinematically viable for the evolution of the Rangit duplex.

We note here that there are two possible scenarios for the temporal evolution of the Rangit duplex. The foreland-dipping duplex may have initiated first followed by a hiatus after which the hinterland-dipping component - antiformal stack component evolved. Alternatively, the Rangit duplex may have evolved in a single continuum of deformation. At this time, we do not have any data to support one scenario over the other.

In the Nepal Himalaya, the growth of the Lesser Himalayan duplex is estimated to initiate at \( \sim 11 \) Ma (DeCelles et al., 1998). In the Sikkim Himalaya, monazite geochronometric studies suggest that the MCT was active at \( \sim 12-10 \) Ma (Catlos et al., 2004). Since, the MCT sheets have been folded by the Ramgarh thrust, we interpret that the initiation of growth of the Lesser Himalayan duplex in the Sikkim Himalaya is younger than \( \sim 12-10 \) Ma. Earthquake data suggest that activity is continuing to the Present.

### 2.4.5 Restored Section

We used line-length and area balancing techniques to carry out a step-wise restoration of the cross section using kinematic model 3. Thus, we restored the last formed antiformal stack first, followed by the hinterland-dipping component, and finally we restored the earliest formed foreland-dipping duplex. The total shortening estimated from the restored cross section of the Rangit duplex is \( \sim 125 \) km or \( \sim 74\% \) (Fig. 2.6b); there is additional shortening in the Daling horses of the Lesser Himalayan duplex lying north of the Rangit window (Fig. 2.6a) (Bhattacharyya et al., 2008, Mitra et al., 2009).

The restored section provides insights into the undeformed Gondwana-Buxa basin geometry. Retrodeformation along the path suggested by kinematic model 3 results in a viable restored section (Fig. 2.6b) with a northward tapered Gondwana-Buxa sedimentary prism, indicating the admissibility of the kinematic model path (Fig. 2.11) and the viability of the deformed state cross section (Fig. 2.6a). In the restored
section both the Buxa Formation and the Gondwana Group become thinner towards the north; the Buxa Formation pinches out within the restored Jorethang horse, while the Gondwana Group becomes progressively thinner northward and directly overlies the Daling Formation within the restored Sorok and Kitam horses. Thus, these horses of the foreland-dipping component were derived from the northern extremity of the basin and are the farthest traveled in the deformed section. The restored section also provides insights into the northward extent of the Gondwana basin of Peninsular India as discussed in the following section (section 2.5).

2.5. DISCUSSION

The geometry of the Rangit duplex is significantly different from the Lesser Himalayan duplex in other parts of the Himalaya along strike where the duplex geometry is generally quite simple. In the Kumaon Himalaya, the Lesser Himalayan duplex has a hinterland dipping geometry (Srivastava and Mitra, 1994), while in the Nepal Himalaya, the duplex has a dominantly hinterland dipping geometry along with a component of antiformal stack in the south (DeCelles et al., 1998, 2001, Robinson et al., 2006); in the Bhutan Himalaya, the duplex has hinterland-dipping geometry (McQuarrie et al., 2008). Lateral (i.e., along strike) variation of duplex geometry from these simple geometries to the complex relationships observed in Sikkim suggests a significant change in kinematic history and total displacement being accommodated by the Lesser Himalayan duplex.

Transport parallel changes in duplex geometry have been previously described from a number of other FTBs (Mitra and Boyer, 1986). These variations are caused by changes in the size of the horses and/or changes in slip on individual imbricate faults. For example, duplexes may show transition from hinterland-dipping to antiformal stack (Western Nepal, DeCelles et al., 1998), or hinterland-dipping to antiformal stack to hinterland-dipping (Haig Brook duplex, Fermor and Price, 1976), or foreland-dipping to antiformal stack (southern Mountain City window, Diegel, 1986). However, to our knowledge, the transition from a hinterland-dipping duplex to an antiformal stack to a
foreland-dipping duplex, as observed in the Rangit duplex, has not been previously described from any FTB. Our kinematic model suggests that the foreland-dipping component formed first, followed in turn by the hinterland-dipping component and the antiformal stack.

Duplex geometry is a function of the initial spacing between the imbricate faults ($s$) and the displacement along these faults ($u$) (Mitra and Boyer, 1986). Therefore, the Rangit duplex with its complex geometry suggests that imbricate spacing ($s$) and imbricate displacements ($u$) were not constant during its evolution. The geometry suggests that the $u/s$ ratio was highest (~2.12) during the initial stages of duplex growth, forming a foreland-dipping component. The $u/s$ ratio reached its minimum value (~0.42) during the intermediate phase of growth of the Rangit duplex, forming a hinterland-dipping component, and increased subsequently (~1) during the final phase of its evolution to form an antiformal stack.

The last formed component of the Rangit duplex, the antiformal stack, played a key role in modifying the final geometry of the duplex. The bedding data of the exposed Namchi horse show a doubly plunging antiformal structure (Fig. 2.5d) with fold plunges of 28, 107 and 25, 264. The cleavage data of the Namchi horse also show evidence for the cleavage having been modified by later deformation (Fig. 2.5d); this indicates the presence of underlying horses within the antiformal stack that have folded the earlier formed cleavage in the exposed Namchi horse. The doubly plunging antiformal stack structure defines a plunge culmination, whose effect can also be seen in the three northern horses that form the hinterland-dipping component of the duplex. The bedding and cleavage data from these three horses suggest that they have been folded on north plunging axes, the northernmost Tatapani horse along 30, 019, the Sikkip horse along 30, 003 and the Dong horse along 30, 347.

This folding has been traditionally interpreted as the result of late-stage cross-folding of the Himalayan sheets (Raina, 1976, Gangopadhyay and Ray, 1980). We assign it to the growth of an underlying doubly-plunging antiformal stack made up of laterally discontinuous horses. The three southern horses (viz. Jorethang, Sorok and
Kitam) of the foreland-dipping component of the duplex, appear to have been unaffected by this folding. This provides additional evidence for a separate evolution of these three horses from the rest of the duplex and argues against a late-stage cross-folding in the rest of the duplex.

It is interesting to note here that the plunge culmination of the Rangit duplex results in a N-S trending, orogen perpendicular anticline that is spatially associated with the Rangit river flowing parallel to its hinge surface. Similar orogen perpendicular anticlines have been observed along the length of the Himalayan arc where the river valleys run along the hinge surfaces; for example, in the Arun valley of eastern Nepal (Bordet, 1955, Oberlander, 1985, Montgomery and Stolar, 2006), and in the Sutlej valley of the western Himalaya (Burg et al., 1997, DiPietro et al., 1999). It has been argued that focused erosion along the rivers causes an increase in the net erosion rate along the valleys compared to the surrounding areas, leading to focused rock uplift and formation of river anticlines (Montgomery and Stolar, 2006). However, the bedding pole data of the Sikkip horse from east of the Rangit river show a spread whose best-fit great circle suggests a fold axis of 13, 340 (Fig 5h); thus the plunge culmination lies ~2 km east of the Rangit river. Therefore, we propose that the Rangit duplex anticline is not a true “river anticline” and is related to the growth of the doubly plunging antiformal stack. However, this structure may have been accentuated by the high erosion rate along the Rangit river.

The proposed kinematic model of the Rangit duplex is significantly different from existing models for the evolution of duplexes (Boyer and Elliott, 1982, Boyer, 1992, Mitra and Sussman, 1997). Our kinematic model suggests that the three different components of the duplex evolved under a complex combination of footwall imbrication (Boyer & Elliott, 1982) and reactivation of one of the major faults (Boyer, 1992). The Ramgarh thrust was reactivated during every stage of footwall imbrication starting with the formation of the Tatapani horse within the hinterland-dipping component of the duplex. In addition, the kinematic history implies that two different faults acted as the major roof thrust during the evolution of the Rangit duplex, the RT 1
during the initial stages and the Ramgarh thrust during the remaining history. Thus, the main Ramgarh thrust acted both as the floor thrust of the foreland-dipping component and the roof thrust of the rest of the duplex during different stages of its evolution. In other words, the Rangit duplex is made up of two stacked duplexes, an early foreland-dipping duplex and a later hinterland-dipping duplex - antiformal stack complex.

In the Himalaya, the Ramgarh thrust is defined as the fault that places greenschist grade rocks of the oldest Paleoproterozoic LHS on top of younger, lesser metamorphosed rocks of the LHS (Valdiya, 1980, Srivastava and Mitra, 1994, DeCelles et al., 1998, Pearson and DeCelles, 2005). In Sikkim, the field relationships suggest that the Jorethang-Ramgarh thrust, defining the northern boundary of the Rangit window, represents the main Ramgarh thrust. However, our proposed kinematic model suggests that the RT 1, defining the southern boundary of the window, was the leading part of the Ramgarh thrust during its early history and became deactivated during the growth of later imbricates of the Rangit duplex. During the later stages of evolution, the Jorethang thrust defined the leading part of the Ramgarh thrust while the trailing portion of the Ramgarh thrust continued to be active throughout the history of duplex growth.

The total shortening of ~125 km along the nine imbricates in the Rangit duplex accounts for ~49 % of the entire Lesser Himalaya shortening in the Darjeeling – Sikkim Himalaya. This can be compared with shortening figures for other parts of the Himalaya to illustrate how shortening varies along the Himalayan arc (e.g., DeCelles et al., 2002, Mitra et al., 2009). In the Bhutan Himalaya, there are two duplex systems within the LHS; the southern duplex involves the upper LHS and contributes ~113 km (~58 %) of the total shortening within the Lesser Himalaya (McQuarrie et al., 2008), while the northern duplex involves the lower LHS and contributes ~80 km (~41%) of the total shortening. Thus, the entire Lesser Himalayan duplex in Bhutan accommodates ~193 km of shortening and accounts for nearly the entire Lesser Himalayan shortening. A similar structure is seen in the Darjeeling – Sikkim Himalaya and the Rangit duplex is equivalent to the southern Lesser Himalayan duplex of the
Bhutan Himalaya. The Rangit duplex accommodates ~125 km of shortening in the Lesser Himalayan duplex, while the Daling horses lying farther north (Bhattacharyya et al., 2008, Mitra et al., 2009) account for an additional ~113 km of shortening. The total Lesser Himalayan duplex shortening is ~238 km which accounts for ~93% of the total Lesser Himalayan shortening.

The magnitude of shortening in the Lesser Himalayan duplex system of the eastern Himalaya is notably greater than that to the west. For example, ~24 km shortening in the Lesser Himalayan duplex of the Kumaon Himalaya accounts for only ~13% of the total Lesser Himalaya shortening (Srivastava & Mitra, 1994), and ~122 km duplex shortening in far western Nepal is ~60% of total Lesser Himalaya shortening (DeCelles et al., 1998). Lesser Himalayan duplex shortening amounts from the Api, Chainpur and Simikot transects of western Nepal (Robinson et al., 2006) are greater (236 – 258 km). However, because the width of the Lesser Himalayan duplex is significantly narrower in the east than along the three transects of western Nepal, the percentage shortening from the duplex in western Nepal Himalaya (56-80% of the total LHS shortening) is significantly less than that is Sikkim and Bhutan (93 – 99%).

The geometry and kinematics of the Rangit duplex has critical implications for the evolution of the Darjeeling – Sikkim Himalaya as a whole. Unlike the other Greater Himalayan klippen that expose lower grade MCT 2 sheet rocks elsewhere along the Lesser Himalayan FTB, the Darjeeling klippe exposes both the MCT 1 and 2 sheets suggesting a larger southward translation of the MCT 1 in this region. The presence of a foreland-dipping component within the Rangit duplex (RD) suggests that the displacements along individual imbricate faults are greater; the three foreland-dipping horses contribute ~51 km (or 41%) of the total RD shortening (~125 km). The large displacements associated with the Rangit duplex were translated to its roof thrusts, the RT 1 and Ramgarh thrust; this displacement helped carry the overlying MCT sheets in the Darjeeling – Sikkim Himalaya and explains their large southward translation as observed in the Darjeeling klippe. The Ramgarh thrust in the Darjeeling – Sikkim Himalaya, with a minimum displacement of ~125 km and a complex and prolonged
history of reactivation further supports the idea that the Ramgarh thrust was a major fault in the evolution of the Himalayan FTB (e.g. Pearson and DeCelles, 2005).

The retrodeformed section of the Rangit duplex (Fig. 2.6b) also provides insights into the palinspastic restoration of the Gondwana basin of Peninsular India. The foreland-dipping horses are the farthest traveled of all the horses in the duplex. These horses carry a relatively thin Gondwana section made up of thin-bedded coal bearing sandstones and black shales. They were probably derived from the northern tapered distal edge of the Gondwana basin. The Gondwana rocks exposed in the foothills of the Darjeeling – Sikkim Himalaya, south of the Rangit duplex, form the proximal part of the Gondwana basin relative to the Gondwana-Buxa rocks, exposed within the Rangit duplex.

The restoration of the duplex suggests that the northern edge of the Gondwana basin extended at least ~142 km north of its present northernmost exposure in the Tatapani horse (Figs. 2.3, 2.12); restoration of the shortening on the frontal Himalayan thrusts would result in the northern extent of the Gondwana basin extending somewhat farther north. Figure 12 shows the locations of the Gondwana basins in Peninsular India (Ghosh, 2002) and their present northern extent along the eastern Himalaya, viz. the central Nepal Himalaya (Paudel and Arita, 2000 ), the Darjeeling – Sikkim Himalaya (this paper) and the Bhutan Himalaya (McQuarrie et al., 2008).

2.6. CONCLUSIONS

In the Darjeeling – Sikkim Himalaya, both the MCT 1 and 2 sheets are translated much farther southward than anywhere else along the length of the Himalayan FTB and are exposed in the Darjeeling and Labha klippen. The Rangit window lying almost due north of the Darjeeling klippe exposes the Rangit duplex which provides critical insights into the evolution of the Darjeeling – Sikkim Himalaya. The upper LHS in the Darjeeling – Sikkim Himalaya is repeated along at least nine horses forming the Rangit duplex whose roof thrust is the Ramgarh thrust and whose
Figure 2.12. Map showing the major Gondwana basins of Peninsular India (Ghosh, 2002) and the northern extent of the Gondwana basin in the eastern Himalaya. 1. Central Nepal (Paudel & Arita, 2000). 2. Rangit window and Gondwana exposures in the foreland of the Darjeeling – Sikkim Himalaya (this study) and easternmost Nepal. 3. Far-eastern Bhutan (McQuarrie et al., 2008). The gray region shows the palinspastic reconstruction of the Gondwana basin from these exposures.
floor thrust is interpreted to be the Main Himalayan sole thrust. The geometry of the Rangit duplex varies from hinterland-dipping in the north to an antiformal stack in the middle to foreland-dipping in the south; this unique geometry is explained with a new kinematic evolutionary model. The model implies that two different faults, the early Ramgarh thrust (RT 1) and the main Ramgarh thrust acted as the major roof thrust during successive stages of evolution of the Rangit duplex. After the formation of the foreland-dipping component, the Ramgarh thrust was reactivated during every stage of footwall imbrication within the duplex. In addition, the growth of the late stage antiformal stack in the duplex core modified the final duplex geometry, resulting in a plunge culmination that manifests itself as a broad N-S trending anticline. This is not a true “river anticline” as its trace lies east of the Rangit river, but it may have been accentuated by focused erosion along the river.

Restoration of the Rangit duplex suggests that ~125 km of minimum shortening (~74 %) has been accommodated within the duplex which was transferred to the roof thrust, the Ramgarh thrust. The large displacement along the Ramgarh thrust carried the overlying MCT sheets in the Darjeeling – Sikkim Himalaya and explains their exposures in the Darjeeling and Labha klippen. The Rangit duplex and the Daling duplex are components of the Lesser Himalayan duplex in this region, and together they contribute ~93% of the total Lesser Himalaya shortening in the Darjeeling – Sikkim Himalaya. The retrodeformed section provides insights into the palinspastic reconstruction of the Gondwana basin of Peninsular India suggesting that the Gondwana basin extended ~142 km northward of its present northernmost exposure in the Rangit duplex.
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