Overburden-induced flattening structure in the Himalaya: mechanism and implication

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Small-scale structures in fold-thrust belt are mainly formed in response to the emplacement of thrust sheets. However, some small-scale structures may not be developed directly in response to the emplacement of thrust sheets, but might be genetically tied with the orogenic process. Metre- to centimetre-scale late-stage folds on foliation in phyllite with near-recumbent fold geometry are selectively developed with a specific spatial distribution, particularly in places where the foliation is steeply dipping, in the Ramgarh thrust sheet in the Darjiling-Sikkim Himalaya. The recumbent-fold structures appear to have been formed in response to overburden-induced vertical compressive deformation on steep dipping foliation, especially in the subvertical southern limb of the antiformal structure of the Lesser Himalayan Duplex in the Darjiling–Sikkim Himalaya. The role of gravity and overburden in the formation of these structures from worldwide orogenic belts may be considered to validate their genesis.

Keywords: Orogeny, overburden-induced flattening, recumbent fold, thrust sheet.

THE geometry of mesoscopic and microscopic structures provides insights into the structural history of fold and thrust belts (FTBs)[1]. Small-scale structures and their tectonic implications are established from different FTBs like Alpine orogeny[2], Caledonides[3], Sevier[4], Himalaya[5–9] and Zagros[10], where small-scale folds and other tectonic structures are common. The genesis of these structures is related with the emplacement of the thrust sheets and are formed in successive stages of progressive deformation during the formation of the FTB[8–11]. Bucher[12] and Gansser[13] described the presence of some apparently unrelated small-scale structures in the Alps and the Himalaya, but the genesis of these structures is not fully understood.

In the southern part of the Lesser Himalaya in Darjiling-Sikkim area (Figure 1)[14], metre- to centimetre-scale recumbent to near-recumbent folds on regional foliation is developed in a narrow, strike-parallel, steeply dipping zone, mainly in the southern side of the Lesser Himalayan Duplex (LHD)[15]. This type of fold is also observed in two other adjacent areas where regional foliation is steep-dipping. In this article, we present the geometry of the small-scale near-recumbent symmetrical folds in the Ramgarh Thrust (RT) sheet in the Darjiling–Sikkim Himalaya (DSH), and also a model is proposed for the possible genesis of the structure with respect to the orogenic movement of the Himalaya in light of the role of gravity and overburden. The formation of these folds, how they are linked to the Himalayan deformation and their kinematic significance are not clear. Given that this type of fold is not discussed by earlier workers and their possible genesis has not been attempted so far in this area, the present study may be helpful to understand the genesis of the structure in the FTBs of the world in general and the Himalaya in particular.

Geological setting

The wedge-shaped fold-thrust belt of the Himalaya consists of several east-west trending south vergent thrust faults, such as the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal thrust (MFT), all of which sole into the Main Himalayan Thrust[16]. MCT carries the high-grade Greater Himalayan sequence in its hanging wall over the low-grade (greenschist–facies) Lesser Himalayan sequence. The Lesser Himalayan sequence is carried by the MBT over the synorogenic unmetamorphosed to mildly metamorphosed Tertiary Siwalik deposits of the foreland. The Siwalik deposits, in turn, are currently being thrusted over Quaternary deposits along the MFT. Recent studies from different parts of the Himalaya have recognized a regional thrust, named as Ramgarh Thrust (RT), which is now considered as a major regional Himalayan thrust, like other major thrusts (e.g. MCT, MBT, MFT) of the Himalayan fold–thrust belt, that transports upper Lesser Himalayan rocks (Pre-Cambrian sequence) over lower Lesser Himalayan rocks (Permian–Eocene–Miocene)[8,15,17–23].

The area of study encompasses a small part of the RT sheet in the Lesser Himalaya in the DSH (Figure 1). The frontal part of the Darjiling–Sikkim–Tibet (DaSiT) wedge has been studied by earlier workers[8,15,24–29]. In this area, the Tista half-window was formed as a result of erosion of folded thrust sheets by the Tista River (Figure 1).

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Tectonically higher and Greater Himalayan rocks are exposed all around the Tista half-window except the southern side. In the western part of the Tista half-window a 'complete' window of smaller dimension, known as Rangit window, has developed due to the erosion of the Rangit duplex structure by the south-flowing Rangit River (Figure 1)[30–32]. The RT sheet comprising Daling Group of rocks, consisting of Buxa Formation, Reyang Formation and Daling Formation[33], is more than 5 km thick in the DSH. The Rangit window exposes the upper ~1.2 km of the Daling Formation[15], and is dominantly a meta-pelitic sequence with limited intercalated quartzite bands. The geometry of the Rangit duplex varies from hinterland-dipping duplex in the north, followed by antiformal stack in the middle to foreland-dipping duplex in the south[15]. Due to the antiformal stack structure in the hanging wall of the RT, an ~East–West trending steep dipping zone has been developed representing the southern limb of the antiformal structure, where the regional foliation is usually vertical or sub-vertical[15].

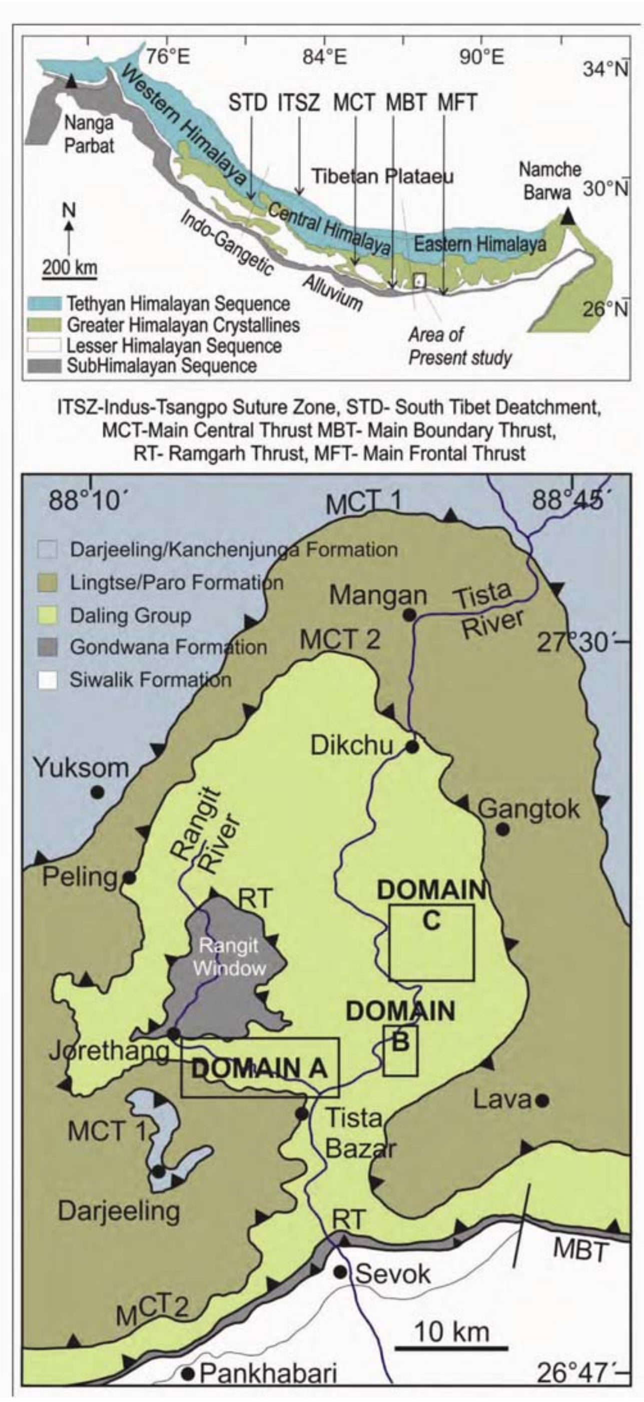

Figure 1. Geological map of the Darjiling–Sikkim Himalaya showing major tectonostratigraphic units (modified after Bhattacharyya and Mitra[15]). Domains (A–C) are the area of occurrence of recumbent folds. (Inset) Geological map of the Himalaya showing major thrusts, tectonostratigraphic units and present area of study (simplified after Yin[14]).

Small-scale folds are common in the RT sheet around Rangit duplex. The earlier small-scale folds are east-west trending, non-plunging to gently plunging and sinistral-shaped in section from the east with axial plane dipping gently towards north in the normal limb (northern limb) of the antiformal structure, while in the subvertical to vertical southern limb (overturned to vertical limb) of the antiformal structure the axial plane of the same folds becomes steeply dipping southward, because of the rotation of the folds when antiformal structure is produced, keeping other characters such as fold axis and shape asymmetry more or less the same (Figure 2). Minor folds linked with large antiformal structure are either absent or insignificant. The later small-scale folds are recumbent folds which are spectacularly developed all along the vertical southern limb of the antiformal structure that extends along-strike for a distance of ~15 km. This zone where

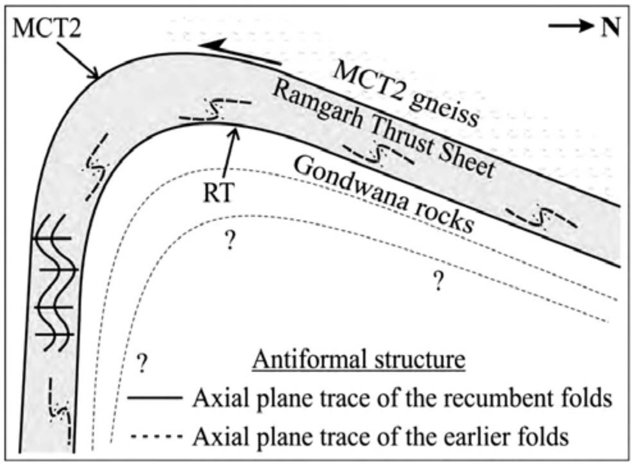

Figure 2. Schematic diagram showing the large-scale antiformal structure of Rangit window in section from the east. Two sets of incongruous minor folds with respect to the antiformal structures are present – earlier folds are sinistral in shape present in both the limbs, while the later symmetrical recumbent folds are restricted to the vertical limb. The earlier minor folds are passively rotated in the vertical limb. MCT2, Main Central Thrust 2; RT, Ramgarh Thrust.

the recumbent folds are developed is marked as Domain A (Figure 1). Apart from Domain A, recumbent folds have also been identified in two more areas along the Tista River (marked as Domains B and C; Figure 1) where the near recumbent folds are developed in limited extent. In all the three domains the overall dip of the regional foliation in the RT sheet rock is either vertical or steep. It is important to note that no equivalence of the recumbent-type fold is present in the gently dipping northern limb of the antiformal structure around Rangit window or in places where the regional foliation is moderately dipping towards north. The recumbent folds are therefore verily restricted only to the areas where the regional foliation is steep dipping to vertical.

The rock in which the particular structure is developed is very low-grade schist characterized by mineral assemblage of quartz + sericite ± chlorite, suggesting early stage of greenschist facies. The deformational structure developed during the formation of the recumbent fold is axial planar pressure solution, which is a proxy of very shallow level of deformation[34]. In the three domains (A–C) there is a little difference of metamorphic condition. In Domain A there is no chlorite with sericite, however, in other domains (B and C) there is a small amount (~5%) of chlorite with sericite. The mineral association of the rock suggests a temperature of around 300°C to 350°C (refs 35, 36). Under normal geothermal condition, it indicates a depth of more or less 10 km. There is no evidence of inverted metamorphism in these three domains of the RT sheet.

Geometry of the small-scale recumbent folds

The recumbent folds are metre- to centimetre-scale structures with horizontal to gently dipping axial planes and occur as sharp-hinged, chevron-type to rounded–hinged, symmetric, gentle to open folds. These are widely developed in all three domains (Figure 1) where the regional foliation in phyllite of the Daling Formation is steep-dipping to vertical. In all three domains recumbent folds are the youngest structures and overprinted on all earlier structures present in the area. The geometry of the recumbent folds from the three domains is described below.

Domain A

In this domain the steeply dipping zone is widest and continues along strike for a distance of ~15 km. The recumbent folds are sharp-hinged to chevron-type, symmetric or M-shaped, open to tight, locally with axial planar spaced cleavage and occasional thin quartz veins present parallel to the axial plane (Figure 3 *a* and *b*). Under microscope, pressure solution is commonly seen in phyllosilicate-rich bands, developed parallel to the axial plane of the recumbent folds (Figure 3 *c*). Although the phyllosilicate-rich bands are invariably crenulated with varying wavelength and amplitude, the quartz-rich bands which alternate with phyllosilicate-rich bands remain unfolded with occasional and incipient development of pressure solution plane (Figure 3 *c* and *d*). This heterogeneous development of crenulation and pressure solution is perhaps due to the varying material property of alternate bands. Quartz grains of quartz veins show mild deformation marked usually with undulose extinction (Figure 3 *d*). The overall orientation of regional foliation (276°/84°N) shows that the foliation is steeply dipping with ~E–W strike (Figure 3 *e*). The overall attitude of the axial planes of the recumbent folds (279°/02°N) is horizontal (Figure 3 *e*).

Domain B

In this domain the recumbent folds are usually round to sharp-hinged, symmetric, close folds with occasional axial planar spaced cleavage (Figure 4 *a*). Crenulation equivalent to recumbent fold is only incipiently developed, but pressure solution is absent. The regional foliation is moderate to steeply dipping with ~E–W strike (258°/57°N) (Figure 4 *b*). The overall attitude of axial planes of recumbent folds in this domain is sub-horizontal (138°/12°W) (Figure 4 *b*).

Domain C

In this domain the geometry of the near-recumbent folds is similar to Domain B (Figure 5 *a*), but the dip of axial planes is a little steeper at places and axial planar structures are absent. Crenulation equivalent to recumbent fold and pressure solution is absent, but locally transgranular fractures parallel to the axial plane of recumbent folds are seen in quartz-rich bands. The foliation on which the recumbent folds are developed is moderately steep (279°/59°N) and the overall attitude of the gently dipping axial plane of the recumbent folds is 089°/26°S (Figure 5 *b*).

Genesis of the small-scale recumbent folds

Since the pioneering experimental study on gravity-induced mesoscopic structure of Bucher[12], several workers have enriched the subject of research from various parts of the world[37–44]. Bucher[12], on the basis of his experimental study, proposed that when an orogenic belt rises to an elevation greater than that which can be supported by the strength of the rocks, it flattens under its own weight, and this generates folds with recumbent geometry. He showed that a simple compression acting on a material weak enough to creep under the action of gravity produces recumbent fold. It is concluded that thrust sheet could play the role of overburden weight with the formation of kink folds in thrust sheet rocks with close spaced bedding[11]. For the Austroalpine nappes, Froitzheim[38]

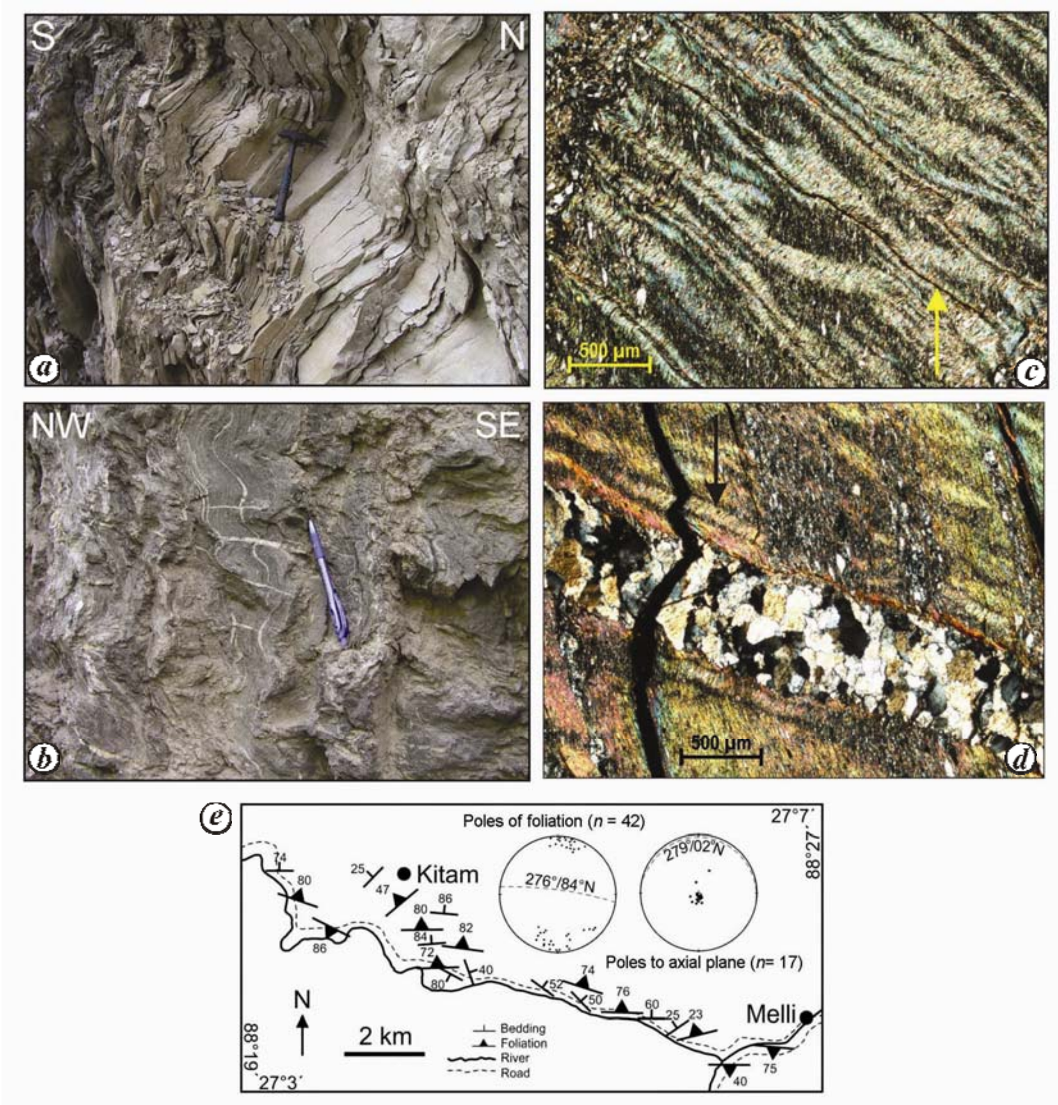

Figure 3. ***a***, ***b***, Recumbent fold on foliation in phyllite (***a***) with rounded to subrounded hinge in Domain A and (***b***) with quartz veins parallel to axial plane of recumbent folds. Earlier foliation parallel quartz veins also participated in folding. ***c***, ***d***, Photomicrographs of Daling phyllite from the recumbent fold zone (***c***) showing crenulation with pressure solution seam (marked with yellow arrow), parallel to the axial plane of the crenulation and (***d***) crenulation (marked with black arrow) with axial planar silica vein. The sections (***c*** and ***d***) are cut perpendicular to the foliation and fold axis of the recumbent fold. (***e***) Structural map of Domain A (Figure 1) showing orientation of bedding and foliation in phyllite. Equal area projection of poles to foliation and axial plane of recumbent folds is shown.

proposed that recumbent folds were formed owing to bulk vertical thinning, from the shortening of vertically oriented layers. However, Maxelon and Mancktelow[45] suggested that small-scale folds with recumbent fold geometry may be formed, as in the nappes, by subhorizontal shearing rather than vertical shortening. Malavielle[46] concluded that recumbent folds from the footwall of a metamorphic core-complex were formed by shearing of layers originally oblique to the shear plane. Recumbent-type mesoscopic folds from Shumar thrust sheet of the Lesser Himalaya in eastern Bhutan, designated as fore-limb folds, are suggested to have developed by shearing of layers originally oblique to the shear plane in a shear zone[47]. Petrini and Podladchikov[41] pointed out that the pressure in the lithosphere will increase with depth due to overburden weight and in the regions of thickened crust, the ductile regions are likely to experience the greatest variation of pressure because of vertical loads of overburden and in the ductile domains, the contribution of horizontal stresses is less important as differential stresses are progressively relaxed.

Therefore, there is no unanimity of opinion on the development of folds under the action of overburden and gravity. In particular, there is a debate over whether overburden and gravity-induced ductile structures are produced or not. It is generally accepted that the

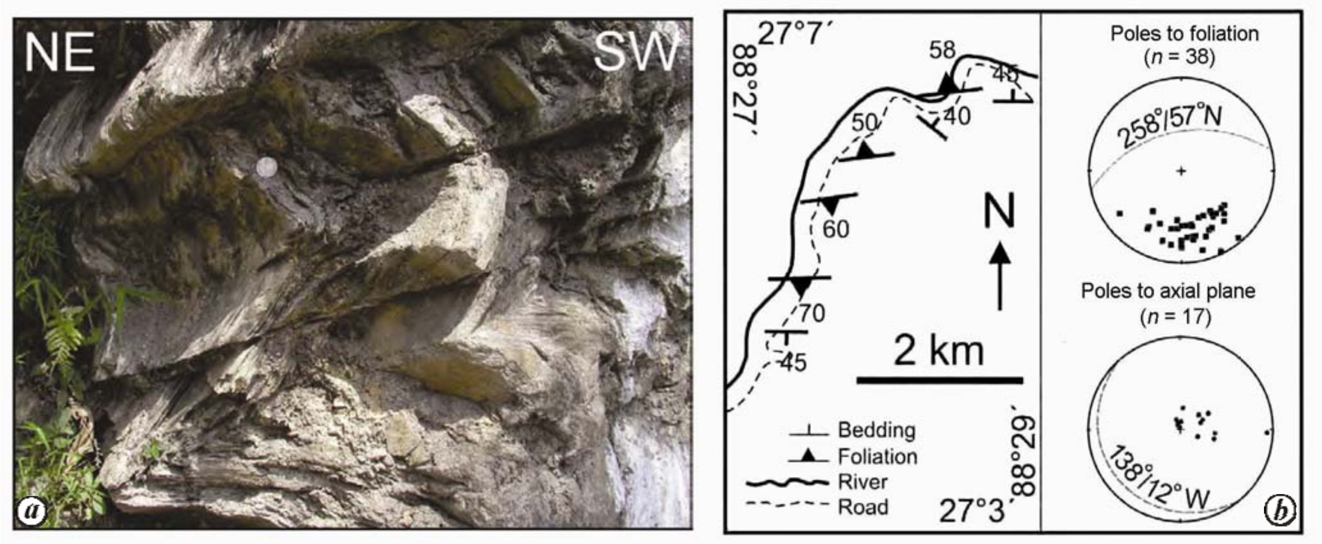

Figure 4. ***a***, Chevron style symmetrical recumbent fold with axial planar spaced cleavage in Domain B. ***b***, Structural map of Domain B (Figure 1) showing orientation of bedding and foliation in phyllite. Equal area projection of poles to foliation and axial plane of recumbent folds are shown.

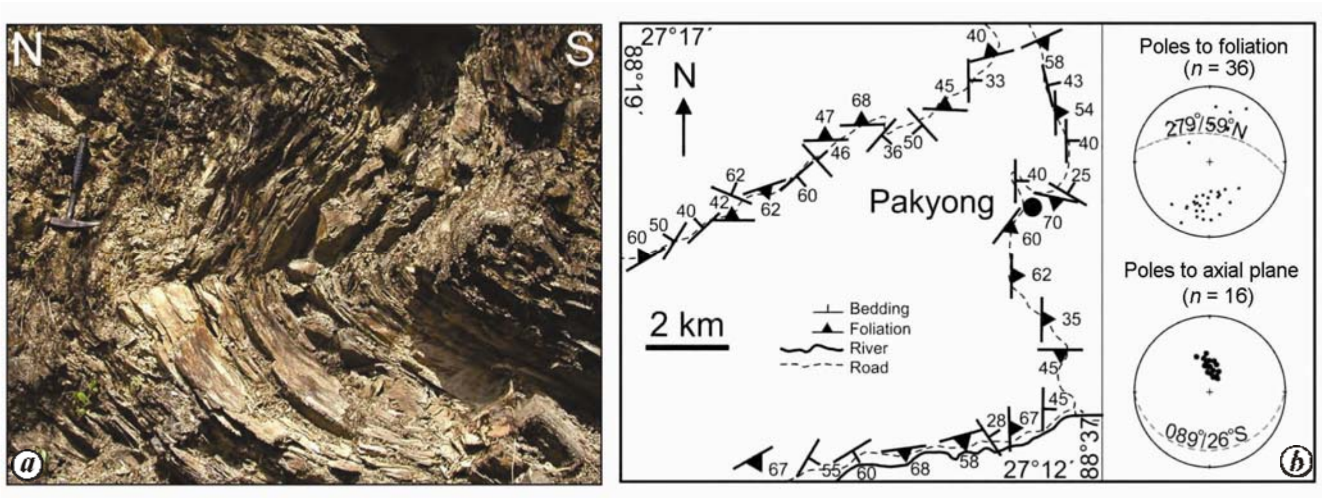

Figure 5. ***a***, Recumbent folds in Domain C. ***b***, Structural map of Domain C (Figure 1) showing orientation of bedding and foliation in phyllite. Equal area projection of poles to foliation and axial plane of recumbent folds is shown.

overburden-induced gravitational force does not result in differential stress; rather it only adds to the hydrostatic or lithostatic pressure. However, *in situ* stress determinations showed that large deviatoric stresses are common in the upper 10–20 km of continental crust[48]. It is concluded that the addition of overburden in a confined elastic medium (the vertical component of the stress tensor is changed equal to the weight of the overburden added) results in the development of non-hydrostatic (deviatoric) stress[48]. From rheological point of view, the Earth's crust behaves as a perfectly elastic material at temperature <300°C and elastic stresses are relaxed above that temperature where the Earth's crust is assumed to be in a state of hydrostatic equilibrium[48].

Given that the geometry of the outcrop-scale and micro-scale structures in the present area of study is symmetrical with no sign of horizontal shearing in and adjacent to the folds, we are convinced that these recumbent folds are not formed by shearing. Again, there is no equivalent recumbent earlier fold structure seen in the thrust sheet that has been rotated to attain recumbent fold geometry in the steep-dipping zones. Therefore, we construe that the recumbent folds are perhaps the result of near-vertical compression with shortening direction nearly parallel to the foliation rather than horizontal shearing after careful consideration of all possibilities. We interpret that the formation of the recumbent fold structure in selective parts of the Lesser Himalaya in the DSH is due to the effect of the weight of the vertical column of rocks (~6–8 km)[29]. Before erosion, the weight of the rock column induced a substantial vertical compressional force on the underlying mass of the rock to initiate folding on the foliation in phyllite of the RT sheet. To get a tentative idea about the approximate vertical compressional force, we have used the equation of Fertl[49] (presented below). It has been estimated that the overburden-induced compressional force over the underlying phyllite before erosion was ~150–200 MPa for a thickness of ~6–8 km of overburden.

$$S = \rho_b \cdot \mathrm{TVD} \cdot g$$

where S is the overburden stress, ρ_b the average density of the Earth's crust, TVD the total vertical depth and g is the acceleration due to gravity. Density of phyllite varies from 2.18 to 3.30 g/cm^3 in dry and wet conditions respectively[50]. It is important to note that the density of phyllite may be higher if the lithostatic pressure is high, the phyllite becomes more compact and denser due to reduction of porosities.

It is likely that there is a variation of gravitational potential energy due to the overburden-induced compressional force in the column of the rock mass. It results in deviatoric stress with vertical stress greater than the horizontal stresses[11,38,41,48] that leads to the formation of folds with subhorizontal to horizontal axial plane in the steep-dipping zone of the foliation. It has been demonstrated that the variation of gravitational potential energy induces compressive stresses that result in shortening[11,38,40–42,48]. The possible response to the vertical compression is flattening, with the XY plane (flattening plane) of the strain ellipsoid being horizontal and the Z axis (shortening axis) sub-vertical. Our model (Figure 6) illustrates that if the dip of the pre-folding foliation is gentle to moderate, the overburden-induced flattening will not produce any fold (Figure 6 a), rather, the foliation rotates to become gentler, since the effective compressive force perpendicular to the foliation is quite low. When the dip of the foliation is steep (~60° or more), (Figure 6 b and c), the overburden-induced compressive force on the underlying rock mass will generate near-recumbent to recumbent folds because the effective compressive stress perpendicular to the foliation will be high enough under the action of gravity.

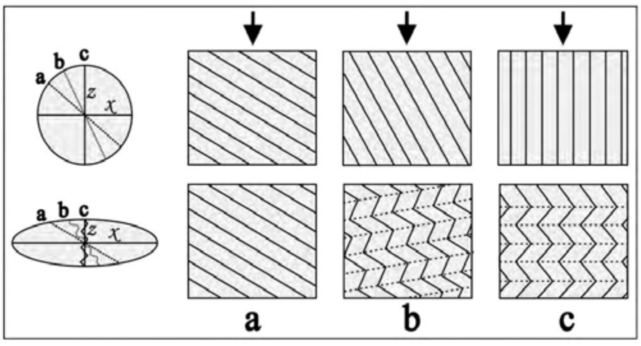

Figure 6. Schematic diagram to illustrate the formation of the recumbent folds. The direction of maximum compression due to overburden-induced force on foliation is shown by arrow. a, No fold is produced on moderately dipping foliation. b, On steeply dipping foliation fold form with gently dipping axial plane. c, Fold with horizontal axial plane and symmetric geometry is produced on the vertical foliation. (X and Z are the longest and shortest axes of the strain ellipse; a, b and c in the circle and strain ellipse represent the trace of foliation before and after folding respectively, with respect to X and Z).

In Domain A (Figure 3 *e*), since the orientation of the foliation is sub-vertical to vertical and the volume of the overburden is also very high due to the effect of regional structure, the development of the recumbent fold is most conspicuous and prolific in comparison to Domains B and C (Figures 4 *b* and 5 *b*), where the dip of the foliation is ~60°. Therefore, it appears that the two important factors that control the formation of recumbent fold structures are (i) the initial dip of the regional foliation, and (ii) the magnitude of vertical compressive force generated by the overburden.

The dip of the axial plane is sub-horizontal in a zone where the foliation dip is sub-vertical, while the dip of the axial plane increases as the dip of the regional foliation decreases from vertical/sub-vertical to steep (Figure 6 b and c). Given that the dip of the regional foliation almost throughout the RT sheet in the DSH is moderate to gentle (usually varies between ~30° and 40°), the recumbent fold structure did not develop in most parts of the sheet (as illustrated in our model in Figure 6 a). Therefore, occurrences of recumbent folds are local and discrete in the RT sheet in comparison to the structures that are produced in response to the horizontal compression (e.g. N–S compression in the Himalaya).

Discussion and conclusion

A tentative idea of the impact of the overburden-related gravitational force in the formation of minor structures in thrust sheet in the DSH is proposed. The structures described are not directly related to the emplacement of the thrust sheets, but formed in response to the duplex structures (here it is LHD) developed in the thrust sheets. Gravity-driven movement of orogenic crust under its own weight has been advocated earlier[44]. The concept of gravitational force, referred to as 'gravitational collapse' in orogenic processes, has been discussed[51]. Although the orogen-to nappe-scale horizontal movement due to gravitational sliding and gravitational spreading has been debated over a long time, the role of gravity in the formation of small-scale structures is rarely discussed in the literature.

As there is no evidence of shear associated with the folding, the possibility of the genesis of the recumbent folds by shearing is also excluded. Therefore, on the basis of our observations we conclude that overburden-induced gravitational force is perhaps responsible for the development of the recumbent folds. In the dynamic process of mountain-building, there may be regions of excess of gravitational potential energy, formed by the regional-scale structure(s) in thrust sheets that might result in gravity-driven ductile flow, which can effectively reduce the built up gravitational potential energy. In the steeply dipping E–W trending zone in the Lesser Himalayan Duplex of the RT sheet, the built up gravitational potential energy might be responsible for the development of the small-scale recumbent folds. The development of recumbent folds is possibly controlled by the magnitude of vertical compressive force resulting from the overburden-induced pressure.

In the kinematics of the Himalayan fold–thrust belt, the vertical compression responsible for the development of the recumbent folds cannot be explained by the principal ~N–S horizontal compressive stress linked to continent–continent collision in the Himalaya and therefore, the recumbent fold structure remains as a 'misfit' in the Himalayan tectonics.

The present work concludes that these prolific outcrop-scale recumbent folds in the DSH are developed in response to overburden-induced flattening which occurred in the area where the dip of the foliation was steep to vertical, before the onset of this deformation responsible for the formation of the structure. It appears that the steep dip of the regional foliation in the Daling phyllite was 'attained' due to the development of duplex structure in the Lesser Himalaya, in an otherwise moderate north-dipping regional foliation in this part of the Himalaya. When the thickness of the overburden increase due to progressive development of large-scale structures, the pile of rocks get flattened under its own weight and thereby form recumbent type folds on foliation. Here, we put forward a simple but effective model to demonstrate the genesis of this kind of structure by vertical shortening in the Himalaya and other orogenic belts of the world.

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