by D C Sati and P Rautela

The significance of cross folding in Himalayan tectonic history

The uninterrupted compressive stress that resulted in the Himalayan orogen remained oriented from the northeast and southwest during the convergence, collision, and post-collisional episodes. However, a prominent phase of northeast-southwest-trending cross folds developed as a result of syncollisional northwest-southeast compression. Minerals in these folds exhibit a remarkable stretching lineation parallel to the transport direction of the major shear zones from the northeast. The cross folds do not fit satisfactorily into the unchanging stress regime and are anomalous. These findings reveal a close linkage between thrusting that was contemporaneous with northwest-southeast extensional features and cross folding that was contemporaneous with northeast-southwest extensional features.

Introduction

The Himalayan orogenic belt is seen as a compressive plate boundary zone between the Eurasian plate to the north and the Indian plate to the south (Dewey and Bird, 1970; Powell and Conaghan, 1973; Crawford, 1974; Gansser, 1977). The intervening Tethys ocean

basin was demolished completely as a result of the convergence and subsequent underthrusting of the Indian plate beneath the Tibetan landmass, part of the Eurasian plate (figure 1). Fuchs (1977) presumed that the welding of the Tibetan block and the Indian plate took place in the Late Cretaceous, synchronous with flysch sedimentation. However, Shanker and others (1976), Frank and others (1977), and Tahirkheli and others (1979) dated this event at around the Paleocene. In either case, the eventual collision of the two plates, which was most severe around the middle of the Miocene, gave birth to the Himalayan orogen. The tremendous compression resulted in intense shearing and thrusting, including the translation of large sheets that travelled hundreds of kilometers southward from their original position to the autochthonous molassic zone. Researchers have recognized three such compressed and translated sheets, which fit well in the form of stacking in the physiographic classification of the Himalaya by Medlicott (1864). These persistent sheets are displayed in longitudinal belts throughout the Himalaya. Detailed geological information about these thrust sheets is given by Gansser (1964, 1977) and Le Fort (1975). In addition, Sati and others (1990) recorded overthrusting from the north in the Ladakh district of the State of Jammu and Kashmir in northwestern India.

Convergence between the Eurasian and Indian plates also resulted in northwest-southeast extension within the Himalayan domain (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Armijo and others, 1984; Sati and others, 1990) because of the continental escape phenomenon. In this process, the material within the collision zone escapes laterally (perpendicular to the direction of convergence) toward a zone of lower compressional strain (McKenzie, 1972). In the collision zone, the northwest-southeast extension produced blocks in the brittle rocks that are defined by a conjugate set of strike-slip faults, and the extension forced these blocks to rotate when strike-slip movement was reactivated. In this process, the structures that had formed earlier in the overlying rocks also were rotated (Sati and others, 1990). This extension formed many pull-apart basins as well (Rodgers, 1980; Hsu, 1982; Gergan, 1989). North- to northeast-striking normal faulting, that was caused by collapse, formed along with the south- to southwest-directed thrusting along the Main Central Thrust and the Tethyan Thrust during post-collisional convergence (Burg and others, 1984; Searle 1983, 1986; Searle and others, 1988; Sati, 1988). These structures are considered to be late(?) Miocene extensional features, produced as a result of the gravitational collapse of the Miocene topographic front between India and Tibet (Royden and Burchfiel, 1987). Similar observations have been made by Baud and others (1984), Coward and others (1988), Valdiya (1988), and Windley (1988). In addition, many geologists in the past have reported features indicating northeast-southwest compression. These features include late-stage folding parallel to the Himalayan trend and tectonic creeping and translation of Paleogene and Neogene sediments over Pleistocene gravels along the Himalayan Frontal Thrust.

Despite the addition of a large quantity of data, due importance has not been accorded to the transition phase between the collision and postcollision tectonic history of the Himalaya, a phase during the collision in which northwest-southeast extension was replaced by northeast-southwest extension along the major thrust zones. In this article, we emphasize the various structural trends observed in the successive tectonic units of the Himalaya that reflect this time of transition, especially the cross folds that have played a significant role in the orogeny but have remained neglected.

Figure 1.—Compressive stress resolved around the northwest and northeast corners of the Indian plate as it collided with the Eurasian plate. This syntaxis resulted in the stresses shown in the inset. Of these resolved stresses, σ_1 produced left-lateral and right-lateral shears, respectively, on the side of the Indian plate. However, within the plane-strain condition, σ_2 generated coaxially flattened cross folds and continued strike-slip movement in the collision zone. Arrows show direction of movement; double lines show spreading axis separated into segments by faults.

by D C Sati and P Rautela

The significance of cross folding in Himalayan tectonic history

The uninterrupted compressive stress that resulted in the Himalayan orogen remained oriented from the northeast and southwest during the convergence, collision, and post-collisional episodes. However, a prominent phase of northeast-southwest-trending cross folds developed as a result of syncollisional northwest-southeast compression. Minerals in these folds exhibit a remarkable stretching lineation parallel to the transport direction of the major shear zones from the northeast. The cross folds do not fit satisfactorily into the unchanging stress regime and are anomalous. These findings reveal a close linkage between thrusting that was contemporaneous with northwest-southeast extensional features and cross folding that was contemporaneous with northeast-southwest extensional features.

Introduction

The Himalayan orogenic belt is seen as a compressive plate boundary zone between the Eurasian plate to the north and the Indian plate to the south (Dewey and Bird, 1970; Powell and Conaghan, 1973; Crawford, 1974; Gansser, 1977). The intervening Tethys ocean

Figure 1.—Compressive stress resolved around the northwest and northeast corners of the Indian plate as it collided with the Eurasian plate. This syntaxis resulted in the stresses shown in the inset. Of these resolved stresses, σ_1 produced left-lateral and right-lateral shears, respectively, on the side of the Indian plate. However, within the plane-strain condition, σ_2 generated coaxially flattened cross folds and continued strike-slip movement in the collision zone. Arrows show direction of movement; double lines show spreading axis separated into segments by faults.

basin was demolished completely as a result of the convergence and subsequent underthrusting of the Indian plate beneath the Tibetan landmass, part of the Eurasian plate (figure 1). Fuchs (1977) presumed that the welding of the Tibetan block and the Indian plate took place in the Late Cretaceous, synchronous with flysch sedimentation. However, Shanker and others (1976), Frank and others (1977), and Tahirkheli and others (1979) dated this event at around the Paleocene. In either case, the eventual collision of the two plates, which was most severe around the middle of the Miocene, gave birth to the Himalayan orogen. The tremendous compression resulted in intense shearing and thrusting, including the translation of large sheets that travelled hundreds of kilometers southward from their original position to the autochthonous molassic zone. Researchers have recognized three such compressed and translated sheets, which fit well in the form of stacking in the physiographic classification of the Himalaya by Medlicott (1864). These persistent sheets are displayed in longitudinal belts throughout the Himalaya. Detailed geological information about these thrust sheets is given by Gansser (1964, 1977) and Le Fort (1975). In addition, Sati and others (1990) recorded overthrusting from the north in the Ladakh district of the State of Jammu and Kashmir in northwestern India.

Convergence between the Eurasian and Indian plates also resulted in northwest-southeast extension within the Himalayan domain (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Armijo and others, 1984; Sati and others, 1990) because of the continental escape phenomenon. In this process, the material within the collision zone escapes laterally (perpendicular to the direction of convergence) toward a zone of lower compressional strain (McKenzie, 1972). In the collision zone, the northwest-southeast extension produced blocks in the brittle rocks that are defined by a conjugate set of strike-slip faults, and the extension forced these blocks to rotate when strike-slip movement was reactivated. In this process, the structures that had formed earlier in the overlying rocks also were rotated (Sati and others, 1990). This extension formed many pull-apart basins as well (Rodgers, 1980; Hsu, 1982; Gergan, 1989). North- to northeast-striking normal faulting, that was caused by collapse, formed along with the south- to southwest-directed thrusting along the Main Central Thrust and the Tethyan Thrust during post-collisional convergence (Burg and others, 1984; Searle 1983, 1986; Searle and others, 1988; Sati, 1988). These structures are considered to be late(?) Miocene extensional features, produced as a result of the gravitational collapse of the Miocene topographic front between India and Tibet (Royden and Burchfiel, 1987). Similar observations have been made by Baud and others (1984), Coward and others (1988), Valdiya (1988), and Windley (1988). In addition, many geologists in the past have reported features indicating northeast-southwest compression. These features include late-stage folding parallel to the Himalayan trend and tectonic creeping and translation of Paleogene and Neogene sediments over Pleistocene gravels along the Himalayan Frontal Thrust.

Despite the addition of a large quantity of data, due importance has not been accorded to the transition phase between the collision and postcollision tectonic history of the Himalaya, a phase during the collision in which northwest-southeast extension was replaced by northeast-southwest extension along the major thrust zones. In this article, we emphasize the various structural trends observed in the successive tectonic units of the Himalaya that reflect this time of transition, especially the cross folds that have played a significant role in the orogeny but have remained neglected.

Table 1.—Summary of tectonic events in the Himalaya based on studies made in the northwestern Himalaya.

		Indus Suture Zone			Tethyan Zone	Central Crystalline Zone	Lesser Himalayan Zone	Outer Himalayan Zone
		Ladakh Molasse	Indus Formation	Nimdam-Lamayuru formations				
Pre-Collision	Late Cretaceous		NW-SE-trending open tight isoclinal upright folds		NW-SE-trending tight isoclinal overturned folds with NE-dipping axial planes		Close to tight isoclinal overturned folds with NE-dipping axial planes	
	Early Eocene	Obduction of ophiolites			Open-closed coaxial and coplanar folds (F ₂ on the limbs of F ₁)		Coaxial coplanar F ₂ folds	
	Mid-Oligocene	NW-SE-trending folds (F ₁ = F ₂)	Gentle-open coaxial folds (F ₂ on the limbs of F ₁)					
Syn-Collision	Mid-Miocene	<<<<<< NE-directed thrusting >>>>>>			<<<< SW-directed overthrusting >>>>			
			NW-SE-trending open cross folds (F ₃)	NW-SE-trending open folds (F ₃) plunging steeply in either direction	Open-closed NE-plunging cross folds (F ₃)	Tight isoclinal cross folds (F ₃). Fold axis parallel to the thrust-transport direction. Indicators of NE-SW extension	Reclined cross folds (F ₃) with NE-dipping axial planes	
Post-Collision	Late Pliocene	Rotation of folds due to strike-slip movement	Strike-slip movement along weak planes		No observable strike-slip movement	Wide, open folds coaxial to F ₁ and F ₂ , cross faults	Wide, open F ₄ folds trending parallel to Himalayan axis	Tight isoclinal overturned with NE-dipping axial planes to wide,open upright folds parallel to the Himalayan axis
	Mid-Pleistocene							
								Neo-tectonic activity

Deformational studies

Detailed structural studies have been carried out in the northwestern Himalaya in a north-south transect from the Siwalik foothills in northern India to the Indus suture zone, which covers sizable parts of the Himalaya in Garhwal (northern Uttar Pradesh), Himachal Pradesh, and Jammu and Kashmir, northern India. The structural patterns recorded in all of the tectonic units in the transect have revealed a remarkable consistency. The distinct structural trends are summarized in table 1 along with other features.

Folding episodes in the geotectonic evolution of the Himalayan orogen

In this discussion, we will focus on the part of the Indian plate that is outlined by two transcurrent faults in the Indian Ocean, the Owen

Fracture Zone in the west and the Ninety East Ridge in the east (figure 1). This part of the plate moved northeast and northward successively, with distinct counterclockwise rotation until it arrived near the Tibetan block of the Eurasian plate. After the initial convergence and subduction, the Indian plate collided with the Tibetan block and caused large-scale folding and uplift in the colliding front of the Indian plate. The compressive stress, as determined from various structures, suggests a northeast-southwest to northnortheast-south-southwest trend. Two generations of coaxial and coplanar folds (F₁ and F₂) trending northwest-southeast to northnorthwest-south-southeast were the outcome of this compressive field (figures 2, 3, 4). As the compression increased, the axial planes of these early folds were sheared (figure 5), which was inevitable as the enormous energy that was involved could not be accommodated merely by folding (figures 2, 6).

Earlier workers supposed this phase, about middle Miocene in age, to be the strongest of all Tertiary movements (Raina and others, 1987; Saini and others, 1989). At that time, the northwest edge of the

Figure 2 above left.—Northwest-southeast-trending F1 folds and thrust slices directed from the northeast near Basgo Monastery, Ladakh district in Jamma and Kashmir, India.

Figure 3 left.—F2 and F3 folds exhibiting a crosscutting relationship in the low-grade rocks of Salkhalas near Goli, Dalhousie, Himachal Pradesh Himalaya.

Figure 4 above.—Folded molassic sediments opposite Basgo Monastery, Ladakh. The orientation of the fold axes and the plunge (50° SSE) of these folds are not in accordance with the regional structural trends. This change is due to rotation of these structures as the block rotated.

Indian plate made its initial contact with the Eurasian plate and subsequently acted as a pivot around which the plate rotated counter-clockwise. This rotation allowed the northeast extremity of the Indian plate to collide with the Eurasian plate. The two colliding corners of the Indian plate, the northwestern Nanga Parbat massif and the northeastern Namcha Barua massif (figure 1), protruded as rigid indenters and resulted in two examples of syntaxis, sharp bends (Krishnan, 1953; Wadia, 1953; Gansser, 1964) that controlled the

tectonic events thereafter. The angular relationship of the stress direction and the plate front caused this perpetual northeast-southwest compressive force to be resolved into its components as shown in figure 1 and as follows. The intermediate principal compressive stress (σ_2) of the resolved stress followed the strike of the colliding front of the Indian plate, that is, northwest-southeast, whereas the maximum principal compressive stress (σ_1) acted at a right angle to the colliding front. On the outer edges of the Indian plate adjoining

Figure 5.—Schematic diagram based on observed structural attitudes that illustrate the development of folds and thrusts in the Himalaya. The principal compressive stress axes maintain uniform orientation, although in C, σ_2 approaches σ_1 . A, Formation of early folds showing zones of axial planar weakness.

B, Beginning of shearing along the plane of weakness. C, Shearing progresses along with cross folding. Abbreviation: Lm, mineral lineation that is parallel to the thrust-transport direction (northeast-southwest), as well as parallel to the F3 fold axis.

the indentations, the response to σ_1 stress was the development of shear belts that trend northnortheast-southsouthwest. These shear belts are the Kirthar and Sulaiman left-lateral shears that parallel the northward continuation of the Owen Fracture Zone in the west and the right-lateral shears in the east that parallel the Naga-Patko strike-slip fault, which is the northward continuation of the Ninety East Ridge (Abdel-Gawad, 1971; Tapponnier and others, 1982). The northwestern shears are thought to be about early to late Miocene in age (Burbank, 1983).

The tremendous horizontal compression that was directed from the northeast and the southwest in the collision zone caused the massive accumulation of material between the zones of higher compressional strain (the two zones of syntaxis on either side of the plate) to partly escape toward the zone of lower compressional strain (that is, the central part of the colliding plate front). This helped to determine the arcuate shape of the Himalaya in plan. The process also magnified the σ_2 compressive stress, which seemingly was a feeble component of the plane-strain condition. In response, the enormous northwest-southeast compression generated within the confined plate produced northeast-southwest-trending coaxially flattened F3 cross folds (Sati, 1988), north-south extensional faults (Tapponnier, Mercier, Proust, and others, 1981; Tapponnier, Mercier, Armijo, and others, 1981; Sati, 1988; and Windley, 1988), and strike-slip

faults (Gergan, 1989; Sati and others, 1990) (figures 3, 7–9). Windley (1988) believes that the postcollisional northward indentation of the Indian plate since the Eocene has reformed the zone and caused 2,000 km of intracontinental shortening.

The thrusting, particularly along Main Central Thrust and the Tethyan Thrust, was much influenced by the commencement of F3 folding with northeast-southwest-trending folds. Therefore, the stretching lineation of minerals associated with this later folding depicts the earlier thrust-transport direction from the northeast. The dextral and sinistral shear sense indicated by the tectonites in the shear zones reflects the switch from northeast-southwest compression to northwest-southeast compression and back again. This deformation also shows a multistage-thrust evolution and crosscutting thrusts and faults (Coward and others, 1988; Sati, 1988).

The thrust sheets that had moved to enormous heights, apparently defying gravity, under northeast-southwest compression slowly began to revert in the hinterland owing to the dominance of the later northwest-southeast compression over the earlier compression. In the process, the advancing thrust sheet retaliated and produced features indicative of gravity gliding (figure 10). Various mesoscopic features supporting the presence of gravity gliding have been discussed by Burg (1983), Baud and others (1984), Burg and others (1984), Brun and others (1985), Pecher and Le Fort (1986),

Figure 6.—Overthrusting toward the southwest in the low-grade Outer Crystalline rocks near Saldhar, Tapovan (Garhwal Himalaya in northern Uttar Pradesh).

Figure 7.—Steeply plunging (westsouthwest) cross fold (F3) in calcareous turbidites near the base of the Lamayuru Formation along Chulungthang nala, Ladakh.

Figure 8.—Reclin ed northeast-plunging cross fold (F3) in mylonitized migmatites near the roof thrust of the Main Central Thrust near Jharkula in Alaknanda valley, Garhwal Himalaya.

Figure 9.—North-south compression produced a dilation joint that served as an ideal site for the growth of quartz fibers (gash vein). Subsequent strike-slip reactivation of this plane, along with earlier fractures and shears, reflects the sense of movement.

Figure 10.—Sinistral shear sense shown by a kink band produced in a flattened boudin as a result of gravity sliding near the sole thrust of Main Central Thrust southwest of Helang in Alaknanda valley, Garhwal Himalaya. The northwest-southeast compression was responsible for the kinking of the boudin in response to the southwest-directed thrust sheet.

Sati (1988), Valdiya (1988), and Sinha (1989). Backfolding, in ophiolite slabs emplaced over the Indian Ocean shelf sediments, was supposed initially to be due to the welding of the Indian continental margin to the Tibetan block (Thakur, 1981). In addition, downbuckling of the eugeosynclinal rocks within the two converging plates was supposed to be due to rapid relative movement and pressure loading prior to the collision (Virdi, 1981). However, the backfolding and downbuckling might be reflections of the later phase. Various microscopic features support this conclusion, and further, the anomaly inherent in the quartz fabric in the Himalayan orogen (Bouchez and Pecher, 1981; Baud and others, 1984; Sati, 1988) can be explained satisfactorily. Almost all Himalayan researchers have recognized some manifestation of the later deformation, such as rapid cooling ($25^{\circ}\text{C}/\text{Ma}$) subsequent to thrusting (Saini and others, 1989), which obviously is related to the fast uplift (Frank and others, 1977), and widespread retrogressive metamorphism in the Central Crystalline Zone (Heim and Gansser, 1939).

As the Indian plate was welded to the Eurasian plate, the indenters lost their significance. However, the strike-slip movements associated with the various thrust units in the collision zone continued (Srimal, 1986; Gergan, 1989; Sati and others, 1990) as a result of the continued northward drift of the Indian plate. Evidence of this post-thrusting deformation can be recognized in the molassic sediments of the foredeep, sediments deposited after middle Miocene time. The structures present in these deposits are parallel to the early (F_1 and F_2) folds and show no evidence of the northeast-trending cross folds. We again state here that the F_3 folds were generated almost synchronously with the thrusting, and hence, evidence of the F_3 folds is not found in the rocks that originated after the thrusting.

The rate of northward drift of the Indian plate has slowed down substantially, but has never died. This is confirmed by the fact that Paleogene and Neogene sediments are creeping over Pleistocene gravels in the foredeep as a result of neotectonic activity. The tear faults across the Siwalik Range and continuing seismicity further support the presence of ongoing northeast-southwest compression.

Conclusion

On the basis of the above facts, we can deduce safely that the Himalayan orogeny progressed uninterruptedly and that the maximum principal compressive stress (σ_1) retained a northeast-southwest ori-

entation throughout the orogeny. The magnitude of this compressive force reached its climax during collision of the plates; when it produced gigantic thrust sheets that travelled south, as well as north. However, toward the time of transition from thrusting to F_3 folding, the plane-strain component (σ_2 compressive stress, acting in a northwest-southeast direction) dominated over the shear-strain component (σ_1 , oriented northeast-southwest) and they thereby exchanged axes (figure 5). This plane-strain component certainly was not uniform throughout, as reflected by the varying degree of tightness of the cross folds in different areas. A gradual increase can be ascertained in the intensity of strain going from the south to the north. This field of plane strain also influenced the thrusting, which is evident from the northeast-plunging stretched-mineral lineation that is exhibited by the fold axes of the cross folds and that parallels the thrust-transport direction from the northeast. Along the thrust plane, many structures portray a sinistral, as well as a dextral, shear sense. The orographic structure of the Himalaya is one outcome of this deformation. This phase again passed into a dominant northeast-southwest compression, which has continued since initial collision of the Indian and Eurasian plates.

Acknowledgments

The authors are thankful to Dr V C Thakur for his help and keen interest in the study and to Professor D Mukhopadhyay, who reviewed the article thoroughly and provided many useful comments. Financial aid by CSIR Award No. 9/420(3)/87 EMR-I is acknowledged by one of the authors (Rautela).

References

- Abdel-Gawad, M, 1971, Wrench movements in the Baluchistan arch and relation to Himalayan-Indian Ocean tectonics: Geological Society of America Bulletin, v. 82, no. 5, pp. 1235–1250.
- Armijo, R, Tapponnier, P, Mercier, J L, and Han Tong Lin, 1984, Quaternary extension of Tibetan Plateau: Field observations and tectonic implications: Himalayan Geology International Symposium, Chengdu, China, Abstracts.
- Baud, A, Gaetani, M, Garzanti, E, Fois-Erickson, E, Nicora, A, and Tintori, A, 1984, Geological observations in southeastern Zaskar and adjacent Lahul area (northwestern Himalaya): Eclogae Geologicae Helvetiae, v. 77, pp. 171–197.
- Bouchez, J, and Pecher, A, 1981, The Himalayan Main Central Thrust pile and its quartz-rich tectonites in central Nepal: Tectonophysics, v. 78, pp. 23–50.
- Brun, J P, Burg, J P, and Ming, Chen Guo, 1985, Strain trajectories above the Main Central Thrust (Himalaya) in southern Tibet: Nature, London, v. 313, no. 6001, pp. 388–390.
- Burbank, D W, 1983, The chronology of intermontane-basin development in the northwestern Himalaya and the evolution of Northwest Syntaxis: Earth and Planetary Science Letters, v. 64, no. 1, pp. 77–92.
- Burg, J P, 1983, Tectogenèse comparée de deux segments de chaîne de collision; le sud du Tibet (suture du Tsangpo), la chaîne hercynienne en Europe (sutures du Massif Central): Montpellier, France, University of Montpellier doctoral thesis, 368 pp.
- Burg, J P, Matte, Ph, Brunel, M, Andrieux, J, Li Ting Dong, Chen Guo Ming, Li Guangcen, and Xiao Xuchang, 1984, Présence et signification d'une phase de déformation antérieure au flysch à blocs, réputé d'âge crétacé supérieur au sud la suture du Tsangpo (Tibet méridional), in Mercier, J L, and Li Guangcen, eds., Mission Franco-Chinoise au Tibet 1980: Étude géologique et géophysique de la croûte terrestre et du manteau supérieur du Tibet et de Himalaya: Paris, France, Centre National de la Recherche Scientifique, pp. 351–356.
- Coward, M P, Butler, R W H, Chambers, A F, Graham, R H, Izatt, C N, Khan, M A, Knipe, R J, Prior, D J, Treolar, P J, and Williams, M P, 1988, Folding and imbrication of the Indian crust during Himalayan collision, in Shackleton, R M, Dewey, J F, and Windley, B F, eds., Tectonic evolution of the Himalayas and Tibet: Philosophical Transactions of the Royal Society of London, v. 326A, pp. 89–116.
- Crawford, A R, 1974, The Indus Suture Line, the Himalaya, Tibet and Gondwanaland: Geological Magazine, v. 111, no. 5, pp. 369–383.

- Dewey, J F, and Bird, J M, 1970, Mountain belts and the new global tectonics: *Journal of Geophysical Research*, v. 75, pp. 2625–2647.
- Frank, W, Gansser, A, and Trommsdorff, V, 1977, Geological observations in the Ladakh area (Himalayas); a preliminary report: *Schweizerische Mineralogische und Petrographische Mitteilungen*, v. 57, no. 1, pp. 89–113.
- Fuchs, G, 1977, The geology of the Himalayas in synoptic view, in Jest, C, ed., *Himalaya; sciences de la terre*: Paris, Centre National de la Recherche Scientifique, Colloques Internationaux, no. 268, v. 2, pp. 172–180.
- Gansser, A, 1964, *Geology of the Himalaya*: New York, Interscience Publishers, 289 pp.
- Gansser, A, 1977, The great suture zone between Himalaya and Tibet; a preliminary account, in Jest, C, ed., *Himalaya; sciences de la terre*: Paris, Centre National de la Recherche Scientifique, Colloques Internationaux, no. 268, v. 2, pp. 181–191.
- Gergan, J T, 1989, Pull-apart basins along Karakoram fault and adjoining region [abstract]: *International Geological Congress*, 28th, Washington DC, USA, 1989, Abstracts, v. 1, pp. 540–541.
- Heim, A, and Gansser, A, 1939, Central Himalaya, geological observation of the Swiss Expedition 1936: Zurich, *Mémoires de la Société Helvétique des Sciences Naturelles* [Denkschriften der Schweizerischen Naturforschenden Gesellschaft], v. 73, p. 245.
- Hsu, K J, 1982, Geosynclines in plate-tectonic settings: Sediments in mountains, in Hsu, K J, ed., *Mountain building processes*: London, Academic Press, pp. 3–12.
- Krishnan, M S, 1953, The structural and tectonic history of India: *Geological Survey of India Memoir*, v. 81, p. 109.
- Le Fort, P, 1975, Himalayas: The collided range; present knowledge of the continental arc: *American Journal of Science*, v. 275A, pp. 1–44.
- McKenzie, D P, 1972, Active tectonics of the Mediterranean region: *Geophysical Journal of the Royal Astronomical Society*, v. 30, pp. 109–185.
- Medlicott, H B, 1864, On the geological structure and relationship of the southern portion of the Himalayan ranges between rivers Ganges and Ravee: *Memoirs of the Geological Survey of India*, v. 3, no. 2, pp. 1–212.
- Molnar, P, and Tapponnier, P, 1975, Cenozoic tectonics of Asia; effects of a continental collision: *Science*, v. 189, no. 4201, pp. 419–426.
- Pecher, A, and Le Fort, P, 1986, in Le Fort, P, Colchen, M, and Montant, C, eds., *Orogenic evolution of southern Asia*, Le Fort, P, Colchen, M, Montant, C, eds., *Mémoires des Sciences de la Terre*, Centre National de la Recherche Scientifique, v. 47, pp. 285–309.
- Powell, C McA, and Conaghan, P J, 1973, Plate tectonics and the Himalayas: *Earth and Planetary Science Letters*, v. 20, no. 1, pp. 1–12.
- Raina, B N, Pati, U C, and Srimal, N, 1987, Himalayan orogeny, in Leonov, Yu G, and Khain, V E, eds., *Global correlation of tectonic movements*: Chichester, UK, John Wiley, pp. 199–225.
- Rodgers, D A, 1980, Analysis of pull-apart basin development produced by en echelon strike-slip faults, in Ballance, P F, and Reading, H G, eds., *Sedimentation in oblique-slip mobile zones*: *International Association of Sedimentologists Special Publication 4*, pp. 27–41.
- Royden, L H, and Burchfiel, B C, 1987, Thin-skinned N-S extension within the convergent Himalayan region; gravitational collapse of a Miocene topographic front, in Coward, M P, Dewey, J F, and Hancock, P L, eds., *Continental extensional tectonics*, Geological Society [London] Special Publication 28, pp. 611–619.
- Saini, H W, Wawraich, R S, Malhotra, N K, Nagpaul, K K, and Sharma, K K, 1989, Cooling and uplift rates and dating of thrust from Kinnaur, Himachal Himalaya: *Himalayan Geology*, v. 9, no. 2, pp. 549–567.
- Sati, D C, 1988, Structural analysis of central crystalline rocks of the area between Helang and Malari, Garhwal Himalaya, UP, India: Srinagar, Garhwal, India, Garhwal University, unpublished PhD thesis.
- Sati, D C, Nanda, A C, and Mehra, G S, *in press*, Collision tectonics and its bearing on the intermontane deposits of Ladakh.
- Searle, M P, 1983, Stratigraphy, structure and evolution of the Tibetan-Tethys Zone in Zaskar and the Indus Suture Zone in the Ladakh Himalaya: *Transactions of the Royal Society of Edinburgh*, v. 73, pp. 205–219.
- Searle, M P, 1986, Structural evolution and sequence of thrusting in High Himalayan and Indus suture zones of Zaskar and Ladakh, Western Himalaya: *Journal of Structural Geology*, v. 8, no. 8, pp. 923–936.
- Searle, M P, Cooper, D J W, and Rex, A J, 1988, Collision tectonics of the Ladakh-Zaskar Himalaya: *Philosophical Transactions of the Royal Society of London*, v. 326A, pp. 117–148.
- Shanker, R, Pandhi, R N, Prakash, G, and Thussu, J L, 1976, Recent geological studies in upper Indus valley and the plate tectonics: *GSI Miscellaneous Publication*, v. 34, no. 1, pp. 41–56.
- Sinha, A K, 1989, *Geology of the higher Central Himalaya*: Chichester, UK, John Wiley, 219 pp.
- Srimal, Neptune, 1986, India-Asia collision; implications from the geology of the eastern Karakoram: *Geology*, v. 14, no. 6, pp. 523–527.
- Tahirheli, R A K, Mattauer, M, Proust, F, and Tapponnier, P, 1979, The India-Eurasia suture zone in northern Pakistan—synthesis and interpretation of recent data at plate scale, in Farah, A, and De Jong, K A, eds., *Geodynamics of Pakistan*: Quetta, Pakistan, Geological Survey of Pakistan, pp. 125–130.
- Tapponnier, P, Mercier, J L, Armijo, R, Tonglin, H, and Ji, Z, 1981, Field evidence for active normal faulting in Tibet: *Nature*, London, v. 294, pp. 410–413.
- Tapponnier, P, Mercier, J L, Proust, F, and others, 1981, The Tibetan side of the India-Eurasia collision: *Nature*, London, v. 294, pp. 405–410.
- Tapponnier, P, and Molnar, P, 1977, Active faulting and tectonics in China: *Journal of Geophysical Research*, v. 82, pp. 2905–2930.
- Tapponnier, P, Peltzer, G, Le Dain, A Y, Armijo, R, and Cobbold, P, 1982, Propagating extrusion tectonics in Asia; new insights from simple experiments with plasticene: *Geology*, v. 10, pp. 611–616.
- Thakur, V C, 1981, An overview of thrusts and nappes of western Himalaya, in McClay, K R, and Price, N J, eds., *Thrust and nappe tectonics*, international conference, London, 1979: Geological Society of London Special Publication 9, pp. 381–392.
- Valdiya, K S, 1988, Tectonics and evolution of the central sector of the Himalaya: *Philosophical Transactions of the Royal Society of London*, v. 326A, pp. 151–175.
- Virdi, N S, 1981, Geotectonic evolution of the Indus suture zone, in Sinha, A K, ed., *Contemporary geoscientific researches in Himalaya*, v. 1: Dehra Dun, India, Bishen Singh Mahendra Pal Singh, pp. 131–136.
- Wadia, D N, 1953, *Geology of India*: London, McMillan and Company Ltd, 531 pp.
- Windley, B F, 1988, Tectonic framework of the Himalaya, Karakoram and Tibet, and problems of their evolution: *Philosophical Transactions of the Royal Society of London*, v. 326A, pp. 3–16. □

Dr Dinesh Ch Sati received his master's and doctor's degrees in geology from Garhwal University, Srinagar (Garhwal), India. He is working as a Research Scientist on a project sponsored by the Department of Science and Technology (Government of India) on the "Geodynamic Evolution of the Collision Boundary in North-western Himalaya, Study Based on North-South Cross Section," at the Wadia Institute of Himalayan Geology in Dehra Dun, India. His research interests focus on shear-zone tectonics in the Himalaya.

Mr Piyoosh Rautela studied applied geology and graduated from the Department of Earth and Planetary Sciences at the University of Allahabad. He is engaged now in his doctoral work at Wadia Institute of Himalayan Geology under the supervision of Dr V C Thakur. He primarily works on thrust tectonics.