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Tectonics and Evolution of the Central Sector of the Himalaya [and Discussion]

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Tectonics and evolution of the central sector of the Himalaya

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[Plates 1–4]

Following the India–Asia collision, intracrustal movements along the Main Central Thrust (MCT) and Main Boundary Thrust (MBT) in a piggy-back-style, thrust duplexes developed that uplifted the Vaikrita (Central) crystallines of the basement to more than 8000 m elevation. Blocking of subduction on the suture and slowing down of movement on the MCT led to the formation of the Trans-Himadri (Malari) Thrust between the Vaikrita basement and the Tethyan cover sediments, and to gravity-induced backfolds and backthrusts in the latter. The Vaikrita crystallines underwent upper amphibolite to lower granulite facies metamorphism at 600–650 °C and more than 5 kbar (1 kbar $= 10^8$ Pa) and migmatistation associated with 28–20 Ma old S-type granites that formed at 15–30 km depth during the culmination of metamorphism and thrust deformation. Delimited by the MCT and MBT, the Lesser Himalaya is made of Proterozoic sediments beneath the Almora nappe constituted of low- to medium-grade metamorphics and 1900 ± 100 Ma old granitic gneisses and 560 ± 20 Ma old granites. The Lesser Himilaya underwent considerable neotectonic rejuvenation during differential movements along the MBT. The frontal Siwalik molasse below the MBT was severely thrusted and folded in the late Holocene, and continued underthrusting of the Indian Shield beneath the Himalaya is manifest in the development and activation of the deep Himalayan Front Fault (HFF), which separates the Siwalik from the subRecent–Recent alluvial plain of the Ganga Basin.

1. INTRODUCTION

For 300 km between Nepal and Himachal Pradesh, the Kumaun Himalaya in the centre of the Himalayan arc (figure 1) is stratigraphically the most representative and structurally a very revealing segment of the mountain chain. It is also the most keenly explored sector since the days of geologists such as G. D. Herbert (1842), who carried out the first-ever mineralogical survey in the Himalaya and Richard Strachey (1851) who crossed the formidable mountain barrier to probe the mysteries of the 'roof of the world'.

A product of repeated deformation of the great pile of sediments at the northern continental margin of the Indian Shield, which collided with the Asian continent some 50 Ma ago, the Himalaya is divisible into five lithotectonically and physiographically distinct domains or subprovinces (figure 2). The dividing surfaces are thrusts of regional dimensions and varying activity. On the extreme south lie the sprawling swampy plains of Tarai, perennially wetted by the springs that emerge from the edge of the gently sloping piedmont gravel fans fringing the hills. The latter, called the 'Bhabhar', is separated from the abruptly rising Siwalik Hills (900–1500 m) by the Himalayan Front Fault (HFF). The ruggedly youthful Siwalik domain, made of late Tertiary to Pleistocene molasse is characterized by steep slopes, swift-flowing consequent streams and deep valleys of antecedent rivers. Synclinal valleys, wherever filled

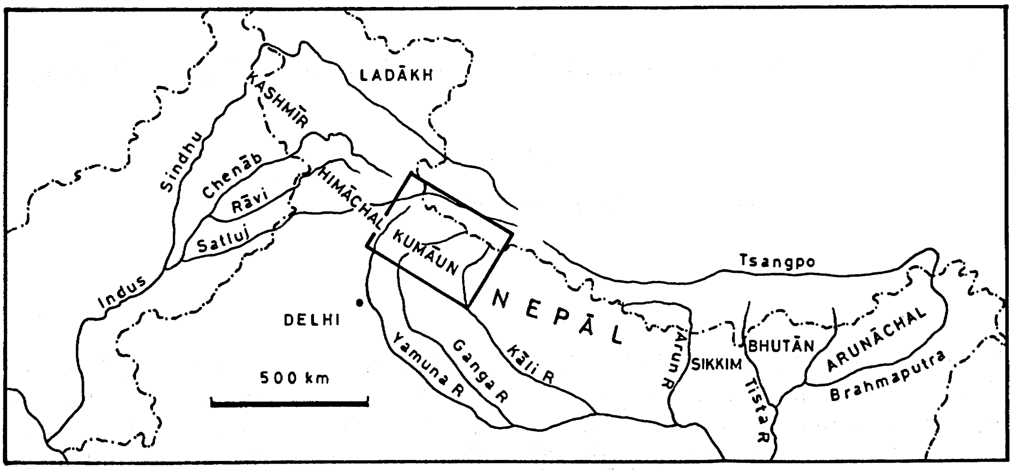


FIGURE 1. Location of Kumaun Himalaya in the central segment of Himalayan chain between Nepal in the east and Himachal Pradesh in the west. Rivers Kali and Tons define the natural boundaries.

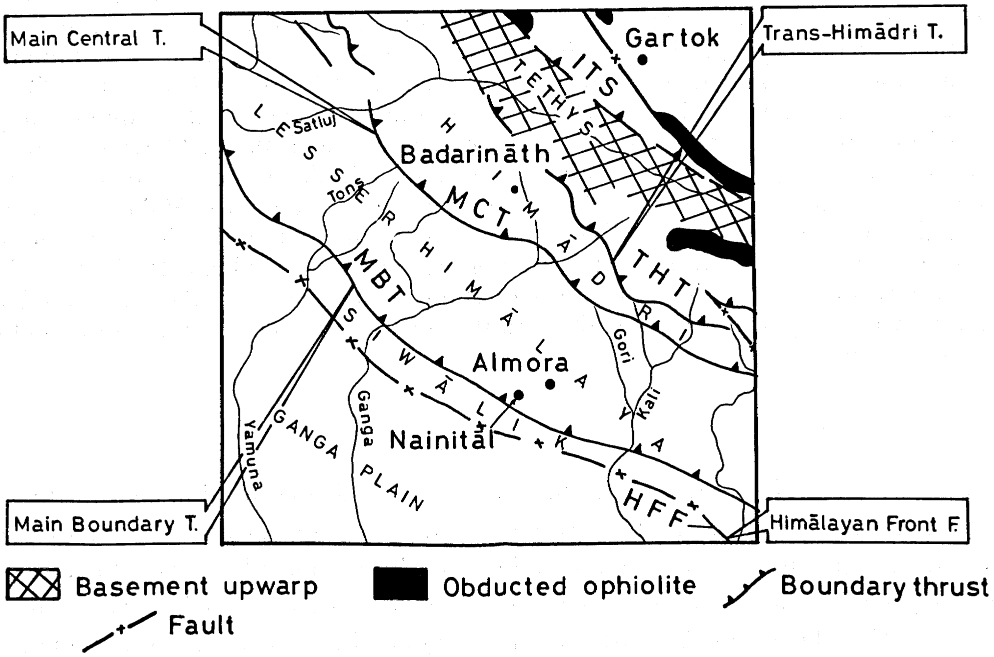


FIGURE 2. Division of the Kumaun Himalaya into five geomorphically and lithotectonically distinctive subprovinces, separated by intracrustal faults and thrusts.

with subrecent–recent gravels eroded from rapidly wasting hills, form flatter tracts called 'duns'.

The Siwalik in turn is separated from the Lesser Himalaya by the Main Boundary Thrust (MBT). The thrust zone is marked by very wide valleys, characterized by fans and cones of landslide debris and by recent–subrecent fault-fashioned triangular facets on spurs. The Lesser Himalaya is made up of Precambrian and partly Palaeozoic sedimentaries overthrust by vast thick sheets of metamorphics and their injected Precambrian–early Palaeozoic granites. Rising to an elevation of 1500–2500 m, the Lesser Himalayan subprovince shows a mild and mature topography with gentle hill slopes. Major transverse rivers, however, flow in deeply dissected valleys still being strongly eroded as a consequence of subrecent tectonic resurgence.

North of the Lesser Himalaya, the Vaikrita or Main Central Thrust (MCT) demarcates the southern (lower) boundary of the Great Himalayan (Himadri) complex of high-grade metamorphics that are extensively injected and migmatized by mid-Tertiary granite. Rising to a height over 6500–7000 m, the Himadri is characterized by extremely rugged and youthful topography, precipitous scarps, sharp peaks, deep gorges with vertical to convex walls and very steep gradients.

Further north, the Malari or Trans-Himadri Thrust (T-HT) marks the boundary between the Himadri basement complex and its thick sedimentary cover of the Tethys domain. Ranging in age from late Precambrian to late Cretaceous, the sediments represent the distal continental margin of the Indian Shield. The synclinorial Tethys subprovince has an extremely rugged topography particularly adjacent to the Himadri. Desolate and virtually bare of vegetation, this domain of frigid climate is a cold desert.

Finally, the Indus–Tsangpo Suture (ITS), passing through Darchen in the Mansarovar area, marks the junction of the Indian and Asian Plates. It is a very deep fault zone characterized by vertically disposed, greatly sheared and shattered seafloor material (ophiolites) and deep-sea sediments.

In this paper attention is focused on five geodynamic belts: (i) the ITS Zone where the leading edge of the northward drifting Indian Plate exhibits pronounced buoyant resistance to slip beneath the Asian Plate as testified by large-scale domal upwarp of the crystalline basement; (ii) the basement-cover contact that broke out into a regional lag thrust (T-HT) following blocking of movements on the suture and on the intracrustal boundary thrust at the

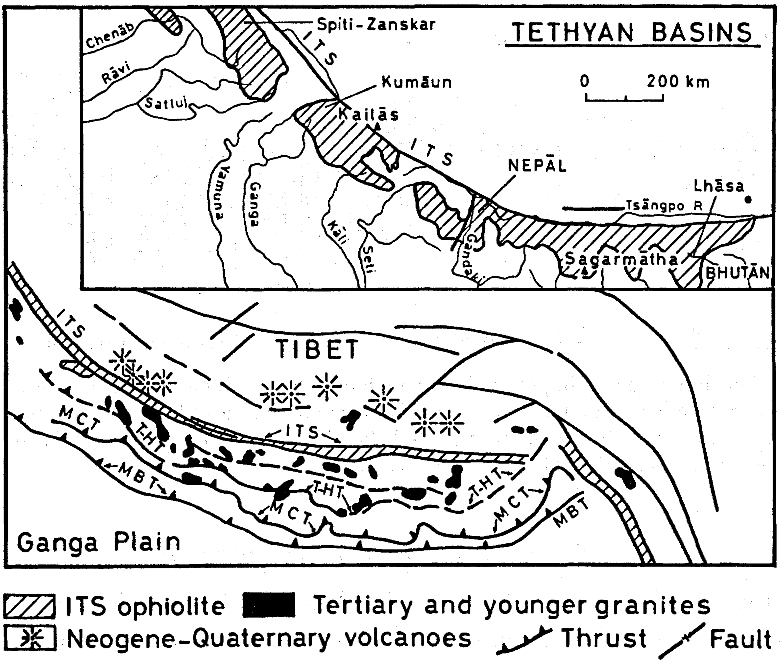


FIGURE 3. Convergence of the Indian and Asian Plates is reflected in widespread acid volcanism (50–48 Ma) at the Andean-type magmatic arc (110–45 Ma) in southern Tibet. (After Zhou *et al.* 1981.) The inset shows discontinuous Tethyan basins with practically uniform pattern of sedimentation and stratigraphy, and with their northern part slightly truncated. (After Valdiya 1988*b*.)

base of the basement; (iii) the MCT zone where repeated slicing with crustal stacking in piggyback manner has uplifted a deep-seated basement to make the loftiest mountain Himadri; (iv) southern rampart of the Lesser Himalaya intimately related to the MBT where repeated intraplate movements (including neotectonic) resulting from the under-thrusting of the Indian Shield under the Himalaya and attendant strike-slip and vertical movements on tear faults in the thrust sheet have caused spectacular block uplift and subsidence; and (v) the emerging new deep fault (HFF) at the truncated edge of the Siwalik prism against the alluvial plain of the Ganga Basin.

This paper is not intended to be a general review of the extensive work carried out by other workers, but summarizes my observations and deductions in recent years.

2. Collision and buoyancy resistance

(a) *Obduction and ophiolite nappes*

As the Indian and Asian Plates converged, an oceanic trench developed in front of the Asian continent. This deepening is reflected in the accumulation of flysch with radiolarian chert of the Giumal and Sangcha Malla formations in Malla Johar. The continental collision (*ca.* 50 Ma) initiated widespread acid volcanism genetically related to the Andean-type magmatic arc of the Kailas–Ladakh Ranges constituted of commonly 80–48 Ma old hornblende-bearing granodiorite–diorite–tonalite association (Sr isotopic ratio 0.7033–0.7036). This magmatic–volcanic arc (figure 3) frames the collision zone, the Indus–Tsangpo Suture (ITS), represented by intensely deformed, and vertically disposed trench sediments tectonically intruded with ocean-floor ophiolitic material (figure 4).

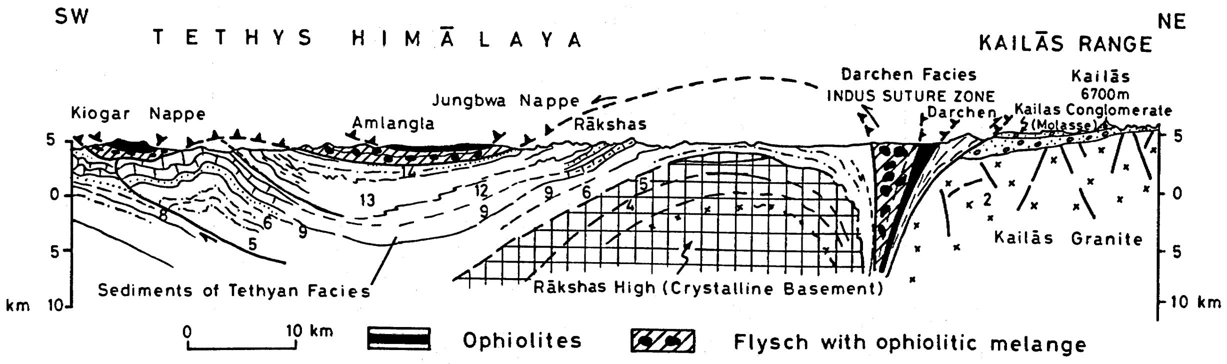


Figure 4. The section shows upwarping of the leading edge of the continental plate owing to buoyancy resistance and simultaneous development a back-arc basin that became the site of late Eocene fluvial deposition. Gravity sliding due to ridging up of basement transported the obducted ocean-floor material to Malla Johar, about 80 km south of the suture. (After Gansser 1964, 1974.)

(b) *Anticlinal upwarp at the leading edge*

The large upwarp of the basement rocks in Rakshastal, immediately to the south of the collision zone (ITS) (figure 4) is a pointer to buoyant resistance encountered by the continental plate to slide any further under Asia (Valdiya 1984*a*). This domal structure, constituted of gneisses, schists and phyllites of the Great Himalayan Vaikrita Group and intruded by older gneissose porphyritic granites as well as younger leucoadamellites, extends southeast from

Nimaling and Tso Morari in Ladakh to Gurla Mandhata in extreme northwestern corner of Nepal. In Nepal it is represented by the 'axial rise of the basement crystallines between Manangobhot and Phijor (Hagen 1956) and the 900 km long Lhagoi Kangri Range embracing 16 gneissic domes (figure 3) just 70–80 km south of the ITS. These gneissic domes in Nepal consist of Lower Ordovician porphyritic granite intruded by Upper Cainozoic (6–15 Ma) leucogranites of Kangmar (Pham *et al.* 1986; Le Fort *et al.* 1986). Both these suites are remarkably similar in mineral–chemical composition (including strontium isotopic ratio) to those of the Tibetan Slab (Vaikrita). The anticlinal ridge of gneissic domes at the leading edge of the northward moving Indian Plate must have evolved as a consequence of the resistance to further subduction (Valdiya 1984*a*, 1987, 1988*b*). An analysis of gravity anomaly data by Lyon-Caen & Molnar (1983) suggests that the Indian Plate was weakened and bent to 10–15° at a position 50 km south of the ITS, presumably as a result of collision that detached the crust from the mantle, as the cold mantle part of Indian lithosphere slid beneath the Himalaya. The detached crust must have been thus folded at its front.

The ridging up of the basement at the leading edge was accompanied by the formation of a backarc basin in the Sindhu–Tsangpo valleys, now represented by the 2000–4000 m thick fluvial accumulations of the Kailas Conglomerate of late Eocene age (figures 4 and 5).

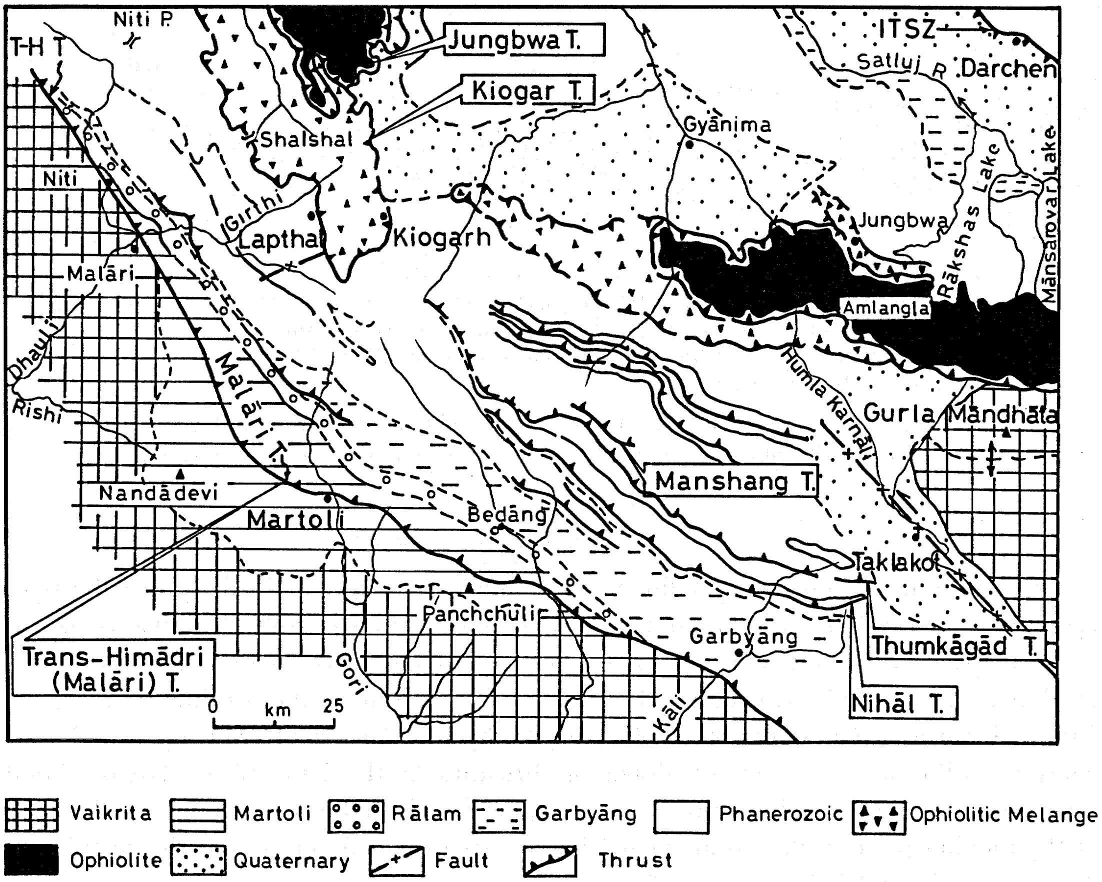


FIGURE 5. Tectonic map of the synclinorial Tethys Zone showing imbrication of thrust sheets in the northeastern area adjacent to the wrench fault of the Humla Karnali valley, and decoupling of the basement and cover along the Malari Thrust (Trans-Himdari Thrust). (After Heim & Gansser 1939; Valdiya 1979, 1987, 1988*b*.)

3. Deformation of Tethys synclinorium and basement-cover decoupling

(*a*) *Thrust-stacking on the northern margin*

The 10–15 km thick sedimentary pile of the Tethys Zone to the south of the basement upwarp is split up in the eastern part into a multiplicity of imbricate thrust sheets (figures 5 and 6*a*), each characterized by isoclinal or overturned to recumbent folds with attendant disharmonic deformation near planes of dislocation (Heim & Gansser 1939; Valdiya & Gupta 1972). To the east is a major NW–SE trending wrench fault, which has not only sinistrally offset the MCT, but also formed this schuppen zone (Valdiya 1979, 1981). It is surmounted in the western part (Malla Johar) by a succession of two nappes constituted of ophiolitic melanges and ophiolites transported 80 km south from their root zone in the ITS. The central part of the synclinorium comprises upright folds, and domes and basins (figure 6*b*).

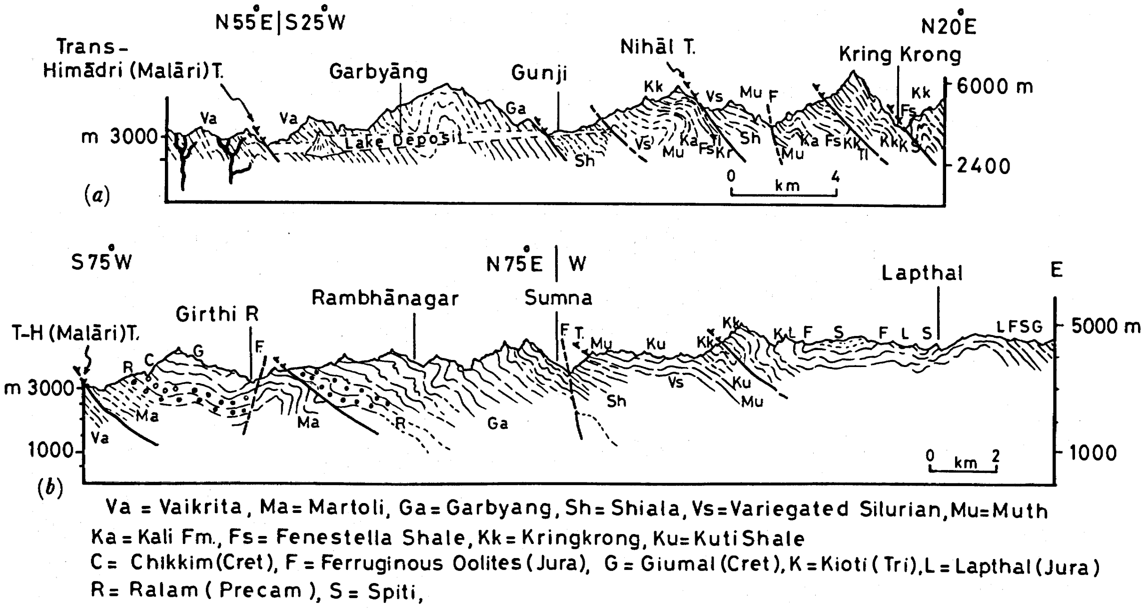


Figure 6. Cross section of the Tethyan Zone along the rivers Kali in the east and Girthi (Dhauli) in the west. (After Valdiya & Gupta 1972; Valdiya 1979.)

(*b*) *Basement-cover decoupling*

The southern margin of the sedimentary domain is sharply defined against the basement crystallines of the Himadri (Great Himalaya) by the Malari Fault (Valdiya 1979), a local name for the Trans-Himadri Thrust, which extends for 1600 km from Kashmir to Sikkim (Valdiya 1987, 1988*b*). It originated as a detachment fault on the continental margin of the Indian Plate as a consequence of blocking of the movements (45 Ma ago) in the zone of collision (ITS) and the slowing down of thrusting at the base of the Great Himalayan crystalline complex. The buoyant resistance appears to have been so strong that the back part of the moving plate broke up along the basement-cover contact, giving rise to this plane of decoupling (figures 5–7).

Genetically related to the gravity-induced backfolding and backthrusting of the sedimentary cover, the Trans-Himadri Thrust has not only caused tremendous shearing and mylonitization of the Vaikrita basement metamorphics, but also attenuated and even eliminated lithostratigraphic units of both the basement and the cover (e.g. Budhi Schist in Dhauli Valley, Martoli Flysch and Ralam Conglomerate in Darma and Kali Valleys). The termination of the movement on the Main Central Thrust at the base of the 10–20 km thick Vaikrita Slab must have reactivated the T-HT as evident from the shearing of the Miocene intrusive leucogranite in the Dhauli Valley (Valdiya 1979, 1987). This reactivation implies upthrusting of the basement to a great height, the sedimentary cover lagging behind and its terminal part sliding down under gravity to give rise to north-vergent backfolds and minor backthrusts (figure 6*b*). Significantly, the NNE-plunging early mesoscopic folds of axial foliation in the basement metamorphics (Vaikrita), which are folded on the NW–SE axis, are absent in the Tethyan sediments (Thakur & Chaudhury 1983).

4. Structural evolution of Himadri

(*a*) *Tectonic design*

Below the Tethyan sedimentary cover is a 10–20 km thick pile of high-grade metamorphics of the Vaikrita Group, intruded extensively by Miocene leucogranites. Bounded by the T-HT at the top and the Vaikrita Thrust (MCT) at the base, the Vaikrita lithotectonic domain is a huge homocline (figures 7 and 13) (Valdiya 1979, 1981). It has been described in Nepal

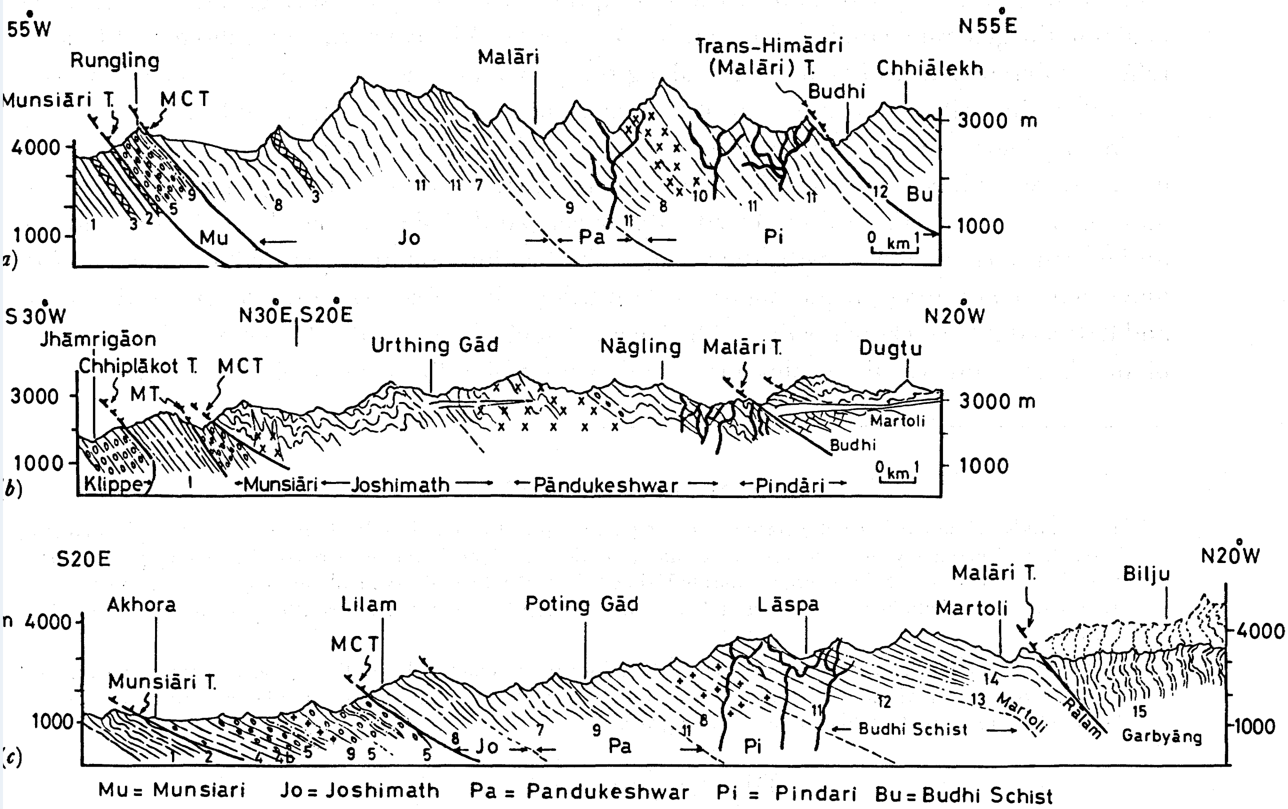


FIGURE 7. Cross sections across the Himadri (Great Himalaya) revealing its structural architecture and the nature of the delimiting thrusts. Numbers: 1, Deoban carbonates; 2, Berinag quartzites; 3, amphibolite; 4, Munsiari sericite–chlorite–schist; 5, Munsiari augen gneiss; 6, Munsiari micaceous quartzite; 7, Vaikrita two-mica–garnet–kyanite–schist; 8, streaky garnet–kyanite gneiss (Vaikrita); 9, biotite quartzite; 10a, migmatite; 10b, adamellite–aplogranite; 10c, pegmatite; 11, calc-silicatefels; 12, biotite-porphyroblast calc-schist; 13, sericite–staurolite schist; 14, Martoli flysch; 15, carbonaceous graphitic phyllite.

by French workers as the Tibetan Slab. The Vaikrita is singularly devoid of large-scale folds, save for macroscopic reclined folds (Roy & Valdiya 1988) recognized on the southern slope of the Himadri (Great Himalaya) and for the fault-bounded granite dome of the Badarinath area (Heim & Gansser 1939; Gansser 1964). Transverse to the general tectonic trend, the large-sized reclined folds are represented by the NNE/NE-striking vertical or nearly vertical S-surfaces in a zone where the general strike is WNW/NW–ESE/SE and the dip rather shallow.

The penetrative synmetamorphic deformation pattern of the Vaikrita is the result of polyphase folding and deep-level ductile shearing involving repeated transposition of foliation planes. The bulk strain was non-coaxial and attributable to variation in the ease of slip on the shear planes during thrust movements (Roy & Valdiya 1988).

(*b*) *Early deformation*

The superposed folds of the Vaikrita are represented by coaxially folded hooks with subparallel to diversely oriented axial planes and complex folds that show strong curvature of hinges and axial surfaces of the earlier folds (figure 8, plate 1) (Roy & Valdiya 1988).

The earliest deformation is represented by down-dip plunging appressed isoclines with their thickened hinges parallel to mineral lineation and attenuated limbs (F_1A) (figure 8*a*, plate 1). The second category of early folds (F_1B) varying in morphology from sharp or round hinged and arrowhead to conjugate kinks are almost upright with their axial surfaces oriented at larger angles to the general tectonic trend (figure 8*b*, plate 1). Widely varying morphology of F_1 folds reflects different stages of deformation along thrust planes. Their constant vergence, however, suggests a sinistral sense of rotation of the axial planes (Roy & Valdiya 1988).

The F_2 folds are asymmetrical to isoclinal, their hinges making high angles with the lineation. Some have updip vergence and others downdip. Formed during the sluggish thrust movements, these folds exhibit considerable layer-parallel shortening along the direction of initial transport coinciding with the strike of the bedding foliation (figure 9*a*, plate 1). With movements continuing on the planes of dislocation, these folds were progressively tightened and flattened into stacks of isoclines. These were detached repeatedly along newly formed shear planes. The result was the evolution of rootless intrafolial folds (figure 9*b*, plate 1).

DESCRIPTION OF PLATE 1

FIGURE 8. Folds of the earliest deformation. (*a*) Negative print of coaxially folded early isoclines (F_1A) evincing hook-shaped geometry in the calc-silicate material (light), which is replaced partly by leucogranite (dark). Locality 5 km north of Suraithota, Dhauli Valley. (*b*) F_1B fold with axial plane at high angles to the F_1A isoclines. A decollement separates the folds of the two types. Locality 1 km south of Rambara, Mandakini Valley.

FIGURE 9. Folds of later deformation. (*a*) Isoclinal F_2A folds with detached lower limbs, showing updip movement. Locality Rambara, Mandakini Valley. (*b*) Small-scale rootless isoclinal folds, some hook-shaped, within thin layers of psammites. Locality Dabrani, Bhagirathi Valley.

DESCRIPTION OF PLATE 2

FIGURE 11. Garnet crystals in the Vaikrita and Munsiari metamorphics showing mutual compositional and structural differences. (*a*) and (*b*) Smooth and rounded edges of ellipsoidal Vaikrita garnet crystals wrapped around by mica flakes. The core and rim show different kinds of inclusions. Locality: Dabrani, Bhagirathi Valley. (*c*) and (*d*) The Munsiari garnet, in contrast, is rotated and characterized by sigmoidal inclusion trails. Locality: Kyarkikhal, Bhilangana Valley. (Photos by S. S. Bhakuni.)

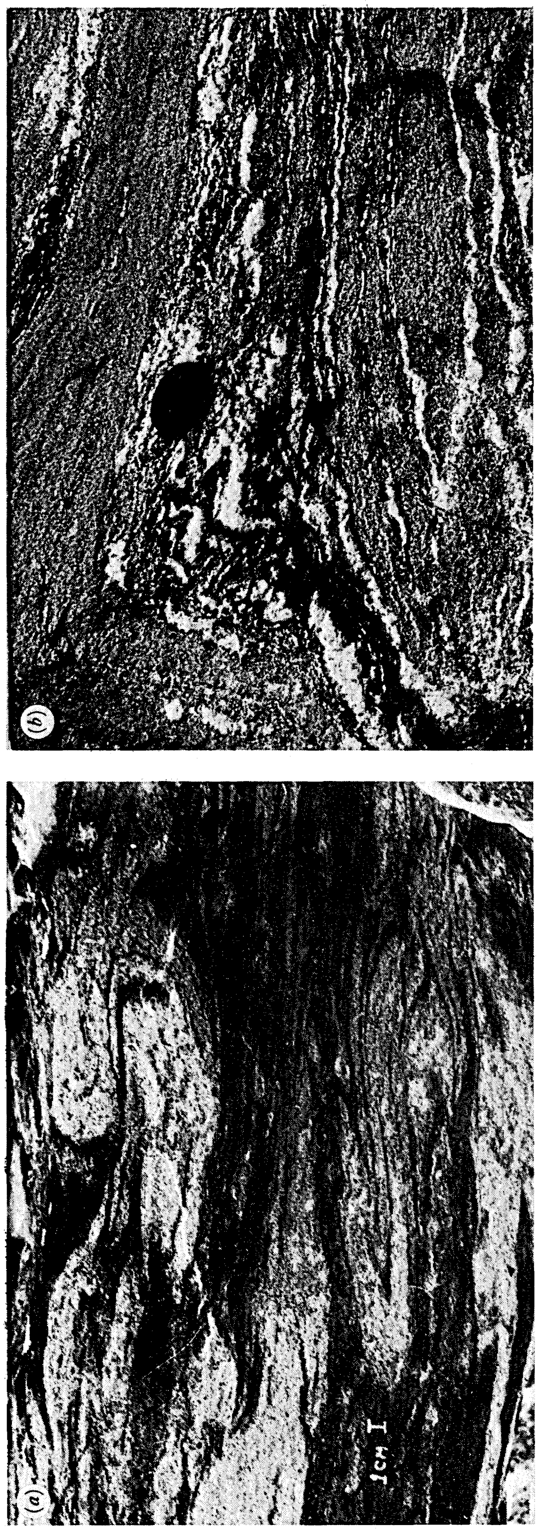
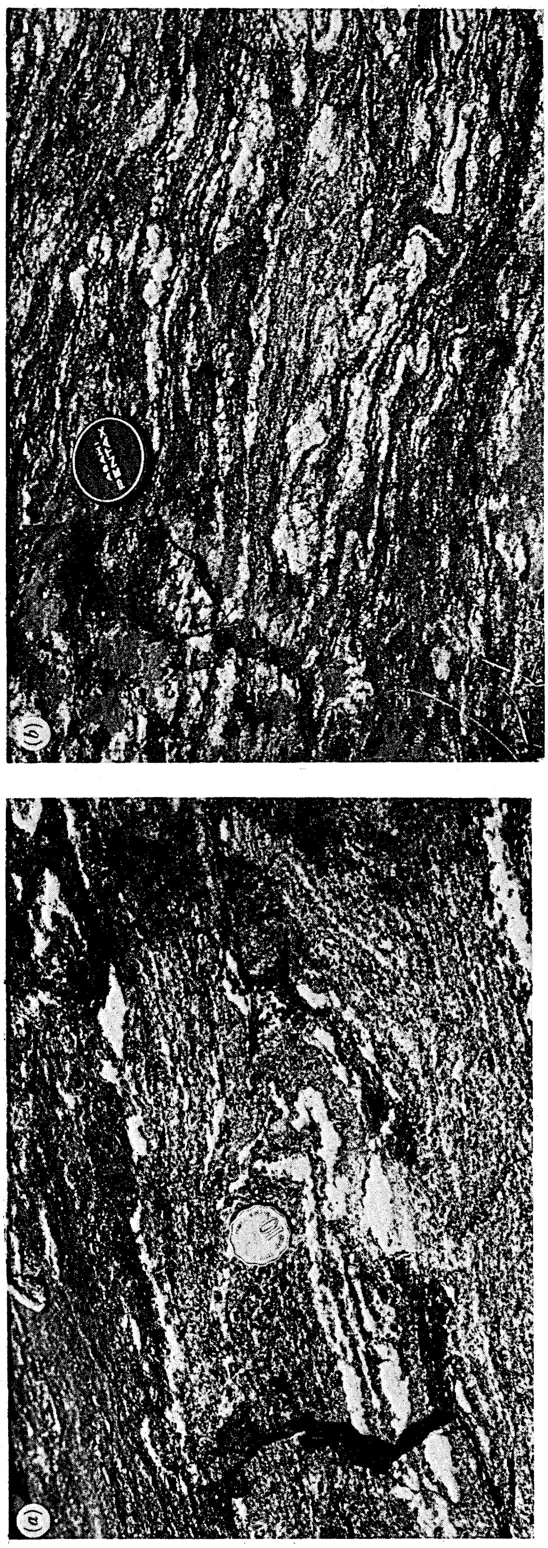


FIGURE 8. For description see opposite.



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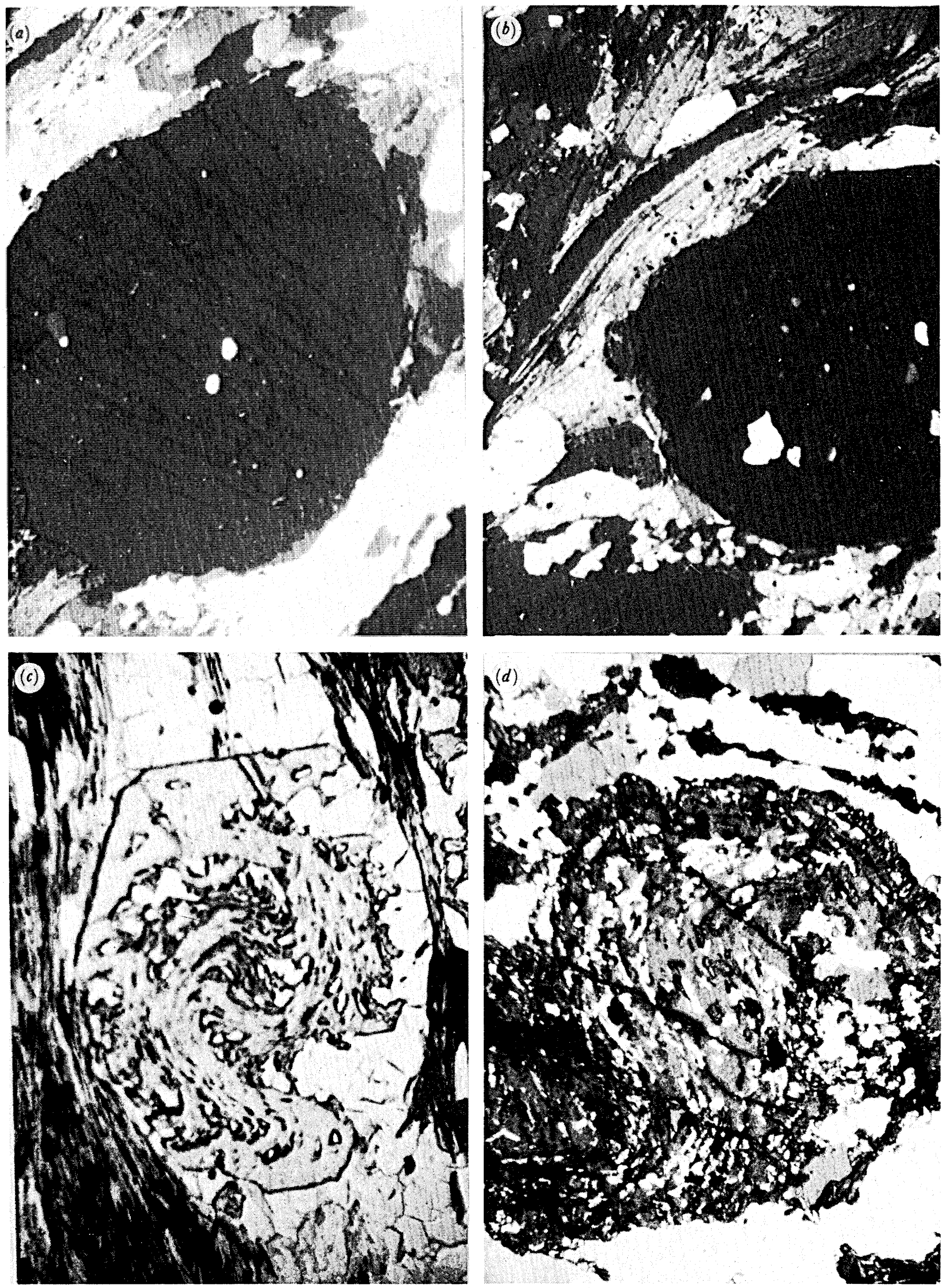

FIGURE 11. For description see p. 158.

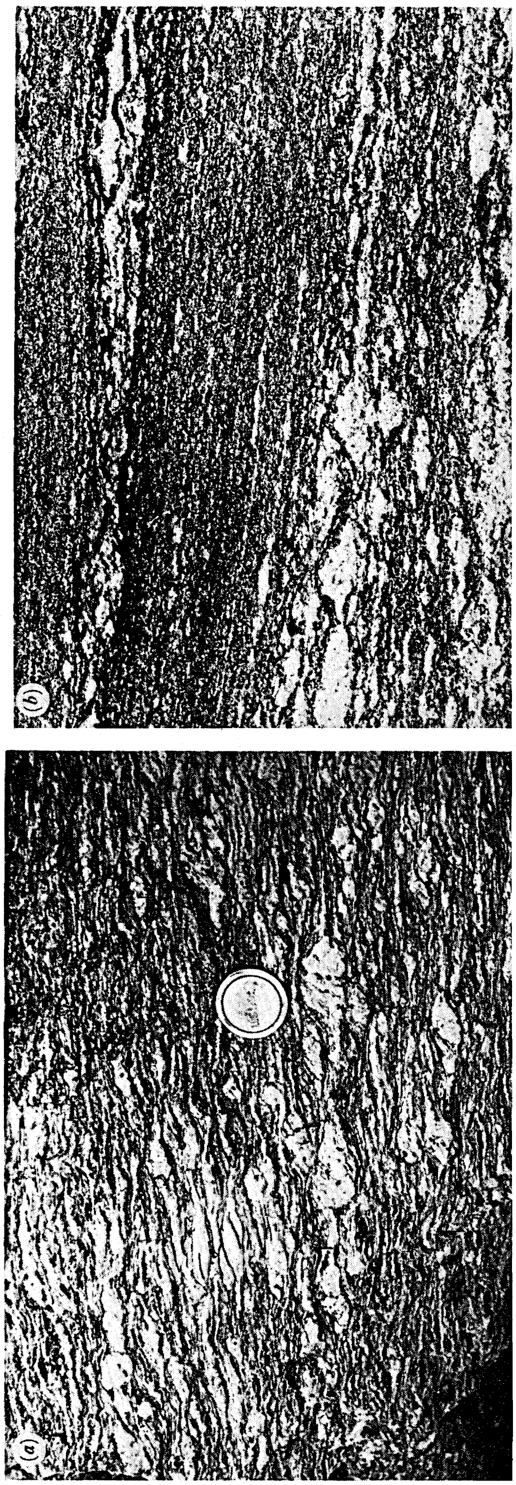

FIGURE 12. For description see p. 159.

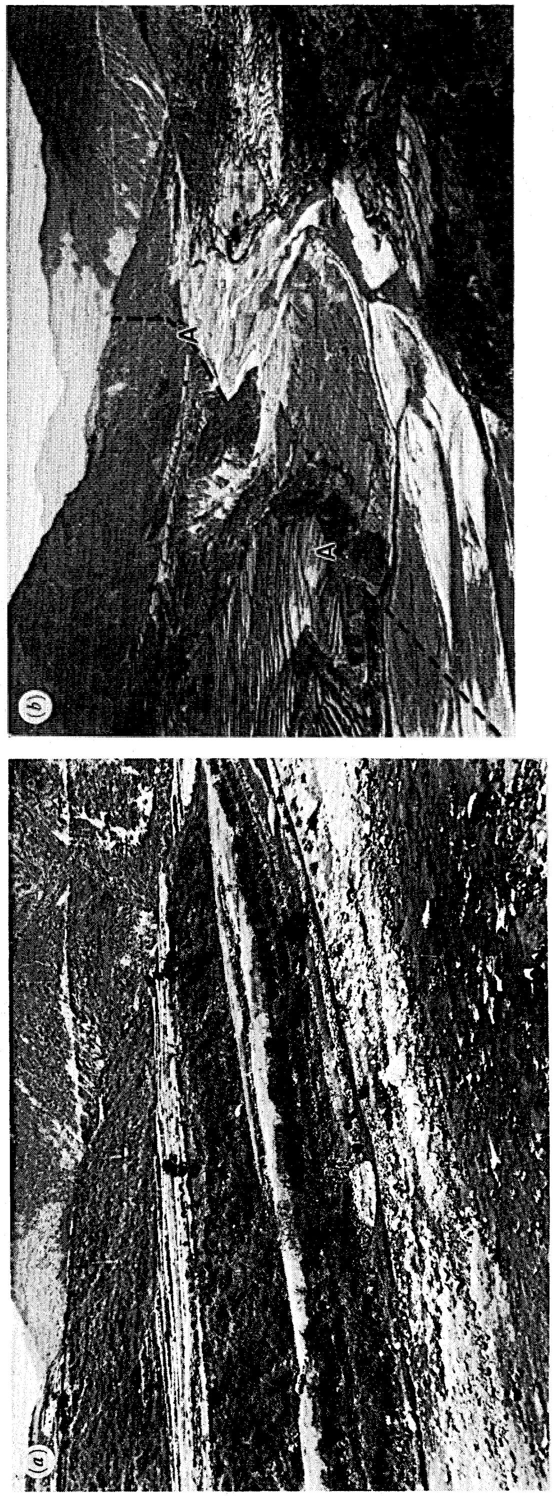

FIGURE 22. For description see p. 159.

FIGURE 24. The northward tilted (2–6°) uppermost Pleistocene to early Holocene gravel deposits in the Dabka Valley.

(*c*) *Formation of Main Central* (*Vaikrita*) *Thrust*

It is evident that later deformation, obviously caused by the revival of convergence of the continental plates in the Middle to Upper Miocene, is related to movements along thrust planes that developed particularly in the lower part of the Vaikrita Slab. It was most pronounced on the Vaikrita Thrust dipping northwards at an angle of 30–45°. This thrust, representing the MCT in Kumaun (Valdiya 1980*a*, *b*, 1981), evolved as the northern part of the Indian crust was sheared following the arrest of movement on the ITS. According to Lyon-Caen & Molnar (1983), the MCT began as a listric fault, detaching the upper crust along a subhorizontal zone in the crust and registering underthrusting of the order of 125 km. The MCT is a wide (*ca.* 5 km) zone of severe shearing and mylonitization on a multiplicity of dislocation planes, giving rise to a conspicuous schuppen zone (Valdiya 1980*a*, *b*). Continued movements along these planes have not only brought the Great Himalayan high-grade metamorphics on to the metasediments and Precambrian sedimentary rocks of the Lesser Himalaya but also lifted the Vaikrita from a zone of ductile deformation to that of brittle deformation (figure 13).

The upward thrusting along the 30–45° northward-dipping Vaikrita Thrust is manifest in the progressive increase in height of the Himadri. Estimated rate of uplift varies from 0.7–0.8 mm a^{-1} (Mehta 1980) to 1.1 mm a^{-1} (Saini 1982). Possibly, the diapiric rise of granitic bodies from deeper levels also contributed to some extent the uplift and increased height of the Himadri peaks. Seismic slip rates of 0.05 mm a^{-1} along the MCT and 0.02 mm a^{-1} along the T-HT deduced by Ye Hong *et al.* (1981) testify to the continuing uplift of the Great Himalaya. However, the majority of epicentres lie just south of the surface trace of the MCT. Excepting a few, almost all fault-plane solutions indicate thrust movements along a 30° north-dipping shallow (10–20 km) plane, quite different from the MCT, but possibly delineating the interface between the underthrusting Indian Plate and the overlying Himalayan mass (Molnar & Chen 1982; Ni & Barazangi 1984).

5. Metamorphic development and thermodynamic conditions

(*a*) *Synkinematic metamorphism*

The uniformity of mineralogical and chemical compositions of the Vaikrita Group is remarkable. Mineral assemblages developed during the early phase of metamorphism are intimately related to folds, foliations and mineral lineations. This early metamorphism probably occurred in the period 70–50 Ma as indicated by the concentration of isotopic mineral dates (K–Ar and Rb–Sr) and fission-track studies (Mehta 1980). The sillimanite–kyanite–garnet–biotite–quartz–felspar (±muscovite) assemblage in the metapelites and

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Description of plate 3

Figure 12. (*a*) Intense mylonitization of the Joshimath (Vaikrita) gneiss in an intraformational shear zone. The streaky gneiss is formed of a row of small isoclinal hinges. Locality: Near the MCT, Ransi, northeast of Ukhimath, Madhyamaheshwar Valley. (*b*) Mylonitized porphyritic granodiorite (augen mylonite) of the Munsiari Fm. Locality: Kalamuni, south of Munsiari, Gori Valley.

Figure 22. Neotectonic evidence discernible in the Kosi Valley (Valdiya 1987*b*).

metapsammites, and the mineral associations of calcite–hornblende–labradorite (An_{50-65})–grossularite and hornblende–diopside–andesine–quartz in the calc-gneisses and calcsilicatefels suggest (figure 10) metamorphism of the Vaikrita Group in the upper amphibolite facies condition within P–T range of 5–5.7 kbar† and 600–650/670 °C (Valdiya & Goel 1983). The intimately associated anatectic granite and migmatites in the upper part of the Vaikrita succession bear testimony to this thermodynamic deduction. The situation is comparable with that prevailing in the Tibetan Slab (Vaikrita) in central Nepal where the Barrovian-type metamorphism occurred at 650–700 °C and 8 kbar, reflecting a normal geothermal gradient compatible with the total thickness of 20–27 km (Pecher & Le Fort 1986). In the east, the Darjeeling Gneiss (lower Vaikrita), recorded the metamorphic conditions of 6.5–7.0 (±0.5) kbar and 570±10 °C to 680±20 °C (Lal *et al.* 1981). The cooling of the Vaikrita metamorphics presumably occurred *ca.* 38 Ma ago as indicated by isotopic studies (^{40}Ar–^{39}Ar) on hornblende from Suraithota in the Dhauli Valley of the study area (D. S. Silverberg, personal communication).

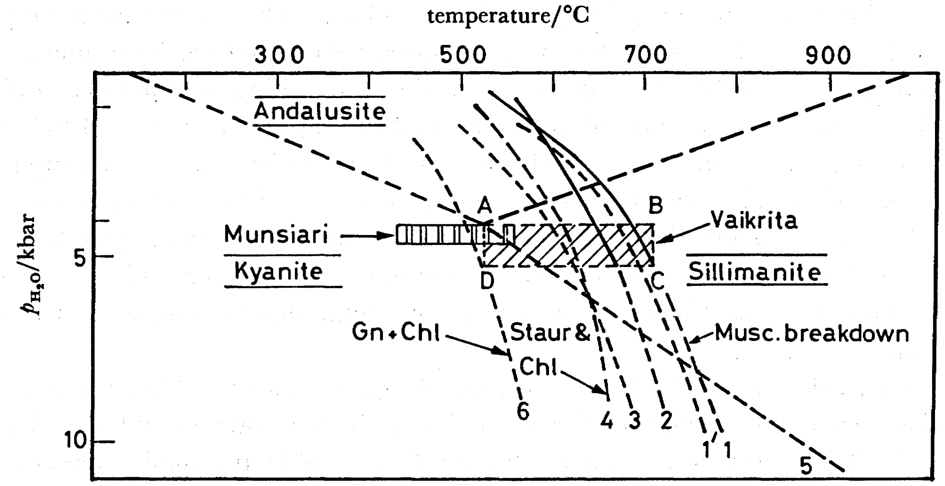

FIGURE 10. The thermodynamic conditions under which the Vaikrita and Munsiari rocks evolved. Curves refer to (1) breakdown of muscovite+quartz, (2) breakdown of staurolite, (3) breakdown of paragonite with quartz, (4) reaction staurolite+chlorite = muscovite+sillimanite+biotite+quartz, (5) Al-silicates and (6) reaction garnet+chlorite+muscovite = sillimanite+biotite. (See Valdiya & Goel 1983.)

Garnet provides an insight into the mode of deformation during late-kinematic phase. Rounded to elliptical garnets (figure 11 *a*, *b*, plate 2) have their elongation coinciding with the mineral lineation, suggesting plastic deformation during flattening normal to foliation. The garnets show two-stage growth manifest in different orientation of inclusions in the core and the rim. Commonly, there is clustering of small-sized inclusions of rounded to subrounded quartz near the core, the margin remaining virtually free (Roy & Valdiya 1988). Significantly, a similar feature was noticed in the garnets of the Himalayan Gneiss (Vaikrita in Nepal) (Arita 1983). In the Tibetan Slab, garnets also show inverse type of zoning: pyrope-rich cores (up to 40% mole) and almandine-rich (up to 70% mole) rim (Pecher & Le Fort 1986).

Muscovite and biotite, occurring in book form and grown discordant to the foliation and lineation, recrystallized during the late-kinematic phase of deformation (Roy & Valdiya 1988).

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† 1 kbar = 10^8 Pa.

(*b*) *Late-tectonic retrograde metamorphism*

As already suggested, the high-grade progressive metamorphism in the Vaikrita Slab, particularly at its base, is overprinted by retrograde metamorphism related to rapid movements on the thrust planes of the MCT zone. The fracturing of porphyroblasts, enmeshing of the porphyroclasts of kyanite, garnet and micas in the phyllonitic matrix, and the stretching and streaking out of constituent minerals (figure 12) including quartz-producing ribbon structure in mylonites are seen in the narrow horizon of the Vaikrita Thrust (MCT) as clearly discernible within a 2 km wide zone between Joti and Gangnani in the Bhagirathi Valley. A similar zone of intense mylonitization (figure 12, plate 3) and pervasive retrogressive metamorphism 0.5–1.0 km in width, occurs further up about 6 km north from the Vaikrita Thrust (MCT), suggesting another shear zone between the Joshimath and Pandukeshwar units.

(*c*) *Anatexis and high-temperature metamorphism*

In the upper part of the Vaikrita succession, early progressive metamorphism is overprinted by high-temperature low pressure metamorphism. This part is intruded extensively by discordant bodies of 28–18 Ma old leucogranite–adamellite and anastomosing dykes and veins of aplite and pegmatite, all intimately associated with widespread migmatization of metapelites. The occurrence of cordierite in the Badarinath area (Gupta 1978, 1980) and of diopside and elongate garnet, kyanite, and sillimanite and orthoclase/microperthite throughout the belt indicate polymetamorphic recrystallization of the Vaikrita rocks. Goel & Bhakuni (1988) mention skarns and anthophyllite–tremolite rocks adjacent to the granite bodies in the Saraswati Valley. There is thus evidence for high-temperature metamorphism overprinting the amphibolite facies assemblages.

The granite is characterized by cordierite, sillimanite, garnet, kyanite, tourmaline, and by a high value of initial strontium ratio (0.743–0.789). They were derived by partial melting of the Vaikrita metamorphics (Powar 1972; Gupta 1978; Valdiya & Goel 1983; Roy & Valdiya 1988) at a depth of 15–30 km (figure 10). The wide range of strontium isotope ratio indicates that a wide variety of rock types of an evolved continent were involved in their genesis. Melting of the crustal material is related to crustal shortening by stacking of thrust nappes in the MCT zone (Windley 1983; Mattauer 1986). It may also be attributed to thrusting of a hot Tibetan Slab over the sedimentary rocks of the Lesser Himalaya that provided fluid necessary to induce partial melting in the overheated slab (Le Fort 1981, 1986). A third possibility is that the accumulation of heat in certain horizons at the top of the Tibetan Slab due to refraction and diversion of heat flux resulting from low thermal conductivity of the Tethyan sediment cover (Jaupart & Provost 1985) caused this heating and resultant differential melting.

The appreciably high concentration of mineral dates (K–Ar, Rb–Sr, fission track) in the periods 40–25 and 20–10 Ma (Mehta 1980) is suggestive of the thermal events leading to anataxis, genesis of granites and attendant late-kinematic thermal metamorphism. That the granitic activity continued even after the main orogenic event, is evident from undeformed intrusives betraying no sign of strains, emplacement of granite in neck zones of boudins in calc-silicate rocks, very young age of the granite of the Kangmar area (6–15 Ma) north of Sagarmatha, and young biotite dates (8.5–3.7 Ma) from the granites in northeastern Nepal.

6. Duplex zone below the MCT

(*a*) *Structure*

Below the MCT (Vaikrita Thrust), lies a thick succession of imbricate thrust sheets evolved in a piggy-back style (Valdiya 1978, 1979, 1980*b*). The schuppen zone (figure 13) is particularly conspicuous and wide in the belt to the west of the Ganga Valley in northern Garhwal (figure 14). Also involved in the tectonics of repeated imbrication are the Lesser Himalayan lithological units of the sedimentary zone, the epimetamorphics associated with basement porphyroids, and the mesometamorphics of the Munsiari Formation at the top. The Munsiari rocks exhibit extreme shearing, mylonitization and related post-crystallization cataclasis. The flattening of mesoscopic folds increases progressively towards the Munsiari Thrust where it is highest (over 60% in the sedimentaries and over 90% in crystalline rocks) (Bhattacharya & Siawal 1985).

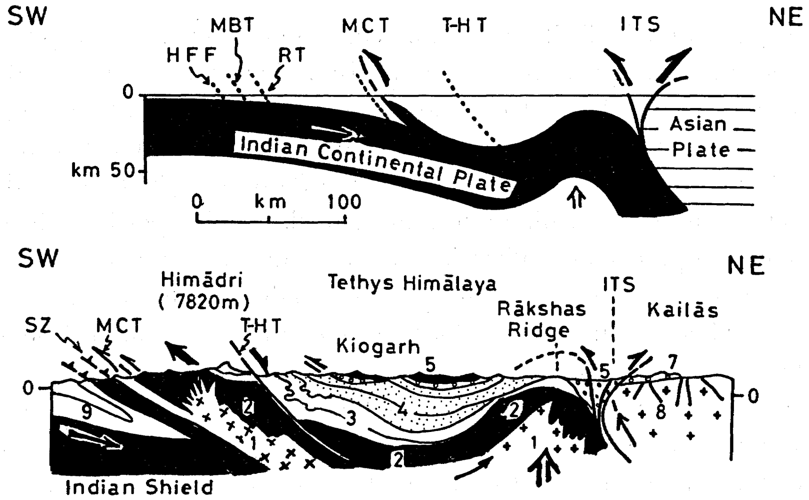

FIGURE 13. The origin of the Main Central Thrust (MCT) and the Trans-Himadri (Malari) Thrust (T-HT) as a result of blocking of movement on the Indus–Tsangpo Suture (ITS) and buoyancy resistance of the Indian Plate to slide under Asia. Numbers: 1, Mid-Tertiary granite; 2, Precambrian Vaikrita crystallines; 3, late Precambrian sedimentary succession; 4, Phanerozoic Tethyan sediments; 5, nappes of ophiolites and ophiolitic mélanges; 6, oceanic trench sediments and seafloor material of the subduction zone; 7, Kailas conglomerate of the back-arc basin; 8, Andean-type magmatic arc (80–45 Ma); 9, Lesser Himalayan Precambrian sediments.

In the duplex system of the area between the Mandakini and Bhagirathi rivers, the crustal shortening resulting from the stacking of nappes is of the order of 55.7% (9.4 km) in the Bhagirathi, 49% (10.9 km) in the Balganga, 82% (34.1 km) in the Bhilangana and 105% (27.9 km) in the Mandakini Valley (Saklani & Bahuguna 1986).

(*b*) *Metamorphism*

The Munsiari consists of mesograde metamorphics, predominant augen gneisses of granodiorite–tonalite parentage and phyllonites. Four samples from the Alaknanda and Bhagirathi Valleys conform to the linear array corresponding to an age of 1950 Ma and reveal small enrichment of radiogenic strontium and low initial strontium ratio of 0.7006 (K. Gopalan, personal communication). Rb–Sr dating by Singh *et al.* (1986) has shown that the gneissic granites of the Munsiari are 1900 ± 100 Ma old and the strontium isotope ratio varying from 0.703 to 0.725, being usually on the lower side.

The sericite–chlorite–quartz and muscovite–chlorite–chloritoid–garnet–quartz assemblages in metapelites and epidote–actinolite–oligoclase (An_{20}) – quartz and epidote–hornblende–andesine (An_{29}) ± quartz in the metabasites suggest greenschist metamorphism (figure 10) taking place at 450–500 °C and 4 kbar (Valdiya & Goel 1983).

There is thus a demonstrable difference in the physical conditions of metamorphism across the MCT (VT) that is also reflected in the morphology and composition of garnets. The Munsiari schist is characterized by synkinematic growth of garnet that shows rotational fabric (figure 11*c*, *d*). Moreover, in sharp contrast to the pyrope–almandine zoning in Vaikrita garnet, the Munsiari garnet shows normal spessartine core and almandine rim (Pecher & Le Fort 1986).

There is no doubt that there is a pronounced metamorphic discordance across the Vaikrita Thrust (MCT).

7. Faulting and thrusting in Lesser Himalaya

(*a*) *Dislocation of autochthonous sedimentary succession*

The larger part of the Lesser Himalayan terrane embodies Lower Riphean to Vendian (late Precambrian) sediments divisible into two groups: the lower flysch and quartzarenite with basic volcanics (Damtha–Jaunsar Groups) and the upper carbonates–shales assemblages (Tejam–Mussoorie Groups) (Valdiya 1964, 1980*a*, 1988*a*). These two groups bear considerable lithological similarity and seem to be homotaxial with the Proterozoic sediments (Martoli–Ralam–Garbyang) of the Tethys Basin. The basal flysch (Rautgara Fm) either rests upon the basement of porphyritic granite (1900 ± 100 Ma old), or perhaps this granite is intruded in the lower part of the sedimentary succession.

The autochthonous subprovince (figures 14 and 15) shows open upright to overturned folds

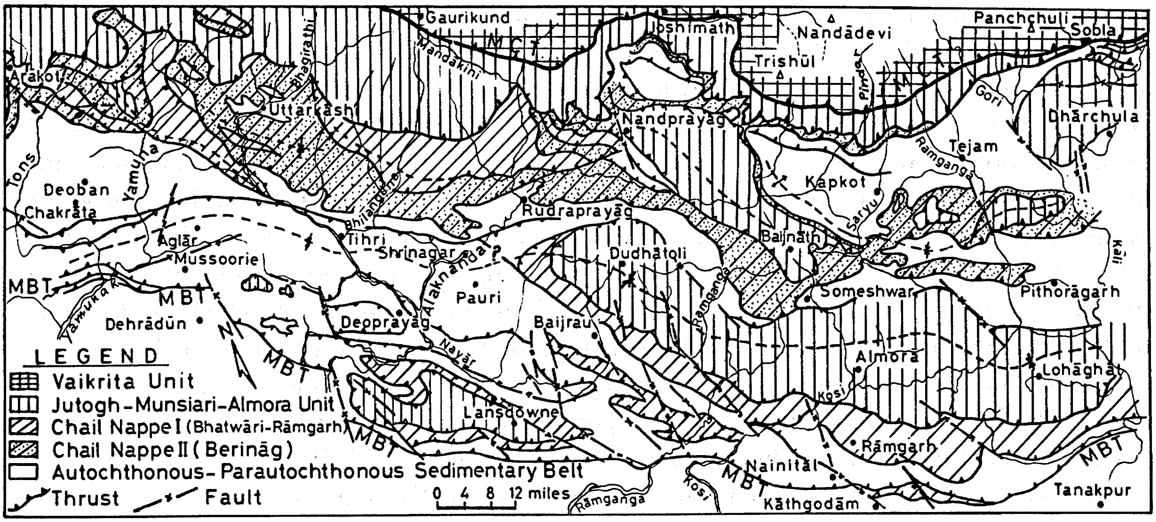

Figure 14. Simplified tectonic map of the Lesser Kumaun Himalaya, delimited by the MCT and the MBT. (Revised and modified after Valdiya 1980*a*, 1981.)

that are locally tight or even isoclinal in the proximity of thrust planes. Immediately to the north of the North Almora Thrust bounding the synclinal nappe of the crystallines, the folds are fan-shaped and extremely tight, where the flattening being as high as 90% (Yedekar & Powar 1986), the sedimentary belt extending from the Indo–Nepal border to the Ganga Valley (Valdiya 1980*a*) has been uplifted to a ruggedly high range over the nappe to the south.

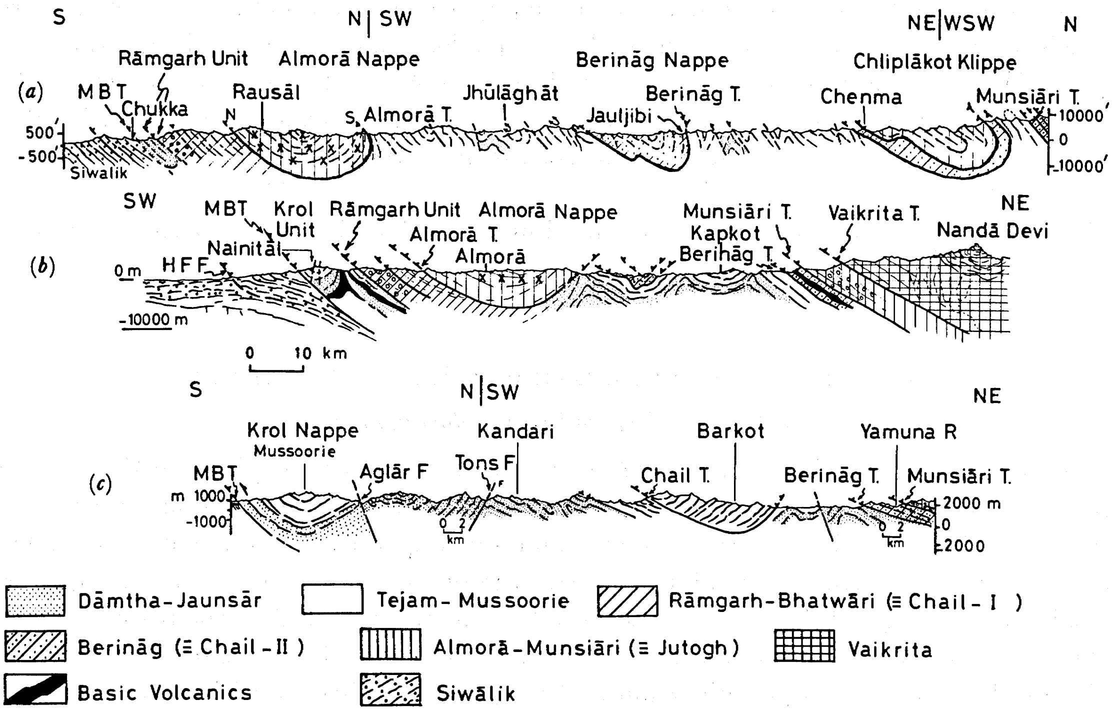

FIGURE 15. Profile of the Lesser Kumaun Himalaya showing in a simplified form the structural architecture of the approximately 20 km thick lithological succession. (Modified after Valdiya 1980*b*.)

Roughly paralleling the South Almora Thrust is another deep fault of considerable tectonic moment called the Ramgarh Thrust (figures 14 and 15), which has brought up a voluminous body of strongly deformed porphyritic granite–porphyry (Debguru Porphyroid) of the basement along with metamorphosed basal flysch (Nathuakhan Fm ≡ Rautgara) to form the northern limb of a west-plunging overturned anticline (figure 16), above the southern limb, that is, the northern flank of the synclinorial Krol Nappe (Valdiya 1987*b*). The porphyritic granite–porphyry of the Ramgarh unit is also old: 1765 ± 60 to 1875 ± 90 Ma with a strontium isotope ratio equal to 0.7335 ± 0.0046, indicating an upper crustal origin (Trivedi *et al.* 1984). My earlier view that the Ramgarh represented an uprooted far-travelled, and granite-implanted Rautgara of the far north (Valdiya 1978, 1981) thus stands modified.

Strongly folded and severely faulted, this vast autochthonous sedimentary pile is dislocated at its southern front and thrust southwards upon the Siwalik along with the porphyritic granite sliced off from the basement (figure 15*a*). The highly tectonized slice or slab of porphyroid represented by the Amritpur Granite in southeastern Kumaun having isotopic age of 1880 ± 40 to 1330 ± 40 Ma (mica ages) (Varadarajan 1978) and of 1584 ± 192 to 1110 ± 131 Ma with a strontium isotope ratio of 0.748–0.741 (Singh *et al.* 1986) is caught in the duplex

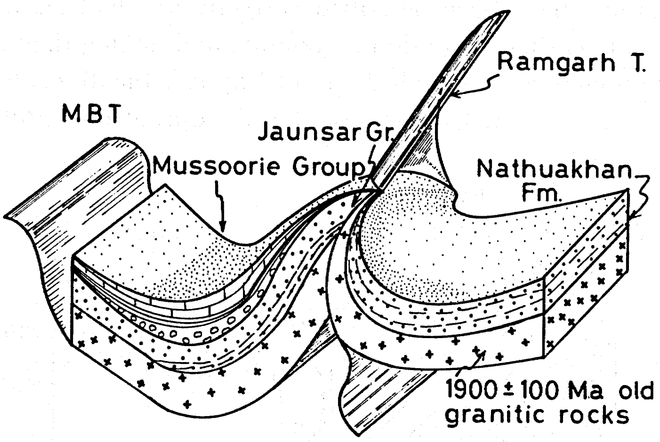

FIGURE 16. Conceptual diagram of a possible shape and structure of the Ramgarh Thrust zone, and faulting up of the basement porphyroids.

structure of the MBT. The dislocated (overthrust) sedimentary succession, the Krol Nappe of Auden (1934, 1937), rides 4–23 km over the Siwaliks in Kumaun. Shah & Merh (1978) and Powar (1980) are of the opinion that the porphyroids form an intrusive body within quartzites and that a part of the Ramgarh unit is really a limb of the Krol succession. However, I regard them to be part of the basement element, which might have remained at a middle crustal level for hundreds of million years, and brought to the surface by thrust faulting.

The intracrustal fault that separates the sub-Himalayan Cainozic subprovince (including the Siwaliks) from the Lesser Himalayan Precambrian rocks has been recognized as the Main Boundary Thrust (Valdiya 1980*b*). In the regional perspective of the Himalaya, the MBT is a series of disparate thrusts which constitutes the tectonic boundary between the two subprovinces. The MBT dips steeply (over 50°) near the surface but flattens to less than 20° at depth. It is characterized by development of 2–7 km wide schuppen zone or duplex made up of imbricate sheets of the Lesser Himalayan formations involved in the severe folding and splitting (figure 17). In some places, wedges and fragments of the granitic basement are caught between the tectonic slabs (Valdiya 1980*b*). The MBT appears to be active seismotectonically and is considered to mark the plane along which the Indian Plate slips beneath the Himalaya.

(*b*) *Uprooted basement and basal units*

The northern part of the sedimentary belt is involved in the duplex tectonics of the MCT. The sedimentary succession below the Munsiari Thrust is severely and repeatedly sliced, giving rise to imbricate stacks of tectonic slabs (Valdiya 1978, 1980*b*, 1981). These slabs are constituted of sedimentary, epimetamorphic and basement gneisses dated 1900 ± 100 Ma; (2120 ± 60 Ma; Raju *et al.* 1982). One of the sheets, the Bhatwari Nappe comprising metamorphosed Rautgara intricately associated with porphyroid, extends westward and joins up with the Chail Nappe (Valdiya 1978) in Himachal Pradesh. The other sheet made predominantly of quartzarenite and intimately associated with penecontemporaneous basic volcanics, covers a vast stretch of the inner Lesser Himalaya in the form of the Berinag Nappe (Valdiya 1979, 1981). These two sheets represent the uprooted and metamorphosed overthrust parts of the lower argillo-arenaceous Damtha Group of the sedimentary succession. The

Bhatwari–Berinag Nappes have been described correctly as Chail Nappes by Fuchs (1980; Fuchs & Sinta 1978). My earlier suggestion correlating and linking the Berinag with the Krol Nappe is apparently untenable. Although the Krol Nappe is the dislocated frontal part of the sedimentary pile, the Berinag–Chail sheets represent the uprooted overfolded back part of the same pile.

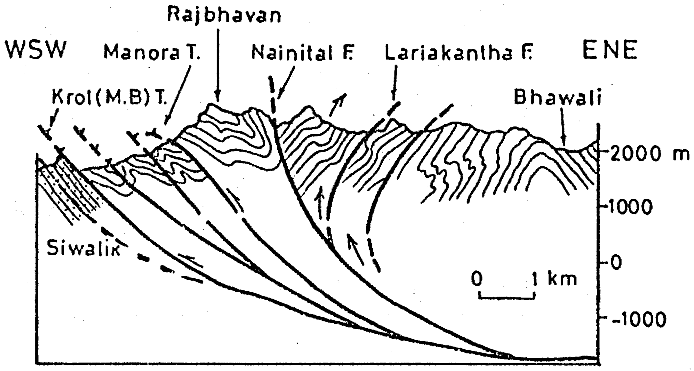

FIGURE 17. The movements along the MBT are transmitted on the thrusts and faults of the schuppen zone of the mountain front (Valdiya 1981).

According to Johnson (1986), the Ramgarh thrust sheet is discontinuous and the separated lenticular masses are horses attached to the base of the Almora–Munsiari sheet at the top of the succession. During the active slip on the basal thrust (or slide of the Munsiari sheet) a lenticular horse 100 km long and less than 9 km thick was cut off from the Ramgarh Formation in the process of 'ramp erosion' on the Munsiari Thrust. This Ramgarh horse has travelled forward for a great distance. Applying the piggy-back model of thrust tectonics, Johnson conceived the evolution of the Lesser Himalayan thrusts in a hinterland-to-foreland sequence in which the Vaikrita Thrust (MCT) developed first, followed in time by the Krol Thrust, the Berinag Thrust and the MBT. According to him, the Lesser Himalaya is underlain by what he called 'Himalayan Frontal Thrust' and which has ramped up towards the surface and has functioned as the sole fault along which the Lesser Himalaya and the Siwaliks have advanced over the foreland.

(*c*) *Far-travelled sheets and tectonic rejuvenation*

The thick pile of mesograde metamorphics of the Almora Nappe (figures 14 and 15) comprises carbonaceous/graphitic schist, garnetiferous mica schists, and amphibolites with concordant gneissose granite bodies (1820 ± 130 Ma and having a Sr isotope ratio of 0.7144 ± 0.0118) at the base and syntectonic tonalite–granodiorite–granite plutons towards the upper part. These later granites are 560 ± 20 Ma old with Sr isotope ratio of 0.7109 ± 0.0013 (Trivedi *et al.* 1984). The Baijnath–Dharamghar–Askot klippen (figures 14 and 15) are made predominantly of the basal augen gneisses (1810 ± 20 Ma old with Sr isotope ratio of 0.7092 ± 0.0015) like the root zone unit the Munsiari (figures 14 and 15), which is constituted dominantly of augen gneisses dated 1830 ± 200 Ma (Sr isotope ratio 0.725), 1890 ± 155 and 1950 ± 200 Ma (Bhanot *et al.* 1977). The Munsiari is thus the much deformed (and compressed) root of the Almora Nappe and its klippen. So far the lower Ordovician granite has not been located in the klippen and the root. The Munsiari extends westward and joins with the Jutogh Nappe of Himachal Pradesh (figure 14).

Significantly, the wide zone of the Almora Nappe exhibits very mature topography recalling those of the Vindhya and Aravali provinces of the Peninsular India. The gentle slopes have thick soil profiles indicating a prolonged period of weathering and tectonic stability until very recent times. The sluggish meandering streams in their wide mature valleys abruptly assume the form of deep gorges, and then descend in rapids or waterfalls as they approach the South Almora Thrust. These features imply resurgent tectonics in subrecent times, and slight northward tilt of the terrane of the Almora crystallines.

8. Evolution of the southern front of Lesser Himalaya

(*a*) *The underthrusting Indian Plate*

The Indian Plate bearing a large prism of the Siwalik molasse at its forefront continues to slide beneath the Lesser Himalaya. The repeated movements over a long period (20 Ma) has caused extremely severe brittle deformation leading to flattening of folds, their splitting along a multiplicity of thrust planes, and stacking of lithotectonic slabs and wedges giving rise to a highly elevated mountain front. Geomorphic features including stream gradient and fluvial and colluvial landforms, eloquently demonstrate continued, albeit episodal, neotectonic activity on the MBT and related faults and thrusts (Valdiya 1981, 1986; Valdiya *et al.* 1984). Uplift (*ca.* 30 m) along the MBT of the Siwalik block (figure 18) in the Nainital area, for example, has not only forced some streams to abandon their old channels but also caused the subrecent fluvial terraces and recent colluvial cones to be cut and differentially uplifted (45–85 m) on the Siwalik side (Valdiya *et al.* 1984; Valdiya 1984*b*, 1986). In some segments the Siwalik has risen up relative to the Lesser Himalaya. Elsewhere it is the Lesser Himalaya that has advanced southward (figure 19) over the deposits as young as the subrecent scree and fluvial gravels (Jalote 1966; Valdiya 1981, 1986, 1987*b*). On the southern slope of the Mussoorie Hills, the subrecent Dun fan has been uplifted (290 ± 76 m) on the Lesser Himalayan side (Nossin 1971). Obviously, the listric thrust has been reactivated as a normal fault in the Nainital area, presumably because of the geometric similarity near the surface between the steeply dipping MBT and a normal fault. The squeezing in of the tectonic slab of the Siwalik adjacent to the MBT has caused rotational movement and uplift of the Siwalik block.

(*b*) *Tear faulting*

The Lesser Himalayan terrane particularly its southern front, is dissected by a large number of tear faults, forming conjugate pairs oriented transverse to the Himalayan trend (Valdiya 1976, 1981, 1988*a*). Following the 'locking' of movement on the MBT, and/or possibly because of differential loading caused by unequal thickness of rock formations, the whole pile of the thrust sheets started deforming by tear faults on fractures oriented transverse to the orogen. Incidently, these fractures and faults are in the line of the basement ridges or promontories of the Peninsular shield extending NNE under the Ganga alluvium and prodding the mountain chain. The tear faults are thus indent-linked strike-slip faults developed particularly in the MBT zone of shortening and attendant uplift.

Many of the transverse tear faults are linked with or become strike faults, as commonly seen in the Nainital Hills (figure 20). In the interior, they are linked with the reactivated weak zone of phyllonites and mylonites (figure 14). For example, in the zone of North Almora Thrust in

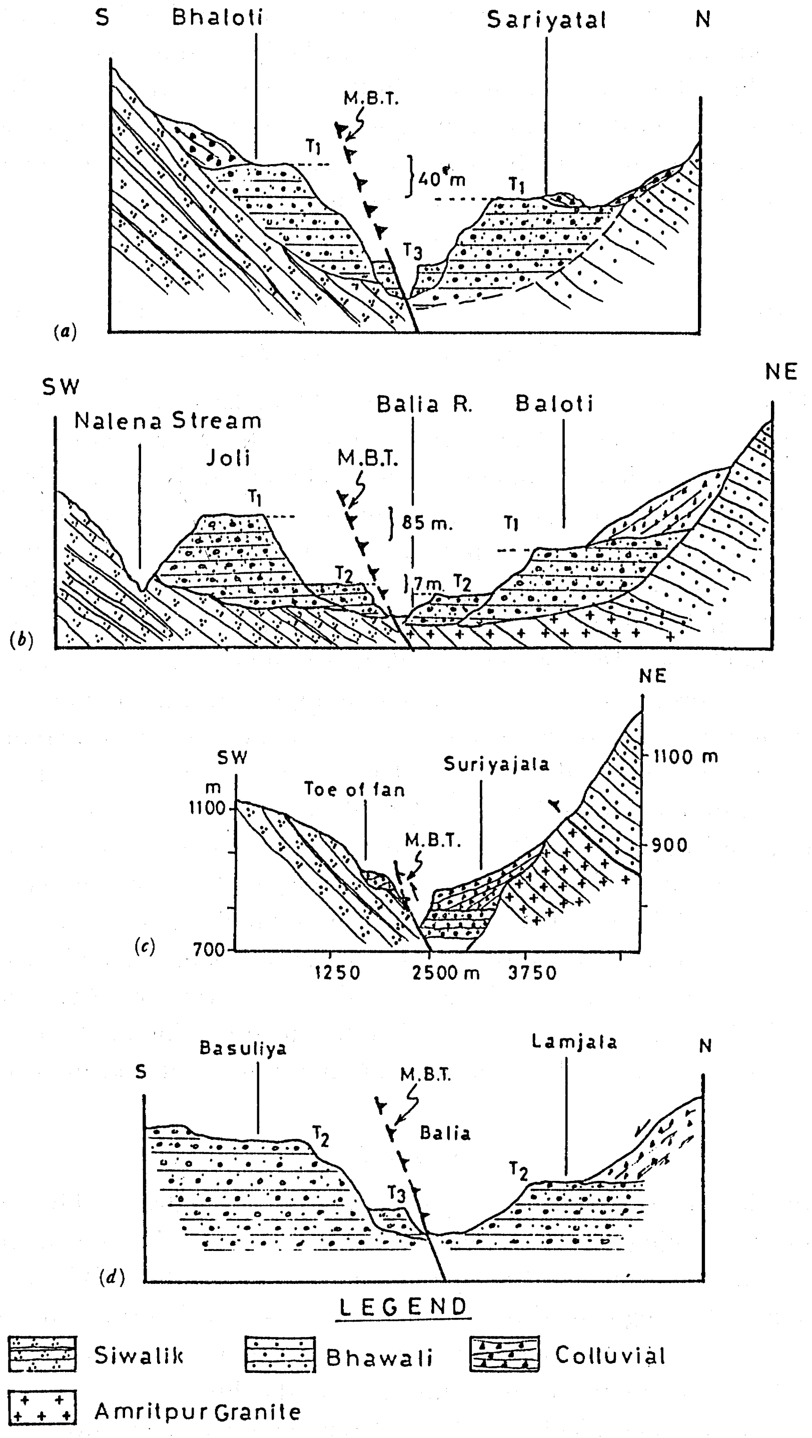

FIGURE 18. A variety of geomorphic features indicate that the MBT is an active fault in the segment SE of Nainital. Where the MBT has been reactivated as a normal fault, the Siwalik has risen up. (After Valdiya *et al.* 1984; Valdiya 1986, 1988*a*.)

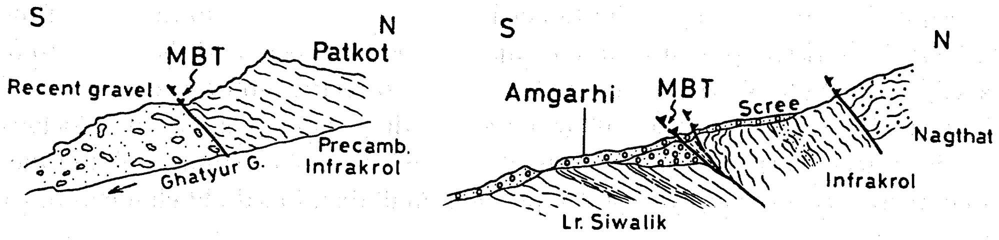

FIGURE 19. In the western segment of the MBT zone in the Nainital Hills, the late Precambrian sediments have advanced over recent fluvial gravels.

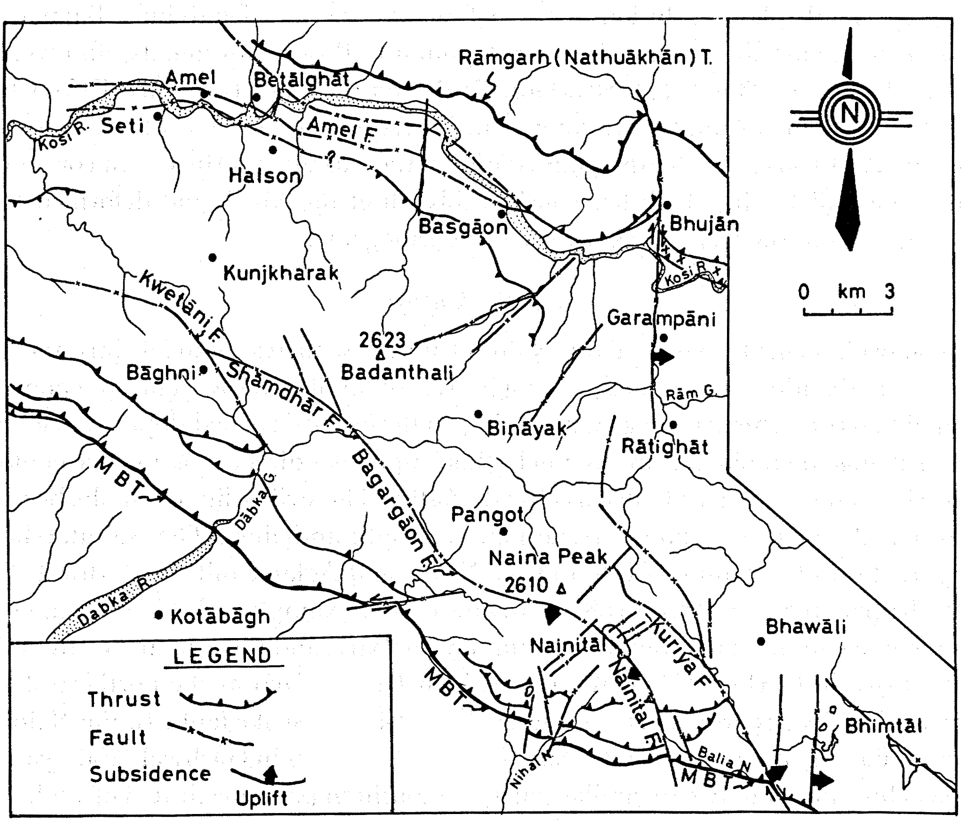

FIGURE 20. The faulted Nainital massif. The tear faults, offsetting even the active MBT, become strike faults along their northwesterly extension. Northeast of the Nainital–Bagargaon Fault, the folds are vergent northwards, whereas to the south they exhibit the normal southwards vergence. (From Valdiya 1988*a*.)

the Saryu Valley in the east and Dwarahat–Chaukhutia belt in the west (Valdiya 1976) where the resurgence of tectonic movements took place episodically along the transition of brittle and ductile rocks. This explains the extreme deformation and elevation of the underlying autochthonous rocks higher than the overthrust sheets of the Almora crystallines.

The tear faults have offset even the very young and still active MBT (late Pliocene to middle Pleistocene) as discernible in the Nainital Hills (figure 20), and in the Dehradun–Haridwar area by distances varying from less than 1 km to more than 12 km. The NNW/N–SSE/S trending faults are predominantly dextral whereas the NNE/NE–SSW/SW oriented ones are sinistral. Neotectonic movements on these wrench faults have caused significant uplift and subsidence of the faulted blocks, giving rise to remarkably elevated transverse spurs in the old mature, deeply dissected terrane of the Lesser Himalaya. The blocks to the west of the NW/N–SE/S faults have risen up relative to the adjacent eastern blocks and the blocks to the west of the NNE/NE–SSW/SW oriented faults have subsided relative to those eastwards (Valdiya 1986). The uplift to the extent of 90–100 m as seen north of Nainital of the fault blocks is borne out by straight steep scarps, waterfalls in the path of winding old streams, uplift of the fluvial deposits characterized by specific clast composition, and abandoned old channels of vanished streams and rivers.

Although the tear faults of the outer Lesser Himalaya, particularly those that are linked with the MBT, have been active, the wrench faults of northern part seem to be seismogenic (Valdiya 1981, 1986). Fault-plane solutions of earthquakes of the Dharchula–Bajang area in northeastern Kumaun, although indicating dominantly thrust movements, do reveal normal faulting in a few cases. The NNW–SSE Gori Fault and the vaguely defined E–W Chhiplakot Fault of this area, for example, are known to be responsible for recent small to moderate earthquakes (Paul 1985). As already pointed out, in the extreme northwestern corner of Nepal, the Humla Karnali Fault, which has considerably offset the MCT and deformed the recent fluvial terraces (Gansser 1977), is known to be seismogenic.

(*c*) *Block uplift*

The geomorphological layout of the Nainital massif with its colluvial fans and cones on hillslopes and abandoned channels, is suggestive of uplift *en bloc*. This phenomenon has precipitated mass movements and gravity sliding on the over-steepened slopes, and forced many a stream to change their old mature channels. Block uplift is a direct consequence of movements along the MBT and many tear faults, as already stated. The strike-slip tear faults become strike faults developed along the axial or crestal planes of tight anticlines. The Nainital–Bagargaon Fault (figure 20) in the Nainital Hills and the Nayar and Aglar Faults in Garhwal (figures 14 and 15*c*) (Rupke 1974; Valdiya 1981) provide classic examples of this phenomenon. This explains the block uplift of the southern mountain ramparts and their great elevation. Possibly, the Tons Thrust in Garhwal (Auden 1937), which I recognized as the northern flank of the Krol Thrust (Valdiya 1980*a*, 1981), is a wrench fault-linked strike fault. In the Nainital Hills, the Nainital–Bagargaon Fault, like the Nayar and Aglar Faults in Garhwal (Valdiya 1981) has split the synclinorium into two dissimilar parts, the southern part constituted of a full succession of sediments comprising groups of argillo-arenaceous and carbonates-shales and characterized by normal south-vergent folds, and the northern part made up of only the lower argillo-arenaceous group of sediments exhibiting pronounced north-vergent folds, resulting presumably from gravity sliding (figure 21).

The northern limit of the Nainital massif is defined by a deep fault of regional extent (Amel Fault) associated with a number of parallel to subparallel strike faults. These faults register differential vertical movements, giving rise to a minigraben and a minihorst in the extraordinarily wide valley of the west-flowing Kosi (figure 20). The Amel Fault continues to be active as evidenced by multiple levels of fluvial terraces, sharply truncated fluvial fans of recent origin (figure 22, plate 3), triangular fault facets devoid of vegetation and lined with colluvial cones at the foot, uplifted (by more than 250 m) channel fills of a river that has vanished or changed course (Valdiya 1987*b*), and debris avalanches of gigantic proportion generated by landslides that repeatedly ravage the terrain.

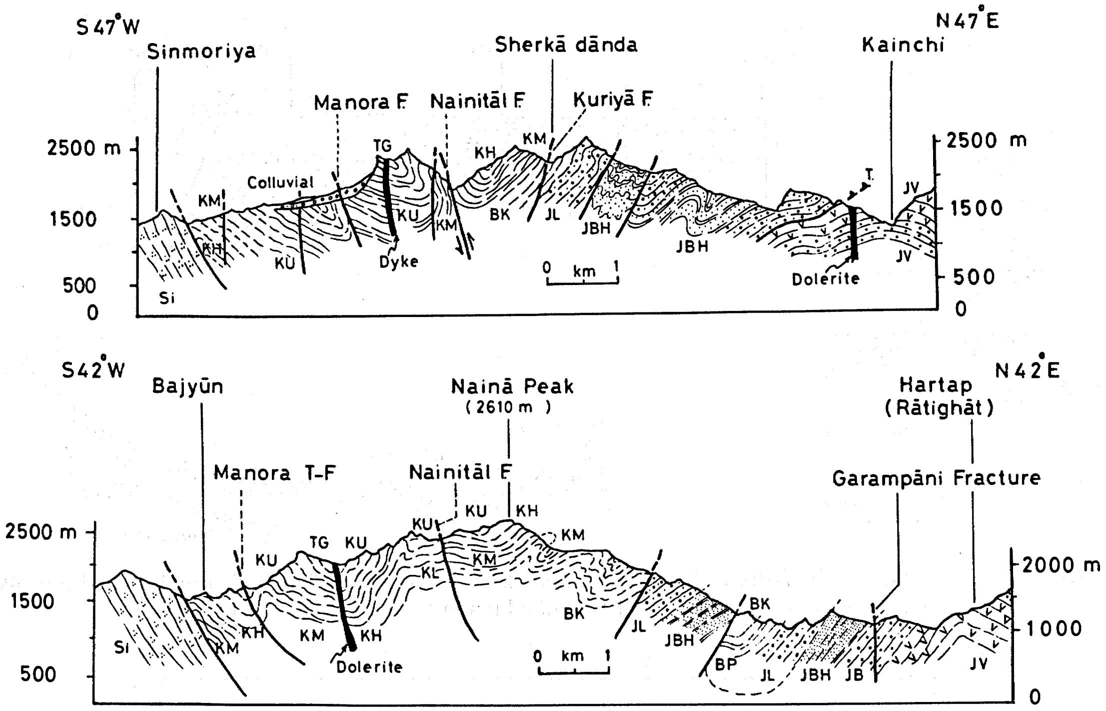

Figure 21. The tear fault-linked strike fault, Nainital Fault, has split the Krol synclinorium into two dissimilar parts. The northern part constituted of only the lower group of the sediments is characterized by north-vergent folds resulting from gravity sliding. The southern part exhibits south-vergent folds. (From Valdiya 1988*a*.)

9. A developing boundary fault

(*a*) *Himalayan Front Fault*

The multicyclic geomorphology of the strongly folded and faulted Siwalik subprovince contrasts sharply with the monocyclic geomorphology of the undeformed Ganga alluvium of Quaternary to Recent age, implying existence of a tectonic break between the two domains (figure 23). The Himalayan Front Fault (HFF) has obliquely truncated the folds and intrabasinal thrusts and eliminated at least two major structural belts of the Siwalik (Valdiya 1984*a*, 1986). The abrupt rise (60 m) in front of the Ganga Plain of the gravel deposits of uppermost Pleistocene to early Holocene age, and their northward tilting (2–6°) as seen in the Dabka and Kosi Valleys (figure 24, plate 4) clearly demonstrate the active nature of the HFF (Nakata 1972; Valdiya 1986, 1988*a*).

Significantly, the Siwalik between the MBT and the HFF is being considerably compressed and thus uplifted at the rate of 0.8 mm a^{-1} in the Dehradun Valley (Chugh 1974). The continuing deformation is evident from the active tear faults connected with the perceptibly active intrabasinal Dhikala–Sarpaduli Thrust in the Ramnagar–Kotabagh area (figure 25). Differential vertical movements along the fault by as much as 20–30 m have given rise to depressions and rises within the basin in the Dehradun area (Nakata 1972; Rao 1977). The depressions have been rapidly filled up by great volumes of gravel deposits of Holocene to Recent age.

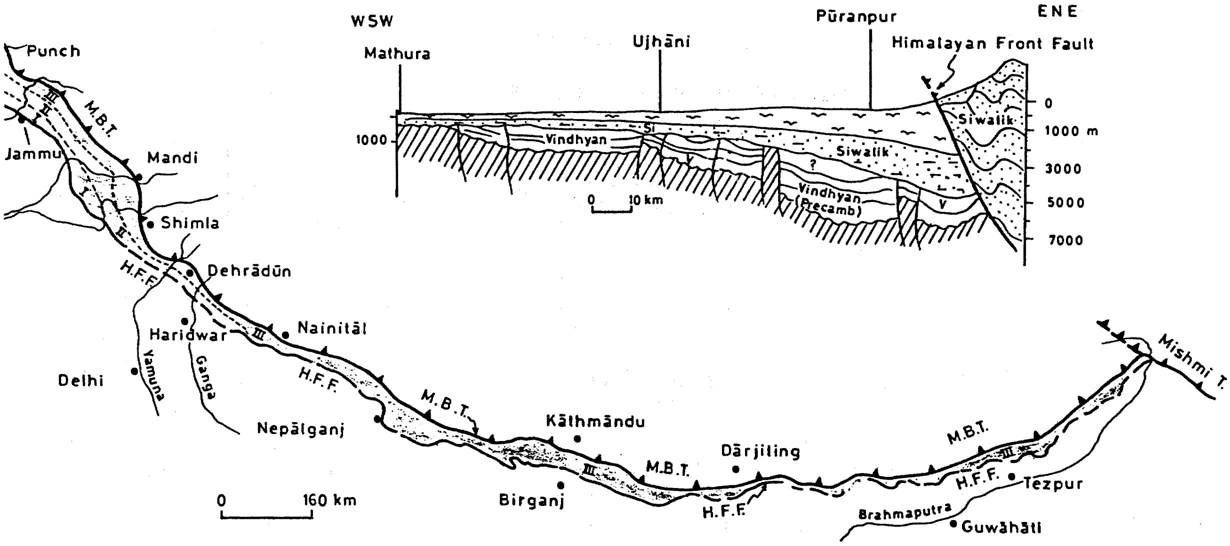

Figure 23. The location of the HFF, delimiting the Siwalik from the plains. The folded and faulted Siwalik is defined against the undeformed Ganga alluvium by the Himalayan Front Fault.

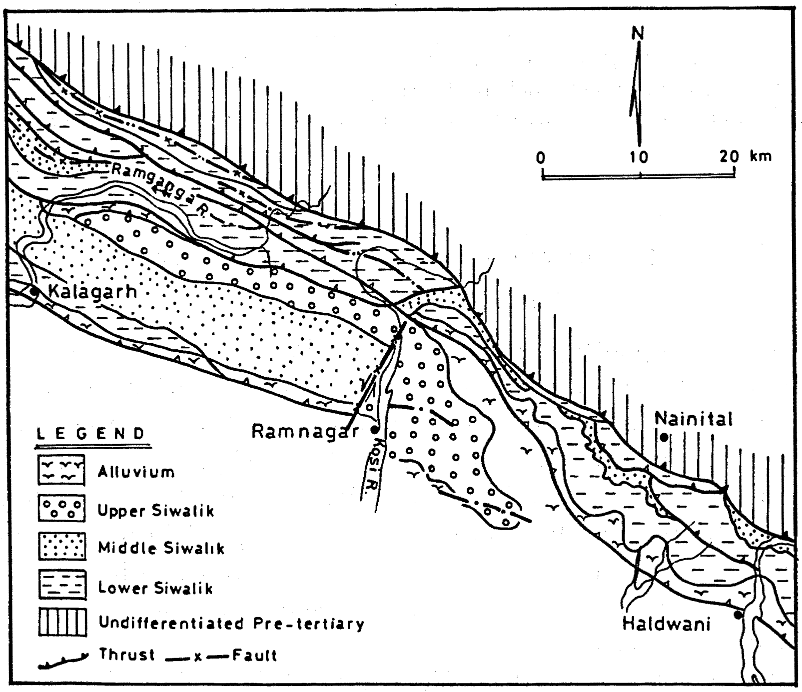

Figure 25. The continuing neotectonic activity in the Kotabagh–Ramnagar belt is evident from, among other things, advance of the Siwaliks over recent alluvial cover and the formation of intrabasinal depressions and rises due to normal faults. The depressions have been filled up by subrecent to recent gravel deposits and given rise to flat 'duns'.

(b) *Shifting belt of deformation*

Looking back into the history of evolution of the Himalaya, it is realized that along with the basin of sedimentation, the belt of deformation has progressively shifted southwards through the time. As the foreland basin of the early Tertiary (Subathu, Dagshai–Kasauli) was deformed in the middle Miocene times, another foreland basin (Siwalik) evolved south of the MBT.

Possibly the flexing down of the Indian lithospheric plate under the load of Himalaya created the foredeep basin. The middle Pleistocene saw deformation and attendant crustal shortening of the Siwalik and formation of the third foreland basin to its south: the Ganga Basin. The logical culmination of the continuing northward push of the Indian Shield would be the deformation of the Ganga Basin sediments and southward advance of the Siwaliks along the delimiting HFF, which will eventually assume the attitude of a listric thrust.

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References

Arita, K. 1983 *Tectonophysics* **95**, 43–60.

Auden, J. B. 1934 *Rec. geol. Surv. Ind.* **67**, 357–454.

Auden, J. B. 1937 *Rec. geol. Surv. Ind.* **71**, 407–435.

Bhanot, V. B., Singh, V. P., Kansal, A. K. & Thakur, V. C. 1977 *J. geol. Soc. India* **18**, 90, 91.

Bhattacharya, A. R. & Siawal, A. 1985 *Geologie Mijnb.* **63**, 159–165.

Chugh, R. S. 1974 Presented at Int. Symp. Recent Crustal Movements. Zurich. (Unpublished.)

Fuchs, G. 1980 In *Stratigraphy and correlations of the Lesser Himalayan Formations* (ed. K. S. Valdiya & S. B. Bhatia), pp. 163–173. Delhi: Hindustan Publishing Corp.

Fuchs, G. R. & Sinha, A. K. 1978 *Jb. geol. Bundesanst, Wein* **121**, 219–241.

Gansser, A. 1964 *Geology of the Himalayas.* (289 pages.) London: Interscience Publishers.

Gansser, A. 1974 *Eclog. geol. Helv.* **67**, 479–507.

Gansser, A. 1977 In *Himalaya, Mem. Sciences de la Terre* no. 268, pp. 181–192. Paris: CNRS.

Goel, O. P. & Bhakuni, S. S. 1988 *Contr. Miner. Petr.* (In the press.)

Gupta, L. N. 1978 *Himalayan Geol.* **8** (II), 717–727.

Gupta, L. N. 1980 In *Structural geology of the Himalaya* (ed. P. S. Saklani), pp. 59–74. New Delhi: Today & Tomorrow Publishers.

Hagen, T. 1956 *Geographica helv.* **5**, 217–219.

Heim, A. & Gansser, A. 1939 *Central Himalaya, Geological Observations of the Swiss Expedition, 1936.* In *Mem. Soc. Helv. Sci. Nat.* **73** (1), 1–245.

Herbert, G. D. 1942 *J. Asiat. Soc. Beng.*, p. 11.

Jalote, P. M. 1966 In *Proc. Third. Symp. Earthquake Engineering*, pp. 455–458. Roorkee: University of Roorkee.

Jaupart, C. & Provost, A. 1985 *Earth planet. Sci. Lett.* **73**, 385–397.

Johnson, M. R. W. 1986 In *Himilayan thrusts and associated rocks* (ed. P. S. Saklani), pp. 27–39. New Delhi: Today & Tomorrow Publishers.

Lal, R. K., Mukherji, S. & Ackermand, D. 1981 In *Metamorphic tectonites of the Himilaya* (ed. P. S. Saklani), pp. 231–278. New Delhi: Today & Tomorrow Publishers.

Le Fort, P. 1981 *J. geophys. Res.* **86**, 10545–10568.

Le Fort, P. 1986 In *Collision tectonics* (ed. M. P. Coward & A. C. Ries), pp. 159–172. London: Geological Society.

Le Fort, P., Debon, F., Pecher, A., Sonet, J. & Vidal, P. 1986 In *Orogenic evolution of Southern Asia* (Mem. Sci. Terre), pp. 191–209. Paris: CNRS.

Lyon-Caen, H. & Molnar, P. 1983 *J. geophys. Res.* **88**, 8181–8191.

Mattauer, M. 1986 In *Collision tectonics* (ed. M. P. Coward & A. C. Ries), pp. 37–50. London: Geological Society.

Mehta, P. K. 1980 *Tectonophysics* **62**, 205–217.

Molnar, P. & Chen, W. P. 1982 In *Mountain building processes* (ed. U. Briegel & K. J. Hsu), pp. 41–57. New York: Academic Press.

Nakata, T. 1972 *Geomorphic history and crustal movements of the foothills of Himalaya*, pp. 39–177. Tohoku University: Institute of Geography.

Ni, J. & Barazangi, M. 1984 *J. geophys. Res.* **89**, 1147–1163.

Nossin, J. J. 1971 *Z. Geomorph.* **12**, 18–50.

Paul, S. K. 1985 Ph.D. thesis: Kumaun University, Nainital.

Pecher, A. & Le Fort, P. 1986 In *Orogenic evolution of southern Asia* (ed. P. Le Fort, M. Colchen & C. Montenat), Mem. Sci. Terre no. 47, pp. 285–309. Paris: CNRS.

Pham, V. N., Boyer, D., Therme, P., Yuan, X. C., Li, L. & Jin, G. Y. 1986 *Nature, Lond.* **319**, 310–314.
Powar, K. B. 1972 *Himalayan Geol.* **2**, 34–46.
Powar, K. B. 1980 In *Stratigraphy and correlations of the Lesser Himilayan Formations* (ed. K. S. Valdiya & S. B. Bhatia), pp. 49–58. Delhi: Hindustan Pub. Corp.
Raju, B. N. V., Bhabria, T., Prasad, R. N., Mehadevan, T. M. & Bhalla, N. S. 1982 *Himalayan Geol.* **12**, 196–205.
Rao, D. P. 1977 *Photonirvachak* **5**, 5–40.
Roy, A. B. & Valdiya, K. S. 1988 *J. geol. Soc. India* **31**. (In the press.)
Rupke, J. 1974 *Sedim. Geol.* **11**, 81–265.
Saini, V. S. 1982 *Proc. Indian Acad. Sci.* **148**, 539–540.
Saklani, P. S. & Bahuguna, V. K. 1986 In *Himalayan thrusts and associated rocks* (ed. P. S. Saklani), pp. 1–25. New Delhi: Today & Tomorrow Publishers.
Shah, O. K. & Merh, S. S. 1978 *J. geol. Soc. Ind.* **19**, 91–105.
Singh, R. P., Singh, V. P., Bhanot, V. B. & Mehta, P. K. 1986 *Indian J. Earth Sci.* **13**, 197–208.
Singh, V. P., Singh, R. P. & Bhanot, V. B. 1986 *Indian J. Earth Sci.* **13**, 189–196.
Strachey, R. 1851 *Q. Jl geol. Soc. Lond.* **7**, 292–310.
Thakur, V. C. & Chaudhury, B. K. 1983 In *Himalayan shears* (ed. P. S. Saklani), pp. 45–57. New Delhi: Himalayan Books.
Trivedi, J. R., Gopalan, K. & Valdiya, K. S. 1984 *J. geol. Soc. India* **25**, 641–654.
Valdiya, K. S. 1964 In *Report 22nd Int. Geol. Congr.*, vol. 11, pp. 15–36. Calcutta: Geological Survey of India.
Valdiya, K. S. 1976 *Tectonophysics* **32**, 353–386.
Valdiya, K. S. 1978 *Indian J. Earth Sci.* **5**, 1–19.
Valdiya, K. S. 1979 *J. geol. Soc. India* **20**, 145–157.
Valdiya, K. S. 1980*a* *Geology of Kumaun Lesser Himalaya.* (291 pages.) Dehradun: Wadia Institute of Himilayan Geology.
Valdiya, K. S. 1980*b* *Tectonophysics* **66**, 323–348.
Valdiya, K. S. 1981 In *Zagros–Hindukush–Himalaya: geodynamic evolution* (ed. H. K. Gupta & F. M. Delaney), pp. 87–110. Washington, D.C.: American Geophysics Union.
Valdiya, K. S. 1984*a* *Tectonophysics* **105**, 229–248.
Valdiya, K. S. 1984*b* *Aspects of tectonics: focus on South-Central Asia.* (319 pages.) New Delhi: Tata–McGraw-Hill.
Valdiya, K. S. 1984*c* In *Proc. Colloquium Tectonics of Asia, 27th Inter. Geol. Congr.*, Moscow, pp. 110–137.
Valdiya, K. S. 1986 In *Proceedings Intern. Symp. Neotectonics in South Asia*, pp. 241–267. Dehradun: Survey of India.
Valdiya, K. S. 1987 *Curr. Sci.* **56**, 200–209.
Valdiya, K. S. 1988*a* *Geology and natural environment of Nainital Hills.* Nainital: Gyanodaya Prakashan.
Valdiya, K. S. 1988*b* *Geol. Soc. Am. Spec. Publ.* (In the press.)
Valdiya, K. S. & Goel, O. P. 1983 *Proc. Indian Acad. Sci.* **92**, 141–163.
Valdiya, K. S. & Gupta, V. J. 1972 *Himalayan Geol.* **2**, 1–34.
Valdiya, K. S., Joshi, D. D., Sanwal, R. & Tandon, S. K. 1984 *J. geol. Soc. India* **25**, 761–774.
Varadarajan, S. 1978 *J. geol. Soc. India* **19**, 380–381.
Windley, B. F. 1983 *J. geol. Soc. Lond.* **140**, 849–865.
Ye Hong, Zhang Wen-Yu, Zhi-Shui & Xia Qin 1981 In *Geological and ecological studies of Qinghai-Xizang Plateau*, vol. 1, pp. 65–80. Beijing: Science Press.
Yedekar, D. B. & Powar, K. B. 1986 In *Himalayan thrusts and associated rocks* (ed. P. S. Saklani), pp. 41–69. New Delhi: Today & Tomorrow Publishers.
Zhou-Yun-Sheng, Zhang Qi, Jim Cheng-Wei & Deng Wan-Ming 1981 In *Proc. Symp. Quinghai-Xizang Plateau*, vol. 1, pp. 363–378. Beijing: Science Press.

Note added in proof (*25 April* 1988). The 'Trans-Himadri Thrust' is a normal detachment fault in a large part of its extent in the northwestern and central sectors but is a thrust in the eastern part.

Discussion

V. S. Cronin (*Department of Geology, and Center for Tectonophysics, Texas A&M University, Texas, U.S.A.*). Professor Valdiya noted a right-lateral component of displacement on the Main Boundary Thrust and on other faults with a northwest trend in northern India (Valdiya 1976, 1981). The oblique convergence of India with the western Himalaya suggests the possibility of a right-lateral sense of shear within the western part of the Himalayan thrust prism. What is his current thinking related to strike-slip displacements in the Himalaya?

The Karakoram Fault is a right-lateral strike-slip fault that is currently active and separates the Karakoram–Himalaya Mountains from the Kun Lun in western Tibet. Total displacement along the Karakoram Fault is thought to be *ca.* 200–250 km (Srimal 1983). The Karakoram Fault is commonly depicted on regional maps as merging with the Indus–Tsangpo Suture Zone. Does Professor Valdiya have any field data that might indicate how displacement along the Karakoram Fault is accommodated by other structures along its southeastern end? Is there evidence for right-lateral faulting along the Indus–Tsangpo Suture Zone?

Reference

Srimal, N. 1983 *Geol. Soc. Am., Abstr. Progr.* **15**, 694.

K. S. Valdiya. I have already expressed my views in my papers (Valdiya 1976, 1981, 1984*b*, 1986).

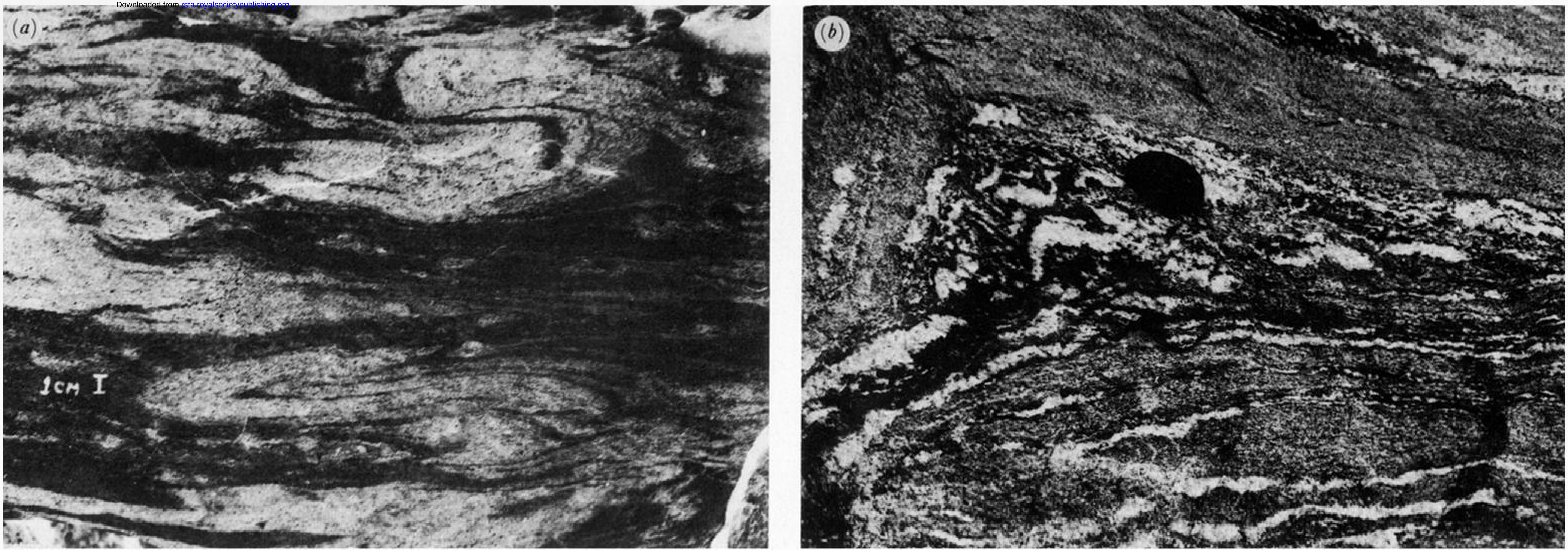


FIGURE 8. Folds of the earliest deformation. (*a*) Negative print of coaxially folded early isoclines (F_1A) evincing hook-shaped geometry in the calc-silicate material (light), which is replaced partly by leucogranite (dark). Locality 5 km north of Suraithota, Dhauli Valley. (*b*) F_1B fold with axial plane at high angles to the F_1A isoclines. A decollement separates the folds of the two types. Locality 1 km south of Rambara, Mandakini Valley.

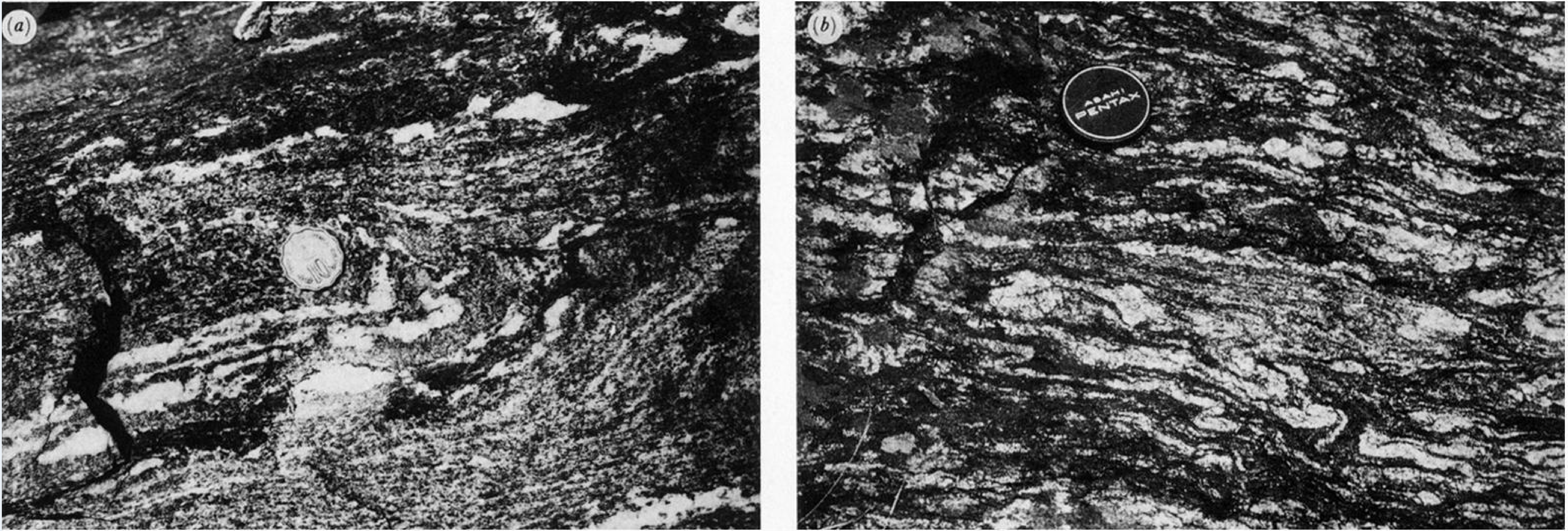
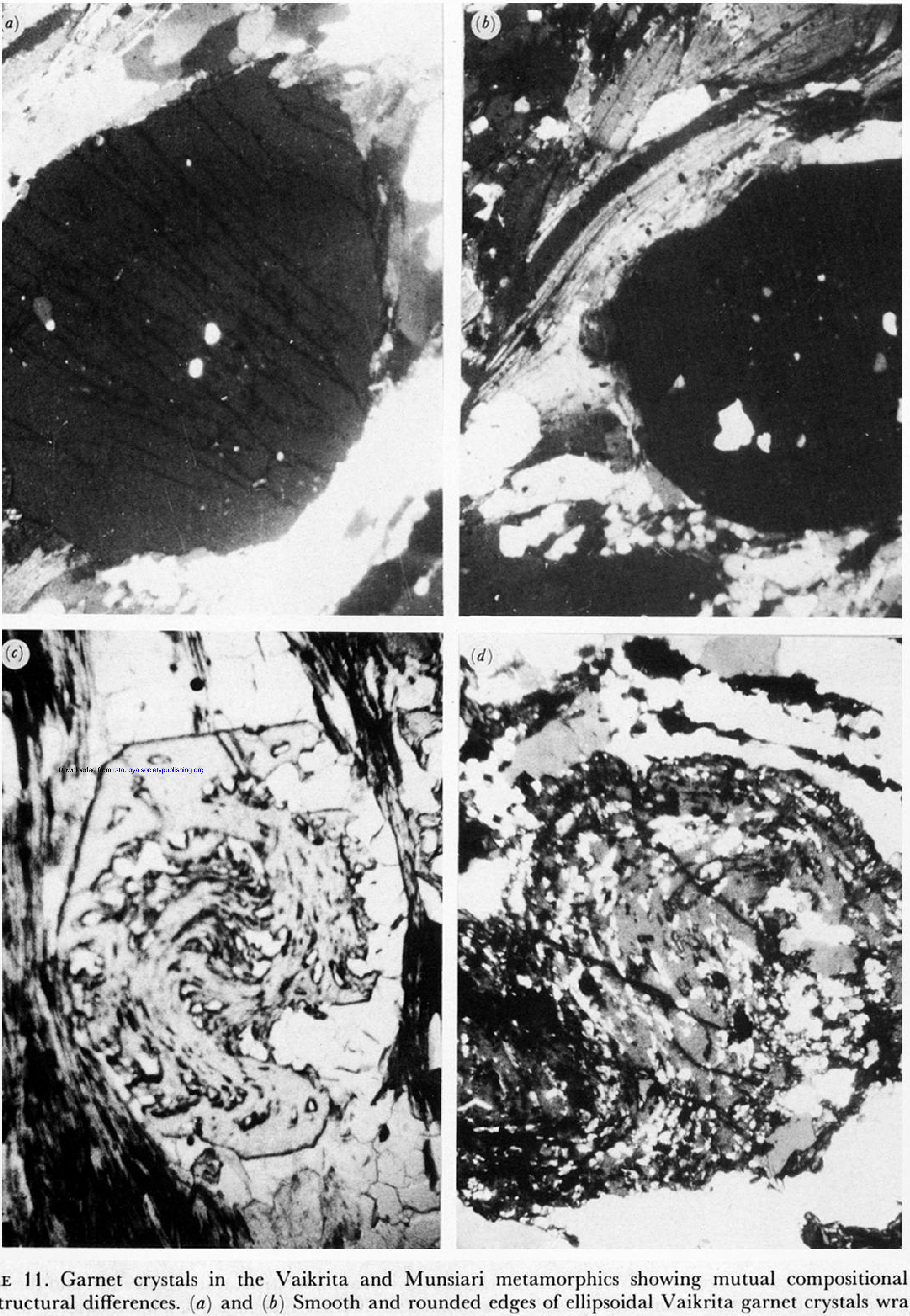


FIGURE 9. Folds of later deformation. (*a*) Isoclinal F_2A folds with detached lower limbs, showing updip movement. Locality Rambara, Mandakini Valley. (*b*) Small-scale rootless isoclinal folds, some hook-shaped, within thin layers of psammites. Locality Dabrani, Bhagirathi Valley.



IGURE 11. Garnet crystals in the Vaikrita and Munsiari metamorphics showing mutual compositional and structural differences. (*a*) and (*b*) Smooth and rounded edges of ellipsoidal Vaikrita garnet crystals wrapped around by mica flakes. The core and rim show different kinds of inclusions. Locality: Dabrani, Bhagirathi Valley. (*c*) and (*d*) The Munsiari garnet, in contrast, is rotated and characterized by sigmoidal inclusion trails. Locality: Kyarkikhal, Bhilangana Valley. (Photos by S. S. Bhakuni.)

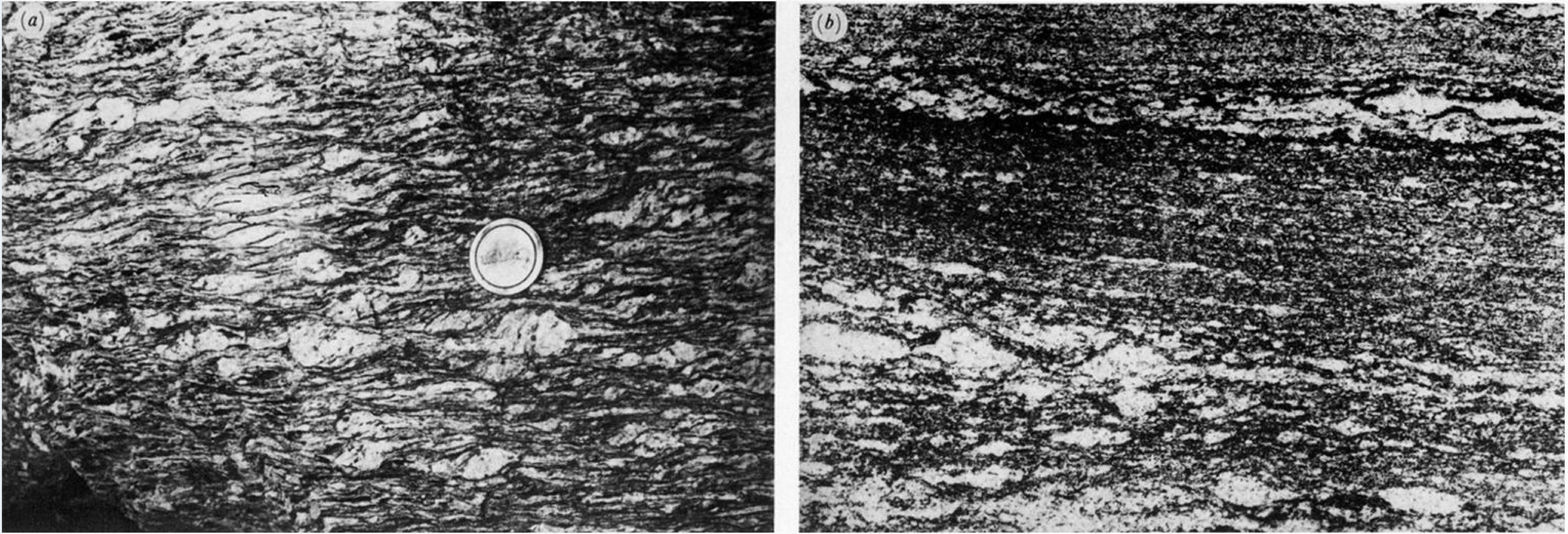


FIGURE 12. (*a*) Intense mylonitization of the Joshimath (Vaikrita) gneiss in an intraformational shear zone. The streaky gneiss is formed of a row of small isoclinal hinges. Locality: Near the MCT, Ransi, northeast of Ukhimath, Madhyamaheshwar Valley. (*b*) Mylonitized porphyritic granodiorite (augen mylonite) of the Munsiari Fm. Locality: Kalamuni, south of Munsiari, Gori Valley.

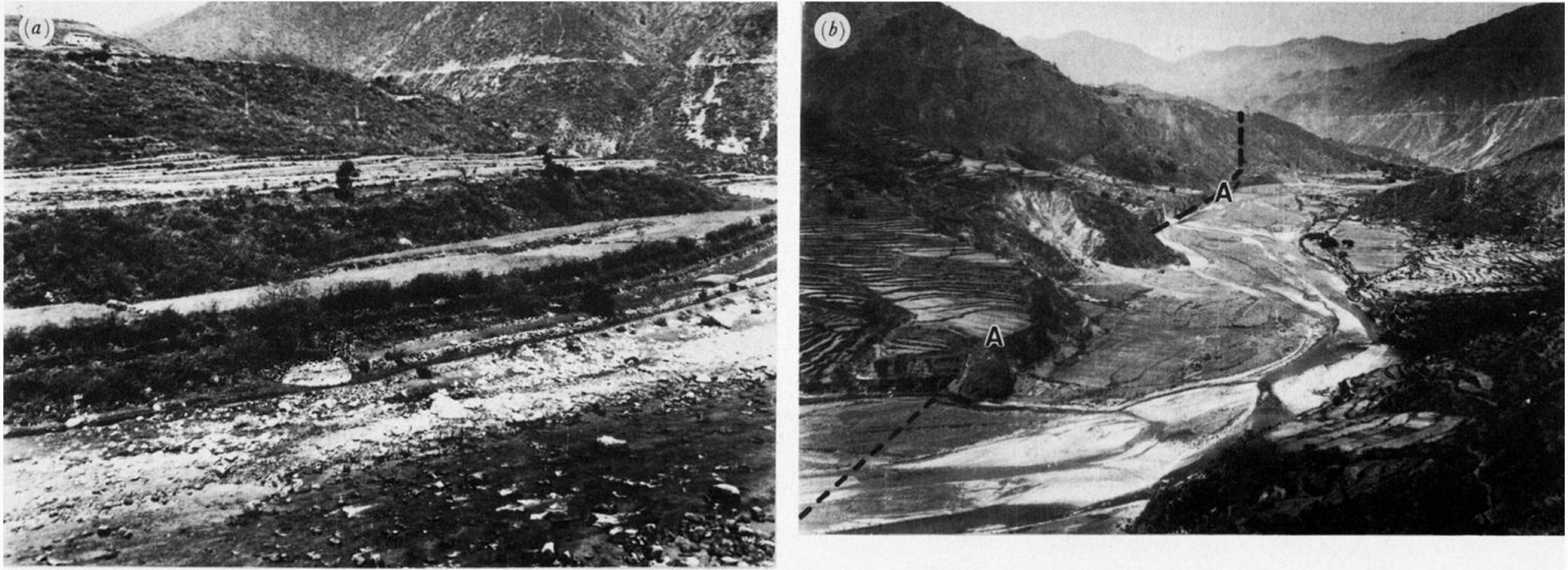


FIGURE 22. Neotectonic evidence discernible in the Kosi Valley (Valdiya 1987*b*).

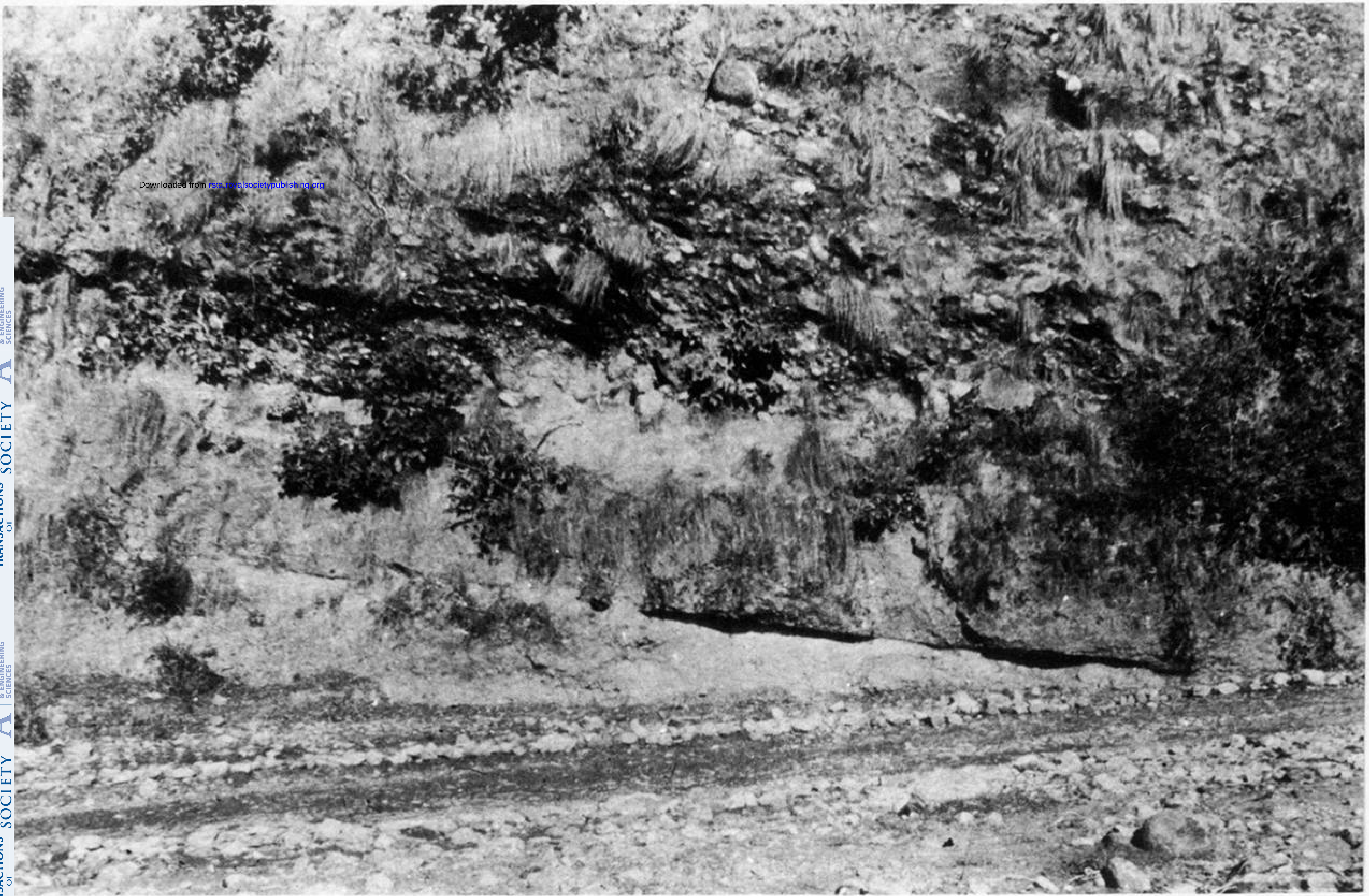


FIGURE 24. The northward tilted (2–6°) uppermost Pleistocene to early Holocene gravel deposits in the Dabka Valley.