Toward a solution for the Himalayan puzzle: Mechanism of inverted metamorphism constrained by the Siwalik sedimentary record

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Since the mid-19th century, inverted sequence ('hot-side-up') of metamorphic rocks in the Himalaya has formed a controversial subject, which has drawn an increasing attention in recent years. Models to explain this phenomenon are either 'thermal' (a heating event in the middle to upper parts of the crust directly responsible for the inverted metamorphism) or 'structural' (tectonic disruption of a normal metamorphic sequence). Data on the heavy-mineral analysis of the Siwalik sedimentary rocks derived from the Himalaya are consistent with 'structural' models. Metamorphic index minerals preserved in the Siwaliks record successive denudation of lower- to higher-grade metamorphic rocks of the Himalaya preserved in the Lower through Upper Siwalik sediments, suggesting differential denudation of metamorphic zones in the Himalaya over the past 18 million years. We argue that this pattern of denudation and deposition, in conjunction with other geological and theoretical considerations, constrains a plausible 'structural' model for the inverted metamorphism in the Himalaya, according to which the apparent inversion of metamorphic sequence was a product of differential uplift and denudation of metamorphic zones probably related to imbricate thrusting and internal ductile shearing of the metamorphic rocks in a collisional tectonic setting.

MOUNTAIN building (orogenesis) encompasses a complex set of changes in rocks both at depth (metamorphism, magmatism and structural deformation) and on the surface (uplift and denudation). The process of regional metamorphism in mountain belts such as the Himalaya requires heat and pressure, and as such, degree of metamorphism should normally increase from top to bottom in the Earth's crust (i.e. a 'hotside-down' sequence). One of the long-recognized and long-standing problems in Himalayan geology has been an actual explanation for the 'inverted' ('reversed' or 'hotside-up') metamorphism observed in various sections of the Himalayan orogen[1]. Although this controversial aspect of Himalayan geology has received much attention over the past two decades, the subject is more than a century old. Mapping of the Himalayan metamorphic terrain by geologists in the Calcutta-based Geological Survey of India during the second half of the 19th century demonstrated that the degree of metamorphism increases from the bottom upward the topographic (and structural) levels. Impressed by his observation of the inverted metamorphism in the Garhwal Himalaya, Richard Oldham[2] in 1883 remarked that 'this is but part of the great Himalayan puzzle'.

Understanding the cause(s) of this phenomenon is undoubtedly important for unraveling the metamorphic and tectonic evolution of the Himalaya. However, its significance is not limited to the Himalaya. Inverted metamorphism has been found in several other mountains; for example, in the North American Cordillera (California), the Scandinavian Caledonides, the European Alps and the Sanbagawa metamorphic belt of Japan. Although inverted metamorphism can be brought about by various processes in different orogens, studies of the Himalayan inverted metamorphism provide better clues to tackle these problems because mountain building in the Himalaya is quite young (and indeed still active) and thus various models can be separated and tested with better accuracy than in ancient orogens, and also because Himalayan geology enjoys a rich tradition of concepts and data pertaining to inverted metamorphism. It is thus surprising to hear from St-Onge[3] that 'Tilley (1925) in his classic account of the metamorphic zones of the Southern Highlands of Scotland, was probably the first to recognize the existence of an inverted metamorphic zonation'.

This paper offers a new approach to constraining the cause(s) of inverted metamorphism in the Himalaya. Rather than merely relying on studies of metamorphic rock assemblages and structures presently seen in the Himalayan mountains (which has been done by numerous authors in the past), this new approach utilizes the erosion record of the Himalayan metamorphic terrain as preserved in the foreland sediments (the Siwalik Group) to shed light on the models proposed for the Himalayan inverted metamorphism. At first, however, a brief review of various models proposed for the Himalayan inverted metamorphism is necessary for our discussion.

Models of inverted metamorphism

Figure 1 shows a geological map of the Himalayan orogen with the following divisions from north to south:

(i) The Trans-Himalayan and Kohistan-Ladakh Batholith (Cretaceous–Eocene); (ii) the Indus–Tsangpo Suture Zone, marking the initial plate boundary between the Indian and Asian tectonic plates along which the Tethys ocean closed; (iii), the Tethys Himalaya representing the Cambrian–Eocene marine sediments of the Tethys deposited on the northern margin of the Indian plate; (iv) the Higher Himalayan Crystalline Complex, composed of amphibolite-facies metamorphic rocks and Tertiary granites; (v) the Lesser Himalaya consisting of Precambrian–Paleozoic sediments and low-grade metasediments and various pre-Himalayan granites; and (vi) the Sub-Himalaya (or the Siwalik Hills) containing freshwater sediments of Cenozoic age deposited in the foreland basin of the Himalaya. These lithotectonic divisions are bounded by large scale faults (Figure 1). Of these, the most relevant structure to our discussion is the Main Central Thrust (MCT) which has brought the Higher Himalaya over the Lesser Himalaya, although its location in various parts of the Himalaya has been controversial[4,5].

The rocks of the Tethys Himalaya and the Sub-Himalaya are essentially unmetamorphosed. The phe-

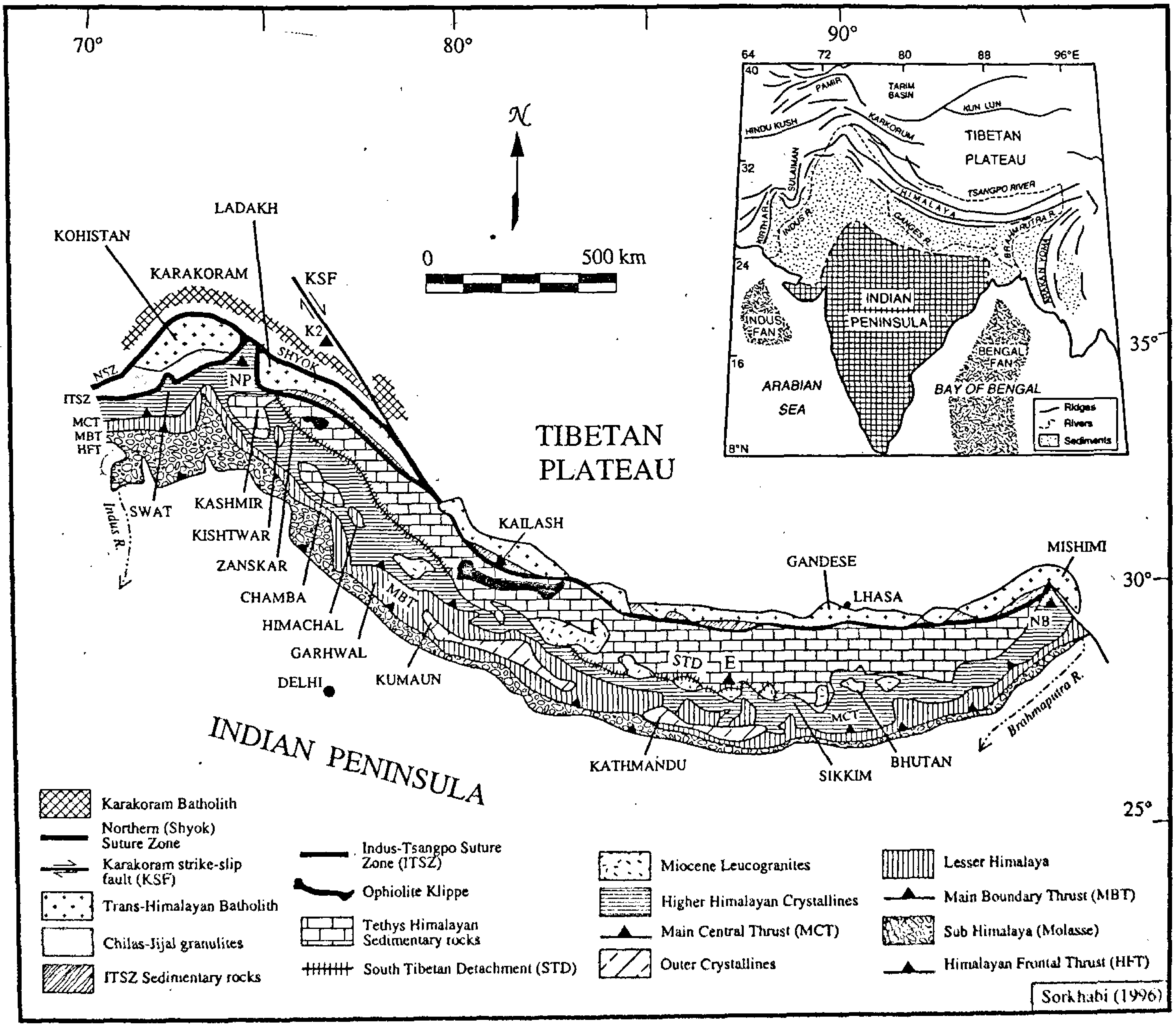


Figure 1. A geological map of the Himalaya, showing various lithotectonic divisions bounded by major faults. The map also shows the relationship between the Himalayan mountains and the depositional basins for sediments derived from the Himalaya.

nomenon of inverted metamorphism involves the Higher Himalaya, the MCT and the Lesser Himalaya. The regional metamorphism in the Himalaya range from the chlorite and biotite through garnet, staurolite, kyanite to sillimanite grade (from greenschist to upper amphibolite facies). Figure 2 depicts the distribution of metamorphic minerals in a section of the Himalaya[6].

Models proposed for the cause of Himalayan inverted metamorphism may be categorized into two broad groups[7,8] described below.

(i) 'Thermal Models', in which a heat source in the middle to upper parts of the crust was the direct cause of metamorphic inversion. As such, these models imply that the inverted metamorphism is an original (genetic) pattern in the thermal structure of the Himalayan rocks. Thermal Models include the following:
Model (1), Large-scale igneous intrusion in the Higher Himalaya[9-12];
Model (2), Overriding of a cold crust (the Lesser Himalaya) by a hot crust (the amphibolite-facies HHC) in an intracontinental subduction setting along the MCT that leads to the folding of paleo-isotherms and downward conductive heating of the Lesser Himalaya (the so-called 'hot-iron' model) (originally proposed by Le Fort[13]; revised in various forms by other authors[5,14-17]);
Model (3), Intense frictional heating on the MCT[6,14,18-20].
(ii) 'Structural Models', in which a post-metamorphic tectonic process inverted a normal (hotside-down) metamorphic sequence into a hotside-up sequence. Structural Models include the following (numbers beginning with 4, following the thermal models):
Model (4), Large-scale recumbent folding of metamorphic isograds (the folded crystalline nappe model) and tectonic transport of this nappe by the MCT (originally suggested by Löczy[21]; supported and elaborated on by others[22-27]);
Model (5), Tectonic juxtaposition of metamorphic assemblages of different ages or different lithostratigraphic units along major thrust faults[28-34]; or more clearly, post-metamorphic differential movement of individual metamorphic zones of a single prograde metamorphic phase as imbricate thrust sheets[35,36];
Model (6), Post-metamorphic ductile shearing of rocks on a small scale distributed across the Himalayan metamorphic zones (the germinal idea suggested as 'synmetamorphic shear-folding of metamorphic zones' according to Frank and colleagues[25,26]; ductile thrusting and shear zone model of Brunel[37]; and a fully developed model by Jain and Manickavasagam[38]; see also references 8, 39–41).

Given the present status of knowledge, it is difficult

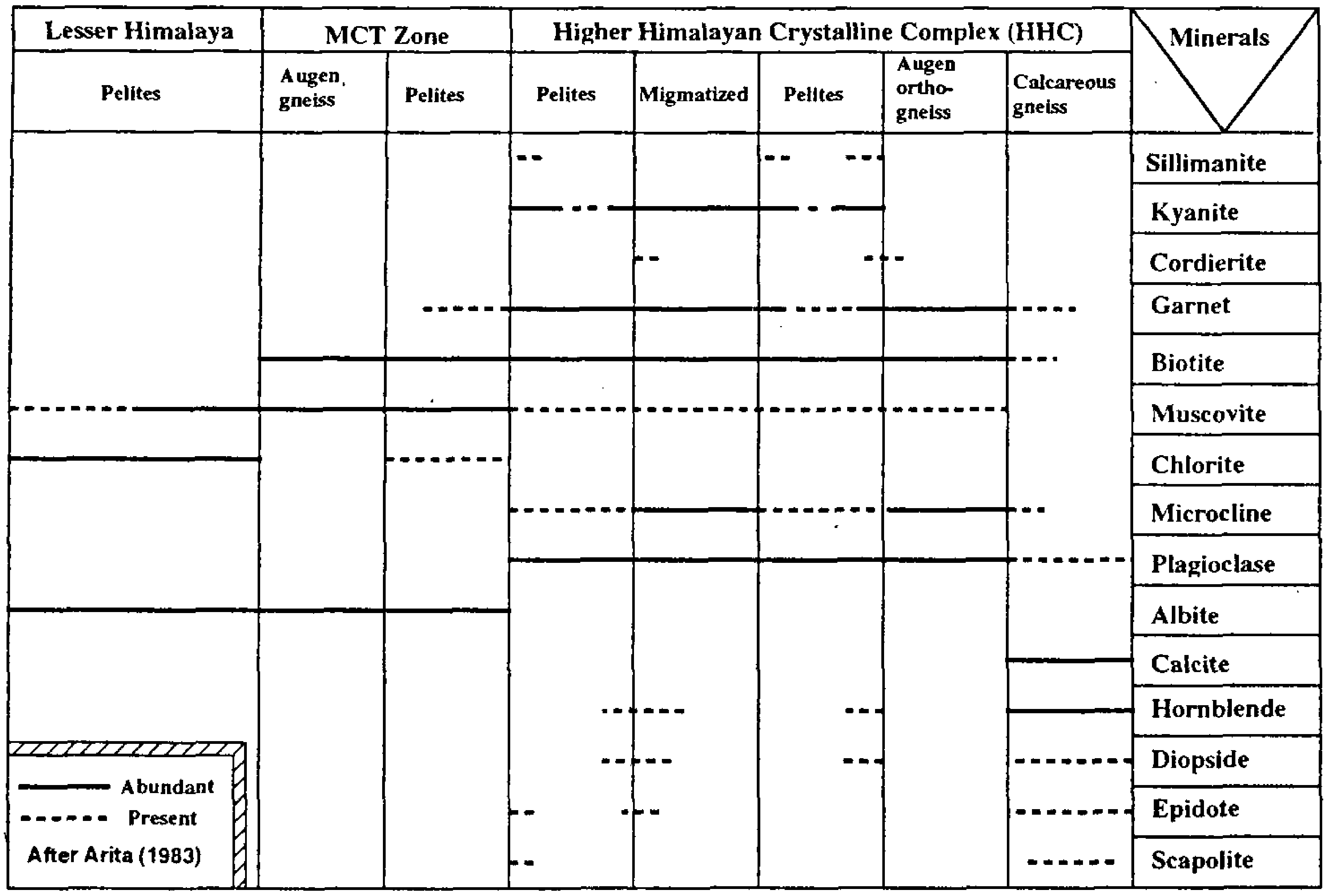


Figure 2. Distribution of various minerals in pelitic, psammitic and calcareous rocks of the Lesser Himalaya, the Main Central Thrust (MCT) zone and the Higher Himalayan crystalline complex. This figure is based on a petrographic study of rock samples across the Modhi Khola traverse in the Annapurna area of Nepal Himalaya. Modified after Arita[6]. Note that the grade of metamorphism increases from the Lesser Himalaya through the MCT zone to the core of the Higher Himalaya.

to determine the chronological boundaries between the Tertiary-age orogenic processes of metamorphism, plutonism, thrusting and folding in the Himalaya. Indeed, several authors referenced above have tried to combine some of these models and propose a multi-process model.

All of the models proposed for the Himalayan inverted metamorphism have been debated by numerous authors (some of whom were only referenced above due to lack of space), and the authors have provided structural, petrologic and thermobarometric data from the Himalaya to support or refute some of these models. However, none has been widely accepted as a unique solution for the whole Himalaya or even for a single sector of the Himalaya. In this paper, we adopt an entirely different approach, and synthesize the heavy-mineral analysis data from the Siwalik sediments to constrain these models.

The Siwalik molasse

The Siwalik Group exposed in the Sub-Himalayan zone is composed of clastic sediments (forming sandstone, shale, clay and conglomerate) transported by fluvial agents and deposited in basins developed in front of the rising Himalaya during Neogene times[1,42]. They are 'molasse' sediments in a truly Alpine sense, and numerous sedimentologic studies have established that the Siwaliks were derived from the Himalayan mountains[43–46]. Since the Siwaliks are rich in fossil content, their biostratigraphy is also well established in several sectors of the Himalaya, and over the past two decades magnetostratigraphic studies have tightened the deposition chronology of the Siwaliks. The Siwalik Group with a thickness of 5000–6000 m has been traditionally divided into Lower, Middle and Upper formations (Figure 3).

In the Potwar Plateau region of the Pakistan Himalaya, where the Siwaliks have been best studied, the Lower Siwaliks range in age from 18.3 Ma to 10.8 Ma and include the Kamlial and Chinji stages; the Middle Siwaliks (10.8–5.1 Ma) include the Nagri and Dhok Pathan stages; and the Upper Siwaliks (5.1–0.7 Ma) consist of the Tatrot, Pinjor, and Boulder-conglomerate stages[47–50]. In the Arung Khola area of the central Nepal Himalaya, Tokuoka *et al.*[51] have adopted a different stratigraphic classification for the Siwaliks. According to them, the Arung Khola Formation consists of lower,

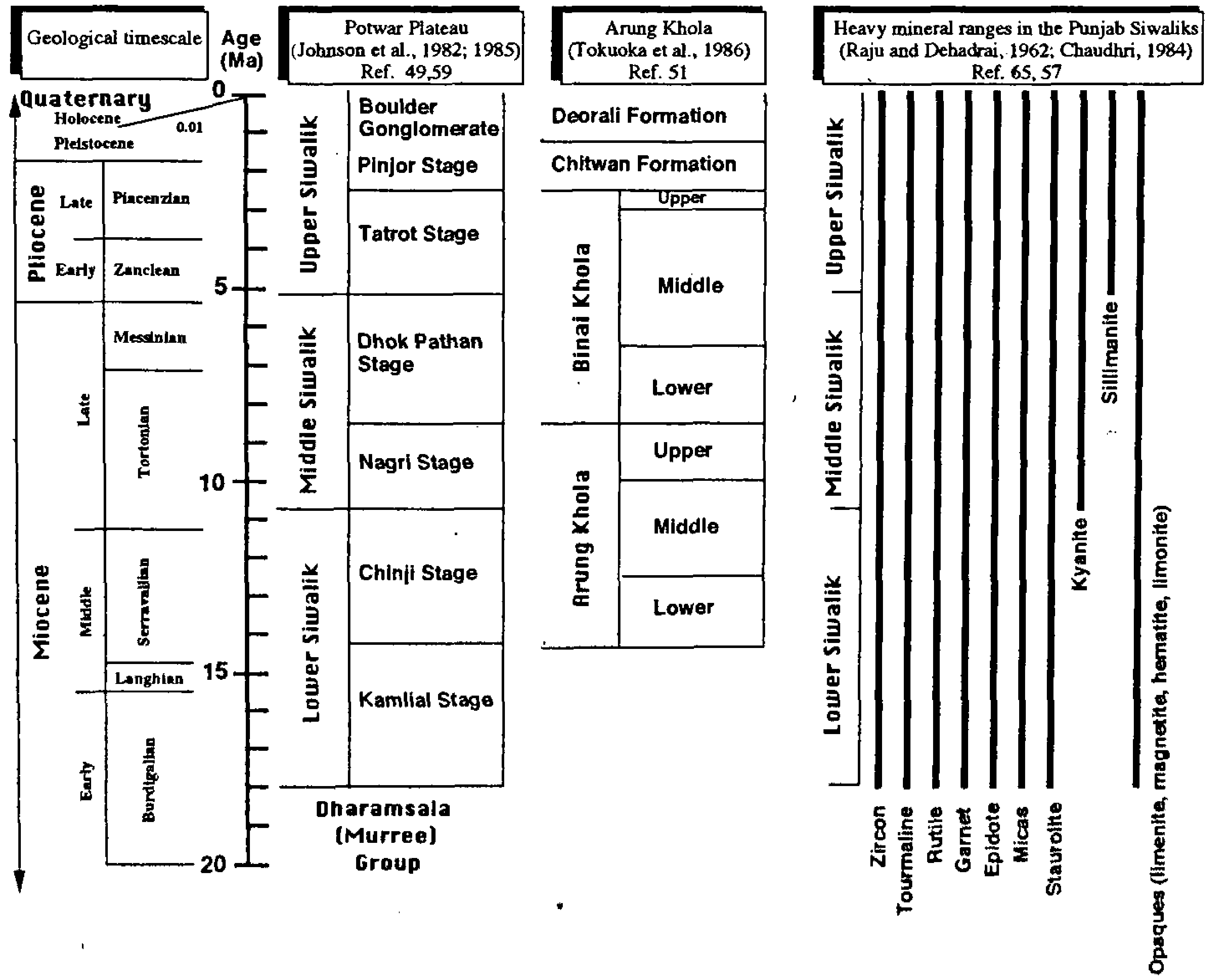


Figure 3. Stratigraphic classification of the Siwalik rocks in the western Himalaya and the Nepal Himalaya, and occurrence of heavy minerals in the Siwalik Group. References are given in the figure.

middle, and upper zones, corresponding in age to the Chinji and Nagri stages of the western Himalaya. The Binai Khola Formation beginning at 8.5 Ma also consists of lower, middle and upper zones, corresponding to the Dhok Patan and Tatrot stages. The Chitwan Formation (cobble conglomerates) beginning at 2.5 Ma is correlated with the Pinjor stage, and the Deorali Formation with the boulder-conglomerates of the western Himalaya (Figure 3).

Heavy-mineral analysis of the Siwalik Group

Heavy minerals in a sedimentary rock are those minerals heavier than quartz and feldspar, and practically defined as minerals with a specific gravity of over 2.9 g/cm^3 (which is the specific gravity of bromoform used to concentrate heavy minerals); they usually constitute less than 1 per cent of a sedimentary rock[52,53]. Metamorphic index minerals include chlorite, biotite, garnet, staurolite, kyanite and sillimanite, in an increasing order of metamorphic grade. These minerals are sequentially formed from the metamorphism of pelitic sediments (clays and shales) with an increase in temperature and pressure in the continental crust[54]. Metamorphic index minerals are also included in the assemblage of heavy minerals if the provenance of the heavy minerals were a metamorphic terrain. Of the metamorphic index minerals, the micas (chlorite, biotite and muscovite) occur in platy habit and have specific gravity in the range of 2.6–3.2 g/cm^3, and thus they cannot be completely separated by treatment with bromoform. For these reasons, the micas are often not considered in heavy-mineral analyses. Furthermore, biotite and muscovite are found in both igneous and metamorphic rocks. On the other hand, the presence of garnet, staurolite, kyanite and sillimanite in the heavy minerals of a sedimentary suite is diagnostic of a high-grade metamorphic provenance[53].

Heavy mineral analysis has been widely used for provenance (source area) studies, paleogeographic reconstructions and stratigraphic correlations. Reviews of this subject are given by Pettijohn[53], Blatt *et al.*[55] and Morton[56]. Over the past three decades, a number of heavy-mineral analyses of the Siwalik molasse have been carried out, mainly in the western Himalaya of India, and only a few studies from Nepal. A detailed review of these studies is out of the scope of this paper. For the sake of our discussion, we reference those papers, in which numerical values of the heavy minerals (usually expressed in percentage frequency) were documented. Furthermore, since we are concerned with metamorphic index minerals, only data for garnet, staurolite, kyanite and sillimanite are compiled here. (However, in some cases where data for micas were given, they have also been plotted, but the mica percentage frequencies should not be considered seriously for the reasons mentioned above.) In this paper, we do not consider the heavy-mineral analyses of the Murree (Dharamsala) Group of sediments, which underlie the Siwaliks, because very few data have been reported and because the stratigraphic (deposition) ages of these sediments are not precisely known.

Figure 4 *a–i* shows the percentage frequencies of garnet, staurolite, kyanite and sillimanite for the Lower, Middle and Upper Siwaliks from various areas of the Himalaya obtained by various authors as follows (arranged geographically from west to east): Chaudhri[57] for the Punjab Himalaya; Sharda and Verma[58] for the Jammu area (Punjab Himalaya); Sinha[59] and Shukla and Verma[60] for the Dehra Dun area (Garhwal); Gill[61] for the Garhwal Himalaya; Soman[62] for the Nainital area (Kumaun); Tandon[63] for the Ramnagar area (Kumaun); Chaudhri[57] for the Kumaun Himalaya; and Chaudhri and Gill[64] for the Nepal Himalaya.

Two major observations are noted from these plots (Figure 4): (1) Overall, the frequency percentages of metamorphic minerals increase through time from the Lower through Upper Siwaliks; (2) While garnet and staurolite occur in all Siwalik formations, kyanite appears in the Middle Siwalik sediments and continues its presence in the Upper Siwaliks, and sillimanite appears in the Upper Siwaliks.

These two observations seem to reflect a 'real distribution' of these minerals rather than 'subjective data' because they arise from studies of various parts of the Siwaliks and by various authors. The first point indicates that the Himalayan metamorphic terrain, which has supplied these detrital minerals, has experienced an accelerated uplift and erosion throughout the past 18 million years (Neogene times) during which the Siwalik sedimentation took place.

The second point is a confirmation of a finding originally made by Raju and Dehadrai[65] and published in this journal more than three decades ago (see Figure 3). These authors argued that staurolite seems to be a 'stratigraphic marker' for the Lower Siwaliks, kyanite for the Middle Siwaliks and sillimanite for the Upper Siwaliks. This observation was in contrast to an earlier study by Krynine[66], who reported that heavy minerals were 'generally equally well distributed throughout the whole Siwalik series'. However, Krynine[66] did not present any quantitative data for this claim. The observation of Raju and Dehadrai[65] was subsequently supported by Sinha[59], Tandon[63], Chaudhri[67] and several other authors mentioned above (see also Figure 4). The only author (other than Krynine[66]) who reported kyanite from the Lower Siwaliks was Soman[62]. However, in his data set, the majority of the samples from the Lower Siwaliks did not yield kyanite, and only two of them yielded 0.6 and 0.8 per cent kyanite (which is statistically insignificant; see discussion in Blatt *et al.*[55], p. 308).

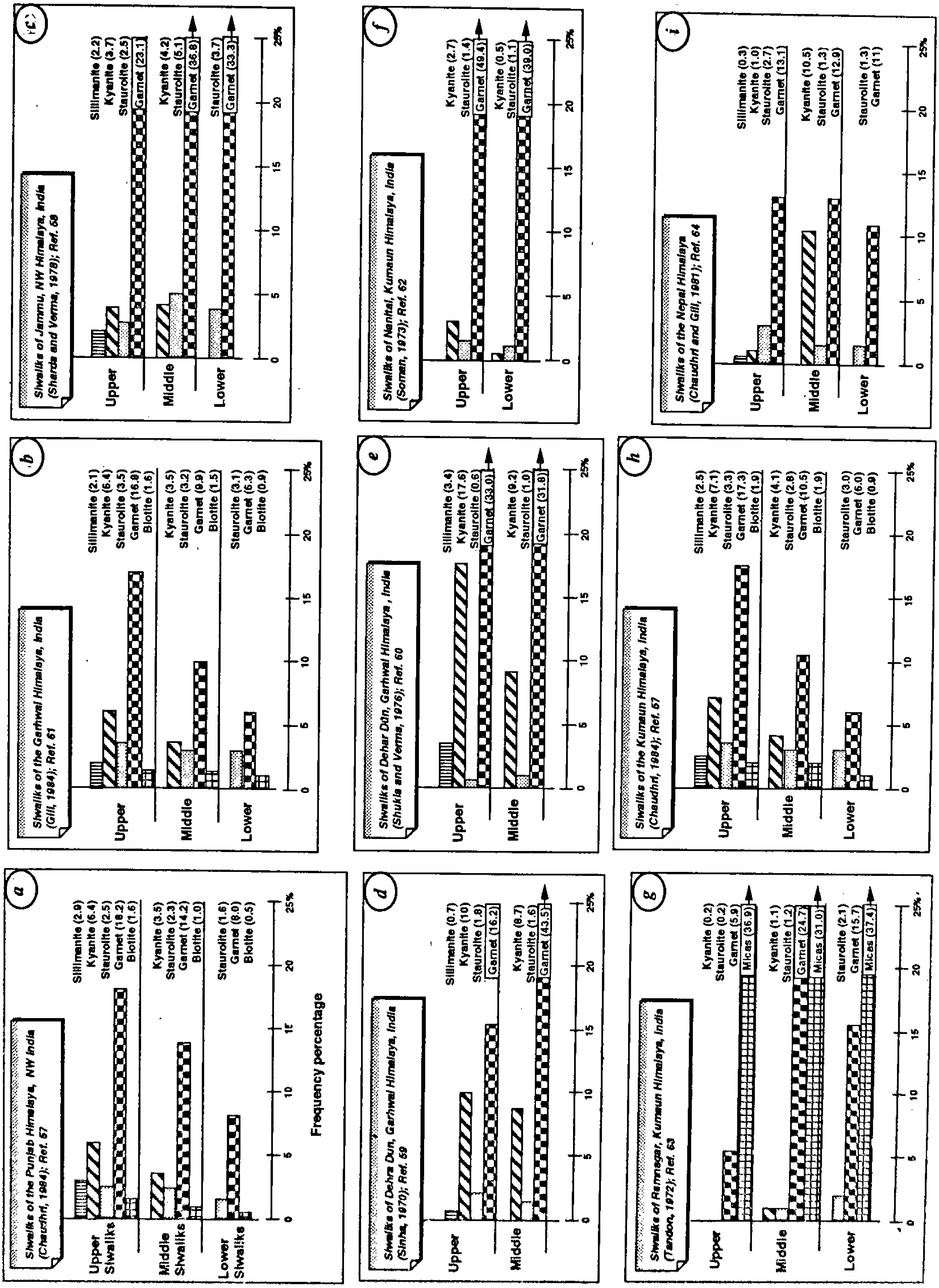


Figure 4. A compilation of heavy mineral analytical data from the Punjab, Garhwal and Kumaun Himalayas of India and the Nepal Himalaya, showing the frequency percentage for metamorphic index minerals (garnet, staurolite, kyanite and sillimanite) from the Lower, Middle and Upper Siwaliks. These plots are based on data reported by various authors, each referenced in *a–i*.

Therefore, his data do not refute observation (2), i.e. kyanite may be a stratigraphic marker for the Middle Siwaliks and sillimanite for the Upper Siwaliks.

Most of the heavy-mineral studies on the Siwaliks have been made in the Punjab, Garhwal and Kumaun Himalayas of India. One study was reported by Chaudhri and Gill[64] from the Nepal Himalaya. These authors used 31 samples for the Lower Siwaliks, 14 samples for the Middle Siwaliks and 10 samples for the Upper Siwaliks. Their observation that kyanite appears in the Middle Siwaliks is also supported by an independent study by Hisatomi[68], who noted that kyanite appears in the Binai Khola Formation and is absent in the underlying Arung Khola Formation (see Figure 3 for stratigraphic correlations of these formations with those of the western Himalaya).

Provenance or diagenesis

Before we conclude that the heavy mineral assemblage in the Siwaliks mainly represents the denudation of their provenance (i.e. the Himalaya), it is essential to establish that the physical and chemical effects such as weathering (in the soil profile), abrasion (during transportation) and diagenesis (after deposition) on the observed diversity of these minerals were insignificant. Here we discuss this subject rather in a greater detail for three reasons; because it has not been treated in a systematic manner in the Himalaya; it is necessary to address this problem both for this discussion and for other heavy-mineral studies of the Siwaliks in the future; and it has implications for long-standing debates over the influence of provenance and non-provenance factors in the assemblage of heavy minerals in sedimentary rocks.

Several charts of resistance or stability of heavy minerals against non-provenance effects have been proposed based on experimental or natural studies (Figure 5). Our discussion will be focused on the relevance of these charts to the heavy mineral assemblage in the Siwalik molasse.

One of the pioneering studies on the role of chemical weathering in the alteration of mineral content of bedrock was made by Goldich[69] using soil profile and bedrock samples of the Morton granite gneiss in the USA. His study was supplemented by that of Dryden and Dryden[70]. A chart of weathering resistance of heavy minerals in soil profile resulting from these studies is shown in Figure 5 *a*. Goldich[69] and Pettijohn[71] noted that there was an apparent relationship between the resistance of a given heavy mineral and its position in the Bowen reaction series (which is an arrangement of minerals according to their crystallization from a magma). In other words, a mineral (such as olivine) formed at highest temperatures in the most anhydrous magma is less stable under surface conditions than a mineral crystallized under lower temperatures in the more hydrous magma. However, this 'mineral stability series' does not imply that minerals less resistant to weathering cannot survive in the soil profile. The effect of weathering will also depends on climate and erosion rate[56]. Indeed, studies of Recent sediments in modern rivers such as the Nile[72], which were subjected to extreme weathering in the tropical source area, show abundant occurrence of less stable minerals such as hornblende and garnet. In the Himalaya, with thin soil and high erosion rates, the effect of weathering on heavy minerals must be very minimal. This is evident from the fact that garnet, a very less stable mineral (Figure 5 *a*), occurs abundantly not only in the Upper Siwalik rocks but also in the Lower Siwalik rocks. This in itself demonstrates rapid uplift and denudation of the Himalayan rocks during the Neogene.

Another possible factor altering a heavy mineral assemblage is abrasion during mechanical transportation of sediments. Thiel[73,74] has studied this effect experimentally and proposed a stability chart of minerals (Figure 5 *b*). However, in natural settings the abrasion effect seems to be insignificant. For example, studies of heavy minerals in the Nile shows no decrease in the diversity of heavy minerals with distance from the source area[72]. The occurrence of kyanite, which is easily destructible by abrasion according to Thiel's experimental chart (Figure 5 *b*), in the Upper as well as Middle Siwaliks indicates that the abrasion influence can be ruled out.

A third factor is the sorting of sediments in a depositional basin according to their density and diameter. This condition of settling in water is usually expressed by hydraulic equivalent size (i.e. the difference in size between a given heavy mineral and the size of a quartz sphere with the same settling velocity in water). Rittenhouse[75] carried out an excellent study of the Rio Grande River sands and found a good relationship between hydraulic size of heavy minerals and their densities (with a correlation coefficient of 0.91; see Figure 5 *c*). van Andel[76] studied grain-size distribution of some detrital minerals supplied by the Rhine River, and found that pyroxene, hornblende and epidote, which have approximately similar densities, were differentiated according to their sizes, i.e. coarse sediments were richer in pyroxene and finer sediments in epidote. The sorting effect (hydraulic size, density and diameter) does not seem to account for the gross assemblage of heavy minerals in the Siwalik molasse. For example, zircon and garnet, which have very high densities and hydraulic sizes (Figure 5 *c*) are found in the Lower, the Middle as well as the Upper Siwaliks, indicating their deposition at all levels of the Siwalik foreland basin. In fact, most of the heavy minerals analyses (Figure 4) show that the abundance of garnet increases from the Lower toward

Upper Siwaliks; this is in contrast to the density of garnet. Similarly, epidote (which tends to be associated with fine-grained sediments) is found in all formations of the Siwaliks (Figure 3), and its abundance does not decrease from the Lower through the Middle to the Upper Siwaliks (see data in references 57–64) while the Upper Siwaliks are the coarsest sediments.

Pettijohn[71] compiled the occurrence of heavy minerals in sedimentary rocks of various geological ages (from the Precambrian to the Present) as reported in numerous publications. From this tabulation, he worked out a 'mineral persistence' scale for heavy minerals (Figure 5 *d*). He found a correlation between his 'mineral persistence' chart and the 'mineral stability series' of Goldich[69], discussed above, and argued that the persistence of heavy minerals through geological time is an artifact of 'intrastratal solution' rather than reflecting their provenance. Although Pettijohn's 'persistence mineral series' has been often cited (partly because of its discussion in his well-known textbook, *Sedimentary Rocks*), he himself pointed out the limitations of his compilation of data[71], and as such, it should not be used as standard scale for interpreting all heavy-mineral assemblages in a given locality as merely product of intrastratal solutions. van Andel[76] has given a thoughtful criticism of Pettijohn's interpretation and has noted that his 'mineral persistence' scale is biased toward stable cratonic sediments for pre-Cretaceous times. In Pettijohn's compilation, heavy-mineral analyses of the Tertiary and Quaternary sediments mostly came from orogenic settings while pre-Cretaceous studies were on deposits of cratonic provenance in North America[76]. Even if we accept Pettijohn's mineral persistence chart and interpretation for heavy minerals on a global (not local) scale, its application to the Siwalik molasse is highly questionable because the persistence mineral chart (Figure 5 *d*) is for heavy mineral assemblages dating back to Precambrian times, while the Siwalik molasse is less than 20 million years old.

Pettijohn's argument for 'intrastratal solution' has been studied in the context of diagenesis (i.e. physical and chemical changes in sediments after their deposition but before metamorphism) by Morton[56]. He noted that two stages of diagenesis may affect heavy minerals. One stage is 'epidiagenesis', or changes brought about by surface waters moving downward. Based on an experi-

Inceasing order

a Ref. 69, 70	*b* Ref. 73,74	*c* Ref. 75	*d* Ref. 71	*e* Ref. 56	*f* Ref. 56
Resistence to Weathering in soil profile (Goldich, 1938; Dryden, 1946)	**Abrasion resistence of minerals (Thiel, 1940, 1945)**	**Sorting effects on heavy minerals: Hydraulic size (and density) (Rittenhouse, 1943)**	**Persistence of heavy mineals in geologic time (Pettijohn, 1941)**	**Stability of heavy minerals during epidiagenesis* (Morton, 1985)**	**Stability during anadiageneis* (Morton, 1985)**
Olivine Augite Garnet Staurolite Hornblende Kyanite Biotite Monazite Tourmaline Zircon	Barite Siderite Fluorite Goethite Enstatite Kyanite Bronzite Hematite Augite Apatite Spodumene Hypersthene Diallage Rutile Hornblende Zircon Epidote Garnet Titanite Staurolite Microcline Tourmaline Quartz	Tourmaline 0.2 (3.1) Hornblende 0.2 (3.2) Diopside (Brown) 0.3 (3.4) Pyroxene 0.3 (3.4) Kyanite 0.3 (3.6) Apatite 0.4 (3.2) Diopside (Colorless) 0.4 (3.3) Hypersthene 0.4 (3.4) Titanite 0.5 (3.5) Baryte 0.5 (4.5) Garnet 0.6 (3.8) Zircon 0.9 (4.6) Ilmenite 1.0 (4.7) Magnetite 1.0 (5.2)	Olivine Actinolite Diopside Hypersthene Sillimanite Augite Zoisite Titanite Topaz Andalusite Hornblende Epidote Kyanite Monazite Staurolite Magnetite Illmenite Apatite Biotite Garnet Tourmaline Zircon Rutile	Olivine/ Pyroxene/ Amphibole. Titanite. Apatite. Epidote/ Garnet. Chloritoid/ Spinel. Staurolite. Kyanite. Andalusite/ Sillimanite/ Tourmaline. Rutile/ Zircon.	Olivine/ Pyroxene. Andalusite/ Sillimanite. Amphibole. Epidote. Titanite. Kyanite. Staurolite. Garnet. Apatite/ Chloritoid/ Spinel. Rutile/ Tourmaline/ Zircon.
		Correlation coefficient between hydraulic size and density: 0.91		***Epidiagenesis: changes due to surface water**	***Anadiagenesis: changes due to deep burial**

Inceasing order

Figure 5. Charts for stability or resistance of heavy minerals against weathering in soil profile (*a*), abrasion during mechanical transportation (*b*), hydraulic size and density (*c*), persistence through geological times (*d*), intrastratal solution or diagenesis (*e* and *f*). The least stable minerals occur at the top of the lists. The compilation is based on various sources referenced in the figure for each chart.

ment of flushing low pH groundwater, Morton[56] listed a chart of stability for heavy minerals during epidiagenesis (Figure 5 *e*). Although this experimental chart is not applicable to all sedimentary basins (due to variation in the chemistry and pH of surface waters), it is cited here to note that the epidiagenesis seems to have little effect on the Siwaliks. For example, according to Morton's chart (Figure 5 *e*), sillimanite is more stable than kyanite, which is more stable than staurolite. But this is the reverse sequence of what is found in the Siwalik heavy-mineral assemblage (see Figure 4). Also, the least stable minerals such as epidote and garnet (Figure 5 *e*) occur in all horizons of the Siwalik sediments (Figure 3).

Another stage of diagenesis which may affect the diversity of heavy minerals is 'anadiagenesis' or changes due to porefluids (intrastratal solution) during deep burial of sediments[56]. There are very few reliable data to quantify this effect, mainly because it is extremely difficult to separate this effect from the provenance factor. Nevertheless, Morton[56] believes that the Paleocene sediments of the North Sea derived from the Scottish Highlands provide a unique opportunity to study the effect of anadiagenesis, and from this study, he has proposed a stability chart for minerals (Figure 5 *f*). Even taking this chart at face value, it seems that anadiagenesis was not a significant factor for diversity of the Siwalik heavy minerals. Epidote, which is less stable than kyanite according to this chart (Figure 5 *f*), occurs in the Lower, Middle, and Upper Siwaliks (Figure 3). Had kyanite deposited in an appreciable amount in the Lower Siwaliks, the population of kyanite could have survived the effect of anadiagenesis.

Three reasons argue against any significant influence of non-provenance factors in the gross diversity and relative abundance of the Siwalik heavy minerals. First, the Siwalik molasse is geologically very young; second, uplift and erosion rates in the Himalaya have been rapid; and third, both stable (e.g., tourmaline) and unstable (e.g., epidote) minerals are found together in the Lower, Middle and Upper Siwalik rocks.

A final testimony comes from Pettijohn himself; he writes: 'If heavy minerals are newly derived from crystalline rocks, they are little worn. Cleaved fragments and more or less euhedral crystals characterize the assemblage. If, however, the 'heavies' are derived from earlier sediments, the less stable species tend to be absent and the more stable survivors show notable rounding' (Pettijohn[53], p. 206). Almost all heavy-mineral studies of the Siwaliks referenced above demonstrate that euhedral heavy minerals such as zircon indicating single-cycled sedimentation from the Himalayan crystalline terrain occur abundantly in all of the Siwalik formations irrespective of their stratigraphic (depositional) ages.

We thus support the conclusions of Sinha[59], Chaudhri[57,67] and Nanda and Tandon[77] that the heavy mineral assemblage of the Siwaliks directly reflects the erosion history of its provenance (the Himalaya).

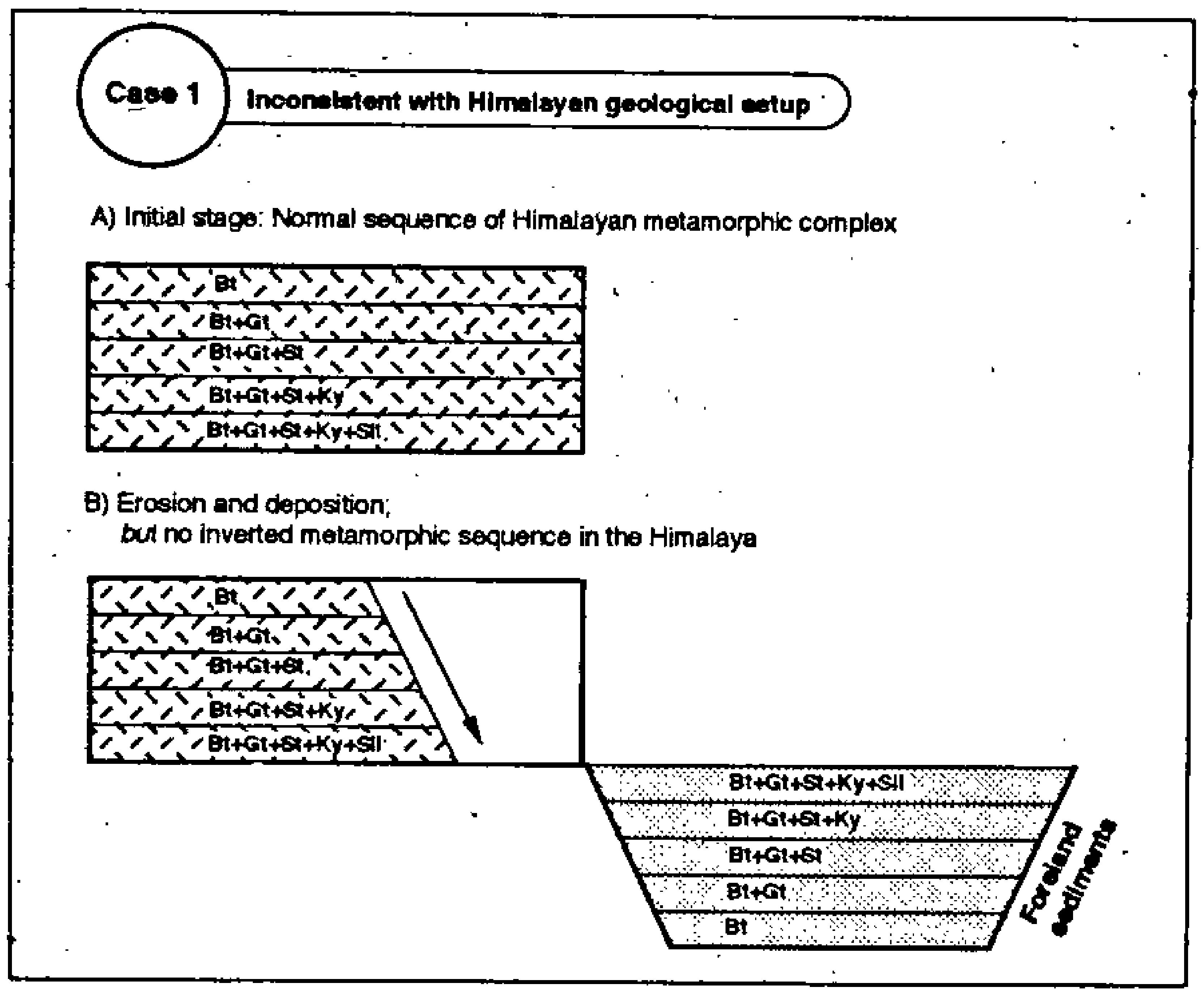
Toward a solution for the Himalayan puzzle

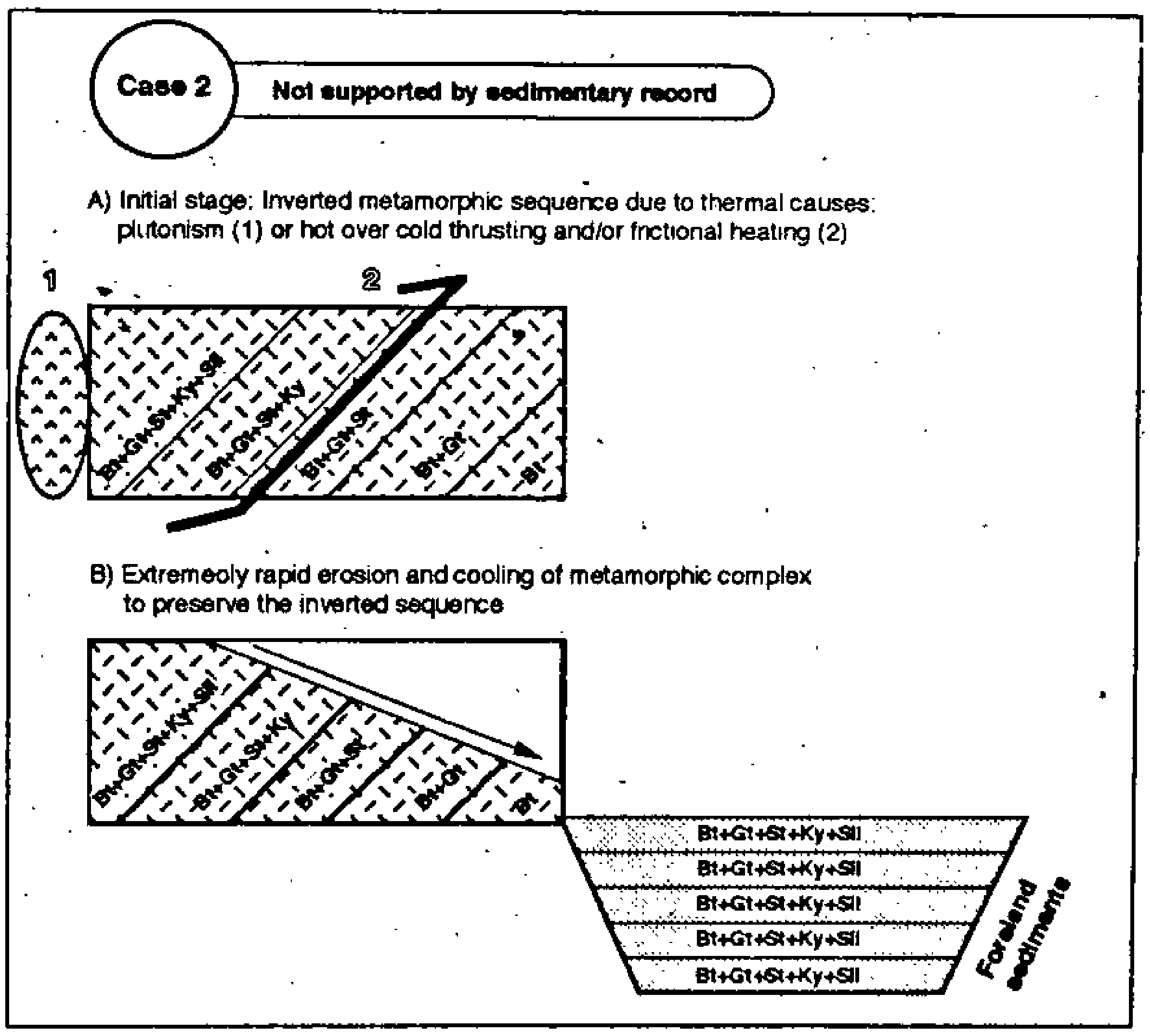
Sedimentary evidence from the Siwalik molasse presented in the preceding sections indicates that sillimanite (an index mineral of highest-grade regional metamorphism) appears in the Upper Siwalik, kyanite appears in the Middle Siwalik and continues its presence through the Upper Siwaliks, while staurolite, garnet, and micas (indicative of lower- to medium-grade metamorphic rocks) occur in the Lower through Upper Siwaliks. In other words, the higher-grade metamorphic zones in the Himalaya were subjected to denudation and deposition at a later time than the lower-grade metamorphic zones as noted by Sinha[59], Chaudhri[57,67] and Nanda and Tandon[77]. However, this pattern of denudation and deposition is not strange in itself; it may indicate successive denudation of a hotside-down metamorphic pile as shown in Figure 6, case 1. Possibly a normal metamorphic pile with the highest-grade rocks in the deepest levels was subjected to uplift and erosion though time, and therefore, the deepest rocks (in the sillimanite grade) were exposed at a more recent time than the lower-grade rocks originally occupying the upper levels of the metamorphic pile. However, what makes the erosion and sedimentary record of the Siwaliks so significant is that in the Himalaya the metamorphic pile is not in a normal sequence; it is hotside-up. For this reason, the sedimentary evidence from the heavy-mineral analysis of the Siwaliks puts important constraints on the models proposed for the inverted metamorphism in the Himalaya as described below.

Geochronological studies in the Higher Himalaya of India and Nepal show that the peak metamorphic conditions for the main metamorphic event that affected the rocks presently outcropped in the Higher Himalaya reached in the Late Oligocene–Early Miocene. $^{40}Ar/^{39}Ar$ ages determined on hornblende kinematically grown in the rock fabric on the hanging wall of the MCT are 20–25 Ma (refs 78–81). Since these are post-metamorphic cooling ages (recording temperatures of 500–550°C) and the peak metamorphic temperatures were on the order of 650–750°C (see Hodges *et al.*[82] for a review), the regional metamorphism must have occurred shortly before these cooling ages. Another age constraint is that the majority of the Higher Himalayan leucogranites probably formed during the main Himalayan metamorphism have been dated as 25–22 Ma by the U–Pb techniques[81,83,84]. Therefore, it is widely agreed that the main Himalayan metamorphism of rocks outcropped in the mountain was a Late Oligocene–Early Miocene event. The Siwalik sediments covering the past 18 million years are also widely considered to have been derived from the Himalaya.

If the inverted metamorphism were due to thermal causes in the middle to upper parts of the Himalayan crust, such as igneous intrusion (Model 1), shear heating along the MCT (Model 2) or hot-over-cold thrusting in an intracontinental subduction setting (Model 3), and if an already inverted metamorphic sequence were subjected to rapid uplift and erosion, one would expect to find both high-grade and low-grade metamorphic index minerals in the Lower Siwaliks through the Upper Siwaliks (Figure 6, case 2). Indeed, a condition necessary for the thermal models is that the inverted metamorphic pile should have cooled (uplifted and eroded) quite rapidly in order to preserve (quench in) the inverted metamorphic zonation[85,86]. But the sedimentary evidence is not consistent with this prediction of the thermal models. Model 1 and Model 2 are also refutable on the basis that the metamorphic effects of granitic intrusion and the MCT frictional heating would have been local, not on a Himalayan scale.

The structural models, on the other hand, predict that the inverted metamorphic sequence is a post-metamorphic event caused by tectonic disruption of metamorphic zones. This is consistent with the sedimentary record because the heavy-mineral analyses demonstrate that there were time gaps between deposition of lower- to higher-grade rocks; the garnet and staurolite zones were exposed to erosion and were deposited during Lower Siwalik times (18–11 Ma), the kyanite zone was exposed





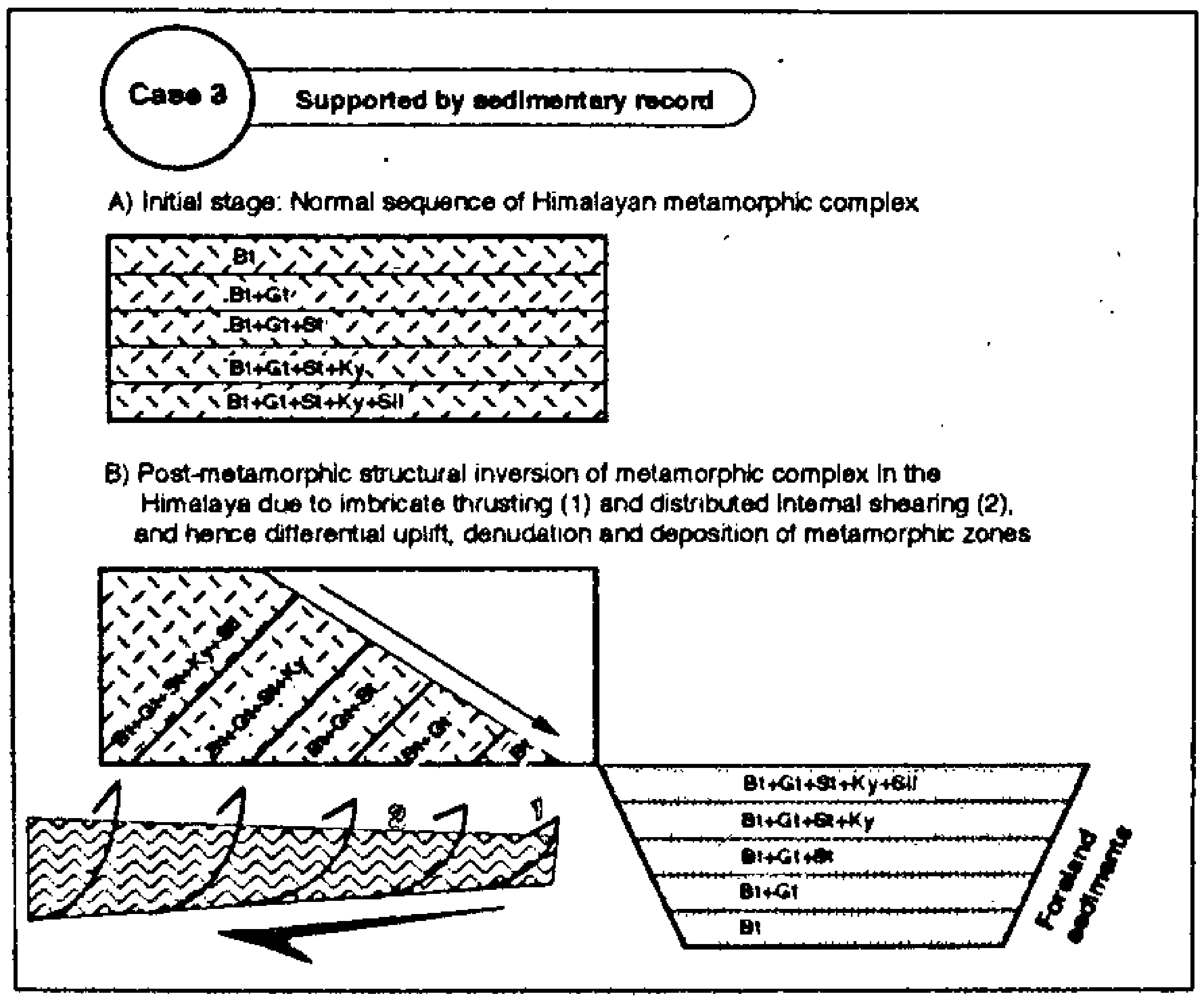


Figure 6. Conceptual models to show relationships between a regional metamorphic sequence in a mountain range and its erosion and depositional record in a sedimentary basin. In case 1, sedimentation record is an inverse of metamorphic sequence; the highest-grade rocks were eroded and deposited at a later time, however, the metamorphic sequence in the mountain is normal (hotside-down). This is not applicable to the Himalaya, which exhibits an inverted metamorphic sequence. In case 2, a thermal event such as igneous intrusion, hot-over-cold thrusting or thrust-related frictional heating caused metamorphic inversion in the middle to upper parts of the crust, and subsequently the already inverted metamorphic pile underwent very rapid uplift and erosion. This is possible but it would need to yield higher-grade index minerals throughout the sedimentary record; there should not be long time gaps between inverted metamorphism and uplift-denudation-cooling (otherwise, the inverted metamorphic sequence could not have been preserved in the mountain). This is not consistent with the Siwalik sedimentary record. In case 3, a normal hotside-down metamorphic pile is transformed into an inverted (hotside-up) sequence by structural mechanisms (imbricate thrusting and distributed ductile shearing) after peak metamorphic conditions. This case predicts an apparent inverted metamorphic sequence in the mountain and time-gaps between deposition of lower- to higher-grade metamorphic zones (hence the sequential appearance of metamorphic index minerals in the sedimentary record). This scenario seems to be most consistent with the Himalayan metamorphism and the Siwalik sedimentary record. However, it should be noted that case 3 depicted in this figure is an ideal model. See text for discussion.

during Middle Siwalik times (11-5 Ma), and finally the sillimanite zone during Upper Siwaliks times (see Figure 3 for geological ages). Unfortunately, the available data from the heavy-mineral analyses do not specify more precise stratigraphic (depositional) ages of the Siwalik samples (i.e. what stage of the Lower, Middle or Upper Siwaliks), and therefore, a more quantitative understanding of the time-gaps between metamorphism and deposition of the rocks is not possible in this study. From the Siwaliks of Nepal, Hisatomi[68] reported the first occurrence of kyanite in lower zone of the Binai Khola Formation at 8.5 Ma (Figure 3).

A simple explanation for the observed pattern of heavy minerals in the Siwalik record is differential uplift, denudation and deposition of metamorphic rock assemblage in a manner that the highest-grade (deeper, hotter) rocks were uplifted and eroded at a later time than the lower-grade metamorphic rocks. This sequence of events is predicted by the structural models for the Himalayan inverted metamorphism.

Structural disruption (and hence differential uplift and erosion) of the metamorphic zone could have been accomplished by either recumbent folding (Model 4), multiple-thrusting (Model 5) or distributed ductile shearing (Model 6). Of these, Model 4 is less likely because recumbent folding of the rocks on the huge scale of the Himalaya is not observed; recumbent folds have been mapped as local features in the Himalaya (for example, the Donara nappe in Zanskar[27]). Recumbent folding requires stratigraphic inversion of rocks in the lower limb of the orogen-scale folded nappe; this is yet to be demonstrated in the Himalaya. Even in the classical study area of the Sikkim Himalaya, where Löczy[21] mapped Himalayan nappes, the nappes seem to be thrust nappes, not a recumbent fold. In the same area, the metamorphic zones are also separated by thrust faults as mapped by Sinha-Roy[5]. Therefore, we tend to support a combination of Models 5 and 6 as most likely causes for the inverted metamorphic sequence in the Himalaya. Both imbricate thrusting and distributed ductile shearing have been reported from the HHC and the MCT zone (see references for Models 5 and 6). And the sedimentary evidence discussed in this paper is consistent with the prediction of these models, i.e. multiple thrusting and internal ductile shearing of the metamorphic pile in the Higher Himalaya causing differential uplift and denudation of metamorphic zones and hence resulting in an inverted metamorphic sequence, which was not an original thermal pattern of the crust but a post-metamorphic structural disruption of metamorphic zones yielding now an apparent inverted metamorphism (Figure 6, case 3).

It should be noted that Figure 6 is an ideal picture showing fundamental concepts relevant to our discussion. The available data do not permit us to show the exact temporal pathways of the Himalaya rocks from crustal depths to mountain heights and then to depositional basins. For example, uplift and erosion rates may have varied through time. Moreover, the thrusting of the Lesser Himalaya over the Siwalik molasse along the Main Boundary Thrust has probably covered portions of the sedimentary record older than the Lower Siwaliks beneath the Lesser Himalaya and of which we have no information. Therefore, Figure 6, case 3 should be taken as a simplified model to interpret the Himalayan inverted metamorphic sequence in the light of the available data from the Siwalik sedimentary record and the structural setup of the Himalayan mountains.

A corollary of this study is that the foreland sediments in the Himalaya have preserved very important information about the thermal–tectonic evolution and uplift-denudation history of the Himalaya. Therefore, more sophisticated and better documented research is encouraged along these lines of thought.

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