Implications of electrical conductivity structures in the tectonic framework of Northwest India

B. R. Arora

Indian Institute of Geomagnetism, Colaba, Bombay 400 005, India

Information on the Trans–Himalayan and the Trans–Aravalli conductive structures recognized through magnetovariational studies are synthesized with the gravity-, seismic wave velocity- and heat-flow data to provide constraints on the tectonic configuration of northwest India. A variety of geophysical signatures suggest that the crust beneath western Indo-Gangetic Plains and Marwar (western Rajasthan) terrain is characterized by high density and higher shear-wave velocities. This tends to support the inference that crustal structural in western part of the Indo-Gangetic Plains has oceanic affinity. The Trans–Himalayan Conductor aligned with the Aravalli Range beneath the Indo-Gangetic Plains is interpreted as representing a Proterozoic accretion zone between the western oceanic-type crust and the eastern continental crust. The present geometry suggests that the accretion zone has undergone upliftment during early Quaternary in response to stresses generated due to the locking of the Indian-Eurasian plates since the early Pleistocene. Since the envisaged model integrates a number of isolated geophysical signatures, it is necessary that more testing is done.

Introduction

EVIDENCE has been adduced for the existence of a high electrical conductivity structure in the crust and upper mantle from regional electromagnetic induction studies in NW India. These electrical structures are closely correlated with the tectonic settings of the Aravalli and Himalaya mountains. The high conductivity may be attributed to the presence of films of graphite or magnetite on grain surfaces[1], thermally-induced silicate melt[2] and/or to electrolyte fluids generated during metamorphic dehydration reactions[3] or released during recrystallization[4]. There is correlation with other geophysical parameters, such as high heat flow, seismic wave velocities or high magnetization. In a high-heat flux region, for example, the source for good conductor at crustal depth is hot saline water whereas for a conductor at upper mantle depth, a few percent of silicate melt is more likely a mechanism[5] when there is evidence for low seismic velocities and high absorption of seismic waves.

Regional tectonic framework

Figure 1 shows the major tectonic units making the tectonic framework of the NW India[6]. South of the dominating Himalayan belt lie the Indo-Gangetic Plains (IGP) which represent a filled-up foredeep basin formed due to the flexuring and subsidence of Indian plate following its collision with Eurasia. Geophysical investigations have revealed that the basement of this basin is characterized by a number of troughs and ridges[7,8]. The important sub-basement structures include the Delhi-Hardwar Ridge and the Moradabad Fault.

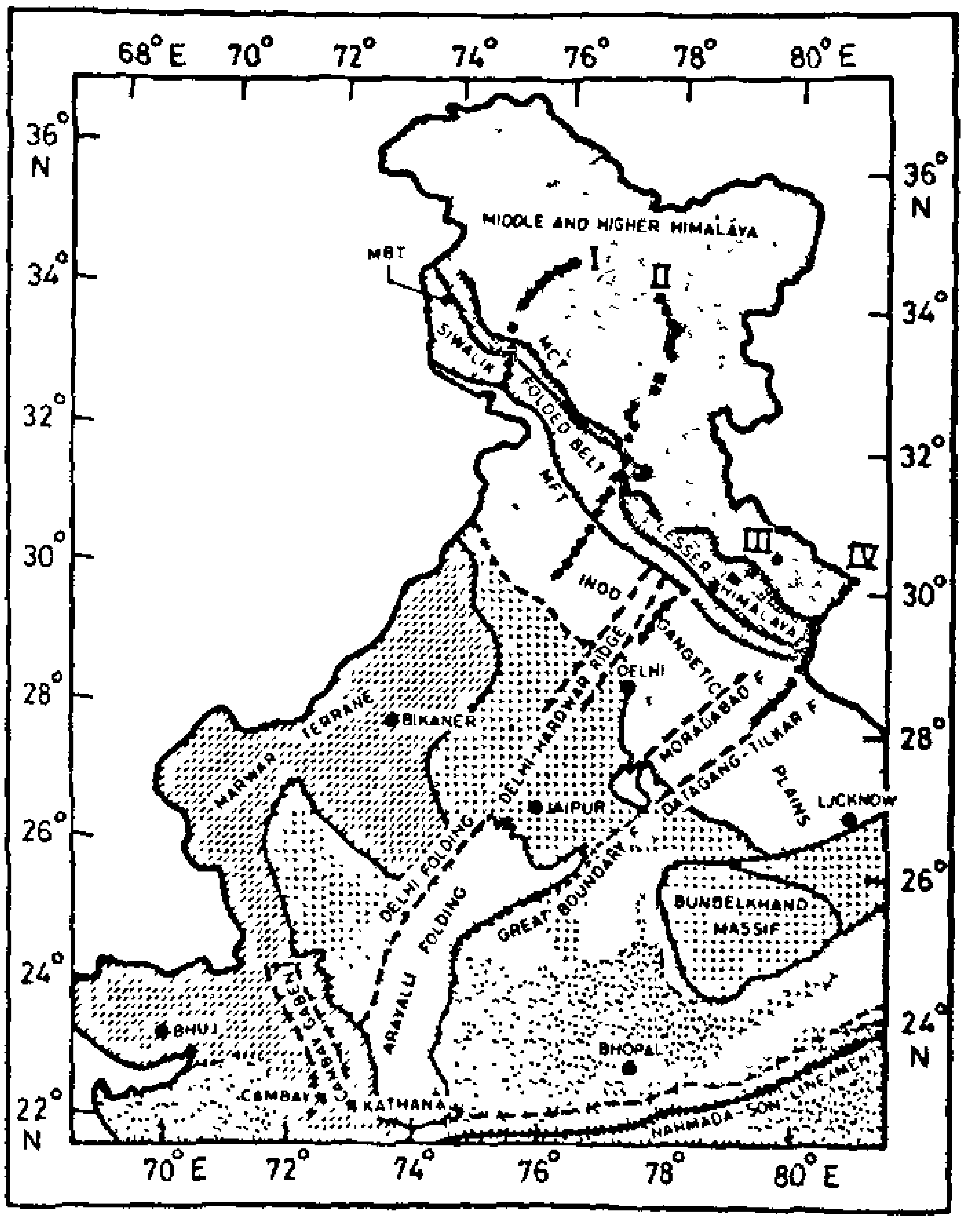

Figure 1. Tectonic framework of northwestern India (modified after Eremenko *et al.*[6]). Four gravity profiles (Das *et al.*[39]) along the Udampur-Kargil, Chandigarh-Leh, Rishikesh-Geldung and Khatima-Kalapani lines.

The NE-SW trending Proterozoic fold belt of the Aravalli is the most conspicuous feature of the exposed Indian shield south of the Indo-Gangetic Plains. The Aravalli-Delhi belt is regarded by Sinha Roy[9] as an aulacogen bounded by faults. The post-orogeny tectonism in the Aravalli belt has been studied among others by Ahmed & Ahmed[10] and Sen & Sen[11]. The Aravalli separates two geologically contrasting crustal blocks—the Marwar (western Rajasthan) terrain in the west and early Proterozoic magmatic terrain of Bundelkhand in the east[12]. The fragmentation of these terrains has played a key role in the evolution of the Aravalli.

Magnetovariational (MV) studies

In the MV method[13,14] 2-D or linear arrays of magnetometers are deployed in order to observe the spatial behaviour of the vector magnetic field as a function of frequency. The location and orientation of the conductive structure is obtained by induction arrows in the geographical grid maps, which point at right angles to the conductive body causing current concentration. Their magnitude (equivalent to Z/H ratio), spatial distribution and period dependence contain information on the depth, lateral extent and conductivity characteristic of the concerned structure, which are isolated through numerical modelling.

Trans-Himalayan conductor (THC)

Detailed account of the large-scale array in NW India has been given by Lilley *et al.*[15] and Arora *et al.*[16]. The nature of induction anomalies corresponding to the reversal of vertical magnetic field variation led to the discovery of a major geoelectric structure striking at right angles to the Himalaya (Figure 2). It was noted that

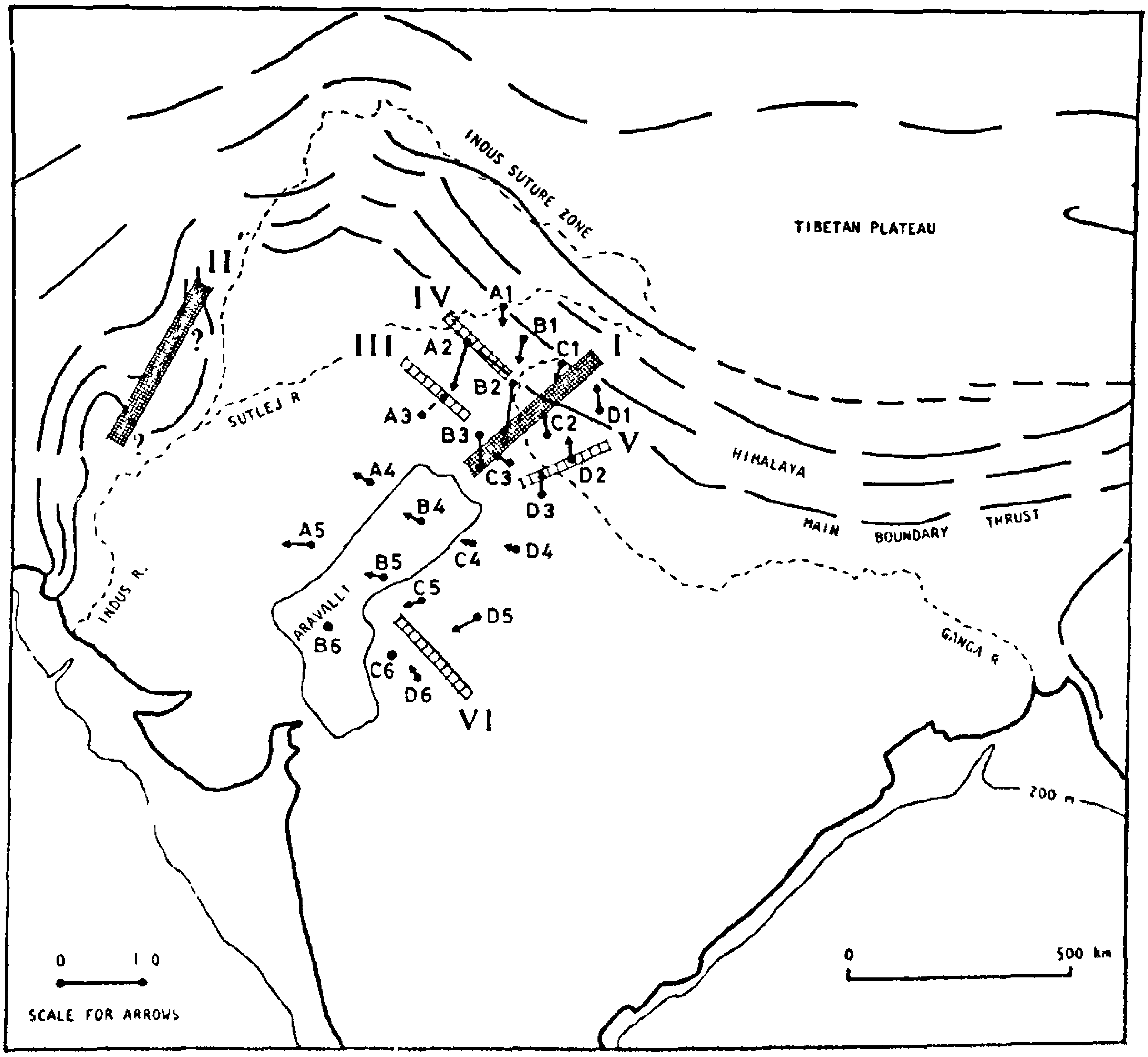

Figure 2. Induction arrow pattern in NW India indicate existence of conductive structures I Trans-Himalayan Conductor (THC) and II Trans-Aravalli Conductor (TAC) (after Arora *et al.*[16]).

this anomaly is aligned with the Aravalli belt as it dips down under the Ganga plain. The closely-spaced linear array deployed over Garhwal Himalaya in 1984 (ref. 17) provided a conclusive evidence of the continuation of the THC into the Lesser Himalaya, allowed quite reliable estimation of the position and orientation of the conductor. The conductor located between Chamba (CHA) in Tehri district and Chaukutia (CHU) in Almora District is oriented N 45–60° E[17]. Combining the data of the 1979 and 1984 arrays, Arora *et al.*[18] showed that many of the spatial and frequency characteristics of the real part of the vertical field response at three periods (Figure 3*a*) could be reproduced by induction in two tabular blocks of 3 Ohm.m as shown in Figure 3*b*. Partial modification of these block structures, shown by stippled area in Figure 3*b*, helps to account for the sharp gradient of the observed response just above the centre of the structure. The inclusion of a surface conducting layer simulating conducting sediments in the IGP, with a thickness equivalent to the depth of basement along the traverse[19] helps to account for the frequency dependence. The overall geometry of the structure can be approximated as an asymmetric domal upwarp in the middle and lower crust located between Delhi-Hardwar Ridge and Moradabad Fault. Hot saline water in fractures or interconnected pores in the nodes—with a few percent of porosity—can provide resistivity of 2–3 Ohm.m, required to model the induction anomaly. Significantly, over the Ganga Basin, the conductive structure coincides with the break in isostatic gravity contours which otherwise follows the strike of the Himalayan collision boundary[20,21]. There is a distinct pattern in the distribution of epicentres[22], that broadly coincides with the area of the anomaly. The area of the conductivity anomaly is characterized by a transverse zone of quantitatively high seismicity[23]. This correlation suggests that the conductivity anomaly may be associated with the present tectonic activity or with an ancient tectonic structure which is reactivating. Noting the alignment of the THC with the Aravalli belt, Lilley *et al.*[15] interpreted it as a continuation of the Aravalli belt having been thrust down due to the collision of India and Asia, and made highly conductive at depth by hydration or by increased temperature and pressure. Significantly, Valdiya[24] specifically links transverse structures of the Himalaya with subsurface structures of the North Indian plains. Earlier Auden[25] had postulated the extension of the Aravalli belt into the Himalaya.

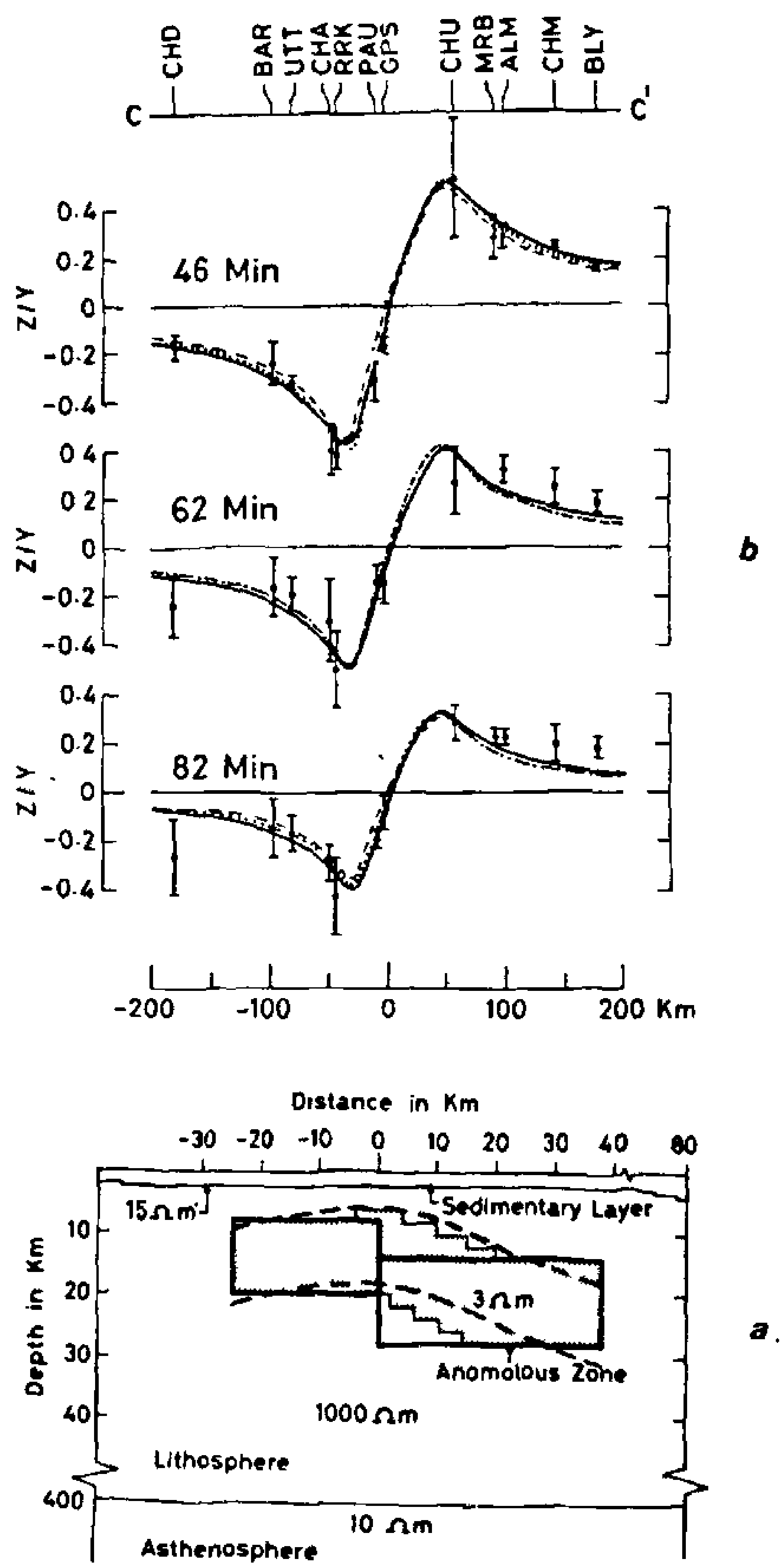

Figure 3. *a*, Numerical electrical conductive structure model for the Trans-Himalayan Conductor, which is approximated as asymmetric domal upwarp shown by thick broken line. *b*, Comparison of calculated induction response for model shown in (*a*) with observed data at three periods. Broken (— —) and dotted (...) lines denote response for two tabular blocks and for structures stippled in (*a*) above, Solid lines represent response including induction in surface sedimentary layer.

Trans–Aravalli conductor (TAC)

A conductor west of the Aravalli belt has been identified[26] in the southern part of the NW India array (Figure 2). The induction pattern which persists for several hundred kilometres is caused by a massive structure of high electrical conductivity contrast beneath the Trans–Aravalli terrain. The results are not compatible with the concentration of currents in surficial sediments in the Indus Valley and the Mesozoic marine sediments that surround the Vindhyan, Aravalli and Delhi[27]. The dominance of the induction effects at long periods suggests deep source. In the absence of additional evidence for the existence of a major geological discontinuity of regional scale, the conductive structure was speculated to be some manifestation of shearing taking place along the Chaman Transform Fault[16]. An anomalous conductive layer is considered at a depth of 12 km beneath the Marwar Terrain (Figure 4). This layer with resistivity of 3 ohm.m and thickness of 10 km simulates an overall conductance (product of thickness and conductivity; $S = h\sigma = h/\rho$) of the order of 3,500 S. The electromagnetic response of geoelectrical model is calculated using the 2-D numerical scheme of Cerv and Praus[28]. The resulting spatial behaviour of normalized vertical field response, equivalent to the magnitude of real induction arrow, is shown in Figure 4, as a function of distance from the edge. To facilitate comparison, the magnitude of real arrows for group of stations on two southern lines of Figure 2 is also plotted with the edge placed at arbitrary distance from the western-most station on each line. A fair agreement in the decay pattern of observed and calculated values suggests that the induction effect can reasonably be attributed to the edge effect of currents induced in the extended conducting layer.

Deep seismic studies in the region of the Cambay graben indicate a sharp transition in the character of the crust between the northern and southern part[29]. The crustal thickness in the Cambay-Kathana region (Figure 1) was found to be about 35–37 km and the compressional wave velocity 6.92–7.04 km/s, typical of basalt, was found between depth of 12 and 37 km. On the other hand the southern part of the graben, barring the top sedimentary layers and the Deccan Traps, showed a velocity of 6.4 km/s, typical for granite, prevailing at a depth of 24 km. These variations in the depth of basaltic layer suggest a step-like jump of about 10–12 km north of the Cambay-Kathana region. In Figure 4, the 10 km thick high conductivity layer placed at a depth of 12 km possibly corresponds to this step in the 10 km thick basaltic layer. Another feature of the Cambay-graben is that there is a change in the level of surface heat flow coinciding with the transition in thickness of the basaltic layer[30]. The heat flow of 55 mW.m^{-2} in the south rises to 105 mW.m^{-2} in the Cambay-Kathana region in northern part.

A heat flow value of 105 nW^{2}.m^{-2}, the expected depth and conductance of conducting crustal layer obtained from equations proposed by Adam[31,32] show good compatibility with those adopted in the model of Figure 4 for the Trans-Aravalli conductor. The depth of this conducting layer also shows good correspondence with the top of basaltic layer in the Cambay-Kathana belt recognized through DSS. Since there is high heat flow, over the northern part of the Cambay-graben, and also over the Marwar terrain (to the west of the Aravalli block) the observed induction pattern indicates a major change in the character of the crust beneath the Marwar terrain. This deduction is further supported by positive isostatic gravity anomaly (Figure 5) in western Rajasthan and the Aravalli. The sharp positive anomaly of the order of +50 mgal over the Aravalli has been interpreted to indicate existence of a horst block beneath which heavy material has moved up from the mantle[33]. Further west, the positive gravity anomalies

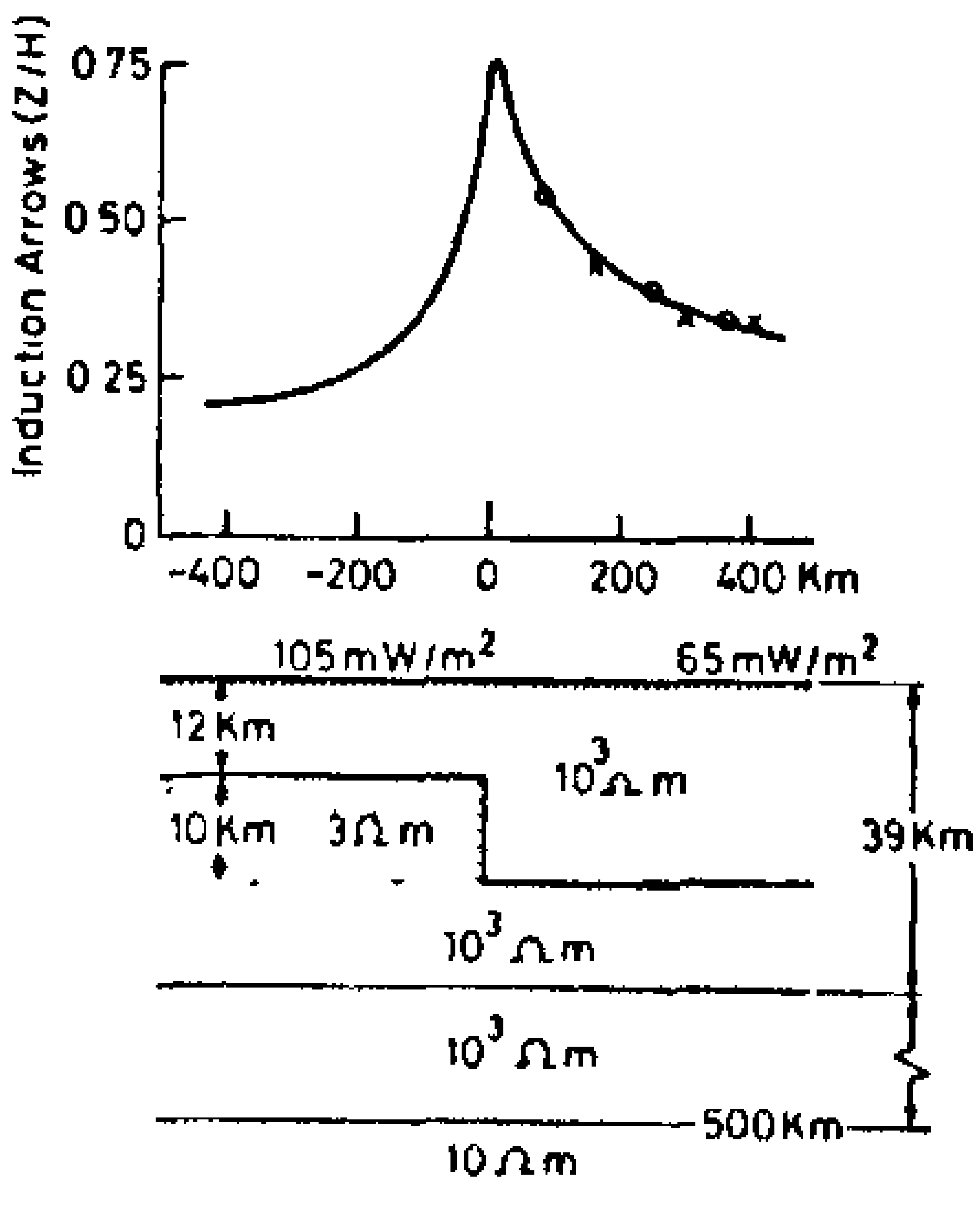

Figure 4. Electrical conductive structure for the Trans-Aravalli Conductor explaining spatial characteristics of induction arrows along the two southern lines in NW India

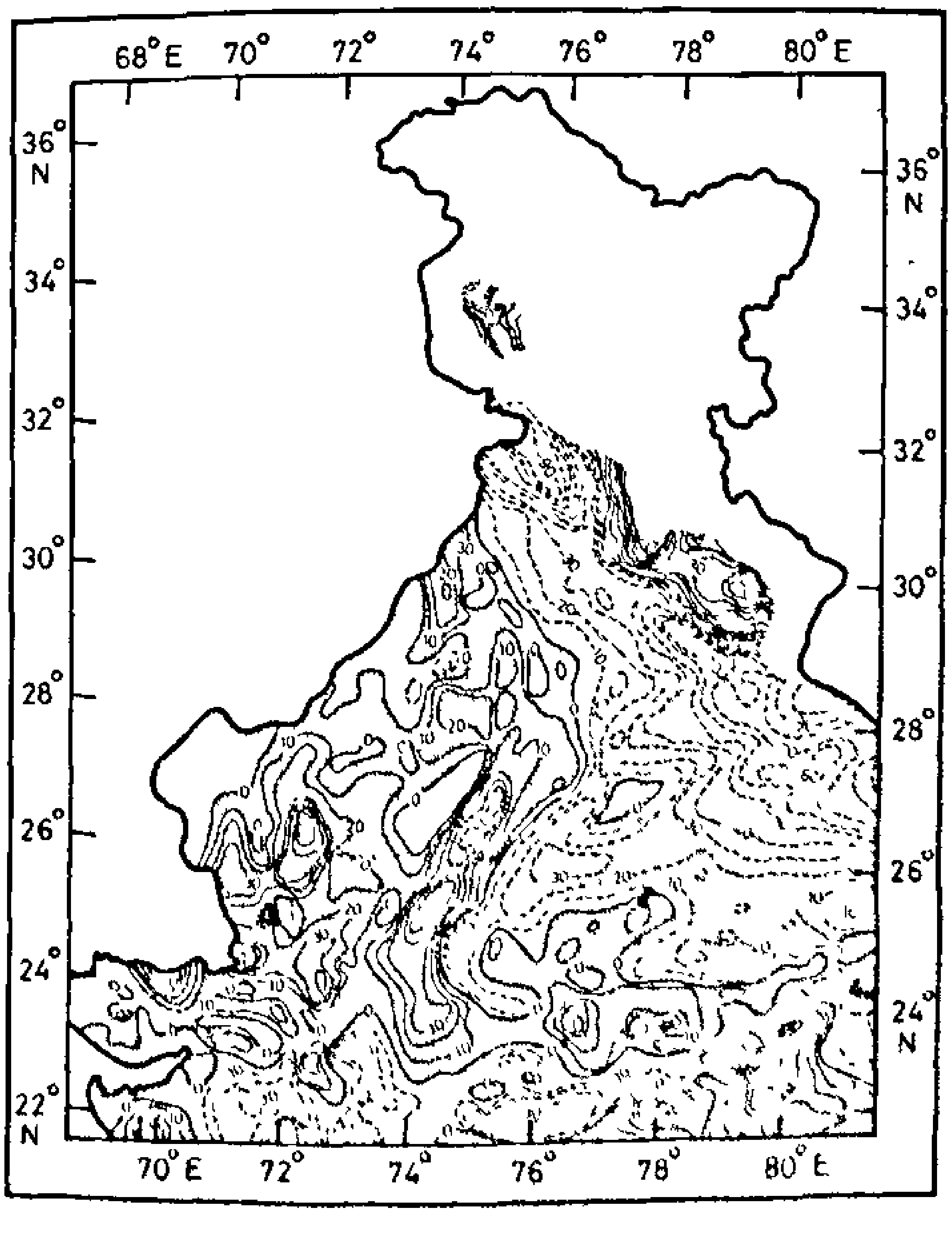

Figure 5. Isostasy map for NW India, extracted from the NGRI gravity map[49]. Note the large positive values over the Aravalli and Marwar Terrain

are suggestive of possible thickening of the basaltic layer. This may be considered to indicate that the crust beneath the Marwar terrain is of the transition type (continental to oceanic). This inference is in agreement with the conceptual model of Sinha Roy[9] who visualizes shallow angle underthrusting of the Delhi oceanic crust beneath the west Rajasthan craton.

The source of high conductivity at mid-crustal depth is the hot saline water released during prograde metamorphic reactions[4,5]. A temperature of 400° C is essential to initiate dehydration process, whereas at temperatures above 500–600° C, the plasticity of the medium does not allow interconnectivity of fluid-filled pores[34,35]. This source mechanism for enhanced conductivity explains why a limited section of thickened basaltic layer and not the entire layer may become conducting.

Shear wave velocity structure beneath Himalayan foredeep

Chun[36] investigated the crustal shear wave velocity structure in Western Indo-Gangetic Plain (WIGP) and compared it with that obtained by Chaudhary[37] for the Eastern Indo-Gangetic Plains (EIGP). The shear wave velocity models (Figure 6), have several features in common: both have a thick (3 to 4 km) surficial low velocity layer, a 40 km thick crust, and a low upper mantle velocity (4.50 km/sec). However, between 10 and 40 km depth the inferred velocity in WIGP is consistently and significantly higher than that beneath the EIGP—and quite higher than that expected beneath normal continental shield. In the shallow depth range of 10–20 km, the shear velocity is 3.80 km/s,.a value normally associated with basaltic or gabbroic rocks. In continental regions, such a high velocity is found only in the lower crust. Modelled as single layer, the lower half crust has an estimated velocity of 3.98 km/s. Note that the shear wave velocity in the upper mantle does not vary from east to west in the IGP region. These observations agree with the results of Gupta *et al.*[38] who showed shield like upper mantle velocity structure beneath the entire IGP.

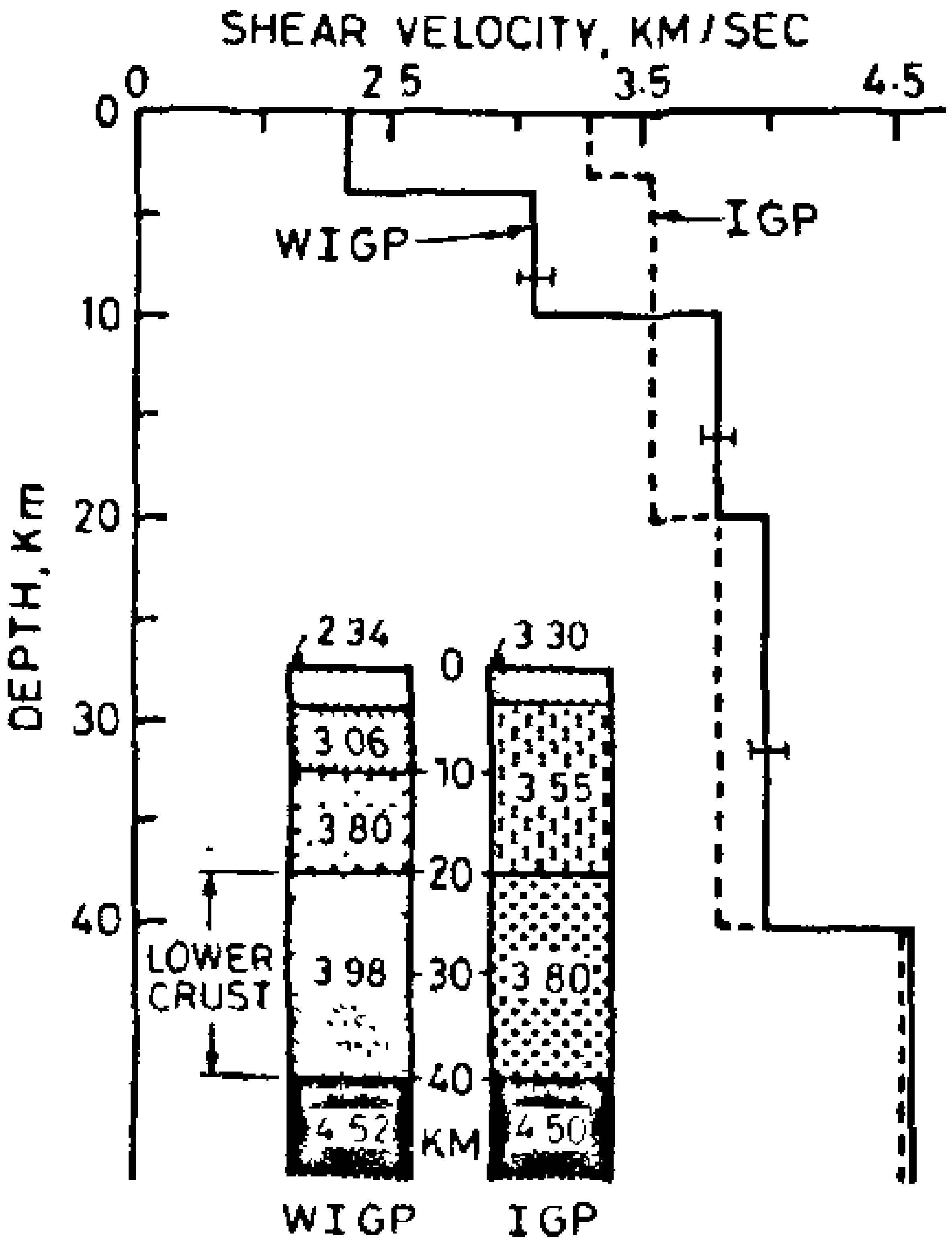

Figure 6. Shear wave velocity model for the western and entire Indo-Gangetic Plains (IGP) shown in two complementary manner (modified from Chun[36]).

Crust beneath Indo-Gangetic plains based on gravity data

Some characteristic east-west differences in the nature of crust beneath the Himalayan foredeep have been indicated from the analysis of four gravity profiles (Figure 1). Extending from Indian shield to Himalayan belt, the profiles are roughly at right angles to the Himalayan collision zone. The inverse relationship between topography (elevation) and Bouguer anomaly along all the profiles[39] (Figure 7) suggests that isostatic compensation[40–42] occurs largely due to the thickening of the crust.

For the given density contrast, the residual gravity variation along four profiles shows characteristic differences, the transition occurring along a boundary roughly coinciding with the position of the identified THC. The residual gravity anomalies along the Udhampur-Kargil and Chandigarh-Leh profiles for density contrast of −0.6 g/cc (2.67 and 3.27 g/cc for the crust and mantle respectively) show large positive values of the order of 200 mGal over Himalayan belt, indicating considerable isostatic under-compensation. In contrast, the residual anomalies along the Rishikesh-Geldung and Khatima-Kalapani profiles are characterized by small positive values of 40 mGals suggesting near isostatic balance. However, when anomalous crust is assumed to have a density contrast of −0.43 (2.84 and 3.27 g/cc for the crust and mantle, respectively) the picture is almost reversed. The large negative residual gravity anomaly over the Himalayan belt along the Rishikesh-Geldung and Khatima-Kalapani profiles indicates over-compensation, whereas the residual anomalies on the first two profiles show marginal positive gravity values over the Himalayan belt. This contradictory behaviour can be explained if it is envisaged that the nature of anomalous crust along the Udhampur-Kargil and Chandigarh-Leh profiles, to the west of the THC is quite distinct from that beneath Rishikesh-Geldung and Khatima-Kalapani profiles to the east of the THC. With more dense crust (2.84 g/cc) along the WIGP (as compared to normal crust

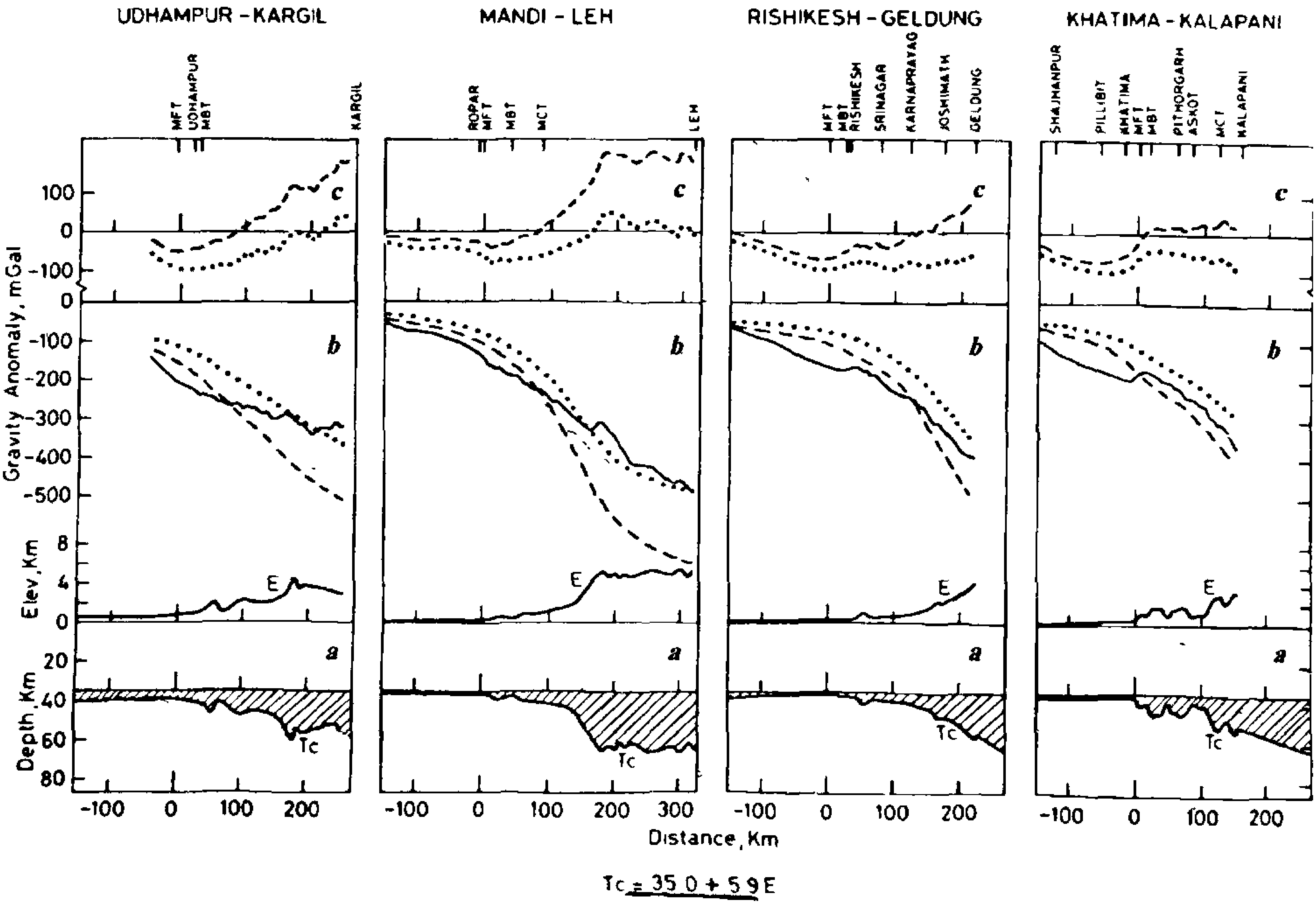

Figure 7. Gravity and related parameters along four profiles shown as I and IV in Figure 1 (modified from Sivaji *et al.*[40]). **a**. The elevation (E) and calculated base of crust ($T_c = 35 + 5.95$ E). ***b***. Observed Bouguer anomaly (solid lines) and calculated gravity effects for thickened crust (shown as hatched area in (*a*) for two density contrast of −0.43 g/cc (dotted line) and −0.6 g/cc (dashed line). ***c***, Residual anomalies (observed Bouguer anomaly minus calculated effect of roots for above referred density contrast).

(2.67 g/cc) to the east), the residual anomalies along the four profiles show similar behaviour.

Discussion

The above-noted anomalies in electrical conductivity, gravity, seismic wave velocities and heat-flow data over NW India are all indicative of the quite different character of the crust beneath the floor of the WIGP (Punjab shelf), which appears to extend beneath the Marwar (western Rajasthan) terrain. Over the IGP, the gravity anomalies and seismic wave velocities are more conspicuous of east-west differences in the character of the crust with the THC forming an effective tectonic boundary between contrasting crustal blocks. The high shear wave velocities in the crustal section beneath the WIGP compared to that in the EIGP, suggest a change in the nature of crust. This is possibly asociated with the change in the thickness or composition of crustal layers. The shear wave velocity of 3.8 km/s, typical of basalt, in shallow depth range of 10–20 km beneath the WIGP is indicative of thickening of the basaltic layer. This inference is corroborated by the gravity anomalies. The noted differences in the behaviour of gravity variation along four profiles running across the Himalaya disappear by the incorporation of thickened dense crust—a conclusion in agreement with the shear wave velocity structure beneath the WIGP. The positive isostatic anomaly prevailing over the Marwar terrain may further indicate that the thickened basaltic crust is perhaps characteristic of a large part of the Trans-Aravalli block. The geoelectric model (Figure 4) which simulates a step-like structure in the basaltic layer for explaining the induction effects associated with the Trans-Aravalli Conductor, provides further support to the deduction that there is a change in the nature of crust beneath the Trans-Aravalli block. In the geoelectrical model (Figure 4), only a section of the thickened basaltic layer is considered to be highly conducting due to the presence of some fluids. Comparing the crustal structure of the WIGP and

EIGP, so inferred from shear wave velocities, with those of typical oceanic and continental models[43] Chun[36] inferred that the WIGP crust bears a remarkable resemblance to the Ontong Java and Seychells Bank of the oceanic plateaus with the thickest known crust[44]. This led Chun[36] to suggest that the crustal block underlying the sediments of the WIGP has an oceanic affinity which became attached to the continental type of crustal block beneath the EIGP by collision. Some independent features which provide further support may be attributed to the east-west asymmetry of the crust beneath the IGP: (a) early arrival of P-waves coming from earthquakes generated in the Hindukush region to sites in Garhwal Himalayan[45], (b) higher P-wave velocity (6.5 km/s) in the basement of the WIGP — more than usually associated with shallow part of the continental crust[46], and (c) variation in the slip vectors of earthquakes across the length of the Himalaya[47] from less than 10° in the eastern Himalaya to 20–25° in the Western Himalaya[48]. The observed east-west variation in the plunge of the slip vector may be intimately related to deep-seated crustal complexity within the underthrusting Indian sub-continent[36], as suggested by the large east-west variation in the crustal velocity structure across the IGP.

Some of the common features seen on diverse geophysical parameters strengthen the deduction that the tectonic framework of NW Indian shield is a mosaic of different crustal blocks welded together during the Proterozoic[12]. The Trans-Aravalli block, including western part of the IGP, possibly represents fragments of the oceanic plateau which was welded to the continental Bundelkhand block east of Aravalli. Beneath the IGP the two blocks of contrasting nature are welded along the THC, which was considered by Lilley *et al.*[15] to be the sub-basement continuation of the Aravalli beneath the Indo-Gangetic Plains. The reversal of vertical field variation across the THC is indicative of an elongated structure rather than a simple contact of blocks of contrasting electrical properties. Elucidating on the post-orogenic tectonism of the Aravalli, Ahmed and Ahmed[10] postulated that central Aravalli range was uplifted as a horst between the Sardarshehr Fault in the west and the Great Boundary Fault in the east during the Quaternary period. Sen and Sen[11] ascribed this post-Neogene tectonism in central Aravalli to flexural bending of the Indian Plate by a movement generated at the back due to the locking of the Indian and Eurasian plates by early Pleistocene time. The upwarping of the middle crust, noted in the geoelectrical model of the Trans-Himalayan Conductor (Figure 3), probably manifests the rejuvenated feature of this early Quaternary tectonism, and also explains the linkage of the THC with the Aravalli mountain range. The clustering of epicentres of recent low and moderate intensity shallow focus earthquakes along the THC[22] bears further testimony to the continued activation of ancient structure. The metamorphic dehydration coupled with invasion of mantle generated fluids as a consequence of collision and attendant crustal interstacking are the most likely causes of enhanced conductivity in the inferred tectonic setting.

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Quaternary sedimentation in the Indo-Gangetic Basin: A review

Charu C. Pant and A. K. Sharma

Department of Geology, Kumaun University, Nainital 263 002, India

The Indo-Gangetic Basin of molasse developed during the Palaeocene is still an active foreland basin. Recent work by ONGC in connection with hydrocarbon exploration has provided extensive information about basin configuration and various structural elements. The alluvial succession is made up of Paleistocene to Holocene sediments, the youngest Holocene being dominated by thick elongate mega-fans of fluvial sediments. The various lines of evidence show the orogenic belts that divide the Indo-Gangetic basin in neotectonically an active domain.

Introduction

THE Indo-Gangetic Basin comprising very thick sediments of the order of 10 km developed as a result of collision of the Indian and Asian continental plates[1–3]. The intraplate subduction along the Main Central Thrust (MCT) caused the 20-km upliftment of the Great Himalaya, exposing the basement rocks to fast erosion and attendant sediment generation, the 'popping up' of southern Himalayan province, and the subsidence of the northern part of the Indian plate to form the Indo-Gangetic Basin. With continued northward push of the Indian Plate, the southern areas also rose up and contributed sediments. The movements in the mid-Pliocene and subduction of the Peninsular Indian plate bearing a large prism of the Siwalik molasse at its front, took place along the Main Boundary Thrust (MBT). Subsequent folding of the northern edge of the Indian Peninsular plate gave rise to the Siwalik ranges during the early Pleistocene. Subject to cannibalism in the subsequent period, the Siwalik has greatly contributed to the sediment influx into the Basin.

In the Indo Gangetic Basin (Figure 1) paralleling the Himalayan Province, sedimentation started with the shallow marine environment which changed to estuarine-deltaic and finally to fluvial. It was during the mid-Miocene that continental sedimentation, mainly under fluvial environment, started and has continued till the present. The Basin had an uneven configuration characterized by a number of ridges and faults extending from the Peninsular shield. These features largely controlled the dispersal of currents and resultant sedimentation. The Basin had predominently transverse dispersal pattern, controlled by southerly flowing rivers descending from the Himalayan domain.

The present work, dealing mainly with the evolutionary history of the Indo-Gangetic Basin (IGB) is a brief synthesis of the studies carried out by many workers on the most productive geological province of