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An excursion into the past—'the Deccan volcanic episode'

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Sahni took a keen interest in the study of the Deccan traps, especially the timing of this stupendous burst of volcanic activity which covered a third part of the Indian continent. He was the first to use fossil plant evidence to prove that lavas were extruded rapidly within a short duration at the dawn of the Tertiary era. The status of our present knowledge of the Deccan volcanic episodes and the light it throws on the evolution of the Indian continental lithosphere is briefly reviewed.

MORE than fifty years ago, as a student just out from the college, I had the privilege of hearing Professor Birbal Sahni. He had come to Madras to preside over the Indian Science Congress and was passing through Bangalore. A public lecture had been arranged which was presided over by C. V. Raman. I do not recollect what Sahni talked about on that occasion, but I distinctly remember his deftly manipulating a working model of Gondwana continent which had all the different continental segments of the Gondwanaland assembled. As he turned a lever, the continents began to move away occupying new positions. Again and again Sahni operated the lever and made continents move, thus giving a visual demonstration of the drift of continents, a hypothesis which had taken the world by storm in the early part of the present century.

Those were days of heated controversy over the Wegener's theory of continental drift. Physicists were on a war path and condemned geologists for their belief in 'so naive a theory'. Geologists were in a woeful minority and could, at that time, provide no convincing quantitative proof. Sahni was a staunch supporter of the continental drift theory and often came to the rescue of geologists.

Sahni realized that India held a key position in the assembly of Gondwana continents. It was also one fragment of the Gondwana which had travelled the longest distance from its original position 30° south of the equator to its present location 30° to the north. In this long drift it necessarily had to traverse many climatic zones. Sahni argued that fossil plants could provide impressive evidence of the changing climatic conditions, lending support to the belief that the Indian continental fragment had shifted its position during the past.

An important aspect of the New Geology that has emerged during the last twenty years is its ability to integrate all knowledge, gathered from various sources. Sahni had realized this important role of the geologist as an integrator of knowledge and strove to bring members of the two disciplines together. It is my object to underscore in this article the importance of the study of the Deccan traps in tracing the evolution of the Indian continental lithosphere.

Deccan volcanic episode

The Deccan traps in western India represent one of the largest accumulations of continental lava flows covering an area of over a million square kilometers with an average present-day exposed thickness of over 1000 m. The importance of this volcanic episode lies in the fact that it occurred around 65 Ma (million years ago), at the junction of the Cretaceous and the Tertiary. Earlier, it was thought that the trap activity was spread over many million years, but recent geochronological and palaeomagnetic researches seem to indicate the possibility of a shorter duration of volcanic activity around 65

Ma (refs. 1–4). On purely geological considerations, West[5] had anticipated this new development. He had argued, based on the absence of weathering between individual flows that the eruptions had taken place in quick succession over a shorter period and did not extend to tens of millions of years. Deccan volcanism with its burst of tremendous volcanic activity, all of a sudden at the close of the Cretaceous and the dawn of the Tertiary, therefore, represents a major geological event of global importance.

Faunal extinction

The extinction of nearly 90% of the fauna and flora at the Cretaceous–Tertiary boundary is a remarkable fact. A whole range of large reptiles (Dinosaurs) and ammonites became extinct at the end of Cretaceous. Gymnosperms declined and there was a great flowering of angiosperms at about this time. The cause of extinction has remained a subject of controversy. The magnitude and the suddenness of the volcanic activity at the end of Cretaceous, it is believed, created an abrupt change in environment, causing the extinction of plant and animal species. If the volcanism was spread out over a longer period, perhaps the animals would have had a chance to acclimatize themselves to the changed conditions and survived. This was obviously not the case with the Deccan volcanism. In the words of Sahni[6], 'this terrible drama of fire and thunder was a brief episode of the very earliest part of Eocene'.

Cause of volcanic activity: extraterrestrial impact?

There has been speculation as to the cause of this sudden burst of volcanic activity. One view is that it was caused through the impact of a giant extraterrestrial object (asteroid) which hit the earth around 65 Ma. The impact is supposed to have triggered Deccan volcanism[7]. The impact crater is believed to have been large enough to cause pressure relief in the mantle and flooding of the crater to form a lava lake. With the accumulation of lava in such a lake, the whole basin sank to give it the shape of a large saucer. The sudden extinction of dinosaurs around this time, the presence of iridium anomaly and shocked quartz in other areas have been invoked as evidences for subscribing to this impact model. Many, however, are sceptic and do not believe that a meteorite could punch a hole in the crust deep enough to tap the magma from the mantle. No pronounced iridium anomaly has been observed in the Deccan.

Reunion hot spot and Deccan volcanism

Hot spots are certain localized volcanic centres in the earth's lithosphere, 200–300 km across, which have remained active for several million years. It is believed that they are stationary, anchored in the deep layer of the earth and have not changed their position with respect to the lithospheric cover above, which shows evidence of having moved over long distances. They thus provide a 'frame of reference' for plate motions following the disintegration of Gondwanaland[8]. The source of hot spot volcano is ascribed to a plume rising from deep within the mantle. When a lithosphere plate moves over such a stationary plume, it leaves a trail of volcanoes that grow older with distance from the present site of volcanic activity (Figure 1), in much the same way as wind passing over a chimney carries off smoke. The volcanic rocks left behind along the track are considered as milestones that mark the different stages of the passage of the lithospheric plate with reference to the stationary hot spot. The group of Hawaii Islands are cited as classic examples of hot-spot activity over a moving plate[9]. Plumes may not reach

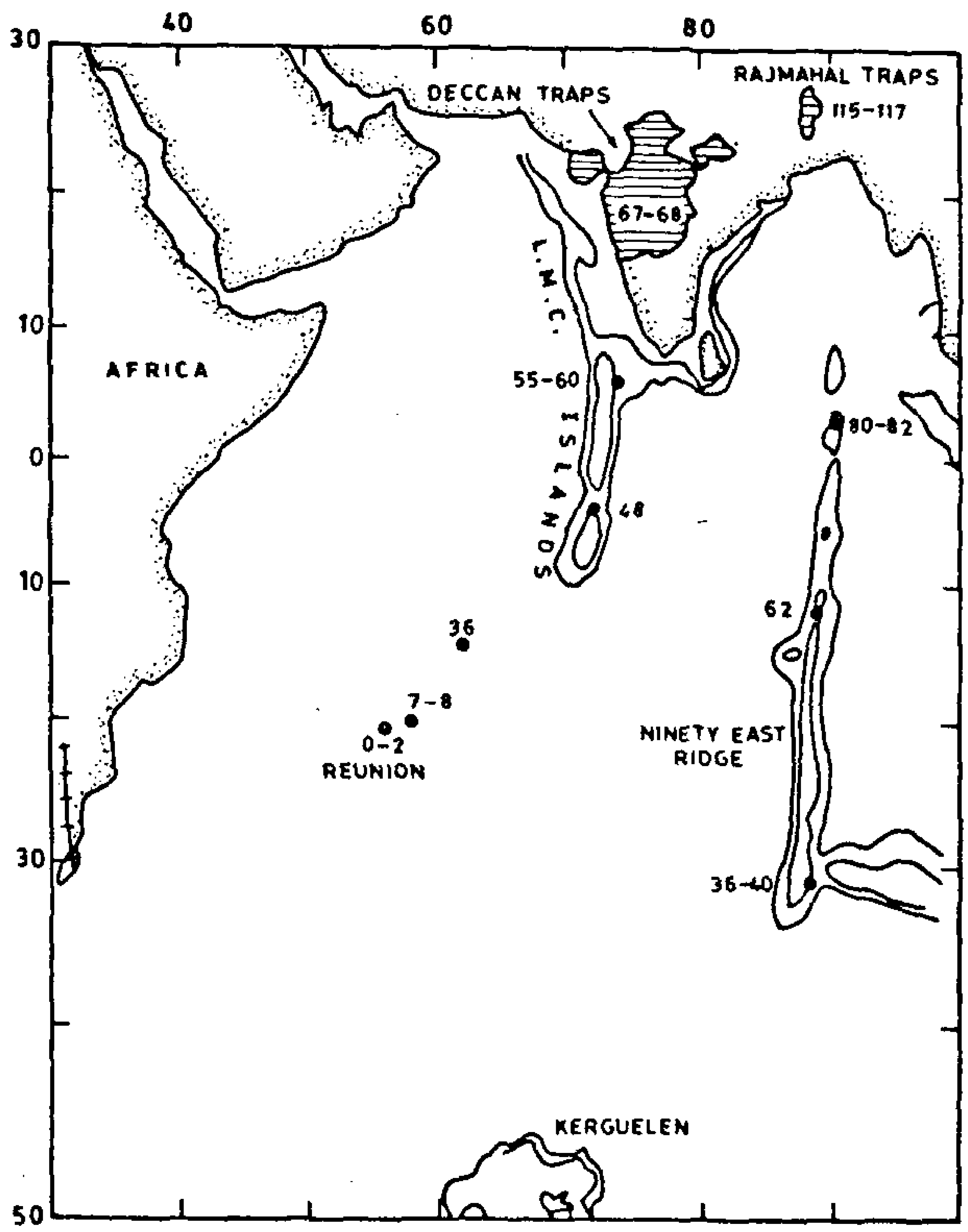

Figure 1. Suggested track followed by India with reference to the Reunion and Keruguelen hot spots in the Indian Ocean. Note the increasing ages over the track as the Indian continent is followed northward (Figure after Duncan and Pyle[3]).

the surface always. They melt the rocks above them to create magma, setting off volcanic eruptions.

Morgan[10] suggested the possible relationship of Deccan volcanism to the passage of India over the Reunion hot spot (Figure 1). Raval[11] of the National Geophysical Research Institute, Hyderabad, has given further thought to the effect of the Reunion and Kergulean hot spots on the moving Indian plate when it passed over them in its northward journey. Figure 2 shows the suggested trace of the two hot spots according to Raval. The interesting point to note is the deflection in the direction of both the tracks, one to the west and the other to the east of the Indian continent. In the case of the Reunion hot spot, the initial track lay below the Delhi–Aravalli fold belt. When this track cut the Narmada–Son lineament, a zone of weakness since the Proterozoic, there was a burst of volcanic activity and Deccan volcanism resulted. In the eastern segment too, the track was initially NE–SW, but rotated anticlockwise around Rajamahal, giving rise to the Rajamahal Traps. Thereafter, the direction of extension of both the tracks was N–S, the Reunion spot lining up with the Laccadives (Lakshadweep)–Maldives–Chagros ridge and the Kergulean track marked by the Ninety East Ridge (NER). The burst of volcanic activity in both instances seems to have coincided with a change in the direction of movement of the Indian plate. As the Indian plate progressed in its journey northward, volcanic activity apparently died down, leaving only a trail of volcanoes represented by a series of islands and narrow ridges in the present day Indian Ocean (Figure 1).

Plateau uplift

One of the consequences of hot spot activity is thermal expansion (see Figure 3) and a domal arching of the crust along the hot spot track. Since the plume volcano has left a track, it is logical to expect evidences of regional uplift all along the track. The uplift of the Aravalli–Delhi region, as also the regional uplift of the Peninsular Indian shield can best be explained as the result of such a thermal swell along the track of the Reunion hot spot. The uplift of the Peninsula can thus be the effect of what Crough[12,13] has called hot spot epeirogeny. The whole of Peninsular India is characterized by strong negative anomaly and according to Kailasam[14], plateau uplift was apparently related to the thermal processes in the earth.

The drainage pattern of the Peninsula of India is indicative of such a regional uplift. The easterly drainage of the Peninsula (Figure 4) was imposed as a result of uplift. Most of the rivers are antecedant or

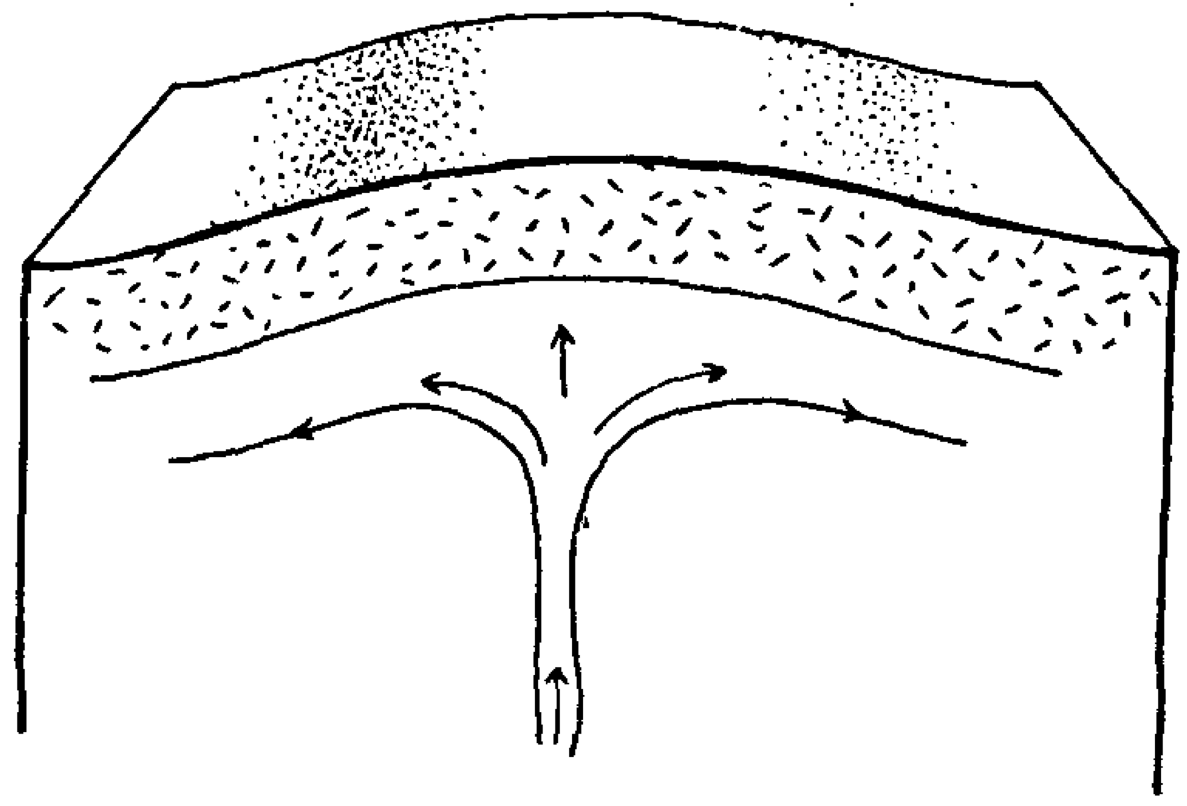

Figure 3. Expansion and swell in the crust above a mantle plume.

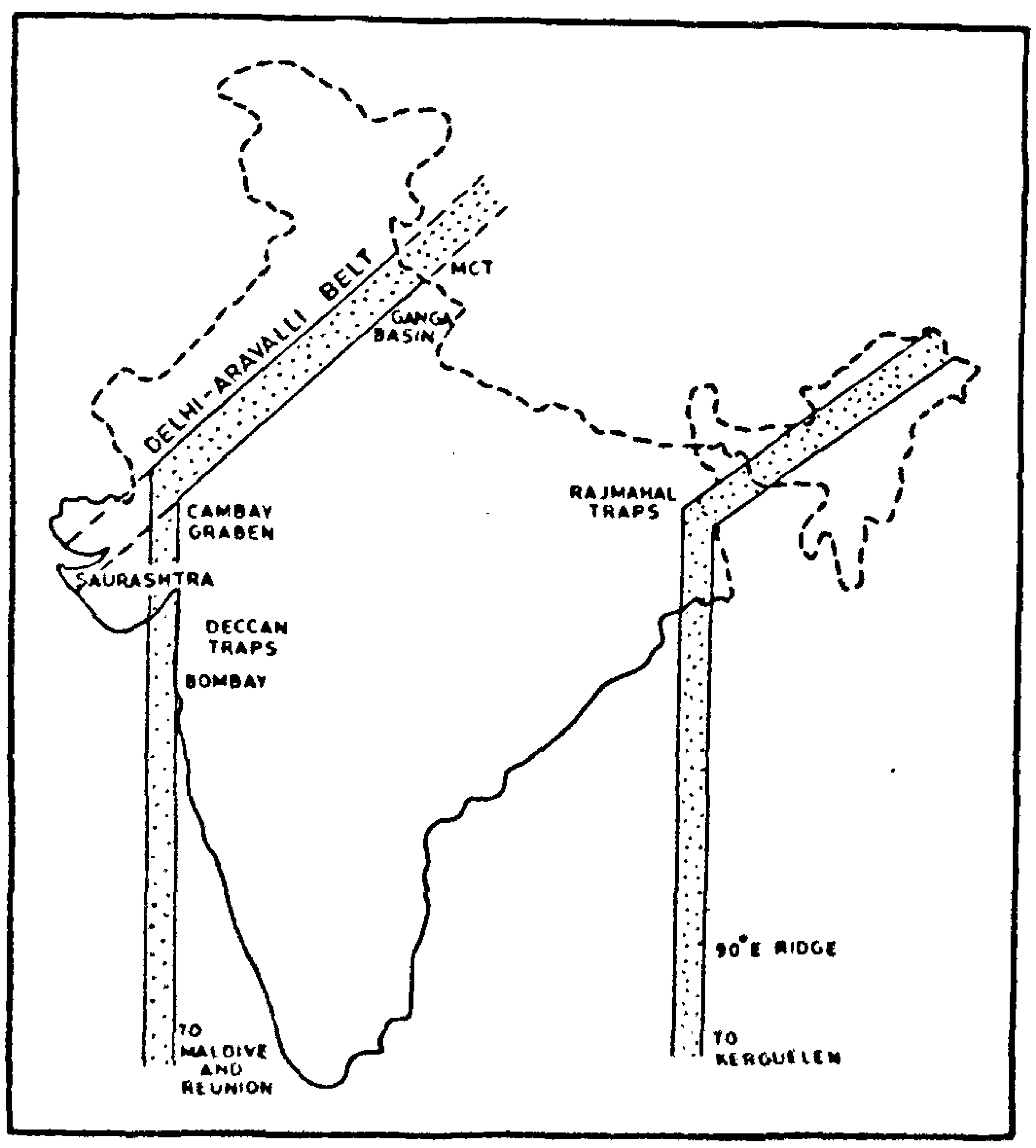

Figure 2. The suggested deflection in the hot-spot track according to Raval[11]). See text for explanation.

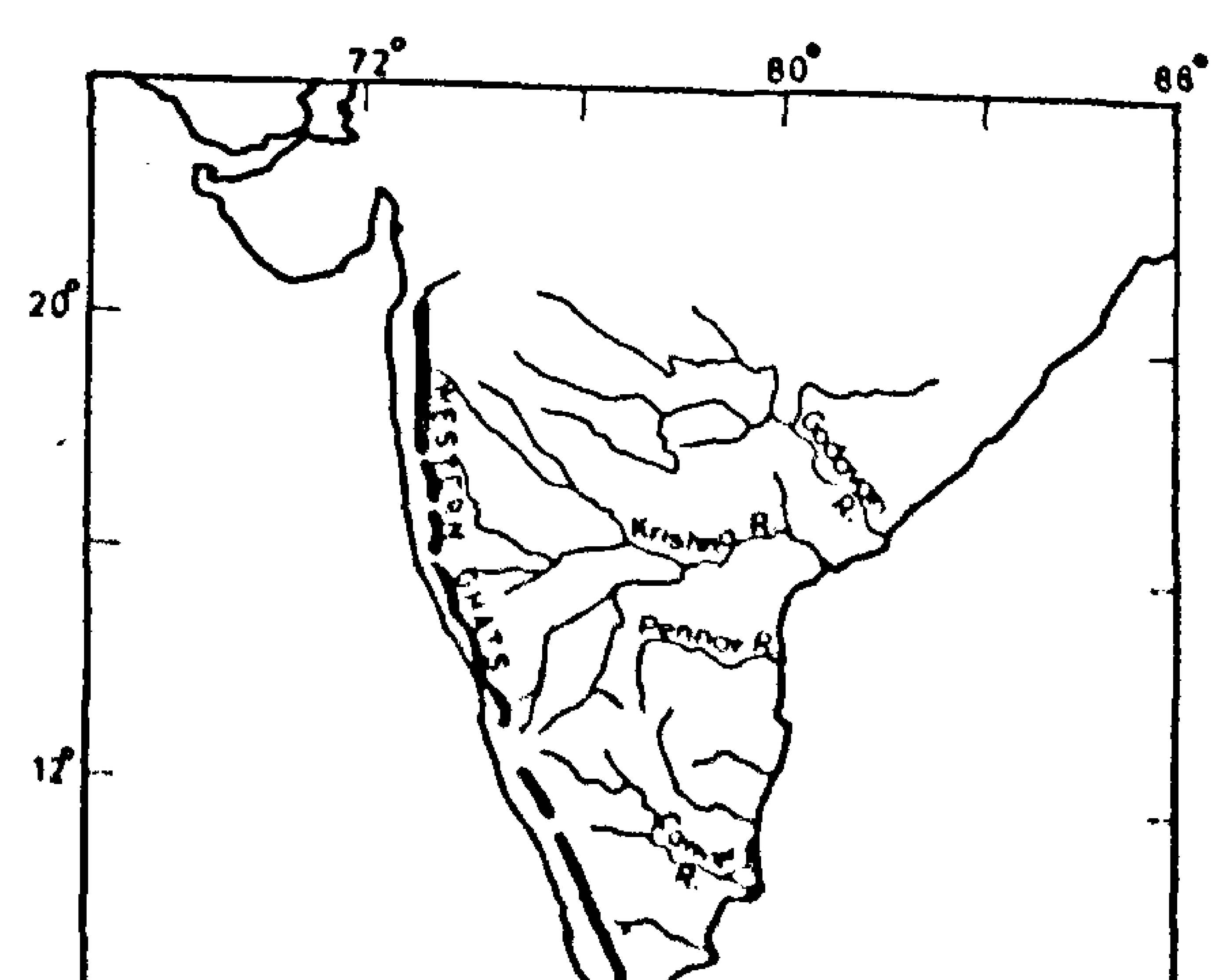

Figure 4. The predominantly easterly drainage of the Peninsula – a result of domal uplift.

superposed. When uplift began, they were able to deepen their channels at a rate that matched or even exceeded the rate of uplift[15]. The Western Ghats is an area of uplift and dynamic change, giving rise to a continuous evolution in the landscape[15].

An opinion has been expressed that as much as 5.5 km of the structurally upper part of the trap has been removed by uplift and erosion[16]. There is no geological evidence for the removal of such a great thickness of trap. Laterite cover still exists on top of the surviving plateau. There is evidence of extensive erosion laterally, but not vertically.

Rifting

A further consequence of such domal uplift was the development of tension and rifting as witnessed by numerous fissures and dyke swarms around the crest of the dome. The tri-junctional rifting of the Narmada and the Cambay (Figure 5) can be cited as examples of rifts which failed to open to form oceans, but remained as fault bounded intra-cratonic basins or aulacogens[17,18]. The continent also developed a major rift along the axial track of the hot spot, splitting the continent and separating the Seychelles from Peninsular India (Figure 5).

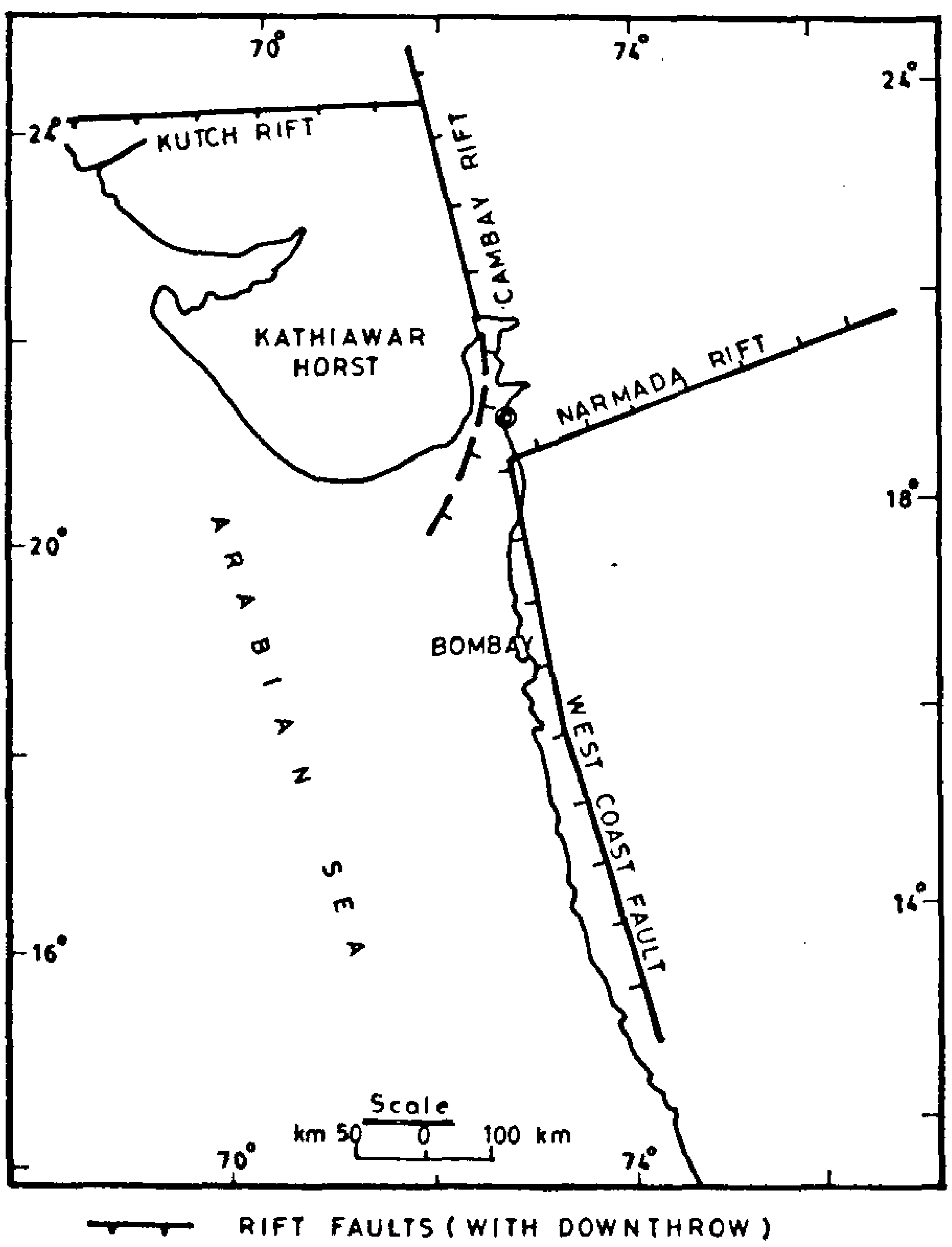

Figure 5. Rifts and grabens developing along the axial track of the hot spot.

Morgan[10] has pointed out that many hot spot tracks could form the locus of local rifting. Hooper[19] has cogently argued that the primary event was upwelling of magma which was followed by crustal extension and rifting.

In the graben which developed to the west of the present day west coast, sediments of Palaeocene and younger ages were deposited. The landward extension of this graben to the north is represented by the Cambay basin. The Chagros–Laccadive archipelago to the south is best considered as the rifted western component of India which separated from the northward moving Indian plate, got submerged and trailed behind as a submerged platform.

Rifts and regions of high heat flow

These rifted belts are also regions of high heat flow. Temperatures recorded in the deep drill hole in the Cambay Graben showed values of 170°C. Many thermal springs are known along the Konkan Coast[20]. More intensive research on the pattern of heat flow along the projected path of the hot spot track could furnish confirmatory evidence.

Geomorphic consequences

The consequences of such domal uplift on the drainage are profound. One of the striking physiographic peculiarities of the Peninsula is its markedly eastward drainage with almost all the major rivers of the Peninsula taking their birth in the Western Ghats at the very edge of the continent and flowing eastwards all the way to the Bay of Bengal. This peculiar character of the drainage had been noticed by many earlier workers. They had explained it on the basis that the Western Ghats formed a watershed at the centre of an ancient landmass and that the portion lying to the west of the Ghats drifted and floundered beneath the waters of the Arabian sea.

The Western Ghats, extending for over a length of 1500 km, lying parallel to the coast hardly 50 km away, form one of the most magnificent escarpments of late Tertiary age. Except for a short gap near Palghat, it is unbroken throughout its length.

The earlier geologists, however, had considered the Peninsula as an ancient land surface remaining undisturbed subject only to subaerial denudation. That such a view was not tenable was first pointed out by Radhakrishna in 1952. The marked diversity of landscape, the youthful character of the rivers, the precipitous escarpments, the narrow gorges and the relative high elevation of the plateau compared to the plains, he pointed out, could be best explained by considering the Peninsula as having suffered from a domal uplift in comparatively recent times[21,22]. The cause of domal uplift over such an extended region was not clear at that time. Hot spot thermal plume activity now furnishes a satisfactory explanation for the regional uplift all along the track of the hot spot. Cox[23,24] conceived of a domal uplift around the centre of volcanic activity, NE of Bombay. If that were so the drainage pattern would have to be radial. The dominantly easterly drainage of the Peninsula is more in keeping with an uplift all along the track of the hot spot running parallel to the present day west coast of India.

Cyclic erosion surfaces

The major uplift took place soon after the out-pouring of the Deccan lavas, i.e. at the dawn of the Tertiary era. At least three surfaces can be recognized: Late Cretaceous (Nilgiri surface), Mid Tertiary (Mysore plateau) and Late Tertiary (Tamil Nadu plains) surfaces. The oldest surface is preserved in the high plateau of the Nilgiris and the high ranges of the Western Ghats. The peninsular region continued to be affected by intermittent episodic uplifts during subsequent periods as exemplified by the identification of different erosion surfaces over the plateau[15,21,25–27]. These surfaces have been identified based on recognition of accordant summits, study of projected profiles and flat areas of considerable extent and occasional *in situ* lateritic cover[28]. There are generally steep scarps separating the individual surfaces. Remnants of the higher surface are preserved, lending support to the scarp retreat model of King[29].

The intermittent uplifts were the result of isostatic adjustments and transfer of sediments from the land to the ocean basins along the east coast (Figure 6). Attempts are being made to link up stratigraphic columns in the sedimentary basins with the uplifted erosional surfaces on the land to arrive at tentative relative ages of the surfaces[26,27]. The Western Ghats represent a tectonically active region with high rates of uplift, high summit altitudes, steep slopes, deep gorges and large potential energy for erosion and correspondingly high sediment yields. It also provides excellent examples of river capture and diversion of the easterly drainage to the west. The Sharavati and Kali

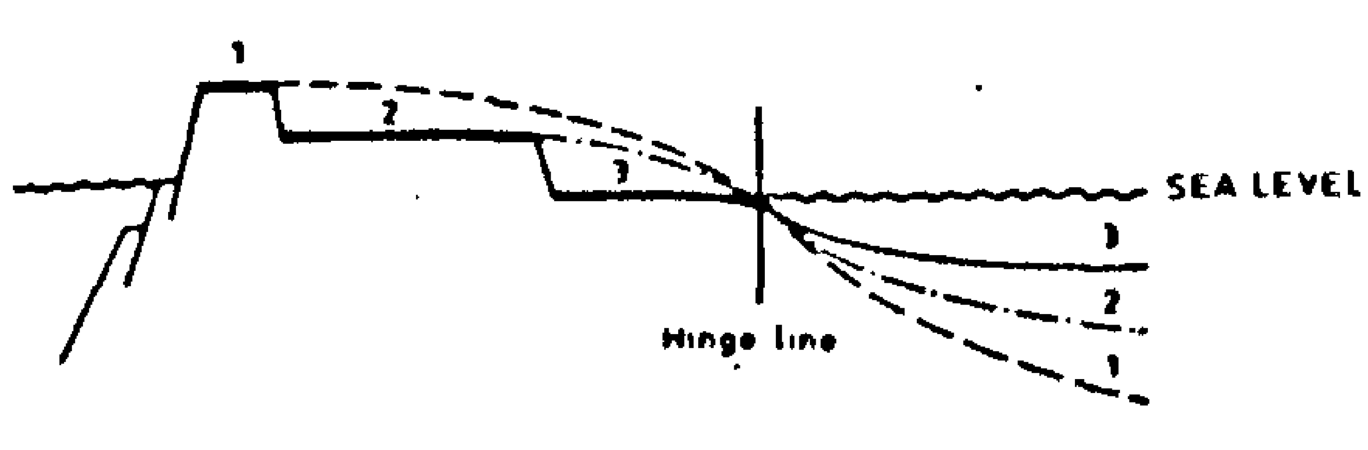

Figure 6. The three cyclic erosional surfaces which can be recognized over the Indian Peninsula and their seaward extension.

are two classical examples of such westerly diversion of drainage as a result of uplift and faulting[30].

The Deccan plateau forms an impressive example of uplift and rock sculpture, of constructive as well as destructive forces of Nature. The landscape around Arthur Dam at Bhandardara near Kalsubai Hill range in Western Deccan is not dissimilar to the scene around Naini Tal in the Himalaya, both examples of Quaternary landscape evolution, the result of recent uplift.

Development of rifts

One other important effect of hot-spot activity requires to be considered. The hot-spot track represents the axis of uplift. It was also a region of weakness along which the continent could most easily split. The continental fragment lying to the west of the Western Ghat apparently parted as a result of rift developing along the axis of the uplift. The western coastline as well the Western Ghat scarp were formed as a consequence of the rift and the drifting away of the western half. The monoclinal Panvel flexure was the result of drag at the time of rifting and floundering of segments of the scarp along the west coast. Orographic-controlled Indian monsoon resulted ushering in the present day climatic pattern over the Indian sub-continent.

Figure 7 depicts the different stages in the evolution of the Deccan plateau, commencing from the outpouring of vast quantities of lava over a pene-plained surface, (i) the sinking of the floor to form a saucer-like depression, (ii) subsequent domal uplift, (iii) leading to rifting, and (iv) down-faulting of the segments and, (v) finally to the sculpturing of the Western Ghats and the west coast of India. Table 1 outlines the different stages of this development.

If the above model is correct, we should expect record of thermal regeneration beneath the Aravalli-Delhi belt around 100 to 80 Ma and older ages for the trap from further north latitude. Younger ages are to be expected as we follow volcanic activity southwards right up to Reunion Islands.

Duncan and Pyle[3] (Figure 1) have demonstrated how Deccan basalts lie at the northern end of the volcanic track of the Reunion hot spot. The ages of volcanoes decrease followed southward. A similar pattern is observed in the case of the hot-spot track represented by Keruguelen Islands, the Ninety East Ridge and the Rajmahal traps. These two lines appear to mark the track along which India had moved northward. The close correspondence between the observed and predicted ages and high heat flow along the track lends support to the correctness of the new interpretation.

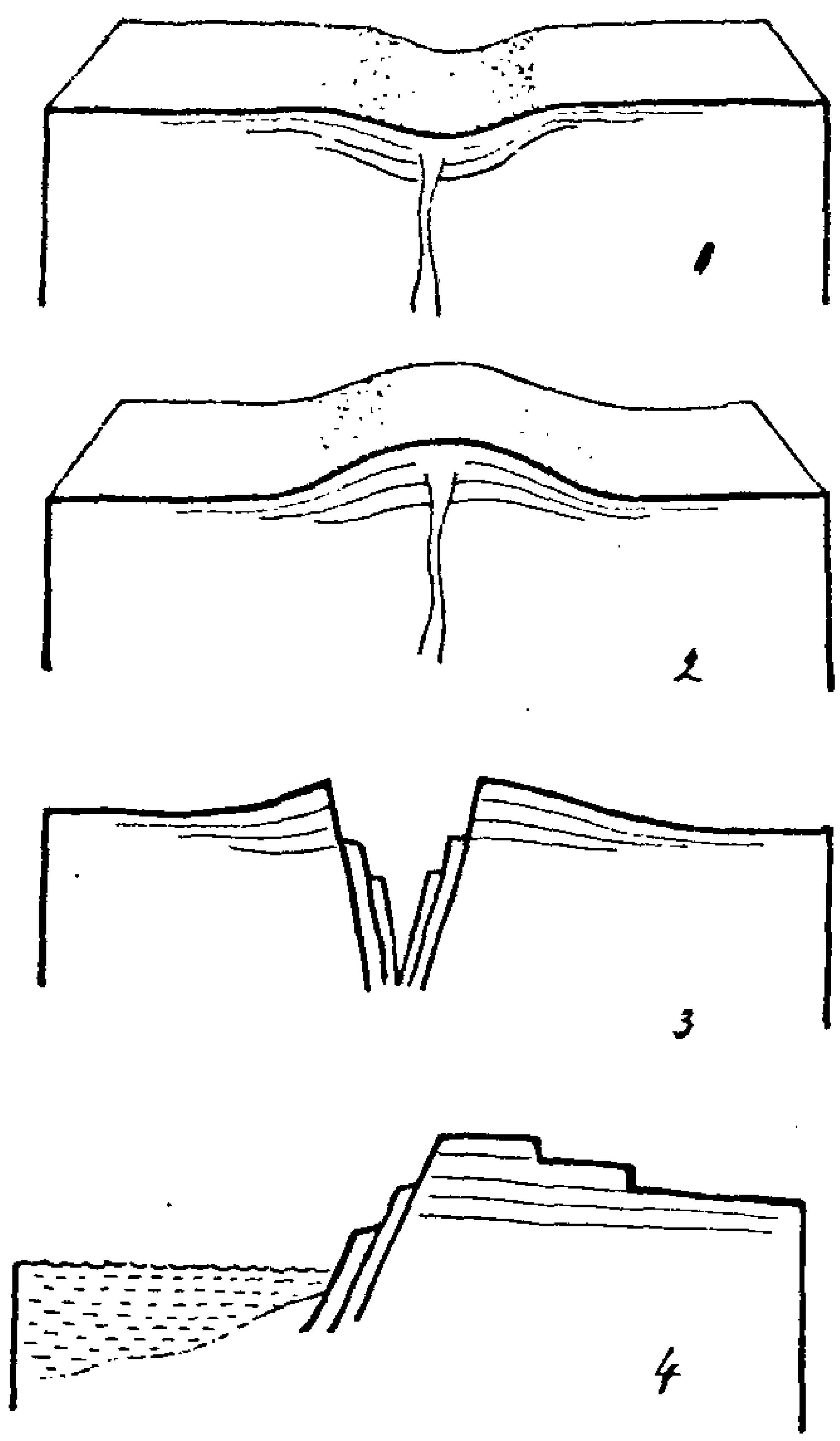

Figure 7. Stages in the evolution of the Peninsular landscape.

Table 1. Outline of Geomorphic events.

Pleistocene and Recent	Upwarps and downwarps; reduction of old plateau to new plateau surface Episodic uplift due to erosion and unloading of trap cover Alternation of short wet spells with long aridity; formation of black soil
Pliocene	Deep weathering of the basaltic rocks—shallow lagoonal condition; formation of clayey black soil
Miocene	Break-up and floundering of the western segment and faulting of the west coast of India–creation of the Western Ghats scarp–establishment of monsoonic rainfall pattern–rapid erosion and retreat of Western Ghat scarp–drainage reversals
Palaeocene	Uplift and upwarp of laterite covered surface (uplift maximum in Western Ghat region which formed the central axial region) Epeirogenic uplift reflected in downwarp along the east coast where older surfaces pass below sea level Formation of laterite over parts of the trap surface Northward migration of India–shifting of centre of volcanic activity leaving a trail behind
Cretacious/ Tertiary Boundary	Indian plate passing over the Reunion hot spot – extensive volcanism – shield volcano type with its centre near Narmada–Bombay–Cambay triple junction – spread of lavas all round
Late Cretaceous	A land surface of low relief – surface covered by shallow water – shallow marine sedimentation along the coasts – separation from Africa and Madagascar
Jurassic	Break-up and separation from Gondwanaland – slow northward movement of Indian segment

Conclusion

The importance of the study of Deccan Traps should now be clear. Starting with speculations on the nature of the mantle, the generation of magma and its ascent to higher levels in the crust, crustal contamination, thermal convection in the mantle and the development of hot spots, passage of India over hot spots in its long northward journey, bursts of volcanic activity, extinction of fauna and flora, tracking of the path which the continent had taken with reference to stationary hot spots, the thermal expansion of the crust over the region affected by the hot-spot tracks, domal uplift, geomorphic consequences of such an uplift on the drainage, the development of cyclic erosion surfaces, the formation of fissures along the coast line and rifting of the continent, the creation of the west coast of India and the Western Ghat scarp, the ushering in of monsoonic climate—all these elements of geologic history are interconnected, giving a most spectacular, vivid and breath-taking picture of a series of events which have shaped the Indian subcontinent in the past.

Sahni was the first to realize the importance of the Deccan Trap as an integrator of knowledge. The Plate Tectonic theory, which is the modern version of the theory of continental drift of Wegener, has given a new dimension to geology combining within it the traditional sources of geological information with the new knowledge gained as a result of application of the principles of physics, chemistry and biology. Preston Cloud called the present as the golden age of unprecedented synthesis. Seemingly isolated facts gathered by geologists assume a dimly recognizable pattern helping to build a conceptual framework of lithospheric evolution. It is important not only for what it explains but also for its ability to stimulate and direct work in the future. The model that has been developed in these pages accounts for a large number of observed facts relating to the geology and geomorphology of the Indian continent and is deserving of further study.

We, in India, have remained too much preoccupied with fact gathering on a local scale. This stage must now give place to a study of larger issues relating to the evolution of the Indian continental segment as a whole. The study of past climatic changes is one of great importance in its relation to forecasting what is in store for the future. As stated by Cloud, the past properly interpreted can be a key to the future. Aspects like volcanism, air–sea–ice interactions, solar viability, changes in CO_2, changes in temperature, changes in rainfall pattern, soil-formation processes—all of these have a profound influence on mankind. Such studies should now claim our attention.

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