A GEOLOGICAL DISCUSSION ON THE SATPURA HYPOTHESIS AND GARO-RAJMAHAL GAP [1]

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CONTENTS

I. INTRODUCTION

Recent studies by Dr. S. L. Hora on the migration of freshwater fish, crocodile, and Chelonian faunas have led him to postulate the possible former existence during the Tertiary era of a mountain range extending from the Shillong plateau, across the Rajmahal gap, westwards to the Vindhya-Satpura region, along which migration is thought to have taken place. The Garo-Rajmahal gap is considered to have been of recent formation and to have blocked the further migration of the Eastern Malayan fauna (Hora, 1944, p. 433; 1948, p. 305). The following note is concerned with the available geological evidence pertaining to the former existence of the Satpura Range and the dating of the Rajmahal gap. Considerable discussion by geologists and others followed Dr. Hora's paper of 1944, while Dr. Tindell Hopwood submitted certain generalizations about the Satpura range in 1948.

To make a satisfactory study of this problem would involve a comprehensive review of all geological processes that have occurred in northern India since the beginning of the Mesozoic era, and would take much more time and research than is possible with other pressing commitments. Consequently, only a relatively cursory review can be undertaken in this paper, without a full consideration of all the literature. It may be pointed out that the opinions expressed herein are my own, and do not necessarily represent those of the Geological Survey of India.

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At the outset it should be emphasized that the problem of earth movements, and changes of land relative to sea-level, is one that is highly involved. Not only is it necessary to consider the effect of earth movements along the mobile orogenic belts, and epeirogenic changes in the more extensive crustal blocks, both arising from stresses indigenous to the planet, but attention in some areas has also to be paid to extraneous changes in the level of land relative to sea caused by the superimposed loads of great ice caps, involving in addition the periodical locking up of immense quantities of water in the form of ice caps and its subsequent release as the ice melted. Moreover, movements must be considered in relation to the principle of isostasy, or the delicate balance which exists over most parts of the planet between the crust, of varying thickness and density, and the weak supporting asthenospheric shell. Erosion in elevated regions removes part of the superficial crust and redeposits the material elsewhere, so that the crustal balance is upset, and adjustments in elevation take place if restraints from other causes are not present.

In actuality, adjustments do not take place at once. Along the orogenic belts in particular there may be prolonged departures from isostasy in narrow zones characterised by high positive or negative gravity anomalies (Vening Meinesz, 1934; Hess, 1938). These narrow zones of gravity anomalies are considered to be due to the existence of stresses in the crust and underlying asthenosphere which have prevented the crust from attaining equilibrium in a vertical sense with the weaker shell below. Even in the more stable epeirogenic regions of the crust there may also be considerable departures from isostasy, though not of the same magnitude as in the mobile orogenic belts.

As an example of the sensitivity of the crust to newly acquired loads, and the subsequent removal thereof, may be mentioned the giant ice cap which occupied approximately 1·2 million square miles of north-east Europe during the ice age (the area of the Indian Union), and at the time of the maximum development may have reached a thickness of 10,000 feet in the centre. This was an additional load which had the effect of depressing the crust into the asthenosphere.

The melting of this ice cap, which is equivalent to the removal of 3,700 feet of rock of density 2·7 in the central region, has resulted in the gradual rise of the land since the end of the last glacial phase. The maximum rise in land took place on the west side of the Gulf of Bothnia, near Lat. 64° N.: Long. 21° E., where the elevation has been of the order of 2,300 feet, and as much as 1,700 feet during the last 9,000 years (Daly, 1940, p. 313). This is equivalent to an average annual rate of rise of 5·7 cms., though it should not be supposed that the rise has been at a uniform rate since its inception.

In considering, therefore, the removal of masses by erosion in a manner analogous to the melting of an ice sheet, it is not possible to regard a given quantity of rock, corresponding to a known vanished stratigraphical succession, as merely worn away from the earth's surface, and therefore only to be added to the present land height so as to provide a figure of the original height of the land before erosion began. The very fact of erosion upsets the isostatic balance of the crust, and results in a compensatory elevation of the crust provided other restraints do not exist. The net effect of erosion over a long period of geological time is therefore to cause an elevation of the crust, though not necessarily to the same level as originally obtained, just as the melting of an iceberg causes the whole mass of the berg to rise in the sea until it eventually melts entirely away. Consequently, it follows in general that the net change in elevation of the crustal surface is less than that which is implied by the actual subtraction of material eroded away.

It is necessary in a study of this problem also to consider recognized stratigraphical horizons, the manner of formation of which is known to within fairly definite physiographic limits. As far as possible, it is desirable therefore to know the palaeogeographical conditions which obtained at the time when given formations were deposited: in which direction lay the highlands that acted as a provenance to the formations being deposited, and the orientation of the main river systems acting as media for deposition.

One major uncertainty exists in the lack of knowledge as to how far given formations formerly extended beyond their present outcrops. This uncertainty naturally affects any calculations based on quantities of rock removed by erosion, and the attendant modification considered above, of isostatic adjustment arising from re-distribution of crustal loads.

Finally, the present level of crustal masses as now exposed is the net effect of all the vertical movements of positive and negative sign which have taken place during the period since given formations were deposited. In certain areas there may have been a complex sequence of subsidence and elevation, the decipherment of which, in the absence of certain key formations removed by erosion, may be very difficult.

II. The Ur-Satpura Range

The term *Ur-Satpura* is used in this paper to describe the possible ranges, or more elevated plateaux, which on this hypothesis extended during the late Tertiary from the northern end of the present Western Ghats in an easterly direction to the present Rajmahal Hills, that is, between longitudes 74° and 88° and latitudes 21° 30′ and 25°. It includes, therefore, the modern Satpura Range rising between the Narbada and Tapti rivers, the Mahadeo Hills or Satpuras near Pachmarhi, the Maikal and Mainpat Hills, and the Chhota Nagpur plateau. Across the present Garo-Rajmahal gap it includes the Garo and Khasi Hills of the Shillong plateau. The first part of this discussion will be confined, however, to the area in the mainland of India between the Western Ghats and the Rajmahal Hills. A later section will discuss the Garo-Rajmahal Gap.

1. *Present Surface Elevations*

I am indebted to my colleague, Mr. A. K. Saha, for the elevation data summarized in Table 1. This list includes only certain representative summits and is

TABLE 1.

	Average elevation of plateau	Highest individual summit	Range in elevation of selected summits on plateau
Parasnath		4,480	
Ranchi East	1,800–1,900	3,517	
Ranchi West	2,200		3,445–3,517
Hazaribagh	1,900	3,200	2,569–3,200
Mainpat	1,800–2,000	3,781	3,476–3,781
East of Ambikapur		3,800	3,283–3,800
Sohagpur Highlands	2,000–2,250 rising to nearly 3,000 in East.	3,651	3,299–3,651
Mandla Highlands..	2,000–2,250	3,065	2,732–3,065
Chhindwara and Pachmarhi	2,000–2,250	4,429	3,481–4,429
Mhow	1,800–1,900	2,891	....
Gawilgarh	2,000–2,500	3,682	3,486–3,682
Satpura, Indore	2,000–2,250	3,522	3,219–3,522
Satpura, Barwani-Bombay	1,800–2,200	4,347	3,274–4,347
Indore Plateau	1,700–1,800	2,451	
Bhopal	1,500–1,700	2,107	
Kotah	1,250–1,500	2,014	1,775–2,014
Panna	1,300–1,400	2,178	1,797–2,178

not to be regarded as a complete indication of height variations. The present elevation of the tract varies from about 200 feet on the east side of the Rajmahal Hills to 4,480′ at Parasnath. The greater part of the inland area consists of plateaux varying within the small limits of 2,000 and 2,500 feet. Sticking up out of these plateaux are higher plateaux and residual summits which average about 3,500 feet and have individual summit variations of only about 300 feet. Exceptional heights include Parasnath 4,480′, Dhupgarh 4,429′ near Pachmarhi, and one peak in the Satpuras south of the Narbada of 4,347′ feet. These heights presumably represent residuals of the highest original plateau, most of which has been completely removed by erosion. Between the Highlands occur the Narbada and Tapti valleys with average elevations of about 1,000 ft. in central India.

2. *Geological Structure*

A glance at the geological map of India shows that the east-west zone of the Ur-Satpura Range includes a great variety of geological formations, which are tabulated below:—

7 Older alluvium and Siwaliks of the Tapti and Narbada Valleys.
6 Deccan Traps of Rewa Kantha, Bombay, Barwani, Gawilgarh, Mahadeo Hills and the Maikal Range.
5 Rajmahal Traps of the Santhal Parganas.
4 Upper Gondwana formations of the Mahadeo and Deogarh Hills, and small outliers in the eastern coalfields.
3 Lower Gondwana formations of the Mahadeo and Deogarh Hills, Surguja, the Damuda rift valleys of the Chhota Nagpur region, Rajmahal Hills.
2 Vindhyan Formations of Bhopal, Saugor, Rewa and Mirzapur.
1 Archaean formations of the Hazaribagh Range extending eastwards to the Rajmahal Hills.

This area, which has to be considered in the light of the Satpura hypothesis, is therefore geologically complex. Aside from the intensely folded and often highly metamorphosed Archaean rocks, the changes in which are not relevant to the present enquiry, the remainder of the formations listed above show only moderate to slight folding. Over large areas the sedimentary and volcanic formations lie with virtual horizontality, pronounced folding in them being confined to narrow zones, such as the crumpled and faulted Vindhyans in Bundi and along the Son Valley (Coulson, 1927; Auden, 1933) and the flexures in the Upper Gondwanas bordering the Narbada Valley (Crookshank, 1936). The greater part of the Deccan Traps are unfolded, but the western end of the Satpura range includes the folded traps of Rajpipla first described by Blanford. The dyke clusters and swarms in the Deccan Traps appear to be closely related to this somewhat abnormal folding to which these traps have succumbed along the Narbada zone (Blanford, 1869, p. 57; Auden, 1949, p. 132). The Lower Gondwana rocks of the eastern coalfields have, however, undergone considerable folding, in particular in the Jharia coalfield, and the high fuel ratios of some of the Barakar coals, in places removed from the thermal effects of mica-peridotite intrusions, is indicative of considerable stress.

The characteristic feature of the Gondwana rocks is the strong faulting which has let them down into troughs in the Archaeans. This is well displayed in the Bokaro coalfield which lies in depressed ground 1,000 feet lower than the flanking elevated Archaean plateaux of Ranchi and Hazaribagh. In several fields the faulting is pronounced only on the south side, and in the Jharia and Raniganj coalfields there is an échelon arrangement of the southern boundary faults.

At the eastern edge of the Gondwana rifts there is a convergence below alluvium of three distinct radiating patterns of down-faulted Gondwanas towards an area near co-ordinates 23° 35′ : 87° 45′, close to Bolpur, represented by the Damodar rifts, the radiating outliers of the Giridih group, and the Gondwanas of the western side of the Rajmahal hills. This converging fracture pattern which broke up the Archaean basement must have reached final development at the close of the Gondwana period or in the early Tertiary.

Between the Raniganj and Hutar coalfields, the coal-measures now follow an east-west system of troughs, although individual boundary faults lie oblique, and en échelon, to the main east-west zone. This east-west pattern continues westwards, being characterized by the elongated outcrop of Upper Gondwanas, synclinally lying upon Lower Gondwanas, which extends to Janakpur and Bandhogarh. Still further west this strike swings round to E.N.E.-W.S.W., and follows the structural feature which is dominated by the Narbada rift.

A tentative schematic representation of the crustal blocks in India during the Tertiary era is given in figure 2. The Peninsula is regarded as being divided into a northern or Aravalli shield, and a southern or Deccan shield, by a pronounced line of weakness which runs along the Narbada and may continue E.N.E., north of Monghyr, to form the northern boundary of the Shillong mass. This Narbada zone is considered to be an ancient feature connected with some primary weakness parallel to the Archaean grain and related in the west to an upwarp of the asthenospheric shell into the superficial crust. The peninsular Gondwana rocks, which have been dropped down along rifts and unilateral tensional faults, are confined to the southern shield (see also Fox, 1931, Plate 10).

The elevated land which might be considered to be the remnants of the original Ur-Satpura range lies along the northern edge of the southern shield and cuts obliquely across all the lines of weakness and fracture which developed in the Mesozoic and reached final emphasis at the close of the Gondwana period. In the eastern part of the Ur-Satpura it is not possible to think in terms of a Range in the sense that the Aravalli Hills and parts of the Himalaya form ranges, for there is no correspondence between structure and the present line of highlands. It is necessary, therefore, to consider the problem mainly in terms of an Archaean basement, broken up by lines of late-Gondwana weakness, that has existed as plateaux undergoing vertical movements of negative and positive sign during the Tertiary and post-Tertiary areas.

3. *Geodetic Evidence*

The gravity anomalies determined by the Survey of India have been developed in the form of a map showing the Crustal Structure Lines of India (Glennie, 1937). These lines are intended to show zones of upwarp and downwarp, after corrections have been made of the observed values of gravity for latitude, altitude, the attraction of neighbouring masses, and some degree of isostatic compensation. They include the effects both of deep sedimentary basins containing rocks with abnormally low density, and zones of upward buckling of the asthenospheric shell (without prejudice regarded as basalt) into the granitic crust. It should be stressed that these so-called downwarps and upwarps are not necessarily represented by corresponding topographical features. One conspicuous downwarp runs through the southern line of peaks in the Karakoram range, which has more peaks over 7,000 metres in elevation than any other region of the world. The major upwarp west of Bombay runs under the Arabian sea and hits the coast of India in the low-lying Gulf of Cambay.

This map has, indeed, led to misunderstandings, and it has been excluded from recent publications of the Geodetic Branch of the Survey of India. The line of the hypothetical Satpura range may, however, be examined in the light of the Crustal Structure map. The Ur-Satpura range starts along the zone of upwarp which runs between the Narbada and Tapti valleys. It continues over the junction of two zones of downwarp which exists near the Mainpat Hills in Surguja and Udaipur, and then strikes obliquely towards the major upwarp which extends from the Shillong Plateau across the Rajmahal gap to Allahabad and Agra.

Except in the western part of India, where upwarp coincides with the Satpura range between longitudes 74° and 76°, the hypothetical Satpura range of antiquity runs oblique to the crustal structure lines as indicated by gravity anomalies. Consequently, the existence of the Ur-Satpura has little support from the basic structural relationship between the superficial crust and the underlying asthenospheric shell.

From considerations of the evidence from both geological and geodetic sources, we are compelled therefore to regard the problem as connected mainly with epeirogenic movements which have depressed and elevated extensive areas of the peninsula, irrespective of both geological strikes in the superficially exposed crust and deep-seated warps which have affected the level of the interface between the base of the granitic crust and the underlying asthenospheric layer.

4. *Key Horizons*

A description of the sequence of earth-movements which affected northern India is given by D. N. Wadia, J. A. Dunn and the writer in the account of the Bihar-Nepal Earthquake of 1934 (1939, pp. 118–160). Of particular importance is Dunn's account of the movements during the Tertiary era which took place between Chhota Nagpur and the Rajmahal Hills (1939, pp. 137–142). There is also information in Crookshank's survey of the Satpura region around Pachhmarhi (1936, p. 376).

Dunn has indicated three base lines which provide evidence regarding vertical movements:—

(1) The base of the Gondwanas;
(2) The base of the Deccan Trap and Rajmahal Trap;
(3) The coastal Tertiary deposits.

In addition, may be added two other formations which throw some light on the problem:—

(4) Base of the Eocene;
(5) The older alluvium, and Siwalik rocks, of the Narbada and Tapti valleys.

Another key formation is found in the glauconitic sandstones of the Lower Vindhyan Semri series (Auden, 1933, p. 212), but uncertainty arises in attempting to unravel the vicissitudes of vertical movements which these ancient rocks have undergone during the course of the approximate 400–500 million years since the beginning of the Palaeozoic.

5. *Base of Gondwanas*

The exposed base of the Gondwanas rises from an elevation of about 200 feet in Bengal to almost 3,000 feet near Sohagpur and Chhindwara though, where depressed by synclinal folding and downfaulting at the bottom of the coalfield troughs, the base must be several thousands of feet below sea-level in Bengal. At the time of deposition of the Talchir tillite, the Gondwana continent must have been more or less devoid of pronounced topographical interruptions, since the tillite of the Salt Range contains boulders derived from the central parts of India, and the ice sheet evidently spread without intervening elevations which would otherwise have caused deflection of boulders from central India away from what is now the Salt Range. The highlands from which the ice sheet spread are considered to have been in the south, and probably south of the present Satpura trend.

The Talchir beds of Umaria (23° 32′ : 80° 50′) are associated with marine beds containing *Productus* (Cowper Reed, 1928, p. 367) and it is clear that these particular glacial beds must have been deposited at and just below sea-level. The present elevation of the outcrops at Umaria is about 1,500 feet. There is evidence that the later coal measures were deposited by an extensive river system which flowed westerly from highlands that lay to the east and south (Fox, 1931, Plate 10).

Since the available evidence suggests that the highlands lay to the east and south, and since the eastern parts of the outcrops are now at much lower elevations than those in central India, it is probable that there has been a rise of some 3,000 feet in central India relative to Bengal. In view of the isostatic rise that has taken place in Scandinavia since the melting of the Pleistocene ice sheets, it is possible that a similar adjustment occurred on the melting of the Talchir ice sheet at the beginning of the Permian. This rise should have been greatest where the ice sheet was thickest, which was by inference in south-central India. Consequently, the topography of Gondwanaland may have changed slightly during the deposition of the coal measures, but not in such a way as to reverse drainage profiles. Indeed, the isostatic rise would tend to restore the original gradients, which were responsible for the radial movement of ice from the centre of the ice sheet, and which were presumably lessened during the period of maximum glaciation as a consequence of the superimposed load of ice. As will be discussed later, however, the greater part of the differential elevation of the Gondwanas between Bengal and central India probably took place after deposition of the whole Gondwana succession and its downfaulting into troughs.

A tillite, almost certainly of Talchir age, is also found sporadically in the outer Himalaya between longitudes 77° and 95°, over a distance measured along an arc of 1,300 miles. In the Simla-Mussoorie region it is associated with a characteristic pink siliceous dolomite, and in Nepal with massive white dolomite and coaly shales (Auden, 1934, p. 374; 1946, p. 346). It was evidently laid down close to the shore line of the sea in which the non-fossiliferous Peninsular-Himalayan rocks were deposited. Present outcrop elevations vary from about 7,000 feet in the Simla region to 370 feet on the banks of the Kosi river in Nepal. There would appear, therefore, to be a larger elevation of these rocks in the neighbourhood of longitudes 77°–82° than east of longitude 86°, in a comparable manner to what is indicated for the Lower Gondwanas of the Peninsula proper.

Finally, may be mentioned the rocks of glacial or fluvioglacial origin which are found at an elevation of 19,500 feet across the main Himalayan range in north-east Sikkim (Wager, 1939; Auden, 1946) and in the Horpatso region of Tibet, at geographical co-ordinates 34° 33′ : 81° 8′ (Norin, 1946, p. 75). These rocks occur at elevations of 18,000 to 22,000 feet. The relationships, however, between the trans-Himalayan glacial beds and those belonging to the Peninsular-Himalaya and Peninsula proper are not at present understood. The Tibetan rocks described by Norin may, in fact, belong to the Angara crustal block, and not to Gondwanaland.

6. *Base of the Deccan Traps*

The base of the Deccan Trap varies within considerable elevations. It is at sea-level 60 miles N.N.W. of Marmagoa and 2,000 ft. above sea-level at Belgaum, only 75 miles away. This particular change in elevation may be connected with the Panvel flexure of post-Deccan Trap age (Auden, 1949, p. 148). East and north-east of Belgaum towards Nagpur the base varies within the approximate limits of 1,000 and 2,000 ft. South of Pachmarhi it is 3,000 ft. Along the south flank of the Maikal range it follows roughly the 500 metre contour (1,640′) but rises to about 2,500 ft. south of Sohagpur. Finally, an outlier in Jashpur, at the south-west end of the highest plateau of the Hazaribagh plateaux, lies at over 3,000 ft. The base is therefore not at all uniform. In certain areas, such as Cutch, Gujerat, and the west side of the Konkan, the traps are considerably folded, but over the greater part of the main Deccan plateau they are, so far as is reported, virtually unfolded and horizontal. It is not possible to assume, therefore, that the irregular floor over most of the trap outcrop is due to folding, for the irregularity is evidently that of the original topography upon which the lava flows were erupted. This has been well described in the Pachmarhi area by Crookshank (1936, p. 276) and by Ball in the Rajmahal area (1877, pp. 59, 60). As I have recently pointed out, the Deccan Traps deserve much more detailed study and it is possible that gentle warps may be found to be more common than is now supposed. But the general conclusion remains true, that the floor upon which the traps were laid down was uneven, and varied usually within a height range of 1,000 feet. The subsequent warps will have tilted the traps together with the local declivities of basement topography.

7. *Nature of the Deccan Trap Floor*

It is necessary now to consider the structural relationships of the traps with the rocks upon which they lie. It is quite evident that there is a very strong unconformity upon the Vindhyan and Gondwana rocks. South of Kotah, near Jalrapatan, and east and south of Saugor, the traps cut across the various subdivisions of the Vindhyan system with a violent discordance. This discordance is very well displaced in south-west Mewar (Heron, 1936: Plate 22).

The full thickness of the Vindhyan system is developed only in central India, near Hoshangabad and the Dhar Forest, where possibly 10,000 to 13,000 feet of sediments are present. Eastwards the upper series of the Vindhyans disappear, and in Mirzapur district (Mallet, 1869; Auden, 1933), and Shahabad district, only the Semri and Kaimur series are exposed. If the Rewa and Bhander series were formerly present in the east, as appears to be very probable, they have now been eroded away, and at least 4,000 feet of sediments are missing. When the problem of the Satpura range was first put to me by Dr. Hora, I had myself argued that the removal of over 4,000 ft. of sediments might, after allowance was made for isostatic rise, account for the former existence of a higher plateau. At that time, however, the regional geological map had not been studied in detail, and the significance of a highly titaniferous bauxitic laterite on the Rohtas plateau (24° 44′ : 83° 58′), at an elevation of 1,600 feet, which was examined in 1939, was not appreciated. As was pointed out above, Deccan Trap outliers occur at a high elevation on the Hazaribagh plateau, only 100 miles south of Rohtas, and numerous outliers exist between Rohtas and Ambikapur. The titaniferous bauxite, with 6·95% of TiO_2, is almost certainly not derived from erosion of the Kaimur sandstones upon which it rests, which lack titanium. It is much more likely to represent the last residue of weathering of an outlier of Deccan Traps resting on the Kaimur sandstone. The former extension of the Deccan Traps into Ranchi District was inferred in 1923 by Fox from the widespread deposits of bauxite found on the high plateau of that area, one major deposit being at Bagra Pat (23° 29′ : 84° 36′). The case is therefore strong for assuming that the Deccan Traps at one time covered Vindhyans and Archaeans alike in this region at least as far east as longitude 85°. This is 190 miles beyond the main existing outcrop. If, therefore, the Deccan Traps formerly rested unconformably upon the Kaimur sandstones of Shahabad, the erosion of the Rewa and Bhander series must have taken place in pre-Deccan-Trap times, and the removal of these sediments would not be relevant to the Ur-Satpura hypothesis. The unconformity would be merely another example of what is still so well displayed in central India, near Jalrapatan, Saugor and south-east Mewar (Fig. 1).

More significant than the Deccan-Trap/Vindhyan unconformity is, however, the unconformity between the Deccan Traps and the Gondwana rocks. The traps and underlying Lametas (Infra-Trappeans), cut across all the exposed members of the Gondwanas south of Chanda and Pachmarhi, and in the neighbourhood of Sohagpur. Further, outliers of traps occur between Sohagpur and Janakpur, and again south and east of Ramkola, resting across the boundary between the Upper and

Lower Gondwanas. This clearly indicates that the folding of the Gondwanas was completed before the eruption of the traps. Crookshank has shown, for example, that the main unconformities in the Pachmarhi area are below the base of the Jubbulpore series (Middle Jurassic) and below the Lametas (Upper Cretaceous). The Deccan Traps, regarded as Eocene on the basis of fossils found in the inter-trappeans, and the sporadic underlying Lametas, overlap almost the whole of the Gondwana succession within a distance of 26 miles (1936, Plate 25). The earth movements in this area took place therefore during the Jurassic and Cretaceous periods.

Coming to the Rajmahal area in Bengal, it may be noted that the Rajmahal Traps, of Lower Jurassic age and 1,500 to 2,000 feet in thickness, have gentle dips to the east, but this tilting probably took place during the Tertiary. Aside from this very gentle tilting, no folding has occurred in this region since the Lower Jurassic (Blanford, 1861, p. 144; Ball, 1877, p. 66). Unconformities occur between the Barakars and Dubrajpur Beds (Upper Gondwana), and between the latter and the overlying Lower Jurassic lavas, and the compressional movements were completed therefore by the end of the Trias. The major N.N.W.-S.S.E. faults forming the western boundary of the Gondwanas of this area are post-Mahadeva, but no contacts are seen with the traps and an upper age limit cannot be given. Hobson has, however, found that the Jurassic lavas, and the igneous intrusions (of either Jurassic or Deccan age), are affected by faulting, and the latest faulting must have been at a much later age, perhaps towards the close of the Deccan episode (Hobson, 1930, p. 145; Fox, 1934, p. 55).

8. *Base of the Eocene in relation to the Traps*

In the Cutch area, on the other hand, there is a negligible unconformity between the mainly Cretaceous Deccan Traps and the underlying Cretaceous and Jurassic rocks. Significantly, however, a very pronounced unconformity exists between the Lateritic and Nummulitic rocks (pre-Laki and Laki, or middle Eocene) and the underlying Deccan Traps, Cretaceous and Jurassic. The so-called sub-Nummulitic rocks or laterities overlap across the traps south of Lakhpat on to Upper Jurassics, while in the outlying areas of Rapar, Patchham and Bela, they rest against Lower Jurassic or Bathonian, without any intervening traps. It is not possible to enter into a discussion regarding the age of the Deccan Traps in this paper, but it is likely that the traps of Cutch are older than those of much of the mainland of India (Auden, 1949, p. 149) and that the earth movements which caused the erosion, lateritization and unconformities took place after the eruption of the Cutch traps, but before that of the eastern Deccan traps, possibly in Lower Eocene or Ranikot times.

Similarly, both east and south of Broach, the Eocene lies against Deccan Traps (Blanford, 1869, p. 62; Bose, 1908, p. 174). Descriptions of this region are not detailed, but Blanford gives convincing evidence for an erosional unconformity and divergence of strike between the Nummulitics and the underlying Deccan Traps near Uskar, 4 miles south-east of Tarkesar. He also describes the traps near Ratanpur (21° 43′ : 73° 11′) in Rajpipla as having a southerly dip of 10° and being overlain by Tertiaries dipping west and N.N.W. Bose, on the other hand, indicates that the anticlinal fold of the Tertiaries between Ratanpur and Damlai has an east-west axis (1908, p. 175), which is more or less coincident with the E.N.E.-W.S.W. strike of the fold axes of the Deccan Traps lying to the east. These particular traps in Rajpipla are considerably folded, and between latitudes 21° 10′ and 21° 45′ are infested with swarms and clusters of dykes (Blanford, 1869, p. 58; Auden, 1949, p. 132 and Plate 8). Both Blanford and Bose agree that the Nummulitics rest upon an eroded surface of the traps, and Bose states that the materials from the traps to some extent made up the composition of the Tertiaries. In this point he is evidently referring to the agates and cornelians which occur extensively as pebbles within the Upper Tertiaries of Ratanpur, but he implies that a few such pebbles also occur in the Lower Tertiaries which immediately overlie the traps. Oldham (1893, p. 300), referring more particularly to the Lower Tertiary Nummulitics cropping out on the banks of the Tapti river about 18 miles east by north of Surat, mentions that interbedded with the nummulitics occur conglomerates containing pebbles of agate. He also stresses that there is a distinct unconformity between the Lower Tertiaries and the Deccan Traps. The fauna of the Nummulitics is a mixed Ranikot-Kirthar type.

Unfortunately, no detailed geological mapping on large scale maps has been done in this area, and the Upper and Lower Tertiaries have not been properly differentiated. But the evidence so far adduced, and the general north-south strike of the boundary of the Lower Tertiaries against the underlying Deccan Traps, which were folded along E.N.E.-W.S.W. axes and intruded by swarms and clusters of dykes parallel to the fold axes, suggest that there is an abrupt truncation of the trap folds by the Nummulitic and later Tertiary rocks. There is no record of any of the E.N.E.-W.S.W. dykes intruding the Tertiaries, and the probability arises therefore that both the folding of the traps and the intrusion of dykes took place before deposition of the Eocene rocks. This critical area deserves further attention.

These relationships in Cutch and Gujerat are in striking contrast to those which obtain in east-central India where, as already noticed, the Gondwana earth movements were consummated, and extensive erosion had occurred, before the traps were erupted. The evidence obtained by B. Sahni, S. L. Hora, H. Crookshank and others suggests that most of the inter-trappean horizons of the Peninsula are of Eocene age. It follows therefore that the earth movements which folded the Gondwanas (and possibly caused rejuvenation of folding along old Vindhyan axes) could not have been later than the beginning of the Eocene. Indeed, the evidence of unconformities indicates that most of the movements resulting in folding and erosion of the Gondwanas were completed in the Mesozoic era. It is true that S. L. Hora has considered on other grounds that the youngest Deccan Traps may be much younger than Eocene (1947, p. 10; 1949, p. 305). If the traps of eastern India which unconformably overlie folded and eroded Gondwanas are proved to be of mid-Tertiary age, and if no Cretaceous Lametas are present below them, the final folding and erosion of the Gondwanas might be placed later than Eocene. So far as fossil evidence goes, however, there are not sufficient reasons for believing that the traps are younger than Lower Tertiary, and we are compelled therefore, both on these grounds and on the nature of unconformities in the Gondwana rocks, to regard the final folding of the Gondwanas as Cretaceous. In the Rajmahal area it was even earlier and probably Triassic. The downfaulting which took place in the Bokaro, Jharia, Raniganj and other coalfields was later, but an upper age-limit cannot be assigned to these displacements. Heron (1938, p. 128) indicates that the rejuvenation of the Aravalli Range, by as much as 3,500 feet in the centre, involved uplift along the Great Boundary Fault. Since this fault is truncated by flat-lying Deccan Traps, the movement was probably completed by the end of the Mesozoic, and may be related to those which affected the Gondwana rocks.

The important point in regard to the Ur-Satpura hypothesis is that these earth movements of compressional type, whether Mesozoic or Lower Eocene, were followed by erosion and the subsequent covering of the Gondwanas by unfolded lavas. Indeed, the very gently tilted Rajmahal traps of Lower Jurassic age prove that no compressional movements took place in the Bengal area since the end of the Triassic. Mid-Mesozoic compression was followed by tension, which evidently began in eastern India during the Lower Jurassic and continued right up to the middle of the Tertiary era, when it was finally succeeded by compression. As the hypothesis requires the existence of a range in Upper Tertiary times, this period of pre-Rajmahal and pre-Deccan Trap folding can have no bearing on the existence of the range. Indeed, the later the age of the Deccan Traps, as now proposed by Hora, the more damaging is the fact of their eruption under tensional conditions to the hypothesis, which is concerned with post-trappean movements. For, as will be seen below, the ecological evidence is that the inter-trappean beds were deposited close to sea-level.

The greater part of the extensive Deccan Trap outcrop, 200,000 sq. miles in area, is unfolded, although Fermor and Fox have located gentle warps in the traps of the Linga area (1916, p. 81). There are, however, as already mentioned, parts of the western region where the lavas show distinct dips and folding. The Cutch lavas have been corrugated into anticlines and synclines. In south-east Saurashtra the traps dip about 10° S.S.E. The Rajpipla lavas are described by Blanford as being folded quite strongly, and now possess dips of up to 20° with axes in an E.N.E.-W.S.W. direction. The Panvel flexure is a conspicuous feature running for a known distance of 200 miles north-south from Chiplun to Panvel and the coast west of Daman. Finally may be mentioned the traps at the foot of the south wall of the Narbada rift, which had been dropped down thousands of feet by normal faults and were subsequently folded (Crookshank, 1936, pp. 261, 265, 286). Such folding, implying compression, presumably arose after the tensional stresses had ceased to operate. Some of it may have taken place as late as the Miocene, although there is no direct evidence in favour of this supposition. Moreover, if the descriptions of the Rajpipla area are correct, it is probable that the successive pulsations of tension and compression were not simultaneous throughout the area now occupied by the traps. As will be discussed later, in connection with the Garo-Rajmahal gap, movement may have continued intermittently along the Panvel and other axes into the Pleistocene.

9. *Depression of the Crust during Eruption of the Deccan Traps*

The evidence regarding the manner of eruption of the Deccan Traps, and by inference also of the traps of the Rajmahal Suite, is that the lava flows were not erupted below sea-level. A study of the fauna and flora in the inter-trappean beds has led to the conclusion that the inter-trappeans were deposited under marshy conditions near the mouth of a large river (Hora, 1938, p. 372). This deduction implies that the associated basalts of plateau type were erupted at an elevation which was not much above sea-level. Since the volcanic pile of the Deccan Suite is certainly over 5,000 feet thick where fully developed (and may be even 10,000 feet thick), it is probable therefore that there was a gradual subsidence of the earth's crust *pari passu* with the eruption of successive flows.

This conclusion is suggested also on other grounds. The indications are that the crust was in a state of tension during the eruption of the Deccan Traps. The crust was broken up not only by deep fractures, along pre-existing lines of weakness, such as represented by the Narbada rift, but by other more numerous tensional faults which developed during the course of eruption (Crookshank, 1936, p. 284). Since the crust was under tension, the tendency would be for it to subside differentially into the asthenospheric shell, rather than to rise as might be expected under compression.

The mechanics of crustal deformation are certainly extremely complicated and cannot be explained in any simple manner. Compression in the orogenic belts is thought to be capable of forcing down the light crust into the lower shell as well as raising adjacent parts above their original level. Moreover, both along the Bombay coast and the Narbada zone gravity data suggest that there has been an upwarp of the basaltic shell into the overlying granitic crust. Indeed, this deep-seated upwarp is probably one primary factor in the formation of the weak zone along the Narbada. Consequently, considering only the interface between the crust and the basaltic shell, there has been an elevation of basic material at the expense of the granitic crust along the Narbada zone.

But the general conclusion would seem to be valid that during the period of eruption of the Deccan Traps, involving the up-welling of probably not less than 100,000 cubic miles of basalt magma from the underlying shell through a crust under tension, the tendency would be for subsidence of the granitic crust along normal faults into the underlying shell.[1] Such faulting inevitably involves the formation of an upthrow as well as a downthrow side, but the emphasis is on relative degrees of tilting, subsidence and floundering, rather than on the elevations of the up-throw sides forming significant heights in the zone of the present Satpura trend.

It is necessary, therefore, to picture an irregular pre-trap topography gradually being depressed and flooded with lava flows. It is known that the Deccan Traps of Kathiawar, Bombay and Bhusawal have been subsequently depressed by as much as 1,500 feet (Fermor, 1925, p. 97; Auden, 1949, p. 148). Moreover, Crookshank has shown that the traps on the south side of the Narbada valley have been dropped down by faults by thousands of feet relative to those on the plateau south-east of Pachmarhi (1936, p. 265). Fermor mentions work by Fox which suggests that the fault scarp along the southern side of the Gawilgarh Hills overlooking the Purna trough of Ellichpur has a downthrow of at least 1,800 feet, and possibly as much as 4,000 feet (1930, p. 409). These movements, involving the whole pile of lava flows as now exposed, evidently took place at the end of the Deccan Trap episode, possibly in Oligocene or Miocene times.

10. *Post-Tension Elevation*

On the other hand, as already stated above, Deccan Traps also occur as outliers at an elevation of over 3,000 feet in Jashpur. This presumably implies a raising of the basement and overyling traps by at least 2,000 or 2,500 feet in the eastern part of the trap outcrop subsequent to eruption. The differential movements between Bombay and Jashpur would amount therefore to not less than 3,500 to 4,000 feet. The distance between the two areas is about 750 miles, so that if there were uniform tilting, the imposed gradient of 1 : 1,000 would be scarcely noticeable.

Now taking the possible north-south component of tilt, the changes in elevation of the trap outliers is from 3,200 feet in Jashpur to 1,600 feet near Ramkola and again 1,600 feet for the titaniferous bauxite (of possible trap origin) on the Rohtas plateau. This northerly tilt between Jashpur and Ramkola is much greater, being 32 feet per mile, or 0° 21′, but would be difficult of observation.

If the lavas are in fact horizontal, the different elevations may be explained either on the supposition that the different outliers do not represent lavas of the same age, or by the existence of block faulting between horizontally disposed traps of the same age. Crookshank has shown that block faulting of post-trap age occurred along the northern edge of the Satpuras near Pachmarhi and that the traps in the Narbada valley were considerably folded. The base of the traps at Pachmarhi is now 3,000 feet, and the uplift relative to sea-level is probably the result of compressional movements which set in after the period of tension. He also points out that the difference in level of traps containing inter-trappeans of approximately the same horizon between Pachmarhi and Nagpur, 100 miles apart, is about 2,000 feet, and suggests that this faulting occurred subsequent to the eruption of the flows (p. 287), though folding and tilting during the post-tension phase may be considered as an alternative explanation. The difference in levels

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[1] Normal faults would not persist throughout the whole thickness of the crust, but would be replaced by curved tensional fractures following shear planes in the lower crustal levels (Auden, 1949, 137, 138). In this discussion the emphasis is on the dominance of normal tensional faulting in the upper crust during the period of eruption of the traps in the Peninsula and in the geosynclines of the northern orogen.

due to this tilting would be 20 feet per mile. This angle of 0° 13′ would not be observable at any particular place, and could only be demonstrated by detailed study along the trap outcrop using characteristic flows as datum lines.

The Rajmahal Traps lie close to sea-level, and Blanford and Dunn have concluded that the crust has undergone little change in elevation at the latitude of Rajmahal since the Jurassic period, the crust at this latitude having acted as a hinge zone (Dunn, 1939, p. 142). This matter will be referred to subsequently.

11. *Older Alluvium of the Narbada and Tapti*

The Narbada and Tapti rifts are of considerable importance to the problem under discussion. The Narbada rift contains fluviatile and probably lacustrine deposits. Representatives of the younger Siwalik rocks are present below the superficial alluvial deposits of the present river (De Terra, 1939, p. 314). Three disconformities, associated with lateritic gravel and soil, are found within an exposed section of 130 feet near Narsinghpur, and a Middle Pleistocene fauna, together with early Palaeolithic tools, occur in the lower group of gravels and concretionary clays. De Terra concludes that the climate had assumed its present dry tropical character at the time of early palaeolithic man (p. 316), but also states that the climate is now drier than it was during the Middle Pleistocene (p. 318). The gasteropods and lamellibranchs found in the Upper Narbada group were all (with one exception) fresh-water forms. Oldham also stated that no marine forms are known (1893, p. 400).

On the other hand, the clays, sands and gravels of the Purna or Purana branch of the Tapti rift along one well-defined zone contain saline water which is extracted from brine wells going down to a depth of 120 ft. The origin of the salt is not known. Common salt is present in contrast to the carbonate, bicarbonate and sulphate efflorescences occurring as *reh* salts in the alluvial plains of the United Provinces and the two Punjabs, and it is possible that the salt is connate sea water that was caught up in the formations at the time of deposition. No marine fossils have been found in these rocks, but Oldham puts forward the very reasonable explanation that during the last Tertiary or early Pleistocene the land was 1,000 feet lower and a branch of the sea may have extended up the Tapti valley to the region of the present Purna river (Oldham, 1893, p. 401). If this explanation is the correct one, and it is difficult to suggest an alternative, it would follow that no major range existed at the end of the Tertiary area in the Tapti area.

It is true that an elevated region is required as a provenance of the rocks of Siwalik type in the Narbada and Tapti. Oldham's explanation was that the land lay to the west, which is difficult to accept as probable if the sea lay in that direction. It might have been the present Satpura range of Pachmarhi, which would imply that the cover of Deccan Traps originally present had been eroded away, with the resultant exposure of the underlying Gondwana sandstones and clays which could have acted as a source for the Narbada sediments. These detrital deposits in the two rifts may thus represent the southernmost extension of the Siwaliks during Pleistocene times. Siwalik rocks occur along the southern foot of the Shillong plateau, and it is not impossible that the Tertiaries of the Chittagong Hill Tracts, Tripura, Sylhet and the south wall of the Khasi and Garo Hills made a sharp deflection and at one time extended in a W.S.W. direction towards Ranchi, Jubbulpore, Seoni and Amraoti, and the Arabian sea.

From two lines of evidence it is suggested that there was uplift near longitude 84°, for the base of the Gondwanas is raised in this region relative to Bengal, whereas the Deccan Traps appear to be similarly raised relative to Bombay. In addition, indications suggest a tilt downwards towards the north. This particular region of postulated uplift is close to the junction of the two downwarps shown in the crustal structure map of India.

In this connection may be mentioned the suggestion put forward 15 years ago by Graaff Hunter that the region of underload in North Bihar has been subject to a secular rise in levels, amounting to a maximum of 0·06 ft. (18 mm.) per annum along a line running between Banaras and Muzaffarpur (1934, p. 236). The existence of this secular rise has been disputed, and it appears still to be undecided to what extent the variation in levels during the course of the last 100 years is due to errors or to a systematic change involving actual secular elevation of the alluvium in the underload area. The line of zero change is shown by Graaff Hunter as passing through Burdwan and heading towards the Mainpat region, where geological evidence indicates the maximum amount of uplift during the late Tertiary and Pleistocene. It is premature at present to do more than point out the interpretation provided, but fuller data are required before the suggested secular rise is substantiated. Graaff Hunter's conclusions are worth bearing in mind in connection with the change in course of the Kosi river during the last 170 years south of its emergence from the Himalaya.

12. Dunn's Uplifts in Chhota Nagpur

Dunn has concluded that at the latitude of Rajmahal (25°) the crust has undergone little change in elevation since the Jurassic, and has acted as a hinge zone. North of the hinge there has been progressive downwarping in response to the Miocene and later Himalayan movements, which has allowed the accumulation of over 6,000 feet of fresh-water alluvial sediments in the north Bihar basin. Nearly the whole pile of these sediments now lies below sea-level (Wadia and Auden, 1939, pp. 133–135). South of this hinge line there has been progressive uplift, which has been summarized by Dunn as follows (1939, p. 141):—

(1) Uplift of 1,000 feet of an early Tertiary peneplane, with a downward tilt to the north-east.
(2) Middle or Upper Tertiary uplift of 1,000 feet reaching a maximum in the Ranchi plateau, with a downward tilt to the north-east.
(3) Further uplift of 300 feet.
(4) Final uplift of 400 feet.

The total uplift in the Chhota Nagpur area along latitude 23° was therefore of the order of 2,500 to 2,700 feet, with nil movement along latitude 25°. Since this uplift has taken place during the Tertiary and Pleistocene, it is evident that in early Tertiary times the land was at a lower elevation, and there is not much support for the idea of a major range existing to account for the migration of faunas.

It is true that Parasnath Hill, 4,480 ft., rises above the highest of the Ranchi plateaux, and may represent the residual of a still higher land surface. But even if it is supposed that a total thickness of almost 4,000 feet of rocks have been removed by erosion in the Parasnath area, it is not possible to assume that the original level of the Parasnath plateau was then at the present level of the top of the hill. Other evidence, discussed above, indicates that the total uplift in the Chhota Nagpur plateau was 2,500–2,700 feet. Allowing for the line of nil movement along the hinge line at latitude 25°, the uplift in the Parasnath area should have been about 1,300 feet. That is, the part of the crust now represented by the residual summit of Parasnath was probably in Tertiary times at an elevation of about 3,200 feet. The erosion into residual plateaux, and uplift, were doubtless controlled in the main by the Himalayan movements further north, rather than by simple vertical isostatic adjustment in a crust devoid of compressional restraints.

Crookshank estimates that about 1,350 feet of lavas and underlying Gondwana rocks have been removed by erosion in the central region around Pachmarhi since the last of the flows was erupted (1936, p. 180). The highest peak of the Satpuras at Pachmarhi is Dhupgarh 4,429′. In this case also it would be most unwise to assume that the original height of the region was 4,429′+1,350′=5,779′, because uplift has certainly taken place concomitantly with erosion.

III. The Garo-Rajmahal Gap

1. *Position of Possible Connection*

The nature and age of the Garo-Rajmahal gap received considerable discussion after the reading of Dr. Hora's paper on 'the Malayan Affinities of the Fresh-Water Fish Fauna of Peninsular India' (1944, pp. 434–439). A. N. Thomas in the first place considered that the real connection between the Rajmahal area and north-east India lay not in the present Garo-Rajmahal gap, but between Monghyr and the Darjeeling-Nepal Himalaya. This hypothesis would appear to be untenable for the following reasons:—

(1) The north-south strike of the Archaean rocks at Monghyr is almost certainly only a local deflection of the general E.N.E.-W.S.W. strike of the northern edge of the peninsula between Gaya and Rajmahal. The regional direction of strike is in fact that of the inliers sticking up through the alluvium along the line Gaya-Sheikhpura-Lakhi Sarai, and at Banka, 20 miles south of Bhagalpur. The strongly compressed folds in the hill mass south of Monghyr, and 12 miles W.S.W. of Bhagalpur, appear to represent no more than acute-angle flexures of local extent. The archaean strikes thus favour the supposition that the connection lay, where it has generally been supposed, between the Garo Hills and the Rajmahal area.

(2) The Gangetic downwarp of North Bihar, characterized by strongly negative gravity anomalies, extends in a W.N.W.-E.S.E. direction as far east as Purnea, almost orthogonal to the connecting range postulated by Thomas. This would be an unlikely disposition since the downwarp, and infilling with a great thickness of alluvial sediments in the form of an orogenic trough, cut right across the supposed connection.

(3) Evans and Crompton have shown that a zone of positive H-anomalies of more than 25 milligals extends for 140 miles in an almost N.E.-S.W. direction from Suri to Dinajpur, accompanied to the south-east by a parallel zone of weaker negative anomalies between Burdwan and Bogra. These zones are suggestive of sub-crustal warps in the general Garo-Rajmahal direction, and lend support to the idea that the original connection lay in the present gap (1947, p. 233).

Both surface strikes in the Archaeans, and the sub-crustal warps indicate, therefore, that the probable connection lay in a N.E.-S.W. direction between Malda and Dhubri, and not between Monghyr and the Darjeeling-Nepal Himalaya as supposed by Thomas.

2. *Age of Connection and Formation of Gap*

Little agreement exists about the age of the Garo-Rajmahal gap. Thomas considered that it is an old and persistent feature which has been of low level continuously from late Cretaceous or early Eocene times. Krishnan and Aiyengar favoured a mid-Miocene age for the gap, remarking that no convincing tectonic cause was available at a later age to explain the formation of the gap (1940, p. 9). That assumption is, however, untrue, because the Siwaliks have been compressed, folded and thrust into well-defined blocks during the later Pliocene and Pleistocene. Major late-Tertiary thrusts are known, for example, in the Siwaliks of eastern Nepal, having been noticed south of Katmandu and Udaipur Garhi (Auden, 1935, p. 144) and having been mapped in detail in the Jhapa area by E. Lehner (unpublished report).

Moreover, such folding is known also to have occurred in the peninsula area. Reference has already been made to the unconformity which exists between the

Laki (Middle Eocene) or pre-Laki lateritic group and the underlying Deccan Traps, Cretaceous and Jurassic rocks of Cutch, which signifies gentle movements and erosion. Subsequently, the middle Tertiary and earlier formations of Cutch were strongly folded into sharp anticlines and synclines, between latitudes 23° and 24°, the northernmost folds of Patchham, Khadir and Bela islands probably occurring in échelon formation against the rigid pre-Cambrian shield of which Nagar Pakar (24° 21′ : 70° 43′) is a conspicuous remnant (Wynne, 1872, pp. 110, 133, 145, 146, 201, 202). This major folding may have occurred during the same Miocene period as the maximum thrust movements of the Himalaya and the uplift of the Shillong plateau. Finally, unconformable relations were involved between the Upper Tertiaries of Cutch and the underlying Miocene, Eocene, Cretaceous and Jurassic rocks. In the Cutch region there were therefore three periods of folding:—

(1) Mild folding in Ranikot (Lower Eocene) times, after eruption of the Cutch traps, with extensive unconformity of the Lower Eocene laterite group across traps and Upper Jurassics.
(2) Strong folding and faulting in post-nummulitic times; probably Miocene.
(3) Moderate folding and faulting in Pliocene or Pleistocene times, involving the whole sequence.

Consequently, both on the north and west sides of the Peninsula there were repeated movements, while in the orogenic downwarp south of the Himalayan Siwaliks movements of a pronounced nature have persisted into post-Siwalik times. Indeed, it may not be straining comparisons too far to relate the pre-Cambrian shield of Rajputana with the wedge of ancient rocks now represented in the Khasi and Garo Hills (Figure 2), and to consider the folds at the east and west extremities of India connected with these wedges as homologous.

It is desirable to extend the discussion of the earth movements which involved the outer Himalaya north of the Garo-Rajmahal gap. Heim has emphasized the forward sweep of the Daling metamorphics which truncate the strike of the Siwaliks to the east of the Darjeeling foothills, particularly between the Kalijhora and Torsa rivers (1938, p. 419). The interpretation put forward by Heim is that the Daling metamorphics were pushed 20 km. (12½ miles) over an eroded surface of the Siwaliks. I do not know the area concerned, but the available evidence in other parts of the Himalaya is that the Daling and equivalent thrusts are of Miocene age, and did not involve translation over the younger Pliocene-Pleistocene Siwalik rocks. An alternative explanation is that the Daling rocks were thrust upon Gondwanas during the Miocene, and that the whole block of Daling and underlying younger Gondwanas was brought forward against the Siwaliks by strong tear faults during the Pleistocene.[1] Whichever explanation is correct, it is certain that late movements of considerable intensity must be accepted and the validity of the argument put forward by Krishnan and Aiyengar is doubtful.

Fox shows that the present area of the Garo and Khasi Hills was under sea until the end of the Mesozoic, and that the sea fell back from the Khasi Hills during the Upper Eocene and from the Garo Hills during the Miocene. The Shillong plateau came properly into existence in the Miocene, at which time Fox considers that the structural sag of the Garo-Rajmahal gap also formed, the implication being that there never was a pronounced topographical expression between the Garo and Rajmahal hills (Fox, 1944, p. 437). South of the Khasi Hills there is a pronounced downwarp, filled with Upper and Lower Tertiary sediments and overlain by alluvium. Evans and Crompton show that the geological correction required for the gravity data amounts in the Sylhet area to over 75 milligals, with a positive sign due to the

[1] Late Pleistocene tear faults are found in the gaps cut by the Ganga and Yamuna Rivers through the outer Siwalik Range, and these lines of weakness were evidently responsible for the courses adopted by the two rivers.

existence of low-density sediments (1947, p. 221). Moreover, the shape of the 75 milligal isogam correction suggests that these Tertiary rocks were folded along north-south axes, in strike continuation with the folds of Tripura and the Chittagong Hill Tracts (1947, p. 228). Since the folding involves also the Upper Tertiary rocks, it is clear that movements subsequent to the elevation of the Shillong plateau took place in the region.

It is not impossible, therefore, that the Miocene uprise of the Shillong plateau also witnessed a similar uprise and connection in the present Garo-Rajmahal gap, and that the gap was breached at a later date, at the same time as the Upper Tertiary rocks of Sylhet, Tripura, and Chittagong were folded along axes with north-south strikes and the last folding and faulting in the Cutch area took place. This late dating of the formation of the gap was the view maintained by Pascoe (1919).

This connection must have had a N.E.-S.W. strike extending from Dhubri to Malda, because the Garo and Khasi Hills lie north of the latitude of the Rajmahal hinge line of zero movement, and more or less on the same strike as the zone of maximum downwarp 200 miles to the west in North Bihar. Indeed, the region of the gap, now covered by alluvium, must clearly be one of great structural complexity, involving sharp changes in strike and abrupt terminations of structures.

In this problem the excellent paper by Evans and Crompton on geological factors in gravity determination is of great value (1946). In figure 4, page 221, these authors have worked out the geological corrections which should be applied to the gravity data in Burma and north-east India, based on extensive geological and geophysical studies. A striking angular insertion of an area of moderate geological correction (+25 to 50 milligals) is noticed in a region of large correction (+50 to 75 mgl.) near Comilla. If the straight western contour between the 25–50 and 50–75 mgl. correction isogams is extended to the north-west, it strikes the edge of an area of very high correction (greater than 75 mgl.) where the isogam contours are steep, and passes in a short distance to a region of negligible correction. These contours indicate the effects of rapidly varying depths of low-density sediments of Tertiary and post-Tertiary age lying within the topmost 40,000 feet of the earth's crust.

Figure 12 of their paper (page 233) shows the gravity anomalies after full correction has been made for surface geological formations and isostatic compensation. It is seen that a zone of low negative anomalies running between Burdwan and Bogra terminates abruptly against a region of high positive anomalies related to the Shillong plateau. Indeed, there is a narrow gap of zero anomaly just west of the Garo Hills which separates anomaly isogams both of different sign and different geographical alignment. There is reason to believe, therefore, that the sharp discontinuity seen on the surface is also reflected not only in the distribution of masses of Tertiary and post-Tertiary sediments of greatly contrasted thickness, but in the deeper crustal structure as well. All these facts point to some form of crustal discontinuity striking in a N.W.-S.E. direction.

It appears to be more than a coincidence that this N.W.-S.E. line, if continued in a north-west direction, connects up with that of the maximum forward translation of Daling rocks described by Heim near Lat. 27° N., Long 89° E., while in a south-east direction the line follows the coast between Chittagong and Cox's Bazar. The suggestion put forward is that this N.W.-S.E. zone between the Baxa foothills, the western edge of the Garo Hills, Comilla and the Chittagong coast represents a direction along which sag faulting, perhaps accompanied by tear movements with a strong horizontal component, took place in the late Tertiary or Pleistocene, thereby fracturing and breaching the former ridge between the Peninsula and the Shillong plateau which may have been elevated during the Miocene.

This depression may be compared with those of the Gulfs of Cambay and Cutch in western India, where the Deccan Traps and younger rocks have been folded below sea-level and covered by alluvium. Deep wells indicate that the alluvium between Ahmedabad and Mehsana is over 1,000 feet thick.

Whether or not the depression of the Gulf of Cambay is related to the Panvel flexure is difficult to determine on existing evidence. It is considered possible that the main faulting and folding of the Deccan Traps occurred between the Eocene and Miocene. Since the depression of the two gulfs involves the folding of the Upper Tertiaries, and infilling with alluvium, the final expression of movement must be of very recent date, and the coincidence between the Gulf of Cambay depression and the Panvel flexure may be an example of the rejuvenation of movements along a previously defined direction of flexure and weakness.

A similar rejuvenation of movement doubtless occurred also along the Narbada direction, which is probably an ancient line of weakness, first developed possibly in pre-Cambrian times, and later followed by the Rajpipla folding, dyke clusters and swarms, downfaulting and the infilling of the Narbada rift. The E.N.E.-W.S.W. direction of the Narbada rift, and the E.N.E.-W.S.W. and E.S.E.-W.N.W. directions noticed in the Tapti depressions (the latter direction being perhaps connected with the Cutch folding), suggest the existence of recent movements. The presence of saline beds in the Purna branch of the Tapti catchment has already been stressed, and it is possible that a narrow gulf of sea extended over a downfaulted region of the Deccan Traps as far as Amraoti in the late Tertiary. The diastrophic history of the region is shown in diagrammatic form in Table 2.

IV. Conclusions

1. *Regarding the Ur-Satpura Range*

The geological history of the region extending from the present Satpura range eastwards to the Mahadeo Hills, the Mainpat, Chhota Nagpur, Rajmahal and the Shillong plateau has been examined in the light of the earth movements which affected the Peninsula during the Tertiary and post-Tertiary eras.

Notwithstanding the uncertainty regarding the range of time involved in the eruption of the Deccan Traps, this formation is considered to be a vital one in interpreting the palaeo-physiography of the area. It is clear that eruption of basic lavas in India was a prolonged phenomenon. It began, and was presumably completed, in Lower-Middle Jurassic times in the Rajmahal area. In Sind, Cutch, Gujerat, and probably also Saurashtra, 1,500 to 3,000 feet of lavas were erupted between the Upper Cretaceous and lowermost Eocene, being subsequently exposed to prolonged exposure, and the chemical effects of lateritisation, before the deposition of Laki beds. But eruption over most parts of the peninsula proper is considered to have taken place mainly during the Tertiary era. The sequence of events may be compared in length of duration, therefore, with that which occurred in the north-western Himalaya, where the eruption of the Panjal Traps lasted throughout the Permo-Carboniferous and Triassic.

While in western India the traps lie with very little unconformity upon the older rocks, in the peninsula proper the unconformity upon folded and eroded Vindhyans and Gondwanas is profound. The major compressional movements reacting on the Gondwana rocks were finished, and erosion had occurred, before the deposition of the infra-trappeans or Lametas, of Upper Cretaceous age. This inference also applies to areas where the Lameta beds are missing and the age of the overlying traps is uncertain, but probably Lower Tertiary. The first folding of the Cutch and Gujerat Traps, accompanied by swarms and clusters of basic dykes, took place either at the close of the Cretaceous or in the Ranikot (Lower Eocene). These compressional movements may also have affected the rest of the peninsula, and intensified the folding of the already folded and downfaulted Gondwanas, but the

Deccan Traps of this area show no sign of them, evidently because they were erupted at a later date.

Accepting on palaeontological grounds an Eocene age for the inter-trappeans over most of the mainland, and a similar age therefore for the associated traps, it follows that the physical conditions favouring eruption of the lavas reached fullest development in the central part of the mainland later than in the bordering Rajmahal, Cutch and Gujerat areas. A condition of tension must have set in after the Mesozoic compression, which first possibly finalized the formation of the Gondwana rifts and then, with closer spacing of fractures, permitted the widespread eruption of lavas upon a crust undergoing progressive subsidence. Basic lavas of Cretaceous-Eocene age, associated with peridotites, occur in the montane zone of Sind, Baluchistan, Nanga Parbat and along the Indus river in Ladak. These rocks were intruded and extruded during a phase of tension when the crustal base of the Himalayan and related geosynclines underwent maximum stretch (Fig. 1). This condition of tension is regarded as a vital consideration in studying the Ur-Satpura problem, for it indicates that no elevated range or plateau could have existed in the present Satpura trend during the Lower Tertiary. If Hora's view of a late-Tertiary age of peninsular traps is accepted, then the period of crustal tension and subsidence must have continued into more recent times.

The second period of folding, accompanied by elevation, which took place after the formation of the Narbada rift, may have been of Miocene age, and contemporaneous with the main period of Himalayan overthrusting. The effects of this compressional phase were clearly confined to localized zones, because the greater part of the Deccan and Rajmahal Traps is unfolded. The rise of the Satpura zone south of the Narbada must certainly have created an elevated plateau, with a cover of unfolded traps, but this plateau was involved in rapid erosion, with the concomitant infilling of the Narbada and Tapti rifts by materials removed from the heights, and there is nothing to indicate that the top of the pre-erosion plateau ever existed at a much greater elevation than now shown by its dissected remnants.

The Narbada rift is regarded as a major crustal feature of ancient origin, reflecting sub-crustal structure, and influencing the deposition and folding of the Vindhyans and Gondwanas. It was subsequently a zone of pronounced volcanic and plutonic activity, the three plutonic centres of Kathiawar lying in a curved zone which is a prolongation of the Narbada fracture (Auden, 1949, p. 128, Plate 11).

In the eastern part of the peninsula the hypothetical Ur-Satpura range runs obliquely across the Archaean and Gondwana grain of the country.

The Deccan Traps are not normally covered by younger formations in the mainland. If such formations were ever deposited on the traps, they have since been eroded away and we have no knowledge of their former possible thickness. It is only in the downfaulted or sagged zones of the Narbada and Tapti rifts that younger formations are present.

The existence of saline beds in the Purna branch of the Tapti rift suggests that at the end of the Tertiary this particular area may have been at sea-level. Oldham's tentative explanation was that the Purna area of the Tapti was subsequently raised 1,000 feet, during the Pleistocene. Presumably the contiguous traps were elevated concomitantly. This uplift of 1,000 feet may possibly be contemporaneous with the final uplift of 700 feet deduced by Dunn in the Chhota Nagpur area. The indications are, therefore, that the region cannot have been very high during the late Tertiary.

Maximum elevation of the base of the Gondwanas relative to the eastern outcrops, and of the Deccan Traps relative to the west, appears to have occurred in the neighbourhood of Lat. 23° N.: Long. 84° E. and to have diminished northwards to zero movement at Latitude 25° in the neighbourhood of the Rajmahal Hills.

Dunn postulates that no movement has occurred in that area since the Jurassic period.

It may be remarked that a somewhat analogous disposition is represented in the Himalayan region. The western Himalaya shows the presence of extensive outcrops of para-autochthonous units in windows below the overthrust schistose rocks (West, 1938, p. 133; Auden, 1948, p. 77). In the eastern part of the Nepal-Himalaya, and in Darjeeling-Sikkim, such windows appear to be rare and much more circumscribed. Structural equivalents of the Garhwal and Shali windows do occur in a relatively small semi-window in the Kosi-Tamur valley (Auden, 1946, p. 346) and, from recent work by Ray, probably appear even north of Darjeeling near Nayar Bazar, but they are much less pronounced than in the west. This disposition suggests that there may be a tectonic culmination in the west exposing the lowest structural units, whereas in the east these units are more depressed and lie mostly concealed below the limit of erosion (Auden, 1935, p. 165). In point of view of longitudes, there is no correlation between the elevation of the Gondwanas and Deccan Traps referred to in the preceding paragraph and the western culmination in the Himalaya, but the two phenomena are probably interconnected.

Erosion has certainly been pronounced in the Pachmarhi and Chhota Nagpur regions and numerous residual plateaux have been left. But the crust has been uplifted *pari passu* with erosion, and the original level of the highest plateau was probably little higher than the present summits, even allowing for the subtraction of eroded material no longer observable above the residuals which now survive.

The evidence is not in favour, therefore, of the conception of a major Ur-Satpura range extending across India during the Tertiary period that has subsequently been worn down to the present elevations. It suggests rather the downfaulting along the Narbada and Tapti rifts at the close of the eruption of the traps, and the unequal elevation of the region since the Miocene.

It is considered probable that a connection did arise between the Shillong plateau and the peninsula during the Miocene and that the final break causing the present Garo-Rajmahal gap took place during the Pleistocene along a N.W.-S.E. line of fracture extending from the Darjeeling-Himalaya to Comilla and Chittagong. Consequently, it is necessary to suppose that while the central part of the peninsula was undergoing mild uplift during the Pleistocene, the bordering areas of Cutch, Saurashtra, and northern Bengal were subjected to depression.

2. *The Pleistocene Ice Age and Climatic Conditions*

If, as is suggested from the above discussion, no major range existed during the Tertiary and Pleistocene along the present Satpura trend, which could account for increased precipitation and humidity, and permit the migration of faunas, some other explanation must be adduced to provide for these ecological requirements. It would appear that the solution is to be found in the Pleistocene Ice Age in India, one that was advocated in the first place by the early pioneers of Indian geology. The question of the Ice Age in India has recently received extensive discussion by H. de Terra and T. T. Paterson. These authors (1939, p. 224) correlate the first glaciation with the Tatrot stage of the Siwaliks (Lower Pleistocene), the first interglacial period with the Pinjor stage and the Second Glaciation with the Boulder Conglomerate stage (Middle Pleistocene). Moreover, Morris (1938, p. 414) has described a glacial boulder bed 6,000 feet below the top of the Siwalik succession at Bain (32° 28′ : 70° 33′). This succession is now folded so that, before removal by erosion of the crest of the Marwat Kundi anticline, the Bain boulder bed would have been at an elevation of about 3,700 feet at the crest, and is now well below sea-level at the flanks. Before folding the disposition of the Bain boulder bed would have been relatively flat, but at a height above sea-level which is impossible now to assess on account of regional changes in elevation which have taken place subsequently to folding. This Bain boulder bed is correlated with the First Glacial Period of Tatrot age, and indicates the widespread occurrence of glacial conditions in the Siwaliks at *what are now low elevations*, a considerable distance from the main montane zone.

Paterson has shown that the glaciers of the Kashmir valley descended to the present elevation of 5,500 feet during the first and second glaciations (1939, p. 79). In the central and eastern Himalaya there are definite signs of glaciation down to present-day elevations of 7,000 to 8,500 feet. But these elevations were clearly not those that obtained during the Ice Age, because the Himalaya are known to have risen very considerably in late Pleistocene and recent times. The tilting of the Karewas in Kashmir shows vividly how strong and recent these elevations have been.

Finally, the existence of the erratic blocks in the north-western part of the West Punjab, north and south of the Kala Chitta Range, may be mentioned. The origin of these blocks has been the subject of some discussion, which was summarized by Cotter in 1929. Cotter's view is that these erratic blocks may have been left in their present position by large scale mud-flows arising in Hazara, at a time when the climate was colder and the glaciers had a wider extension. He concluded that (p. 334) :—

> '. . . . profound changes have taken place in this region of the Northern Punjab since Pleistocene times, and it does not seem impossible that at a former period natural forces were on a sufficiently grand scale to bring about such catastrophic glacial outbursts of water or of mud-avalanches as might have brought the erratic blocks of Attock District to their present position.'

It is likely that the land in Northern India may have been from 1,000 to 3,000 feet lower in the early Pleistocene than it now is, and that the glaciers must have descended to levels which were then that much nearer sea-level. While the present glaciers of the Karakoram and Himalaya, great though some of them are, have little effect on the climate of the Peninsula, it is almost certain that with a snow line and glacier line possibly 6,000 to 8,000 feet lower than now obtains (allowing for glacier recession as well as isostatic rise) the temperature and humidity conditions in northern India must have been markedly different. The temperature would be lower, and the relative humidity greater. It is considered probable, therefore, that it is these climatic factors, associated with a lower elevation of the Himalaya mountains, which permitted migration of faunas rather than the existence of any pronounced elevation along the present Satpura trend.

3. *Evaporation Losses and Run-off*

Engineers have long been concerned with the calculation of run-offs from catchments in connection with estimates for reservoir storage. Barrows (1943, p. 117) has quoted a formula developed by Vermeule for river basins in the north-eastern part of the U.S.A.:

$$E = (11+0{\cdot}29\,R)\,M$$

in which—
E = annual evaporation or water losses, in inches.
R = precipitation, in inches.
M = factor depending on the mean air temperature, varying from 0·77 for 40° F. to 1·47 for 60° F.

Other formulae include factors such as slope and degree of vegetal cover. Recently A. N. Khosla (1949), following the same lines as Vermeule, has introduced a new formula in which all losses, whether by evaporation, transpiration, or percolation into the ground, are regarded entirely as a function of temperature. His formula is:

$$L_m = \frac{T_m - 32}{9 \cdot 5}$$

L_m= monthly losses due to all causes, in inches.

T_m= mean monthly temperature in degrees Fahrenheit.

By subtracting the monthly losses from the monthly precipitation and summing for the whole year he arrives at a figure for the annual run-off. For a given precipitation, therefore, the losses are higher and the run-off is consequently smaller in proportion to the increase in temperature. This is of course to be expected, but the close correspondence between calculated run-offs, on the assumption that temperature is a complete measure of all the various factors which are responsible for the loss of rainfall to run-off, and the actual run-offs is certainly surprising.[1] A comparison is given in Table 3 between catchments with more or less similar precipitations but widely different mean annual temperatures, the figures being selected from Khosla's paper.

TABLE 3

	Precipitation in inches	Annual mean temp. °F.	INCHES		
			Calculated loss	Calculated run-off	Actual run-off
Mahanadi	56·68	80·07	29·31	27·37	28·33
Ashni, Simla Hills	57·20	58·10	22·93	34·27	35·80
Difference	0·52	21·97	6·38	6·90	7·47
Indian rivers flowing into Arabian Sea	47·00	70·0	23·7	23·3	..
Brahmaputra system	48·11	46·8	18·47	29·64	..
Difference	1·11	23·2	5·23	6·34	..
Cauvery, India	38·91	72·7	34·13	4·78	..
Merrimack, U.S.A.	41·63	45·6	21·50	20·13	..
Difference	2·72	27·1	12·63	15·35	..

These figures show that, for a difference of 20°–30°F. in the mean annual temperature, the run-offs for these particular catchments with closely similar rainfalls differ in magnitude by 6 to 15 inches. This affords an indication of the increase in run-off which might be expected in India during the Pleistocene, when temperatures were lower. The monthly temperature variations were also probably smaller, which would tend, with a lower mean annual temperature, to equalize evaporation losses, and cause both a more uniform monthly discharge and a greater total annual discharge. The land elevations were, of course, different during the Pleistocene, being without question lower over most of the montane zone in the north. But the influence of lower elevations in decreasing precipitation was probably less than the effect of a lower mean annual temperature on relative humidities and evaporation losses to the precipitation, and it may be assumed that the net effect was that the run-offs and river discharges were higher than at the present day. The emphasis would be therefore not so much on the physiographic conditions necessary to cause

[1] That exceptions to this generalization exist may be seen, however, in comparing the Damodar and Chattahoochee Basins, and the Sabarmati and Mississippi basins.

TABLE 2

DIASTROPHIC CYCLES (*Vertical time intervals are not to Scale*)

⊙ ⊙ ⊙ = Plutonic Centres. = Traps.	Cutch.	Kathiawar, Gujerat.	Narbada, Tapti, Chhindwara.	Chhota Nagpur and Damodar.	Rajmahal Hills.	Garo-Rajmahal Gap.	Shillong Plateau.
Pleistocene	Depression Gulf of Cutch. Folding and Erosion.	Depression Gulf of Cambay.	?Elevation of 1,000 feet of Saline beds in Tapti alluvium. Middle Pleistocene Gravels Clays.	↑	Tilting.	Sag and tear-faulting along N.W.-S.E. Zone, with formation of gap.	
Pliocene	Marine Beds.	Marine Beds and Agate Gravels.		Elevation of 2,700 ft. in Chota- Nagpur.	Inferred hinge line of no movement.		
Miocene	Folding. Erosion. Marine beds.	?Rejuvenation of folding along L. Eocene axes.	Compression and elevation. Downfaulting of Rifts by several thousand feet.	Marine beds in Mayurbhanj. ↓		Presumed uplift and formation of bridge.	Uplift of Garo Hills.
Oligocene	Folding. Erosion.						
Eocene Upper .. Middle ..	Marine beds and some continental beds with coal.	Marine Beds. Agate Conglomerates.	Tension and subsidence.	Tension and subsidence.			Uplift of Khasi Hills. Estuarine Beds.
Eocene Lower ..	Lateritization. Folding and Erosion. Dykes.	Lateritization. Folding and Erosion. Dyke Swarms ⊙ ⊙ ⊙ Kathiawar.		Dolerite Dykes.			
Cretaceous	Cutch Traps Tension. Marine beds.	Malwa Traps Tension.	Folding uplift and erosion.	Faulting and Folding.	Post-trap faulting.		Marine beds.
Jurassic	Marine beds and Coal formations. Sandstone dykes and slumping of sediments due to Earthquakes.		Continental formation with lenticular coal.	Mica peridotites.	Tension.		Sylhet Traps age uncertain, but pre-Cretaceous.
Triassic	?		Folding.	Folding.	Folding.		?
Permian	?		Folding. Coal formations.	Folding. Coal formations.	Coal formations.		Continental.

increased precipitation, but on the factors responsible for reduced losses to the precipitation, which need not have been very different from what it is at the present day.

The primary factors involved in this problem of faunal migration would appear, therefore, to be the following:—

(1) A secular climatic change, involving 4 or 5 glaciations, with interglacial periods which were probably cooler than any climate experienced now in central and southern India.

(2) The glaciers during the periods of ice advance reached much lower down the valleys, and glacial boulder beds have been found recently even to be incorporated within the Siwalik succession of northern India.

(3) Not only did the glaciers reach to lower levels as a consequence of a colder climate, but during the Pleistocene the montane zone must itself have been at smaller elevations. The influence of the glaciation on the climate of the Peninsula must therefore be considered from the dual point of view of an intrinsically colder climate in the mountains and the existence of glaciers at lesser elevations than even the present heights of maximum ice advance indicate. During the phases of maximum glacier advance the snouts of the glaciers may have been, from combined climatic and isostatic causes, some 6,000 to 8,000 feet lower than at the present time.

(4) It is difficult to avoid the conclusion that these conditions in the montane and bordering zones of northern India must have resulted in a diminution of the temperature in the region now represented by the Satpura and Vindhyan ranges. A lowering of the mean annual temperature in these regions of only 20° to 30°F., which would still be considerably above the freezing temperatures of the glaciated region to the north, would permit much greater run-off and larger river discharges for an equivalent rainfall.

(5) The greater relative humidity and higher river discharges would perhaps be sufficient explanation for the migration of the faunas postulated.

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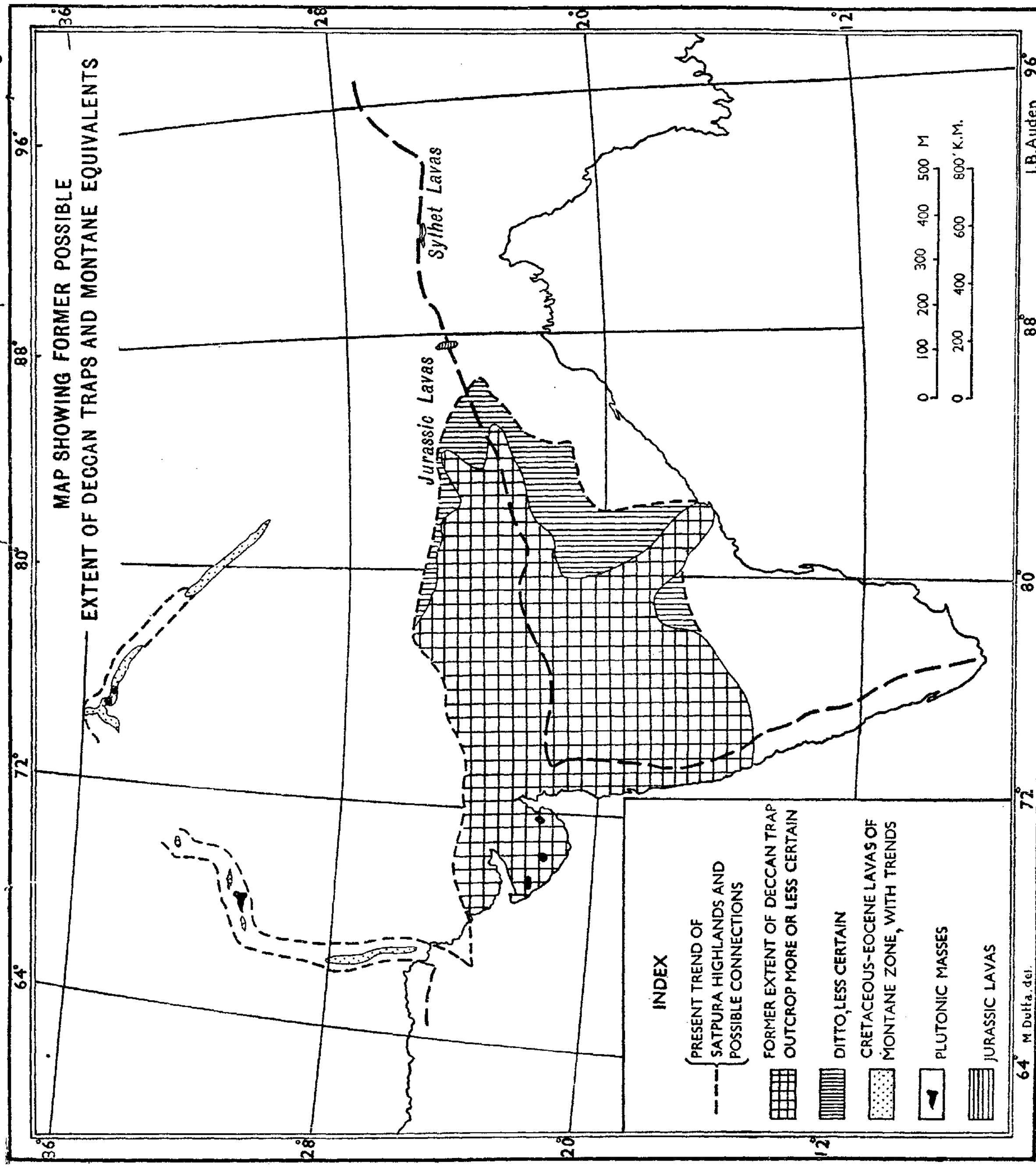
Fig. 1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Sylhet Lavas
0 100 200 300 400 500 M
0 200 400 600 800 K.M.
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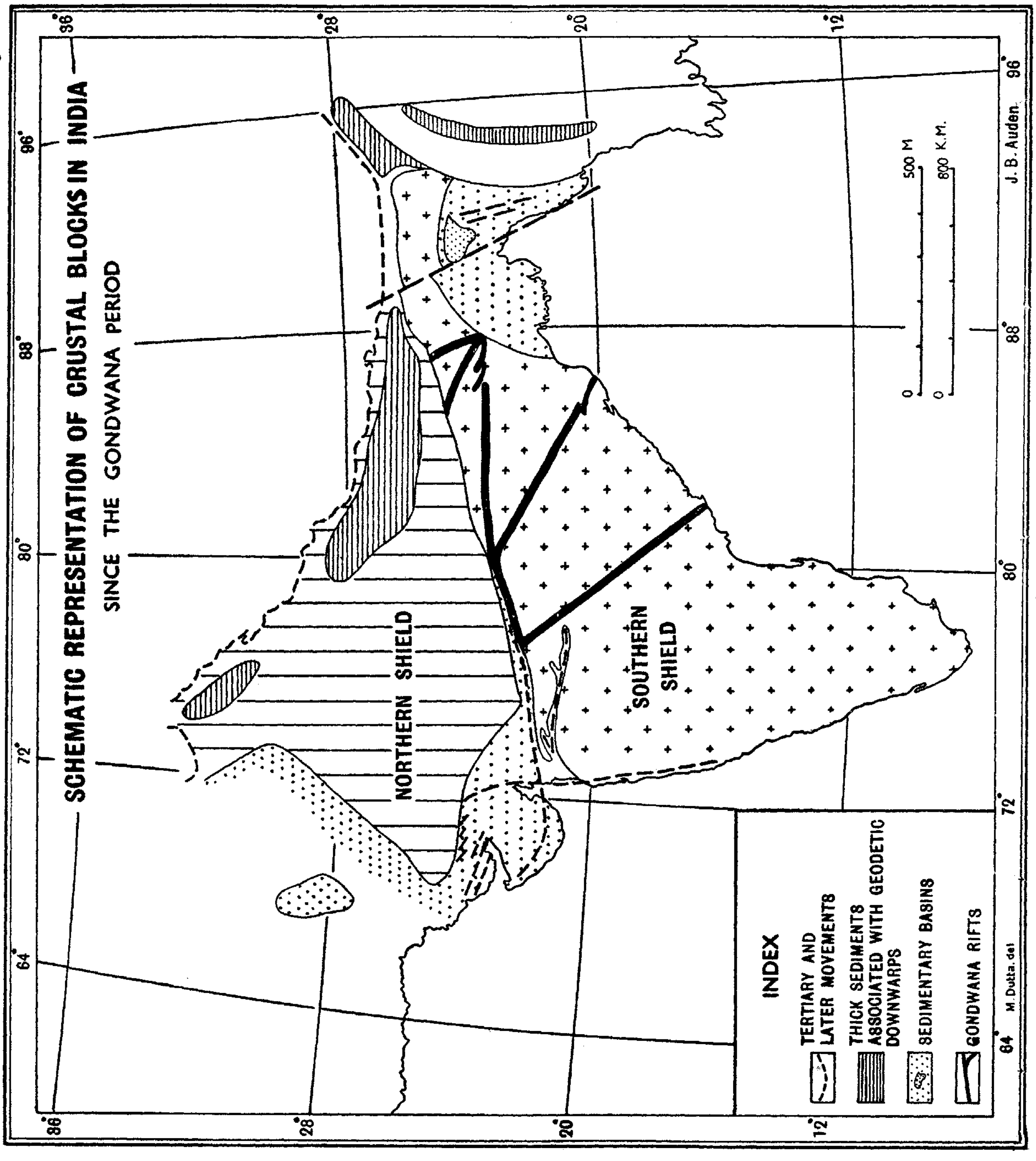
PLUTONIC MASSES
JURASSIC LAVAS
M Dutta. del.
36°
28°
20°
12°
64°
72°
80°
88°
96°

Fig.2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