SOME ASPECTS OF GEODYNAMICS OF THE INDIAN SUB-CONTINENT

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The data furnished by geophysical investigations in search of hydrocarbons have been used to interpret and reconstruct the tectonic history in the areas explored. The results show that two of the areas bordering the present Indian shield experienced crustal stretching during a period extending from Mesozoic to Paleogene. The area of Cambay basin in Western India experienced tensional forces oriented in ENE-WSW direction beginning in the Cretaceous period which gave rise to the formation of the Cambay rift. The state of tensional stress tapered off towards the close of the Paleogene. Similar tensional forces were operative in different parts along the eastern coast beginning from the Jurassic which died down by the close of the Cretaceous or early Paleogene period.

The intense compressive forces which caused crustal shortening and the ultimate rise of the Himalaya did not affect the molasse deposits known as Siwaliks of the Middle Miocene-Pliocene age, laid under the Indo-Gangetic plains. Only a northward tilting of the strata is observed here. The ancient Aravalli trend of the Archaean shield has been traced in the pre-Tertiary sediments under the plains, however, there are tectonic elements parallel to the Himalaya as well in these formations. A very high seismic velocity (6.8—7.0 km/sec) has been observed in the area close to the foot-hills as compared to a velocity of 5.4 km/sec. recorded in the areas lying south of the Ganga and the exposed rocks of the shield. The question that the characteristic difference in velocity signifies two different crustal blocks remains to be solved.

The geophysical investigations in the Brahmaputra Valley in the northeastern India have brought out that there have been vertical or near vertical movements along faults in the basement which have affected overlying sediments of Eocene to Pliocene age. A system of E-W trending faults have been mapped which are parallel to the Dauki fault system characterising the southern margin of the Shillong plateau. Some of these faults appear to be active even today. In the Bengal basin a hinge zone trending in NE-SW direction has been delineated. Rapid subsidence has occurred to the southeast of this zone.

A NW-SE trending basement arch has been delineated in the Rajasthan basin. The overlying sediments of ages ranging from Tertiary to at least Jurassic have also been arched over this basement feature.

Summarising it may be stated that the sedimentary basins in India, barring the folded belts of Himalaya and Assam-Arakan and the Pre-Tertiary stage in the Gangetic plains have not experienced any major compressive deformation cycle. They have been affected largely by block faulting.

INTRODUCTION

The surface features of the earth are due to the geodynamical processes that involve not only the near surface layers but also the lithosphere and upper mantle.

While the geologic phenomena observed at the surface are inadequate to completely understand the complex geodynamic processes, nevertheless their study is a starting point in rationalizing the various processes that may have been active in the geologic past. Such investigations allow to categorize the areas of tectonic activity in terms of time and space and also the type of activity.

The tectonic history of the Indian sub-continent has been the subject of study by geologists for over a century. The results of this extensive study have been synthesized by Krishnan (1953). Krishnan's study concerned itself mainly with the exposed tectonic lineaments. There are considerable areas which are blanketed by alluvium and there were number of gaps in the peripheral areas of the shield where the knowledge of structure and tectonics was lacking.

Since the year 1957, the Geophysicists of the Oil and Natural Gas Commission have been conducting extensive gravity, ground magnetic, aeromagnetic, seismic refraction, reflection and well log investigations in the sedimentary basins of the country. This work was done within the framework of the exploration for hydrocarbons. One of the notable contributions of geophysical studies has been mapping of the basement structures in the basins and the thickness and tectonic history of the overlying sediments. These data, to a considerable degree, have filled in the gaps in our knowledge regarding the tectonic evolution of the border areas of Indian shield. The present article briefly presents the data with the hope, that it will serve a useful purpose in building up a coherent picture of the geodynamic processes that have shaped this part of the earth.

RESULTS

Cambay Basin—The alluvial covered Cambay basin is situated in the Western part of the country. Metamorphics of the Aravalli age exhibiting the NE-SW tectonic lineament, border the basin on the northeast. Towards the west and south-east exposures of Deccan Traps are present. Sedimentary formations of Upper Jurassic to Middle Cretaceous age are exposed in small patches along the northeastern and northwestern margins of the basin. Marine Tertiary formations are exposed overlying the Deccan Trap in the southern part of the basin on both sides of the Gulf of Cambay. Drilling has revealed the presence of complete Tertiary sequence overlying the Trap floor (Chandra & Chowdhary 1969). In the deepest part of the basin the thickness of sediments may be over 6 km. The Deccan Trap flows are considered to have erupted in Upper Cretaceous to Paleocene times (e.g., Krishnan 1953; and Raju 1968).

The gravity and magnetic anomalies in Cambay basin are shown in Figs. 1 and 2 respectively. These anomalies characteristically outline the limits of the basin, which trends in north-northwest direction in the form of a narrow graben (Khattri *et al.* 1964; and Rao 1968). Both the eastern and western edges of the basin are typified by narrow bands of very sharp gravity gradients which indicate down to the basin faults. The NE-SW Aravalli trend can be beautifully traced right upto the eastern margin of the basin in the northeastern part on the basis of linear gravity and magnetic anomalies aligned along the Aravalli trend. Further to the southeast, however, this trend is not visible and is replaced by the NNW-SSE trend characterising the basin. The basin axis is characterised by strong linear positive Bouguer anomalies. The magnetic picture also exhibits an axis of high anomalies where the gravity shows

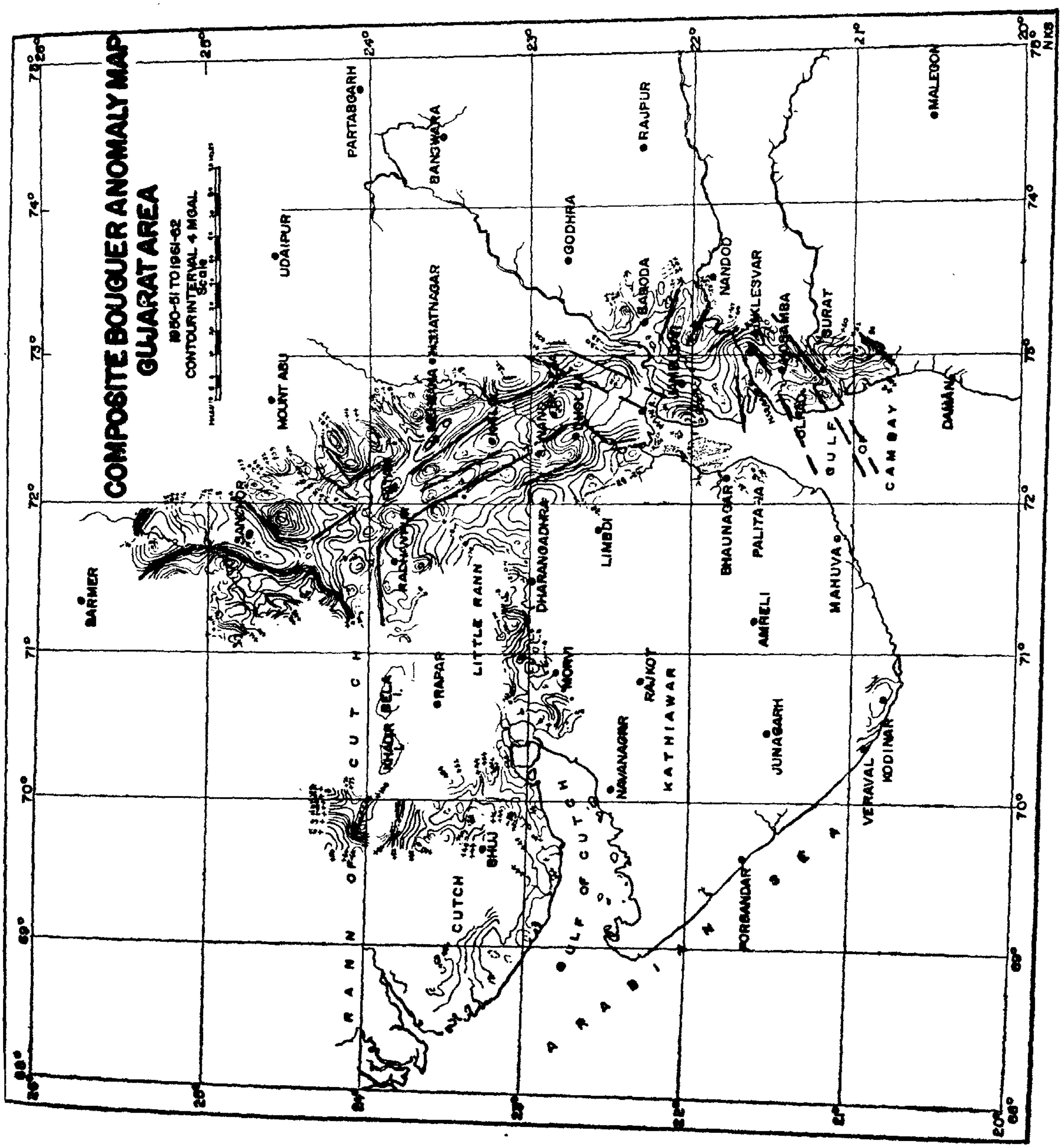

FIG. 1. Bouguer gravity map of Cambay basin (after Khattri *et al.* 1964)

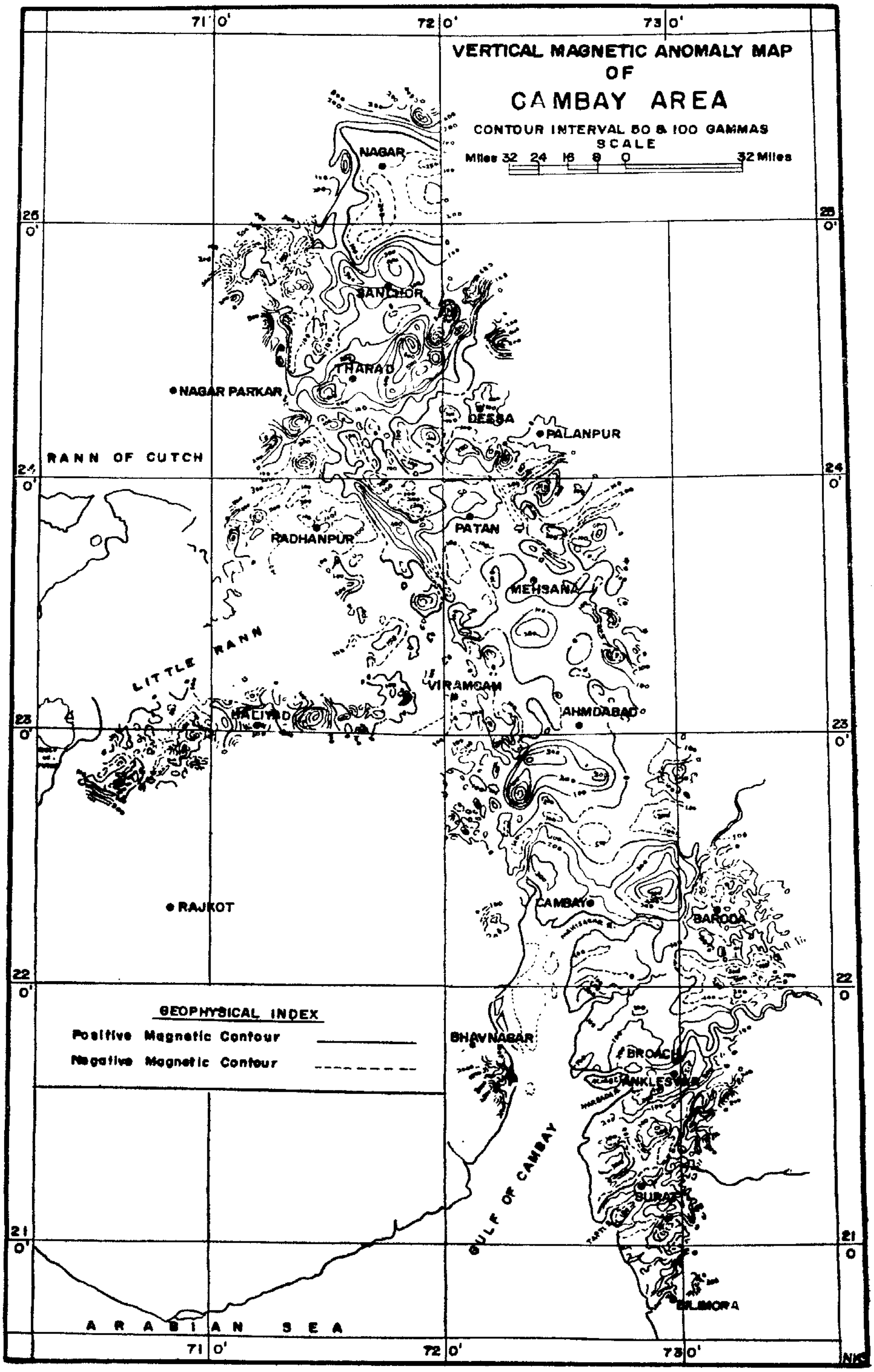

FIG. 2. Vertical magnetic anomaly map of Cambay Basin (after Khattri *et al.* 1964).

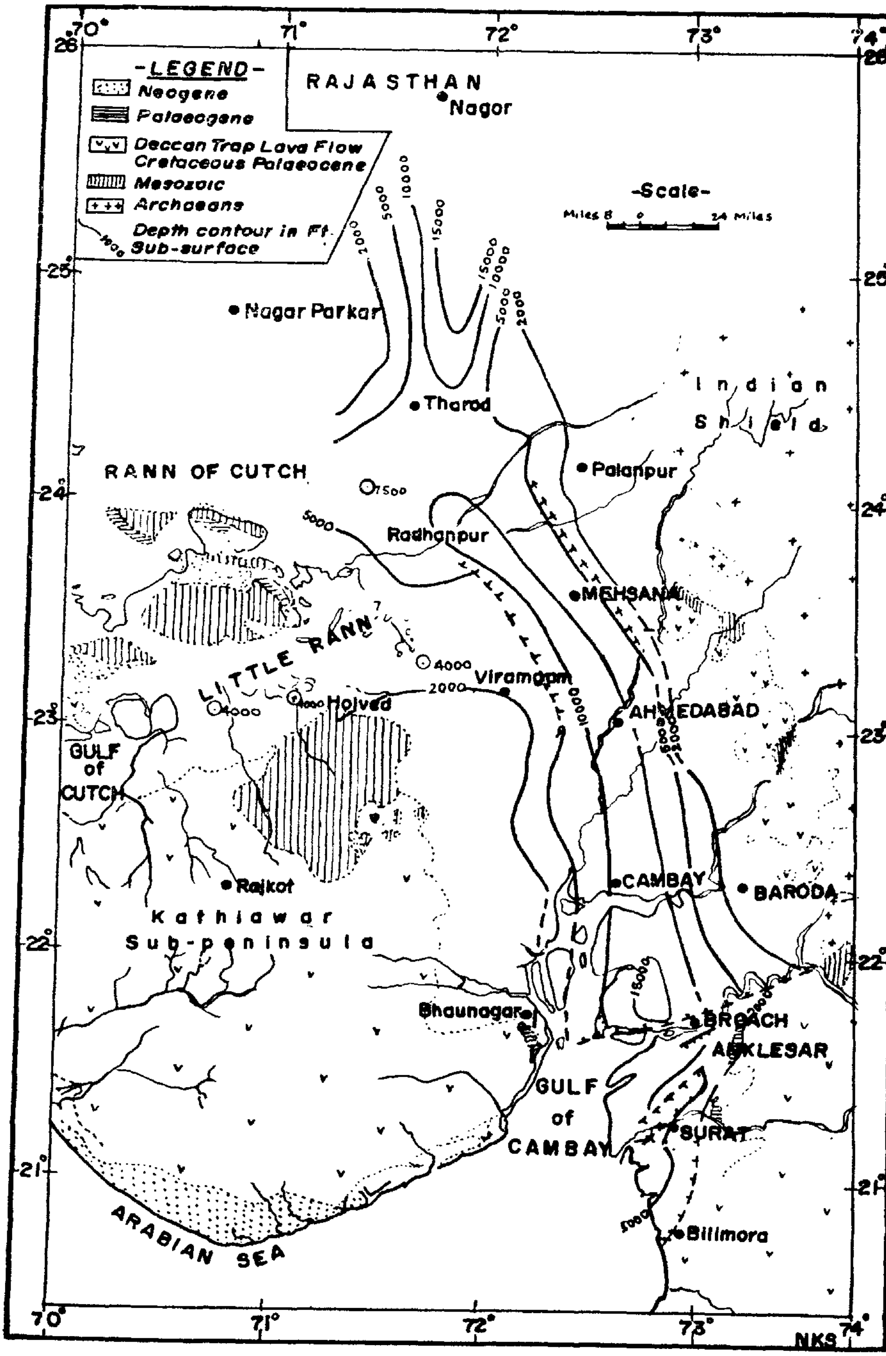

FIG. 3. Basement (Traps except in northern most parts of the basin) depth map of Cambay basin as interpreted from magnetic data (after Khattri *et al.* 1964).

an axis of highs. In the south of the Narmada river, however, the gravity and magnetic anomalies display an ENE-WSW alignment. Fig. 3 shows the generalised basement (Trap) depth map as interpreted from the magnetic data. It brings into focus the salient features of the basin as discussed above. It may be mentioned here that the Narmada river is considered to be flowing along an ENE-WSW trending geofracture system (cf. Krishnan 1953; Kalinin 1964; and Eremenko *et al.* 1969).

The seismic reflection survey (Sastry *et al.* 1964) produced a number of reflections of fair to good quality which could be traced over a wide area. A generalized seismic section along the basin is shown in Fig. 4. It highlights the Ankleswar oil field structure, the deep Broach syncline and intervening zone characterised by the Narmada rift. Reflection data coupled with refraction profiles have revealed basin margin faults in the Deccan Traps which occur in en-echelon pattern. The throw on some of these faults is as large as 1000 m. The trap surface is broken into narrow horsts and grabens within the basin (Avasthi *et al.* 1971). Many of the faults continue upwards in the overlying sedimentary formations, though with considerably attenuated amplitude. Reactivation along the basement (Trap) faults and differential movements are the main agencies for the development of structures in the overlying sediments (Mathur *et al.* 1968; and Sudhakar *et al.* 1970). A number of transverse faults cutting the basin along NE-SW direction have also been delineated. These seem to follow the ancient Aravalli grain. An episode of faulting with trend along ENE-WSW Satpura lineament occurred in post Miocene epoch in the area lying south of the Narmada river. This diastrophism gave rise to the formation of structures in the overlying sediments (Mathur *et al.* 1968; and Sudhakar *et al.* 1970).

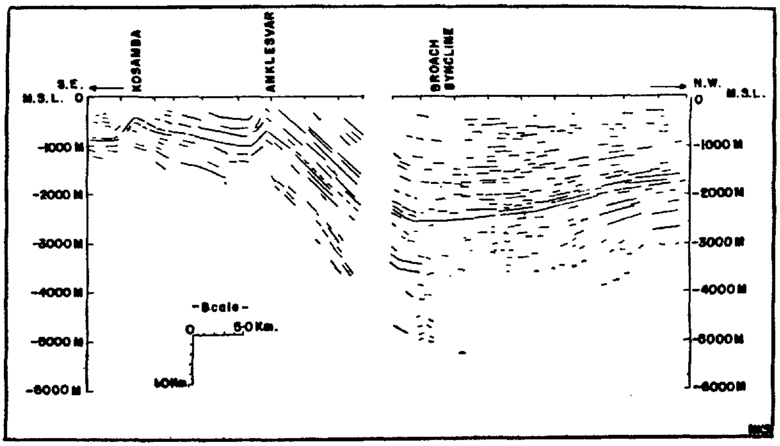

FIG. 4. Seismic depth section along the axis of the Cambay basin (after Sastry *et al.* 1964).

Studies on isopach made on the basis of reflection horizons have shown that there was a gradual migration of the basin axis towards the southwest. There was a reactivation of the Narmada rift in post Miocene times as is indicated by the rapid increase in thickness of post Miocene sediments.

The continuation of Cambay basin has been traced in the Gulf of Cambay and the adjoining shelf in the Arabian Sea. The limits of the basin have not yet been fully established in the off-shore area (Sengupta 1967; and Sengupta & Khattri 1972).

High geothermal gradients have been observed in the deep wells drilled near Cambay in this basin (Gupta *et al.* 1970).

Kerala-Laccadive Area—Gravity-magnetic surveys on the Kerala coast have indicated that the thickness of the sedimentary sheet is about 1.0 km only. Seismic survey in the offshore area between Kerala coast and Laccadive islands has revealed the presence of sediments dipping and increasing in thickness towards the west. These sediments attain a thickness of 2.0 km near the shelf break. Zones of tectonic disturbances of the sediments which are controlled by faults are found in the area of continental slope. It is rather difficult to ascertain the ages of the sedimentary formations in the shelf area and their tectonic setting on the basis of presently available data. However, one may speculate that the Kerala-Laccadive area may be forming the southern part of a rift commencing from the Cambay basin in the north and encompassing the entire western coast (cf. Krishnan, 1953; Sengupta 1967; Eremenko & Datta 1964; and Eremenko & Gagelganz 1966).

Basins on the East Coast—The results of geophysical investigations in three coastal basins will be summarised in this section. These basins comprise of the Cauvery, Godavari-Krishna and Mahanadi basins. The Cauvery basin is the most intensively surveyed area, both on land and offshore (Das & Sengupta 1966; and Raiverman *et al.* 1966). The gravity surveys on land have shown that the basin is dissected into troughs and ridges trending in NE-SW direction which is parallel to the ancient Eastern Ghat lineament present in the archaean shield. The Bouguer gravity anomaly in Cauvery basin is shown in Fig. 5. The anomalies depict the structural trends. Seismic surveys have confirmed these features on land and have traced their continuity in the offshore areas also. In addition to the above mentioned main tectonic trend, N-S and E-W trending lineaments are also discernible. The ridges are characterised by disappearance of reflectors towards their crests. The upper reflectors show just a gentle draping over these highs.

Deep drilling in the area has revealed upper Gondwana to Neogene sediments. Correlation of stratigraphy with the reflection data shows that block faulting of the area faded out by the end of Paleogene era. The sediments attain thickness of the order of 4.5 km in the depressions (Sastry *et al.* 1973).

The Godavari-Krishna basin, like the Cauveri basin, is characterised by NE-SW trending linear gravity-magnetic anomalies which represent the topography of the archaean basement exposed in the west. The seismic exploration has broadly confirmed the indications obtained from the potential field anomalies. The general dip of the sediments is towards southeast. The faults in the basement and the deeper sediments die upwards with the younger formations generally showing no disturbance. (Das *et al.* 1969; and Sastry *et al.* 1973).

The Mahanadi basin on the land is relatively shallow. The geophysical data indicates that the structural elements have a dominant ENE-WSW strike. Folded structures seem to be absent, faulting being the main form of structural disturbance. The sedimentary formations dip gently in the southeast direction (Sastry *et al.* 1973).

West Bengal Basin—The West Bengal basin represents the shelf region of the Assam—Arakan geosyncline in the eastern part of the Indian shield. This area has been studied in considerable detail by geophysical techniques (Sengupta 1966; and

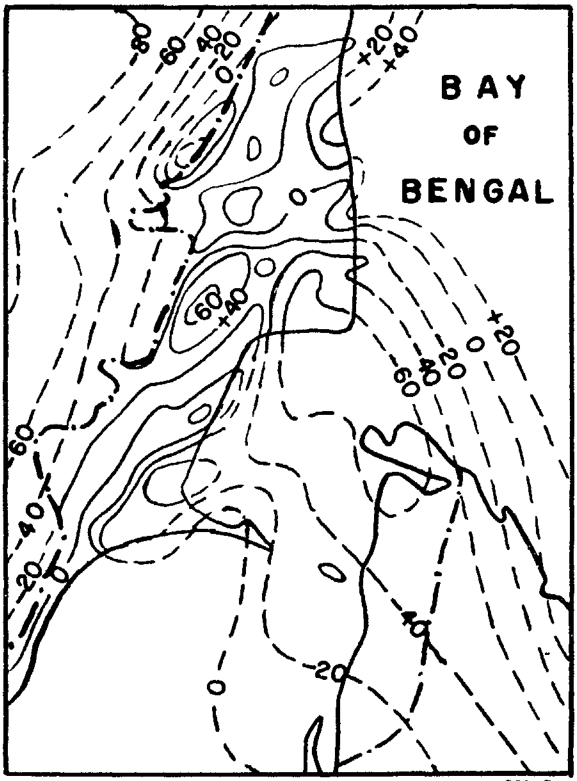

FIG. 5. Bouguer gravity map of Cauveri basin (after Raiverman *et al.* 1966).

Choudhury & Datta 1973). Drilling has revealed the presence of a complete sequence of Upper Gondwana, Cretaceous, Tertiary and Recent Sediments which are lying unconformably over the Rajmahal Trap flows (Sengupta 1966). Gravity and aeromagnetic data are typified by ribbons of sharp gradients in anomalies in the basin rim area. They characterise en-echelon faults which trend in N-S direction in the south and gradually turn to NNE in the northern area. These features are confirmed by seismic evidence. The Bouguer gravity shown in Fig. 6 is characterised by elongated highs and lows with their axes in NNE-SSW direction. A general fall in the level of gravity anomalies is noticed in the SE direction which is interrupted by the linear gravity high anomaly trending from Calcutta to Mymensingh in a NE-SW direction. Although the cause of this anomaly is not understood clearly, this prominent anomaly is in some way related to the basin development.

Several seismic reflectors are recorded in the shelf of which the marker reflector arises from an Eocene limestone bed. Another reflection arises from the Rajmahal Traps (upper Jurassic). The horizons display a very gentle dip towards SE which is occasionally interrupted by down to the basin minor faults. A hinge zone trending in NE-SW direction and passing through just southeast of Calcutta has been established. A gradual thickening of the sediments takes place upto the hinge zone

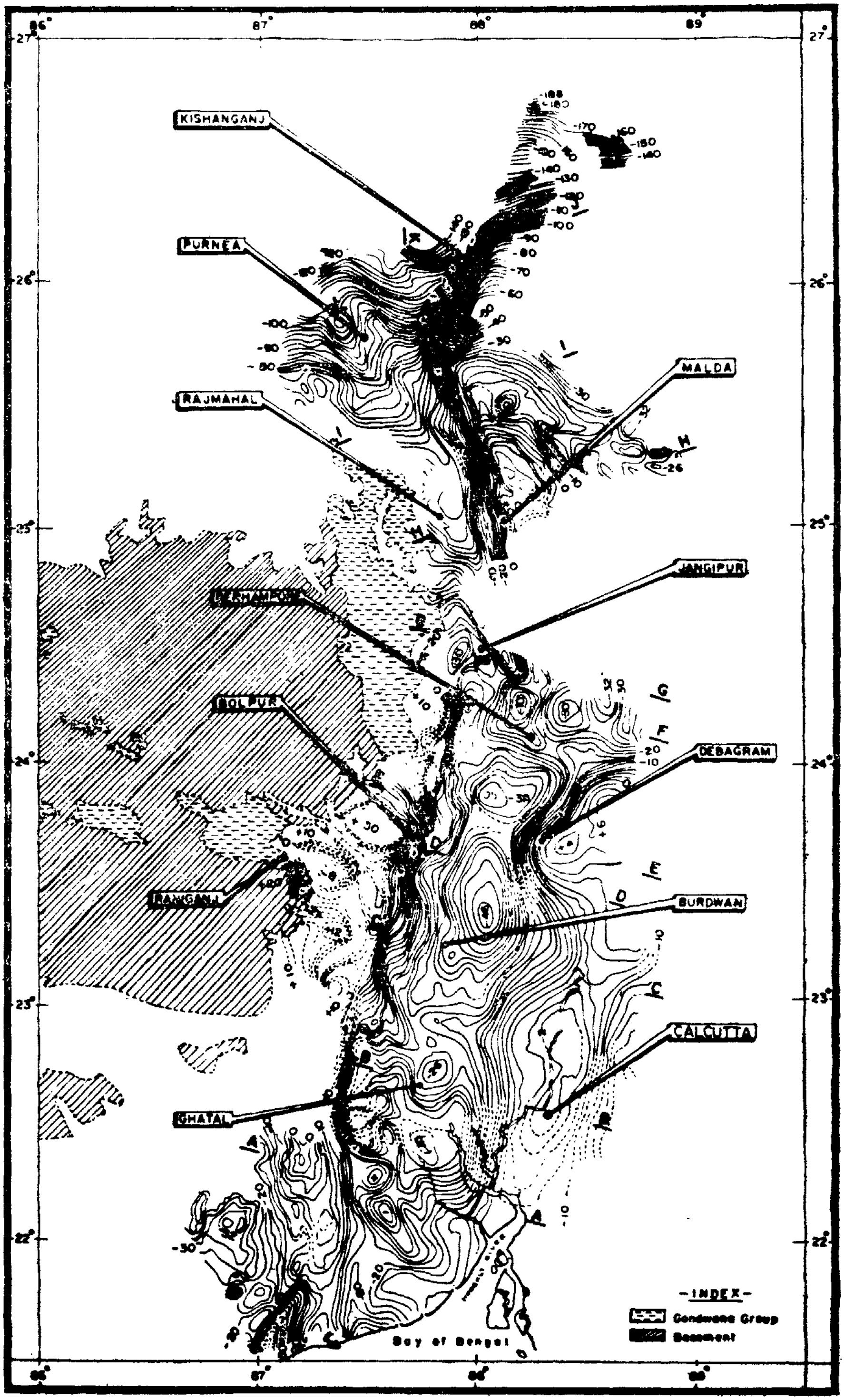

FIG. 6. Bouguer gravity map of West Bengal Basin (after Chaudhury & Datta 1973).

beyond which there is an abrupt increase in thickness. Flexures parallel to the hinge zone have developed in the sediments. The hinge zone coincides with the eastern margin of the Calcutta-Mymensingh gravity high. It is, therefore, possible that although the cause of gravity anomaly appears to be deep seated, its ramifications helped in the formation of the hinge zone in the overlying sedimentary mantle.

The isostatic gravity anomalies are slightly positive in the region of the West Bengal basin (Gulatee 1956; and Qureshy 1971). This would suggest that the huge thickness of (4 to 6 km) of lighter sedimentary material is compensated by the reduction in thickness of the depressed continental crust. Such a reduction could have taken place by a gradual oceanization of the continental crust in this area.

Bramhaputra Valley (*Assam-Arakan Basin*)—The narrow tract covered by alluvium of the Bramhaputra river in the north-eastern corner of the country has been the scene of intense geophysical investigation (Ray *et al.* 1964). The area is bordered by the folded belts of the Himalaya on the northern side and the Naga hills on the south and south-east. The Shillong massif and the Mikir hills outline the basin on the south-west (Raju 1968).

The gravity anomalies show a relative high in the valley with a steep decrease in values both towards the northeast and southeast. It may be interesting to note that the Shillong massif in southwest is an area of positive Bouguer and isostatic anomalies. A number of seismic reflections, which arise in well defined groups, have been mapped in this area. One of these bands of reflections is persistent over a large areal extent, although its quality deteriorates considerably in certain areas. The major structutal components revealed by the seismic surveys are shown in Fig. 7. The basement slopes from the Shillong plateau side in the southwest towards northeast. In addition, this northeast plunging wedge of the Indian shield has slopes towards the north and northwest and south and southeast. The sedimentary foımations increase in thickness on both the flanks. Correlation of seismic data with well data indicates that while the thickness of early Tertiaries increases in the southeast direction, only the thickness of the Upper Tertiaries do so in the northwest direction. This would indicate that the tilting of the shield in the northerly direction was a relatively younger event. The seismic mapping has revealed that the strata are faulted in a rather complicated manner. The more persistent of the trends are the NE-SW and E-W. The E-W trending fault system is parallel to the well known Dauki fault characterising the southern flank of the Shillong plateau.

Sindhu-Ganga Basin—The alluvial covered flood plains of the Sutlej and the Ganga and its tributaries at the foot of Himalaya have been covered by extensive geophysical surveys (Sengupta 1962: Aithal *et al.* 1964; Datta *et al.* 1964; and Mool Chand *et al.* 1964) A relatively limited volume of investigation has also been conducted in the foot-hills, notably in the western part of the basin.

The gravity and magnetic pictures in the plains of Punjab and Haryana show a dominant NW-SE alignment of linear anomalies parallel to the general trend of Himalayas in this region (see Figs. 8 & 9). The gravity decreases steadily towards the north-east attaining rather a sharp gradient close to the foot-hills. Corresponding to the sharp gradient zone in gravity, the magnetic map shows an alternate series of sharp linear positive and negative magnetic anomalies. The cause of this feature

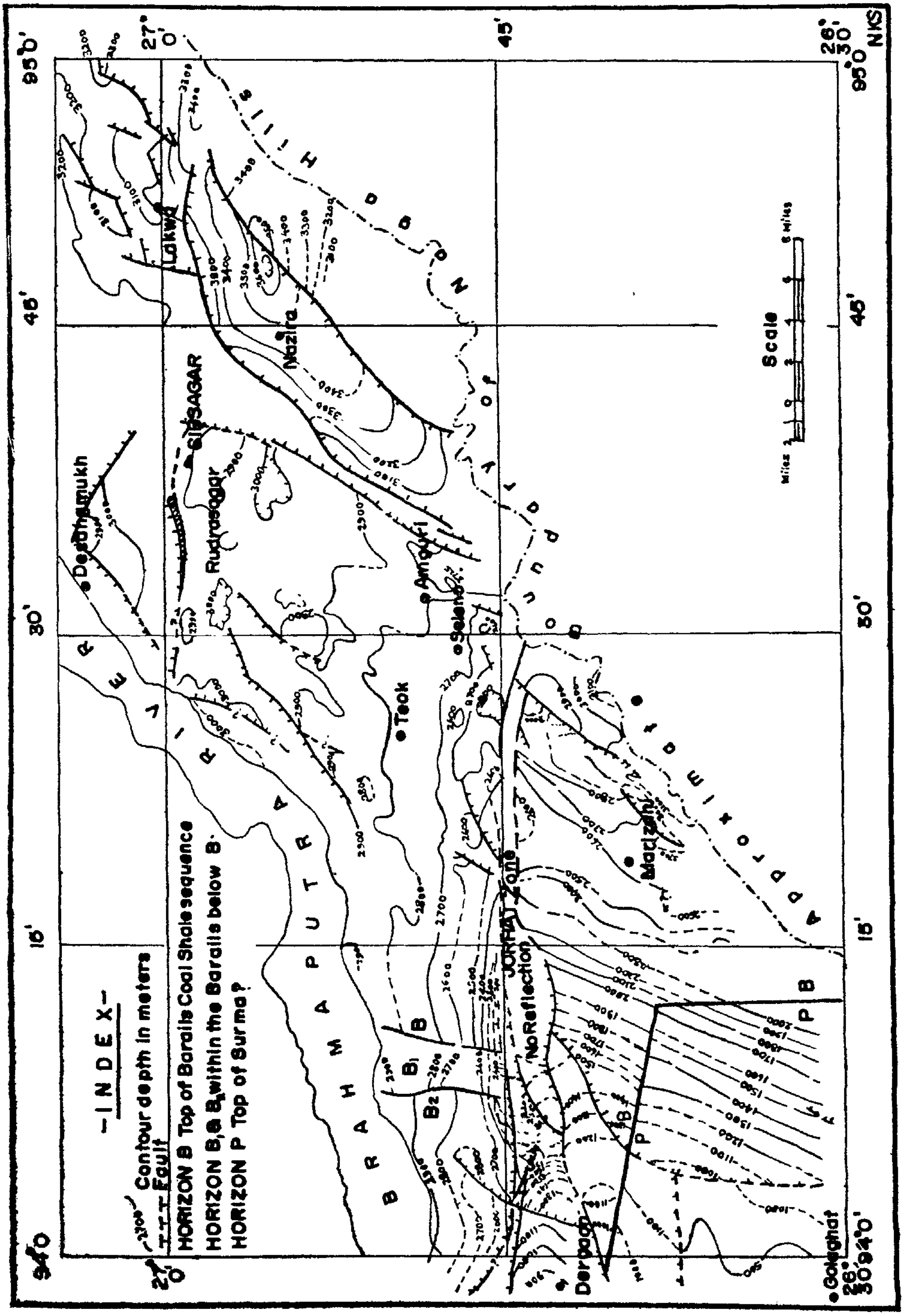

FIG. 7. Seismic structural contour map in Brahmaputra Valley, Assam Arakan Basin (after Ray *et al.* 1964).

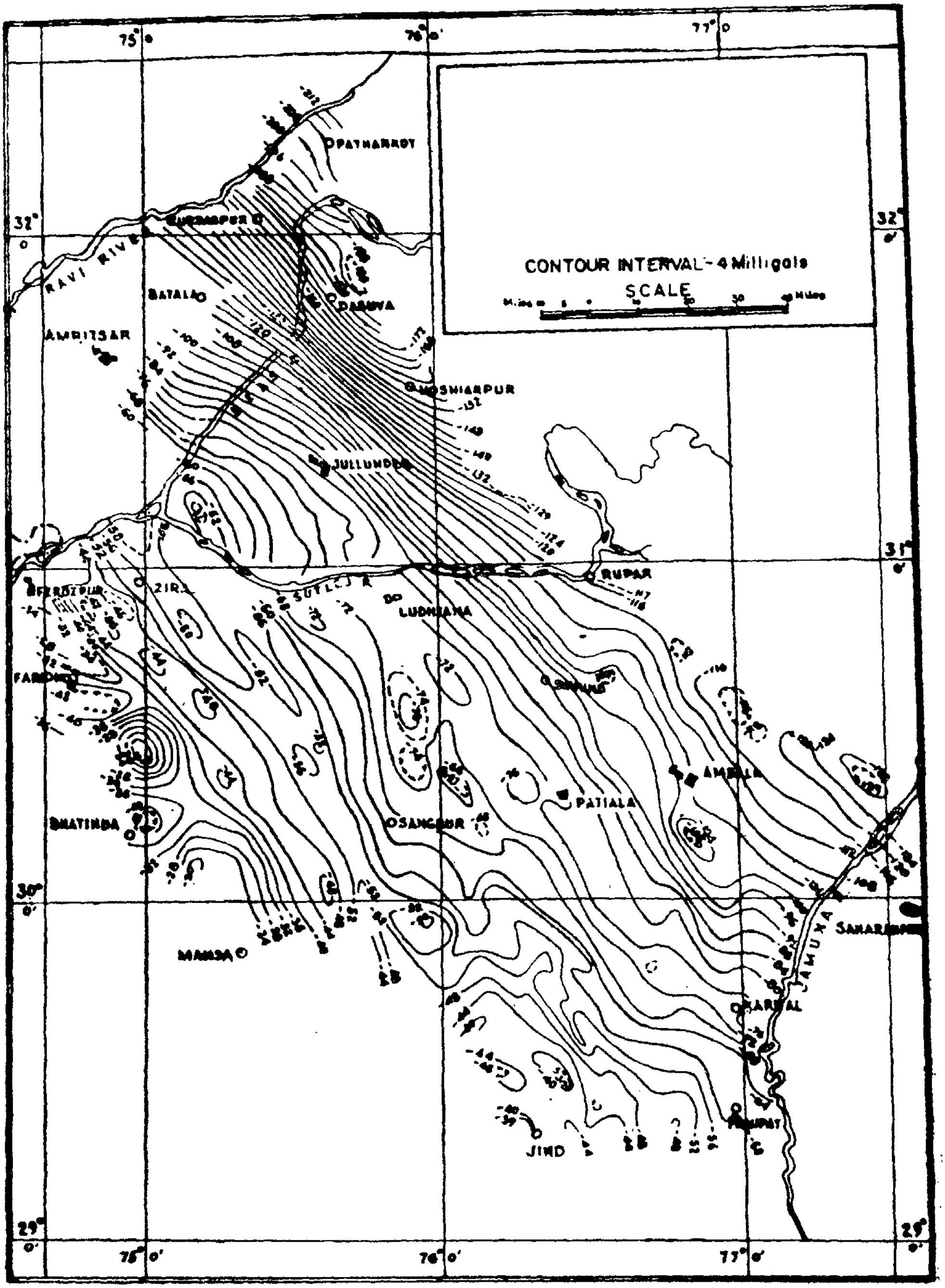

FIG. 8. Bouguer gravity map of Amritsar–Saharanpur area of Sindhu–Ganga basin (after Aithal *et al.* 1964).

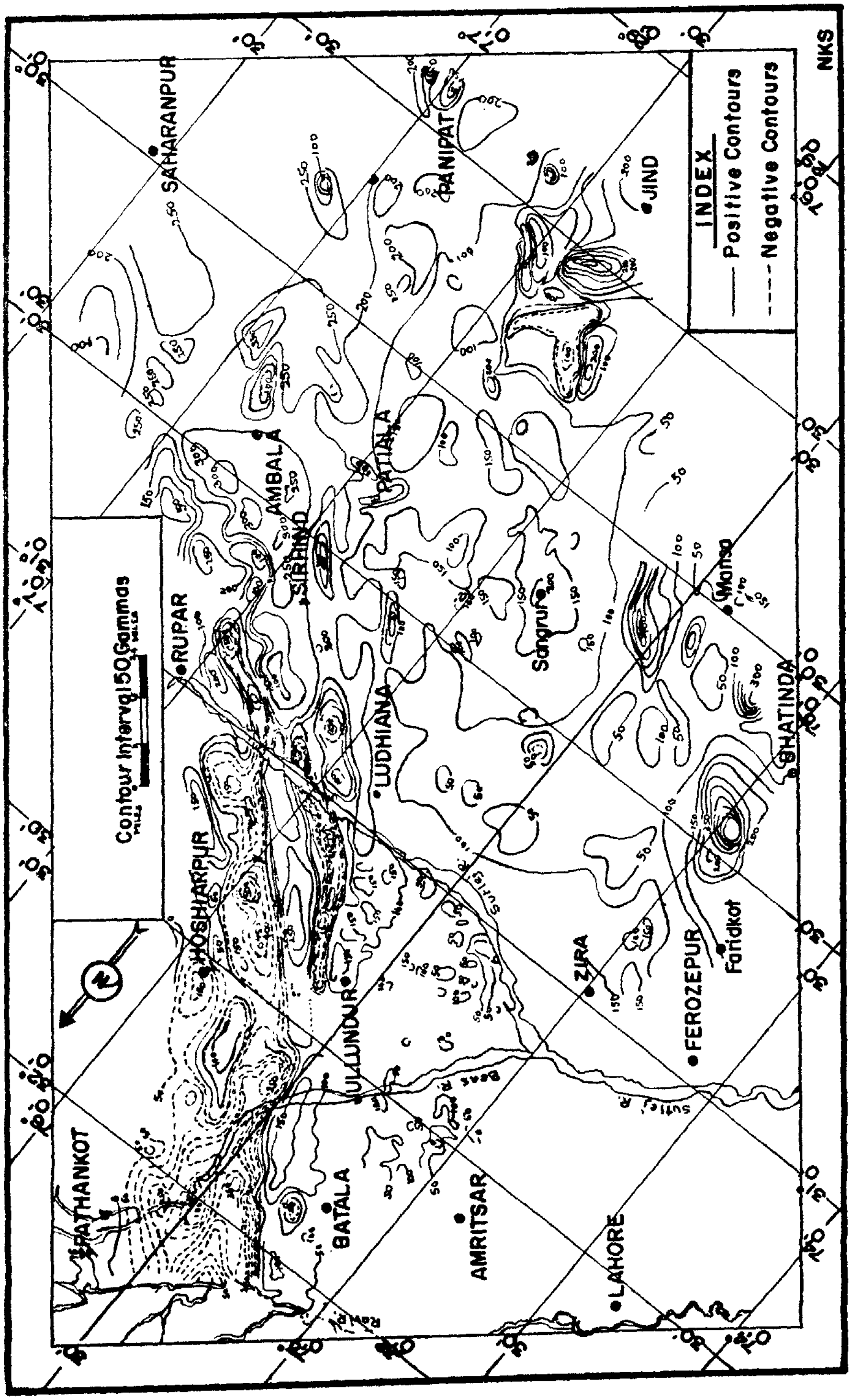

FIG. 9. Vertical magnetic anomaly map of Amritsar–Saharanpur area of Sindhu-Ganga basin (after Aithal *et al.* 1964).

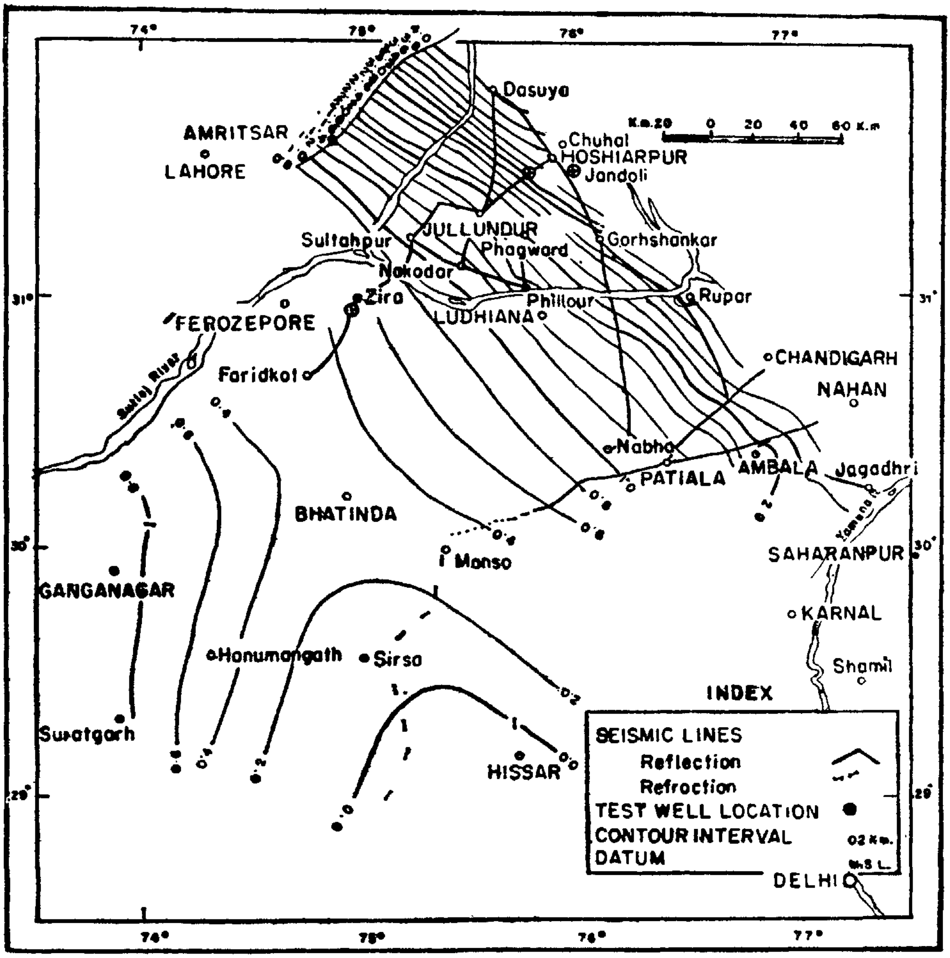

FIG. 10. Seismic structural map on basement in Amritsar–Patiala-Hissar area of Sindhu-Ganga basin (after Datta *et al.* 1964).

is not clearly understood as the basement map prepared on the basis of refraction surveys has not revealed any tectonic disturbance. The basement map prepared from refracrion data is shown in Fig. 10. The contours show the steady monoclinal plunge of the basement surface upto the foot-hills in northeasterly direction. In the southwestern side a broad arch has been outlined along Hissar-Ferozepur line. The overlying Siwalik sediments, which are of Middle Miocene and younger age, do not exhibit any folding at all, except for some very minor ones just in front of the Siwalik hills. To the southwest of the aforementioned arch Paleozoic, Mesozoic and Lower Tertiary formations have been met. It may, therefore, be concluded that the northeastern side of the arch was a positive land mass until Middle Miocene period when this crystalline mass began to sink and tilt towards northeast to receive the Siwalik clastics.

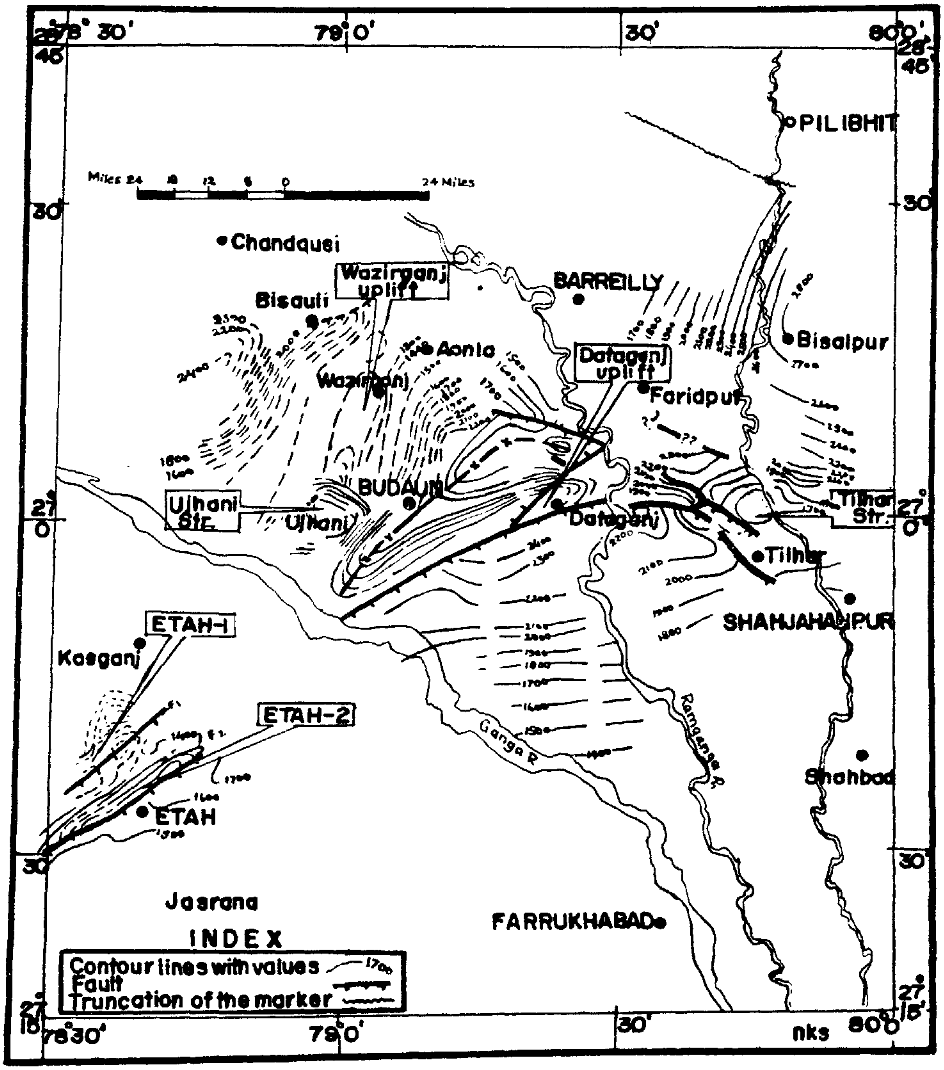

FIG. 11. Seismic structural map in Badaun–Shahjahanpur–Etah area of Sindhu–Ganga basin (after Mool Chand *et al.* 1964).

The plains of Uttar Pradesh and Bihar comprise a distinctly different part of the Sindhu-Ganga basin. This major unit can further be sub-divided into sub-units on the basis of geophysical-geological data. The gravity anomalies are strongly influenced by the isostatic effect and exhibit contours parallel to the Himalayan trend with their values decreasing in the direction of the Himalayas. Towards the South close to the exposure of the shield, however, this monotony in the gravity picture is broken by NE-SW trending features in the Lucknow-Moradabad area. The basement configuration estimated from the aeromagnetic data displays tectonic lineaments parallel to the NE-SW Aravalli trend in the western part in Moradabad area (Sengupta

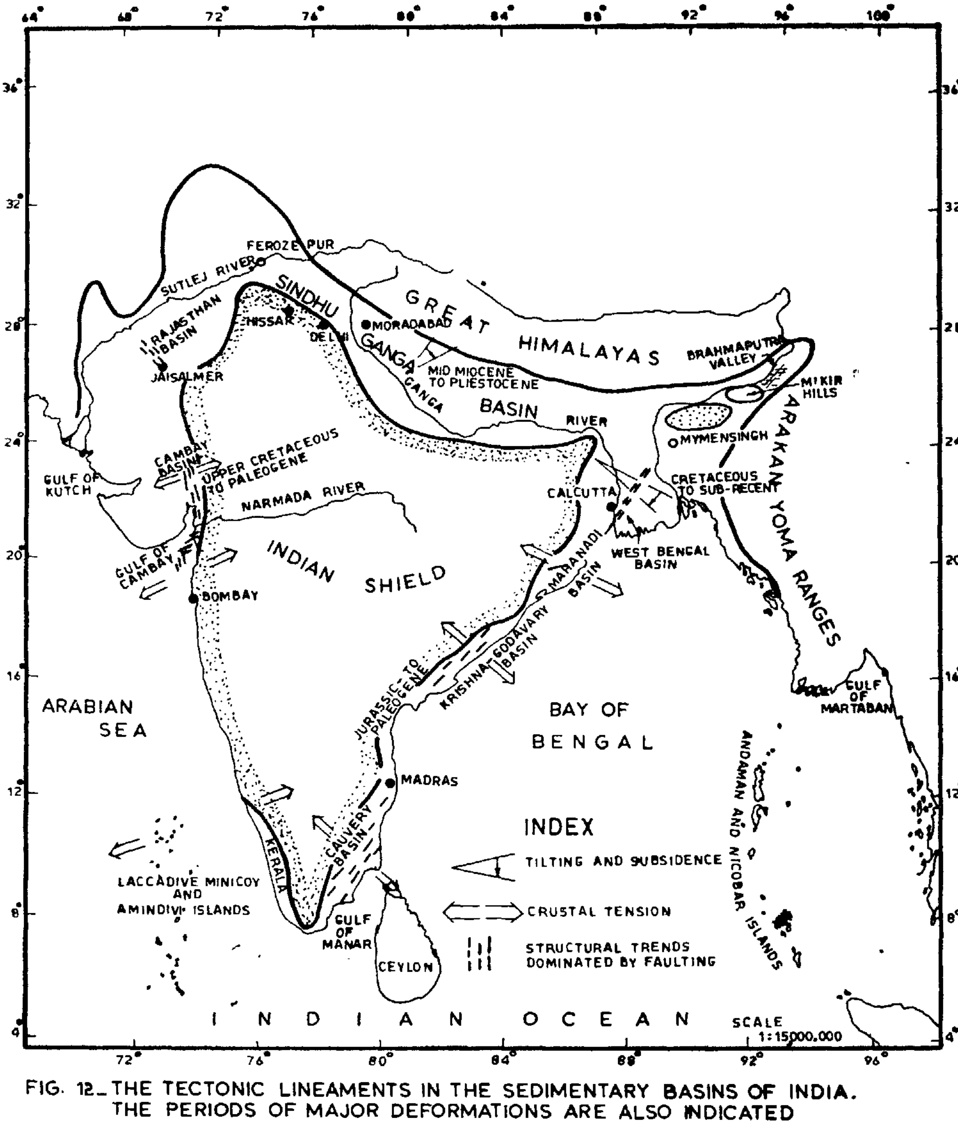

FIG. 12. The tectonic lineaments in the sedimentary basins of India. (The periods of major deformations are also indicated).

1962; and Rao & Sengupta 1964). However, as the foothill area is approached there is evidence of structural trends parallel to the Himalaya making appearance. Towards the east the Lineaments swing to take a dominantly E-W trend.

The seismic reflections are obtained at several levels which define a pronounced and wide-spread unconformity. Rather a sharp velocity contrast exists across this unconformity. The horizons above the unconformity constitute the Siwalik formations and dip gently from the edge of the Indian shield in the direction of Himalaya.

There are no significant structural deformations in this stage. The pre-Siwalik stage, in contrast, is complex and is characterised by strong deformation and faulting in many places. Fig. 11 shows the structural contour map on pre-tertiary formations in a part of the area under consideration. The structures are parallel to the Pre-Cambrian Aravalli trend in areas towards the southwest. However, tectonic lineament becomes parallel to the Himalayan trend in areas close to the foot-hills (not shown in Fig. 11). Very high seismic refraction velocities ranging between 6.8—7 km/sec have been recorded in this area at a depth of about 4.5 km. The normal basement velocity recorded on the exposures of Pre-Cambrian rocks in the shield as well as in sediment covered areas south of the Ganga river is of the order of 5.4 km/sec. The presence of the high velocity rocks in the vicinity of foothills is an interesting result. Whether this characteristic difference in velocity signifies the presence of two different crustal blocks, or emplacement of some material brought up from lower crust is at present a speculative question and needs further study.

There is a controversy regarding the age of the formations underlying the Siwaliks. They may be Lower Paleozoic or Pre-Cambrian. However, the characteristics of the basin may be quite different in the easternmost part of the basin where Gondwana formations are present.

Rajasthan Basin—The Rajasthan basin constitutes the shelf zone of the Indus Geosyncline. The area is covered by sands of Thar desert. A salient feature of the geophysical exploration in the region is the mapping of a NW trending basement arch from Jaisalmer where the existence of the same is exhibited in the exposures. The overlying sediments have also been disturbed. En-echelon faults characterise this arch and the overlying sediments.

Conclusions

The basins on the periphery of the Indian craton on the eastern and the western coasts are characterised by epirogenic setting. A secular sinking of the basement in these areas took place beginning from Jurassic or Cretaceous periods. The main tectonic elements are due to the consequence of block faulting which are parallel to the ancient tectonic lineaments in the bordering shield areas. Fig. 12 schematically illustrates the tectonic lineaments mapped in the sedimentary basins. There is a lack of folding in the sediments which could be ascribed to secular compressive forces. While it is realised that the structure of the crust at the surface may not be related directly to the forces deforming the lithosphere, it may still be surmised that the present data indicate the existence of tensional forces in the crust in the coastal areas at least from the beginning of Jurassic era. The effusion of basalts appears to be related to this state of stress of the crust. The block fault structure of the basins also testifies to the same conclusion.

Paleogeographic studies based on paleomagnetic data (cf. McElhinny 1968), fitting of the continents (cf. Bullard *et al.* 1965; Dietz & Holden 1970; and Smith & Hallam 1970) and marine magnetic data (McKenzie & Sclater 1971) point out that upto the Late Paleozoic era the Indian-Sub-Continent was a part of either Gondwana-land or of the super continent known as Pangea. Thereafter, the break up of this continent started with northward drifting of India. The presence of block faulted basins of early Mesozoic age on the coastal areas of the Indian peninsula are in consonance with this hypothesis of continental drift.

The Tertiary deposits in the Sindhu-Ganga basin in the plains again have not been affected to any significant extent by the orogenic forces which have folded and thrusted the sediments in the foothills and further north. A secular sinking and north-ward tilt took place in this part of the basin since Middle Miocene period.

The considerable sinking of the crust that has taken place in the basin areas to receive the sedimentary deposits does indicate a response from the asthenosphere where related mass adjustments may have taken place by lateral flow of mass.

It is hoped that the above information on the surfacial geotectonic characteristics brought to light by geophysical investigations would yield important clues to the dynamic processes within the earth.

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