TECTONICS WITH SPECIAL REFERENCE TO INDIA*

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ABSTRACT

The chief elements in the structure of the earth's crust are shield and stable areas (platforms), sedimentary basins; geosynclines, folded mountain ranges and the present mobile belts formed by compression; mid-ocean ridges, rifts and faults forming another group, due to tensional phenomena. Seismic and volcanic activities are associated with the folded and mobile belts as well as with the rifts. Both these types occur in a definite pattern. The compression phenomena are more or less confined to the Pacific margins and the Alpine-Himalayan belt of mountains on either side of Mediterranean. The tension rifts follow the middle of the Atlantic and Indian Oceans with branches going out into the South-Eastern Pacific and around Antarctica.

In the case of the mobile belts, the continental margins which were the loci of sedimentation were compressed, folded and thrust over the ocean side, forming circular arcs of various dimensions. This is very clearly seen around the Pacific Ocean. Though arcuate mountain chains are also found along the Alpine-Himalayan mountain belt, the former Mediterranean Ocean has largely disappeared by the continents coming together.

The mid-ocean ridges, particularly in the Atlantic and Indian Oceans, are broad mountain features which appear to have arisen from the stretching of the crust and extrusion of large masses of basic igneous material (Sima). Recent observations have shown that the middle of these ridges are marked by deep rifts with seismic and sometime volcanic activity.

India consists of a stable peninsular shield with a mobile belt around the whole of its northern border. The structure of the peninsula is controlled by the Dharwarian, Eastern Ghats, Satpura and Aravalli structural trends, which are responsible for the triangular pattern. The Aravalli belt extends north–east from Gujarat through Delhi to Garhwal. To its east is the great Vindhyan basin which is moulded on the Bundelkhand granite massif and which presumably extends also into the Sub-Himalayas of U.P. and Nepal. It is not yet known whether there is a

* Paper presented to the Symposium on Tectonics, December, 1959.

continental nucleus in the centre of the peninsula. The structural trends have determined more or less the shape of the coast and also the direction of faulting of the three major troughs of coal-bearing rocks, one along the Damodar and Sone valleys, the second along the Mahanadi valley and the third along the Godavari valley. There is also a well-marked rift along the valley of the Narmada which has been a marine belt from the Permo-Carboniferous to recent times.

It is known that Madagascar was separated from East Africa in the Permian. The Mozambique Channel gradually widened, and from the Jurassic times marine strata were deposited, these being very closely related to the rocks of the same age found in Cutch, in the Baluchistan arc, and on the eastern side of Arabia. The eastern coast of India seems to have taken shape in the Upper Jurassic and there is a good marine succession from the Albian upwards. In Australia also there is evidence that its western coast was invaded by the incipient Indian Ocean in the Jurassic and more extensively in the Cretaceous.

The great fissure-eruptions of basic igneous rocks which occurred in Africa, South America and India (Rajmahal) in Upper Triasic or Jurassic times are apparently the manifestations of tension which resulted ultimately in the breaking up of the southern continents which constituted Gondwanaland. That the final break-up occurred in the early Cretaceous times is proved by stratigraphic data from the different parts of Gondwanaland but, as stated already, the incipient Arabian Sea seems to have opened up from Permian times which is also the period during which the Narmada rift was formed. Another great fissure-eruption occurred in Western India, Somaliland and Ethiopea in the Upper Cretaceous to Eocene.

The Alpine-Himalayan mountain ranges resulted from the compression and uplift of the great Equatorial Mediterranean geosyncline which existed during the Mesozoic era. The initial compression took place in the Upper Cretaceous when ultrabasic igneous rocks were intruded into the core of the mountain belt in Oman, in the Baluchistan arc and in the Himalayas as well as further east. The other major phases occurred in Upper Eocene, Lower or Middle Miocene and in the Plio-Pleistocene. These phases can be recognised over most of the Alpine-Himalayan belt though in varying degrees of intensity.

The rocks of the southern part of Indian Peninsula have a close connection with those of Ceylon, Madagascar and East Africa with which they are closely related structurally. This indicates that they all probably formed parts of one unit, with Australia lying on the one side and Antarctica on another. India began to drift away from the rest of Gondwanaland early in the Cretaceous by translatory motion as well as by anti-clockwise rotation through something like 60 degrees of arc. It travelled far to the North and intensely crumpled up the Tethys basin and wedged itself into what is now Central Asia. The last is a region of numerous, more or less parallel, mountain ranges gathered up sheaf-like in the Pamir region. The ranges concerned are the Tien-Shan, Trans Alai, Kunlun-Lokzung, Altyntagh, Karakorum, Kailas, Zanskar and Himalaya from north to south. Their ages range from the Hercynian period in the north to the Alpine period in the south, the middle ranges having been affected by both of these revolutions, and perhaps also by the Cimmerian. All these ranges are characterised by high negative gravity anomalies which reach a maximum of a little over -560 milligals in the Kunlun and Lokzung ranges. This indicates that there is a very great thickness of Sial in Central Asia, which is still a very disturbed region as indicated by the occurrence of earthquakes along these mountain belts. This region will ultimately attain equilibrium by a redistribution of mass which is now occurring as a spreading of the Asiatic continent to the east and south-east as indicated by the active island arcs of Kurile, Japan, Riukiu, Philippines, Banda and Sunda arcs on the inside and the Marianas-Yap-Palau and the Nias-Mentawei-Andaman arcs on the outside. The movement of India to the north-east was accompanied by the movement of Arabia also in the same direction creating the tension rifts of East Africa as well as the Red Sea rift. The Persian Gulf is probably of the nature of a *fore-deep* similar to the Gangetic plains, though it is continuous with the Mekran fault. Mountain building has presumably eased off around the northern borders of India, but as stated already it is still going on in South-Eastern and Eastern Asia. Perhaps even the spreading out of the Indian Ocean area is also still going on.

The deep penetration of India into Central Asia is indicated by the enormous compression evident in the Himalayan region as well as by the two spectacular hair-pin bends near Nangaparbat on the west and Nancha Barwa in the east. The Kashmir and the Assam wedges have gathered up the mountain ranges in the north-west and north-east corners beyond the Indian shield, these regions being highly seismic. Most of these facts about the tectonic features of India and its neighbourhood are best explained by the hypothesis of continental drift associated with the names of Taylor, Wegener and Du Toit.

General

The earth's crust can be classified into a few major Tectonic units. These are the shield and stable areas (Platforms); sedimentary basins; geosynclines; folded mountain ranges or mobile belts; rifts and fault troughs and mid-ocean ridges. These units are essential elements in the structure of the globe and constitute the expression of the nature and structural history of the land and sea areas.

The *shield areas* are of Pre-Cambrian age and have remained more or less unaffected by folding movements since they were originally crystallised from a molten or semi-molten condition or were transformed by metamorphism of the pre-existing materials. They are the oldest land masses known at present. Their greatest age, indicated by measurements of the products of radioactive disintegration, is of the order of 3,000 million years. This must be taken as the most remote time the rocks formed in which have managed to remain essentially unchanged at a few places, though igneous and metamorphic activity has taken place elsewhere at later periods. The chief shield areas known at present are Central and North-Eastern Canada, parts of Brazil, Central and East Africa, Peninsular India, Western Australia, the Baltic region and part of Siberia.

The shield areas are often associated with ancient sedimentary areas which have attained more or less stability. These are generally known as 'Platforms'. The only disturbances which shields and platforms have been subjected to are vertical movements by faulting and rifting and also perhaps some loss along their margins by the sinking of fractured fragments. The erosion of these shields and platforms leads to accumulation of sediments in the ocean basins around them and ultimately these sediments may be folded and raised up into mountains.

The oceanic areas fall into two types of somewhat different characters; one is the Pacific basin with its unique characters, hemmed in almost entirely by folded mountain arcs converging upon it from all sides. The bottom of this ocean has no *sial* cover, being formed of a layer of *sima* (basaltic rock) ordinarily about 5-6 km. thick, directly overlying the mantle, and in turn overlain by 1–2 km. of sediments (Hess, 1959). This ocean basin is intersected by a series of fractures running E–W, NE–SW and NW–SE (Menard, 1959) along most of which basic volcanic materials have been extruded to form huge volcanic cones some of which rise to the surface. There are many other submerged flat-topped cones called 'guyots'. Some of these support coral islands and Atolls and are situated on certain well-marked 'swells', being thus different from the volcanoes found on anticlinal ridges of island arcs (Dietz, 1954). The individual blocks marked off by these major fractures are level plains but may be 2,0C0 to 5,000 ft. higher or lower than the adjacent blocks. The borders of these blocks show step-like scarps and terraces.

In contrast with the Pacific Ocean, the Atlantic and Indian Oceans are bordered by fractured and faulted coastlines. The geological structures of the lands surrounding them often terminate abruptly at the coasts. It is thought that these oceans were formed by the breaking up of a former great continent, the fragments of which moved away from each other. The bottoms of these oceans may have a small thickness of sial overlying the usual simatic material. They are also characterised by the presence of large mid-ocean ridges lying roughly symmetrically between the land masses on either side. The mid-Atlantic ridge occupies the middle of the Atlantic Ocean right through and can be traced northward from Iceland through Spitzbergen to the mouths of the Lena river in Siberia, the whole of the course of the ridge being marked by volcanism and seismicity (Hope, 1959). At the other end it continues between Africa and Antarctica and joins the mid-Indian Ocean ridge in the region of Rodriguez through Prince Edward Island. The mid-Indian ridge in the north is the same as the Carlsberg ridge passing by Chagos and going on to New Amsterdam and St. Paul Islands. To its west are two concentric ridges. The more conspicuous of the two is the one on which Seychelles, Saya de Malha and Mauritius stand. Another narrow submerged ridge is shown in the bathymetric map of the Arabian Sea, between the two above-mentioned ridges, in the *Report of the John Murray Expedition* (Sewell, 1932). The mid-Indian ridge in the south branches off from near Rodriguez and continues as a broad feature to the east between Australia and Antarctica, joining the Easter Island-Galapagos ridge which occupies south-eastern Pacific basin. In the mid-Pacific is a continuous ridge system known as the Tuomotu-Christmas Island ridge and the mid-Pacific mountain range which first trends north-west and then west. From this a branch leads off in a north-westerly direction, marked by the Emperor Sea-mounts (Menard, 1958).

The mid-ocean ridges have in recent years been found to be huge mountain chains several hundred kilometers wide at the base and rising to various heights below sea-level. Indeed the mid-Atlantic ridge occupies one-third of the width of the Atlantic Ocean. At only a few places do the ridges come up to the surface as volcanic islands. By far the greater part of the mid-Atlantic and mid-Indian ridges are presumably composed of basic volcanic rocks. They may have been formed by the eruption of huge masses and simatic material through rifts which opened up perhaps repeatedly, as a result of stretching of the crust by the separation of the continental masses. It is now known that along their crest line there is a continuous and well-marked graben, often more than a thousand meters deep, occupied by basaltic or ultrabasic rocks and marked by earthquakes and volcanism throughout their length (Heezen, Tharp and Ewing, 1959). In the opinion of the writer these ridges owe their origin to tension which has riven the sial

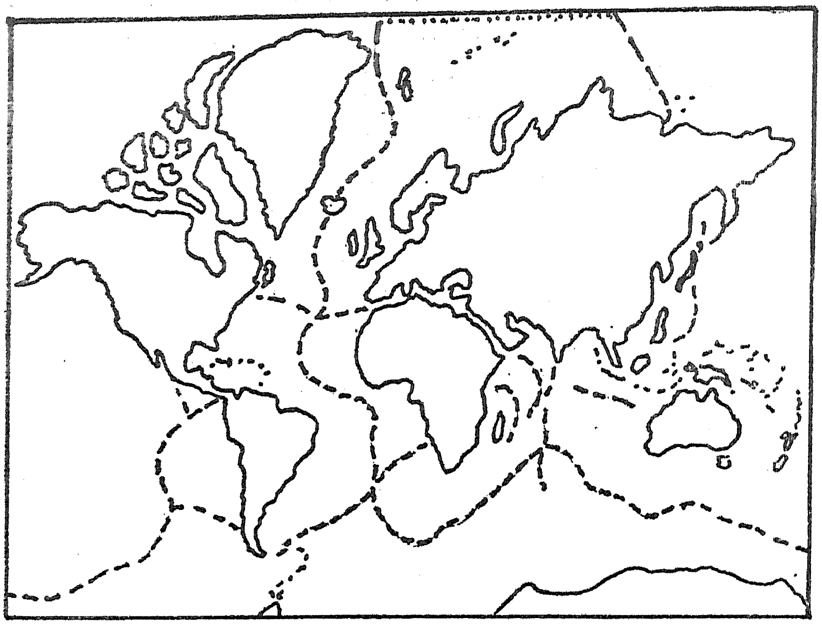

FIG. 1. Showing mid-ocean ridge systems of the world.

crust asunder, and brought up simatic material from below. The earthquakes in the mid-ocean ridges are all of shallow origin in contrast to those in the folded mountain belts surrounding the Pacific and along the Alpine-Himalayan belt where intermediate and deep focus earthquakes occur. They indicate that adjustments are taking place in these mid-ocean ridges at depths of 20–60 km. at the most. The fact that the gravity anomalies found over these ridges and rifts are moderate to small, indicates that isostatic equilibrium is comparatively easily reached along them, probably through the movement of magma in the zone below.

ISLAND ARCS AND TERTIARY MOUNTAIN RANGES

As already stated, the Pacific Ocean is surrounded by arc-shaped ridges mainly of Mesozoic and Cainozoic ages emerging out of the ocean one behind the other, often with an imbricate pattern. They show varying convexities, from almost straight ridges like the Tonga-Kermedec to those which have various curvatures and finally to sharply bent arcs such as the Banda and Antillean arcs. In all cases, the convexity is towards the Pacific Ocean except in the Antillean arcs and between Fiji and New Guinea around the Caroline basin. The general pattern of island arcs consists of the following units (Gutenberg and Richter, 1949):—

(1) A very deep narrow trench in the ocean; (2) a semi-emergent ridge coinciding with high negative gravity anomaly, adjoining the trench on the

continental side; this is the zone of shallow earthquakes; (3) the main anticlinal ridge with a volcanic zone on the inside; this is a zone of positive gravity anomalies and of earthquakes at about 60 km. depth, being situated some 150–200 km. behind the trench; (4) a second zone of volcanoes, extinct or showing decadent activity and sometimes earthquakes occurring at depths of 200–300 km.; (5) a sunken area or shelf sea with deep focus earthquakes. There are often combinations of certain zones and slight variations. The sunken land is generally of recent geological age. On the Asiatic side the arcs can be seen in various stages of development from the latest arcs which form the Marianas-Yap-Palau Island groups to those which are older like New Zealand, the Philippines and the Japanese Islands which are really parts of old continental borders, now separated from the continents by shallow seas. On the American side the arcs have been welded on to the continents, except in Central America where the Antilles arc faces the Atlantic and the Central American arc the Pacific.

The island arcs apparently indicate continental spreading—the annexation of the ocean by continental sial. Each arc represents sialic material from the continent expanding into the ocean. The shelf seas to the rear are in the meanwhile being filled with large quantities of sediments and are thus destined to become land. Indeed in some cases, the shelf seas were land at some previous time but had sunk to a shallow depth in response to adjustments taking place in the under-crust. There is one important distinction in the nature and composition of volcanic materials found in the Pacific Ocean on the one hand and in the land areas and island arcs on the other. The volcanoes on land and in the island arcs are predominantly andesitic, with subordinate basaltic, alkali and acid types. In the open Pacific the lavas are exclusively basaltic, with or without olivine. The great volcanic floods on land (plateau basalts) derived from fissure eruptions are also basaltic (mainly tholeiitic and more acid than ocean basalt). The outermost arcs in the Pacific from a well-marked petrological boundary known as the *Andesite Line* (Marshall, 1909; Hobbs, 1926). Two explanations have been offered for this demarcation; one is that andesite represents the contamination of basaltic material by sial through which the basalts pass on their way to the surface. The other view, due to J. T. Wilson (1954), is that the andesite comes from deeper down in the mantle and represents the partly differentiated material of the mantle from which the earth's crust has grown, separating ultimately into sial and sima. Perhaps there is some substance in both the views.

In all the island arcs, the island ridges represent the continental sial which is being thrust over a segment of the ocean; the oceanic crust, therefore, under-thrusts the continents in the opposite direction as visualised by W. H. Hobbs (1944). This is generally believed to result from convection currents in the mantle. Compressive forces are set up along the continental margin where the current takes a downward plunge, the upward direction of flow of the returning currents being under the continents themselves.

Only a short segment of the Pacific front shows concave arcs (ignoring for the present the complex Celebes arc which is concave towards the head of New Guinea), namely the Fiji-New Hebrides-Solomons, New Britain and New Guinea arcs. Gutenberg and Richter merely state that the Solomons and New Britain have their convexity *in an unusual direction* (1949, p. 50). The curvature of these arcs and the distribution of earthquake foci indicate a southward thrust of the superficial crust of the Ellice-Gilbert-Caroline block over the Tasman Sea, which in turn is being over-thrust eastward over the New Zealand-Tonga-Fiji salient. The deeper shocks associated with the above-mentioned arcs are found on the Pacific side of the arcs whereas in every other island arc, including the Tonga-Kermede arc, the intermediate and deep-focus earthquakes occur on the continental side. But in every case without exception, the deeper earthquake belt occurs on the concave side of the arc.

The formation of *island arcs* appears to be the normal mode of continental spreading or growth. This is certainly the case in the Pacific border where Hercynian, Cimmerian and Laramide orogenic episodes are recognisable in the arcs, the later arcs appearing successively more on the ocean side. It may be expected that the same arrangement holds for the equatorial Alpine-Himalayan belt where mountain ranges have been developed on the borders of the Mesozoic Mediterranean Sea (Tethys). But it is rather difficult to recognise and disentangle the mountains of various ages because the land masses have met and there has been considerable uplift, over-thrusting and intermingling of strata. Most of the arcs in this belt have their convexity to the south, the Alps forming an exception. The various units are—the Burma arc which is a continuation of the Indonesian and Andaman arc; the large Himalayan arc which is continued to the west by the Baluchistan and Zagros mountains; the Taurus arc of Turkey which continues westward into the Pindus mountains of Greece and the Dinaric Alps of Yugoslavia; then the Apennines going into the North-West Africa as the Atlas mountains. There is a second series of arcs practically all along, which may represent the opposite border of the former Mesozoic sea and may also include a Mesozoic Orogenic element. This second series comprises the Pyrenees, the Alps, the Carpathians in Europe; further east the Caucasus and the Elburz mountains which continue into the Hindukush and Karakorum mountains whose extension is to be found in Tibet and South-West China. Arkell (1956) has shown that the Caucasus and possibly the Elburz mountains are mainly of Cimmerian age and that they were later affected by the Himalayan movements also. De Terra (1936) considered the Karakorum mountains to be mainly of Hercynian age, but they are likely to include an element of Cimmerian orogeny also. Along some parts of these various ranges, it is possible to recognise the former existence of island arcs only in a vague manner because most of the original structures have disappeared in the great thrust movements of later age. In the Himalayan Tibetan region the original sedimentary basin has been subjected to the most intense compression imaginable because of the direct impact of the continental masses from both sides whereby the most complex structures have been produced, involving overriding, overturning, vertical thrusting and horizontal translation.

TECTONICS OF INDIA

The Peninsula of India is a stable mass (shield) which has been free from folding movements since the end of the Pre-Cambrian times. It has, however, supported epi-continental seas in the late Pre-Cambrian and early Paleozoic, resulting in the deposition of sediments of Cuddapah and Vindhyan age. There are three areas of late Pre-Cambrian and early Paleozoic ages in the Peninsula, *viz.*, the Cuddapah basin in the south, the Great Vindhyan basin in Central India and U.P. and another large area in the north-eastern part of the Peninsula. The last has, however, been fragmented into a number of patches by erosion and removal. The Cuddapah basin is found to have a crescent shape with the concave side towards and parallel to the east coast, along which there has been some shearing and thrusting in Post-Cuddapah but Pre-Vindhyan times. Similarly, there has been some movement also in the Vindhyan basin, particularly on its western margin, where Pre-Cambrian rocks of the Aravalli belt have been thrust over its edges (Krishnan, 1953).

The Peninsula shows certain major structural trends which have a rough triangular pattern. The oldest of these is that of the Aravalli mountains which extend from Cambay in Gujarat through Delhi into Garhwal in the Sub-Himalayan region. This structure is found to splay out in the south; it is very likely that it continues partly into the Dharwar-Mysore region. The Aravalli trend has a NE–SW direction and the region shows orogenic disturbances of at least two ages, the earlier one affecting the Aravalli formations, and the younger one involving also the Delhi formations which overlie them more or less along the same belt. This trend

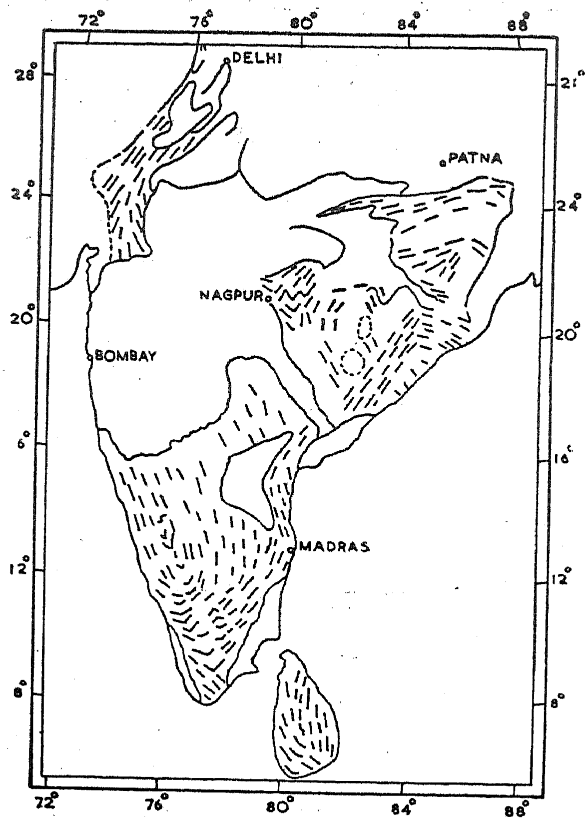

FIG. 2. Structural trend lines in the Archæans of Peninsular India.

continues into Garhwal in the Himalayas where it has escaped destruction probably because it is parallel to the direction of the forces which produced the Himalayan movements (*i.e.*, perpendicular to the strike of the Himalayan folds and thrusts). Coming to the Mysore region, we find that the rocks of the Dharwarian system have a general NNW–SSE strike, consisting mainly of strips of schistose rocks folded in with the Peninsular Gneiss. This trend continues to the south of Mysore city where it appears to blend with Eastern Ghats structure which comes in from the east. The southern part of Mysore shows rocks of higher grade metamorphism than the northern part, this being due to an upward tilting of the rocks in the south which has brought rocks from deeper zones to the surface. The ages determined for galena from Chitaldrug and for monazite from a pegmatite near Bangalore show 2,600 and 2,400 million years respectively (Holmes, 1954).

The eastern border of India contains rocks having the trend of the Eastern Ghats which run parallel to the coast from the Mahanadi valley down to Krishna valley in a S-W direction and then follow the eastern edge of the Cuddapah basin down to Madras where they turn to the south-west and proceed through Arcot and Salem into the Nilgiri mountains. Though the Eastern Ghats comprise somewhat heterogeneous lithological elements, they have some structural unity. Near the Krishna valley the trend seems to spread out and a part strikes out slightly east of south into the sea and is found to continue into Ceylon. This island consists of rocks of typical Eastern Ghats facies forming a big synclinal fold with a nearly N-S axis. In South-Western Ceylon there are structures which are aligned in the direction of the southernmost part of the Indian Peninsula, namely, Travancore. It is probable that Travancore and the southern districts of Madras belong to the Eastern Ghats Province in which some later rocks may have been incorporated. Age data are available only for some Monozites and Cheralite of Travancore which give ages ranging from 490–650 million years. These apparently belong to late granitic rocks formed in the Upper Pre-Cambrian and in the early Cambrian era. This region also does contain more ancient rock groups including Charnockites and schistose rocks which still await investigation. Several pegmatite minerals from the Eastern Ghats belt from Nellore, Visakhapatnam and Orissa indicate ages around 1,550–1,800 million years (Mahadevan and Aswathanarayana, 1955; Aswathanarayana, 1956). The Eastern Ghats were considered by Fermor to be a range rejuvenated after they were originally formed, because their typical rocks, the Charnockites and Khondalites, bear the impress of deep-seated metamorphism. They also appear to cut through other rocks having a different trend which occupy the coastal region and the hinterland. At their north-eastern end, the trend of the Eastern Ghats veers round to the east where it ends abruptly at the coast. It is an interesting fact that rocks similar to those of South India, including the Charnockites, Dharwars and Cuddapahs, are found in Western Australia which may have originally lain close to the eastern part of India. The hinterland of the Eastern Ghats is not yet sufficiently known but it seems to contain rock formations with N-W as well as N-E trends.

The northern edge of the peninsular mass in Northern India is marked by yet another major trend which has an ENE direction. This has been designated as the *Satpura trend,* after the Satpura mountains which border the Narmada valley in Western India. This belt splits up into two branches, the northern branch going through Jabalpur and the Sone valley to the north of the Ranchi plateau, while the southern one passes through the manganese and iron ore-bearing region of the Central Provinces, Gangpur and Singhbhum, extending down to the Eastern Ghats north of the Mahanadi valley. In Bihar, the two branches are separated by the huge batholithic granite mass of Ranchi-Hazaribagh-Gaya. The Satpura trend continues into the Assam plateau across the Rajmahal-Garo gap through which the Ganges and Brahmaputra rivers flow south to their delta. The age of some of the pegmatites of Gaya in this belt is around 950 million years. The Satpura belt rocks appear to be intermediate in age between the Eastern Ghats rocks and the post-Delhi pegmatites of Rajasthan which indicate an age of about 730 million years. Suitable materials from other localities in this area await investigation (Krishnan, 1953).

PROMINENT WEDGES OF THE PENINSULA

The Assam plateau is without doubt a part of Indian Peninsula but it is now isolated from it by the Ganges delta. Its rocks are very similar to those of Bihar and Orissa. The ancient rocks become covered by Tertiary formations beyond the Mikir Hills in Upper Assam but they presumably extend far to the north-east as a wedge. The presence of this wedge has been responsible for the sharp hair-pin bend of the formations at the eastern extremity of the Himalayan mountains east of the peak Namcha Barwa. On either side of this region, the rocks have nearly a NE-SW trend. On the Indo-Burma border they gradually swing to the south and follow the frontier to the Arakan coast and then go into the East Indies through the Andaman-Nicobar Islands. Attention may also be drawn to certain other features like the high seismicity of the Sikang region (S-W China) with its succession of mountain ranges. Though this is one of the least known regions of the world, there is little doubt that it is similar in structure to the Pamir region at the other end of the Himalayas. All the great rivers of South-East Asia rise in this region—Zayul and one or two other tributaries of the Brahmaputra, the Chindwin, Irrawaddy, Salween, Mekong, Chin and Yalung (Yang-tse-Kiang). In this region they all flow along neighbouring, close-set, parallel gorges within a few miles of each other, in a south-east and then southerly direction for over 250 miles before they diverge and fan out in different directions to their destinations which are spread between Dacca in East Pakistan at the head of the Bay of Bengal and Shanghai on the East China Sea to the south of Japan.

There is a similar wedge or rather a series of wedges on the north-western side of the Peninsula. The most impressive of these is the Punjab-Kashmir wedge which seems to be under-thrust to a great distance below Kashmir into the region of the Pamir mountains. The Himalayan ranges of U.P. and Punjab have a north-west direction and the geological formations execute a very sharp hair-pin bend near Nangaparbat and turn round to the south-west and south (Wadia, 1931). Several mountain ranges are gathered up in the Pamirs wherefrom they spread out towards the east, south-east, west and south-west. From north to south they comprise the

Trans-Alai, Kun Lun, Hindukush–Karakorum, Trans-Himalaya, Kailas and the major Himalayan ranges. In Hazara in the North-West Frontier Province, some ranges branch off towards Afghanistan while others proceed to the south and south-west. The major ranges bordering the Indus Valley are the Sulaiman, Laki and Kirthar. There are two subsidiary wedges of the Peninsula, one near Dera Ismail Khan and the other near Quetta, where also their effect is clearly seen in the gathering up of the formations into well-marked festoons which finally spread out in the Makran region of Baluchistan and turn round to the west to continue into Southern Persia and the adjacent Oman region of Arabia.

As already mentioned, the apical regions of wedge-like prominences are tectonic features showing high seismicity. The Pamir region is known for its numerous large earthquakes at depths of about 200–230 km. (Gutenberg and Richter, 1949). The Quetta region is also similarly visited by frequent earthquakes though these have shallow foci. The whole of peninsular border, occupied by the Himalayan and allied arcs, is of course a well-marked seismic belt indicating that the mountain building activity has not yet completely died out.

The Coasts of India

There is definite geological evidence that the eastern coast of India took shape in the Upper Jurassic or in the earliest Cretaceous. At several places along this coast, from Ramanathapuram (Ramnad) and Tiruchirapalli (Trichinopoly) in the south to the Mahanadi valley in the north, there are patches of Upper Gondwana sediments which are generally assigned a Jurassic age as they are correlated with the Rajmahal plant-bearing strata. At some places, particularly in the Guntur District, these strata are associated with marine formations which have yielded a few fossils whose age has been determined as Lower Cretaceous. It may, therefore, be stated that, by the early Cretaceous, the coast had taken more or less its present shape, and later in the same geological period there were large marine transgressions in the South Arcot–Tiruchirapalli region in the south and along the southern border of the Assam plateau in the north. The Cretaceous rocks on the Bay of Bengal side have a very close resemblance in facies and fauna to those found along the coasts of East Africa, Madagascar and Natal as also of Western Australia.

The western coast of India seems to have been evolved in two or more stages. It is known, however, that in the Permo-Carboniferous times, an arm of the Tethys extended southwards from Arabia over Eritrea towards East Africa, this period being marked by lagunal sediments indicating the formation of a shallow sea. Somewhat later the region of the present Mozambique channel appears to have opened up, separating East Africa from Madagascar. About the same time there was established direct marine connection from Baluchistan over Cutch to the Mozambique Channel. By the beginning of the Jurassic, this channel had become large enough to enable marine deposits to be laid down in along the western coast of Madagascar and in Cutch and S-W Rajasthan. It is interesting to note that along the Narmada valley there are small patches of marine Permo-Carboniferous rocks at Umaria and one or two other places near about in Central India, which indicate that there was an arm of the sea along this belt. A small area of Permo-Carboniferous rocks has also been found in North-Western Australia, containing a fauna similar to that of Umaria (Dickins and Thomas, 1958). A large part of the Narmada valley belt is now covered by the lavas of the Deccan Trap and by later formations, which naturally obscure what is underneath. It is almost certain that the Narmada valley was an inlet of the Tethys sea which entered here from Rajasthan and Cutch which are now occupied by marine Jurassic deposits. These Cutch deposits have extraordinarily close resemblances to those of Madagascar, East Africa and the Punjab Salt Range in their lithological characters and fossils. The Narmada valley depression was partly filled by the Deccan Traps but seems to have persisted till recent times, for in the Valley of the Purna which is a tributary of the Narmada, we know of the existence of fairly thick Pleistocene deposits.

There are also three important fault troughs in Peninsular India, now marked by the presence of coal-bearing formations. These coal formations must originally have occupied much larger areas but have been preserved from denudation by having been faulted down sometime after their deposition. These troughs are occupied by the Damodar-Sone valley, the Mahanadi valley and the Godavari valley. It is not unlikely that the Narmada rift connected with the Sone and Godavari rifts. They are parallel to the regional strike of the basement rocks on either side of them, and are fundamental features in the structure of India. It is now known that there are faults roughly parallel to the western border of the Ganges delta, for the Rajmahal Traps which crop out on the Rajmahal hills at the head of the delta are found at progressively larger depths in a south-easterly direction (over 10,000 ft. deep near Burdwan).

On the eastern border of the Aravalli belt there is a well-marked thrust zone which is known as the Great Boundary Fault of Rajaputana. It has been traced over a distance of more than 500 miles along the Chambal valley where the older rocks of the Aravalli belt have been thrust over the Vindhyan formations of the Great Vindhyan Basin. The age of this fault is not known but it may be contemporaneous with the Hercynian movements.

THE INDO-GANGETIC PLAINS

These plains occupy a depression in front of the mountain belt of the Himalayas and its associated ranges. The borders of the Indian continent have evidently been bent down and thrust under the mountains. This depressed zone, therefore, forms a "fore-deep". Recent aero-magnetic data indicate that, near the front of the mountains, the fore-deep contains a vast thickness of sediments of the order of 25,000 ft. or even more, lying over the basement rocks. The thickness decreases gradually on in a southerly direction towards the Peninsula. These sediments may include the whole Mesozoic and Kainozoic succession and may contain some oil-bearing structures where the rocks have not been too much disturbed or fractured.

THE EXTRA-PENINSULA

The region bordering India and its north, north-east and north-west constitutes the Himalaya mountains and associated chains. Of these, the Himalayas proper represent a region of tremendous crustal shortening in which a vast thickness of sediments, which must originally have occupied a great width of marine basin have been compressed and raised up to form a series of more or less parallel mountain chains between the borders of India in the south and the Kun Lun mountains in the north. The Himalayas are usually divided longitudinally into four zones. The southernmost is the *Siwalik Zone* which contains coarse sediments of the "molasse" type formed by the rapid denudation of rising mountains after the major uplift had taken place in the stage of mountain building. To the north of this zone are the *Lesser Himalayas* consisting mostly of non-fossiliferous sediments, whose age is difficult to determine but part of which must in any case have been deposited along the borders of the Indian shield. Beyond this comes the *Central Himalayan Zone* with high peaks and batholithic granite intrusions. These two zones are marked by enormous thrust sheets in which the rocks are often crumpled, inverted and over-ridden by older rocks from the north. Beyond the zone of high peaks is the *Tethys-Himalaya* which shows a magnificent series of fossiliferous sediments of all ages up to the earliest Tertiary. Farther on are the Ladakh and Kailas ranges, followed by the Trans-Himalaya range. As we proceed further north the successive ranges tend to become more straight. The more northerly ranges are also of earlier geological age. The Kun Lun and Karakorum ranges are of

Hercynian and Cimmerian (Jurassic) ages whereas the Tien-Shan ranges further north are entirely Hercynian or even partly earlier.

Central Asia is well known for its high altitude averaging about 12,000 ft. to 14,000 ft. above sea-level. In spite of this great altitude, this region shows negative gravity anomalies almost everywhere, and particularly along the various mountain chains. There are indeed a series of parallel zones of negative gravity anomalies in which high and low anomalies alternate. The highest negative anomalies (Bouguer) in the whole world (so far as I am aware) occur in the eastern part of the Kun Lun mountains, and the Lokzung Range where they attain a value of over —560 milligals (Norin and Ambolt, 1950). Even the old platform to its north, known as the Tsaidam depression, shows negative anomalies of the order of —50 to —100 milligals. It is obvious, therefore, that in this region an enormous thickness of sediments and granitic materials must be present.

Woollard has attempted to show the general relationship between Bouguer anomaly and the crustal thickness (depth to Mohorovicic discontinuity). The plotting of the values, using both earthquake wave velocities and quarry blast velocities, showed a good deal of scatter of points (Woollard, 1959, pp. 1530, 1542). Extrapolation of the curve for the maximum magnitude of the Bouguer anomalies indicated above would give a crustal thickness of the order of 75 km. which does not appear to be excessive for the conditions in Central Asia.

To the east and west of the Himalayas are the Burma and Baluchistan arcs respectively. The Burma arc is a single large circular arc which continues in an unbroken line through the Andamans and other islands of the Indonesian Archipelago. It is a mountain formed at the same time as the main Himalayan chain, namely, in late Cretaceous (Laramide) times. The central ridge in the south exposes Cretaceous and Tertiary rocks but in the north there are evidently older rocks to be found, though their distribution is not known because of the great inaccessibility of the territory. When this ridge was formed, the original sea occupying Assam-Burma was split into two arms, the eastern one in Burma showing a complete Tertiary succession with comparatively gently folded strata. This Tertiary basin contains a number of oil-fields which are being exploited at present. It also shows a volcanic line in which volcanoes have been active in the Upper Tertiary and recent times. This line lies just to the east of the major arc and parallel to it and is marked by Barren Island, Narcondam, Mount Popa, etc. It continues into the volcanic zone of Sumatra and Java and other islands. To the east of the Tertiary belt of Burma is the Shan-Tenasserim belt containing Palæozoic and Mesozoic rocks belonging to the Cathasiyan Province which have become welded on to the Burmese arc after the rise of the Himalayan mountain chains. The age of mountain building and uplift of the Shan belt is the Cimmerian (Nevadan) of middle or upper Jurassic age. This belt, which is marked by much granitic material, passes through Malaya, the Tin islands of East Indies and Central part of Borneo and finally into Northern Philippines. A good part of it is known to be rich in tin and tungsten deposits.

On the other side of India we have the Baluchistan arc made up of three or four short subsidiary arcs, presumably because of the presence of wedges of the Peninsula which have been thrust under the mountain belt and have produced festoons. The apices of these wedges are in the region of the western end of the Salt Range, near Dera Ismail Khan and near Sibi-Quetta. The northern part of this arc which traverses Hazara-Kashmir and the N-W Frontier Province shows two distinct marine facies lying side by side, the western one being very closely allied to the Tethys-Himalaya and the eastern one characterised by Calcareous rocks and hence designated the *Calcareous Zone* of Baluchistan. The Tethyan facies apparently continues in a westerly direction into Afghanistan. The Calcareous zone, particularly in the southern part of the North-West Frontier Province and in Baluchistan, does not show rocks older than the Permo-Carboniferous. This arc becomes much broader in Makran and continues westwards into Persia where it forms Zagros Mountain belt. The Kirthar Mountain range, which forms the boundary between Sind and Baluchistan, strikes into the sea near Karachi but turns to the WSW and continues under the Arabian Sea as a series of sub-parallel sub-marine ridges and ultimately merges into the Oman ranges in Eastern Arabia. The Oman Mountains are known to have been formed in Upper Cretaceous times and are therefore a continuation of the Sind-Baluchistan ranges. They are undoubtedly a branch of the Zagros ranges which they leave near the kink at the entrance of the Persian Gulf, the Oman structure being attributable to the overthrust of a small part of the marine basin over the Arabian shield to its west and southwest.

The Himalayas were uplifted in four major impulses; the first period of compression and uplift was in the Upper Cretaceous as clearly indicated by the shallowing of the Upper-Cretaceous seas and also by the presence of ultrabasic intrusives and radiolarites in the root zone of the mountains. The second period of mountain building was in the Upper Eocene when the ocean basin was split up into long narrow shallow strips. The deposits formed after this movement are the well-known Murrees which have the character of 'flysch' sediments, derived from the rapidly rising mountains partly even by sediments gliding down the slopes. The third period of disturbance was in the Lower Miocene which also was apparently a period of great uplift and igneous intrusion. After this uplift, all bodies of water disappeared entirely from the Himalayan region and the newly risen mountains together with the closely associated intrusive granitic rocks gave rise to coarse clastic sediments of 'Molasse' type known as Siwalik formations. Movements also took place later, in the Pliocene-Pleistocene. De Terra (1936) records that uplift took place in the Western Himalayas even after early man had appeared. It is known that Pleistocene sediments occupy tilted positions on the flanks of the Pir Panjal range in Jammu-Kashmir and there are abundant evidences of early human culture during the Second Interglacial period.

It will be noticed that all the mountain chains surrounding India along its northern, north-eastern and north-western borders have their convex sides facing India and *the rocks have been thrust towards India from outside*. This simultaneous thrusting from all sides is possible only if we envisage the drift of the Indian continent into the area occupied originally by the Tethys Sea. Other features in the Himalayas and the neighbouring lands are also explained by the assumption that the Indian continent has thrust back the whole of the marine belt to a considerable distance to the north. It is obvious that these sediments of the Tethyan basin have undergone very great compression and have been raised to the greatest heights ever attained by mountains on land, about 29,000 ft. or nearly 9 km. Aa a result of such compression, rocks of certain facies, almost identical with those of the Dachsteinkalk and Hallsfatt marble of the Eastern Alps, which are exposed in some thrust sheets, are not to be found *in situ* in the basin, for they have undoubtedly been submerged under the huge piles of other sedimentary facies and zones. Compared to the compression in the Himalayan belt, the compression on the two flanks of India is much less intense, as can be readily understood.

The compression and raising up of the Tethys basin is considered to be the result of the drift of India from south to north. The drifting of India began presumably from early Cretaceous times up to which it was attached to Madagascar (and the Southern Continents). The early Cretaceous faulting of the eastern coast of Madagascar is attested by the fact that it is a straight faulted coast and its earliest marine strata are of Lower Cretaceous age. On the western side of Madagascar, however, a depression had begun to form in the Permian. It became part of a deep open sea only in early Jurassic, after which a well-developed marine succession appears. Similar

Jurassic marine strata appear in the adjacent Kenya coast as also in Cutch in India, all these having almost identical fossil species and zonal succession. It is, therefore, clear that an arm of the Tethys extended south-west from Baluchistan to the Mozambique Channel, which gradually widened after the Permian. That sea extended further along the east coast of South Africa in the early Cretaceous times and reached Argentina. The great similarity of the Pre-Cambrian rocks of the southernmost part of India, Ceylon, Madagascar and East Africa supports the idea of all these having been parts of a large land mass. The structures are also conformable if India is placed by the side of Madagascar and the latter close to East Africa as was presumably the case in the early Mesozoic. It is also possible that India's neighbour on its east was Australia. The Pre-Cambrian metamorphics and sedimentaries in the two countries have much in common.

The relative drift of India from Africa seems to have taken place in four or five stages, each major impulse being separated from the next by a period of comparative quiescence. The major line of separation in the crust should be taken as the Carlsberg-Mid Indian Ridge, the median rift in which is continued north-westwards by the Gulf of Aden and the Red Sea. The Red Sea is a wide rift underlain by basic igneous rocks showing positive gravity anomalies of 50–150 milligals. It is 300–400 km. wide and has a depth of about 2,000 metres. The African rift valleys are much narrower and shallower though their features are of the same type and are marked Tertiary volcanic rocks showing negative gravity anomalies of 50–100 milligals (Girdler, 1958).

According to Tromp (1950), the Red Sea region was domed up in the Eocene prior to its breaking up in early Oligocene, and was gradually widened to its present dimensions at a later age. The physiography of the region clearly shows that shearing movement (left-handed) has taken place in addition to simple rifting. It is bordered on both sides by parallel faults along which volcanic phenomena have been manifested in the later Tertiary, this being particularly well seen on the Arabian side. The positive gravity anomaly of the Red Sea is to be attributed to the large size of the rift which permitted the free movement of magma from the basaltic layer which has occupied the bottom of the rift.

The delineation of the African rift valleys, the Red Sea, and the Dead Sea rifts in Palestine are all genetically collected. According to Tromp, the main direction of shear is N–S with conjugate structures in N-W and S-E directions as will be seen in a general map of the region. J. W. Gregory also pointed out that the rifts have developed along the meridian where the southward moving Zagros-Taurus segment meets the northward moving Alpine segment. In a recent paper (*Proc. Geol. Soc.*, London, 1960, No. 1579, p. 79) Quennel states that the rift valleys have resulted from the doming up of East Africa and subsequent fracture and that they are definitely tensional features.

The Carlsberg Ridge being a part of the major Mid-Ocean system should be expected to be of the same character as the Mid-Atlantic ridge. The latter has a broad base, several hundred kilometres wide and is composed of parallel ridges which gradually rise towards the middle. Along the crest of this zone is a longitudinal cleft 20–30 km. wide and 2–5 km. deep containing basic or ultrabasic igneous rocks at the bottom. The sides of the ridge system appear to be composed largely of basic rocks for the dredgings from these ridges have yielded basalts and related igneous rocks.

It is likely that the ridge system may include a small amount of Sialic material at the junction zone of separated continents at the time of their drifting from each other. Prof. Lester King (1958) has expressed the

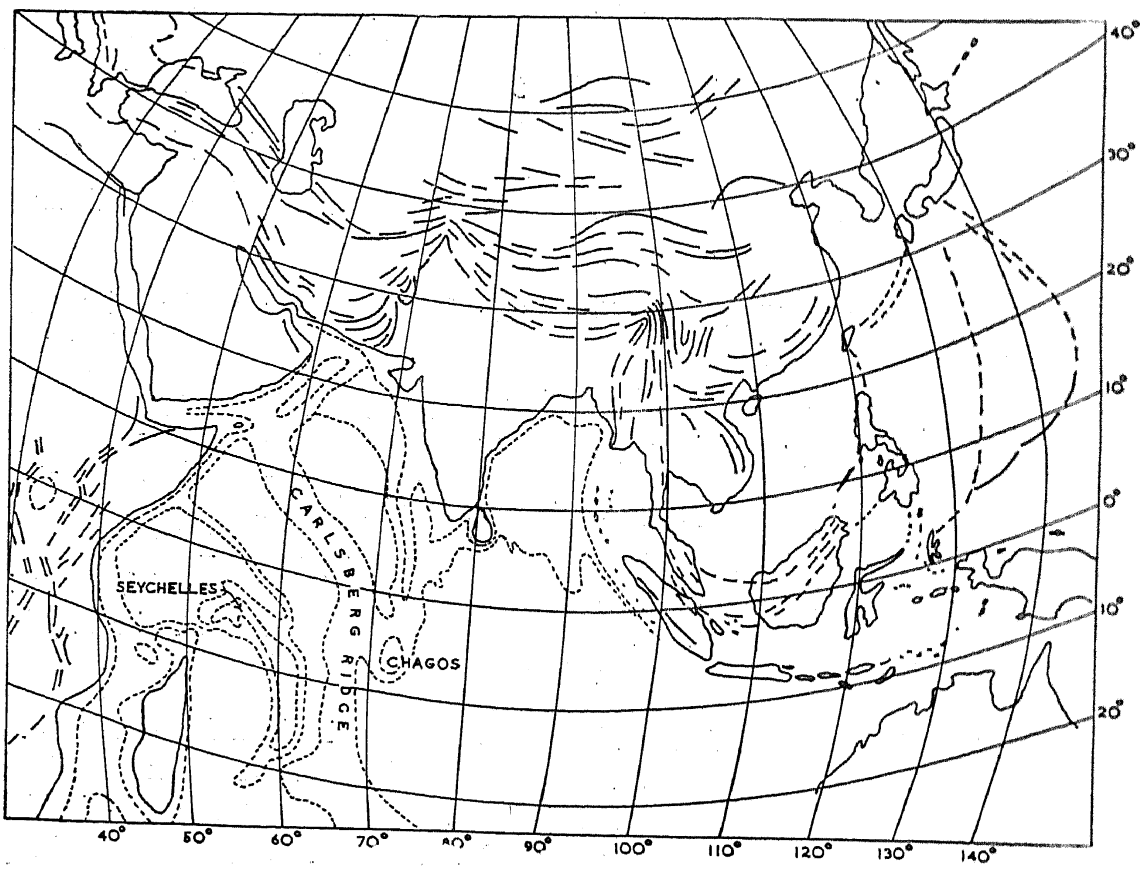

FIG. 3. Southern Asia and the Indian Ocean showing the mountain arcs, mid-Indian ridge and East African rift valleys.

opinion that mid-ocean ridges are of the nature of cicatrices left behind by the separated continents but they appear to be much more, for this would imply only a comparatively narrow rib of Sialic material. It would appear that the subsequent movements of the continents on either side have stretched the crust repeatedly, resulting in the welling up of basic lava along the middle zone and forming the system of parallel ridges. The mid-ocean ridge would, therefore, have been gradually built up by a series of such eruptions, new material coming up in the middle zone after every appreciable movement of the separating land masses.

A single symmetrical ridge system may be formed when the drift is steadily in one direction without any rotation. In the case of India, whose present position has been attained by a translatory as well as rotatory motion, —the motion being in a north-east direction and the rotation in a counter-clockwise direction through about 60°—subsidiary features have also been developed. These features are the Seychelles-Sayade Malha-Reunion ridge and a minor ridge concentric to and north-east of it. The Seychelles ridge though containing some granitic material in the Seychelles, is known to be formed of volcanic islands capped by recent coral growth while the Carlsberg ridge, so far as known, is made up largely of basic igneous rocks. Such an explanation would appear to make a pattern consistent with the idea of the north-eastward drift of India.

The Persian Gulf is a recent feature which originated in the Pliocene and is continuous with the Makran coast fault, along which the original southward extension of Makran has been faulted down in the sea. This faulted area shows a series of parallel ridges and valleys which are the (under-water) continuation of the ridges seen on land. The Oman Mountains are overthrust against the Arabian foreland while the Zagros Mountains which are continuous with them are thrust in a south-west direction over another part of the same foreland. The Persian Gulf is a fore-deep or a furrow formed in front of the Zagros Mountains and is similar to the Indo-Gangetic fore-deep and the ocean deeps in front of the island arcs, there being of course a difference in magnitude between the fore-deep and the ocean deeps. The Persian Gulf bears the same relationship to the Zagros Mountains as the Ganges–Brahmaputra valley does to the Himalayas and both have been filled up during the Pliocene and Pleistocene by sediments derived mainly from the mountain side.

We may digress for a moment to consider the probability of the existence of oil-bearing structures in the folded belt and its neighbourhood. The Himalayan belt represents a marine basin compressed into a small width marked by numerous high ridges separated by a number of thrust faults. In comparison, the Zagros mountains have probably suffered only a third or fourth of that compression and shortening. Hence, the existence of oil-bearing structures of any appreciable dimensions in the Himalayas is unlikely. The fore-deep may contain some structures, as this belt appears to be less disturbed. There is nothing in India corresponding to the broad foreland of Saudi Arabia with gently folded Mesozoic strata containing some of the richest oil deposits of the world. The southern side of the Gangetic plains which extend towards the Vindhyan uplands may contain some oil fields, but not of the sizes comparable to Saudi Arabian fields.

Finally we come to Central Asia where there is a large thickening of the siatic crust. That this is very abnormal is indicated by the fact that the axes of all the major mountain ranges traversing it are seismically active. Large earthquakes occur also along the Tien Shan and Tannu Ola mountains up to Lake Baikal in Southern Siberia and this may probably connect with the Verkhoyansk Range at one end of which the mid-Atlantic ridge terminates near the mouths of the Lena. As the great gravity anomalies indicate, Central Asia is in a state of disequilibrium which needs readjustment. Such adjustment is in fact taking place along the eastern borders of Asia. As a result of the movement of sialic material from under Asia towards the Pacific (whatever the exact nature of the mechanism) we have a series of island arcs forming along the eastern end south-eastern coasts of Asia. These arcs are of different ages, from the Palæozoic onwards. The outermost arcs of Marianas and Palau islands are being formed at the present day. The Sunda arc constituting the western part of the Indonesian Archipelago has an outer line of small emergent islands which are similarly very young. The main parts of the Japanese, Philippine and the Sunda arcs are of older age, having been raised up in one or two stages before the Tertiary era. The mountain belts on the continental margins as well as these older arcs have experienced the effects of every pulse of compression and uplift over a long period of geological time. And these movements will continue until the Central Asian mass attains equilibrium which is itself affected by the movement of the continental masses.

It will, therefore, be seen that the tectonic features of India and the immediately surrounding areas all fall into a consistent pattern. The drift of India in a north-easterly direction is accompanied by the stretching of the crust in the Indian Ocean which has resulted in formation of the Seychelles ridge, the Red Sea–Carlsberg ridge and the minor ridge between the two. The Tethys basin which existed as an open ocean to the south of Eurasia in the Mesozoic has been converted into a series of mountain ranges by the movement of and actual impact between Central Asia and India, the original shape of the Indian shield being reflected by the festoons on its northern borders. The result of the drift of India and Australia is the encroachment of continents on to the Pacific by the formation of a series of imbricate mountains and island arcs. These various manifestations are all parts of a single scheme of crustal movement the ultimate cause and mode of operation of which are obscure at present.

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