© *Proc. Indian natn. Sci. Acad.*, **47**, A, No. 6, 1981, pp. 588–630

Printed in India.

Palaeogeography of India.

DARASHAW NOSHERWANJI WADIA MEDAL LECTURE-1980

INDIA'S FORMER CRUSTAL NEIGHBOURS*

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Some of the various attempts at reconstructing the configuration of crustal masses in relation to India during the Phanerozoic are discussed. On the basis of radiometric ages of the pre-Vindhyan and pre-Raipur metamorphic and granitic basement the Cis- and Trans-Aravalli Vindhyans and Raipur limestone are regarded as late Pre-Cambrian to Eo-Cambrian in age. The evaporites common to both wings of the Vindhyans indicate a similar climatic environment of deposition to that in which the saline series of the Karampur well, Salt Range, Mandi, Iran and Oman were deposited. The existence of an extensive province of arid sedimentary formations, involving the close association of India with neighbouring areas to the north and west, as long ago as 600 m.y., is suggested. The Mascarene submarine plateau, which includes the 600 m.y. old granite of the Seychelles, probably always existed between India and Madagascar, and renders improbable the widely held proposition that, during late Mesozoic, Madagascar lay in contact with the present edge of the continental shelf and only 70 to 300 km from the west coast of India. Similarly, it is suggested that the Gaussberg submarine plateau, which includes the island of Kerguelen, was probably present during the Mesozoic between India and Antarctica in a manner which would not allow the presence of the Napier peninsula of Antarctic within 200km of the Indian coast as has been shown in some reconstructions. The concept which places the Indian peninsula 6500km from Eurasia during the Mesozoic, and then migrating as a solitary crustal unit across a wide Tethys ocean over a period of 70 m.y., is contrasted with the more probable interpretation of F. Ahmad, Owen and others, who regard India as having been separated from Eurasia during the Permian by a shallow epi-continental sea of no great width. The plate boundary of India which has been proposed by Kaila and Hari Narain is discussed in the light of difficulties in drawing boundary limits in complete discordance with the structural grain of the Hindu Kush and tri-junction region of India, Burma and China. The Sunda Arc 7500km long, with its extremities linked to India and the Sahoul self of New Guinea-Australia, and zonal countinuity throughout its length, is considered to render the supposition of the proximity of Australia to Tibet improbable. The lecture ends with a discussion on the conflict of evidence regarding horizontal crustal movements between palaeomagnetism and palaeontology, and suggests that considerable areas of continental crust may have sunk in the Indian Ocean in contrast to the phenomenal rise of continental crust in Tibet and the Himalaya since the Pliocene.

Keywords : Plate Movements; Horizontal and Vertical; Limits of Indian Continental Crust.

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*The lecture was delivered on 2 January 1981. The manuscript was received around July 1981.

INTRODUCTION

FIRST let me thank you for the great honour you have given me in the award of the D. N. Wadia medal. Wadia was a colleague of mine, 20 years older, but unfortunately we seldom met working as we were in different parts of the continent. We did, however, collaborate in writing two chapters together of the Memoir on the 1934 Bihar-Nepal earthquake. He left the Geological Survey of India with the permanent legacy of extensive work in the western Himalaya. His text book on the Geology of India was the principal source of general information for many generations of students including myself.

In my case I like to think of the medal as an award for joint work with colleagues of the Survey and Irrigation Departments. First with Professor West who introduced me to his area around Simla in 1928. Then Dr Wadia in our collaboration 46 years ago over the Memoir on the 1934 earthquake, and finally, from 1941 to 1953 to the geologists who were part of our Engineering Geology and Groundwater Divisions, as well as to the engineers throughout India who presented us with their problems and were with us in the field. Of these I shall only mention one, Dr A. N. Khosla, who made northern India conscious of the importance of dams for irrigation, flood control and generation of hydroelectric power. The Bhakra Dam is his monument 225m in height.

On what indeed could I lecture ? It is 50 years since I studied the Vindhyans, 40 years since I last did sustained work in the Himalaya and 28 years since relinguishing connection with the Engineering Geology and Groundwater divisions of the Survey. Since then the Geological Survey has expanded, the Oil and Natural Gas Commission has been founded, the Wadia Institute of Himalayan Geology was started and has flourished, Universities have multiplied, and Indians and foreign geo-scientists have worked in large numbers. It has been impossible to keep up with all the geological work arising from these sources, some of it already classic, as for example Augusto Gansser's Geology of the Himalayas, a book of outstanding importance.

So there has been a quandary and I decided eventually to continue in part the theme discussed by Professor Jhingran a recipient of this medal, and by Professor Ahmad, and to consider certain aspects of palaeogeography as they concern India, with the title India's former crustal neighbours. By India I imply the Indo-Pakistan-Bangla Desh subcontinent. By neighbours I mean the various crustal masses which have been placed by different authors against the southern parts of the continent now occupied by ocean, up to the Cretaceous, and those neighbours to the north in areas now occupied by Afghanistan, the Pamirs, Tibet and Burma.

Since all reconstructions of proto-India figure the Indian peninsula and its present continental shelf as at present known, for scale I shall adopt the distance of 1650 km between Cape Comorin and the Gulf of Cambay as a basis, together with the length of that part of the Madagascar ridge which is now exposed above sea level, 1560 km, as a check when that island is discussed. In regard to azimuth there must certainly have been considerable rotation of the Indian continent during the last 200 m.y. with a change of meridian, but for ease of reference in relating crustal masses to India, the modern meridian will be adopted regardless of any rotation that may previously have occurred.

It is quite impossible to discuss all the suggested reconstructions, and such data as I have been able to read regarding palaeomagnetism and faunal and floral distribution can only partially be referred to. It is realised that a formidable body of evidence based on polar-wandering curves suggests the virtual unity of Africa and South America, and the proximity of North America to Europe, reinforcing attempts to unite these continents based on the geometry of the continental shelves. Again the volcanic and seismic activity of the oceanic ridges, flanked by simple zebra patterns of magnetic reversals, testify to an oceanic activity now regarded as due to successive intrusions of magma along parallel dykes pushing aside oceanic crust and any continental crust resting thereon. So a cosmology of plate movement has developed covering the whole world. India has been particularly subject to moves across the chess board and it is some of these that I hope to discuss in this lecture.

The majority of plate reconstructions around the Indian Ocean date back only to the Cretaceous (135 to 65 million years), but in regard to India it will be necessary to consider possible neighbours during the Eo-Cambrian to Cambrian (600 to 500 m.y.), and also from near the end of the Palaeozoic (300 m.y.).

Indications Regarding Former Proximity of Continents

The indications which have led to the conclusion that many of the now separate continents may once have formed a vast single continent, or Panjaea, may be briefly summarised :

1. Similarity between the coast lines, edges of continental shelves and other bathymetric levels, of now distant continents. The fit between South America and Africa led Wegener in 1912 to suggest an original proximity and to discuss geological similarities. The fit between these two continents has been subject to successive refinements, including computer study.
2. The similarity of geological formations when now distant continental crustal units are brought into what is thought to have been the original juxtaposition. Formations of special interest are : glacial tillites; characteristic coals; desert-type formations, evaporites such as gypsum, anhydrite, sodium chloride; and distinctive metamorphic types such as Charnockites and Khondalites.
3. Comparable assemblages of rocks with similar radiometric ages. For example, rocks with radiometric ages between 500 and 800 m.y., flanked by rocks over 2000 m.y. in age, may show a common symmetrical distribution when continents are joined.
4. Faunal and floral assemblages, a whole subject in itself, and ably discussed by Ahmad (1961, 1978).
5. The fit of the gold-ore and rare-earth provinces in South Africa, Madagascar, India and Australia if these crustal units are brought close together.
6. Apparent continuation of alignments of tectonic zones between distant blocks when placed in contiguity.

7. Palaeomagnetic positions of poles, and systematic movement of poles during geological time.
8. Particular oceanic ridges marked out by incessant minor seismicity now monitored decade by decade.
9. Zebra strips of normal and reversed magnetism disposed symmetrically on either side of the active oceanic ridges.

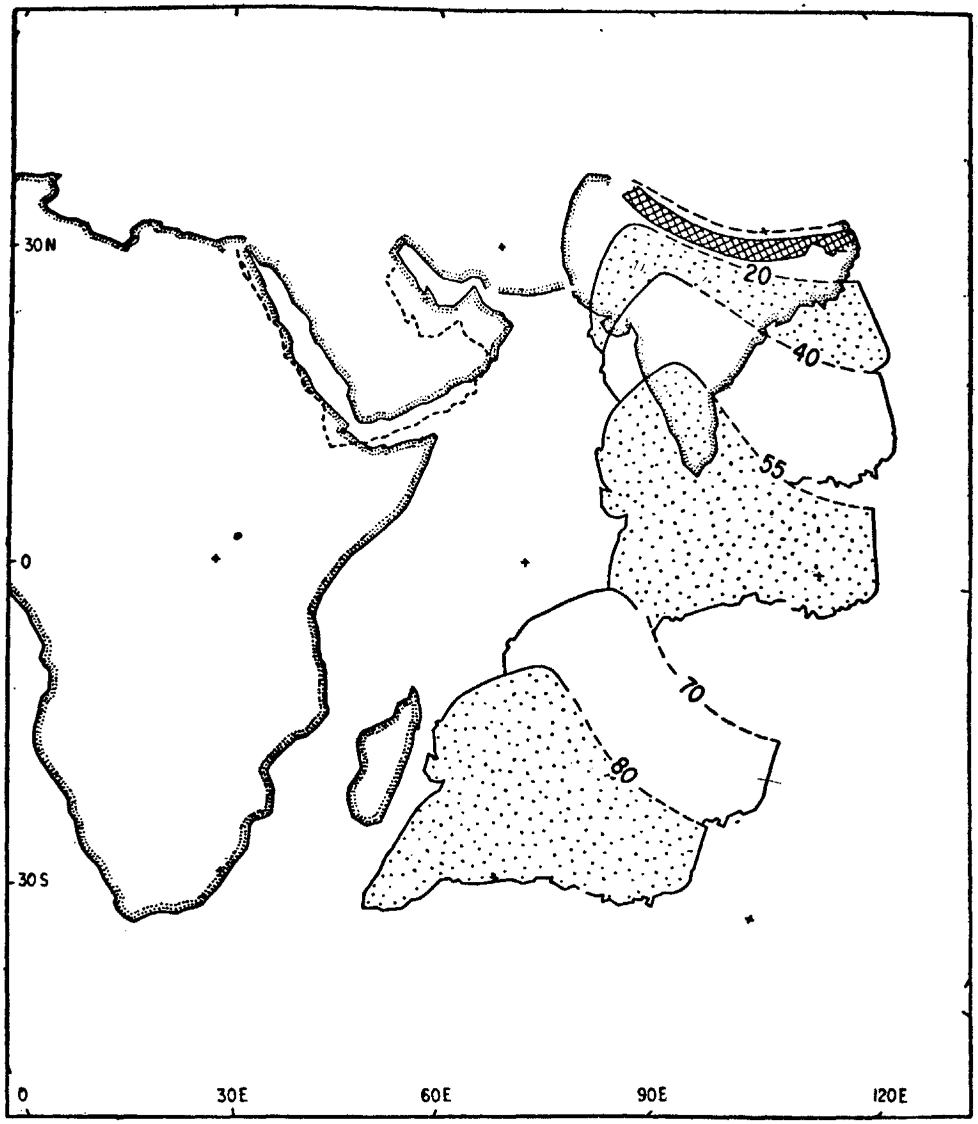
There are so many variations in the arrangements of the crustal places *vis a vis* India that it is difficult to make any simple classification. Broadly, however, the reconstructions may be divided into four groups :

1. The attempts which consider that an immensely wide Tethyan ocean occurred between India, Africa, Australia and Antarctica in the south and Eurasia in the north. Different versions have Antarctica and Australia close to the Madras coast of India. Some versions have Cape Comorin at 30° south latitude opposite Durban 80 m.y. ago. Others place Cape Comorin near latitude 10° S. close to the Tanzanian embayment. India leaves its neighbours Africa, Australia and Antarctica and migrates as a solitary unit some 6500km since the mid-Cretaceous, across the Tethyan ocean, and has recently joined up by collision with Eurasia (*see* Map. No. 1).
2. In other reconstructions India is placed during the Cretaceous near Somalia and Arabia. A much narrower Tethys area is suggested which is part open ocean and part epicontinental sea. Australia is regarded by some authors as filling the Madras embayment, while other authors place Australia adjacent to Tibet, and consider Antarctica to have been in the Madras embayment (*see* Maps 2 & 8).
3. Some authors ignore the Mascarene Ridge, the Chagos-Maldive Laccadive ridge, and the Gaussberg Ridge, in their attempts to bring continental masses together. A few authors recognise the probable existence of these ridges during the Mesozoic (McKenzie & Sclater, 1971, 1973; the Termiers, 1977; Stoneley *et al.*, 1974; and Kamen-Kaye and A. A. Meyerhoff, 1980).
4. In regard to the northern limit of India many reconstructions indicate that India terminated northwards near modern Chitral, Swat and the Himalaya. The tendency now is to extend it into Tibet, and even as far north as the Kun Lun-Astin Tagh (Veevers *et al.*, 1971, 1975) and the Tien Shan (Kaila & Hari Narain, 1976).

Before attempting to consider some of these reconstructions it is necessary to go back in time to the Eo-Cambrian and Cambrian, and to discuss the probable connection between the Vindhyana, the rocks in the Salt Range and those of Iran and Arabia.

VINDHYAN INDIA

The Vindhyans may be divided into the Cis-Aravalli and Trans-Aravalli groups. Because of the then apparent thinness of the Trans-Aravalli Vindhyans, Heron

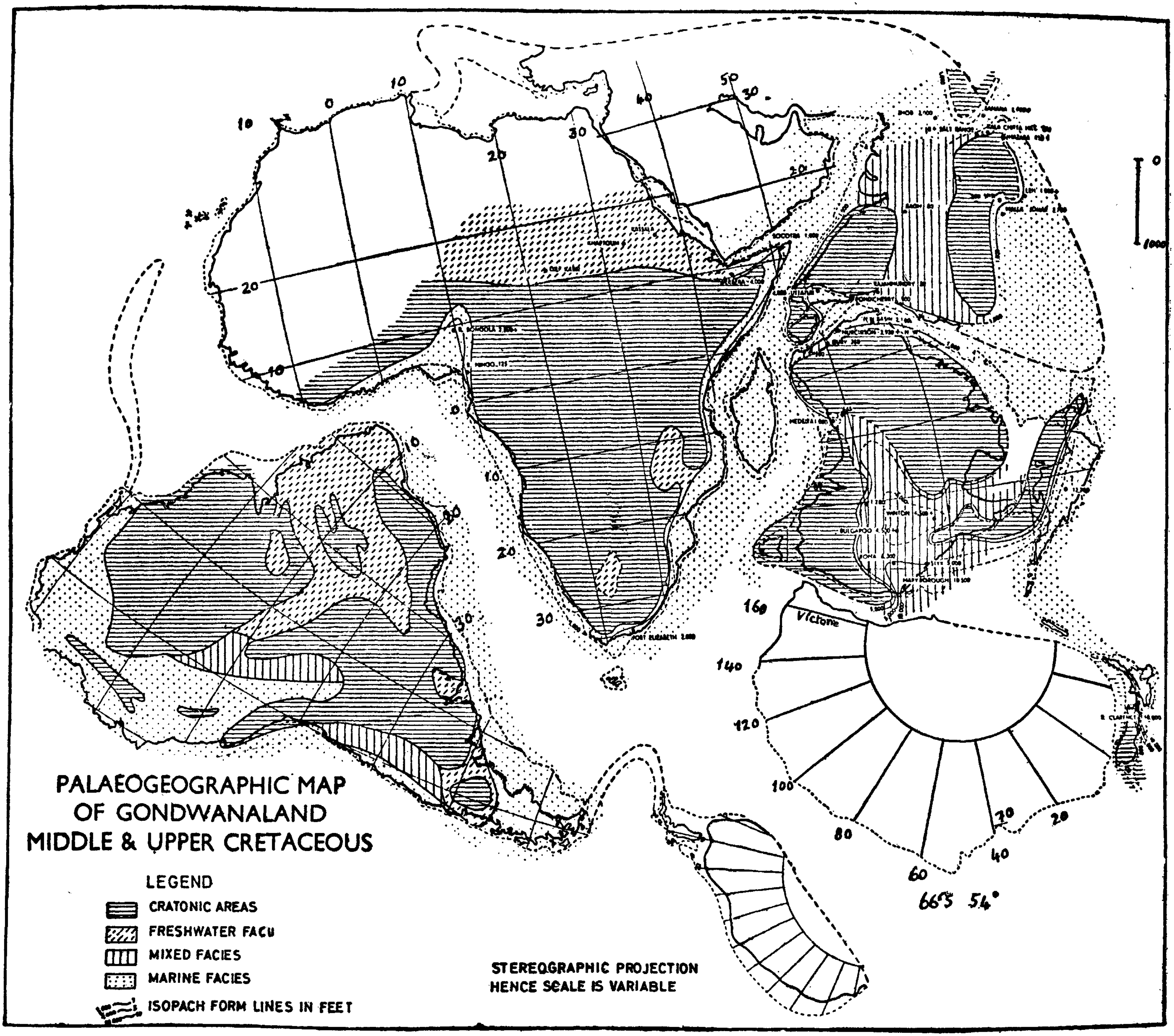


MAP 1. Northward Migration of India since the Cretaceous (After C. McA. Powell, 1979). Figures in millions of years. See also Maps 13 & 14.

suspected that they may represent a different series, but this was before sub-surface data became available, and a greater thickness of the Trans-Aravalli Vindhyans was established than had hitherto been suspected.

Trans-Aravalli Vindhyans

1. They rest on granites with a radiomentric age of 750 m.y. and are not likely to be older than 600 m.y.



MAP 2. Paleogeographic Map of Gondwanaland, Middle to Upper Cretaceous (after F. Ahmed, 1961). North-west Cape of Australia located within the Godavari-Krishna Embayment, which is approximately 7,000km distant from the Napier Peninsula of Antarctica.

2. The Geological Survey of India has established the presence of 930 million tonnes of gypsum-anhydrite in Vindhyan-type rocks at Nagaur within an area of 74km^2, around coordinates 27° 12′ N : 73° 43′ E.
3. In the Rajputana Desert Symposium of 1952 published by this Academy (it was then the National Institute) Dr P. K. Ghosh described a boring in Bikaner City which went through 544m of Vindhyan-type sandstones, limestones and shales, with minor seams of gypsum. Near the bottom were found more gypsum as well as efflorescences of sodium chloride and magnesium chloride (1952; p. 109).
4. At Karampur, near Multan, Pakistan, a deep boring penetrated the Mesozoic and Palaeozoic, and then went through 884m of saline series, with gypsum and salt, underlying the *Productus* limestone and overlying Basement at 2860m below sea level. This series is similar to that exposed in the Salt Range, 270km to the north. On the reasonable assumption that the whole sequence at Karampur is autochthonous, with no thrust between the Purple Sandstone and the underlying saline series, which are Cambrian or Eo-Cambrian in age, this is strong evidence against the concept widely held that the Punjab Saline Series is Eocene and separated by a thrust in the Salt Range from the overlying Cambrian.
5. The saline series of Mandi in the Himalayan foothills, which occurs along a belt 110km in length, has been dated as Permian on the basis of some sulphur isotope studies of uncertain reliability. This series is more likely to be Cambrian or Eo-Cambrian since, so for as I know, no evaporites have hitherto been found of Permian age in Indo-Pakistan.

There is, therefore, a virtually continuous series of rocks characterised by evaporites between the Salt Range and Nagaur. The Salt-Range and Karampur rocks are Cambrian. The exposed Jodhpur sandstones are not older than about 600 m.y. As far as the Trans-Aravalli formations are concerned, it may be assumed that they range in age from the latest Pre-Cambrian to Cambrian. The area covered by these rocks is possibly of the order of 400,000km^2.

Cis-Aravalli Vindhyans

The main Vindhyan area south-east of the Aravalli Range covers an area of approx. 200,000km^2. About 50 years ago, C. S. Fox, followed in 1933 by myself, discussed the possible relationship between the Vindhyans and the Cambrian of the Salt Range, and I had adduced evidence for the deposition of the Vindhyans under arid conditions. Adopting that view, the Cis-Aravalli Vindhyans would be roughly of Eo-Cambrian to Cambrian age. All this was knocked on the head when Soviet radioisotope studies were made of the glauconite obtained from the group which I had mapped along the Son Valley. The Russian studies on the basis of Glauconitic ages suggested an age for the Lower Vindhyans of 1,400 m.y., some 800 m.y. earlier than the Cambrian.

Crawford and Compston (1970) also discussed the Rb-Sr data for samples of 1,000 to 1,140 m.y. These results, therefore, favour a much older age for the Lower Vindhyans than we had supposed, and much earlier than the Eo-Cambrian to

Cambrian. On the other hand, there is a considerable amount of evidence to indicate that the Cis-Aravalli Vindhyans may be younger than the age suggested from glauconite and Kimberlite samples.

1. Eight samples from pre-Vindhyan metamorphic rocks in the Chhota Nagpur area around Hazaribagh and south of Patna give radiometric ages which range between 880 and 955 million years and an average 932 million years. Since these rocks are not metamorphosed Vindhyans but pre-Vindhyan, the strong presumption is that the Vindhyans must be younger than the metamorphics upon which they were deposited by an interval of years involving an erosion cycle, and the Lower Vindhyans might be of the order of 700 m.y.
2. Metre (1978) states that the age of the metamorphics underlying the Vindhyans in the Ujhani exploratory well at a depth of 2,115 m. gave a K-Ar dating of 1,045 m.y. Again, it may be assumed that the Vindhyans at Ujhani are at least an erosion cycle younger than the metamorphics.
3. It may be noted that the Basement rocks of the Kirana Hills, which are inliers within the Indus alluvium and possibly an off-shoot of the Aravalli Range, are dated at 870 $\pm$ 40 m.y. by Davies and Crawford (1971, 235).
4. Anhydrite occurs in the Vindhyans of the Kasganj well. Salt Pseudomorph beds occur in the Sirbu Shales over an area of about 4,000 km^2 around Panna. While these occurrences of sulphates and chloride pseudomorphs are on a much more subdued scale than in the Trans-Aravalli Vindhyan rocks, they point to conditions of evaporation, in conjuction with other signs of arid conditions which I attempted to show 48 years ago.
5. S. N. Sarkar and three Russian workers (1967, p. 538) have found that the Raipur limestone near coordinates 21° 15′ N : 81°00 E overlies Dongargarh granite with a radiometric age of 710 m.y. This limestone is usually considered to be late Cuddapah, but is stated by Sarkar and co-workers to be not older than 600 m.y. The Dongargarh and Erinpura granites are evidently contemporaneous, and the Raipur limestone becomes homologous with the Trans-Aravalli Jodhpur Vindhyans. On radiometric evidence, with a somewhat wider time interval, the Raipur limestone appears also to be equivalent to the Cis-Aravalli Vindhyans to which it is geographically more closely situated.
6. The fossil *Diplocriterion* was found in Vindhyans in the Tilhar exploratory well and is indicative of a Palaeozoic age (Metre, 1968, p. 46).
7. Salhuja, Rehman and Arora (1971) have described microplankton, trilite spores, and discoidal bodies from 238 samples of shales, sandstones and limestone in the Semri, Kaimur and Rewa sediments of the Son Valley. However, they do not indicate whether these plant microfossils are pre-Cambrian or Palaeozoic.

Conclusions

These data all point to an age for at least some of the Vindhyan sediments southeast of the Aravalli Range not older than Eo-Cambrian, and to the broad equivalence of the formations on both sides of the Aravalli Range.

The much older age suggested by some authors for the Vindhyans may be connected with the fact that K-Ar determinations in glauconite tend to give systematic errors and to indicate ages greater than the actual. One might suspect also that the samples of Kimberlite and phlogopite from the Majhgawan pipe are derived from the underlying pre-Vindhyan basement, from which they were intruded as a pipe into the post-metamorphic younger Vindhyans.

The purpose of this discussion is not solely to stress the view that the Cis- and Trans-Aravalli arid formations are indeed contemporaneous and Vindhyan, but also to renew the suggestion that at least part of the Vindhyans is equivalent to the Cambrian of the Salt Range. Stöcklin (1968, p. 1233) and the Meyerhoffs (1972, p. 293) have demonstrated the similarity of the Salt-Range Cambrian to the Cambrian of Iran and in the Afar region of Oman (approx. 22°N : 58°E). There are also important deposits of Cambrian evaporites in Somalia. It is evident that evaporite rocks and arid-type formations were deposited over a very wide area, now extending from western Iran, through Afghanistan to Bihar, a longitudinal distance of 40°, and from the Salt Range to Somalia, separated by 22° of latitude, and involving an area of about 4 million square kilometres.

It is possible, therefore, that some 500 to 600 m.y. ago India was, in fact, a part of this great area of evaporites, and strongly current-bedded red sandstones, and was consequently linked even then to Asia, although separated by epicontinental seas.

It does not follow, of course, that all arid formations at any given period were part of a single desert region, with associated saline waters. The Kalahari desert of southern Africa has no connection whatever with the Takla Makan desert of Sinkiang and the Dasht-i-Margo in Afghanistan. Hence, it may be considered that the particular resemblance and proximity between the Indian system (between the Salt Range and Bihar) and the Iranian and Oman formations, is fortuitous, and only became evident when India, under the prevalent hypothesis, joined up with Asia some 400 to 500 m.y. after the beds in question had formed in once widely separated continents. Of these alternative hypotheses, the first would appear to explain more satisfactorily the coincidence of geographical distribution of Cambrian arid deposits, and the similarity in stratigraphical and faunal sequence, covering an area which would be somewhat smaller than the present Sahara and Arabia Deserta. If this view is adopted it would require, as indicated by the Meyerhoffs, a modification of concepts involving a long migration of India to its Motherland, and would bring India into close association with the present neighbours on the northwest side long before the Gondwana ice caps and later characteristic coals, flora and fauna raised more problems of continental distribution.

Gondwana India

It is necessary now to consider the disposition of the Gondwanas north of the Indian peninsula before continuing to discuss the varied interpretations of continental distribution in relation to India.

Coal-bearing Gondwanas have been known for over a century in the Darjeeling foothills, and the coals have been periodically worked. In 1933, L. R. Wager found a diamictite at Lachi on the Sikkim-Tibet frontier which he showed to me that year when I was on leave in Europe (*see* Wager, 1934, p. 333). The material looked very similar to Blaini diamictite. In 1934, I found a fossiliferous group above the Lachi horizon which was termed the Tso Lhamo series. This group proved to be Upper Permian in age, and indicated that the Lachi beds are not younger than Lower Permian.

In 1935, I suggested the division of Himalayan rocks into those belonging to the Peninsular Himalaya and to the Tethys Himalaya, and indicated that major thrusting had affected the northern edge of the Indian craton including Gondwana beds. Since then, much more work had been done on this problem and outcrops of Gondwanas have been found from Nepal right through to Arunachal Pradesh. In the 1950's, coal seams were found by the Geological Survey of India along the Rangit tributary of the Tista River in Sikkim, associated with diamictites, Glossopteris, Spiriferids and Fenestella. These outcrops occur in the form of a tectonic window, $100km^2$ in area, located within the Himalaya at a distance of 30km from the Plains, surrounded and overlain by Daling phyllites and Darjeeling Gneiss. A semi-window was located on the Sapt Kosi in eastern Nepal, while investigating the site for a 225m high dam, in which are exposed a magnificent boulder bed, sheared coaly shale and dolomite. In the 1960's, during work for the F. A. O., Rome, on alignments for a diversion tunnel from the Sun Kosi, Gondwanas were traced for 120km westwards in Nepal to longitude 86°.

Ganesan of the Geological Survey of India has found a rich Rajmahal flora in north-west Bhutan, 100km north of the southern edge of the Himalaya and only 17km east-south-east of Chomolhari peak 7290m. In Arunachal Pradesh, Acharya and his colleagues have found another window of Gondwanas 100km north of North Lakhimpur and 570km east of the Rangit window (1975, p. 60).

Finally, mention may be made of a paper by Waterhouse and Gupta (1979) which draws attention to a discovery by Chinese geologists north of Mount Everest of a Permian fauna which is very similar to that of Umaria 240km SSW of Allahabad and to that in the Bijni Nappe at Jogira, Garhwal. The exact locality is not stated by the Chinese.

There is, therefore, abundant evidence for the occurrence of terrestrial Gondwanas, intermixed with marine beds, in the central and eastern part of the Himlayas, comparable to the long-known Gagamoptreris beds of Kashmir, and extending north of the main range into Tibet. The most continuous exposures are allochthonous and thrust upon the Tertiaries along the main boundary fault. Other exposures, also allochthonous, are definitely located within tectonic windows in the heart of the Himalaya. A third category lies north of the main range and may have been carried on the backs of the overthrust sheets of Peninsular Himalayan rocks.

Pamela Robinson (1967, p. 217) has produced a palaeogeographic map of the early Permian Talchirs, which she has divided into 4 types :

*Continental facies, *Craton shore facies, *Marginal marine facies, *Tethyan facies. It is evident that there were considerable oscillations of the shore position, between Umaria and Tibet, a distance of 700km or say 6° of latitude.

The Indian craton thus extends north of the Himalaya, but uncertainties exist in regard to how far north. The Chinese claim that the Tsango-po follows a barrier between a cold terrestrial and marine environment to the south, and a warm marine environment to the north. Ahmad (1978) depicts a shallow epicontinental sea between India and Eurasia during the Permian, approximately 1500 to 3000km wide. The Termiers show the presence of a Fusulina Sea flanked on the south by Iran and the Tien Shan. Fusulina occurrences are shown in the Tien Shan area and western Tibet, but not in the Tethys Himalaya (1977, p. 319).

The Tsang-po feature is an extension of the Indus, and the Indus fault has for some time been termed the Indus suture which is claimed to be the plane of collision zone between India and Eurasia. The Indus fault zone is unquestionably, with the Tsang-po, a megatectonic feature, but lacks, however, any sign of subduction and is relatively aseismic. Like the Chaman fault in Pakistan and Afghanistan, it is a deep crustal fault, but its role in demarcating independent continental blocks is uncertain. As will be mentioned later, Veevers, Powell and Johnson (1975) consider that the Indus-Tsang-po ophiolite belt is the surface expression of the suture between Gondwanaland and Asia, but that India has penetrated at deeper crustal level as far north as Kun Lun, Astin Tagh and the Nan Shan.

It should be stressed that the assemblage of continents suggested by Ahmad and the two Termiers place India close to Eurasia during the Permian system (240–280 m.y.), whereas the advocates of a far travelled India start the long migration from the southern hemisphere towards Eurasia during the late Jurassic to late Cretaceous, not less than 100 m.y. later than the Permian.

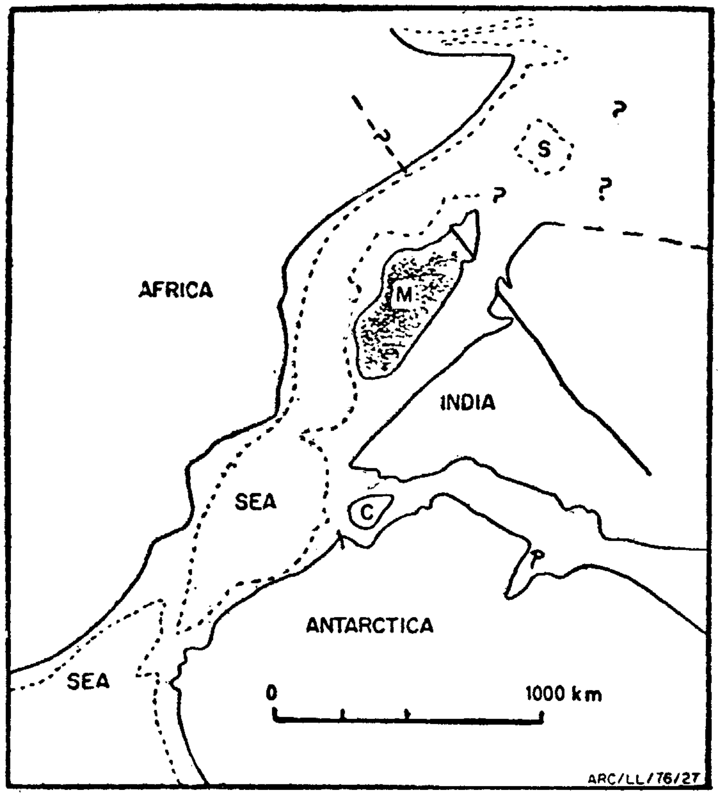
Mesozoic India : West Coast (Maps 3 & 4)

Several authors have placed Madagascar against the continental shelf of western India. Katz and Premoli (1979) have given two positions. In one of these, the coast lines are 130km apart at modern latitude 16° and 70km at latitude 9°. In an alternative position the coast lines are 280km apart at latitude 19° and 100km at latitude 9½°.

Crawford (1974, 1978, 1979*a*, *b*) adopts a third position, with the Antalaha peninsula of Madagascar opposite Saurashtra and 200km distant. Madagascar is not however drawn to the same scale as India, and its representation should be reduced by a factor of 1.2.

Madagascar and Transcurrent Faulting

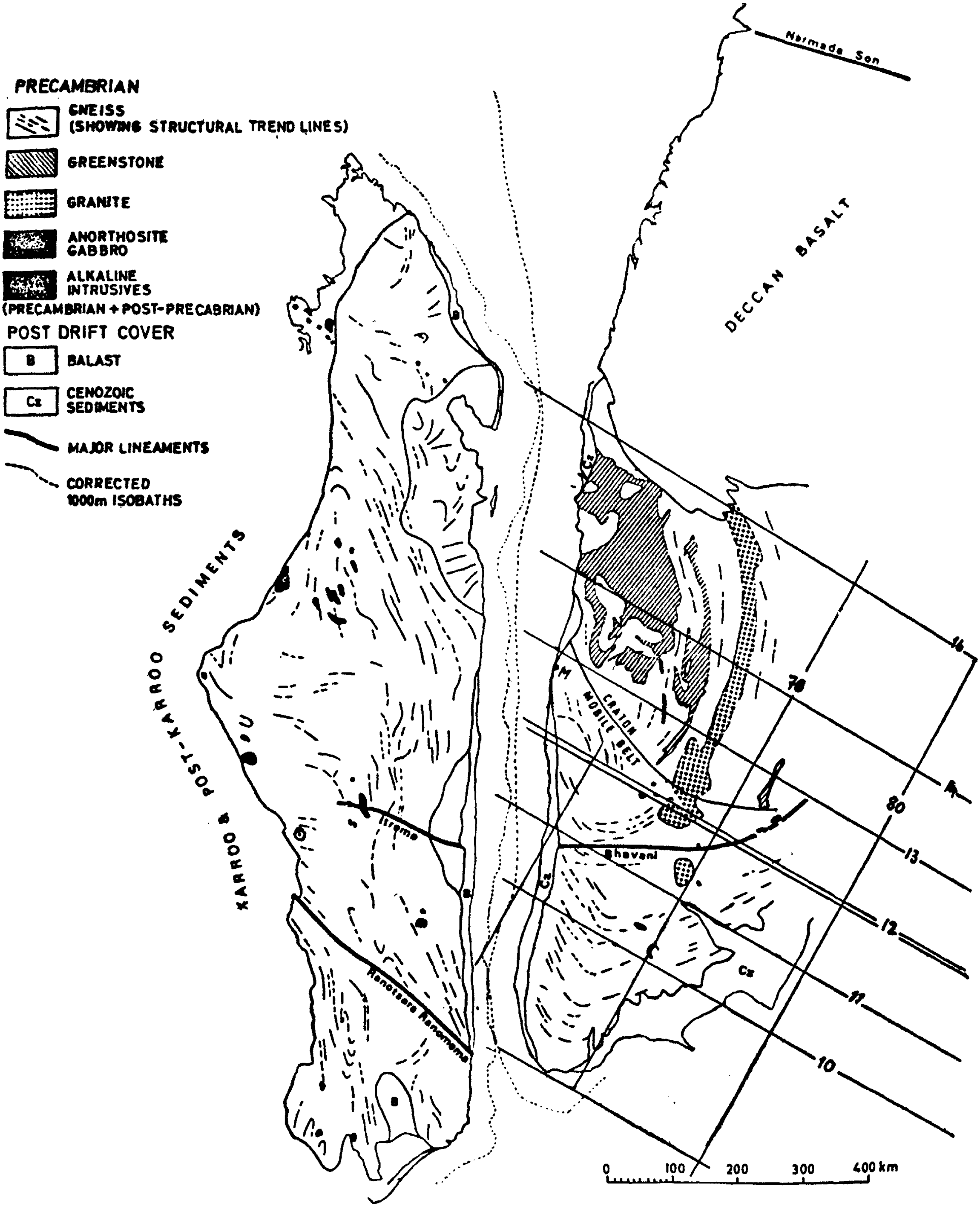
The varied positions are attempts to relate lineaments and geological terrains between Kerala and Gujarat with those in Madagascar, and Crawford (1978) extends the Narmada-Son lineament westwards into the Antalaha peninsula and Ampasindava complex. The three different positions testify to the ambiguity of the evidence for geological correspondence between the two crustal masses. Crawford has a possible



A re-assembly of India, Madagascar, Africa and Antarctica based upon available palaeomagnetic data (see text for references) and other criteria. Areas of sea include some submerged or partly submerged areas of probable continental crust north and south of Madagascar. Full black lines, present coasts. M, Madagascar. C, Ceylon. S, Seychelles group of granitic islands. Thick black line, Narmada-Son lineament and its probable and possible extensions. On the scale of the map read 2000 km for 1000 km.

MAP 3. Assembly of India, Madagascar, Africa and Antarctica (after A. C. Crawford, 1978) Napier Peninsula is located within the Godavari-Krishna Embayment.

extension of the Narmada-Son lineament even into Somalia, a distance which as indicated would be 3500km or 31½°. His location of the lineament cutting through Saurashtra in western India was evidently based on my paper of 1949, when no data existed regarding off-shore structures. Work by the Oil and Natural Gas Commission has shown that the Narmada structures cut the continental shelf just south of Saurashtra and, even if allowance is made on Crawford's interpretation for the change of scale between Madagascar and India, it would be difficult to extend the Narmada faults and folds into Madagascar without a major rotation of orientation. It was suggested by the author in 1975 that the WSW-ENE Narmada fault and fold zone has a dextral transcurrent movement on the continental shelf, with a westward shift on the south side of the Cambay Graben amounting to approximately 150 kilometres, [Auden, 1975 (Fig. 1), cf. Map No. 7]. There is nothing like this feature in northern Madagascar, and the supposed extension appears to be mainly a zone of pyrochlore mineralisation with a modern N. W.-S. E. orientation.



MAP 4. Madagascar located adjacent to India, with only 100 km separation opposite to Kerala (after M. A. Katz & C. Premol, 1979). A correction may be noted. Against *B* under Post Drift Cover on top left, for 'Balast' read 'Basalt.'

The known transcurrent faults do not exceed 1400km in length, such as the Philippines fault 1400km : San Andreas 1200km : Erzincan (Turkey) 800km : Chaman 900km : Alpine (New Zealand) 800km : Toctogul (Soviet Asia) 800km. The Narmada-Son lineament is anomalous since, while there are manifest indications of complex major faulting east of longitude 77°E, and on the continental shelf south of Saurashtra, over 400km of its presumed extent it is covered by Deccan volcanics which do not, as far as I know, show important faulting on the outcrops along that alignment, and it is only the straight course of the Narmada River which is suggestive of the existence of topographical control by sub-surface geological structure. What is certain, however, is that the top of the Deccan volcanics is at a depth of over 6,000m at Broach, whereas near Ankleswar, 30km to the south-east, it is only 2,400m. below sea level, and a series of ENE-WSW faults in assumed to exist between these areas. The total length of this lineament, exposed and concealed but presumed extant, is about 1,600km, or a little greater than the Philippines fault.

It is possible that the limit in length of transcurrent faults so far known, 1400–1600km, may be controlled in part by the thickness of the crust. The chord between the end points of an arc of $13\frac{1}{2}°$ would be 45km below the circumference or crustal surface at mid-point. This figure is comparable to the Moho depth of 40km found by the N. G. R. India for western India. The extension of the Narmada-Son lineament into Somalia would involve a chord depth of 240km at midpoint, far in excess of known crustal thickness.

Such a speculation does not of course apply to subduction zones, that on the west coast of South America being not less than 55° of latitude in length or 6000km (between 10°N and 45°S latitudes). There it is presumably a question of the whole crust being forced down below crust belonging to another plate, rather than strike-slip faulting within the crust.

Reflexion Seismic Work

Reflexion seismic work has shown that 2500m of Palaeogene and Neogene sediments exist between Indian and the Laccadive Islands which are 400km distant from the west coast of India. Whatever the nature of the Chagos-Maldive-Laccadive ridge, it is shown by O.N. G. C. work to have a floor of Basement rocks at 4–5km b.s.l. The presence of this thickness of Cenozoic sediments resting on Basement indicates that by the end of the Cretaceous Madagascar cannot have been closer than 400km to India. DPDP 219 (9°05′N : 72°50′E) is 380km WSW of Cochin and located shallow-water Palaeogene at the bottom. With its distance of 380km from the west coast of India, the boring would be located, on the assumed Cretaceous positions of Madagascar suggested by Katz and Premoli, near the west coast of the island where there is a thick Cenozoic and Gondwana succession. With the southern alternative position of Madagascar *vis a vis* India, which is figured by these authors, the coordinates of DSDP 219 bring it within Basement in an as yet unrifted Madagascar. Rifting from India is considered to have taken place during the Cretaceous, and it must be supposed on this hypothesis that DSDP 219 encountered sediments which had been formed in the newly created oceanic gap left by separation of India from Madagascar. The boring did not go deep enough to establish if Mesozoic sediments were present below the Palaeogene. On the above hypothesis no sediments older than topmost Cretaceous could be present, since rifting began during the Cretaceous.

The continental shelf in the Bombay area has 6,000m of Cenozoic sediments at a distance of 200km from the coast. This large sedimentary column rests on Cretaceous-Palaeocene Deccan volcanics as far west as the edge of the continental shelf, where seismic reflexion work by Harbison and Bassinger located anticlines even 300 km west of Bombay (1970). D. N. Basu and co-workers (1980, 212–214) have shown that along one NNW-SSE zone on the Bombay shelf Tertiary sediments lie directly over Pre-Cambrian, without intervening Deccan volcanics. To what extent the Basement existed as a topographical ridge, which was too high to be over-topped by Deccan lavas, or was uplifted and eroded subsequent to lava extrusion, is not clear. S. Rananathan, in an as yet unpublished report has shown that some of the igneous rocks encountered in the Basement are probably Tertiary plutonic centres related to the Deccan volcanic province, in the same manner as the Barda Hills and Mount Girnar of Saurashtra, and Amba Donga. Examples are the syenite found at a depth about 1700m. in a test boring at Kadi (23°18′ : 72°20′), and a granodiorite in one of the Bassein structures about 80km offshore from the Bombay coast.

In a later work Harbison and Bassinger (1973) have indicated the existence of a ridge of continental crust running 400km off the west coast of India between the Laccadives and latitude 20°N. This discovery, and the continental crust known to occupy the side shelf west of Bombay, suggest that Madagascar, if it had ever been near India, was probably never closer than 400km from the coast line. Not only is the Laccadive archipelago floored with basement, but this basement evidently extends north to the 20° latitude. No deep crustal element, such as must be allowed for Madagascar, could have been located on the area of the Laccadives where basement is at such a shallow depth.

Madagascar Ridge

Those attempts which have been made to position Madagascar against the west coast of India have adopted the present exposed length of the island, which is 1560m. The Madagascar ridge however, extends southwards below sea level as far as the Walters Shoals which are only 18m from surface and the full length of the ridge is in fact about 2500km. It is this full length which must be shifted to the west coast of India if attempts are made to indicate proximity of the two crustal masses, and the Madagascar ridge exceeds the 2300km coast line between Karachi and Cape Comorin.

Mascarene Ridge

The principal objection against the suggested juxtaposition of India and Madagascar is the existence of the Mascarene Ridge, which is over 2000km in length, has an area of approximately 350,000km^2 at the 2000m bathymetric contour and

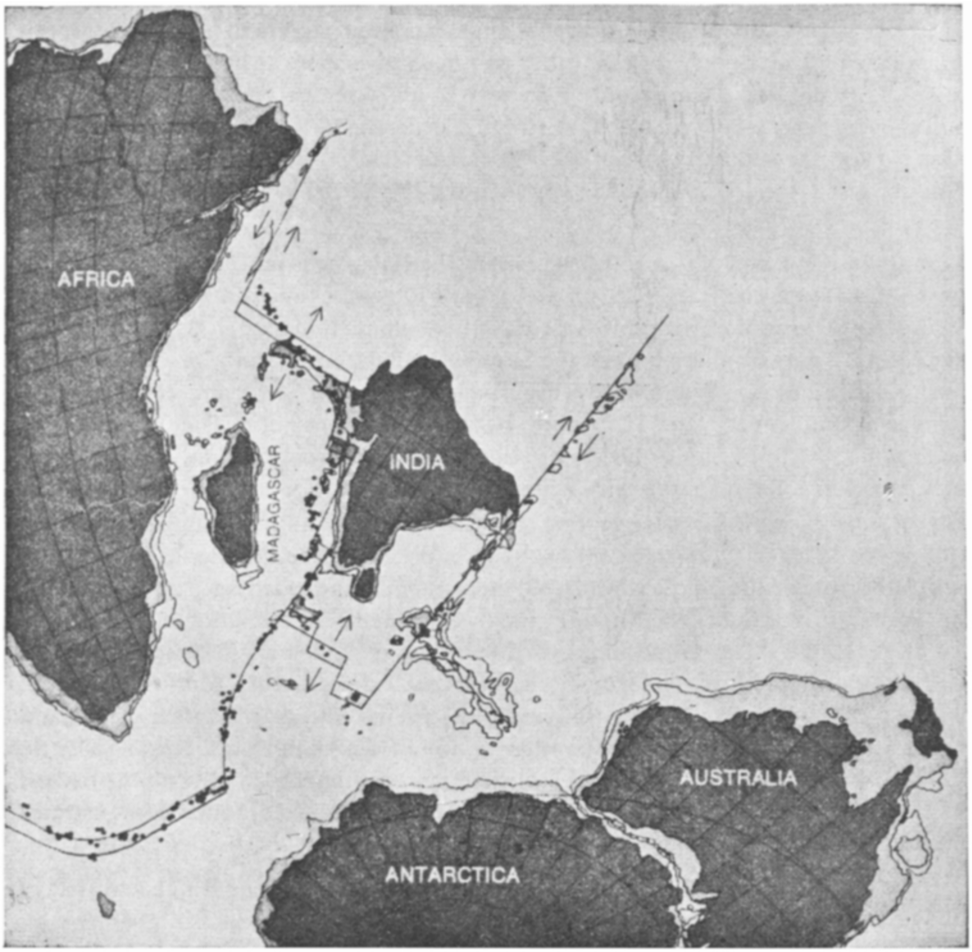
Harbison, R. N., and Bassinger, B. G. (1973) Marine geophysical study off western India. *J. Geophys. Res.*, **78**, 432.

lies between India and Madagascar. The existence of a granite of late pre-Cambrian age on Mahe and Praslin Islands, 50km apart, in the Seychelles has been known for some time. This part of the Mascarene Ridge has been regarded as a microcontinent which became detached from other continental masses when Gondwanaland broke up. Crawford places it out of the way in his attempt to bring Madagascar and India together (1978 p. 149). A totally different origin has, however, been suggested for the southern part of the Mascarene Ridge, including Mauritius and Reunion, which the 1977 UNESCO Geological Atlas of the World suggests may be the result of a hot trail.

Kamen-Kaye and Meyerhoff have within the last year given a detailed discussion on the Mascarene Ridge (1980), and regard it as an extinct aseismic island arc with a long history of vertical movements and non-compression. Aside from the pre-Cambrian granite and basalt of the Seychelles, Palaeocene and probably somewhat older rocks are found in two deep exploratory wells SM-1 and NB-1 sunk on the ridge at latitudes 9½° and 15½° south, but the holes were not drilled deep enough to determine the formations underlying the basalt-type rocks found at the base. SM-1 ended in 830m of basalt with a radiometric age of late Oligocene to middle Miocene, *underlying* Palaeocene marine limestones. The authors suggest that the basalt is too thick to represent a sill intruded into Palaeocene limestones, and favour the possibility that the basalt is probably older than its indicated age on account of diagenesis. It is still a possibility that the basalt may be an exceptionally thick sill, such as are found in the Gondwanas of the Satpuras and the Jurassic of Kutch. In a boring at Port More, Northern Ireland, a basalt-dolerite sill 223m in thickness, belonging to the Thulean igneous province, was found intruded between Lias and Keuper. A syenite of much younger age is found on Silhouette Island (4°29′S : 55°13′E) dated at 46 m.y. or Eocene, (which may be compared with the Miocene syenite found on Kerguelen Island, shortly to be discussed) and demonstrates periodic igneous activity along an already existing structure.

The authors conclude that the history of the Mascarene Ridge and that of Madagascar are closely related and the two areas, with intervening ocean basin, must be treated as a geological entity. It is significant that the late pre-Cambrian granites of Mahe and Praslin are comparable in age to many of the granites of Madagascar.

The existence of this Madagascar-Mascarene entity would preclude any close contact between India and Madagascar, since the Mascarene Ridge, or sub-marine plateau, must have intervened in arcuate form between the two crustal units. The Mascarene arc has a radius of curvature of approximately 1200km, in contrast to the straight edge now displayed by the Bombay-Cochin continental shelf. To attempt to fit the Mascarene arc against the Indo-Pakistan coast line requires placing Seychelles opposite to the Makran coast and the middle of the arc within the 125° angle in coastline near Karachi. This has in fact been attempted by McKenzie and Sclater (1973) to whom reference is made below. Madagascar lies west of the chord of the Mascarene arc, and any position of the arc would be a barrier between Madagascar and India (cf. Map. No. 5).



Seventy-five million years ago, after breaking away from the ancient primitive continent named Gondwanaland, the plate carrying India started to move rapidly toward the northeast. The motion was accompanied by the generation of new plate along the ridges indicated by pairs of parallel lines. Large transform faults east and west of the connected series of ridges enabled the Indian plate to move unimpeded. The original fit of India, Africa and Madagascar with Antarctica is not yet established.

MAP 5. India in relation to continental masses 75 m.y. ago (Upper Cretaceous) (after D. P. McKenzie & J. C. Sclater, 1973).
The authors accept the existence of the whole Mascarene Ridge, which is placed between the Makran and Bombay coasts, touching Pakistan and India. The Kerguelen-Gaussberg Ridge is indicated joined to the Southeast India, or Broken, Ridge, before these two ridges became separated by activity along the Carlsberg expanding ridge.

Chagos, Maldive, Laccadive

Next, there is the problem of the Chagos-Maldive-Laccadive Ridge 2600km in length, regarded by Powell as a recent excrescene. This ridge also lies between India and Madagascar but geological details are scarce. The Laccadives, 400km off-shore from India, are known to rest on Basement which is continuous with south India. Termier and Termier (1977) indicate its existence during the Permian, but on what grounds is not known.

According to the Oil and Natural Gas Commission, about 2500m of Cenozic sediments extend for 400km out from the Mangalore-Calicut shore, resting on Basement, but so far as is known the Laccadive Islands have not been studied and may all be coral atolls. Harbison and Bassinger have located a NNW trending Basement ridge extending from the Laccadives northwards to latitude 20° N and 400km offshore. These features surely vitiate the concept of a Madagascar lying immediately adjacent to the edge of the Indian continental shelf (1973).

McKenzie and Sclater

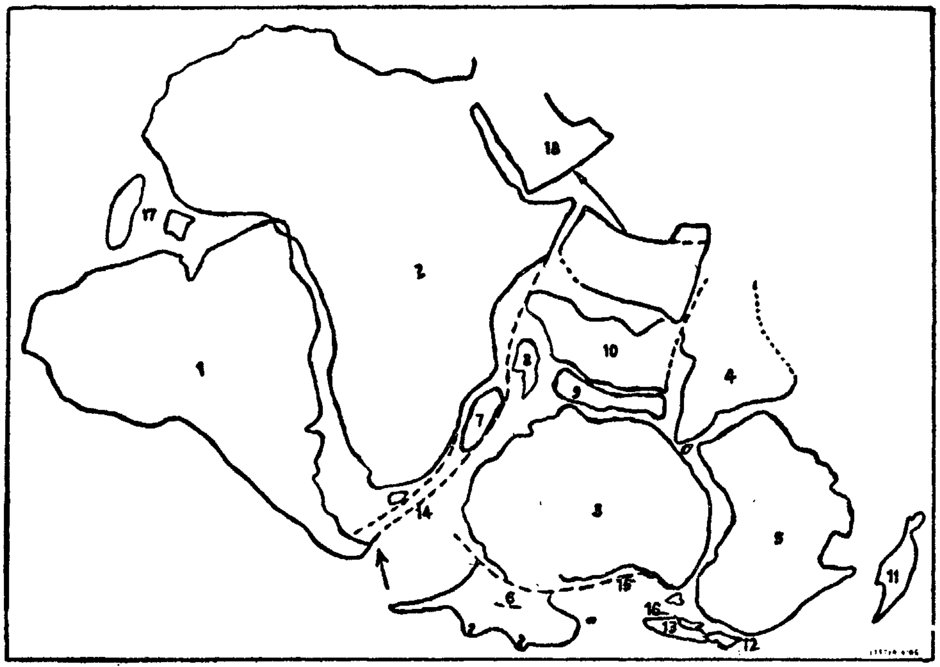
McKenzie and Sclater adopt a totally different arrangement on the west side of India. They assume that the Seychelles-Mascarene Ridge existed during the Cenomanian and fitted it into the Makran-Karachi embayment, Mauritius and Reunion being placed opposite to Bombay and the Seychelles close to Jask in Iran. Madagascar is left in its present position *vis a vis* Africa. The old Mahe granite would be a strange neighbour to the lower Tertiary melange of the Makran, which is much more comparable to the melange formation of the southern Arakan Yoma and the western Burmese isles of Ramree and Cheduba (cf. Map. No. 5).

Lester King

One more attempt at continental grouping may be mentioned. Lester King (1980) places Cape Comorin against Queen Maude Land of Antractica, while the west side of India is flanked by the Kerguelen-Gaussberg Plateau Ridge and a block termed Iran-Afghanistan, west of which is the Mascarene Plateau. Madagascar is given its present position opposite Mozambique, and over 3300km from India. Australia lies close to the east coast of India. The complete divorce of Iran-Afghanistan from Arabia, and their southern position facing Kutch and Mangalore, do not appear to be realistic. Eurasia is not included, and Burma and the Sunda Arc must evidently be regarded as belonging there notwithstanding a long-standing connection with India. This attempt at the continental jig-saw is of interest in including the Kerguelen-Gaussberg Ridge, which is ignored in most of the reconstructions (cf. Map. No. 6).

MESOZOIC INDIA : EAST COAST [MAP NO. 8]

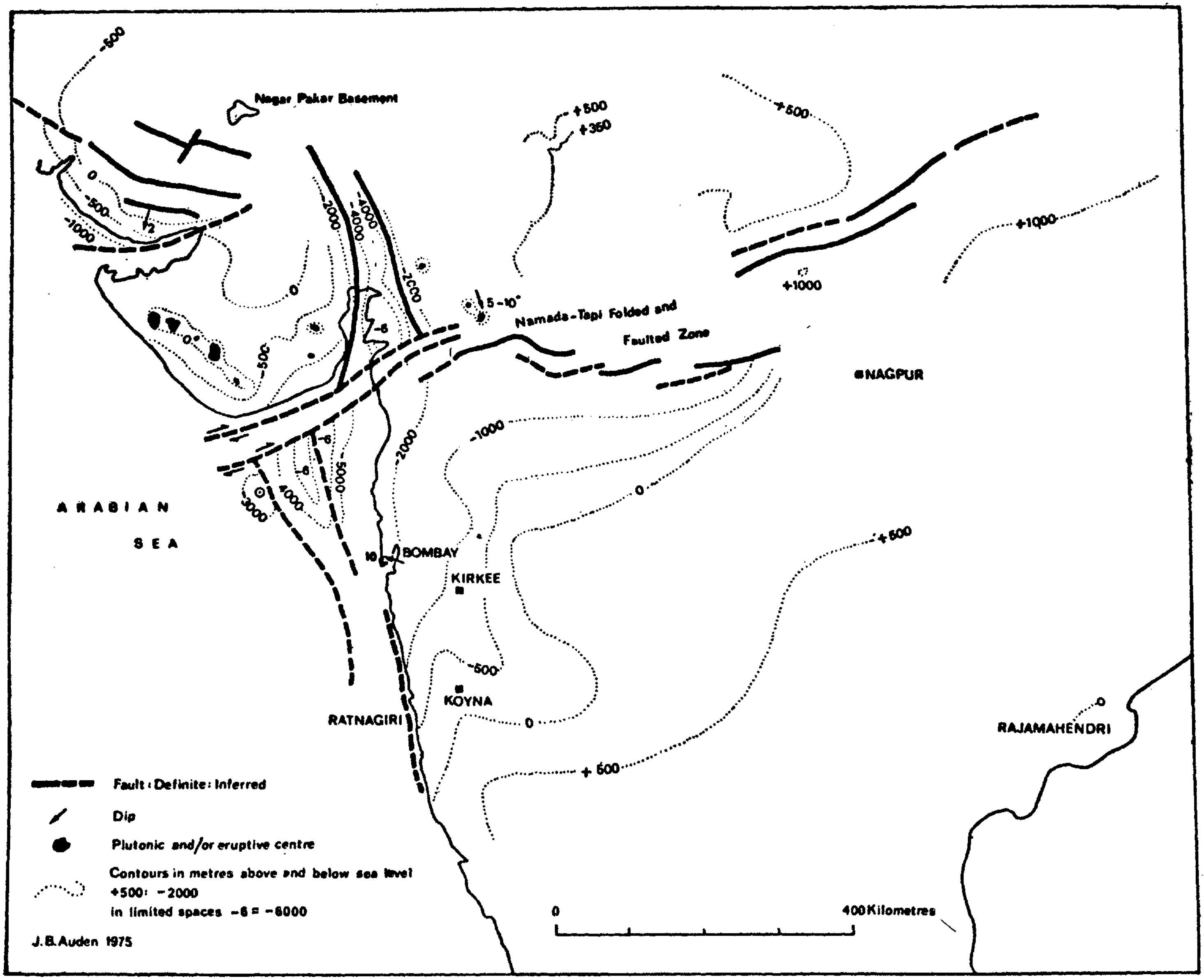
The two principal contenders for a place during the Cretaceous adjacent to the east coast of India are Antarctica and Australia. The Napier peninsula of Antarctica is shown by several authors including Crawford as located within the Godavari/Krishna bend on the east coast at present-day latitude 16° N, at a distance of as little as



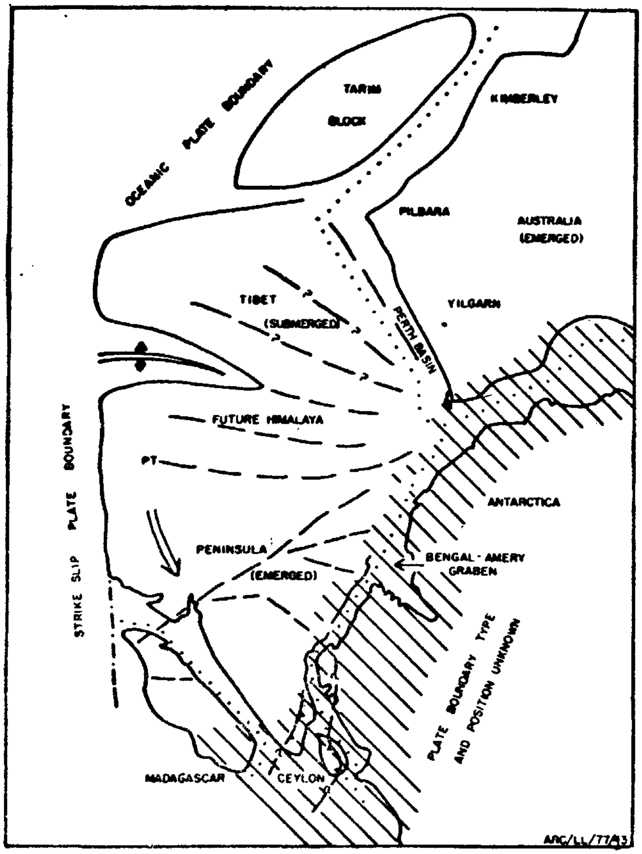
Supercontinent of Godwanaland reconstructed from stratigraphic structural data. 1, South America, with broad continental shelf in southeast. 2, Continent of Africa, with Agulhas submarine plateau. 3, East Antarctic Shield. 3, Peninsular India. 5, Australian continent. 6, West Antarctica, part of orogenic girdle of Gondwanaland; broad continental shelf of western Weddell Sea corresponds to similar shelf of South America. 7, Madagascar; position here assigned is in accordance with structural and stratigraphic comparison with Mozambique (Flores 1970; Kent, 1972; Tarling, 1972). 8. Mascarene submarine plateau, with granite on Seychelles. 9, Kerguelen submarine plateau (wirh schists and siliceous slates). 10, Iran-Afghanistan with Gondwana stratigraphy and structure. 11, New Guinea (united with Australia by continental shelf) forming part of orogenic belt about Gondwana. 12, New Zealand, formerly an arc structure about southeast Australia. 13, Campbell submarine plateau. 14, Falklands-Agulhas and Prince Edward fracture zones. 15, Monoclinal fault front of Transantarctic Mountains. 16, Alpine fault of New Zealand. 17, Azores submarine plateaus with coarse gneisses and granites, red sandstone, and other rocks of continental affinity. 18, Arabia. Reconstruction is now left with one gap, between Africa (2), Iran-Afghanistan (10), and India (4). This hiatus may well have been occupied by Arabia, with ancestral geosyncline of Zagros Mountains as part of Gondwana orogenic margin. If so, withdrawal of Arabia to its present position must date from Early Permian time, and Red Sea Basin must be of different origin from modern African rift valleys.

MAP 6. Gondawanaland re-united (after Lester King, 1980). The Kerguelen and Mascarene ridges separate southern India from Madagascar. Lester King prefers the term "submarine plateau" to the word "ridge" in describing Seychelles-Mascarene and Kerguelen-Gaussberg features.

200 km between the coasts. It may be remarked that in the attempts to fit Antarctica into the Madras embayment, the Napier peninsula is placed by some authorities opposite to the Krishana-Godavari delta, but in other reconstructions it is rotated



MAP 7. Major faulting in Western India (J. B. Auden, 1975) The Narmada-Son Lineament is a Major feature, but over a distance of 400 km appears to lack distinctive topographical expression, its place possibly being taken by the important fault zone of the Tapi (Tapti) valley, especially Gawilgarh. The western extension of the Narmada fault system is regarded as transcurrent, with dextral displacement.



Part of Godwanaland during the Permian, Triassic and Jurassic (after Crawford, 1974). Area now Indus Suture Line is suggested to have been a temporary narrow opening in which oceanic type crust developed as the Peninsular part rotated away from Tibet about a pole near the southwestern tip of Australia. This opening closed later as the rotation reversed in direction as Gondwanaland broke up. Broken lines : major rift zones. Hatching : Late Precambrian—Early Paleozoic zone of mobility. Final crustal separation took place along dotted lines.

MAP 8. The Napier peninsula of Antarctica is placed 100 km distant from the Godavari-Krishna embayment, while Australia is adjacent to Tibet and the Tarim Basin.

by 90° to 180° from that position. The broadly circular coast line of Antarctica over a distance of 8500km, between the Antarctic circle and 70° S, lacks marked topographical expression, and the criteria for placing any particular part of the Antarctic coast line within the Madras embayment are not of a definitive nature, since detailed geological information is lacking over much of the Antarctic coast line. Others place the North-West Cape of Australia in that position, and in the reconstruction of Ahmad, Australia lies between India and Antarctica, with the Napier peninsula being some 8,000km distant from the Godavari-Krishna deltas. Crawford places the west coast of Australia against the Tarim basin, Tibet and the south coast adjacent to Antarctica.

Kerguelen-Gaussberg Ridge

First in regard to the placing of the Napier peninsula against the Godavari-Krishna bend of India, with the modern coast lines only 200km apart, it would appear that the Kerguelen-Gaussberg ridge in the South Indian ocean has been overlooked by almost all authors.

This ridge is 2,200km long and covers an area of about 250,000km^2 at a depth of 1,000m. The Kerguelen Islands at the north-western end of the Gaussberg ridge have an area of 6,232km^2, surrounded by an area of 64,000km^2 at the -200m bathymetric contour. They are 2200km distant from the Napier Peninsula of Antarctica. Recent studies by a French Mission have shown that the Kerguelen islands comprise a series of volcanic rocks, with one major plutonic mass of granitosyenite covering 380km^2, and 4 minor outcrops not exceeding 4km^2 in area. The greater part of the lavas are plateau basalts, but rhyolites, trachytes and phonolites are also present. Thin beds of lignite occur in four areas, associated with Araucaria, Angiosperms and Pteridophytes.

Radiometric dating indicates lava ages from the Oligocene to Recent, while the syenite is 8.6 m. y. The lignite is associated with lavas of lower to middle Miocene age.

While no rocks crop out with a radiometric age earlier than the Oligocene, it is inferred that the basal basalts may be of Eocene age. Moreover, according to Lester King (1980), schists and siliceous slates have been found on the Kerguelen-Gaussberg submarine plateau which would imply that the floor of the volcanics may be Palaeozoic or older.

In several areas the plateau basalts have regional dips of 10° to 20°. The lavas are cut by a prominent series of fractures, extending up to 40km in length, with a predominant NW-SE trend. In the Ile Foch, the fractures are 500m apart and strongly recall those which I have described cutting the Deccan volcanics over a distance of 500km between the Koyna Project and the Narmada (Auden, 1954, p. 94; 1975, p. 12). Near the Monts Ballons, the fractures form a triangular pattern and have acted as avenues for the intrusion of trachytic magma. The major fractures, some almost straight, as in the Val Studer 19km in length, others spreading out in arcuate form, eastwards from the Cook Ice Cap, exert a significant control over the topography, which is immediately manifest in the excellent 1 : 200,000 topographical map prepared by the French.

The beds of Miocene lignite are only a few centimetres thick and of no economic importance, but they are of geological significance in indicating that Kerguelen was periodically above sea level and supported a complex land vegetation.

The Gaussberg Ridge is aseismic, like those of Mascarene, Chagos, and 90° East, in contrast to the Carlsberg Ridge. No doubt minor seismic activity occurs during periodic volcanic disturbance on Kerguelen and Heard Islands, but such seismicity is of a different category to that associated with the Carlsberg and Mid-Atlantic ridges which is manifest, although seldom of large magnitude, throughout the decades of monitoring.

The aspect of the Kerguelen Island group is reminiscent of parts of Newfoundland, but more particularly of the coast lines of the North Atlantic Tertiary Thulean igneous province, as in north west Scotland, the Faeroe Islands, and the Bardastrunda peninsula of Iceland. The volcanic terrain is not like that of recent volcanic islands, such as Reunion and Heard Island (a recent volcanic mass rising from the Gaussberg Ridge), which are essentially endogenous circular cones with radial lava outpourings from a vertical axis. The terrain has more the aspect of a regional volcanic complex, characterised by plateau basalts and plutons, in many areas displaying significant dips not due to radial outpourings on a central volcanic cone. The widespread fracture pattern points to the imprint of a diastrophism that has influenced the whole island complex. The Gaussberg Ridge is, therefore, no recent excrescence, but has the character of activity throughout the Cenozoic and probably long prior to the Eocene. This ridge, standing out obliquely from Antarctica, may have developed only after Antarctica, by supposition lying within the Madras embayment, had been left isolated by the northward migration of India. It would appear more probable that the Gaussberg Ridge existed between India and Antarctica from Mesozoic time. If that be so, India and Antarctica may never have been such close neighbours as has been maintained.

Some workers, including several Russian geologists, regard the Kerguelen-Gaussberg Ridge as an intumescence of oceanic crust, arched up during the Cenozoic. Others consider the ridge to be a thalassocraton, or micro-sialic fragment of recent continental crust. On either hypothesis at least part of the Gaussberg Ridge must have been dry land during the Miocene to allow for the development of a forest cover and the formation of lignite.

According to McKenzie and Sclater (1973), Kerguelen was originally joined to the Broken Ridge (South-East India Ridge attached at 30° S to the 90° East Ridge) from which it is thought to have become separated by the fissiparous Carlsberg Ridge splitting the pair of twins. This view is also expressed in the explanatory notes to plate 21 of the World Geological Atlas (UNESCO, 1977). On that assumption the twin Gaussberg and Broken Ridges, at one time joined together, should have been an even wider obstruction between India and Antarctica.

Sunda Arc

There is another line of argument by which the postulate of the former juxtaposition of India, Antarctica and Australia may be questioned as of doubtful validity.

A major difficulty in placing the North-West Cape of Western Australia within the Godavari-Krishna embayment of India is the existence of the Sunda Arc which now extends for 7,500km between Upper Assam and Northern Burma at the northern end and Ceram close to New Guinea. In Ahmad's reconstruction the Australian cratonic mass forming southern New Guinea involves a distance of only 1500km from the Central Indian craton (existing continental dimensions being used as a scale). It is difficult to accommodate the immense Sunda arc within such short distances, for it cannot be assumed that the arc developed *pari passu* with the inferred separation of Australia-New Guinea from India throughout the Cenozoic. If that were so, there should have been a progressive age difference between the ends of the arc and its mid point.

It is not possible to assume that this major arc arose from oceanic crust. It developed as a series of parallel geosynclines and geanticlines, which became accentuated during the Mesozoic, with a basement of continental crust extending from the Shan plateau, through Malaysia to the Sunda shelf, opposite to the Australian/Irian-Bharat craton. Basement also occurs intermittently along the Arakan Yoma over a distance of 1,000km, including Mount Victoria, Webula and the Naga Hills (Brunnschweiler, 1974, 285, 293).

The zone of maximum convolution is within eastern Indonesia, where the ends of the island arc, including Timor, Jamdena, Seram and Butunga, are separated by 2,600km of island chain which has become so folded that they are only 600km apart (Audrey-Charles 1974, 350-370). Such a convolution must have arisen as a result of rotational stress, in Umbgrove's view between the Sunda and Sahul cratonic masses, while with the current concepts of plate tectonics there was collision between four plates...Asian, Indian Ocean-Australia, Pacific Ocean and Philippine Sea (Audrey-Charles, 1974, 372).

The northern part of the Sunda arc, as now developed, lies between India and Burma. The south-eastern end of the arc, as just discussed, lies close to the West Irian extension of the Australian craton. If Crawford's hypothesis of the juxtaposition of Australia and Tibet between the Permian and late Jurassic is accepted, there would have to be a complete distortion of the Sunda arc, for the Banda end of this arc, structurally linked with Western Irian and Australia, would then have been in the region of modern central Asia, while the northern end of the arc between present-day India and Burma, would imply an inversion of relative position. Since, however, in the same reconstruction Crawford places Antarctica immediately adjacent to the east coast of India, and spreading over what is now Burma and the Bay of Bengal, there would in fact be no place for the northern end of the Sunda arc (1974, 374).

The reconstruction of Lester King (1980) does permit of the existence of the Sunda arc without reversal of end positions, while Australia slipped away from India, although preserving its cratonic status in relation to the Sunda Arc.

It is necessary to stress the characteristics of this extraordinary four-fold arc, with a Basement of Permo-Carboniferous and older rocks extending 3,500km from Upper Burma to Billiton island between Sumatra and Borneo, and continuing eastwards as the Sunda Shelf. The next element is the sedimentary basin of the Pegu Yoma, Sumatra, Java, characterised by thick Tertiary deposits, hydrocarbons (coal, oil and natural gas) and volcanoes. The third element forms the Arakan Yoma axial zone of west Burma, Chin Hills, Manipur, Nagaland, continuing southwards to the Andaman, Nicobar and Mentawai islands. Finally there is the western Tertiary zone of thick flysch deposits and hydrocarbons (oil, natural gas and coal), which extends for 1100km in a series of Jura-style folds from Ramree to Chittagong, Tripura, Sylhet, Cachar, up to Digboi.

The width of the arc is 500–700km. While the component zones remain parallel and of fairly uniform width, there are systematic variations along the strike. The Arakan Yoma in Burma for example forms a continuous range 1400km in length, and includes mountains such as Victoria (3053m). Further south this zone changes to a series of islands along an arc 2600km in length and spaced 90 to 130km apart. In the volcanic zone, the spacing of the volcanoes in Java is approximately 60km, whereas in Sumatra it is about 110km and in Burma there are 6 volcanic centres between north latitudes 21° and 26° or approximately 1 : 100.

The changes are, however, systematic and there is a remarkable regional unity and symmetry of homologous zones in the compound arc over a distance which is almost one fifth of the present circumference of the earth.

Sunda Arc Coals

Of great significance is the presence of Tertiary coals throughout the greater part of the Sunda Arc.

Assam Upper Palaeocene coals in the Sylhet Limestone. Oligocene coals in the Barail series with seams up to 6m in thickness (Evans, 1932, 203).

Sylhet Miocene lignites

Ramree, Cheduba, Cap Islands Tertiary, probably Eocene coals, upto 2m in thickness (Pascoe, 1964, 1590)

Central Burma Eocene coals Hinzada, Pondaung (Pascoe, 1964, 1598)

Central Sumatra Eocene coals mined at Sawahlunto.

S. E. Sumatra Pliocene coals mined at Bukit Assam.

Borneo Pliocene coals

Production of Oligocene coals in Assam is about 300,000 tons p.a. In Sumatra, some 600,000 tons of Eocene coals and 800,000 tons of Pliocene coals are mined annually. These coals imply actual or neighbouring land conditions, to provide the drift timber for carbonisation, over a large extent of the Sunda arc during several periods of the Tertiary, when by hypothesis there lay the immense funnel-shaped Tethys ocean. In a recent number of the *J. geol. Soc. India*, Trivedi has described proboscidean teeth from the Boka Bils of NW Tripura of U. Aquitanian to Lower Helvetion age, stratigraphically immediately preceding the lignitiferous Tipam sandstone.

Sunda Arc Oil & Gas

The existence of oil and natural gas throughout two of the zones between Assam and Burma in the north, and Indonesia, is also of significance in indicating comparable environments, but is less diagnostic than coal in regard to specific depositional conditions due to uncertainties about source beds and migration of hydrocarbons. It suffices to stress the occurrence of oil fields in Upper Assam and Central Burma, gas fields in Sylhet and Arun (north Sumatra), and oil fields in south-central Sumatra, where daily production of oil is 800,000 barrels (almost

130,000 m^3). There are, in addition, numerous occurrences of oil in islands such as Ramree and the Barongas, which have been worked on a village scale.

Arc Development

As Van Bemmelen showed, the Sunda Arc has developed from a series of geanticlines and geosynclines migrating progressiv ly south-westwards from Natuna island and the Semitan ridge in Borneo during the Permo-Carboniferous, to the Jurassic tin-bearing granites of Malaya, Bangka and Billiton which are part of the Sunda Shelf, the Laramide to Quaternary orogenesis of the Barian Range, and the Mentawai islands off the south-west coast of Sumatra. This regional activity was taking place simultaneously with the supposed separation of Antarctica and Australia from the east side of India.

The present-day condition of the arc is indicated by the presence of a Benioff Zone. In Indonesia, this zone extends from northern Sumatra to Jamdena, a distance of 4500km, with northward to N. E. dips of 50–60° from the horizontal, down to a depth of 600km. In Central Burma, a more subdued Benioff Zone occurs between latitudes 21° and 26°, the dip being to the east.

North End of Sunda Arc

At the northern end of the Sunda arc the structural units of Wizo, Manipur, Tripura, Cachar, Meghalaya and Upper Assam are linked to India. The Lower Cretaceous Rajmahal-Sylhet traps are continuous below the Bengal deltaic deposits, overlain by the Eocene Sylhet limestone. The Disang series of the Arakan Yoma and Upper Assam are found south of the Shillong plateau as far west as 25° 03′N : 92° 27′ E, associated with the full Tertiary succession of Cachar and Sylhet. A gap of only 60km separates the detailed seismic reflexion survey work of Bogra from that undertaken over the most westerly anticline of the Tripura-Comilla group of folds at Bakhrabad (23° 37′ N : 90° 52′ E) which is 50km E. S. E. of Dacca. There is a virtually continuous record of geological formations, from the Cretaceous to the Quaternary, between India, Bangla Desh and Burma, not only along latitude 25° N, but also 170km further south.

At the one end of the Sunda arc, therefore, the Sahul Cratonic mass of Australia and New Guinea formed a crustal unit opposed to the Sunda shelf, between which plates the most extreme convolutions of the Sunda arc units took place. At the other end of the Sunda arc, 7,000km distant from present-day New Guinea, the formations among India, Bangla Desh and Burma were in process of development from before the Eocene. The whole arc in between these ends has geographical continuity and an inter-related diastrophism throughout the Cretaceous and Tertiary. It is difficult to imagine that during the Cretaceous the extremities of this mega-tectonic arc could have been condensed into about 1500km. On Crawford's construction, with western Australia adjacent to Tibet and the Tarim Basin, Antarctica would have lain where the modern Sunda arc now curves, and New Guinea, without any attached arc, lay some 5,000km north-east of India (adopting India's present orientation), instead of as it now is 6,000km to the south-east.

Where Was the Sunda Arc ?

On the hypothesis which places Antarctica next to Madras, with Australia wedged between Tibet, the Tarim Basin and Antarctica, there is no place for the Sunda arc in the postulated surroundings of India. The land mass which was necessary to provide the thousands of metres of Cenozoic sediments, together with the coal deposits ranging in age from Eocene to Pliocene, would have had to be Antarctica.

There is a less drastic distortion of the surroundings of the Sunda arc in the reconstruction favoured by Ahmad, in which Australia lies next to Madras and New Guinea is located about 1500km east-north-east of Bengal (adopting the present-day orientation of India). New Guinea now lies 6,000km distant in a south-east direction. This would involve an excessive, indeed seemingly impossible, lengthening of the arc, realising that all the elements of the arc were in existence throughout its length at the very time that Australia and its northern satellite New Guinea are assumed to have begun to split off from India during the Cretaceous.

It may be noted that the whole of this extraordinary Sunda arc developed within the wide Panthalassa ocean postulated by Dietz and Holden, which they figure as 7,500km wide at the mean longitude of India and 10,000km wide at the longitude of their *Sinus Australis*. Within this inferred ocean there were the coal-bearing fluviatile deposits of Eocene, Oligocene, Miocene and Pliocene age and extensive forested land masses to provide the coal-forming vegetation.

Smith and Briden (1977) recognise part of the Sunda arc as belonging to the Eurasian mass, but leave it disconnected with India and Burma at one end, and New Guinea at the other end, right up to the early Miocene. Before then, India and New Guinea could have had no influence on the development of the arc, whereas the evidence is that the Sahul and Sunda shelves were vital factors in the formation of the structures at the south-east end, while in the north the basement formations now represented by the Shillong and Shan plateaux were a controlling influence.

Principal Features of Arc

The principal features of the various zones of the Sunda arc are tablulated below. It should be noted that these zones are comparable with, but not identical to, those detailed in articles on the Indo-Burman Ranges, the Banda Arcs, and Sulawesi, by Brunnschweiler and Audrey-Charles in Special Publication No. 4 of the Geological Society of London (1974).

Interpretation of M. F. Ridd

Ridd (1971) (cf. Map No. 9) has produced a totally different reconstruction for the Jurassic period before the break-up and continental drift. This obliterates western Burma and brings the Shan plateau next to Bengal and the Khasi Hills. The northern 250km of Sumatra, separated from the rest of that island by a fault, lies in the

TABLE I

Principal features of the Sunda arc

	Outer Tertiary	Arakan Axials Andamans Nicobars Mentawais	Irrawaddy Basin Pegu Yoma. Barisan Ranges	Basement Shan Plateau Malaysia. Tin Belt Palembang-Sunda Shelf
Main Characteristic	Thick Miocene succession. Jura-type folds Ramree; Cheduba; Barongas; Chittagong Tripura; Sylhet; Cachar; Upper Assam	Cretaceous-Eocene Disang Shales & slates. Exotic blocks of limestone with *Globotruncana*. Melange in south Arakan Yoma. Ultrabasics. Islands 30–130km apart over arc of 2600km.	Thick Tertiary succession of Irrawaddy Basin. Complex nappes of Barisan Range	Pre-Cambrian to Palaeozoic Basement in Burma. Tin-bearing granites Malaysia, Bangka, Billiton. Stable shelf Djambi Palembang.
Oil & Natural Gas	In many structures Ramree-Cheduba to Upper Assam over 1100km : mainly in Miocene, but source often Eocene-Oligocene		Oil fields & oil shows over distance of 500km in Burma. Pliocene oil & gas fields Djambi, Minas, Arun. Java, Borneo, Ceram.	
Coal	Eocene coal Shillong, Ramree. Oligocene coal in 300m of Barails over 450km outcrop. Seams up to 6 m. Production 300,000 t.p.a. U. Miocene lignite in Sylhet.		Eocene & Oligocene coals Yaw, Pondaung, Shwezetau beds Burma Eocene coal Sawahlunto Central Sumatra 600,000 t.p.a. Pliocene coals Bukit Assam SE Sumatra. 800,000 t.p.a.	Cretaceous Coal Kalow Burma
Volcanoes			6 volcanic centres in Burma 21° to 26° N. Narcondam. Barren Island. One volcano every 100km in Sumatra. One every 30km Java. Total length of volcanic arc 7200km.	

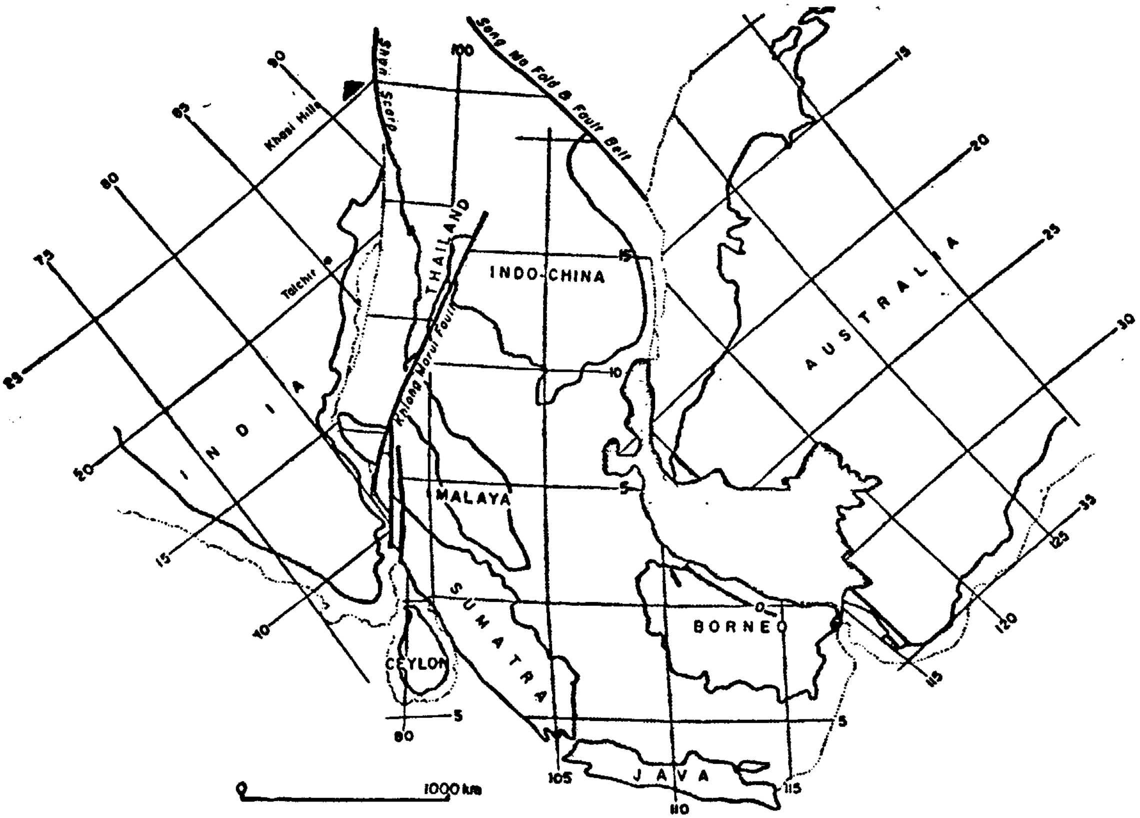
(*Table I continued on p.* 613)

(TABLE I—*continued from p.* 615)

Mud Volcanoes	Ramree & Cheduba	Jamdena & Kei islands	Minbu, Prome, Hinzada in Burma.	
Gravity Anomalies		Negative gravity anomalies from Mentawais to Java Trench & north to Halmahera. More recently proved extending from Mentawais to the Andamans.		
Seismicity	April 1762 probable epicentre shock 19° N : 93° E. M > 8 Srimangal E. Q. 1918. M = 7.5	Intermediate focus between 20° and a 26° north, partly along Axials partly upper Irrawaddy.		
		Swarm of shallow focus shocks Andamans, Mentawais, east to Timor	Intermediate focus shocks along Barisan Range.	Line of deep-focus shocks 100–150km north of north coast of Java eastwards to Banda, & underneath the southern boundary of the Sunda Shelf.

Godavari-Krishna embayment, and most of Sumatra is placed against the Thanjavur peninsula and Sri Lanka. Western Australia overlaps northern Borneo. In this interpretation, the greater part of the Sunda arc did not exist in the north, where the Irrawaddy basin and Arakan Yoma had by supposition not been formed. Yet Pre-Alpine metamorphics occur intermittently over a distance of 1200km along the line of the Arakan Yoma, and exotic blocks of limestone with *Globotruncana* and small *Assilina* occur at various levels in the flysch, Pascoe (1964, p. 1607), Brunnschweiler (1974, p. 284), suggestive of orogenic activity at least as far back as the Eocene. The complex system of arcs east of modern east longitude 115° is not figured by Ridd, but his drawing (1971, p. 533) indicates that this part of the arc would have been 35° of latitude, are about 4,000km, south of New Guinea, and hence lacking the very Sahul cratonic mass which, with the Sunda craton, is regarded as responsible for the convoluted formation of the islands of the Banda sea.

These ideas have since been modified (1980) and the author now suggests that the Thai-Malay peninsula was once part of Gondwanaland, from which it was rifted away during the late Palaeozoic, leaving a Palaeo-Tethys sea which eventually closed up as the Thai-Malay unit joined up during the late Jurassic with the southern China Block.



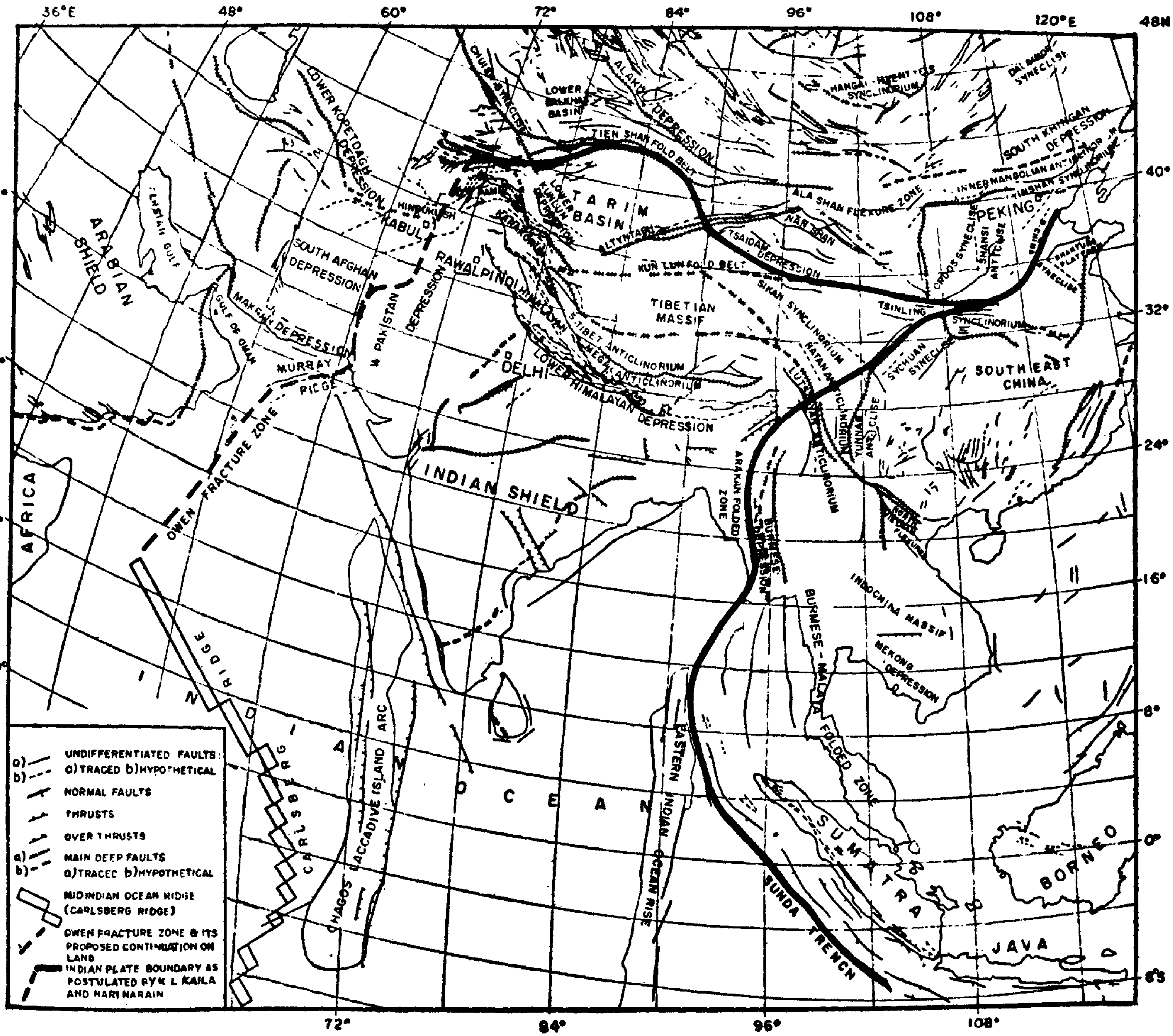
Reconstruction of India, South-East Asia and Australia before break-up and continental drift. The stippled areas are bounded by the continental slope which, for India and Australia, has been taken as the 1,000 m bathymetric contour; for South-East Asia the equivalent boundary varies in depth from about 400 m on the east to 2,800m in the Andaman Sea. Black area is overlap of Australia and South-East Asia (see text), Maps are on Bonne Projection.

MAP 9. Eastern side of India during the Mid-Trias to Jurassic. M. F. Ridd, 1971. North-west Sumatra lies within the Godavari-Krishna embayment, while the Shan plateau is placed next to the Khasi Hills, with no intervening Arakan Yoma, Naga and Patkai Hills.

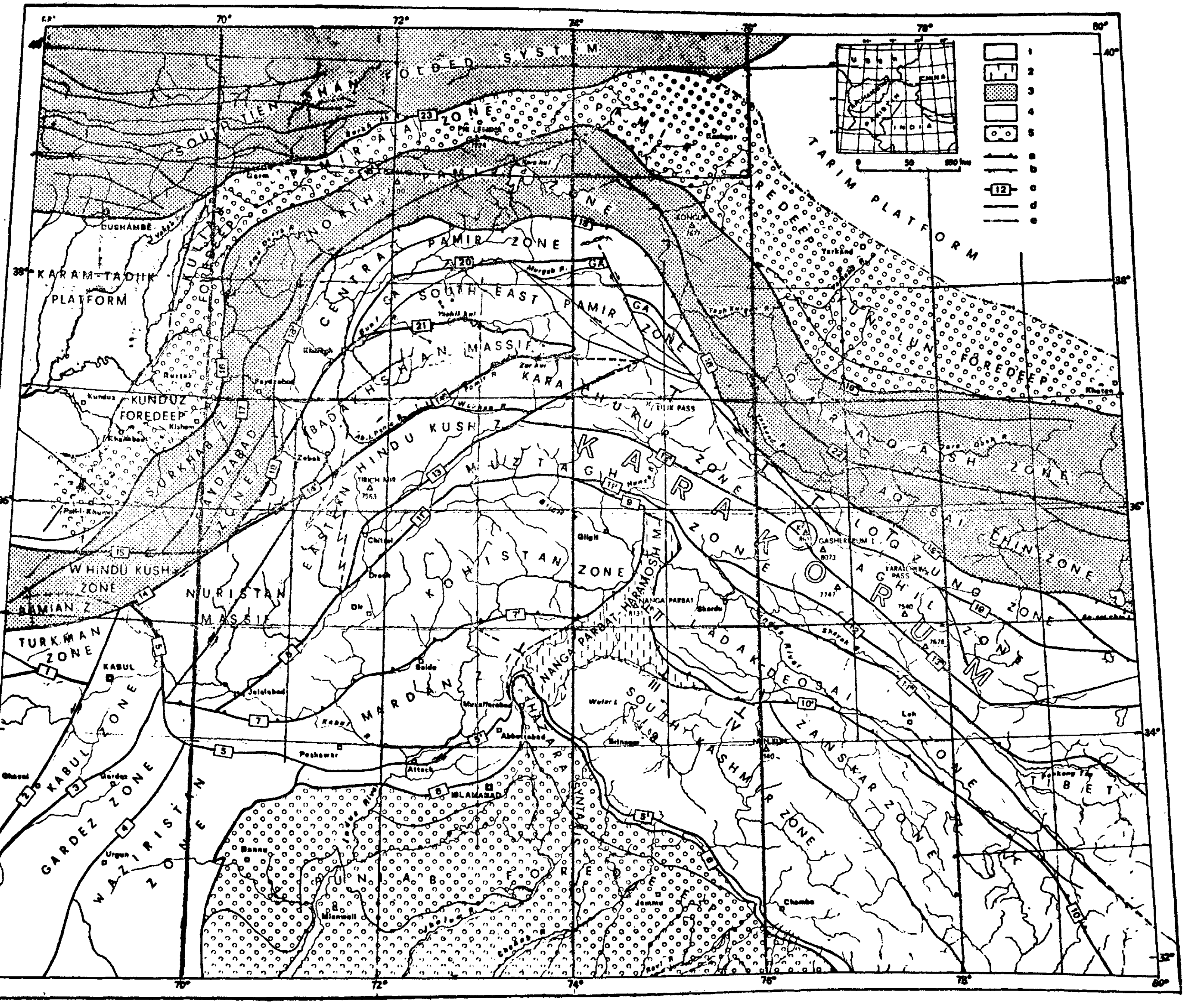
On neither view would it have been possible for Australia or Antactica to have been adjacent to India during the mid-Mesozoic. In his later reconstruction, oceanic crust is shown as dipping under the Andaman-Nicobar-Mentawai island arc from the Cretaceous to the Present, whereas in the 1971 concept it would have been an extension of the Indian continental crust which was subducted towards the east.

Position of Sri Lanka

In one reconstruction, by Veevers, Jones and Talent (1971, 385), Sri Lanka is placed in the Godavari-Krishna embayment, 900km from its present position relative to India. A test boring near 10° 41′ N : 79° 47′ E about 47km to the north of Point Colimore, went through 2300m of Cenozoic, and 1700m of Cretaceous, without



MAP 10. The Indian Plate Boundary suggested by K. L. Kaila and Hari Narain (1976). The Indian plate includes Tibet and extends north as far as the southern edge of the Tien Shan. On both the east and west sides, the boundary cuts across existing structures without displacement.



MAP 11. The highly faulted region between Attock, the Karakoram and the Pamirs, according to Ardito Desio (1979). On present evidence, it is difficult to select a likely northward termination of the Indian Plate, from such a complexity of arcuate faults.

reaching the bottom of the Cretaceous or the Basement (Metre, 1968, p. 36). Unless Sri Lanka had moved from the embayment to its present position before the Cenomanian it would have had to plough through part of the column of sediments found in the test boring. Bearing in mind the widely held view of the extensive northward migration of India from the southern hemisphere since the Cretaceous, Sri Lanka was on this supposition left lagging behind peninsular India, hugging the coast. It is difficult to see the grounds for supposing that Sri Lanka, which is so well attached to India, and went through the same erosion cycles involving the Nuwara Elya, Cardamom and Nilgiri plateaux, could have been a mere floating excrescence with such a tenuous connection with India that it was unable to keep pace during India's northward Odyssey.

Mesozoic India : Northern Extent

The majority of reconstructions in which the Indian plate is figured suggest that the north-south length from modern Cape Comorin was 3,000 to 3,200km, which implies a northern limit to the plate in the region of Chitral, Swat and latitude 35°N. Even if that limit is accepted, it is impossible to select any particular ligation line due to the complexity of the arcuate fault pattern present in the western Karakoram, such as figured by Ebblin and Desio. The region where one might except the collision zone to occur is surely associated with and north of the 700 km long arcuate zone of intermediate focus earthquakes in the Pamirs extending from near Faizabad to south of Kashgar. This zone implies the existence of an approximately 30° south-dipping Benioff subduction belt, the surface expression of which should lie to the north in the region of major shallow focus shocks, close to latitude 40°N. Such a position is some 600km north of the limit given in many of the representations of a migrant India, and is in agreement with that of Kaila and Hari Narain, although I must express reservations about other aspects of their Indian plate boundary (cf. Maps Nos. 10 & 11).

North-East Plate Boundary

These authors have extended the Indian plate northwards to about latitude 42½°, north of the zone of intermediate focus earthquakes. I would suggest, however, that certain parts of the plate boundary run counter to the known geology and topography. On the north-east side, from 29½°N : 101°E to 27°N : 97°E, the suture cuts right across the structural trend. The postulated boundary in China and Burma over a distance of 500km crosses major north-south oriented topography, and within a mere 70km transacts three world-order north-south rivers, the Yangste, Mekong and Salween (close to 28½°N : 99°E), with intervening ridges rising from 5,000 to 7,300m in elevation. The rivers follow the tectonic grain of the country, and the postulated contact of the Indian plate with its Eurasian host would surely have created a major line of rupture oblique to the grain. The ridges, however, follow their course on both sides of the proposed suture line without any indication of a zone of megatectonic collision which, had it been in existence in that area, would inevitably have interrupted them.

In the reconstruction of Kaila and Hari Narain (1976, p. 18), the southern part of the eastern boundary of the Indian plate passes within and then east of the Arakan Yoma, indicative of a fundamental geological divide which is not, however, manifest in the zonal disposition of Brunnschweiler (1974) and in the table on p. 615 of this paper. Stoneley on the other hand draws his boundary right across the well-mapped folds of the Tripura, Lushai and Cachar Hills. Here, there is no question of any mega-tectonic oblique fault dislocating the 150km wide zone of Jura-type folds in Miocene sandstones, shales and flysch over 3,000m thick. There are indeed thrust faults bounding the western sides of many of these anticlines, which have been drilled for oil and natural gas, but these thrusts are part of the local structural development, and have no megatectonic significance.

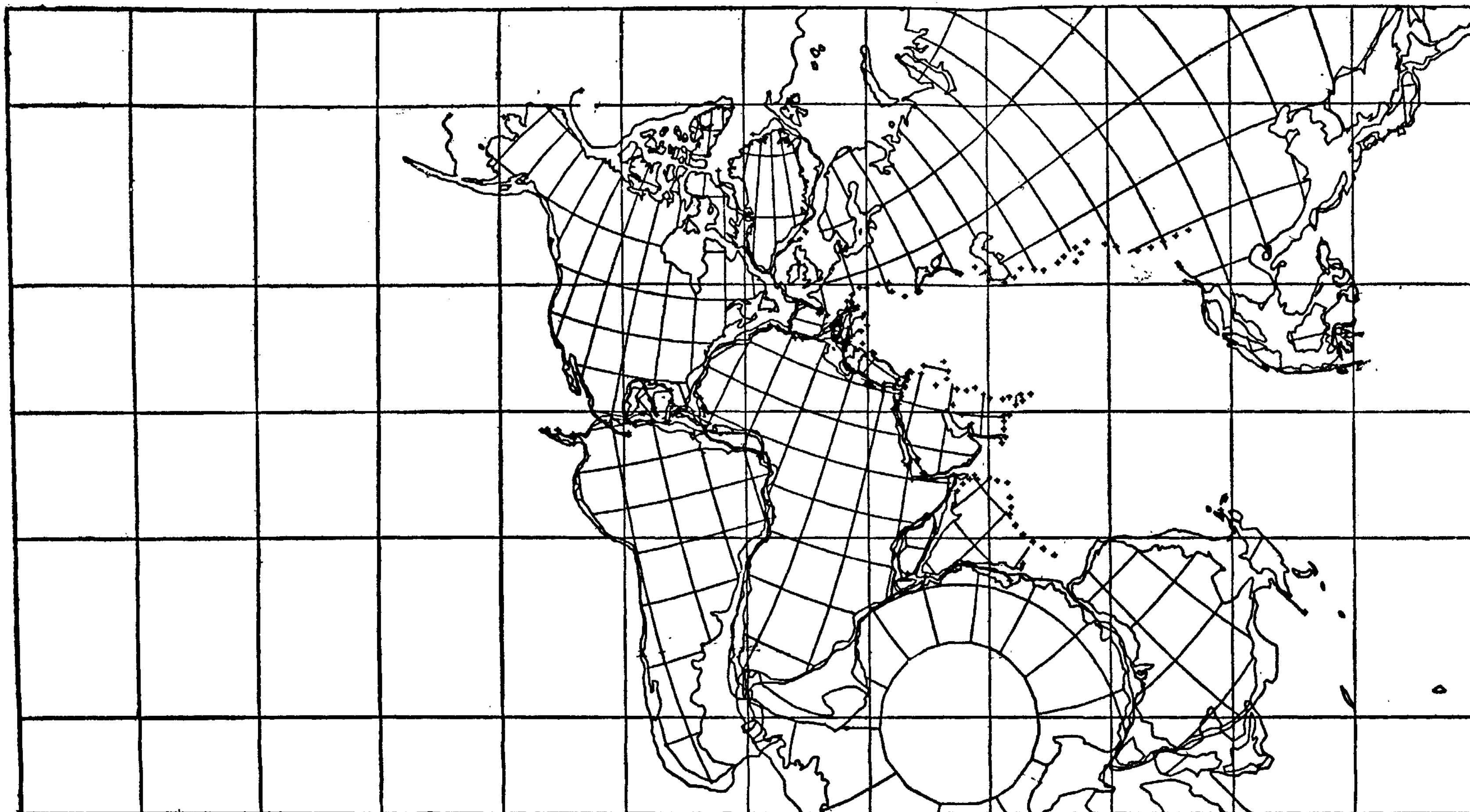
North-West Boundary of Plate

The same geological objections apply, in my opinion, to much of the western boundary of the Indian plate suggested by Kaila and Hari Narain which follows the 70° east longitude over a distance of about 400km without effect on the complicated structural grain of the Hindu Kush and Badakhshan, the Sibi-quetta re-entrant and down the Poralai zone. The really significant fault zone, along which I have suggested a transcurrent movement of some 300km, is the Chaman fault, which may well be a suture line. This fault, which is 900km in length, *runs, however,* 150 *to* 200*km west of the plate boundary indicated by these authors*, and is a conspicuous feature manifest on the air photographs by the abrupt truncation of formations on either side.

Inferred Northern Island Arc

Another interpretation regarding the northern limit of the north-migration Indian crustal mass is provided by Tahirkheli, Mattauer, Proust and Tapponnier (1979, 125–130). These authors propose that the Kohistan sequence covering 30,000 km^2 of amphibolites, metagabbros and volcanics between Gilgit, Kalam and Dir in western Kashmir, represent in island arc which has been underthrust by the Indian crustal unit. The angle of this Main Mantle Thrust, which is shown as passing through Patan (35° 07′ : 73° 01′), is considered to be 20–30° northward from the horizontal. The north side of the inferred island arc is not well defined by the authors, but is represented as a steep fault passing through Yasin and midway between Gilgit and Hunza. This tectonic line should, therefore, be the boundary beetween the Island Arc and the Eurasian continent. It lies, however, 100–200km south of the 700km long arc of intermediate focus earthquake shocks, with focal depth down to 300km below surface, and 400km south of the zone of major shallow-focus shocks with magnitudes greater than 8 on the Richter scale.

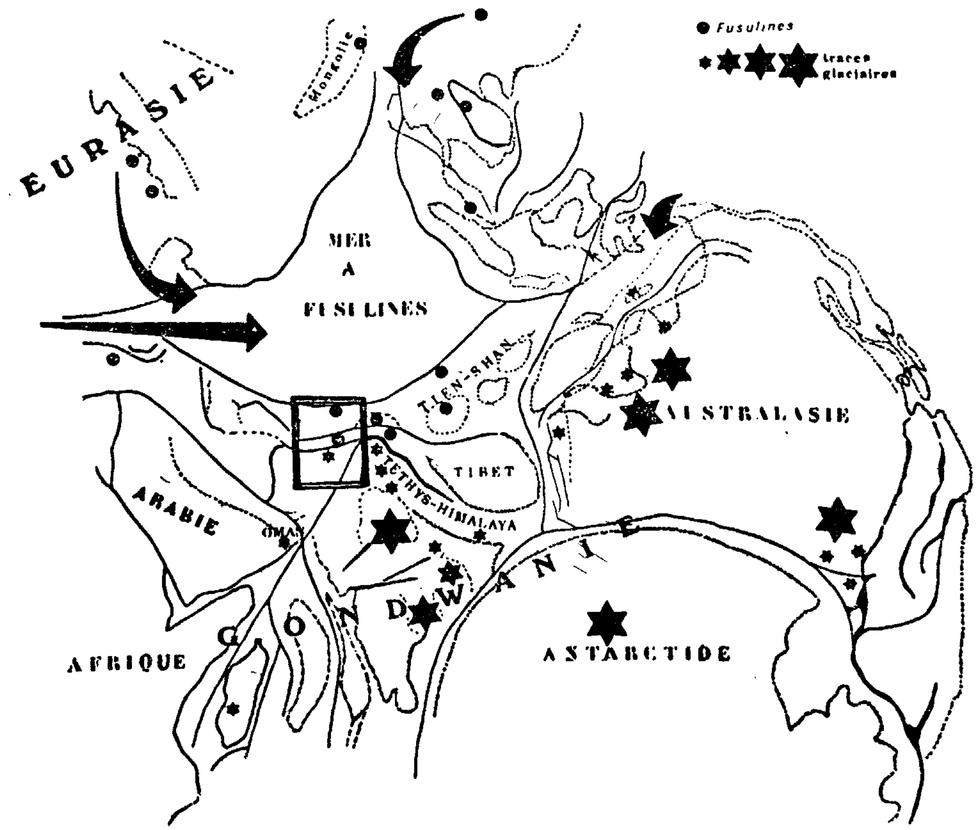
As mentioned on page 618, it is in that region of Soviet Asia, where there is a true Benioff zone, dipping south at an angle which may be 30–40° from the horizontal, as inferred from the depth distribution of seismic foci, that there would appear to the writer to be the more likely boundary between the Indian and Eurasian plates. At its northernmost development the zone passes close to north latitude 39°. The Wanch-Akbaytal of Stöcklin (1977, p. 340) may be interpreted in that light. It lies 270km north of Yasin, close to Ozero Karakul.



MAP 13. India's position during the latest Trias, according to A. G. Smith and J. C. Briden (1977). Madagascar is wedged between the west coast of India and Tanzania, while on the east side the Napier peninsula of Antarctica lies within the Godavari-Krishna embayment. To the north-east and north of the Indian plate occurs an ocean 6,000 km wide, through which India is figured as travelling from the Triassic to the present day *See* Fig. 14.

Termiers' Construction

One more reconstruction (*see* Map. No. 12) may be mentioned which is by the two Termiers, (1977, p. 319). On the basis of the occurrence of signs of glaciation during the early Permian, and of contrasted cold and warm water faunas, they have placed southern India between the Mascarene Ridge, Africa and Arabia on the west, and Antarctica on the east. The northern part of India is connected with the Tethys Himalaya (suggested 46 years ago by the writer), Tibet, Iran and the Tien Shan, all in conjunction bordering a wide Fusulina Sea. As remarked earlier, these authors recognise the existence of the Chagos and Mascarene Ridges between India and Madagascar during the Permian, but they place Burma, Malaysia and Indonesia 3500 to 6000km north of India, with Australia next to Tibet (proposed also by Crawford.) This scheme accepts the presence of most of the units forming the Sunda Arc,



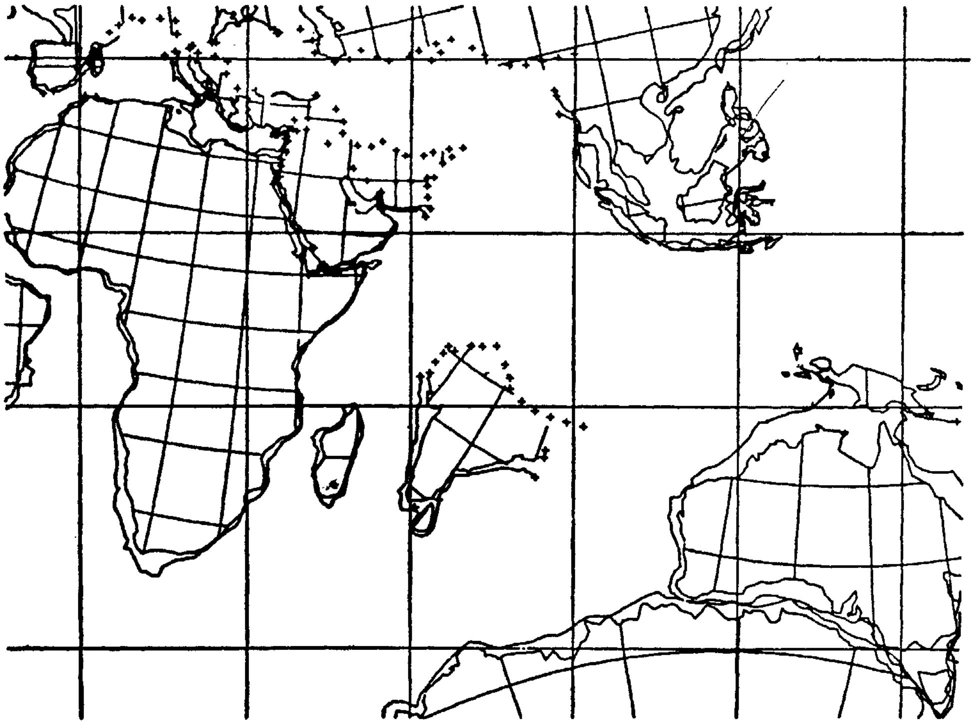
Map 12. Reconstruction of continents around the Fusulina Sea during the Lower Permian by Henri and Genevieve Termier, 1977.

India lies adjacent to the Oman Peninsula and is flanked on the west side by the Chagos and Mascarene ridges and on the east side by Antarctica. Australia lies east to Tibet. The Sunda Arc extends from near Mongolia to north-west Australia over 4,000 km north of India. This reconstruction relates to the Lower Permian, 170 m.y. before India is considered by Powell to have been situated with Cape Comorin at 30°S.

including the Sahul craton, but disengages the northern part of the arc entirely from India. It would require a clock-wise rotation of the Sunda Arc, Australia and Antarctica of at least 6000km in order to bring Burma into its present position relative to India and the northern end of the arc.

India's Northern Odyssey

The 6000 to 6500km journey of India from the southern hemisphere since the Cretaceous figured by Powell (1979, p. 10) (*see* Map No. 1) with average progress of 9 cm/year, has already been discussed. There remains to consider the series of figures prepared by Smith and Briden in their Atlas of Mesozoic and Cenozoic Paleocontinental Maps. In these maps, (1977, 12–24) from early Triassic to the present day, they have indicated the progressive break up of Panjea, with the release of India, from having been wedged between Madagascar and Antarctica, across an unnamed ocean the size of Africa, virtually the same as the Panthalassa of earlier



MAP 14. India's position during the late Cretaceous. Smith and Briden (1977), reproduced by A. R. Crawford (1979), who commented on the complete isolation of India. In both figures 13 and 14 the Sunda Arc is shown as belonging to Eurasia, but without links to New Guinea and India, which could have exerted no control over the arc formation. The southern limit of central Eurasia, and the eastern edge of Iran-Afghanistan, are shaped, as if in anticipation, to receive the northern limit of India as it travelled its solitary route, without neighbours, through the wide ocean over a period of about 100 m.y.

writers. India and Sri Lanka are given a north-south length of 3300km and an east-west breadth of 2400km and the northern limit of India has the shape of the modern land south of the Himalayan mountain system. On the northern side of this great ocean, the southern boundary of the Eurasian plate already has the shape to permit the migrant India to dovetail into the Eurasian module. It is difficult to envisage that India, moving northwards over such a great distance as an isolated continental mass, with its own structural grain, could finally fit neatly into the loose ends of structure in Eurasia, and then that these disparate units should be so welded together that recognition of the ligation has not yet been definitely established in the field. It would be expected that in the case of a far-travelled Indian plate, docking so to say within the Eurasian module, there would be not only great disturbances, but also the juxtaposition and truncation of masses totally alien in nature and divergent in structure. Instead, in many areas the proposed plane of ligation transects identical bordering formations, as if there had always been a common history of deposition of the originally far-separated units, which eventually coalesced along the collision zone, with unification of their once disparate heritage.

Sub-Crustal Penetration

Crawford regards Tibet as having been a shallow epicontinental sea on continental crust which is an extension of the Indian plate, and suggests that the real suture line between India and Eurasia is along the Tien Shan. As mentioned earlier, Veevers, Powell and Johnson (1975, p. 386) consider that the ophiolite belt along the Indus and Tasng-po headwaters of the Brahmaputra does represent the surface expression of the suture between India and Eurasia, but they suggest that the Indian plate has underthrust the Tibetan crust as far north as the Kun, Lun, Astin Tagh and Nan Shan mountain belt. This would explain according to these authors the abnormally thick crust of 70km under Tibet. Such a concept of sub-crustal penetration requires a horizontal latitudinal underthrust of some 12°, 1300km, at modern longitude 95° E, for no inclined Benioff zone exists along the Himalayan front. This would indeed be a cosmic phenomenon. Stoneley includes the Indus line in his diagram, and like Crawford evidently accepts it as an important structural feature, but he places the edge of the Indian plate approximately along the north edge of Tibet.

Manifest Fault Zones

Two fault zones may be considered as possible lines of intercontinental union, the Indus fault, with its eastern extension of the upper Tsang-po, and the Chaman-Ornach fault system. Gansser has long considered that the Indus fault is the suture between the Indian mass and Eurasia. There is a considerable body of opinion, however, that regards the Indus fault as a deep fracture within the Indian continental crust, but not as the termination of the Indian mass.

The Chaman fault of Pakistan and Afghanistan is certainly a major feature, along which Eocene-Oligocene flysch has been highly sheared, and a sinistral movement of perhaps 300km may have taken place, based on what appears to be offsetting of the flysch zone. The fault may also represent a faunal barrier, although the principal barrier, between the cold-water Eurydesma sea and the Fusulina sea, appears rather to have been oriented east-west approximately along the present Oxus or Amu Darya. On both flanks of the Chaman fault are important outcrops of ultra-basic rocks, such as at Shuidar and Hindu (now Muslim) Bagh, and between Kandahar and Spin Baldock. It should be noted that these ultra basics are at latest Cretaceous to Palaeocene in age and, as they are clustered in proximity to the narrow zone affected by the Chaman and Ornach faults, to which they are probably related, it is reasonable to assume that the fault was in movement at that time. Consequently, the crustal blocks on either side of the fault may be inferred to have been in proximity at the end of the Cretaceous, although in my view they were then in different relative positions. In the map of Smith and Briden, Pakistan and Afghanistan were still separated by about 3000km during the Palaeocene, and the ultrabasics in Afghanistan and Pakistan, on opposite sides of the Chaman fault, would have been unrelated to the collision, considered to have occurred during the late Miocene or early Pliocene.

East-West Symmetry

There is a symmetry between the zones bordering the east and west sides of the Indian sub-continent, from the Shan plateau to the crustal blocks of the Dasht-i-Margo and Lut in Afghanistan and Iran (Auden, 1974, p. 243). The zonal sequences are comparable, each side with cratonic shields, volcanic line, axial zone with melange and ophiolites, thick flysch, mud volcanoes, and occassional severe seismicity. The older flysch formations of Disang and Khojak, mainly of Eocene age, are both in certain areas partially metamorphosed.

On the east side, the linkage between the Shan Plateau and Himalayan crystallines is near the trijunction of India, China and Burma (28° 13′; 97° 21′) and Putao (27° 20′ : 97° 26′), and the Himalayan crystallines form part of peninsular India. The Eurasian basement of Burma, and the Himalayan crystallines which belong to the Indian peninsula, are in juxtaposition and form the framework to the Indo-Burman zonal complex.

This disposition is not in accordance with the current concept of an Indian crustal unit migrating across a wide ocean towards Eurasia since the Cretaceous, with what must have been a totally independent development of sedimentary basins connected with far-separated and unrelated shore lines. On the supposition of far migration, these basins could only have coalesced since the Plio-Pleistocene into the Indo-Burman and Makran zonal complexes. The inference is that throughout the Mesozoic and Tertiary the Indian and Eurasian crustal units were in sufficient proximity to exert a common influence on sedimentation of the intervening zones and geanticlinal development of the axial ranges.

Discussion

Five years ago, in the controversy about the position of Madagascar *vis a vis* Africa, P. J. Smith considered that on the basis of paleomagnetic pole positions the issue had been finally settled and that Madagascar must originally have been located in the Tanzania embayment 1700km north of its present position. He continued:

> 'Any geological "anomalies" must now be reconciled with Madagascar's northern origin : they can no longer be regarded as convincing evidence against it.'

> Conclusions drawn from geophysical data, were taken therefore, to have precedence over those obtained from geological observations. Qualitative geological information could not contradict the conclusions drawn from palaeomagnetism.

Referring not to palaeomagnetism but to computer fits, Tarling and Tarling wrote (1979, p. 32) :

> "...the areas where the continental edges are clearly defined fit remarkably well; so well, in fact, that (it) is impractical to explain the fit in any other way than that they once formed a huge continent which has subsequently been fragmented."

This computer fit is reinforced in the case of South America and Africa by the polar wandering curves, and it is difficult to do other than accept the probability that these two continents may have been in juxtaposition.

When it comes, however, to the possible positions of the continents now bordering the Indian ocean there is much less certainty, and it is with some of the very varied interpretations that we have been concerned.

Tarling and Kent (1976, p. 304) pointed out that Mesozoic sediments had been found by reflexion seismic survey to be present in the very place where Madagascar is supposed to have been at that time. This is a similar argument to that which I used in 1972 in regard to the postulate of P. Evans that the Shillong Plateau had migrated some 200km eastwards, for Gondwana sediments are found at Singrimari at the west end of the plateau in an area which by hypothesis was thought to have been occupied during Permo-Carboniferous times by plateau basement.

Palaeomagnetism and Diagenesis

Hence, there are seen to be discrepancies between the conclusions drawn from palaeomagnetism and from geology, and exponents on both sides have to be careful not to issue anathemas. Tarling and Kent indicated possible sources of error in the palaeomagnetic data. They suggested that the observed remanence is complex and that thermal and alternating magnetic field de-magnetisation may not have effectively separated the different magnetic components. Detrital grains in sediments may be changed during diagenesis, particularly in the case of haematisation, which may be delayed for 100 m.y.

Turner (1979, p. 289), in discussing the palaeomagnetic evolution of continental red beds, has shown that in many instances magnetisation has little or no connection with the depositional age of the rocks, much of the magnetisation being acquired over a long period of time and after considerable changes in the ambient magnetic field.

In some cases, magnetisation represents the ultimate end product of the diagenetic evolution of the red beds, a process lasting millions of years.

These conclusions refer to red beds, but it may be supposed that most rocks undergoing diagenesis and metamorphism may show the modifying effects and overprint arising from magnetisation long subsequent to the time during which they were actually deposited or intruded. It would be interesting for example to determine the palaeomagnetic properties of the Khojak Shales in Pakistan, known to be of Eocene-Oligocene age, but now presenting a fracture cleavage which is so intense that it obscures the true bedding planes.

While there can be no doubt of the great relevance of geophysical data to the understanding the geological processes, it must also be allowed that stratigraphical and palaeontological data, much of it not expressible in mathematical terms, are also of critical importance, notwithstanding the somewhat dogmatic statement of P. J. Smith.

Palaeontological Data

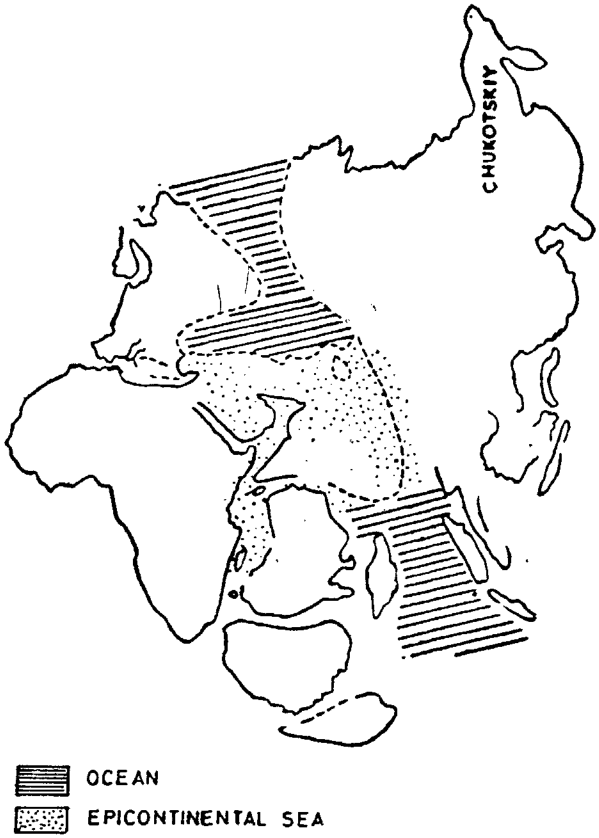
The palaeontological problem has been ably discussed by Professor F. Ahmad in his *Birbal Sahni Memorial Lecture* four years ago. He concluded from the distribution of fauna and flora that the so-called Gondwanaland extended into China and Siberia at least until the Triassic, implying that land connections must periodically have existed between India and the north across the Tethyan epicontinental sea (Map No. 15). Crawford, while adhering to his view that Madagascar formerly lay against the continental shelf of India, stresses the discovery of Permo-Triassic vertebrate fossils of Gondwana type in the Tien Shan and Turfan basin, and cites Colbert's conclusion that the Indian dinosaurs of early Triassic to late Cretaceous times necessitate land communications between India and the Eurasian continent (1979, p. 108).

Kamen Kaye (1978) in a detailed analysis of the Permian to Tertiary faunas between Somalia, Madagascar and South Africa indicates that pelagic waters existed between Madagascar and Australia in Aptian time, rendering it unlikely that India could have existed attached to Madagascar and interrupting the faunal migration route between Madagascar and Australia. It should be noted that these pelagic waters would not be the Tethys, which has always been regarded as lying north of India in its supposed southern position. On the contrary, the pelagic waters represented the proto-Indian ocean south of India.

In contrast to the palaeontological evidence, palaeomegnetism has led Smith and Briden (1977, p. 24) to indicate that during the early Triassic, (220 m.y.). India was wedged between Madagascar and Antarctica, and the northern limit was separated from Eurasia by 50° to 70° of latitude occupied by the Tethyan ocean, or approximately 5500 to 8000km if the earth then had its present dimensions.

Conflict of Evidence

There is, thus, a manifest conflict of evidence and it is unsound to claim the certainty and finality of palaeomagnetic evidence when the physical phenomena are



MAP 15. Permian Palaeography as deduced by F. Ahmad (1978). Compare with Map. 2. The southern part of India is close to Somalia, and a shallow epicontinental sea separates India from Eurasia. This disposition is comparable to that of the Termiers (Map. 13) except that Australia is not located next to Tibet but is placed by Ahmad within the Godavari-Krishna embayment, and Antarctica is separated from India by the whole width of Australia.

themselves liable to revised interpretation as more data about the size and changing internal status of this planet become available, and more is known of the effect of diagenesis and metamorphism subsequent to the magnetisation of the rocks as they were originally formed.

Pre-Cretaceous rocks are now present in areas which were, according to many authors, occupied by Antarctica and Australia during the Cretaecous. It is difficult to conceive how these older rocks could replace two large continental masses and create a totally different structural pattern inherited from their previous pre-emplacement environment.

The present coast lines and continental-shelf edgs make a convenient apparent but, it is suggested, often deceptive, termination of continental crust, along which attempts can be made to match the outlines of reciprocal coast-line features. It is a different matter away from the coasts, where the locations of continental masses are by supposition replaced by other masses with no residual palimpsest or outline to mark the former configuration of the departing continents.

While Australia and Antarctica, covering 22 million square kilometres, are assumed to have left Tibet and India, Palaeozoic and early Mesozoic rocks must have moved in to take their place. Manifestly, the Bayar Kara Shan triangle 500,000km^2 in area centred on 32° N : 101° E, and largely comprising Triassic rocks with long narrow intrusions of granite could not have been in their present relative position *vis a vis* India if Australia had actually been occupying that space.

Simultaneously, Antarctica, with a radius, of 2,000km and part of which coast line is supposed to have been adjacent to the Madras embayment, must also during the Cretaecous have covered on this hypothesis what is now Burma, Malaysia, Thailand, Sumatra and Viet Nam, each area with its own long geological history pre-dating the Cretaceous when their present positions were supposed to be occupied by Antarctica. These complex areas may, too, have moved since the Cretaceous, but from where ? Antarctica would have overlapped the northern half of the Sunda arc, the development of which, however, began as a megatectonic entity during the Laramide orogeny, involving the whole space between Burma and New Guinea, without the obstruction of a land mass 13 million square kilometres in area. It would be sounder perhaps to assume that the present configuration of geological formations between India and the China Sea is the result of indigenous processes that were operating *in situ*, and that neither Australia nor Antarctica was in the usurping position postulated for them during the Cretaceous. It is true that folding and thrusting have modified the original zonal relationships which now characterise the Sunda arc, and that strictly it is impossible to suggest that any development along an orogenic belt is *in situ*. It is reasonable however to use that term broadly for processes which occur in a well-defined group of zones in contrast to the contortions necessary to bring the Sunda arc to its present position if New Guinea were really opposite to the Tarim basin at the end of the Mesozoic.

Coming to the Indian Ocean, a related argument may apply to the Mesozoic and Cenozoic rocks proved by deep-sea drilling and indicated by magnetic reversal profiles, to exist in the Indian Ocean. The UNESCO Geological Atlas of the World shows four major development of Cretaceous rocks, in aggregate about 22 million km^2 in area separated by activity along the Carlsberg Ridge, and its off-shoot, and by evident transcurrent faulting along the 90 degree East ridge. In addition, there is an important occurrence of Jurassic rocks between the nort-west cape of Australia and Java. On the assumption that Antarctica and India were closely adjacent during the Cretaceous, the immense spread of Cretaceous rocks in the Indian Ocean could only have developed after the crustal masses had become progressively separated. Alternatively, the sub-marine Cretaceous formations may have been deposited, without the postulated presence of Antarctica and Australia in immediate proximity with India and Tibet, and in continuity with the visible Cretaceous outcrops of Trichinopoly, Assam, Arakan Yoma, and the Andamans. The Jurassic found in deep sea drill hole 261 between Australia and Java is important because, being in the path between Australia and Tibet, it would not have survived the later Mesozoic migration of Australia from eastern Tibet to its present position. Deeper holes are required to penetrate below the so-called basalt basement, located in many of the existing borings, and determine what lies underneath the basalt.

Vertical Movements

The long-continued emphasis on horizontal movements of crustal masses has tended to obscure the importance of vertical movements. The classic case of an area of the crust which has been subject to vertical uplift is that of the Himalaya and Tibet.

Tibet has been the subject of detailed investigation by Chinese scientists, various papers having been read at a recent symposium in Beijing (Peking). A brief summary by Liu Tung-Sheng and Sun Hung-Lieh has just appeared in the *Geographical Journal* **147**, 23, 1981, after the author's Wadia lecture had been given. The *Hipparion* fauna found in Xizang (Tibet) implies that even in the late Tertiary the plateau may not have exceeded 1,000m in elevation, and that three successive periods of uplift at the end of the Pliocene, during the last 100,000 years, have raised the plateau to its present level at the rate of 10 mm/yr. That uplift is also manifest in the Himalaya, south of the watershed, for river terraces which are clearly part of the present river system are found as high as 500m above present valley bottom (Wadia & Auden, in Dunn *et al.*, 1939, p. 139). The Tibet plateau has an area of approximately 2,400,000km^2, but if the Himalayan zone and neighbouring ranges are included, the total area subject to recent uplift may be not less than 3,000,000km^2, with radius of almost 1,000km had the area been circular. This is a megatectonic phenomenon, however it is to be explained. The immense upraised plateau is too vast to be considered as a mere peripheral bulge adjacent to the narrow Gangetic sedimentary depression.

In contrast, there is abundant evidence throughout most continents of deep sedimentary basins. with the basement crust sunk thousands of metres. The Basement. and Rajmahal volcanics of Lower Cretaceous age. crop out in Bihar but are some 8 to 9km below sea level near Dacca 300km to the east of the outcrops. On the edge of the continental shelf west of Bombay, there are 6km of Cenozoic sediments overlying Deccan volcanics and pre-Cambrian basement. This basement in fact extends further off-shore to a distance of 400km from the coast line. The narrow Cambay graben, only 50 to 80km wide, involved rift faulting which has brought down the top of the Deccan lavas to a depth of 6km below Broach. These are just two examples of crustal depression, involving the east and west sides of the present coastal configuration of India. It should be stressed that the Deccan lavas are associated with coal-bearing Ranikot (Cretaceous-Palaeocene) sandstones in Sind, and were subject to contemporaneous lateritisation in Maharashtra, Kutch and Sind. They were, therefore, for the most part terrestrial in origin, and not the products of deep-oceanic eruptions. Hence their depth below sea level is due to subsidence by tilting and faulting.

Within the continental areas as at present exposed above sea level, there is evidence for regional sinking of the basement. The question also arises whether or not certain areas of the ocean floor may represent cratonic crust that once existed at the surface and has since sunk below sea level. These would represent concealed extensions of the continental c ust developed beyond the areas of the present continental shelves, and the shelf edges as now developed would not be the limits of the continental crust against which now distant crustal masses could formerly have been in juxtaposition. If such sunken continental crust exists over some areas of the Indian Ocean, it would negate attempts to bring existing shelf edges of now distant surface geographical units into juxtaposition during the Mesozoic by horizontal migration. Quite regardless of the problem of the Mascarene and Chagos Ridges intervening between Madagascar and India, it has been suggested above that Madagascar could not have been closer than to the west coast of India than 400km because of sunken continental crust.

The basalt encountered at the base of many of the DSDP holes is likely in many instances to be a lava, or a sill, connected with neighbouring continental volcanic environments, and not the topmost layer of the mantle. A beautiful example of a thick sill intruded in the Beacon Series is figured by Holmes and Holmes (1978, p. 36) from the Taylor Glacier, Antarctica (160°E : 78°S).

The recent seismic reflection profiles in the Indian Ocean SSE of Cape Comorin and just south of the equator, are considered by Weissel and co-workers to represent basement deformation, which they regard as oceanic crust (1980, p. 286). The faulted folds which are figured on pp. 287–88 are identical in form to those profiled by R. S. White along off-shore Makran (1979, pp. 297, 298 and 300). These Makran profiles represent with fair certainty tectonically disturbed Cenozoic sediments. The Cenozoic inland, and just north of the Makran coast, is some 8km in thickness. It is possible, therefore, that the structures figured by Weissel may be in continental crust rather than in oceanic crust, and that they may be a sunken cratonic crust in the Indian Ocean 1200 to 1600km SSE of Cape Comorin.

The location by Harbison and Bassinger (1973) of a Basement ridge 400km offshore from the west coast of India, and regarded as part of the Indian peninsular crust; has already been noted. This ridge, and the basement between it and the Indian coast, has sunk, carrying with it zones of sediments. Taken in conjunction with the possibility that continental crust has also sunk in the region S. S. E. of Cape Comorin, the presence of these areas of down-faulted crust is relevant to the problem of continental migration. The present edges of the continental shelf in parts of the Indian Ocean may not in fact represent planes of separation between continental masses that had formly been united, for they were not the original limits of the Indian peninsular crust.

Conclusions

An attempt has been made to demonstrate the numerous conflicting continental assemblages around the Indian Ocean during the Mesozoic. However perfect the fit may be between South America and Africa, there is little agreement regarding the former distribution of continental masses which now form the perimeter of the

Indian Ocean. Some of the Mesozoic jigsaw puzzle groupings would appear to have been bassd on the wilder shores of improbability. A cardinal factor, which is often omitted during attempts to reconstruct Panjaea, is the existence of vertical movements. Such movements, taken in isolation as a single vector, do not solve the problem of mountain ranges, but they surely need to be considered in attempts to play-back the present-day configuration of continental shelves to fit Mesozoic and older cratonic masses.

It is seen that the suggestions regarding configuration based on palaeomagnetism, faunal and floral distribution, tectonics, and other geological considerations are extremely varied and tentative. It would seem, however, from the above discussion that there is considerable support for the view that India may have been throughout the Phaneozoic close to Eurasia, whatever immediate crustal neighbours it may then have had.

The idea of an immense ocean between India and Eurasia is probably untenable. In contrast, there may have been an epicontinental sea, as advocated by Ahmad. Crawford in his latest paper (1979, p. 7) has come out strongly against the myth of a vast Tethys Ocean. He has also, following Carey, suggested the importance of the idea of an expanding earth, pointing out that what on a non-expanding earth is a movement of a crustal block becomes on an expanding earth a change of parallel of latitude. Since crustal tectonics demand relative movements of crustal blocks, an expanding earth adds another vector as distances between latitude increase[1].

The existence of the formidable mountain systems bordering the Indian subcontinent necessitates movements, but the problem is to determine the scale of the movements. If the migration of India over a distance of 6500km during the last 70 million years is excessive, and contrary to much geological knowledge, what would be accepted as a likely magnitude of movement of crutal plates, bearing in mind the manifest fore-shortening within the Himalayan and related chains ? Expansion along active oceanic ridges, such as the Carlsberg and mid-Atlantic, is regarded as established. The Benioff zones next to the Tonga and Mariana trenches, Indonesia, Pamirs, Greece and the eastern border of the Pacific Ocean, are considered to represent the subduction of lithosphere that is being forced down and under other crustal plates. The convolutions of the island zones in the Banda Sea imply rotational movements between coupled forces. All this indicates mobility and extensive movements, even though not on the scale required by some exponents of telemigrations.

It has been suggested above that some of the combinations of continental masses which have been proposed appear to be improbable. This does not mean that the continents around the Indian Ocean were distributed during the Mesozoic in their present geographical locations, but solely that the right agglomeration of continental

1. It may be wondered how significant expansion is in the matter of interpreting migration of crustal blocks. Holmes (1971, p. 704), basing his figures on Strahov's maps, adopts a radius of the earth 600 m.y. ago of 6130km, the present mean value being 6371km. A radius of 6130km implies a circumference during the Eo-Cambrian of 38516km, as compared with 40030km at present. One degree of latitude 600 m.y. ago would then have been 107km, only 4km less than the present value.

units, which does no offence to the geological histories of the different components, some of which have been almost ignored, does not yet appear to have been deciphered. It would seem to the author that India has had a relatively close association with Eurasia throughout the Phanerozoic, notwithstanding the allowance which must be made for crustal shortening during the formation of the Himalaya.

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Note : Maps numbered 3, 5, 6, 8 and 9 in this paper include both the original comments of their authors as well as those underneath which are by the writer.