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The Indian Ocean and the Himalayas

A Geological Interpretation

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with 4 figures in the text and 2 plates (I and II)

ABSTRACT

The recently discovered lineaments of the Indian Ocean indicate a northwards shift of the Indian Shield which is directly responsible for the Himalayan Orogeny.

The western and eastern N-S-directed major lineaments in the northern Indian Ocean continue on land into the Quetta Line (W) and Arakan Yoma Line (E) which are related to the western and eastern syntaxial bends of the Himalayas.

The tectonic analysis of the Himalayas suggests a crustal shortening of at least 500 km, which corresponds to the minimum amount of northwards drift of the Indian shield that is indicated by the physiographic pattern of the Indian Ocean.

1. Introduction

During the past few years the International Indian Ocean Expeditions have produced such a wealth of most interesting and some quite unexpected results that one of the least known oceans has now been turned into one of the best known. A compilation of these results is reproduced in the Physiographic Diagram of the Indian Ocean (Heezen & Tharp, 1965a). This diagram is accompanied by a bathymetric sketch-map of physiographic provinces, which, together with the general chart, give a reasonable picture of the morphological configuration of the floor of the Indian Ocean.

Away to the north of the Indian Ocean there towers the highest mountain range of our globe – the Himalayas. These in turn border against the most extensive elevated areas of the continental land surfaces – the Tibetan Plateau. An up to date compilation of the geology of the Himalayas has been published recently by the author (Gansser, 1964).

The regional structural picture of the Himalayas with their adjoining ranges and the newly discovered physiographic pattern of the Indian Ocean show surprising features which indicate that some genetic relationship must exist between the configuration of the Ocean floor and the building of the Himalayan chains. This relationship and its geological consequences are discussed in the following. We are fully aware that the information we have so far from the sea floors and also from parts of the land areas is still so vague that only the broadest of concepts can be given, and even this may be prone to drastic alterations once additional data are forthcoming.

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2. The structural analysis of the Indian Ocean

Based on the latest information about the Indian Ocean by HEEZEN & THARP, 1966; LAUGHTON, 1966 a, b; MATTHEWS, 1966, and others we can distinguish two main structural features:

1. Broad oceanic ridges with the marked trench on their crest. They are characterized by seismicity, magnetic anomalies and frequently abnormal heat flow. Topographic and magnetic lineations run parallel to the trenches. The broad oceanic ridges can be connected with the Mid-Atlantic ridge, with which they may be compared in most of their details.

2. The oceanic ridges are clearly cut and partly displaced by surprisingly straight mostly N-S directed lineaments, which occur as long narrow ridges or as sharply pronounced deep fractures. The latter type is well outlined where they intersect and displace the oceanic ridges, and they can reach depths of 1000 m below the surrounding abyssal plains. Some of these fracture zones, such as the Ninety East Ridge, form the longest straight lineaments known on our globe (4800 km) and were totally unknown in this magnitude prior to the Indian Ocean investigations. It is interesting to note that these huge N-S lineaments are unknown in the other oceans of the world. Compared to the oceanic ridges, the fracture zones show only a limited seismicity, or none at all, and also the heat flow and the magnetic anomalies are much less pronounced.

When mentioning these anomalies we must, however, realize that quite apart from the scattered and still scanty nature of the information, we can assess only the most recent effects. This is specially true for the so-called seismicity, which is outlined by plotting the epicenters of the known earthquakes and which can be only a sketch of the seismic activity of the last 100 years. Such a picture may be quite different from that of the previous 100 years, and certainly has a greater chance of differing from that of the period which interests us most, namely the interval from the end of the Alpine-type orogeny to the present day. The differences between earlier anomalies and those recorded by recent research may be especially strong for the fracture zones, which from all appearance are features which were formed rather rapidly and have not been further reactivated. On the other hand, the oceanic ridges, which are certainly much older than the fracture zones and which correspond to a world-wide lineament pattern, are, regardless of an assumed genetic relationship, still slowly active. This fact is emphasized by their vulcanicity, though it is not so clearly established in the Indian Ocean.

The relationship of the seismic epicenters and the Indian Ocean lineaments is presented on Plate I. Modern plotting methods will eventually show that the coincidence of lineaments and seismic epicenters is much clearer than is so far indicated, in spite of some adjustments which have already been made. The coincidence on the land areas, where the scatter of the seismic points is still rather wide, will also become much clearer.

The Indian Ocean Ridge spreads into three branches in the central part of the ocean, one connecting westwards with the Atlantic Ridge, one to the southeast into the southeastern Indian Ocean south of Australia, and a northern one which continues into the Gulf of Oman and then divides into the Red Sea and the East

African rift systems (LAUGHTON, 1966 a, b). All these branches are cut by the more or less north-south running fracture zones, and in most of the intersections a marked displacement of the ridge by the younger fracture zone is visible. At many of the intersections deep, fault-like depressions reach down below the level of the surrounding ocean bottom. Similar depths of water have also been observed where faults dissect the Mid-Atlantic ridge just north of the Equator. The sharp, often 1000 m deep depressed features have not yet been filled by sediments; this points to their young age, and also indicates scouring by deep-water circulation between basins otherwise separated by the oceanic ridges (HEEZEN & THARP, 1965a; MATTHEWS, 1966). Several such N-S aligned fracture zones cut the Indian Ocean ridges in the southern part of the Ocean. All indicate a clearly defined northwards drift of the central portion of the ocean floor, with a left lateral shift along the western fractures and a right lateral shift along the eastern ones. These displacements are well supported by the stepwise north-shift of the Mid-Ocean Trench (Plate I).

In the northern Indian Ocean three main fracture lines indicate lateral shifts. In the west the Owen Fracture Zone, with a right lateral movement where it cuts the Carlsberg Ocean Ridge, indicates movement in the opposite sense (younger or older?) in its southern continuation (E of Madagascar) and possibly also along its northernmost extension. Here the Owen fracture continues into the Murray Ridge, and evidence from the land suggests again a left lateral displacement²). It seems evident that changes in the direction of shift on one and the same lineament may reflect different phases of activity, most probably involving large displacements but geologically speaking of only short duration.

Further in the east, the Chagos-Laccadives Ridge is another sharply outlined feature which seems to form in its northern part the western edge of the Indian Shield. Similar to the Owen Fracture Zone, it trends towards Karachi, where the Murray Ridge joins the land area. Displacements along the Chagos-Laccadives Ridge are not evident, but the regional configurations suggest a left lateral shift along this zone with a northwards drift of the Indian continental area.

The most surprising lineament of the eastern Indian Ocean is the Ninety East Ridge, a straight, N-S trending feature which can be followed from the central Indian Ocean for 4800 km to the north. In the south it cuts and delimits the huge Diamantina Fracture Zone which trends from the south of Australia as a major E-W feature towards the central Indian Ocean. In the southern part of the Ninety East Ridge a right lateral shift is evident, and is underlined by the displacements along subordinate lineaments that parallel the eastern Indian Ocean Trench.

The whole area framed between the western and the eastern N-S fracture zones seems to have been drifting northwards. This large portion of the globe includes not only the central part of the Indian Ocean floor with its older Mid-Oceanic Ridge system, but also the area of the Indian Shield. This picture is well visible on Plate I. The remarkably straigth, N-S directed younger lineaments leave little possibility of a westwards or eastwards drift since the time of formation of the Mid-Oceanic

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²) See also SNELGROVE (1964). His Indus Lineament would not, however, coincide with what I have called the Quetta Zone further to the west, and which would correspond to the main lineament on land.

Ridge. The clarity of the picture is unique and seems to be unrepeated outside the Indian Ocean.

Within the Indian Ocean, the marked differential northern drift seems to be responsible for the «dismemberment» of the eastern extension of the African continent. Madagascar, though still attached to Africa by abnormally thick Permian and younger sediments (PEPPER & EVERHART, 1963), is sharply cut along its east coast by lineaments that run parallel to the Owen Fracture Line. The Seychelle Islands, which expose granitic rocks that have been dated as 700.10^6 years old, are completely torn apart. The Seychelle bank is of continental type crust and the Moho (8,2 km/sec velocity) 30 km deep. The bank is bounded by steep faults and the adjacent deep sea floor is truely oceanic; just west of the Seychelles the crust below a depth of 5000 m water is only about 2 km thick, and is one of the thinnest parts of the crust so far known (LAUGHTON & MATTHEWS, 1964). Sea bottom photographs show well recognizable pillow lavas and patch sands with strong ripple marks (LAUGHTON, pers. com.). Unfortunately the published information of bottom samples from the Indian Ocean is still scanty, and from the few scattered sources it is not yet possible to understand the distribution of the ocean bottom lithology. Scattered sialic rocks are probably more frequent than has been suspected. Of special interest are some samples obtained from parts of the Mid-Oceanic Trenches. Detailed studies of the Carlsberg Ridge (LAUGHTON & MATTHEWS, 1964 b, c; MATTHEWS, 1965; CANN & VINE, 1966) describe besides pillow lavas and fresh basalts, «dynamically metamorphosed gabbros and spilites as well as chlorite-actinolite and chlorite-talc breccias». Serpentinites were found on the same ridge (BEZRUKOW, 1964). Gabbroic inclusions are mentioned from volcanic flows on Rodriguez Island (UPTON & WORDSWORTH, 1964), which is situated at the junction of the oceanic ridges and the Rodriguez Fracture Zone in the Central Indian Ocean. Together with the reports of chlorite schists and serpentinites from the Mid-Atlantic ridge these finds clearly show that apart from young basaltic rocks, members of an ophiolitic suite seem to occur quite frequently along the trenches of the oceanic ridges. These may probably represent material from the mantle (STUBBS, 1965) and their «mise en place» could have been during the Upper Cretaceous to Lower Tertiary. The ophiolitic rocks may correspond in age to the world-wide ophiolite suite (GANSSER, 1959); they may also indicate some relationship with the initial formation of the Oceanic ridges (Upper Cretaceous?).

The direct continuations of the major western and eastern N-S trending lineaments of the northern Indian Ocean into the continent are masked by two conspicuous deltas, the Ganges-Brahmaputra delta in the east and the Indus delta in the west. Both deltas are of astonishing size and are well visible on Plate I. The Ganges delta, which incidentally derives most of its material from the Brahmaputra, extends for over 2800 km to the south. Various channel systems have been observed, some reminiscent of braided rivers. The delta deposits are mostly clays and silts with some sands. Slumping has been noted along some of the steeper channels (SEWARD et al., 1964). The Indus delta, with an extension of about 1800 km to the south, is similarly built and submarine channels are well noted. The thickness of the deltaic deposits in both deltas is still little known; the unconsolidated sediments can be up to 400 m thick. The total sedimentary cover over crustal rocks in the Bay of Bengal is reported to measure from 2000 to 3000 m and 1000–2500 m in the Arabian Basin (NEPROCHNOW et al., 1964).

The oceanic charts clearly indicate that the major N-S lineaments in the western as well as in the eastern northern Indian Ocean disappear below the younger deltaic deposits (see Plate I). The deposition of these huge deltas must therefore have taken place after the formation of the lineaments and after the completion of the northwards drift of the area framed by them. The spreading of the deltas and the corresponding strong erosion of the hinterland could begin only after an uplift of the hinterland subsequent to the northwards drift of the Indian Shield (see below).

Three main episodes seem to be responsible for the striking structural picture of the Indian Ocean:

1. The formation of the Oceanic Ridges and their central trenches towards the end of the Mesozoic and during the early Tertiary. The outpouring of the Deccan Traps may have occured during the same time interval.
2. The formation of mainly N-S directed sharp Fracture Zones which clearly cut and displace the Oceanic Ridges, associated with a regional northwards drift of the Indian Ocean and a related northwards drift of the Indian Shield. As we shall see, this episode may have taken place towards the end of the Tertiary and during the earliest Pleistocene.
3. A period of strong erosion in the continental area north of the Indian Ocean and the formation of two huge deltas on both sides of the Indian Shield. These deltas are younger than the N-S directed lineaments which they cover. Erosion and deposition are still going on.

3. The relationship of the structural picture of the Indian Ocean with the regional Himalayan orogenies

Plate I clearly shows that the regional structural picture of the Indian Ocean indicates a marked northwards drift of the central part of the ocean floor and its northern extension in the Indian Shield. From the whole geological situation and the regional framework it appears that the present triangular shape of the Indian Shield may represent the original form of the northwards shifted mass. The western as well as the eastern margins of this mass received a considerable amount of Mesozoic together with some Lower Tertiary marine sediments. These sediments now outcrop in well-outlined N-S trending fold belts which, on the western side of the shield, have been forced into syntaxial garlands during the late Tertiary and early Pleistocene. The folds of these ranges are Juratype structures which have been sheared from their crystalline basement; the sediments are no longer fully autochthonous to the shield.

The lineaments of the visible part of the Indian Shield proper were forged by the pre-Aravalli and the Aravalli orogenies (early and late Precambrian) and have not been distorted by the later tectonic events of the surrounding areas. The complicated structures of the shield are sharply cut by the younger Himalayan orogenic belts or are transgressed by Gondwana sediments. The tectonics of the shield do not seem to have had any influence on the outpouring of the Deccan Traps in the Late Cretaceous and early Tertiary, but we are restricted from giving a definite statement by the fact that so far the pattern of the feeder channels is not known.

Towards the western and eastern edges of the shield area the belt of marginal shelf sediments as well as its folded extensions are cut abruptly by major tectonic lines that coincide with a sudden change from shelf to flysch-type orogenic sediments and that mark the locus of outbursts of ultrabasic and basic ophiolites. Whilst the western structural trends are relatively well known (Hunting Survey Corp., 1960), the outline of the eastern ones is still sketchy (Evans, 1964; Chhibber, 1934).

The Western Structural Belt or the Quetta Line

We have already noted that the Owen Fracture Zone as well as the Chagos-Laccadives Ridge trend towards Karachi. The Murray Ridge, the northern continuation of the Owen Lineament, abuts against the continental margin west of

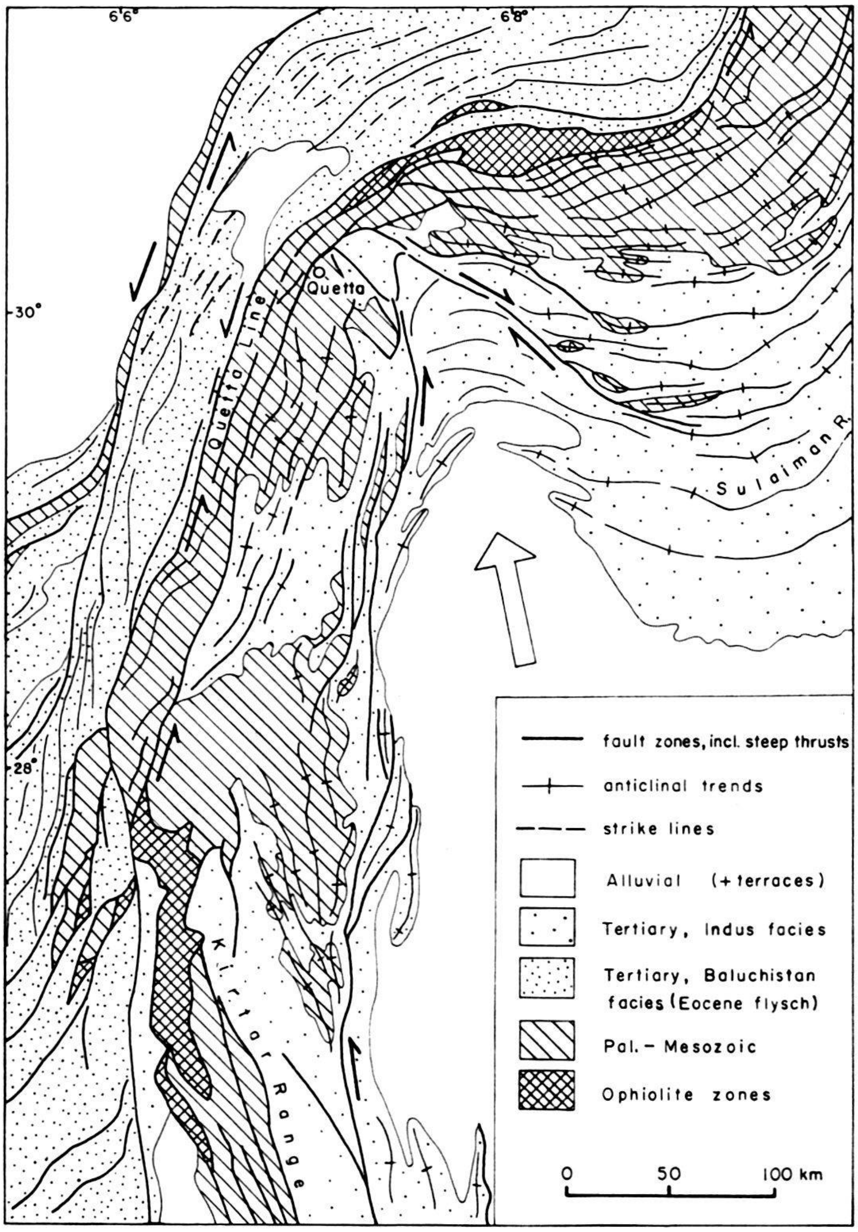

Fig. 1. *The Quetta Syntaxis in the Kirtar-Sulaiman Range.* Based on Geological Map of Pakistan 1: 2000000, 1964 Interpretation by the author.

Karachi, and it is in this same region that the western structural line, or Quetta Line, runs into the sea (Plate I). A structural connection of the western lineaments of the northern Indian Ocean with the Quetta Line seems well supported by the available evidence in spite of the cover of the Indus delta (BARKER, 1966; SNELGROVE, 1964).

The Quetta Line delimits the shelf sediments that cover the western extension of the Indian Shield from the complicated flysch zone of Baluchistan. Both ophiolites and older rocks (Permo-Carboniferous) are known to autcrop along this highly disturbed lineament. The seismic unrest (the famous earthquake of Quetta and frequent subsequent tremors) as well as the structural complications point to a zone of major disturbances. The N-S trend changes at Quetta into a E-W direction, and then after 200 km again into a SSW-NNE trend. The change in strike at Quetta coincides with the marked Quetta Syntaxis, which separates the Kirtar Ranges in the south from the Sulaiman Arch in the north. The Syntaxis reflects a northwards driven spur of the western Indian Shield (Fig. 1), and can be compared to the more pronounced Western Syntaxis of the Himalayas (see later). The Quetta Line continues past Kohat, to the west of Attok and into the Western Himalayan Syntaxis, still outlined by intermittent outcrops of ophiolitic rocks. Fig. 2.

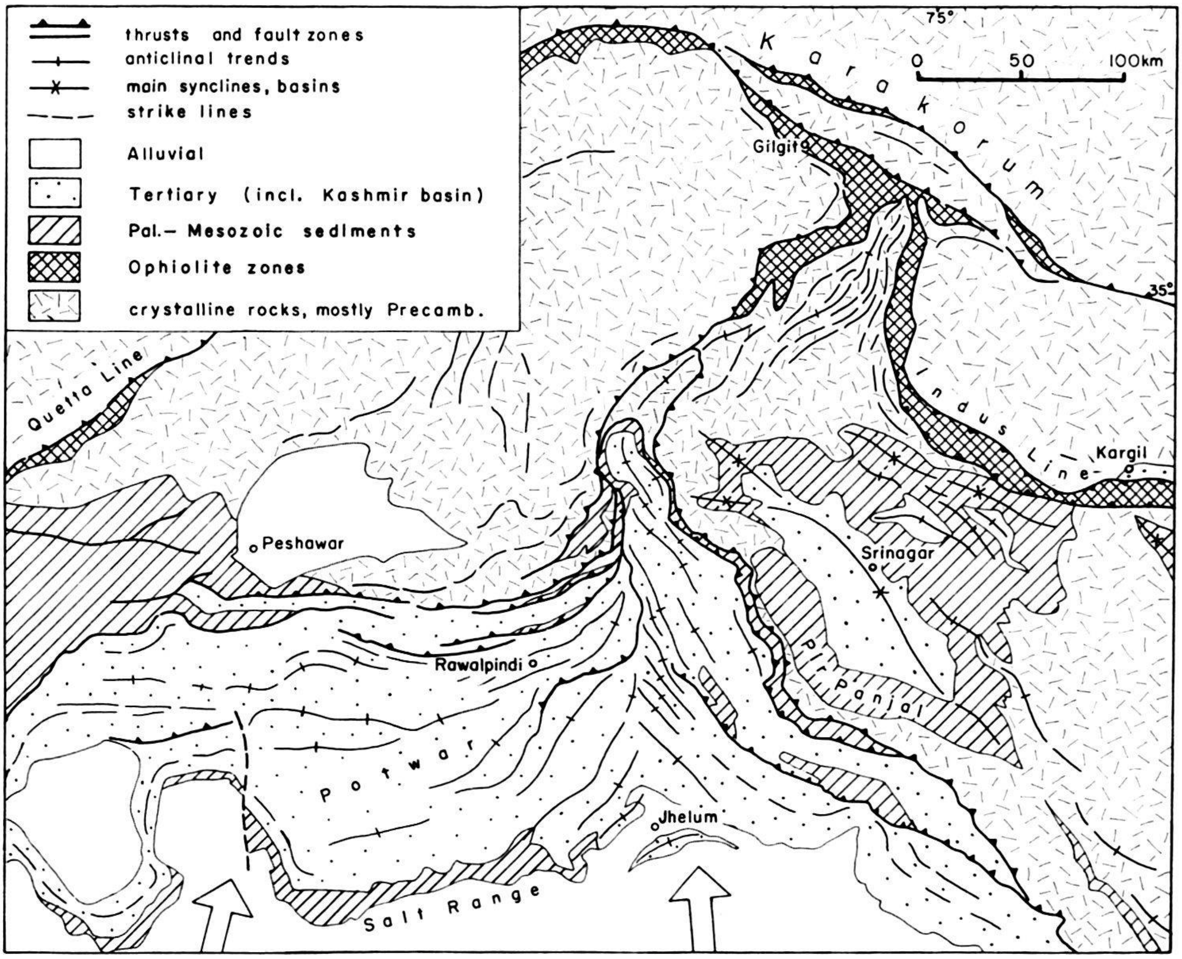

Fig. 2. *The Western Himalaya Syntaxis.* Based on Geological Map of the Himalayas 1 : 2000000 by A. GANSSER, 1964, Geological Map of Western Karakorum 1 : 500000 by A. DESIO, 1964.

The sedimentary facies and the structures on the E and W sides of the Quetta Line are completely different along its whole length. The structures, such as the marked drag of the Baluchistan flysch anticlines, indicate that differential shifts in a left lateral sense have accumulated since the later Tertiary, though the first outline of the Quetta disturbance may date back to the Upper Cretaceous (ophiolites). The available evidence seems to indicate that the Quetta Line in its present layout originated by the northwards drift of the Indian Shield mass, of which it forms the western tectonic margin.

The Eastern Structural Belt, or the Arakan Yoma Line

In the northeastern Indian Ocean the largest known lineament on our globe, the Ninety East Ridge, runs in a straight line towards the western Burmese coast, which it meets west of the Irrawaddy delta. In a style similar to that of the western margin of the Indian Shield the junction of the marine ridge with the continent is masked by the Ganges-Brahmaputra delta and the eastern margin of the shield is covered by marine Mesozoic to Tertiary sediments, which towards the east become thrown into well-pronounced N-S striking Jura-type anticlines. Intervening syntaxial bends as known from the Quetta region are not present, but the N-S structures of the shelf sediments are truncated in the north by an E-W running fault-zone (the Dauki Tear-fault) that borders the Shillong plateau, a northeastern extension of the Indian Shield (EVANS, 1964).

Between the shelf-type sediments and the Central Burmese crystalline Shan Plateau, the still little-known Arakan Yoma structure builds a complicated N-S aligned uplift of mostly Cretaceous flysch-type rocks which is limited by steep faults and thrust zones on both its east and west sides (CHHIBBER, 1934). Ophiolitic rocks occur along the eastern N-S directed and steeply thrusted structure. The Arakan Yoma Ridge and in particular its eastern border, here called the Arakan Yoma Line, represents a major tectonic element that is comparable to the Quetta Line in the west. It forms a slightly offset landwards continuation of the imposing Ninety East Ridge of the NE Indian Ocean and limits the northwards shiftet Indian Shield in the east (Plate I). The Arakan Yoma Line continues in a NNE direction south of the steeply northwestwards thrusted Naga Hills and then, after turning to the NE, is cut at the Eastern Himalayan Syntaxis by the steep crystalline thrust of the Mishmi Hills. The latter thrust runs from the SSE to the NNW and it is still doubtful if a direct continuation into the main crystalline thrust of the Himalayas does exist or whether this thurst continues northwestwards into eastern Tibet (Fig. 3).

In spite of the many unsolved problems, our deductions indicate that on the west as well as on the east side of the Indian Shield major tectonic trends run into the Western and Eastern Himalayan Syntaxes respectively, and that both trends, the Quetta Line as well as the Arakan Yoma Line, seem to be the landwards continuations of major lineaments of the NW and NE Indian Ocean. These lineaments as well as their landwards continuation indicate that the Indian Shield mass between them has driftet to the north (Plate I).

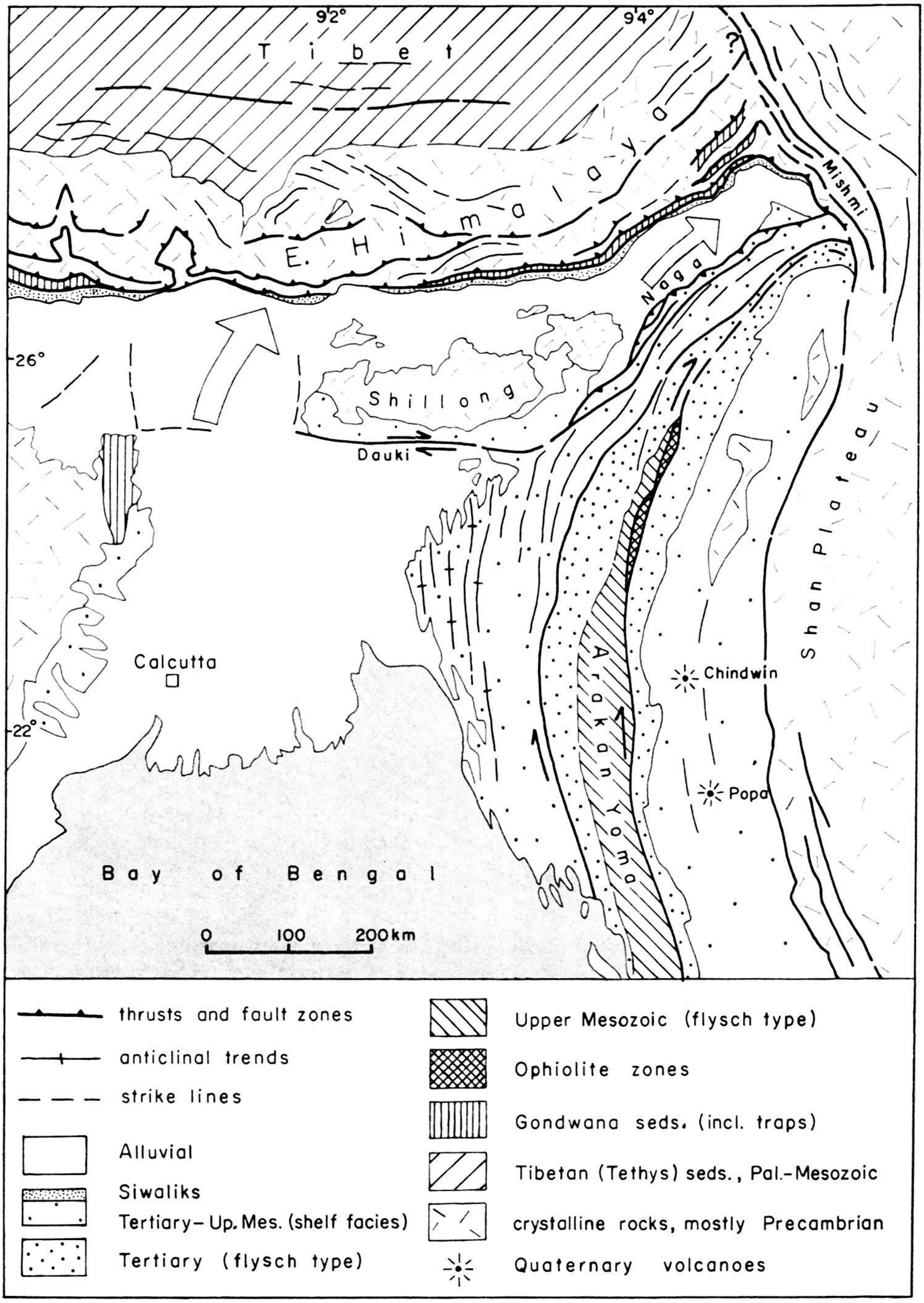

Fig. 3. *The Eastern Himalaya Syntaxis.* Based on Geological Map of the Himalayas 1 : 2000000 by A. GANSSER, 1964, Fig. 2 in EVANS, 1964 and Plate 24 in CHHIBBER, 1934. Interpretation by the author.

4. The Himalayas

The western and eastern syntaxes span between them the 2400 km long Himalayas, the largest and highest mountain range known. Here we find the largest thrusts towards the south against the north drift of the Indian Shield. Every geologist well acquainted with the Himalayan geology must accept a considerable amount of crustal shortening between the south edge of the Tibetan Mass and the Indian Shield. In spite of well-established facts it is surprising how some authors are still reluctant to accept this evidence (Rezvoi, 1964). It is not the purpose of this paper to enter into details of the complicated Himalayan geology; for this we refer to the recent monograph by the writer (Gansser, 1964). We are interested here in trying to evaluate the possible amount of crustal shortening and in comparing the structural history of this mountain chain with the main events of the geology of the Indian Ocean. Along schematic cross-sections (Plate II) we can follow the various structures from south to the north.

Contrary to the general opinions, the foreland of the Himalayas, the broader area of the Ganges plains, does not correspond to the foredeep one would expect in front of a mountain range of Himalayan dimensions. We recognize that the Indian Shield is depressed in the north and passes into a trough which is filled mostly by very young detrital sediments, and not by marine geosynclinal deposits. Only relics of Gondwanda-type sediments have been found directly covering the Precambrian basement (here the Vindhyans are included in the basement). The Siwaliks, the southern 'Molasse' of the mountain chain, form the narrow belt known as the Sub Himalayas; flysch-type deposits are conspicuously absent. Recently the underlying red and purple Murries were described as 'Flysch' (Swami Nath, 1961), an assumption with which the writer cannot agree.

The Siwaliks are folded into narrow, assymetric structures and exhibit locally steep superficial thrusts which may turn into bedding plane thrusts at depth. A shortening of the original deposits by 5–10 km can be assumed.

The structures of the Lower Himalayas are still the most complicated and enigmatic of all. The Lower Himalayas are thrust over the Siwaliks along the Main Boundary Fault, which is actually a steep thrust at the surface. Various structural elements of the Lower Himalayas are found to border this main thrust, and these various structural units are again separated by additional thrusts. Frequently we find Gondwana rocks with occasional coal seams thrusted directly over the 'Molasse', the thrust rocks usually showing a highly tectonized condition and cut by a multitude of secondary faults and thrusts which suggest a great amount of squeezing. Older rocks, such as sediments of the Daling type, or even crystalline rocks, are in turn thrust over the Gondwanas. No tectonic windows of molasse rocks are known, but outcrops of Gondwanas and even Eocene rocks below the next higher thrusts do exist (Shali window of the Simla area, Rangit window of the Darjeeling area, etc.). Thrusts over the Siwaliks and over the Damudas (Gondwanas) are often parallel, and both have a tendency to flatten at depth; this is well exhibited by the respective windows. In view of the well-outlined windows we must assume a large amount of overthrusting: 30 km must be taken as the very minimum for the thrusting over the Siwaliks, while the amount of next higher thrusting over the Damudas is considerably larger. Eocene relics must be expected far to the north below the thick Cambrian (?) and late Precambrian sediments of the Lower Himalayas , and a total thrusting of about 100 km or more is a reasonable estimate.

The most peculiar reversed metamorphism in many of the Lower Himalayan crystalline sheets is another problem to be accounted for. Large reversed sedimentary sections do exist, and may be covered by cristalline sheets with upwards increasing metamorphism. Such crystalline sheets with the same reversed metamorphism may, however, lie above normal, i. e. not reversed sediments. Saucer-shaped klippes of crystalline masses occur far to the south on top of non-metamorphic sediments; their normal upper cover is unknown. An additional large thrusting seems here evident. Even if huge recumbent thrust folds (nappes in the real sense) are suggested as an explanation for the reversed grade of the metamorphic rocks covering the thick sedimentary sections, a large amount of crustal shortening must be assumed. A crustal shortening of 150–200 km in the Lower Himalayas seems, based on the structural outline known so far, a reasonable estimate.

Further to the north the Lower Himalayas are then overthrust by the Higher Himalayas; these are built of an enormous structural unit that is quite different from the Lower Himalayas. A sheet of crystalline rocks 15–20 km thick forms the foundations of an almost continuous marine sedimentary section that stretches from the late Precambrian to the Upper Cretaceous. The marine sediments belong to an environment reminiscent of the Tethys and contrast sharply with the relic sedimentary sections of the Lower Himalayas. The crystalline sheet does not show reversed metamorphism and exposes all gradations from high grade migmatites into low grade argillaceous sediments of late Precambrian age. Some of the granitization phenomena and a corresponding mobilization lead to local intrusions of typical young Tertiary tourmaline granites.

The Main Central Thrust, which forms the base of this crystalline thrust sheet, is well visible when it passes over the sediments of the Lower Himalayas, but it is difficult to detect when it covers crystalline rocks, as it often does in the eastern Himalayas. A large amount of displacement along the Main Central Thrust is suggested by the different structural style, the different types of crystalline rocks and particularly by the sharp change to the Tethian facies sediments above the thrust. An overthrust (or underthrust) of 80–100 km can be suggested also on the basis of the flat northwards extent of the crystalline sheets in the eastern Himalayas and the lack of structural indications of autochthonous crystalline massifs such as, for example, the external massifs of the Alps. In addition to this, the total shortening seems to be increased in some areas by flat thrusting within the crystalline rocks; some of the secondary thrusting and assymetric folding of the younger sediments is, however, independent of the crystalline basement.

The largest and most important structural feature of the Himalayas is found further to the north along the upper Indus River. Between the northern ranges of the Himalayas and the Transhimalayas, the latter already the southern edge of the great Tibetan Mass, we observe a sudden rootlike downbuckling along a structure of fundamental importance that has been called the Indus Line or Indus Suture Line (GANSSER, 1964). The Middle Cretaceous marine sediments display the first evidence of orogenic movements. The flysch-like Upper Cretaceous contains ophiolites; the sedimentation becomes chaotic, and huge exotic blocks of unknown origin are embedded in the flysch and the ultrabasics. In some places the whole olistostromal mass forms a vast thrust sheet issuing from the Indus Line and pouring over the Tethys sediments for a distance of more than 90 km south of the famous Kailas mountain. The exotic blocks harbour a miscellany of Permian to Upper Jurassic sediments. But these sediments are totally different from the normal Tethian deposits; the facies of most indicates pelagic sediments that are unknown in the wider Himalayan region. They must have been deposited in deep basins situated between the present Himalayas and the Tibetan plateau; these original basins have completely disappeared and are now testified only by the presence of the Indus Line.

Along the upper Indus river and south of the Kailas range, highly tectonized, mostly vertical sediments, ophiolites and exotic blocks mark the area in which a great length of original crust has disappeared by downbuckling. This must have begun during an episode of the early orogenesis of the Himalayas in the Upper Cretaceous. Large masses of ultrabasic rocks were squeezed out subsequently and became mixed up with the excessive, displaced sedimentary material of the exotic blocks. The large sheet of peridotites of Amlang La may be mantle material originating from a deep, primary fracture zone which follows the Indus Line. Some of the olistostromal masses and related ultrabasics have been thrust northwards over coarse detrital, Molasse-like, probably Lower Tertiary sediments of the Transhimalaya, which are in striking contrast with the exotic rocks.

All these facts seem to indicate that a large amount of the crustal layer must have disappeared along the present Indus Line. The crustal shortening through downbuckling must account for the sharp facies differences of the sediments and the presence of Upper Cretaceous ophiolites, which are otherwise unknown in the Himalayas. The shortening may be considerable, and 200 km may be a reasonable amount to explain the facts so far observed. Summing up our tentative estimates we arrive at a figure, admittedly vague, of approximately 500 km for the total crustal shortening during the Himalayan orogeny. In estimating the amount of thrusting for the various tectonic units, ample reduction for a reasonable estimate of stretching has been made. It may be interesting to note that EVANS (1964) suggest 150–300 km for the crustal shortening along the Naga Hill Thrusts (Assam) and assumes an equal amount (which he calls 'almost certainly an understatement') for the thrust sheets of the Eastern Himalayas.

The crystalline rocks of the Lower Himalayas and their late Precambrian sedimentary cover with fragmentary remnants of Gondwana deposits (tillites) recall the rocks of the Indian Shield. Geosynclinal sediments are missing. In the same way, the basal crystalline thrust sheets of the Higher Himalayas also recall rocks reminiscent of the Shield. It is only further north that Tethys-type deposits set in. This fact indicates that the greater part of the Himalayan range consists of shield material which has been thrust over shield material, or rather underthrust by the northwards drifting mass of the main Indian Shield. The greater part of the largest mountains on our globe thus do not form a geosynclinal range, and have not evolved through the 'classical geosynclinal history'. Only along the Indus Line were deeper water, marine sediments deposited in a 'geosynclinal' basin, which now has completely disappeared during the orogeny.

As we have seen, the Himalayan orogeny began in the Upper Cretaceous after a long period of sedimentation in the northern part which had continued since the late Precambrian, interrupted only by epeirogenic, not orogenic disturbances. Thrusting must have been active mainly towards the end of the Tertiary and in the early Pleistocene; along the Main Boundary Fault the Lower Himalayas are thrust over Lower Pleistocene Upper Siwaliks. Later in the Pleistocene the morphogenic phase began with mostly vertical uplifts, the formation of the present day morphological range and the onset of strong erosion. This phase continues at the present time.

The effect of a strong northwards drift of the Indian Shield is, moreover, not only manifested in the Himalayas, but also in the adjacent ranges and platforms. The most pronounced influence is the NNW protrusion of the western part of the Shield, which caused the Quetta Syntaxis (Fig. 1), the smaller garlands of the Salt Range and the remarkable Western Himalayan Syntaxis (Fig. 2). The latter is cut across its northern end by the western continuation of the Indus Line, which here separates the Western Himalayas from the Karakorum. This tectonic line is bent around the syntaxis, forming a wider conformable arch around the inner ranges, and continues to the SSW into the Quetta Line.

The Karakorum and its western continuation in the Hindu Kush are convex to the north. The Pamirs further in north are equally convex and still show the influence of the northwards drift of the shield. Differential movements are known from the eastern border of the Pamirs, the Mustagh Ata Range and its westernmost equivalent, the Badakshan ranges (DESIO, 1964). In the north, the Pamirs are delimited by an important EW-striking, southwards directed thrust zone, the Kashgar zone, which forms the southern border of the Tien Shan and Altai Ranges. The orogenies of Himalayan type, which were already decreasing gradually from south to north in the Pamirs, almost disappear along this same thrust zone, and only young morphogenic movements are overprinted on older, pre-Himalayan orogenic structures. Many authors attribute these older structures to the Variscan (Hercynian) orogeny (GUNDLACH, 1934; BARKHATOV, 1963), but in the writers opinion they are predominantly late Precambrian. The visible effects of a northwards drifting Indian Shield end with the Kashgar Zone. The gap between the Indian Shield and the Arabian Shield is covered by the westwards opening sheaf-like bundles of ranges that extent from the high constricted mountain ranges in the northern Pamir region. These 'sheaf ranges' are characteristic, for instance, of the Fergana region, the western Badakshan and the Kopet Dag (GANSSER, 1964).

East of the Pamirs, between the Tarim basin – a stable depression since the late Precambrian – and the Himalayas in the south, the constricted ranges open out into the Tibetan Mass. This, the largest surficial land mass on earth, is situated just north of the Himalayas and therefore just north of the northwards drifting

Indian Shield. It is most likely that the uplift of this huge landmass is directly related to the northwards drift of the Indian Shield. Even the Tibetan Mass itself may have moved to the north, probably before the thrusting of the Himalayas, and been the direct cause of the final build-up of the Kun Lun ranges, which border the Tibetan Mass on its northern side. These ranges were first affected by several Precambrian orogenies, then by some pre-Devonian movements and again by an orogeny following the Angara type deposits in the north and preceding the Cretaceous transgression (Bohlin & Norin, 1960). The Kun Lun forms the important facies-divide between the Angara sediments in the north and the marine Jurassic and Cretaceous of the Tibetan Plateau in the south. Ophiolites along this zone indicate a deep seated orogenic belt.

5. The history of the Indian Ocean and the Himalayas

If we now reconsider the above-mentioned facts and deductions and return to our regional picture of the Indian Ocean (Plate I), we realize how certain deductions about the oceanic configuration fit into the complicated picture of the continental structures of the wider Himalayan region.

The ophiolitic phase that began in the Middle to Upper Cretaceous may coincide with the formation of the Mid-Oceanic Ridges and their superimposed trenches. We note that on the land many of the lineaments are characterized by ophiolites. The initial movements of the Indus Line began during this early phase; we can visualize the downbuckling of a narrow, deep sea basin with intrusion and extrusion of ophiolites and the slipping of sedimentary masses which later formed the olistostromes with exotic blocks. The Himalayan orogeny began, as did the Alpine, in the Middle to Upper Cretaceous; this was a time of great world-wide revolution related to the formation and/or deepening of the major oceans.

Subsequent to the build up of the Oceanic Ridges, elements of the Indian Ocean commenced its northwards drift along most remarkable NS-directed lineaments corresponding to fracture zones and narrow ridges. There is reasonable evidence that this northwards shift affected principally the central part of the Indian Ocean and with it the whole of the Indian Shield.³)

We must assume that the formation of the large thrusts of the Himalayas are directly related to this northward drift of the Indian Shield and that they are restricted to the Himalayas north of the Indian Shield and are missing from the adjacent Asiatic ranges. We have noticed that a crustal shortening of 500 km for the Himalayas alone is a reasonable amount. It is not surprising that this amount is a very minimum for the northwards drift of the Indian Shield as displayed by the structural configuration of the Indian Ocean.

It is also a remarkable fact that subrecent and recent volcanism is widespread west and east of the northern Indian Ocean but is missing from the area where the northern drift was most active and where the large thrusts have been formed (Fig. 4). Huge thrusting and volcanism evidendly do not agree.

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³) Evidence of a strong lateral drift (De Boer, 1965; Van Hilton, 1964) is not convincing, though admittedly our data bearing on other than the well outlined northwards drift are still so vague that any other drift direction can be assumed.

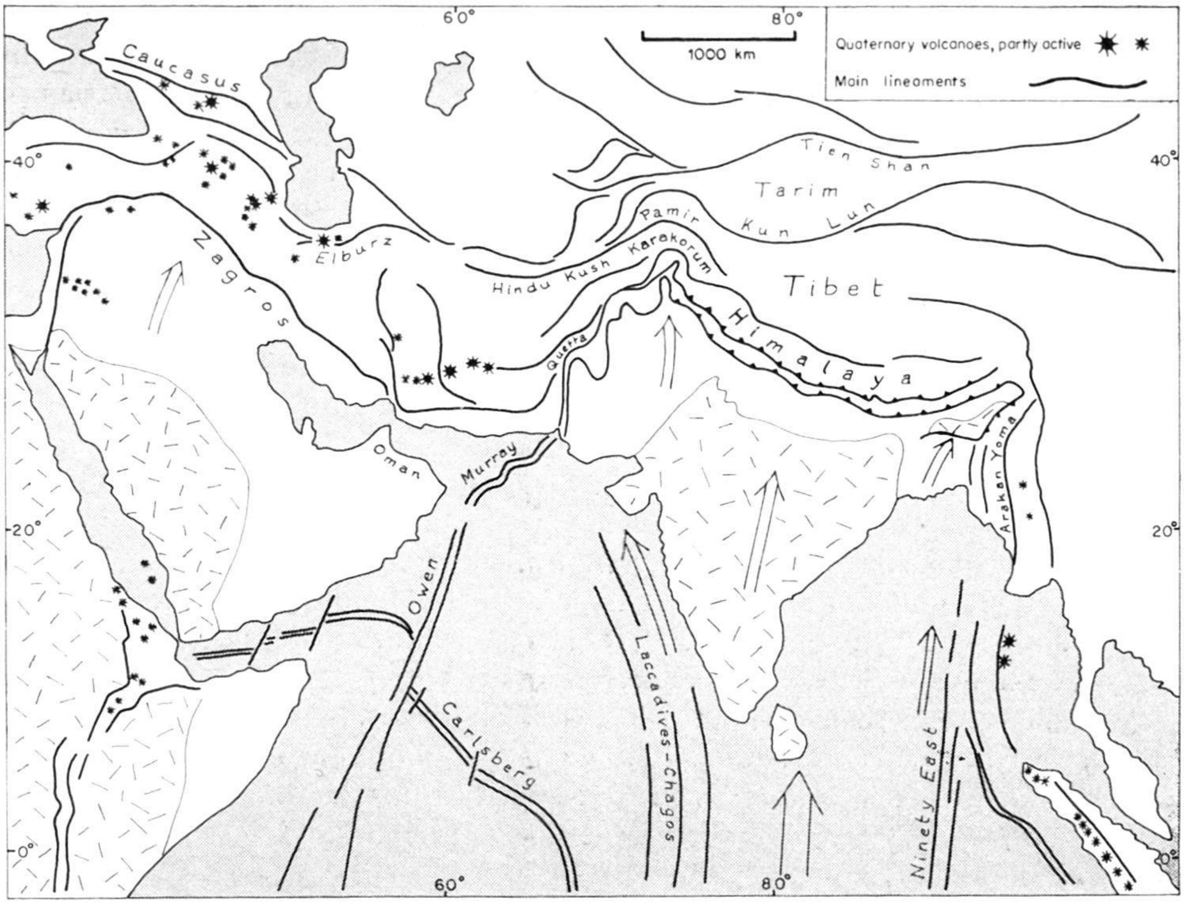

Fig. 4. *Subrecent and recent volcanism in the Indian Ocean area and Middle East.* Compiled from various sources by A. GANSSER.

The Zagros Thrusts opposing the drift to the N and NNE of the Arabian Shield (LAUGHTON, 1966b) are minor incidents compared to the Himalayas, but on the other hand the drift of Arabia is, if compared with that of the Indian Shield, of a smaller amount.

Thrusting in the Himalayas began in the post-Eocene and reached its strongest phase in the Plio-Pleistocene. A similar age can be suggested for the N-S lineaments of the Indian Ocean, since, as we have mentioned, they are younger than the formation of the Mid-Oceanic Ridges an are related to the northwards drift, which in turn was responsible for the thrusting of the Himalayas.

Subsequent to the very conservative 500 km north drift of the Indian Shield and the resulting main thrusting in the Himalayas, a phase of considerable uplift occurred which was responsible for the present morphological outline of the range. This has been called the Morphogenic Phase of the Himalayas (GANSSER, 1964). This uplift, active in the late Quaternary, still continues, and the present mountain range is being attacked by a strong, active erosion. The drainage system had already been diverted to the south towards the end of the north drift of the Indian Shield, which was probably largely, but not completely responsible for the uplift of the Tibetan Mass. Large rivers emptied into the Indian Ocean west and east of the Indian Shield. During the strong morphogenic phase the erosion of the main rivers, the Indus and Brahmaputra, kept pace with the rising Himalayas and, together with the Arun river, cut through the ranges where the highest mountains exist at present. The morphogenic phase is thus responsible for the formation of the large river deltas of the Indus and the Ganges-Brahmaputra systems, which are major features of the northern Indian Ocean (Plate I). The main formation of these deltas is clearly of a younger date than the outline of the NS-directed major lineaments of the Indian Ocean, for the latter disappear and are covered by the great mass of the deltaic deposits. The covering of the young oceanic features by the deltas coincides with the morphogenic phase which followed the main Himalayan orogeny and the associated thrusting. Here again, the regional tectonics of the continents are reflected by the configuration of the Indian Ocean. The volume of the two deltas is not yet known, but considering the young fill of the Indo-Gangetic plain together with the deposits of these deltas, the volume may greatly exceed the amount of the Molasse-like Siwaliks, which represent only a small amount of the total visible volume of the Himalayas. The main denudation of the huge mountain range is of a recent date and the wild character of the Himalayas is a witness to the present activity. This is the last phase of the geological history of the Himalayas that can be compared with the major tectonic events in the Indian Ocean.

We fully realize that events of both continent and ocean floor are still little known, the oceanic areas much less than the land, but on general lines the relations as exposed above seem to make sense; at least they may form a basis for future elaborations, when more and newer information is at hand.

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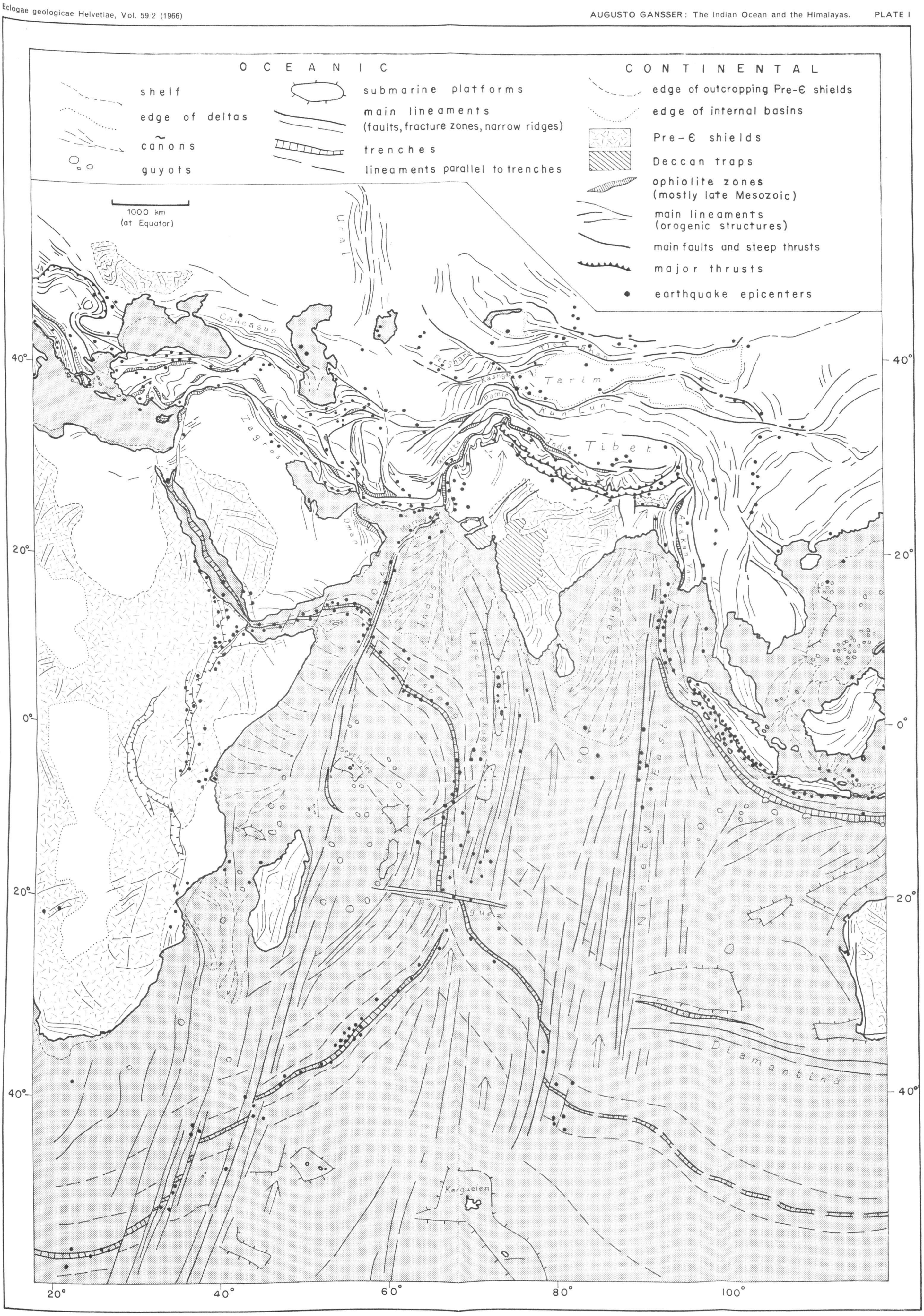
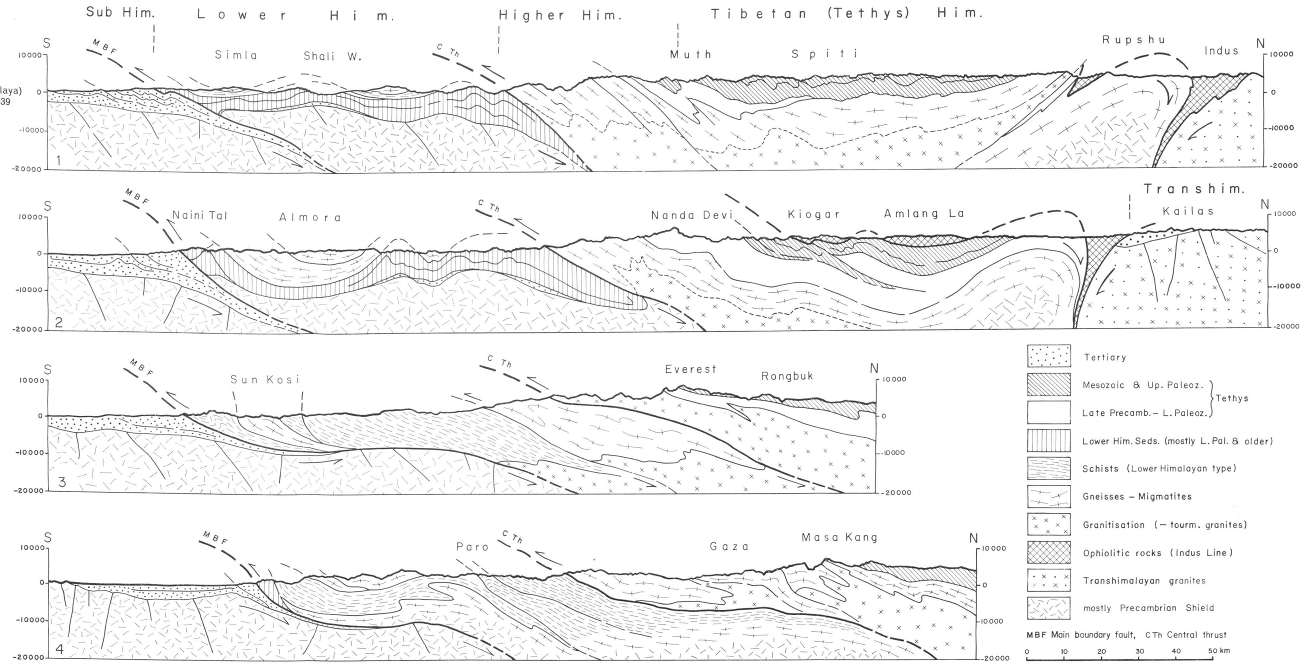


PLATE I. The relation of the Physiographic Pattern of the Indian Ocean with the Himalayas and adjoining structures.
Based on Physiographic Diagram of the Indian Ocean by B. C. HEEZEN and M. THARP, 1964, Tectonic Map of the Himalayas and Surrounding Areas 1:10 000 000 by A. GANSSER, 1964, and other sources. Interpretation by the author.



1)

Simla-Spiti Rupshu area (Western Himalaya)
Based on BERTHELSEN, 1951 and WEST, 1939

2)

Almora-Kailas area (Central Himalaya)
Based on A. GANSSER, 1964

3)

Everest area (Central Himalaya)
Based on BORDET, 1964, LOMBARD, 1958, HAGEN, 1959, and WAGER, 1952.

4)

Western Bhutan (Eastern Himalaya)
Based on GANSSER, 1964.

PLATE II. Generalized Crossections through the Himalayas. Interpretation by the author.