METAMORPHIC ROCK SEQUENCES
OF THE
EASTERN HIMALAYA

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HIMALAYAN OROGENESIS IN PERSPECTIVE*

JOHN HALLER

> *"C'est un fait connu de tout le monde, que la visage de le Terre se déforme continuellement"*
>
> Pierre Termier, 1922

One of the Huttonian tenets of modern geology—vicissitudes of the Earth's surface—is illustrated by the Neogene rise of the most spectacular of all intracontinental mountain ranges: the Himalaya. It forms an arc convex to the south, some 2500 km and up to 300 km wide, and virtually override the Indian subcontinent. To Indian culture throughout all ages, these mountains have been of great significance as their grandeur also shelters some of the most sacred shrines of Hinduism. Their eternal snow has been considered the symbol of serenity. The very name Himālaya comes from Sanskrit *hima*, snow, and *ālaya*, home; the accent is on the second syllable. Geographically the Himalayan arc extends from the valley of the Indus in the west to that of the Brahmaputra in the east, where in each case a high mountain massif rises the average summit level and orographic trends turn sharply to the south. The landmarks are Nanga Parbat and Namcha Barwa respectively. Between them stretches the range of the Great or Higher Himalaya (6000-8000 m), notable for its bold southern face. Along the entire length of its arc, the range is paralleled by the Lower Himalaya (1660-4000 m), and, bordering the Indo-Gangetic plain, the Siwalik Range or Sub-Himalaya (900-1200 m). In the northwest, behind the Great Himalaya, follow the Zaskar and Ladakh Ranges and the towering Karakorum, which are usually considered part of the orographic system too. Of the world's seventeen highest peaks, all exceeding 7900 m, eleven are clustered along the Great Himalayan Range of Nepal and six in the Karakorum, Pakistan. The area in between provides the source for India's major river systems, and has offered passage across the mountain barrier from the subcontinent to central Asia since the dawn of human cultures. Nevertheless, the puzzling geography of the Trans-Himalayan Ranges and the headwaters of the Indus, and the Brahmaputra (Tsangpo) in particular, were resolved only in the late 19th century by the Swedish explorer Sven Hedin.

From Kashmir to Bhutan, the Great Himalayan Range forms a climatic barrier, dividing the arid uplands of Tibet from the rainy, partly tropical

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southern slopes. On the eastern spurs, where the monsoon from the Bay of Bengal forcefully reaches the mountains and runs into the dead end of Assam, rainfall is high and moisture is carried by the winds right over the Himalayan crest deep into Asian heartland. At the western end of the Himalaya the situation is reverse. Along its passage up the Indus Valley, the monsoon rapidly weakens and does not bring much rain to and across the mountains, thus turning the region into steppe and desert.

A note on modern history may clarify some geographic terms entrenched in Himalayan literature. The important date is 1947, when the Republic of India attained independence after two centuries of British rule. This change affected the international borders as well as the internal political subdivision of India. Names related to British India and used in standard references on Himalayan geology (Gansser, 1964) have disappeared from modern geographic maps, while recent geologic publications, in turn, may not refer to past political entities. For example, the former British Province Kumaon, known to geologists as the Kumaon Himalaya, has since become part of the states of Himachal and Uttar Pradesh. Similarly, the North Eastern Frontier Agency and hence the NEFA Himalaya are now the union territory Arunachal Pradesh.

GEOLOGICAL EXPLORATION

With regard to geological studies in the Himalaya it is important to note that only Kumaon and Kashmir of British India have been accessible to Western scientists. The rest of the Himalayan arc, with the exception of the small Sikkim protectorate, was closed to exploration until after World War II. The classic studies on Himalayan stratigraphy and structure were confined, therefore, to Sikkim, and to the northwest where British dominated territory reached across the entire mountain system.

Widespread thrusting of the Himalayan ranges over the subsiding Indo-Gangetic plain was recognized by Oldham (1893), and even before. Von Lōczy, after his traverse of the valley of Sikkim in 1878, had aired the notion of large-scale thrust tectonics in the Eastern Himalaya. It is remarkable that these views were expressed at a time when the nappe structure of the Alps was still a matter of heated debate. Nevertheless, it was only during the Swiss Himalayan Expedition in 1936 that Heim and Gansser (1939) were able to work out the first modern structure section across the Kumaon ranges around the landmark Nanda Devi. It was then that the regional significance of the major structural elements, the *Main Central Thrust* in particular, was perceived. The tripartite orographic zoning along the mountain arc—the Higher, Lower , and Sub-Himalaya—was shown to result from Miocene to Recent shoves that migrated from north to south. The allochthony of the 'exotic' thrust sheets (Kiogar and Amlang La nappes) was established as well as their relationship to the steeply inclined Indus-Tsangpo suture zone.

The Transhimalayan Ranges were shown to be strikingly different from the Himalaya in both lithology and structure. Due to the fairly complete fossiliferous Tethys sequence in the Higher Himalaya (Tethyan Himalaya) and the lithologically well defined structural units of the Lower Himalaya of Kumaon, this section has been considered representative of the structure of the entire Himalayan arc.

When modern Nepal opened its frontier to the outside world, mountaineering expeditions began their conquest of the 8000-meter mark. The first to succeed was a group of Frenchmen climbing Annapurna I (8,078 m) in 1950, followed by Hillary's triumph on Mount Everest (8,848 m) in 1953. In Pakistan, Nanga Parbat (8,116 m), fell the same year to Buhl's stupendous solo effort, and in 1954 an Italian team reached K2 (8,611m), the highest peak in the Karakorum. These climbs aroused worldwide enthusiasm, attracted further mountaineers and, in this context, geological investigations sponsored by various nations, inlcuding UNESCO programs. Once more the climatically favored western and central segments of the Himalayan arc received befitting attention. But in the Eastern Himalaya where rains are severe and jungle vegetation reaches up to 4000 m of elevation, geological mapping was taken up only recently under the auspices of the Geological Survey of India and the Wadia Institute of Himalayan Geology (founded in 1968).

NEOTECTONICS AND GEOPHYSICS

In comparison bevelled lowland shields such as the Canadian or Baltic, the Indian shield exhibits rather distinctive geomorphic features, notably the Western Ghats with peaks of over 2000 m along the Arabian Sea. Of smaller extent and elevation are the Aravalli, Vindhya, and Satpura Mountains of central India. These hilly ranges are the result of Late Cenozoic crustal arching, block faulting and tilting. Their neotectonic uplift has been accompanied by subsidence along the northern periphery of the Indian shield where clasts shed from the towering Himalayan mountain front are being dumped into Miocene to Recent foredeep basins. To both sides of the emergent shield, the sediment-filled depressions now extend far into the Arabian Sea and the Gulf of Bengal respectively, where huge deep-sea fans point to their sites.

Mount Everest was named in honor of George Everest, the Surveyor-General of India, over a century ago. It was under his direction that gravity data was gathered systematically and India so became the cradle of geophysics. A geodetic survey across the Indo-Gangetic plain showed that the gigantic mountains of the Himalaya caused much less deflection of the plumb-line than would be expected from a uniform Earth. This discovery gave rise to the two theories of isostatic compensation by Pratt (1855) and Airy (1855). In spite of their contention both models led to the early conclusion that the

Himalaya is underlain by an abnormally thick crust. Modern seismic studies appear to strengthen this conclusion. While the Indian subcontinent is underlain on the average by 30 to 40 km of crust, the Himalaya is supported by over 60 km. To the northwest, beneath the Karakorum and the Pamirs, the crust thickens to 75 or possibly 80 km, a maximum thickness for the Earth's crust. Abnormally thick crust also underlies the Tibetan Plateau, which reaches an average elevation of over 5000 m:

Over the past two decades a large number of *gravity* observations have been gathered over Peninsular India, while over the Himalaya only a few traverses have been surveyed. Free air and Bouguer gravity anomalies show a correlation of negative patterns over the Indo-Gangetic plain and the Himalaya, a wide belt of relatively positive values over central India and negative anomalies in southern India. The gravity high of central India largely coincides with the distribution of Late Cretaceous—Early Tertiary plateau basalts (Deccan traps) as well as with the neotectonic upwarps of shield elements. At the Himalayan front the Bouguer anomalies reach values of – 160 to –180 mgals and drop to less than—350 mgals beneath the Higher Himalaya. Unfortunately the traverses end in the Higher Himalaya. Farther north, over the Tibetan Plateau, the Sven Hedin expeditions obtained near zero free-air values and Bouguer anomalies of some—600 mgals. It is likely but not positively known that the Tibetan Plateau and the Indian shield are essentially in isostatic equilibrium. Whether or not the Himalayan arc has yet reached equilibrium is, however, a matter of dispute. The uncertainty stems from the lack of independent estimates of the crustal thickness beneath that arc and, consequently, gravity models can be made close to isostatic compensation or far from it. However, when Warsi and Molnar (1977) modelled the gravity low beneath the Indo-Gangetic plain, they noticed that sedimentary fill alone would not account for the low. They suggested, therefore, that underthrusting of the Indian shield, modelled at dip angles of $15^\circ \pm 5^\circ$, contributes to the gravity effect and the Himalayan arc thus was not isostatically compensated. They also called attention to the gravity high of central India which resembles the 'outer gravity high' that usually characterizes the seaward side of arc-trench system. It is suggested that the similarity of these gravity patterns is the expression of a common process in lithospheric dynamics.

Earthquakes are frequent over much of central and southeastern Asia, with a belt of *seismicity* clearly discernible along the entire length of the Himalayan arc. These shallow crustal events do not appear to be restricted to narrow zones, although it has been claimed that the 'Main Boundary Fault' as well as some of the northerly trending transverse structures are the surface expression of seismic slip. Such qualification, however, is said to be ambiguous, because there are no seismic stations along most of the Himalayan arc to allow the focal depth to be accurately determined. At both considered an intra-continental deformation: an orogeny within an ensialic regime.

Contrary to popular belief, the structure of the Himalayan arc is not the result of a continent-continent collision. Rather, the continental blocks of India and central Asia (Tibet) were interlocked before the onset of the Himalayan orogeny. If they were parts of different continental entities at all, their convergence and hence the losing of the intervening Tethys seaway would have to be an event of pre-Himalayan vintage. Moreover, there are convincing arguments that the Himalayan arc grew by way of tectonic slicing and scaffolding of the once northward extension of the Peninsular continent.

The intra-continental setting of the Himalayan orogeny, in turn, resulted in a rather unique pattern of *regional metamorphism* which appears to have been controlled by the particular thermal regime that evolved during the southward thrusting of the Higher Himalaya. This major unit carries Cambrian through Cretaceous Tethyan strata on a thick sole of Precambrain basement, called *Dalle du Tibet* (Lombard, 1958; Bordet, 1977). Within this 'slab' a normal sequence of Barrovian metamorphism developed syn-kinematically to movement along the 'Main Central Thrust' or its predecessor. In places, Neogene metamorphism reached the stage of metasomatic granitization, and granitic melts mobilized at depths intruded late to post-kinematically. In the Lower Himalaya, the metamorphic effects cannot be readily ascribed to one simple pattern. The metamorphic isograds cut across startigraphic and lithic boundaries and, in general, indicate an *inverted* sequence. It is assumed that the latter phenomenon was mainly caused by the relatively fast overthrusting of the hot sole of the 'Dalle du Tibet' which thus induced the inverted isotherms. The vigorous scaffolding of the Himalayan arc is thought to have effected a virtual 'outflow of the metamorphic belt' (Frank *et al.*, 1973; Le Fort, 1975). The inverse metamorphism is thus considered to be the result of an exceptional interaction between metamorphism and rapid lateral movement, on the order of 5-10 cm/yr at times. Wenk (1968) pointed out that it is this peculiarity that makes the Himalaya the 'enfant terrible' among orogenic belts.

CONTINENTAL DRIFT AND PALEOMAGNETISM

Wide areas of the Indian shield are covered by flat-lying sedimentary formations of the *Gondwana System* (Permo-Carboniferous to Early Cretaceous). It is remarkable that these cover beds are largely terrestrial and, except for normal faulting, have not been affected by deformation. The character and distribution of these formations testify to the cratonic nature of the Indian shield since Precambrian time. The term *Gondwāna* is derived from the ancient Gond[4] kingdom of central India, where the coal-bearing

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[4] *Gond* is one of the aboriginal tribes who are believed to have inhabited India before the advent of the Aryan Hindu race.

rock sequence is largely confined to linear fault troughs. It was discovered early that similar coal-bearing 'Lower Gondwanas' also occur within the Eastern Himalaya. The Gondwana coal measures are associated with glacial boulder beds (tillite). They contain, moreover, a unique, apparently stunted fern flora, typifield by the genus *Glossopteris*. As early as 1875, it was noted by Blanford that equivalent floras also occur in South Africa and Australia, but not in Europe and North America, where a different Permo-Carboniferous coal-swamp flora had developed. The striking appearance of *Glossopteris* floras on the southern continents caused Suess (1885) to bring together these distant regions under the term Gondwanaland. Ever since, the quest for lost land connections has stirred up vexing problems. In particular, the assumption that in pre-Tertiary time dry land had stretched from India to South Africa over what is now the Indian Ocean disavoewed the doctrine of the permanence of continents and oceans. It required the Indian Ocean to have formed only in the Cenozoic, by way of fragmentation and subsidence according to Oldham (1893). But the same author noticed also that the traces of Gondwana glaciation in India, Africa, and Australia, all within, or just beyond, only thirty degrees from the Equator, necessitate substantial latitudinal changes of these continents with respect to the present position of the poles. By reckoning these circumstances, drastic changes in paleogeography had to be conceded henceforth within the realm of the Indian Ocean. It is for this reason also that geologists from southern continents were traditionally more open-minded towards the emerging concept of *continental drift* championed by Taylor (1910), Wegener (1912), and Du Toit (1937).

The tectonic setting of India is commonly interpreted as if the subcontinent had rigidly indented a ductle landmass, Asia. The kinematics inferred from this notion has prompted much conjecture on the amount of the northward flight of the subcontinent, and the recognition of substantial crustal shortening implicit in the structure of the Himalaya has made the portrayal all the more plausible (Argand, 1924; Staub, 1928) Nevertheless, the search for a reliable yardstick with which to measure this northward motion has proven difficult. A creditable approach has been considered Wegener's principle of *congruence*, which is based on the geometrical fit of continental outlines, defined by a chosen bathymetric contour. It is assumed thereby that bathymetry corresponds to crustal composition and that the pristine break is still discernible due to a lithogenetic immutability of the continental crust. Although both of these assumptions have turned out to be unwarrantable, numerous attempts have been made to re-assemble the dispersed fragments of Gondwanaland via a straightforward geometrical fit. Most authors prefer to join the west coast of India to Madagascar and Africa. With regard to the east coast of India, however, there is disagreement as to whether Antarctica or Australia should be matched. Ironically, the most convincing link between India and West Australia, which was based on Precambrian ore deposits and Permian paleogeography (Ahmad, 1961) had been assembled on base maps of entirely different scales, Again, whatever reconstruction is deemed acceptable, it would disclose merely the total relative motion between Gondwanaland fragments themselves and not the displacement of India relative to Eurasia.

Before the Second World War, the main objection to continental drift was the lack of definitive evidence and, most of all, the lack of a viable driving mechanism. Geophysicists in particular denied the feasability of the large-scale dislocation proposed by geologists. The controversy focused on the motion of continents, which occupy barely one third of the Earth's surface. The discussions tended to become emotional and, too often, they challenged a response that was 'pro' or 'con Wegener' rather than straight to the point. During the 1950's however, serious interest in the issue revived in the wake of the study of *paleomagnetism*. It was the design of a very sensitive magnetometer (Blackett, 1952) that allowed henceforth a possibility of checking direction of the fossil magnetization(remananće) of rock samples. Recent lavas so measured showed directions close to true north and inclinations close to those expected from a simple axial dipole field. If polar-wandering had occurred or continents had drifted, the orientation of magnetization should differ, depending on the age of the rocks. Among the first samples tested were basalts from the Deccan Plateau of central India. The result was startling as it required India to move to the Southern Hemisphere in order to satisfy the orientation of the fossil magnetization. Since then paleomagnetic data from India have become a textbooked example of how a continent appears to have changed position relative to the dipole axis, namely from 30°S some 65 m.y. ago to its present position of 20° N, that is, a northward move of 50° of latitude, which equals 5500 km (McElhinny, 1973). Nonetheless, paleomagnetic data such as these cannot provide a description of the motion itself. They may be used for testing a palinspastic reconstruction but they alone do not contain enough information to make one. This is because the paleolongitude remains undertermined. The data simply yield a path of apparent polar-wandering, and this only under the condition that the samples used have retained a stable remanence that was acquired in a geocentric dipole field. (The latter is assumed but cannot be proven.) Because in the present geomagnetic field the magnetic latitude may deviate from the geographic latitude by as much as 2000 km, the information that can be safely extracted from paleomagnetic data is much less definite than is ordinarily reckoned. Moreover, recent advances in multi-component remanence analysis of rock samples cast doubt on many of the earlier results, though obtained from 'acceptable' data (Storetvedt *et al.*, 1978).

PLATE TECTONICS

The concept of continental drift on one hand appeared to solve a number of paleogeographical and paleontological puzzles, but on the other hand it obviously created a host of new questions with regard to the physical property of crustal materials on a global scale. Structural geologists had pondered that question before, on a smaller scale and with limited success. Today the problems of large-scale material science are still far from being solved, but since the late 1960's we have entered a renaissance in the mobilistic interpretation of global structures. The Earth Sciences are said to have gone through a revolution by accepting the theory of *plate tectonics*. Most of the ideas incorporated in the theory were not new, but they had not previously been brought together into a unifying theory that readily explained the major structural features on the globe. What distinguishes plate tectonics from earlier precepts is the simplicity of its basic postulates. It states that dislocations within the lithospheric outer shell[5] of the Earth occur along narrow seismic belts, and that the regions in between remain torsionally rigid. These large and underformed regions are called *plates;* they have the shape of spherical caps and do not correspond to the conventional subdivision of the Earth's surface into continents and oceans, with the exception of the entities that underlie the Pacific Ocean. The disposition of the latter, in fact, has enlivened the theory all together. It is the seismotectonic characteristics of the Pacific Ocean and its perimeter which led to the premise that 'plates are created from rising magma along oceanic ridges, spread from the region of their creation, cool off, and become rigid and strong, only to be reabsorbed into the interior by consumption under deep-sea trenches' (Press and Siever, 1974). Thus, based on simple geometric ideas, plate tectonics rapidly provided a profound understanding of continental drift and the evolution of the sea floor, but without making any statements at all about the driving mechanism, which is not needed for the description of the motion, anyhow. As McKenzie (1977a) alludes, it is very much this separation of the kinematics from the dynamics that simplified the subject to the point where it was ensured its aficionados.

The principal method used to determine the *direction* of relative motion is the focal mechanism solution of earthquakes. This method makes use of the World-Wide Standard Seismograph Network (WWSSN), which was

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[5] The *lithosphere* includes the Earth's crust and the uppermost layer of the Earth's mantle; its total thickness varies from a few tens of kilometers under the tectonically active areas to over one hundred kilometers under the more stable regions. Beneath it is a 'softer' layer called *asthenosphere* where the velocities of seismic waves slightly decrease (Low Velocity Zone). The theory of isostasy assumes that there compensation takes place by flow. The theory of plate tectonics considers this zone a 'lubricant' for the laterally sliding lithospheric caps. To theoretical petrologists the zone is a likely site for partial melting and thus for the generation of magma.

installed in the early 1960's in order to monitor underground nuclear tests. The method is effective for earthquakes of intensity 5 and up on the Richter scale. Depending on the geographic location of the earthquake, a three-dimensional radiation pattern of the first arrivals of body waves can be reconstructed and consequently the orientation of the deviatoric stress at the focal point determined. The result appears on the map as focal sphere projection, which is divided into quadrants of initial rarefaction (blank) and initial compression (black). In terms of the mechanism solution of the seismic events, these quadrants contain the axes of maximum compressive stress (P) and minimum compressive stress (T), respectively. The dislocation itself, however, is not uniquely defined; it still depends on a number of assumptions. An orientation consistent with the geometry of the surface structures is, however, customarily preferred.

Divergent margins, where new plate is added, are called *constructive*[6], and convergent margins, where plate is destroyed, *destructive*. Offsets within such boundaries, or displacements between them, necessitate a *transform* element (Wilson, 1965). Along the latter type of boundary the plates simply slide past each other; no surface area is added or eliminated. By implication, the trend of the transform fault corresponds to relative motion vectors. Because the lithospheric plates are constrained to move on a *spherical surface* the trend of the transform ought to reflect a small circle to the virtual pole of relative rotation between the two plates. Under the assumption that the plates are rigid, their change in position can be described by an *angular displacement* about that pole (Euler's theorem)[7]. The finite rotation of a body[8] about a fixed point has direction (axis of rotation) and magnitude (angle of rotation), but it is *not* a vector quantity as it does not obey cummulative addition. Consequently, the inversion of rotation—the reconstruction of past plate boundaries—leads to histories of appalling complexity (Hobbs, *et al*, 1976). Only coplanar and *instantaneous* axis of rotation can be treated as velocity vectors (they are pseudovectors, see McKenzie and Morgan, 1969). Any attempts at a numerical modelling of a global plate kinematics, therefore, have to be confined to instantaneous relative motion (Minister *et al.*, 1974). It is for this reason also that the study of plate kinematics, on one had, has appealing predictive capability, but on the other hand, is rather constrained in its analytical resolving power (Dewy, 1975).

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[6] It should be noted that in the geologist's traditional terminology these terms have been used in the opposite way: belts of crustal compression are referred to as *constructive*, and belts of crustal extension, *destructive*.

[7] When Bullard *et al.*, (1965) produced the celebrated fit of the 500 fathom lines of the Atlantic coasts, their computer program was bsaed on *Euler's theorem* (which states that any motion on a sphere is a rotation about a pole of rotation that contains the center of the sphere). Bullard's computer program was the first application of this 200-year old theorem to megatectonic problems.

[8] For the mathematical treatment of rigid body rotation see Shonle (1965).

Seismic strain release in the form of elastic waves is the only direct information that can be obtained from the interior of the Earth. Seismic events occur at a *strain rate* of 10^5 per second, like explosions. At this high strain rate any part of the solid Earth is rigid, and the entire Earth becomes transparent with respect to seismic waves. From this point of view the siesmologist is correct in his portrayal of *rigid* plates. But deformative processes of such high strain rate merely mark the ultrafast end of the spectrum of tectonic strain rates, which range over twenty orders of magnitude. At lower strain rates the rheologic behaviour will be plastic or viscous, which means, instead of fracture and shatter, identical material may bend or flow. The significance of intraplate tectonism, including expressive seismicity, has been emphasized only recently (Sykes and Sbar, 1974; Sykes, 1978).

Because the outlines of a plate are defined by seismic activity, the notion was correctly introduced as an 'instantaneous phenomenological theory' by McKenzie and Parkar (1967). But unlike other theories, plate tectonics soon proved so successful in integrating diverse geological phenomena into an intelligible picture of the Earth's evolution that it 'passed all its major tests with flying colours' (Hallam, 1973). May be it was just its wide acceptance that also helped to obscure the shortcomings of some egregious extrapolations. For example, the 'instantaneous' character of plate boundaries gave way to the tacit assumption that the character of a plate boundary has been maintained from the time of its inception. It is only after a decade of world-wide testing that the short-lived nature of seismically defined plates again is being appreciated. By 1976, in order to stress this very point, the Inter-Union Commission on Geodynamics even suggested that the term be changed to '*actuo-plate*.'

To the question of how recent in geologic time seismic belts may have developed, clues are suggested by the patterns discernible in one of the most earthquake-prone regions, namely the Middle East. In this segment of the Alpine orogenic system, the principal tectonic units began their development in the Upper Cretaceous. By Middle Miocene time, major thrusting and folding was largely completed, except for the upfolding of the Zagros Ranges, the Makran, Baluchistan arc, and the latest phase of compression in the Alborz and Kopet Dagh. For the rest of the region, from the Afghan Ranges to the Aegean Sea, Late Miocene to Recent tectonics has been dominated by vertical displacement, accompanied by widespread volcanicity. The topography of the present land surface, as also the bathymetry of the adjacent marine depressions, results from Pliocene to Recent movements, which appear to be largely independent of earlier structural trend. Some of these neotectonic elements run strikingly transverse to the general orogenic trend, such as the uplift of Caucasia and Armenia, or the collapse of the Aegean region, which began in the Pliocene only. Except for the belt of shallow earthquakes beneath the Pliocene to Recent Zagros fold belt, the pattern of seismicity does not readily relate to any structural grain of the region. Instead, the stresses deducible from seismic events more likely point toward future structural configuration than reflecting past tactonic history. It is for this reason that the 'plate' models proposed for the reconstruction of any part of this region were bound to fail. For the Aegean in particular an assessment is found in McKenzie (1977b).

Although entirely different in physiography and internal structure, the Himalayan arc bears a resemblance to the Zagros Ranges. The resemblance relates primarily to the peri-cratonic setting of these commensurate Neogene belts, each being built onto the edge of a Precambrian shield. But in each case also the pattern of seismicity appears to be compatible with the Neogene history of the belt. For the Himalaya in particular, the deviatoric stresses deduced from seismic events are so consistent with the prevalent low-angle thrust tectonics of the mountain arc that Toksoz and Bird (1977) proposed a cognate dynamic process for its entire history, with the process continuing still at a convergence rate of 1 cm/year. Moreover, it appears that consensus has been reached about the elementary building blocks of the Himalayan arc: Sialic crust, capped by marine platform sediments, was sheared and sliced in the process of a north-south convergence. The fracture-slices piled on top of each other thus producing today's structure, the total crustal shortening of which is estimated to be 300-500 km (Gansser, 1966; Mattauer, 1975; Warsi and Molnar, 1977). Because these movements are in progress since at least the Middle Miocene, their rate averages 1-2 cm/year, depending on the time of onset.

EVOLUTION OF THE INDIAN OCEAN

The theory of continental drift was not concerned with processes that take place beneath the ocean floor. Interest in such questions arose only with the advent of novel exploration tools developed during the Second World War. The echo-sounder in particular made the 1950's a time of major oceanographic discoveries, with research focused on two important geomorphic features: the oceanic ridges and their fracture zones. From these studies it became apparent that the continents do not plow like rafts through a sea of basalt as Wegener (1912) had envisioned. Instead, the continents are conceived to be carried passively on a mantle that is overturning due to thermal convection (Holmes, 1929). In his 'geopeotry' of 1962, Hess identified the major oceanic ridges as the sites where hot mantle material comes to surface and virtually forms new crust. He proposed that in this way the ocean floor is so generated continuously along the linear, fissured ridges, which he considered transitory in nature, having a life of 200 to 300 m.y. in concordance with the life of the convecting cell. He noticed that in due time the whole ocean would be 'virtually swept clean' by this process for which Dietz (1961) aptly coined the term *'sea-floor spreading'*. Hess did not fail to conclude, moreover, that the Indian Ocean, like the Atlantic, is surrounded by 'trailing edges' of continents, which move away from the centers of spreading. In contrast the Pacific Ocean is faced by strongly deformed 'leading edges' of continents which impinge upon the downward moving limbs of the convecting mantle.

The recognition of the sea-floor spreading process provided geophysicists and geologists alike with a long needed rationale for the inevitable formation of new ocean basins between the fragmented and dispersed supercontinent Gondwanaland. It now became apparent that the Indian subcontinent, while drifting away from Australia and Antrarctica, never had to cross the present Indian Ocean. Instead, the ocean formed behind its trailing edge. This means, in turn, that the northward flight of India and its collision with Eurasia is intimately tied to the history of the Indian Ocean. Gansser (1966) was first in venturing the idea that the disposition of the structural elements in the Indian Ocean is genetically related to that of the Himalaya. In particular, the surprisingly straight meridional lineaments were considered pertinent, namely the Chagos-Laccadive Ridge and the Ninetyeast Ridge, the world's longest lineament (4800 km). However, neither of these ridges can be attributed to past or current sea-floor spreading. Such processes are seemingly confined to the 'Mid-Indian' Ridge, which consists from north to south of the Carlsberg, Central Indian, Southeast Indian, and Southwest Indian Ridges. The latter branches connect the 'Mid-Indian' Ridge with the Pacific-Antarctic Rise and the Mid-Atlantic Ridge, respectively.

The crest of spreading oceanic rises are earmarked by colinear patterns of *magnetic anomalies*. These are intensity variations in the present-day geomagnetic field measured at or above sea level with a magnetometer towed behind a ship or aircraft. The disturbances recorded in this way are typically one or two percent of the total intensity in amplitude and range in wavelength from several kilometers to several tens of kilometers. For a number of years the characteristic colinear patterns had been recognized. But it was only in the wake of the exploration of the Carlsberg Ridge by the International Indian Ocean Expeditions that Vine and Matthews (1963) proposed their celebrated magnetic block structure model of the newly formed oceanic crust. They assumed the oceanic crust to be lithologically uniform and thus related the observed intensity variation in the Earth's magnetic field simply to the compound effect of (1) *remanence* (thermoremanent magnetization of the basaltic layer at the time of sea-floor generation) and (2) *polarity grouping* (intermittent reversals of the geomagnetic dipole field frozen into the spreading ocean floor). In short, Vine and Matthews hypothesized that the observed intensity variations would be caused by a magnetization contrast between normally and reversely magnetized stripes of crustal blocks. L. W. Morley, a Canadian geophysicist, who was then engaged in an aeromagnetic survey of the North Atlantic had conceived the same idea before but was not able to publish it in any reputable journal. In his unpublished manuscript, however, he poignantly remarked that "this explanation has the advantages over many of the others put forward that it does not require a petrologically, structurally, thermally, or strain-banded oceanic crust.'[9]

If the Vine and Matthews model is correct, it will effectively translate present-day disturbances of the geomagnetic field into geologic time. The age scale of the model is the *geomagnetic reversal time-scale* which is based on the polarity of the remanent magnetization of radiometrically dated lava flows. However, due to the increasing range of error in the dating techniques,t he binary sequence of normal and reverse cannot be extended beyond 4 or 5 million years. It is for this reason that the time calibration of the model had to be done exclusively within the past 3.35 million years, that is, the beginning of the Gauss normal polarity epoch. At first, supporting evidence for the model came mainly from the bilateral symmetry of the anomaly patterns over the Reykjanes Ridge and the Pacific-Antarctic Rise. The symmetry of the latter was discovered during the *Eltanin* voyage 19 (Pitman and Heirtzler, 1966; Pitman *et al.*, 1968), and virtually caused a sweeping conversion of most skeptics. Assuming constant spreading rate for the Reykjanes Ridge, Vine (1966) graphicaly extrapolated and calibrated the reversal time-scale back to 10 million years. The success of his technique led Heirtzler *et al.* (1968) to obtain a similar calibration from the V-20 profile in the South Atlantic back to 80 million years. Under the assumption that the ocean floor has been spreading at a constant rate (determined from the past 3.35 m.y.), the authors dated graphically all major intensity peaks of the profile and numbered them as anomalies 1 through 32. With this extrapolation from the Present back to the Upper Cretaceous, the reversal time scale became extended by another order of magnitude. More important, over wide portions of the world's oceans the increments of crustal growth could be dated magnetically, because the anomalies are considered crustal 'isochrons'. But the authors also did not fail to warn the unwary reader about the daring assumptions implicit in the calibration of what has since become the standard numbering of marine magnetic anomalies. There had been no need for that, however, as only two years later both the magnetic source block model and the extrapolated dating of the South Atlantic magnetic anomaly pattern stood their critical test by the Deep Sea Drilling transect (JOIDES Leg 3; Maxwell *et al.*, 1970). That out of those nine drill sites, the lithologies of only one accords with the predicted model will probably be of greater interest to the historian of science than it was to bigoted contemporaries.

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[9] L. W. Morley's unpublished manuscript was eventually included in an aticle on 'Canada's Unappreciated Role as Scientific Innovator' in the Saturday Review of September 2, 1967.

For the entire year 1972, the DSDP drilling vessel *Glomar Challenger* was assigned to the sampling of the floor of the Indian Ocean (JOIDES Legs 22 to 27). This made it possible to check the validity of the proposed reconstructions and to verify some of the events that contributed to the formation of this ocean, at least since Late Cretaceous time. On first approximation and in a general way, the drilling confirmed the proposed structural scheme. On closer inspection, however, the pattern of sea-floor generation turned out to be more complex and in some areas significantly different from that previously postulated. At several sites intrusive dolerite sills and baked sedimentary contacts were cored. Such manifestation of off-ridge igneous activity is in dissonance to the sea-floor spreading model. Moreover, there appeared to be systematic differences between the biostratigraphical ages obtained from the sediments directly at the contact with basaltic rocks, and the 'magnetic' ages deduced from the interpretation of the magnetic anomalies. Nevertheless, the drill data can be made consistent with ridge-centrered spreading histories in the Arabian Sea and the Central Indian Basin where the age of the crust appears to increase from south to north. The Central Indian Basin is bounded by the Ninetyeast Ridge whose volcanic rocks are of Paleocene-Eocene age in the south and of Upper Cretaceous age in the north, too. East of the ridge, however, in the Wharton Basin, the age of the crust apparently increases from north to south. According to Sclater and Fisher (1974) this may be explained by spreading from a ridge that existed in Early Tertiary time but has now disappeared into the Java Trench. The change of polarity in crustal growth across the *Ninetyeast Ridge* is thought to confirm the supposition that the outline of this peculiarly straight ridge originated from transform motion in Late Cretaceous to Oligocene time. The volcanic rocks recovered from the crest of the ridge are subaerial flows and ash layers of tholeiitic composition. They differ mineralogically and chemically from the 'Mid-Indian' Ridge basalts in the same way as Icelandic tholeiites differ from Mid-Atlantic Ridge basalts. At 10° S, coal was found to be associated with the Paleocene-Eocene volcanics. A rapid but diachronous sinking of the ridge is indicated at all sites by a change in sedimentary facies and faunal content. At its northern end, the Ninetyeast Ridge is buried beneath the Miocene to Recent *Bengal Fan* whose turbidite deposits spread into the Central Indian Basin over a distance of 3000 km and also reach far into the Wharton Basin (Nicobar Fan). The modern fan accumulation is some 4 km thick in the Bay of Bengal; beneath its landward extension, which is the *Bengal Basin*, there is an additional 12 km of clastic sediments, most of it of supposedly Early Tertiary age (Sengupta, 1966; Alam, 1972). The eastward deepening Bengal Basin and the Nicobar branch of the modern deep-sea fan occupy the foredeep in front of the Indo-Burma Ranges. This active foredeep extends along the Andaman arc into the Java Trench (Curray and Moore, 1971; Eguchi *et al.*, 1979).

From the data and conclusions presented it appears that the latest chapter in the evolution of the Indian Ocean accords fairly well with the known tectonic history of the Himalayan arc. But what about the more obscure pre-Miocene events, the geological record of which is much more fragmentary? The answer to this question follows from the application of geophysical data, mainly magnetics, to large-scale tectonic problems in general. Most confident in this novel approach were probably McKenzie and Sclater (1973) when they noted that 'a geologist's life is too short for him to study a large part of a major mountain system in any detail'. In particular, 'the rocks that form the Himalaya have been so strongly deformed and eroded that it is not possible to discover the extent of the relative motion of India and Asia from the study of the rocks themselves. That left the ocean as the only other place to look for evidence of a collision'.

There is, of course, nothing wrong with shipboard gadgetry. But when it comes to evincing matters of continental geology the landlubber tends to be alert. And so it has not escaped his attention that a whole decade of worldwide research did not turn up a single marine magnetic anomaly that could be attributed to remanence and polarity grouping, the way Vine and Matthews assumed. On the contrary, the deep penetration of the oceanic crust on the Mid-Atlantic Rigde (JOIDES Leg 37, IPOD Legs 45 and 46) and in the western central Pacific (IPOD Leg 61) have clearly demonstrated the *interferential* nature of these anomalies, the source of which cannot yet be identified (Strakhov *et al.*, 1971; Drake, 1975; Hall and Robinson, 1979). It now appears that all those factors which Morley in the early 1960's had listed as discountable, in fact, are quite important, namely variation in rock types, thermal field, tectonics and ambient stress-strain in the oceanic crust (tectonomagnetism). In short, the widely accepted magnetic 'isochrons' ended up by becoming another fallacy that the Earth Sciences had to endure. Ironically, this 'simplest and most powerful technique for deciphering the history of oceanic crust' also remains to be one of the 'most important tools for measuring plate motions past and present' in the words of Chase *et al.* (1975).

With regard to the spreading of the Indian Ocean it is useful, moreover, to refer to the fundamental analysis of symmetry characteristics by Schouten (1971). This study points out that the widely observed symmetry of marine magnetic anomaly patterns can not readily be created by polarity reversals only, because of (1) latitudinal effects and (2) the deviation between spreading axis and isogon. Consequently, on a mobile Earth the proper application of the Vine and Matthews model would require the convolution of any observed magnetic 'signature' (a technique that so far has been applied to the correlation of sets of presumed Mesozoic marine magnetic anomalies only). In this context it is interesting to note that in their original paper on the Carlsberg Ridge, Vine and Matthews (1963) had invoked already a latitudinal effect in order to account for the marked negative axial anomaly of the ridge.

If the magnetic 'isochrons' are fallacious, indeed, why then does the the technique work so well for deciphering the history of ocean basins? The answer may lie partly in the vested interest that leading scholars have accumulated in the technique. But even so, the main reason appears to lie in the close association between a magnetic anomaly (disturbance in the present-day magnetic field) and the structural grain of the crust, with currently active structural patterns playing the dominant role. For the purpose of a qualitative structural analysis, therefore, sequential trends, truncation and superposition may be discernible from the magnetic anomaly pattern, as is clearly the case with the major patterns in the Indian Ocean. To measure virtual increments of growth, however, and so calculate rates of spreading requires the substantiality of the Vine and Matthews model, which proved to be incorrect. From the maverick point of view of this writer, therefore, the oceans in general and the Indian Ocean in particular do not hold the propitious yardstick with which the landlubber can henceforth calculate the extent of the pre-Himalayan collision.

NORTHWARD FLIGHT OF INDIA

At this time and in this age of directed research, when consensus is all, the Establishment is alert to heresy and eager to drag the skeptics to the stake (McArthur and Pestana, 1975). And yet, truly amazing ambiguity surrounds the celebrated 'northward flight' of India, although friend and foe concede that substantial relative motion between India and Eurasia has occurred. But what divides them still is the question of *how much* and *at what times*? From the structure of the Himalaya the amount of Miocene to Recent displacement appears to be reasonably well established with figures between 300 and 500 km. Much more difficult, however, is the assessment of the Late Mesozoic and Early Tertiary displacement which resulted in closing of the Tethys Sea. It is this question that poses the real challenge, and pitfalls. So far three different approaches to this problem have been mentioned: (1) Patrons of the *congruence principle* try to establish India's place of origin in the Gondwana re-assembly. Any of these geometric solutions obviously concur with the notion of relative motion between India and Eurasia but do not provide a reference for the absolute displacement. (2) *Paleomagnetic* data, in theory, should provide the information sought. In practice, however, it is almost impossible to establish a precision that is commensurate with the tectonic problem. (3) To measure the amount of sea-floor spreading from the pattern of *magnetic anomalies* is tenuous at best, although firmly believed in by its practitioners. In the case of India, again, marine magnetics, even at face value, would merely provide a figure for the dispersal of the Gondwana fragments and not for the absolute motion the '*Greater India*' *concept* (Veevers *et al.*, 1975; Powell and Conaghan, 1975). The pre-Himalayan Indian subcontinent, presented in this manner, had to include an additional surface area that is commensurable with the present Tibetan Plateau. Specifically, the paleogeographic outline of extra-Peninsular India is surmised on the basis of the abnormally thick crust we find today. However farfetched this reconstruction may be, on the Cretaceous Gondwanaland re-assembly it neatly fills an open space alongside southwestern Australia (Johnson *et al.*, 1976). In terms of paleogeography, the 'Greater India' concept surmises the former northern edge of Gondwanaland to have lain along the Indus-Tsangpo suture, where the Tethyan seaway had vanished by the Middle Focene. In post-Oligocene time, the supposedly intercontinental shortening commenced by way of larger-scale underthrusting of the sialic block all the way to the northern rim of the Tibetan Plateau. This requires an underthrusting over a width of some 2600 km, which is difficult to conceive, as many authors admit.

A drastically different interpretation, known as the '*Greater Gondwana*' *concept* (Crawford, 1974) appears to be better in tune with geodynamic traits as well as geological data. India and Tibet are considered part of the same Gondwanaland fragment, with the Himalayan mountain arc (and its Late Mesozoic predecessor) formed entirely within the 'Greater Gondwana' fragment proper. Contrary to the traditional assumptions, this concept holds that India's Gondwanaland extended much farther northwards. The virtual juncture between the northern and the southern continents is envisaged beyond the Tibetan Plateau, namely along the Tien Shan. The evidence for this emerging view is based on lithological and regional tectonic conisderations rather than compelling paleontological data though. Still, it is significant, as Crawford (1974) remarked 'that the characteristic Gondwana rocks of Upper Paleozoic-Mesozoic age, of glacigene, sub-aerial, fluviatile or lacustrine facies, do extend across the Himalaya into western Tibet and into Skkim and southern Tibet'.

'Greater Gondwana', as envisaged by Crawford, has been the prelude to the growing notion of *mobile platform tectonics* (Ray, 1976) that evolved along the northern periphery of the Indian Shield as did the Afghano-Iranian platform with respect of the Afro-Arabian craton. In particular, Stöcklin (1977) brought together some striking stratigraphic and structural correlations that exist between the Alpine ranges of the Middle East and those of central Asia. He concludes that the main part of the Iranian Ranges (the Alborz and the vast Central Iranian region) structurally corresponds to the Transhimalayan realm, that is the Pamirs, Hindu-Kush, Karakorum, and probably to Alpine structures in Tibet. The Himalaya proper has no structural continuation, neither east nor west, but they are intimately associated with the Indian craton, as the Zagros Ranges are with Arabia. Of striking continuity, on the other hand, are the belts of Tethyan ophiolite. These extend from

Cyprus and southern Turkey to Iran, Baluchistan, and around the Nanga Parbat spur to the Indus-Tsangpo suture zone. They are considered the remnants of oceanic crust that had developed in the course of Mesozoic time along a major zone of separation between stable platforms to the south and mobile platforms to the north. Stratigraphic correlations between the Himalaya, the Karakorum, and Tibet are tenuous still. Nevertheless, in all three regions a shallow marine platform environment seemingly prevailed from Early to Late Paleozoic time (Bassoullet *et al.*' 1977). Crawrord (1974) envisioned that India and Tibet then consisted of 'one huge crustal unit, the southern half emerged, the nothern half submerged'. Although lateral facies changes within these Paleozoic sequences point to episodic oscillatory movements, actual folding is not known, except for the northern rim of the Tibetan Plateau where two orogenic events of *Hercynian* vintage are recorded (Chang and Cheng, 1973). But in Permian time widespread rifting began to affect this supposedly coherent crustal unit, with major fractures of dominantly latitudinal trend. On the Indian shield and presumably within the Lower Himalaya too, Gondwanic rifts are still discernible. But farther north they had expanded seemingly into simatic ocean troughs, as can be concluded from the formation of ophiolitic belts and distinctive sedimentary facies changes during Mesozoic time. By analogy with the Middle East, the major break and separation is thought to have developed along the site of what is now the Indus-Tsangpo suture (Crawford, 1974; Stöcklin, 1977). In the context of such changing paleogeography between India and central Asia, the postualted interaction between Gondwanic and Tethyan biota is of particular importance. Within the Himalayan segment such inter-fingering has been established (Gansser, 1964). But to what extent the Gondwanic reached into central Asia is still a matter of dispute.

DERIVATION AND CLOSING OF THE TETHYS SEA

Ever since Hayden (1904) investigated the fossiliferous strata of the Spiti synclinorium, geologists have been aware that within the Great Himalayan Range the floor of the *Tethys Sea* (Suess, 1893) is now stacked up to lofty heights. It must be remembered, however, that in the Himalayan region this seaway ceased to exist some 60 or 50 million years ago due to major shoves, generally referred to as *Eoalpine* movements.[10] On the other hand, the present mountain scenery along the northern boundaries of India came into being only during the past 20 million years or so. These movements, referred to as Himalayan, have effectively obscured the history of the Tethyan realm and now leave the inductive field geologist with some tantalizing problems. But there are, of course, those elegant shortcuts via deductive reasoning. In recent years it has become axiomatic also that the Permo-Triassic reasembly

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[10] De Terra (1936) called these movements the '*Karakoram phase*' of Himalayan folding.

of Wegener's *Pangaea* leaves a large, wedge-shaped ocean separating India from central Asia. This ocean realm, called *Extra-Tethys,* is assumed to have been underlain throughout by oceanic crust. In the course of Mesozoic time, and extending into the Cenozoic, this large ocean vanished completely. It disappeared, seemingly into the upper mantle, under one or both of the continental margins around it. Widely accepted, though, this premise is at variance with many aspects of Alpine-Himalayan geology. Particularly relevant to the problem are the Tethyan *ophiolites*, the only tangible evidence of assumed former oceanic crust[11]. Ironically, the sequences that constitute the ophiolites are remants of marine basins which themselves came into existence only in the course of Mesozoic time, and thus hardly square with the vanishing of that pre-Triassic ocean, assumed to have been larger than Africa in size.

The key to the understanding of the history of the Tethys Sea appears to lie within the Indus-Tsangpo suture (Frank *et al.,* 1977; Gansser, 1977). This fundamental junction parallels the arcuate trend of the Neogene to Recent mountain ranges and delineates both structurally and physio graphically the northern extent of the Himalaya. Like the Zagros thrust zone in Iran, the Indus-Tsangpo suture marks and masks the site of major orogenic events in Cretaceous and Early Tertiary time. It is here that a substantial tract of Mesozoic sea floor fell victim to severe crustal foreshortening. In the form of a shallow shelf structure Extrapeninsular India then extended much farther to the north. Himalayan structures had not yet been formed at all, except for the 'exotic' thrust sheets, which were being shoved

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[11] The tectonic and paleogeographic significance of *ophiolites* has been a controversial question ever since G. Steinmann in 1905 recognized the intimate association of greenstone (pillow lava, gabbro, variably serpentinized peridotite and dunite) and radiolarian chert in the Mesozoic sequence of the Alpine-Mediterranean fold belts. The mafic igneous rocks of the sequence, extrusive and intrusive in nature, and associated with sediments of presumably deep-sea origin, have been regarded as axial elements of the Tethys Sea. Thus, by definition, ophiolites have always been equated with ancient ocean floor. But controversy arose with regard to the origin and mode of emplacement of the igneous rocks. The difficulty of interpretation is due to the severe deformation and physicochemical transformation most of these rocks have undergone after their formation.

Petrologists debate whether the ultramafic and mafic igneous rocks could be coevally generated (syngenetic model) or reflect diachronous and unrelated magmatic events (polygenetic model). Evidence has been cited for both views, although the ultramafic rocks usually predate the rest of the igneous suite. The proponents of the polygenetic model distinguish between the *locus of formation* and the *site of emplacement*. They point to the similarity between ophiolites and the petrology of present-day ocean floors and therefore call for tectonic processes that (1) move mantle material (ultramafics) upwards, (2) create ensimatic crustal segments (sea-floor spreading, oceanization), and (3) emplace slices of thus formed ocean crust onto the edges of adjacent continents. However, the multitude of events makes it ardous to define more specifically the paleogeographic or palinspastic setting of ophiolitic belts.

onto the present Tethyan Himalaya. The latter were then the inactive continental margin of India along the southern border of the Tethys Sea (Stoneley, 1974).

The petrotectonic assemblages contained in the 'exotic' thrust sheets—ophiolitic mélanges and large sheets of peridotite—document the presence of simatic crust within the Tethys realm. But fossil data relates the formation of such ensimatic basins to the Mesozoic, predominantly to the Cretaceous. By analogy with the Tethyan ophiolites in Asia Minor and the Middle East the history of these ensimatic basins implies tectonic regimes of repeated crustal distension and spreading along elongated tracts of limited extent. For the Indus-Tsangpo suture zone, in particular, Gansser (1977) suggests a basin width on the order of 300 to 500 km.

In Turkey and Iran, the development of ophiolitic troughs began within a formerly continuous platform of Precambrian vintage which seemingly was connected to the Afro-Arabian craton. Along the northern bounds of the Indian shield an analogous peri-cratonic regime is suspected. Indeed, the evolutionary pattern of the peri-Arabian ophiolitic 'crescent' (Ricou, 1971) is amazingly similar to the 'Axial Belt' of the Baluchistan arc which extends through the southern front of the Hindu-Kush and Karakorum in the Indus-Tsangpo suture zone. At the eastern end of the Himalayan arc, related ophiolites and ultramafics occur in the Mishmi Hills, and farther south become dominant once more in the backbone of the Arakan Yoma (Indo-Burma Ranges). The peri-Arabian 'crescent' thus has its peri-Indian counterpart. In either case these pericratonic basins appear to have effected the widest known paleogeographic separation and therefore are aptly called *Neo-Tethys*.

As mentioned in the previous section, the separation of the cratonic Gondwanic domains from the postulated mobile platform segments to the north appears to have started in Permo-Triassic time. It is conceivable that the andesitic volcanics of the Western Himalaya (Panjal) and of the Eastern Himalaya (Abor) relate to this event as well. Moreover, the Indian and Afro-Arabian cratons themselves appear to have become separate tectonic entities since that time.

Within the northern mobile platform fragmentation and widening seemingly continued well into Cretaceous time. Nevertheless, it is important to note that within this particular domain of the Tethyan realm folding and granitic plutonism of *kimmerian* age[12] also brought about regroupment

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[12] Eduard Suess called attention to the pre-Cretaceous folding of Mesozoic strata on Crimea and in Dobruja; he introduced the term *Kimmerian* to designate this fold belt. (The Kimmerian Peninsula form the eastern spur of Crimea..) On closer inspection, however, it turned out that this area, including the Greater Caucasus, had experienced two episodes of major movements, one at the Triassic-Jurassic boundary and one in the Upper Jurassic. Subsequent authors therefore used the terms Eokimmerian and Neokimmerian (Nevadan) for the two events.

and consolidation within selected belts. Today this domain can be followed from Armenia through central Iran, Afghanistan, and Hindu-Kush, Pamirs and Karakorum into the Transhimalayan highlands of Tibet (Vialov, 1939; Stocklin, 1977). In Eoalpine time, the southern fringes of the same domain became the site of large-scale foreshortening, which effected the closing of the Neotethyan throughs. In the course of these Late Cretaceous thrust movements, the debris of the Mesozoic oceanic crust was partly *obducted* onto the margins of the southern craton, while a larger part is thought to have been removed by *subduction.*[13]

Further information on the Eoalpine events of the Himalayan region may be extrapolated from the backbone structures of the Kirthar-Sulaiman Ranges and Arakan Yoma, which fringe the Indian shield in the west and east respectively. But it is important also to note that imprinted on the shield itself one finds Late Mesozoic and Cenozoic structure patterns that are remarkably informative with regard to the Alpine-Himalayan orogeny.

DECCAN TRAPS AND THE CAMBAY-MALDIVE LINEAMENT

The evolution of the Deccan volcanic province sheds light on important events that affected the Indian craton while farther north the Tethys Sea began to vanish and the Eoalpine orogenic system developed at the Tethyan site. The formation of the *Deccan basalt plateau* was preceded by a marked period of quiescence, which lasted through most of Cretaceous time, and which resulted in a widespread peneplanation of the emergent subcontinent. In the Upper Cretaceous, as it were related to Eoalpine events, this peneplain was uplifted, faulted and subsequently dissected by a younger cycle of erosion. The resulting landscape is still seen as an undulating erosion surface at the base of the Deccan basalt flows, which also buried fluviatile and estuarine beds of Cenomanian-Senonian age. The basaltic flows are all of subaerial origin. They are intercalated by lacustrine and alluvial deposits which occasionally contain Palaeocene to Lower Eocene fossils, including plant and vertebrate remains. The basalt (trap rock) covers an area of more than 500,000 km^2 and reaches an aggregate volume in excess of 10^6 km^3. Isolated remnants suggest that at one time the basalt plateau may have extended over twice the present area (Aswathanaraiana, 1972). On its eastern margin the basalt plateau is rather thin (100-200 m). It thickens westwards to an average of 600 m and, approaching the west coast, the pile of lava flows increases rapidly to more than 2100 m near Bombay. The bulk of the flows is of tholeiitic composition. But alkali basalt terminated the build-up of the plateau in the coastal region, where during the late phase hypabyssal intru-

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[13] Simatic crust which is tectonically emplaced onto a sialic substratum is said to be *obducted,* while lithosphere of any genre unaccountably disappearing into the abyss is said to be *subducted* (Coleman, 1971).

sions were emplaced, such as the gabbro-diorite-syenite complex of Girnar Hills in the northwestern coastal region.

A restricted area of tholeiitic flows in northeast India (Rajmahal traps) may represent the initial phase of plateau basalt eruption at the end of Lower Cretaceous time. It is conceivable that these eruptions were related to the pre-Deccan uplift of the region. In view of these early flows and the general westward thickening of the otherwise Upper Cretaceous-Eocene Deccan traps, an overall migration of the igneous activity from east to west has been proposed. However, recent stratigraphic and radiometric dating do not support this notion. Rather, the present coastal belt of west India is considered to be a zone of intensified tectonic and igneous activity throughout the history of the Deccan province. In the vast trap country of central India some of the flows have been traced continuously for 100 km or so, a result that led speculation about long-distance flooding from feeders in the west. Nevertheless, it would appear unreasonable to attribute all flows to distant sources in spite of the notable absence of feeder dikes. Conversely, of all the visible dike swarms, those running N-S parallel the Bombay coast and those along the E-W course of the Narmada River, postdate the build-up of the Deccan basalt plateau and merely relate to post-Deccan faulting and flexuring (Auden, 1949). The two trends, roughly normal to each other, played an important part in Cenozoic tectonics of the subcontinent. Both are inherited from the grain of the Precambrian shield. The significance of the N-S trend, however, has come to light only recently through oil exploration in west India and along the shelf off Bombay.

The Deccan traps originally extended for an unknown distance to the west and a large part of the trap country must have sunk beneath the Arabian Sea off the present coast line, which owes its course to post-Trappean vertical displacement. The Bombay coast in particular is shaped by the 400 km long *Panvel flexure* and its associated dike swarm. On the north, the coastal flexure flanks the Gulf of Cambay and extends into the fault-bounded *Cambay trough*, which is of Early Tertiary age. Southward, the meridional trend of the flexure is taken up by the Maldive Ridge off the southern tip of India. Combined with the meridional structures in the trap country of west India, the Maldive Ridge forms a remarkable lineament, and it appears to be more than a coincidence that its northward projection runs into the western syntaxial bend of the Himalaya, just as the projection of the Ninetyeast Ridge corresponds to the eastern termination of the Himalayan arc. But so far the history of the Cambay-Maldive lineament has been unravelled only for the segment of the Cambay trough, whose development may be diagnostic for the entire element. In the Cambay area the stack of Deccan traps was faulted down by 3 to 4 km. In the south, where the Cambay trough is intersected by the post-Miocene Narmada rift, the top of the traps has subsided to as much as 5,800 m (Raju *et al.*, 1972). There are indications that active subsidence along the graben axis had already begun during the time of Deccan basalt eruption, as the traps forming the graben floor are of Upper Cretaceous age. The graben fill consists mainly of Paleocene-Eocene sediments, which refer the major subsidence to Paleocene time. It is noteworthy that the Maldive Ridge, too, subsided some 2000 m at the Paleocene-Eocene boundary (JOIDES Leg 23a, drill site 219). The subsidence along this lineament may have been contemporaneous with the late intrusions already mentioned from the coastal belt. Along this meridional trend differential vertical movements continued in post-Eocene time but were minor in comparison to these Early Tertiary events. Nevertheless, Neogene to Recent movements caused the entire block of south India to be tilted to the east. Quaternary displacement and high heat flow along the west coast are signs of ongoing crustal deformation. Moreover, the coninental crust of south India thins markedly across this meridional structure, from 40 km beneath the Western Ghats to 17 km beneath the Maldive Ridge where the crust is assumed to be of intermediate type (Narain *et al.*, 1968). West of the Ridge it is assumed to take on an oceanic character and a thickness of merely 6 km beneath the abyssal plain.

LATITUDINAL RIFTING AND EASTERN SPUR OF THE PENINSULAR SHIELD

The far-reaching geotectonic implications of Late Paleozoic rift patterns became apparent from the discussion on the 'northward flight' of India and the derivation of the Tethys Sea. Although a major break and paleogeographic separation is attributed to the latitudinal Indus-Tsangpo suture zone, rifts of similar trend are thought to have broken the coninental crust now stacked up in the Himalayan arc (Crawford, 1974; Ray, 1976). Attention has been called especially to the lower nappe system of the Eastern Himalaya where Gondwana freshwater beds are found along a narrow belt over a distance of 1200 km (Acharyya, 1978). These clastic beds of Permian age contain coal measures and, in the extreme east, are associated with serpentinite and andesitic flows (Abor volcanics). The remarkably linear distribution on these now allochthonous rocks, together with their distinctive lithologies, prompted the suggestion of rift origin. In the Central Himalaya, glacigene Gondwana beds are found in a structurally similar position. And in the Western Himalaya, the andesitic Panjal traps are associated with correlative sediments. When reconstructing Late Paleozoic events one should keep in mind, of course, that the Himalayan crustal segment was several hundred kilometers wider at that time.

At the beginning of the Tertiary, when the Deccan basalts flooded the emergent Indian shield, and mobile flysch troughs developed within the Eoalpine system, the Himalayan segment was covered by the shallow Nummulitic Sea. Transgressions and regressions, however, indicate oscillatory movements. Moreover, Eocene alkaline magmatism in the Lower Himalaya connects the Eastern Himalaya with the Indo-Burma Ranges. But recent investigations show that no syntaxial bend exists at the eastern end of the Himalayan arc. Instead there are three separate thrust systems around the Brahmaputra alluvium which covers the eastern spur of the Peninsular shield. The Himalaya encroach from the northwest, the Naga-Andaman belt from the southeast, and the Mishmi Hills from the northeast. The thrust system of the latter appears to be of post-Pliocene age and sharply truncates both the Naga Hills and the Eastern Himalaya. Structurally the Mishmi Hills relate to the Sino-Burma Ranges. Lithologically they contain elements that are reminiscent of both the Lower Himalayan crystallines as well as the Late Mesozoic plutons of the Transhimalaya (Thakur and Jain, 1974, 1975). The palinspastics of this Neogene to Recent superposition of polyvergent thrust systems leads to perplexing geometry and a riddle of crustal kinematics. Although no syntaxial bend exists at the east end of the Himalayan arc, Gansser (1977) notes that in the Lower Tsangpo Valley, in the allochthon of the Lower Himalaya, a concentration of Abor volcanics outlines a 'paleo-syntaxial' structure which in size and shape is surprisingly similar to the active inner syntaxial bend of Punjab.

The significance of *tectonic heredity* to orogenic structures has been the favored subject of many scholars. The setting of the eastern spur of the Peninsular shield, or conversely the Eastern Himalaya, poses a particular challenge to that question. Ever since Auden (1933) hinted at shiled affinities to be recognized within the crystallines of the Lower Himalaya in particular, there has been the question of how much a meridional *transverse trend* may reflect heredity of Precambrian grain (Gansser, 1964). The question becomes especially intriguing where fold structures and linear tectonites of E-W running metamorphic belts display such a transverse trend. The deciphering of the metamorphic rock sequences in the Eastern Himalaya, therefore, will shed new light on this old question. This, in turn, may also establish the presumed relationship between pre-Himalayan structural trends and the positioning of axial culminations and depressions within the present mountain arc. Along similar lines and not less intriguing is the question about the nature and origin of the numerous faults that interesect transversely the Himalayan structures. It appears that *transverse faults* are quite common in the Central and even more so in the Eastern Himalaya. Some of them are morphologically spectacular and hence received attention, such as the Thakkhola graben in Nepal (Hagen, 1968). Several transverse faults are reported to cut the Main Central Thrust, some even the Main Boundary Fault. The time of the faulting appears to range from the Pliocene to Recent, with some of the structures assumed to be seismically active. The observed fault displacements are normal as well as left-lateral and right-lateral strike-slip, thus suggesting block adjustments within the southward migrating and still widening mountain arc.

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