CHAPTER 4

PREVIOUS LITERATURE
ON
AREA AND THEORY
The prime objective of this thesis is to elucidate the morphotectonic evolution of the study area, which lies on the Narmada - Son Lineament, using remote sensing techniques. During the course of research work it was strongly felt that any such attempt would require an immense understanding of the Phanerozoic geology of Central India as a whole, and that of the Narmada - Son Lineament in particular. In the process of development of an evolutionary model on a regional basis, it became clear that the most vital morphotectonic element is that of a multitude of rift valleys which traverse Central India and that Narmada - Son Lineament is but an essential component of it. Therefore, a careful and critical examination of the existing published literature on regional geological aspects of the study area has been carried out (Section 4.1) and an attempt has been made to implement the concepts of 'taphrogenesis' derived from classic studies on other rifts of the world. This inherent regional nature of the problem has made it difficult to avoid mentions of other associated rifts, though utmost precaution has been taken to keep it to the bare minimum.
The "process of building of an evolutionary model", which is by far the most important part of the research work, comprises a detailed study of the comparable but thoroughly investigated and well documented continental rifts of the Earth (including some on the Mars and the Venus), within a framework of the Plate Tectonics theory. A brief account of important developments related to taphrogenesis has been given followed by short explanations of the related terminology in Section 4.2.

4.1 REGIONAL GEOLOGICAL SETTING OF NARMADA - SON VALLEYS.

Narmada - Son line, by virtue of their singularly straight river courses has attracted the attention of geologists since the days of Crookshank (1936). In the light of his monumental work on the geology of the northern slopes of Satpuras, he regarded the Narmada Valley as a rift structure which formed under tensile stress regime at the end of the Deccan Trap period and suggested that after the Deccan Trap era, compression reappeared resulting in crushing of the rocks in the vicinity of the Narmada Rift Valley. Auden (1949 a) regarded the Narmada Valley as a major crustal feature of ancient origin, reflecting subcrustal structure, and influencing the deposition of the Vindhyan and Gondwanas. Auden (op.cit.) suggested that the Narmada Rift originated by prevailing tension in the Late Cretaceous period which finalized the formation of Gondwana rifts accompanied by crustal fracturing, basalt volcanism and crustal subsidence.

West (1962) accelerated the pace of studies on the Narmada -
Son Valleys when he pointed out that north of this line, no Gondwana rocks occur and south of it no Vindhyan rocks are known to occur. Based on this observation, West (op.cit.) concluded that this line is perhaps an ancient line of weakness and that the land to the north and south of this line has been going up and down in the geological past.

Krishnan (1963) mentioned that "The Narmada Valley is well known to be a faulted trough. It is the only zone in the central and western part of India which shows Permo-Carboniferous marine deposits, fluvialite to continental Upper Gondwana (Kota-Jabalpur beds) and fairly thick Tertiaries".

Based on the subsurface information gathered during the Oil & Gas exploration of Broach region, Raju et al. (1971) considered the Narmada fault system to be a subcrustal feature originated in the post-Miocene times and suggested that in the region south of Narmada River, the Traps have been block-faulted into a number of horsts and grabens with a maximum depth of 2500 m for the Trap.

Roy (1971) called the Narmada basin a rift valley formed by the down-faulting of rock formations on both sides though he considered the view to be inconclusive. Based on a study of the crustal deformation in India, Agarwal & Gaur (1972) suggested that a major fault, an E-W rift, 70 km in width is extending along the Narmada - Tapti river systems.
Stressing on the plate tectonic implications of Deccan Volcanism in the Indian plate, Bose (1973) referred to the Narmada - Son Valley and suggested that this E-W trending fracture zone should more aptly be described as Narmada Swell and Rift.

Krishna Brahman and Negi (1973) presented a summary of the results of some geophysical investigations undertaken on the Deccan Traps and proposed Precambrian age for the initiation of Narmada - Son Rifts.

Adyalkar (1975) suggested that the intense faulting and dislocations of the earlier sediments, at the end of Cretaceous resulted in the formation of Narmada - Tapti and Purna Rift Valleys and the basaltic lava was erupted through these fractures in several spells. Pre-, syn- and post-Trap faulting episodes with the latter giving rise to the true picture of the rift valleys as well as the continuation of late phases of rifting upto Middle and Late Pleistocene was suggested.

Ghosh (1976) demonstrated absence of rifting and faulting and suggested that the "Narmada - Son Lineament represents an erosional post-Deccan Trap Narmada Valley formed at the crest of a domal upwarp with tension fractures and probably shallow depression along the crest".

Based on the plate tectonic interpretation Desikachar (1977) called the Narmada - Son Valley region, a rift zone and referred to
an "... east-northeast down-warping of the Indian plate along the Narmada-Son trough simultaneous with the first major uplift of Himalayas as it came into contact with the Eurasian Plate."

Sarkar (1978) postulated large scale vertical movements along the so-called Narmada-Son Megalineament.

Ray (1978) suggested that the comparatively high gravity value along the Narmada-Tapti zone, high heat-flow, high seismicity and the Deccan Trap Volcanism along with evidence of neotectonic movement, tend to indicate that the Narmada-Tapti-Son Lineament is an incipient continental rift.

Murthy and Mishra (1981) put forward geological, geomorphological, geophysical, petrological and mineralogical evidence to establish rift valley structure of the Narmada-Son Lineament (Fig. 4.1 A,B).

Roday (1982) described the overall herring bone lineament pattern for the Narmada-Son belt because the NE trending linears and lineaments north of the Narmada-Son line curve and meet the latter at small or moderate angle. Some of them curve and assume N-S, NNW-SSE and NW-SE trends before joining this mega-lineament (e.g., the Aravalli orographic axis) and appear to merge and become a part of the rhomboidal lineament pattern prevalent to the south of the Narmada-Son line (coming finally to have the NW-SE trends similar to those of Godavari and Mahanadi lineaments).
FIG. 4.1: Geological plan view (A), and cross-section (B) showing structure of the Narmada Rift Valley (After Murthy and Mishra 1981, redrawn by Valdiya 1984).
Biswas (1982) indicated that the Narmada Geofracture is an intracontinental arch volcanic type rift zone of Milanovsky (1972) which originated in the Late Cretaceous period (Fig. 4.2).

Konda (1984) considered alkaline magmatic activity as characteristic of grabens and remarked that "... there is considerable doubt as to whether the tectonism in the Narmada Valley was associated with igneous activity producing a graben type alkali rock. At present, the present writer does not agree that the Narmada Valley is a rift system because of the absence of sedimentation which should accompany the subsidence and thus considers the Narmada Valley to be simply a tectonic zone."

Garson (1984) suggested that the Narmada - Son Lineament acted as a transform fault during the period of carbonatite intrusion and the collisional event.

Considerable difference of opinion about the nature of the Narmada - Son Lineament can be observed from the aforesaid passive scanning of the previous literature. However, other aspects such as the possible lateral extension, the Precambrian ancestry of this Lineament and the probability of wrench fault tectonics have been more vigourously debated, a critical review of which is given below:

4.1 A EXTENSION OF NARMADA - SON LINEAMENT.

Krishnan (1956) thought that the Narmada Valley has suffered dislocation along the ENE - WSW direction continuing into Saurashtra.
FIG. 4.2: Tectonic map of western margin of India showing three rift basins viz. Kutch, Narmada and Bombay (After Biswas 1982).
The existence of a fault bordering the southern part of Saurashtra peninsula — a possible continuation of the Narmada geofracture was suggested by Dasgupta (1967, cited in Roychoudhary & Deshpande 1982). Tipnis and Srivastava (1968 a) showed that the 'Satpura Rift' with Narmada trough at its western end, extends uptio Rajmahal and Sylhet at its eastern extremity. In a reconstruction of Pangaea, the Narmada - Son feature was matched with the part of African Rift System (Dietz & Holden 1970, cited in Garson, 1984). Pal & Sreenivas (1976) supported easterly extension of the Narmada - Son Lineament to the ENE - WSW striking axis of river Brahmaputra thus forming a composite 'Narmada - Son - Brahmaputra Lineament'. Ghosh (1976) suggested that the Narmada upwarping may be a part of the regional mega-lineament extending along north of Chhota Nagpur Plateau to Shillong massif and the syntaxial region of the northeastern Himalayas.

Solokov et al. (1976) showed the Narmada - Son Lineament as a dextral wrench fault and extended it to the Aden basin on the west. Based on gravity and magnetic data Mishra (1977) proposed the extension of the Narmada - Son Lineament from the Murray ridge (Arabian Sea) on the west and the eastern syntaxial bend of the Himalayas on the east and considered it to be a part of the worldwide rift system. On the basis of these postulated extensions of the Narmada - Son Lineament for over 4000 km from Aden basin to the eastern Himalayan syntaxis, Das & Patel (1984) considered it to be a Proto - Plate boundary.

Crawford (1978) suggested that the Narmada - Son Lineament can be traced across north Madagascar due to the Lineament having been
continuous in the Gondwanaland. Sarkar (1978) conducted palaeodynamic investigations of metasedimentary belt of Rajgir, Bihar which occurs on the possible ENE strike extension of the so called Narmada - Son Megalineament. He suggested that the study corroborates the postulate that the Narmada - Son Lineament extends further towards ENE grossly along the metasedimentary belt of Rajgir, and that it occurs as a zone characterized by large scale vertical movements.

Similar geological and tectonic setting as well as the presence of carbonatite bodies led Misra (1979) to postulate the western extension of the Narmada - Son Lineament into southern Saurashtra. Bose (1980) also considered the rift zone of Kutch - Kathiawar region to be the western extension of the Narmada Rift. He further indicated that the Narmada Rift arm may be a reactivated ancient lineament extending beyond the Indian Shield (to Madagascar).

Based on the morphotectonics of the Deccan Volcanics of Kathiawar Peninsula, Subramanyan et al. (1983) suggested that its southeastern coast is shaped by the westward extension of the ENE - WSW trending Narmada fault. Shrivastava et al. (1983) also suggested that the Narmada - Son Lineament is traceable for more than 600 km and appears to have continued upto Haflong thrust in Assam.

4.1 B WRENCH FAULT TECTONICS.

Pal and Bhimasankaran (1976) carried out preliminary palaeomagnetic studies in the central Narmada Valley region to examine the nature of Narmada - Son - Brahmaputra Lineament. They found that the lava sequence on either side of river Narmada, studied
along a NW – SE traverse from Asirgarh to Indore have different flow polarity patterns and thus do not appear to be coeval. They suggested two different models, one involving *rift tectonics* and the other incorporating *wrench tectonics* to explain this observation and favoured the latter, though it was admitted to be an inconclusive inference.

Based on the Bouguer gravity anomaly and palaeomagnetic data, Pal & Sreenivas (1976) favoured a model of Narmada - Son Lineament involving *wrench-fault tectonics* associated with *crustal warping* and *subduction*. Despite nearly identical positions of the Proterozoic and younger palaeomagnetic poles from the Dharwar, Aravalli and Singhbhum protocontinents which suggests that no major displacement of about 500 km may have taken place along the lineament (*op.cit.*), they supported a strike-slip movement of the order of 200 km without assigning a sense of motion along the fault. Self-contradictions in the aforesaid model as well as inclusion of highly improbable subduction process in the model, are obvious and need no special emphasis.

Sundaram *et al.* (1964) also postulated *strike slip movements* along the faults underlying the Narmada - Son and other lineaments, but Powar & Patil (1980) suggested that such movements, if any should have caused the development of an *en-echelon system* of the lower order lineaments which has not been observed during lineament mapping on LANDSAT imageries.

Das & Patel (1984) mapped ten major and several minor faults from Handia to Barwaha area along the Narmada - Son Lineament and
identified them as right-lateral wrench fault system originated by NW-SE regional stress pattern. They suggested that "Narmada - Son normal wrench fault steeply dipping towards south, and Pachmarhi - Jabalpur normal fault dipping towards north constitute a graben structure", and that the Narmada - Son Lineament has existed since Late Archaean which got rejuvenated from time to time. It should be noted that all reported strike slip faults affect Bijawars and Archaean granite except in one case where presumably a Deccan Trap dyke truncating against a strike slip fault is reported (op. cit.), which should, however, be an older dyke as nowhere along the Narmada - Son line, dextral displacement of post-Vindhyan rocks is seen or reported. It is therefore, self-evident that the stress pattern giving rise to the dextral strike slip faulting in Proterozoic times (as Bijawars are also affected), was different from the one which caused successive development of horsts and grabens along the Narmada Rift in Late Palaeozoic and Late Mesozoic periods. This later rifting event, which may have exploited older weakness planes, should be treated separate from the much older wrench-tectonics. Even otherwise, a graben can not be bound by a wrench fault on one side and a dip-slip normal fault on the other.

4.1 C PRECAMBRIAN ANCESTRY OF NARMADA - SON LINEAMENT.

Tipnis and Srivastava (1968 a) suggested that the Satpura Rift, controlled by pre-existing orogenic lineaments situated within the continental shield, is similar to the Baikal rift of the U.S.S.R. Eremenko et al. (1968) believed that the Upper Carboniferous intense movements along ancient faults of the Indian subcontinent resulted
in the formation of several grabens (including Narmada - Son - Damodar and Godavari Grabens) probably along major basement lineaments.

Choubey (1970, 1971 a,b) suggested that a late faulting most probably the rejuvenation of tectonic activity along the ancient line of weakness is, chiefly responsible for the formation of Narmada Rift Valley and thought it to be a deep seated crustal lineament reaching the upper mantle which originated in early Precambrian times. Krishna Brahman and Negi (1973) suggested that all the continental rifts of India including Narmada, Son, Godavari, Koyna and Karduvadi rifts followed Precambrian weakness zones.

Naqvi (1974) discussed the protocontinental growth of the Indian Shield and the antiquity of its rift valleys and wrote:

"It appears that as the Dharwar, Aravalli, and Singhbhum protocontinents grew in size and came nearer due to accretion, a Y-shaped lineament between three protocontinents developed, which probably extended into mantle ... This lineament along with the Mahanadi lineament between the Eastern Ghat nuclei and Singhbhum nuclei, became rejuvenated and developed into the Godavari - Narmada - Mahanadi (?) rift system during the pre-Gondwana period through the process of graben formation."

Choudhary (1977) suggested that structurally weak zones persisted in the Precambrian craton trending ENE-WSW of the Satpura strike in the north and NW-SE of the Mahanadi trend in the south. Murthy & Mishra (1981) and Das & Patel (1984) also believed in the Precambrian or Archaean ancestry of the Narmada - Son - Lineament
and suggested recurring rejuvenation and tectonic activity along the Lineament.

Biswa (1982) surmised that the three craton margin embayed basins - Kutch, Cambay and Narmada - occupy grabens bound by faults which were developed by reactivation along major Precambrian tectonic trends (Fig. 4.2) during the northward migration of the Indian Plate after its break-up from the Gondwanaland in Late Triassic to Early Jurassic. He related Kutch, Cambay and Narmada rifts with Delhi, Dharwar and Satpura Orogenic trends respectively (op. cit.). Batta et al. (1983) also suggested that "the influence of basement anisotropy is often critical in defining the orientation of faults in the graben framework of the Gondwana basins. In some regions, the major faults affecting the basin floor also have developed along pre-existing zones of crustal weakness ...".

Some of the above cited examples which show the Precambrian ancestry of the Narmada - Son - Lineament appear to be a result of the overprinting of Late Palaeozoic - Late Mesozoic rift - tectonics along the craton bounding fault of Satpura orogen and the then Vindhyan molasse, which acted as a susceptible weak zone later to be exploited by the mantle perturbation culminating in the rift - tectonics and Deccan Volcanism (Section 6.3). The question as to how did the uprising material from asthenosphere "know" that an old line of weakness is present in the crust on the top, is best answered by Illies (1974a) by means of an interplay between the beaten tracks of lineaments within the rigid Lithosphere and ascending tendencies of the plastic asthenosphere. Therefore bulging
of the mantle due to the magma formation with attendant crustal fracture propagation, followed by further pressure release and more magma generation in the mantle appears to be a self-perpetuating system. Based on this mechanism Illies (1974a) concluded that an upswelling material of the upper mantle causes taphrogenic cycle, though old weakness zones may induce the ascent of magmatic substratum. McConnel (1974) reported similar set-up in Africa where the Late Archaean taphrogenic lineaments, once established were so modified by a combination of tectonism and penetrative thermal convection that it became preferred channel for all subsequent revivals of activity, culminating in Phanerozoic time in the World-wide rift system of modern global tectonic theory.

Neumann and Ramberg (1978b) suggested that the rifts may form as the passive by-product of inter-plate motion alone (without any sublithospheric thermal anomaly), yet if a plate passes over a thermal anomaly of sufficient magnitude, the chances of it causing penetrative magmatism and rifting are greatest in those parts of the plate which are weak and already under tension.

4.2 CONTINENTAL RIFTS.

4.2.A MONOGRAPHS ON TAPHROGENESIS: A SYNOPTIC VIEW.

The word taphrogenésis (meaning trench formation in Greek) was introduced by E. Krenkel in 1922 in his classical monograph on the East African Rift Valleys. One of the most striking milestone on taphrogenesis was marked by the publication of "Hebung - Spaltungs-Vulkanismus" by Hans Cloos in 1939. Cloos proposed an up-to-date
hypothesis on taphrogenesis of the Rhinegraben of West Germany, and that of continental rifting in general, by means of synthesizing field observations as well as experimental data. He was able to reproduce the structure of graben experimentally by uparching a 'Crust' made of layered moist clay.

Rhinegraben, which is neither the largest, nor the most active, nor the most typical example of continental graben, played key role for understanding the processes and mechanism of taphrogenesis because it is by far the most elaborately explored and studied graben by generations of geo-scientists of various European nations. The Rhinegraben Research Group presented three symposia: "The Rhinegraben Progress Report" (1967) edited by Rothe and Sauer, and the "Graben Problems" (1970) edited by Illies and Mueller were the first two publications to respective symposia. Third part of the Rhinegraben trilogy - "Approaches to Taphrogenesis" focussed on geodynamic aspects of taphrogenesis based on the concepts like plate tectonics, and the publication was edited by Illies and Fuchs (1974).

In the meantime, two special issues of the Journal of Tectonophysics were published; first being "The World Rift System" edited by Knopoff et al. in 1969, and the second one "East African Rifts" edited by Girdler in 1972. These publications immensely contributed to the understanding of the world rift systems.

Another important contribution on the taphrogenesis was a conference on the continental rifts held in Oslo in July - August 1977 under the auspices of NATO Advanced Study Institute. The
proceedings were published in the form of two volumes: "Petrology and Geochemistry of Continental Rifts" edited by Neumann and Ramberg and the "Tectonics and Geophysics of Continental Rifts" edited by Ramberg and Neumann, both in 1978. Subsequently, a landmark in the history of taphrogenesis appeared in the form of the "Mechanism of Graben Formation" edited by Illies in 1974. This Elsevier publication was a collection of papers presented at the 17th I.U.G.S. General Assembly, Canberra, Australia.

Besides the above mentioned hard-core monographs on taphrogenesis, illustrious treatment of certain aspect of rifting process was undertaken in the Royal Society Discussion/Publication "The Evolution of Passive Continental Margins in the light of recent deep sea drilling results" (Kent et al., 1980). An in-depth study of the plateau uplift, using Rhinish Shield as an example was carried out through inter-institutional collaboration and inter-disciplinary co-operation over a period of six years. Results of this commendable study (Fuchs et al., 1985) throw considerable light on the mechanism of processes involved in the taphrogenesis.

Hundreds of research papers published on various aspects of taphrogenesis in the aforesaid monographs as well as other scientific journals have been frequently consulted during the research work and the most relevant have been cited in appropriate places. However, a very brief description has been extracted from the above mentioned publications and incorporated in subsequent subsections to highlight the important aspects of the rifting process.
4.2.3 **THEORIES AND MECHANISM OF TAPPROGENESIS.**

This section contains important theoretical developments and the mechanism of taphrogenesis as proposed by various authors from time to time. Theories discussed in the sub-section on the "taphrogenic stages" have not been incorporated here to avoid redundancy. Theories based on the concepts of plate tectonics and sea-floor spreading, as well as those unrelated or opposed to these concepts have been included in order to assess their relative merits:

Various concepts of graben formation including the **wedge subsidence hypothesis** (Vening Meinesz 1950) and its modified form (Fuchs 1974 and Bott 1980), the **undation hypothesis** (Van Hemel 1964, 1972), the **thin skinned taphrogenesis** within the framework of deformable plate tectonics as opposed to the conventional rigid plate tectonics (Voight 1974), the **membrane stress hypothesis** (Turcotte & Oxburg 1973), reflect the evolution of ideas on the problem of taphrogenesis. The concept of membrane tectonics derives from the fact that the earth is not a perfect sphere but an oblate spheroid and consequently a plate moving from the equator towards one of the poles must increase in its radius of curvature and will therefore be subjected to peripheral tension resulting in brittle deformation of a tensional nature. On the other hand, a plate moving towards equator will decrease its radius of curvature and therefore suffer compressional stress in the peripheral part and tension in the centre. These stresses could be large enough to propagate lithospheric fractures and explain the initiation of
intracontinental rifts as observed in the case of West and East African Rifts.

Mueller and Rybach (1974), and Mueller (1978) emphasized the role of low velocity channel of the upper crust in the initial phase of graben formation. The development of graben tectogene within a crustal plate overlying an upwelling magma cushion was explained by the dilation as a result of arching along the crest of the rising crustal dome besides motion due to gravity sliding along glide plain between the lower crust and the upper mantle (Illies 1974 a).

Morisawa (1973) elucidated the relationship between the plate tectonics and surface geomorphology and suggested that the rifting and graben formation may ultimately result in the continental break-up which is possibly taking place in the African continent.

Burke and Dewey (1973, 1974), Dewey and Burke (1974) and Burke (1978) who discussed the evolution of rifts in the light of plate tectonics suggested that rifts develop on the thermal domes over the hot-spots or rising mantle plumes and that the continental break-up occurs by the linking of hot-spot related rift arms to form a zone of ocean floor spreading (Fig. 4.3). Burke and Whiteman (1977) studied the relationship between the uplift, rifting and break-up of Africa and suggested that the formation of uplift is a response to a rising mantle plume resulting in partial melting of mantle material and the formation of large volume of alkali basalt magma at the base of the lithosphere. This magma is
FIG. 4-3: DIAGRAMMATIC REPRESENTATION OF CONTINENTAL BREAK-UP BY (A) LINKING OF HOT SPOT RELATED RIFT ARMS TO FORM (B) A ZONE OF OCEAN FLOOR SPREADING. (AFTER DEWEY AND BURKE, 1973, 1974)
responsible for a mass deficiency to which the elongated domal uplift is an isostatic response, over which the triple rift junctions are formed (op. cit.). If the structure can not be accommodated then the existing plate motion will bring other parts of the lithosphere over the plume or the plume may subside. Or else, one, two or three rift arms may develop into sea-floor spreading centres.

Logatchev et al. (1972) discussed the development of the East African Rifts and criticized the attempt to explain their origin by breaking-up and separation of continents based on the concept of sea-floor spreading. They suggested that the Gregory rift floor is entirely made up of the continental crust though its lower part is impregnated and intruded by basic igneous intrusions (op. cit.). Later findings, however, did not support their conclusion. One such study is the interpretation of seismic refraction and gravity data (Long et al. 1973) which demonstrated crustal separation along the Gregory Rift. It is logical to infer that the basic igneous intrusions described by Logatchev et al. (1972) support, rather than contradict the phenomenon of sea-floor spreading and merely represent its incipient developmental stage.

The tectonic effects of asthenospheric upwell and wedging of mantle-derived material on the elastic crustal plate and probable patterns of development of ridge-rift valley structures in the oceanic and continental crusts were analysed by theoretical and experimental studies by Bhattacharji and Koide (1975). Analyses revealed that such wedging into the lithospheric plate produces horizontal extension immediately above, in a broad, funnel-shaped
zone but causes wide areas of compression at the sides at depth. Origin of ridge-rift structure is initiated first by wide domal uplift followed by formation of elongated rift valley bounded by marginal inward dipping (in the range 30° to 60°) funnel-shaped normal faults. Extension and propagation of fractures occurs immediately above the intrusion, however, further away these fractures tend to branch upward and outward into a set of en echelon extensional or normal faulted shear zones. Further wedging produces rifting and the following developments in the crustal plate: graben; graben and horst; block faulting; axial rift valley opening by magmatic intrusions as axial dykes producing lateral stretching; further rifting and onset of spreading. This may be followed by flank uplift; central rift valley or marginal volcanism; possible block rotation; further development of complex graben and horst structure; possible sedimentation in faulted blocks with end-phase volcanism producing extensive plateau lavas. This analysis indicates the probable development of marginal reverse faulting as associated with many rifts due to the effect of lateral compression with progressive wedging.

Talwani et al. (1978) suggested that a zone of anomalous crustal structure forms by the sharp rise in the depth of high velocity layers, occupying the region immediately beneath the rift proper while virtually no crustal modification occurs outside the rift. It was proposed that the agents of crustal modification should be more intense and concentrated in shape, such as a rising diapir in the asthenosphere instead of a domal uplift of isotherms.
Based on the occurrence of 250-300 km wide anomalous mantle below the Baikal rift, Zorin (1981) suggested that the cause of continental rifting is the intrusion of asthenospheric material into the lithosphere.

Artyushkov (1981) developed a mathematical model to explain the mechanism of continental rifting and explained that the "Rift valleys are formed along high and strongly elongated uplifts on the continents, which are underlain by a low velocity mantle of high temperature. Tensile stresses of high magnitude appear in the lithosphere of such regions. High heat flow from the low velocity mantle strongly decreases the viscosity of the lower crust. Ductile extension arises in this layer, reducing its thickness. This results in faulting and subsidence of the overlying upper crust, producing deep elongated depression or rift valley on the earth's surface."

4.2 C TAPHROGENIC STAGES (STAGES OF CONTINENTAL RIFTING).

It is evident from the preceding section that the formation of continental rifts is associated with numerous major geological processes such as asthenospheric upwelling, large scale crustal domal upwarping, formation of rift faults, volcanism, crustal extension, rift shoulder upliftment, rift floor subsidence and sedimentation. These features are widely considered to be typical of graben structures but there is diversity of opinion about the sequence of their formation in time during the history of rift development.
Attempts to define the stages of continental rifting include those of Heezen (1960), Tipnis and Srivastava (1968 b), Artemjev and Artyushkov (1971), Fuchs (1974), Falvy (1974), Burke and Whiteman (1977), Peterson (1978) and Bott (1981), but certain better evolved and recent models are discussed here.

Bridgwell (1978) suggested a genetic sequence outlining physical processes of rifting which involves:

i) Initiation of a thermal pulse in theasthenosphere which convects mass and heat upwards, creating magma chambers in the plastic upper mantle.

ii) Buoyant uplift of the overlying lithosphere to form broad arches.

iii) Thinning of elastic crust due to enhanced shear stress regime.

iv) Initiation of extensional normal faulting along the crest.

v) Magmatic injection and extrusion of volcanism along fault zones.

vi) Accelerated uplift as a response to the reduction of strength during both faulting and increased temperatures.

vii) Development of deep, elongate, clastic - filled rifts whose bottoms are moving downward relative to adjacent arches but whose total motion is probably upward relative to the convecting mass below.
Curray (1980)* formulated a simplified working model (Fig. 4.4) for the development of passive margins based on modern seismic surveys and deep sea drilling results. The model which admittedly adapted ideas from many published sources incorporates four stages:

1) **Doming:** Rifting is sometimes preceded or accompanied by a period of uplift or doming. Recent studies, however, suggest that in some rifted margins doming may not have occurred.

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FIG. 4-4: I.P.O.D (INTERNATIONAL PROGRAMME OF OCEAN DRILLING) MODEL OF FORMATION AND EVOLUTION OF RIFT SEGMENTS & PASSIVE CONTINENTAL MARGINS (CURREY 1980).

FIG. 4-5 STAGES OF TAPHROGENIC CYCLE (ILLIES 1981a).
ii) **Rifting:** The rifting may follow subparallel system or a trilete pattern. Commonly one of the arms of trilete pattern fails, leaving an aulacogen trending inland at an angle of approximately 120° from the continental margin. The basic structural framework of margin is determined by the pattern of rifting and pre-existing zones of structural weakness. Within the rift, basic and alkaline intrusive rocks may be intercalated with coarse clastic continental sediments. Depending on the altitude of the rift valley and climate, repeated transgressions and regressions may result in evaporite deposition on the continental crust and also perhaps on some of the oceanic crust formed early in the next stage. Faults formed during the rifting stage are of the normal listric type.

iii) **Drifting:** Oceanic crust begins to accrete at the edges of the separated blocks of the attenuated continental lithosphere. Variations in the width of the continent-ocean boundary zone reflecting differing amount of extension of continental crust in the rifting stage, pervasive jointing and injection of the continental crust by dykes are characteristic features of this stage but the exact nature of change from rifting to drifting and development of continent-ocean boundary zone are not yet fully understood. Cooling of continental margin
as it moves away from the spreading axis, subsidence and widespread transgression on the margin, and reversal of drainage pattern due to gentle oceanward tilting of the margin are other observed phenomena during this stage.

iv) Post-rift evolution: Subsequent evolution of the margin is a function both of age and the poorly understood interplay between regional and local differential subsidence, sedimentation, eustatic sea level fluctuations, climate, and oceanic circulation.

According to Illies (1981 a) the mechanism of graben formation and the splitting of continental crust involves following stages of taphrogenic cycle:

i) Formation of near parallel, convergent master faults of graben (normally along pre-existing weakness zones) and subsidence of intervening triangular wedge-block in extensional regime. The apex of wedge block resides over the ductile layer of mechanical decoupling (Fig. 4.5 a).

ii) Wedge-block subsidence and disintegration of the wedge into a mosaic of rotating tilt blocks, possibly along the listric faults indicates sideward crustal spreading. For the underlying upper mantle, necking of the crust causes unloading effect triggering phase transformation. A body of low velocity material, thus grows up to create a subcrustal dome underneath
the physiographic rift phenomenon (Fig. 4.5 b).

iii) In case, regional tectonic setting does not permit further sideward yielding of the block units framing the rift valley on both sides, a regional uplift of the graben floor will be observed (Fig. 4.5 d).

On the contrary, if the stress conditions favour further gravitational slide over the mantle bulge, crustal spreading by tilt block rotations and fissure eruption will be supported. In this stage, extreme tensile conditions on top of the mantle bulge will favour the development of open fissures and related dyke injections in inner portion of the rift valley. A rift-in-rift feature will result which precedes the semioceanic conditions and the onset of oceanfloor spreading (Fig. 4.5 c).

4.2 D: TERMINOLOGY OF TAPHROGENESIS.

Gregory (1921) used the term rift to describe the large scale structural valleys of East Africa and defined the rift valley as a long depression between parallel normal faults. Belousov (1969) suggested that these structures are formed as a result of extension. Burke (1980) defined the rift as an "... elongate depressions overlying places where the entire thickness of lithosphere has ruptured in extension". Structurally, a continental rift is a complex graben where the vertical displacement commonly consists of a great number of longitudinal steep dipping normal faults creating the step-like pattern. Directions of throws along the particular faults are different resulting in the formation of secondary grabens and horsts of different orders. Widespread
occurrence of en echelon longitudinal faults and numerous transverse faults are characteristic features of the rift.

**TYPES OF RIPTS**

Milanovsky (1972) identified following fundamental categories (Fig. 4.6) of rift zones:

- **Oceanic or Intraoceanic (axial graben bordered by oceanic crust)**
- **Continental or Intracontinental (both rift floor and shoulders of continental crust)**
- **Intercontinental (rift zone has oceanic crust and shoulders have continental crust)**

- **Rift zones of Platform (Epiplatform)**
- **Rift zones of Orogenic Belts**

- **Arch Volcanic**
- **Crevice-Like**
  - Without marginal uplifts
  - With one marginal uplift
  - With two marginal uplifts
  - With internal uplift.

Milanovsky (**op. cit.**) suggested that epiplatform rifts are characterized by single axial grabens with alkaline volcanism and frequent carbonatites while the rift zones of orogenic belts develop numerous grabens and horsts with calc-alkaline volcanism.
FIG. 4.6: THE CHARACTERISTIC STRUCTURAL TYPES OF RIFT-ZONES (AFTER MILANOVSKY 1972).

1= arch-volcanic epiplatform rift zone;  
2-5 = crevice-like epiplatform rift zones:  
2= without marginal uplifts;  
3= with one marginal uplift;  
4= with two marginal uplifts;  
5= with internal uplift;  
6= zone of one side tilted blocks;  
7= rift-like epeirogenic belt;  
8= intercontinental rift zone (Red Sea type).
Arch volcanic type rifts have exceptionally intense and long volcanic activity such as the rifts in Ethiopia and Kenya, and are associated with basic and intermediate lavas of highly alkaline series. Branching rifts with 1-2 km deep grabens develop along the axial part of arch associated with a Bouguer gravity anomaly low apparently due to melting in the lower part of the crust and top part of the mantle, while the axial grabens show a narrow zone of gravity high.

Crevice type rifts are characterized by grabens of great depth, e.g. the Baikal Graben (5 - 6 km) where the marginal uplift zones are narrower and sometimes absent. These are associated with both vertical and horizontal displacements, sometimes latter exceeding the former. These seismically active rifts have little or no volcanism (confined along the flanks rather than axial part of the graben) and are characterized by narrow negative Bouguer gravity anomaly due to the thickness of sediments.

Milanovsky (1978) defined pericontinental or perioceanic rift zones as bounded by continental type crust on one side and oceanic type on the other, occurring in passive buried state along the periphery of continents bordering the Atlantic and Indian Oceans.

RIFFS IN WILSON CYCLE

J. Tuzo Wilson (1968) argued before the American Philosophical Society, that plate tectonics shows that on the surface of the earth,
oceans are opening in some places and closing in others. The history of the earth's surface can therefore be considered as a record of the opening and closing of oceans. Wilson analysed these cycles in terms of oceanic evolution from youth (continental rupture) to old age (continental collision). Dewey and Burke (1974) suggested that complex interwoven cycles of ocean opening and closing of this kind recorded within the continents be called the Wilson Cycles.

Wilson Cycle is the concept that permits application of plate tectonic principles to the record of historical geology within the continents including rift valleys which occur at all stages because extensional tectonics can develop at all stages of the Wilson Cycle (Burke 1980). Burke (op. cit.) proposed four types of rifts on the basis of their position in the Wilson Cycle:

(i) **Continental Rupture**: Rifts associated with the active continental break-up, e.g. the East African Rifts which are particularly well developed and accessible to study.

(ii) **Failed Rifts**: Rifts which fail to develop into active spreading centres during the continental break-up and normally stretch into continents at a variety of angles from Atlantic type ocean margins. These rifts are very common and also known as aborted or fossil rifts.

(iii) **Convergent Boundary Rifts**: Rifts which develop at Andean type continental margins and in island arcs. Rifts of the Basin and Range province of U.S.A. and marginal back-arc basin
such as the Japan Sea are examples of this type.

(iv) **Collisional Rifts**: These rifts include *impactogens* which develop in association with continental collisions as a result of intercontinental strain established during the collision. *Ex. Rhinegraben* of West Germany, *Aulacogen* term is used for the rifts striking into fold belts (Shatski 1947, cited in Burke 1980). Plate tectonic interpretations view aulacogens as aborted oceans of branching rift systems whose other members continued to evolve into full fledged oceanic basins. The craton margins to either side of the mouth of an aulacogen are thus rifted continental margins early in their history and eventually become orogenic belts when the adjacent oceanic lithosphere is later consumed.