CHAPTER-VII
DEPOSITIONAL ENVIRONMENT AND PROVENANCE

The ultimate aim of present investigation is to unfold the sedimentation history of the Upper Gondwana sediments with special reference to Pachmarhi, Denwa and Bagra Formations of Satpura Gondwana basin of central India, (Madhya Pradesh). A sedimentary rock is by and large a complex of physical, chemical and biological conditions under which a sediment accumulates (Krumbein and Sloss, 1963) in which the clastic sediments are the residues derived from the pre-existing rocks due to physical and chemical weathering (Pettijohn, 1957; 1975). In recent years there has been increasing interest and emphasis on the synthesis of sedimentary facies, facies assemblage, and depositional environments of ancient and recent sediments (Pettijohn, 1975; Walker, 1984; Reading, 1986; Miall, 1984a; 1993; Einsele, 1992). The sedimentological evidence from facies analysis, paleoflow and paleodrainage, texture, petrography and heavy mineral analysis are used for understanding the depositional history of the given sediments. Facies analysis in particular, provides evidence for reconstruction of environment of deposition and prevailing hydrodynamic processes during the deposition of these sediments. Paleocurrent analysis and petrographic study provide useful evidence in respect of the paleoslope and paleodrainage of the basin, including composition and location of the provenance providing
sediments. Indeed, the great thickness of Pachmarhi sandstone (>750 m) and common lack of associated fine clastics made it unique and interesting to analyse these sequences, vis-a-vis overlying argillaceous Denwa and conglomeratic Bagra. The ultimate aim is to decipher the sedimentary evolution of the Mesozoic Satpura Gondwana rocks in this part of Satpura basin with special reference to depositional events and models based on sequences of modern and ancient fluvial environments (Walker, 1976; Miall, 1977; Reading, 1986 etc).

**Pachmarhi Formation**

This predominantly arenaceous assemblage consists of recurring sequences of multistorey sandstone bodies, which are by and large conglomeratic, pebbly, coarse grained and profusely cross-bedded to horizontally bedded in lower part, exhibiting progressive decrease in thickness and grain size towards top of each recurring sequence (Fig.16). The individual sandstone bodies are commonly elongated or oriented in the direction of depositing streams and locally oriented diagonally/transversely. These may well be attributed to longitudinal/diagonal/transverse sand bars in the channel framework of low sinuosity (bed load) braided streams (Miall, 1977; Walker, 1979). Evidence cited for such interpretations include multistorey sand bodies
Fig. 16 A generalised facies model and interpretation of Pachmarhi Formation.
with uneven (? erosional) basal contact, upward decrease in grain size and thickness (scale) of cross-bedded units, and similarity in facies assemblage with essentially unidirectional paleocurrent. The frequent migration of these channel bars, a common phenomena of braided rivers, have possibly resulted in multilateral coalescing sandstone bodies. Locally, the longitudinal and diagonal channel bars are progressively replaced by linguoid bars. Transverse channel sand bars comprising very coarse, coarse to medium sand also developed locally particularly in the middle and upper parts of the Pachmarhi Formation. Thin layers of clast-supported conglomerate and subrounded quartzose pebbles in cross-bedded sandstone occurring in the basal part and occasionally at intervals throughout the assemblage may suggest periodic uplift of source rocks with supply and deposition of fine to medium sized, subangular to rounded gravels in shallower parts of migrating dunes/bars by strong turbulent currents.

Besides the various depositional features referred to above, the abundance of sandstone lithofacies and unimodal paleocurrent with high vector strength (75%) and low current variability (47°) are other features commonly associated with low sinuous bed load (braided) streams of the type which are known to carry large amount of coarse to medium sand deposited dominantly as...
sand bars and locally as sand dunes (Miall, 1977; Walker, 1979). The sporadic occurrence of fine sandy/silty clastics as thin lenticular interbeds of shale in the upper part of many fining upwards cyclical sequences imply restricted and localised deposition and (or) preservation of fine clastics in lean periods, further corroborating the contention of low sinuous nature of depositing streams during Pachmarhi sedimentation. The aforesaid braided river model of Pachmarhi is closely akin to the Platte-type river or more generally Saskatchewan-type model of Miall (1977, 1985). Figure 17 illustrates the schematic depositional model and pattern of sedimentation of the Pachmarhi Formation.

Considerable thickness (~750 m) of sandstone and recurrence of fining upward multistorey sandstone bodies may be attributed to continued subsidence of (?) downfaulted basin (Saxena, 1973). The river system, however, maintained its steeper slopes and streams remained by and large braided with paleodrainage and paleoslope directed dominantly towards northwest throughout the course of Pachmarhi sedimentation. Furthermore, the Pachmarhi sandstones dip gently (5° to 10°) towards northwest-north in the direction of paleoslope with occasional tendency to becoming horizontal. It is, therefore, suggested that the
Fig.17  Schematic depositional model of braided river system for the Pachmarhi Formation, Satpura Basin.
existing dip pattern of Pachmarhi sandstone may correspond with the original configuration of the basin which was gently tilted towards north. The northwesterly direction of sediment transport and paleoslope persist through time and across the basin upto the existing northern limit of the formation, which evidently implies that depositional limit of the Pachmarhi basin extended farther north beyond the existing northern boundary in the direction of paleoslope. Thus, the Pachmarhi basin which was 150 km wide from east to west, extended from Tamia in the south to as far as Son-Narmada Lineament Zone and possibly further north beyond the existing boundary (Casshyap et al., 1993b).

Denwa Formation

Lithofacies assemblage of the Denwa Formation is characterised by recurring fining upward sequences of cross-bedded channel sandstone in lower part and mudstone and shale in upper part (Fig.18). The paleocurrent pattern exhibits fan-shaped unimodal distribution with principal mode directed towards northwest, north, and northeast representing deposition by meandering stream. Overall, the finning upward cross-bedded sandy facies may well be attributed to channel or as point bars, and overlying mudstones and
Fig. 18 A generalised facies model and interpretation of Denwa Formation.
Fig. 19  Schematic depositional model of meandering river system for the Denwa Formation, Satpura Basin.
calcarius shales to the adjoining overbanks and backswamps, as shown schematically in Figure 19.

**Bagra Formation**

The Bagra Formation which occurs along the northern margin of the Satpura basin transgresses various underlying formations including Pachmarhi, Denwa, as also Talchir, and Precambrian. It is essentially a conglomeratic sandstone assemblage. Commonly the sequence commences with matrix supported (Gms-facies), followed by clast-supported conglomerate (Gm-facies), pebbly coarse sandstone and finally ends with mudstone and shale in the upper part as shown diagrammatically in Figure 20. The important characteristics of Gms-facies with respect to depositional processes include poorly sorted coarse conglomerate consisting of pebbles, cobbles and boulders, commonly subangular to angular, set in sandy/muddy matrix. Occurring as coalescing sheet-like bodies, it is essentially massive and polymictic in composition. This facies forming basal part of the formation and occurring along the northern margin, possibly represents viscous debris flows in the proximal reaches of alluvial fan. The associated clast-supported conglomerate (Gm) facies containing subrounded polymictic clasts occur as local interbeds in Gms facies, but gradually as well developed
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Fig. 20 A generalised facies model of Bagra Formation.
assemblage downslope towards south, representing reworked gravels by out-flushing waters of alluvial fan. The clast-supported (Gm) conglomerate facies is well developed between proximal and distal parts in medial part of out spreading fans. The distal facies is characterised by pebbly, cross-bedded coarse to medium grained sandstone, with overlying mudstone and shale forming upper part of the Bagra Formation. The size gradation from coarse to fine clastics through time and across the formation, through space, is in the direction of southwardly paleocurrent and paleoslope which evidently underwent a reversal from north to south during Bagra sedimentation as brought out by paleocurrent study (Fig.7) discussed earlier. Considering this type of sequence in terms of down fan changes in lithofacies and particle size as observed in certain modern fans (Rust, 1978), there are possibilities such as follows (Casshyap et al., 1993a):

An increasing rate of uplift in the source area provided a greater abundance of eroded debris through time. The production of coarser grained and increased quantities of debris along with increased slope would probably have resulted a fan progradation and encroachment of progressively coarse grained sediments over earlier fan-toe areas.
In the lower reaches of alluvial fan it formed braided alluvial plain sand characterised by a down stream decrease in grain size, especially for sediments which constituted bars and a down stream variation in bar morphology.

Combined evidence from the present study, including coarse grained nature of sediments, facies assemblage, fining upward distribution, petrography, paleocurrent, heavy mineral and grain size, suggest that the Bagra conglomeratic sequence may possibly have deposited as a coalescing alluvial fan braided complex that prograded southward from highland (source area) located immediately north of the present outcrop belt as schemetically shown in Figure 21. Tectonically, the preferred vertical sequence of Bagra comprising conglomerate, sandstone and shale closely resembles those of graben/half graben or rift basin (Burke, 1977; Burke and Dewey, 1973). Modern and ancient analogous of alluvial fan and braided river systems have been widely reported in recent years (Boothroyd and Ashley, 1975; Miall, 1977; Heward, 1978; Nemec and Steel, 1984; Ethridge, 1984).

PROVENANCE

Provenance deals with climate, relief and kind of source rocks from which the sediments were derived
Fig. 21  Schematic alluvial fan model of the Bagra Formation in downfaulted trough to the south of uplifted highlands of Precambrian granite and metasediments.
(Pettijohn, 1957). The clastic sediments are basically and fundamentally insoluble residues left after chemical and mechanical break down of pre-existing rocks. The composition of the resultant sediment depends in part on the nature of source rock(s), relief and climate, and in part on its maturity which is a measure of the extent to which the decompositional and hydrodynamic processes were carried towards completion. Therefore, one of the aims of petrographic examination of framework constituents of sandstone was to find out the probable composition and possible location of the source area, taking into account the evidence derived from paleocurrent study.

According to sandstone classification after Mac Bride (1963), Dott (1964), Casshyap (1969) and that recommended by Pettijohn et al., (1972), the Pachmarhi sandstone are entirely quartzarenite, Denwa sandstone constitutes about 90% quartzarenite, and 10% subarkose. However, the Bagra sandstone consists of some 30% litharenite, 25% sublitharenite, 20% subarkose, 15% quartzarenite and 10% arkose.

Evidence from Detrital Quartz

The detrital quartz is both physically and chemically durable and most abundant constituent of framework. It has been used as a useful guide to
composition of provenance. In this study quartz types have been recognized and related to source rocks on the basis of shape, texture, extinction and mineral inclusions (Krynine, 1940; Blatt and Christie, 1963; Folk, 1980; Blatt et al., 1980).

Common quartz or monocrystalline quartz is the predominant detrital component of the studied sandstone. Common quartz ranges from 62% to 89% (average 78%) by volume in Pachmarhi, 73% to 88% (average 81.80%) in Denwa and 34% to 72% (average 55.88%) in the Bagra Formation. Monocrystalline quartz is believed to have been derived largely from granitic and granite gneisses (Blatt and Christie, 1963; Folk, 1980). This implies that granitoid and metamorphic including metasedimentary rocks were the main source of quartz in all the formations.

Evidence From Feldspar

The feldspar constitutes a small percentage of detrital framework in each formation. They comprise 0.59% to 3.50% (average 1.99%) in Pachmarhi, 1.0% to 7.40% (average 3.07%) in Denwa, and 0.23% to 17.44% (average 7.93%) in the Bagra Formation. The potassic varieties including orthoclase and microcline are more common than plagioclase. Presence of perthite grains in Bagra sandstone indicates that the parent rock is of
granitic origin. Excess of quartz over feldspar and orthoclase over plagioclase may indicate greater weathering in source area and/or greater abrasion of sediments during transport (Pettijohn et al., 1972, p. 307).

**Evidence from Heavy Minerals**

Heavy minerals have long been used as a guide to the composition of the source rocks (Krumbein and Pettijohn, 1938; Pettijohn, 1975). The heavy mineral suit of the Pachmarhi and Denwa sediments contains in particular tourmaline, zircon, rutile, garnet, kyanite and opaques. Prismatic, angular to rounded, brown and yellow coloured tourmaline is more common than zircon in Pachmarhi sediments. The well rounded tourmaline may suggest greater abrasion and (or) long transportation from source rocks or derivation from pre-existing sedimentary rocks. The euhedral zircons are thought to have been derived from acid to intermediate igneous rocks.

The species present in the Bagra Formation are epidote, kyanite, garnet, hornblende, sillimanite, tourmaline, spinel, biotite, muscovite, rutile, actinolite and opaques. Some of the species are by and large common in the Pachmarhi and Denwa Formations; others like epidote, hornblende, sillimanite, actinolite, muscovite and spinel are present only in the Bagra Formation. The presence of distinctive heavy
mineral species in the Bagra Formation indicates that the sediments have been derived from different variety of source rocks.

The six varieties of heavy mineral species including opaques from Pachmarhi and Denwa sandstones are by and large similar implying that a similar provenance may have existed throughout the course of sedimentation providing sediments for the above sandstone formations. The heavy minerals are mostly of metamorphic origin and partly derived from acidic and basic igneous rocks. Euhedral zircon and tourmaline (green, brown) characterise granitic source, and blue tourmaline are derived from pegmatite rocks (Krynine, 1946; Poldervaart, 1950). Contribution from basic rocks are indicated by the presence of opaques. It is concluded that the Pachmarhi and Denwa sediments have been derived from a mixed composition of provenance comprising plutonic igneous rocks, low-medium and high grade metamorphic, and basic rocks.

Dominance of epidote in Bagra sandstone suggests its derivation from basic source (Krumbein and Pettijohn, 1938; Pettijohn, 1975). Other minerals like opaques and rutile also indicate contribution from basic rocks, the latter may partly be derived from shists (Force, 1980). Presence of various species of garnet in almost all the
samples indicates source from medium to high grade schists and gneisses (Krumbein and Pettijohn, 1938). Occurrence of muscovite also favours the presence of schists and gneisses in the source area (Blatt et al., 1980). A part of detrital muscovite may have had its origin from acid igneous rocks including pegmetites (Folk, 1980). A small amount of actinolite also indicates low to medium grade metamorphic rocks. Presence of sillimanite indicates its derivation from metamorphosed argillaceous rocks. Thus, various heavy mineral species of Bagra sandstone suggest a provenance comprising basic rocks, acid igneous rocks, medium and high grade metamorphic rocks, and metasedimentary rocks.

Evidence from Embedded Pebbles

The embedded clasts in conglomerate and sandstone provide the most reliable and direct clue to the identity of source rocks composition. The embedded pebbles in Pachmarhi sandstone consist of quartzite and vein quartz. Some pebbles are subrounded to rounded possibly due to long transport or prolonged abrasion which eliminated unstable and metastable rock fragments from the sediments. The embedded clasts of Bagra conglomerate, however, comprise of red quartzite, green phyllite, red japer, granite, gneiss, basic igneous rocks and vein quartz. Thus, the lithology of embedded
clasts indicates a distinctive assemblage of metasedimentary rocks in the respective source areas of Pachmarhi and Denwa on one hand, and Bagra on the other hand.

Evidence from Rock Fragments

Likewise, sand-sized rock fragments in sandstone framework are among the most informative of all detrital components in diagnosing and determining the provenance composition. They comprise 0.54% to 4.88% in the Pachmarhi Formation (average 2.01%) of the rock by volume, though lacking in Denwa Formation. Interestingly, their percentage in Bagra Formation ranges from 1.06% to 50.33% averaging 14.18%; the rock fragments include shale, siltstone, chert, phyllite, quartzite and slate etc.

The labile rock fragments of sedimentary and metamorphic origin are generally not resistant to abrasion and so a large part was probably destroyed during transportation of sediments. The labile rock fragments occurring in these sediments evidently indicate derivation from sedimentary and metamorphic rocks.
COMPOSITION OF PROVENANCE

Combined evidence from composition and texture of minerals, pebbles, sand-sized rock fragments, heavy minerals and Qt-F-L and Qm-F-Lt plots suggest that the sediments were largely derived from a mixed source of acid, intermediate to basic plutonic igneous rocks, metasedimentary and metamorphic rocks. The sand sized detrital metamorphic quartz (recrystallised and stretched), vein quartz, and rounded heavy mineral species indicate that phyllite, slate, schist, older sedimentary rocks and locally pegmatite have also contributed sediments to the present rocks. Heavy mineral species and embedded clasts indicate a distinctive assemblage of source rock for Pachmarhi and Denwa on one hand and Bagra on the other hand, as discussed above.

LOCATION OF PROVENANCE

There is strong evidence on the basis of lithology, mineralogy and consistency of paleocurrent direction through time that the bulk of the sediments of the Pachmarhi and Denwa Formations were supplied by northwest flowing current system (Fig. 22) during Early Triassic (Pachmarhi) and Middle to Late Triassic (Denwa), indicating that the provenance supplying sediments to both the formations was situated to the
Fig. 22  Provenance map showing present day distribution of pre-and post Gondwana rocks. Arrows indicate the deduced direction of sediment transport and location of provenance during Satpura sedimentation in the study area.
southeast of the study area.

Contrary to Pachmarhi and Denwa, the Bagra Formation exhibits a reversal of paleocurrent system i. e. directed from north to south implying that the provenance in this case was located towards north-northwest (Fig. 22).

At present, the outcrop terrain towards south and southeast and to the north of Satpura basin is made up of Precambrian complex. Figure 22, illustrates the present day distribution of Precambrian rocks to the southeast and north of the study area, i. e. the region where the highlands comprising provenance of Pachmarhi, Denwa and for the Bagra sediments, respectively, were possibly located. The arrows indicate dominant paleoslope and sediment transport pattern vis-a-vis the respective source for Pachmarhi, Denwa, and Bagra during the span of Mesozoic sedimentation in Satpura basin of central India.
TECTONO-SEDIMENTARY EVOLUTION

Mesozoic Satpura Gondwana basin witnessed at least two tectonic events. These events are manifested by tectonic dislocation that caused marginal uplifts, downwarping, and deformation. These tectonic events have controlled the lithofacies assemblage, paleoslope, paleocurrent and stratigraphic disposition.

The first tectonic event is manifested by the onset of Lower Triassic Pachmarhi sedimentation which is marked in the basal part by sudden increase of conglomeratic, pebbly, gritty coarse sandstone (Fig. 23A), as compared to the underlying fine clastics of Upper Permian Bijori Formation. This evidently reflects tectonic uplift in the source area to the southeast of the Mesozoic basin during or prior to the deposition of Pachmarhi Formation. Periodic pulses of minor uplift may have continued in the source area during lower Pachmarhi time as manifested by frequent interbeds of pebbly conglomerate and pebbly sandstone. The pebbly, coarse sandy facies of the Pachmarhi Formation representing by and large braided river assemblage is overlain by meandering river facies of the Denwa Formation. The progressive change in lithofacies and grain size upward, from dominantly pebbly coarse to medium sandstone in Pachmarhi to medium to fine
Fig. 23 A. Schematic geological plan of Pachmarhi, Denwa and Bagra Formations (Not to scale).

B. Schematic geological section showing tectonic setting and paleo-drainage during Pachmarhi, Denwa and Bagra sedimentations (Not to scale).
sandstone and interbedded shale and mudstone in the overlying Denwa, implies that source area became progressively peneplaned and basin got stabilised as sedimentation progressed following upliftment. The persistence of northwesterly paleoslope up to the end of Denwa sedimentation also corroborates the contention of general tectonic stability.

The second and last tectonic uplift is manifested in the north, resulting in the deposition of Late Jurassic/Early Cretaceous Bagra conglomerate and sandstone-shale facies along the northern margin of the Mesozoic basin. This formation overlying the older formations unconformably or against a faulted contact (s) represents an example of proximal and distal facies of alluvial fan in a rifted (? pull-apart) basin with a paleoslope directed from north to south (Fig. 23B). This event representing the termination of continental Gondwana sedimentation preceding the widespread eruption of Deccan Traps is indeed a significant feature of Gondwana history and may well be related to the fragmentation of Indian subcontinent from Antarctica in the Late Jurassic/Early Cretaceous (Casshyap, 1976; Craddock, 1979; Veevers and Tewari, 1975) and doming and rifting prior to eruption of Deccan Trap. As a consequence, northward sloping Peninsular craton was tilted southward and small rifted (pull-apart) basins
developed along the peripheral parts of the Gondwana basin of Peninsular India. In the north of the study area, the doming before the Deccan volcanism and tectonic movement along Son-Narmada Lineament caused upliftment of the Mahakoshal/Bijawar. This uplift was accompanied by reversal of the paleoslope and paleocurrent from north to south, as borne out by alluvial fan-braided complex of the Bagra Formation.