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Tectono-sedimentary evolution of the Gondwanan Satpura Basin of central India: evidence of pre-Trap doming, rifting and palæoslope reversal

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ABSTRACT—The Mesozoic Gondwanan Satpura Basin of central India, comprising an approximately 1300 m thick sequence of the Pachmarhi, Denwa and Bagra Formations, was subjected to at least three major tectonic events. These events are manifested by tectonic dislocation, marginal uplifts, basin subsidence and deformation, as well as by stratigraphical disposition, lithofacies assemblage, and palæoslope and palæocurrent patterns.

The first tectonic event is manifested by the onset of Early Triassic Pachmarhi sedimentation, which is marked in the basal part by a sudden increase of conglomeratic, pebbly, gritty to coarse-grained cross-bedded sandstone. This contrasts with the underlying fine clastics of the Late Permian Bijori Formation. The stratigraphical relationship and lithofacies, together with palæocurrent and petrographic data, reflect tectonic uplift in the source area to the southeast of the Satpura Basin during or prior to the deposition of Pachmarhi Formation. The pebbly coarse sandy facies of the Pachmarhi Formation represents a braided river assemblage, overlain by a meandering river facies of the Denwa Formation, with river systems flowing dominantly from southeast to northwest. The progressive change in lithofacies and grain size upward from Pachmarhi to Denwa implies that the source area became peneplained and that the basin stabilised.

During the prolonged gap of non-deposition, following the Mid-Triassic break in sedimentation after deposition of the Denwa Formation, a second tectonic event resulted in the widespread faulting and uplift of Permo-Triassic Gondwana sediments and basement rocks, respectively, to the south and north of the Narmada-Son Lineament Zone of Peninsular India. A third tectonic event is manifested by Late Jurassic-Early Cretaceous Bagra conglomerate and sandstone-shale facies in the northern part of the Satpura Basin. This formation, which unconformably overlies the Precambrian, and Permian and Triassic Gondwana formations or abuts against faulted contacts, represents proximal and distal facies of an alluvial fan deposit in a rifted (pull-apart?) basin with uplifted highlands to the north. This tectonism, representing the termination of continental Gondwana sedimentation, preceded the widespread eruption of the Deccan Traps (65 Ma) after the break-up of India from Antarctica. As a consequence, a northward sloping, peninsular craton was tilted southward and small rift basins developed along peripheral parts to the north, west and along the east coast of Peninsular India. To the north of the study area, the doming before the Deccan volcanism and tectonic movement along the Narmada-Son Lineament caused uplift of the Palæoproterozoic Mahakoshal/Bijawar terrane. This uplift was accompanied by a reversal of palæoslope. Consequently, north to south palæocurrents followed the deposition of the Pachmarhi and Denwa Formations, as borne out by the alluvial fan-braided complex of the Bagra Formation.

RÉSUMÉ—Le bassin gondwanien mésozoïque de Satpura en Inde centrale contient une séquence de quelque 1300 m d'épaisseur avec les Formations de Pachmarhi, Denwa et Bagra et a été le

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témoin d'au moins trois événements tectoniques majeurs. Ces événements se manifestent par la dislocation tectonique, la surrection des bordures, la subsidence et la déformation du bassin, ainsi que par la disposition stratigraphique, l'assemblage des lithofaciès et l'arrangement des paléo-pentes et des paléo-courants.
Le premier événement tectonique au Trias inférieur se manifeste par le début de la sédimentation de Pachmarhi, qui se marque à sa base par l'augmentation brusque des grès conglomératiques graveleux à grossiers à galets qui contrastent avec les clastites fines sous-jacentes de la Formation de Bijori du Permien Supérieur. Les relations stratigraphiques, les lithofaciès, ainsi que les données sur les paléo-courants et les observations pétrographiques montrent que la région-source au sud-est du Bassin de Satpura a subi une surrection tectonique pendant ou avant le dépôt de la Formation de Pachmarhi. Le faciès sableux grossier à galets de la Formation de Pachmarhi représente un assemblage de rivières en tresses, recouvert par le faciès de rivières à méandres de la Formation de Denwa, avec des systèmes fluviatiles coulant surtout du sud-est vers le nord-ouest. Le changement progressif de lithofaciès et de granulométrie vers le haut de Pachmarhi à Denwa implique que la région-source est devenue pénéplanée et que le bassin s'est stabilisé.
Durant la période prolongée d'absence de dépôt, suivant l'arrêt de la sédimentation après le dépôt de la Formation de Denwa au Trias moyen, un second événement tectonique a induit une fracturation répandue et la surrection des sédiments gondwaniens permo-triasiques et du socle, respectivement au sud et au nord de la Zone Linéamentaire de Narmada-Son de la Péninsule Indienne. Un trosième événement tectonique se manifeste par le conglomérat tardi-jurassique et éo-crétacé de Bagra et un faciès de grès-shale dans la partie nord du bassin de Satpura. Cette formation, qui recouvre en discordance le Précambrien et les formations gondwaniennes permiennes et triasiques, ou bute contre des contacts faillés, représente les faciès proximaux et distaux d'un dépôt de cône alluvial dans un bassin de rift (en pull apart?) avec des reliefs rehaussés au nord. Cette tectonique marque la fin de la sédimentation continentale gondwanienne et précède l'éruption des Traps du Deccan (65 Ma) après la dislocation de l'Inde et de l'Antarctique. En conséquence, le craton péninsulaire à pente nord a été basculé vers le sud et de petits bassins de rift se sont développés à la périphérie nord et ouest et le long de la côte est de la Péninsule Indienne. Au nord de la région étudiée, le bombement avant le volcanisme du Deccan et le mouvement tectonique le long du Linéament de Narmada-Son a provoqué la surrection du terrain paléoprotérozoïque de Mahakoshal/Bijawar. La surrection s'est accompagnée du renversement de la paléo-pente. Par conséquent, des paléocourants du nord au sud ont suivi le dépôt des Formations de Pachmarhi et Denwa, comme le montre le complexe alluvial de cône de la Formation de Bagra.

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INTRODUCTION

The Late Palæozoic-Mesozoic intracratonic Gondwana basins of Peninsular India have been the subject of considerable global interest and attention for more than a century. Compared to the Mesozoic Gondwana sequence (upper Gondwana sequence), the Late Palæozoic, lower Gondwana sediments, including the coal measures, have been studied in far greater detail (Casshyap, 1970, 1973, 1979; Ghosh and Mitra, 1975; Casshyap and Qidwai, 1971; Casshyap and Khan, 1982; Casshyap and Kumar, 1987; Casshyap and Srivastava, 1988; Casshyap and Tewari, 1984, 1988; Tewari, 1995; Tewari and Casshyap, 1996; Khan, 1997). Consequently, understanding of the Mesozoic Gondwana sedimentation and related tectonics is limited.

The present paper aims to describe the tectono-sedimentary evolution of Mesozoic Gondwana rocks of the Satpura Basin, central India, on the basis of lithofacies organisation, palæocurrent and palæoslope, and sedimentary petrography. An analysis of the origin and tectono-sedimentary evolution may have significant palæotectonic and palæogeographic implications.

GEOLOGICAL AND TECTONIC SETTING

The Gondwana rocks of Peninsular India occur in three well-defined linear basins (Fig. 1). The Satpura Basin of central India extends underneath the Palæocene Deccan Traps in the west and is bounded (truncated?) by the Narmada-Son Lineament Zone to the north.

The Mesozoic Gondwana sequence, known as the upper Gondwana, occurs in the central and northern parts of the Satpura Basin. These comprise the Pachmarhi, Denwa and Bagra Formations. The Pachmarhi Formation crops out largely in the southern and central parts as sandstone-forming lofty hills and

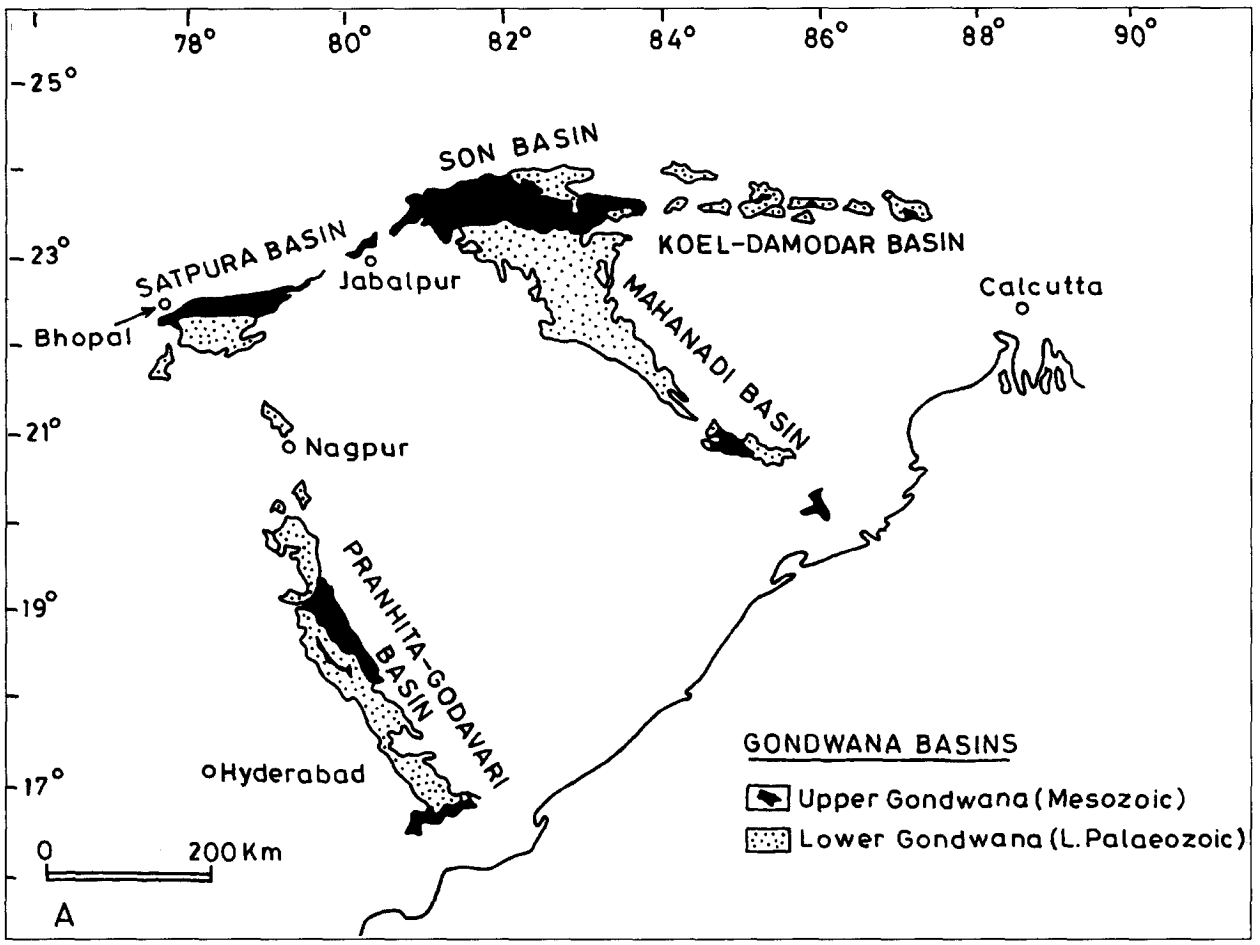

Figure 1. *Map showing the distribution of the Gondwana basins in Peninsular India.*

plateaus, whereas the Denwa and overlying Bagra Fromations occur along the northern margin (Fig. 2).

The Early Triassic Pachmarhi Formation overlies the Late Permian Bijori Fromation disconformably (Crookshank, 1936; Pascoe, 1959; Raja Rao, 1983; Casshyap *et al.*, 1993a) and is devoid of fossil remains except for a few ill-preserved ferns and sporadic occurrence of estherids (Sastry *et al.*, 1977). The Denwa Formation follows the Pachmarhi Formation conformably and has been assigned a late Lower Triassic to Middle Triassic age on the basis of the occurrence of plant fossil *Phoenicopsis* sp. and labyrinthodonts *Mestodonsaurus indicus* etc. (Chatterjee and Roy Chowdhury, 1974). Early workers believed the Bagra Formation to be Late Triassic in age, based on interdigitation with rocks of the Denwa Formation. However, recent field studies have demonstrated that the Bagra Formation overlies an uneven terrain comprising Precambrian basement and almost all the underlying Permian-Triassic litho-units, indicating a post-Denwa break in sedimentation (Casshyap *et al.*, 1993a; Veevers and Tewari, 1995). Consequently, the Bagra Formation is considered to be post-Triassic and most likely Late Jurassic to Early Cretaceous in age in view of its conformable relationship with the overlying Early Cretaceous Jabalpur Formation (Casshyap *et al.*, 1993a; Geological Survey of India, 1994).

The regional strike of the Mesozoic Gondwana rocks of the Satpura Basin is east-west with low dips of $< 10°$ directed towards the north, though southerly dips ($\sim 15°$) are recorded in the Bagra Formation along the northern margin. Structurally, the basin represents a half-graben bounded by west-northwest–east-southeast faults (Fig. 3).

LITHOFACIES ASSEMBLAGE AND SEDIMENTARY CHARACTERS

Figures 4, 5 and 6 document the generalised lithofacies sequence, sedimentary characters, mean palæoflow and depositional environments of the Pachmarhi, Denwa and Bagra Formations of the Satpura Basin.

Pachmarhi Formation

The total estimated thickness of the Pachmarhi Formation is about 750 m. It is dominantly arenaceous,

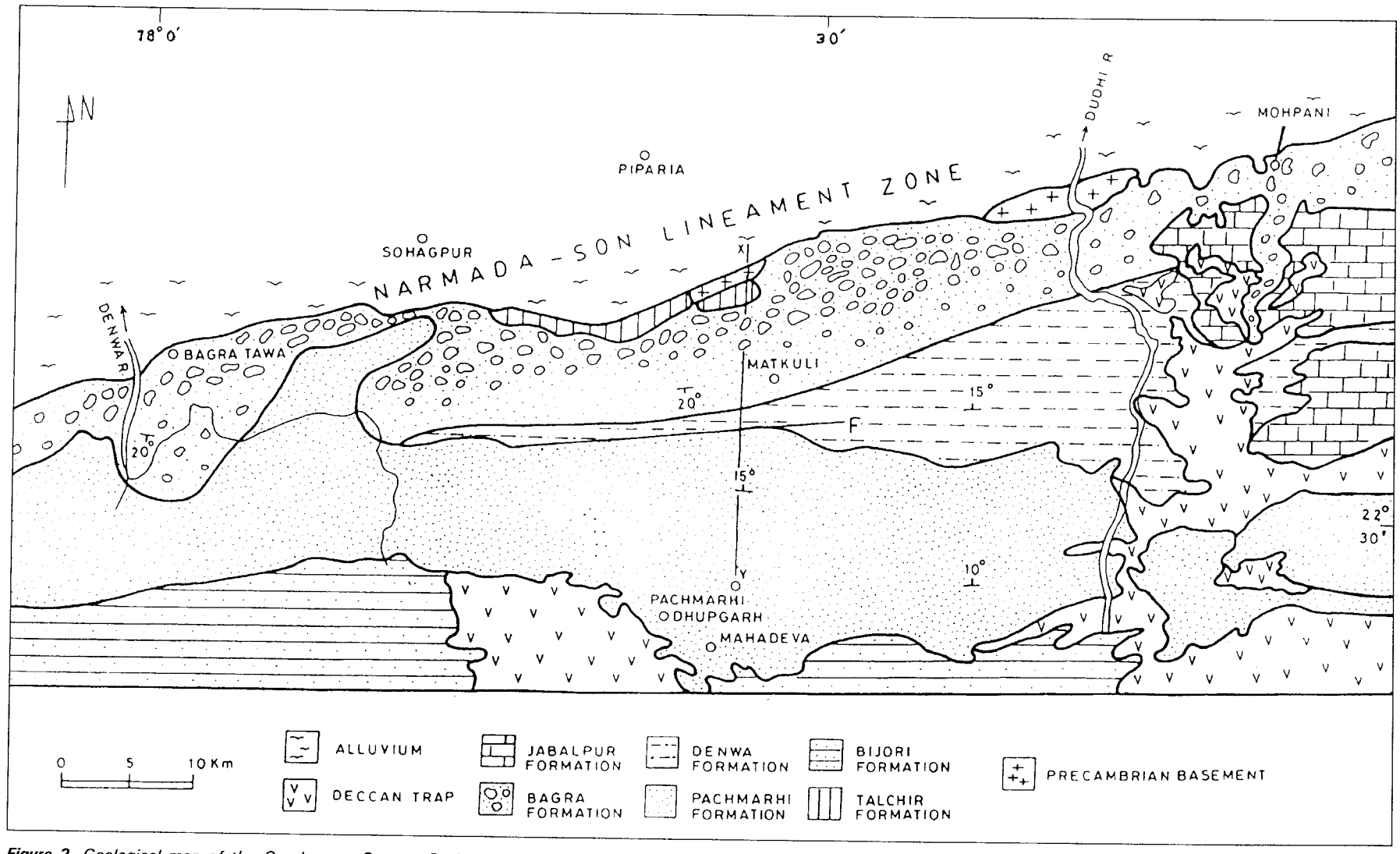

Figure 2. *Geological map of the Gondwanan Satpura Basin of central India (modified after Raja Rao, 1983). Geological section along line X-Y is shown in Fig. 3.*

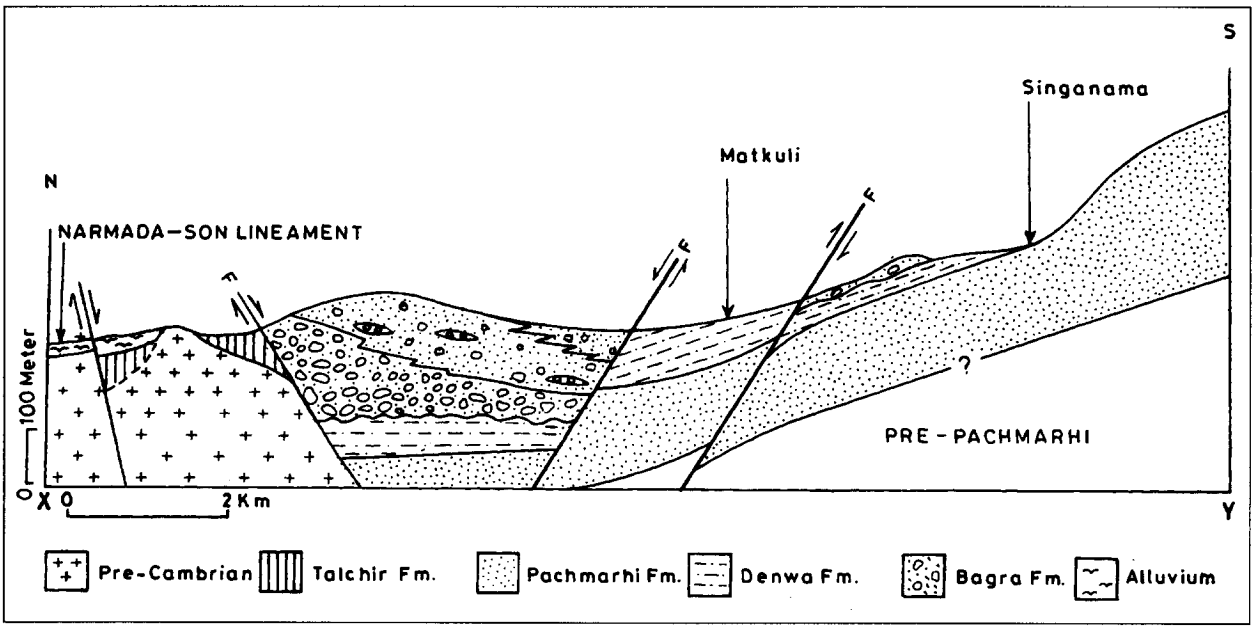

Figure 3. *Schematic geological section along line X-Y from Fig. 2 showing the stratigraphical and structural relationships of the Pachmarhi, Denwa and Bagra Formations with underlying strata. F: Fault line.*

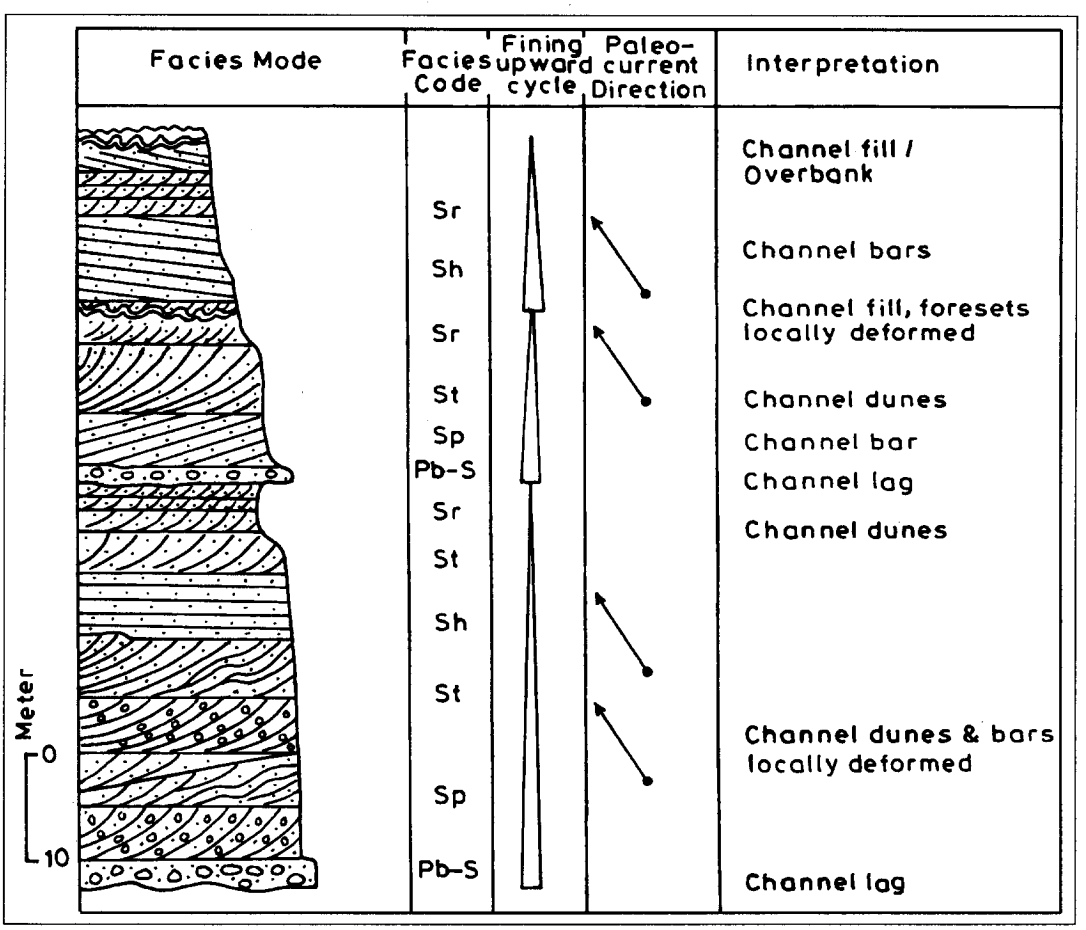

Figure 4. *A generalised facies model and interpretation of the Pachmarhi Formation. Abbreviations: Sr: ripple cross-bedded sandstone; Sh: horizontally plane-bedded sandstone; St: trough cross-bedded sandstone; Sp: planar cross-bedded sandstone; Pb-S: pebbly sandstone.*

comprising pebbly, gritty, very coarse- and medium-grained sandstone (~75%), thin interbeds of conglomerate (~15%) and subordinate amounts of sandy shale (~10%) (Fig. 4).

The Pachmarhi sandstones occur as laterally coalescing, channel-shaped multistorey bodies 5–20 m thick. The channel bodies are commonly characterised by 1–2 m thick interbeds of conglomerate or massive pebbly sandstone with an uneven erosional base. The pebbles of mostly quartzose composition and are subrounded to subangular. The pebbly unit is succeeded by successive sets of sandstone bodies (2–15 m thick) showing large-scale trough and planar cross-bedding. Each multistorey body exhibits a fining upward sequence with a progressive decease in thickness, grain size and scale of cross-bedding from base to top.

Denwa Formation

The Denwa Formation (~300 m thick) consists of an interbedded sequence of coarse-, medium- or fine-grained cross-bedded sandstone and red shale/clay (Fig. 5). The buff coloured clays are carbonaceous, locally containing calcareous nodules. The interbedded medium- to fine-grained sandstones are more argillaceous and much softer than the Pachmarhi sandstones. Overall, the individual sequences show fining upward cycles of 1.5–5 m thickness.

Bagra Formation

The Bagra Formation, showing a maximum thickness of about 250 m, is essentially a coarse, conglomeratic unit deposited along northern parts of the basin. The formation comprises conglomerate in the lower part succeeded by gritty, coarse-grained sandstone and variegated shale in the upper part (Fig. 6). The coarse constituents of the conglomerate are often angular to subrounded and vary in size from small pebbles to boulders. They are held together by a matrix which is usually sandy/argillaceous, or else they are clast-supported. However, unlike the conglomeratic interbeds of the Pachmarhi, which are dominantly monomictic, the Bagra conglomerates are composionally polymictic, comprising red quartzite, green phyllite, red jasper, granite, basic igneous rocks and vein quartz. The authors suggest that the Bagra Formation, with its thick pile of polymictic, conglomeratic bodies, represents a significant tectono-sedimentary event.

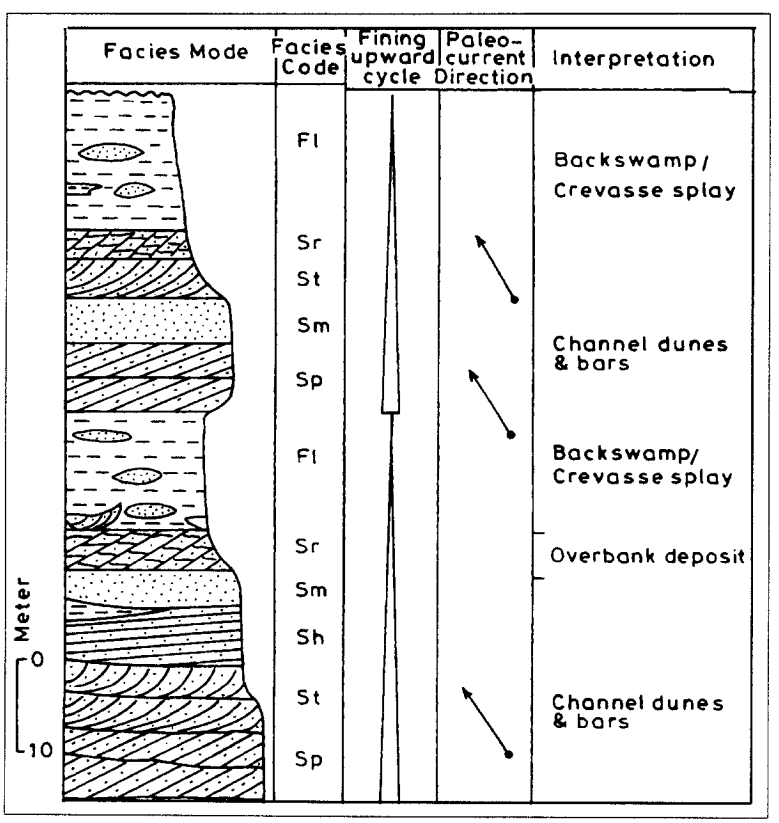

Figure 5. *A generalised facies model and interpretation of the Denwa Formation. Abbreviations: Fl: laminated shale/mudstone including sandstone lenses; Sr: ripple cross-bedded sandstone; St: trough cross-bedded sandstone; Sm: massively-bedded sandstone; Sp: planar cross-bedded sandstone; Sh: horizontally plane-bedded sandstone.*

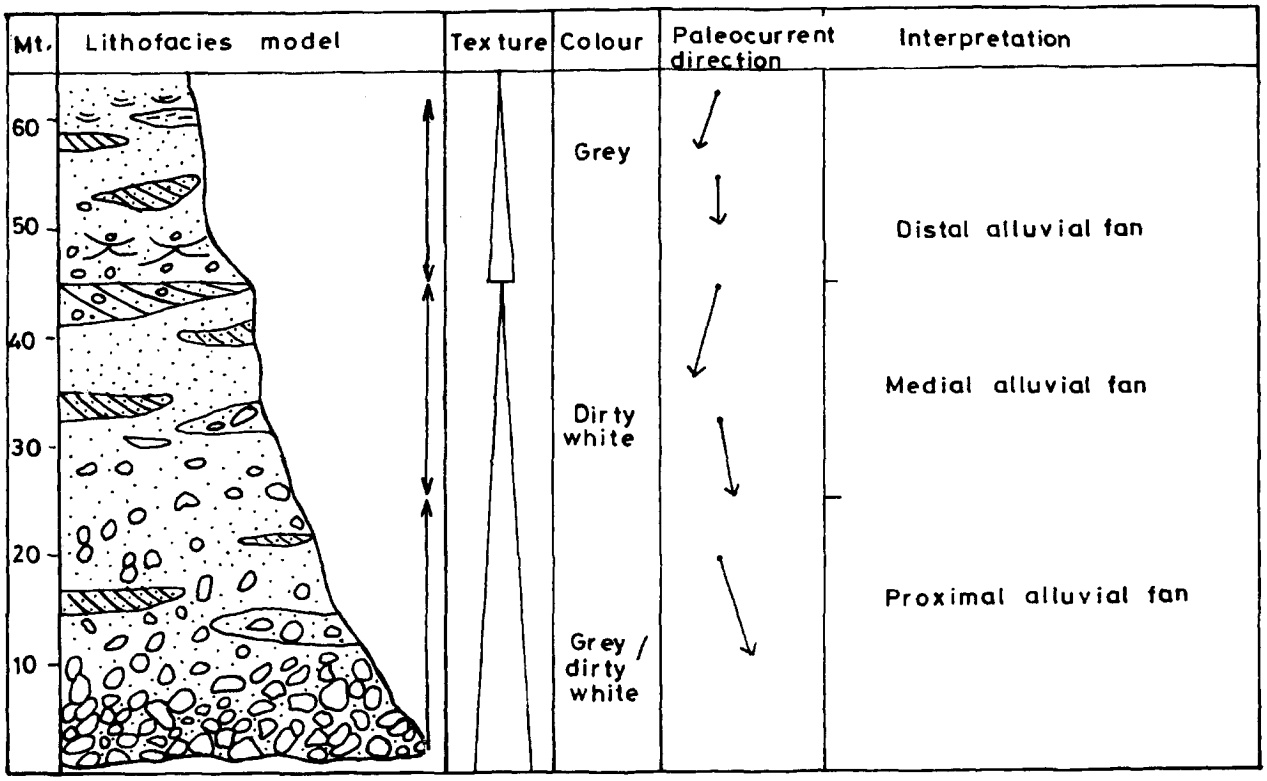

Figure 6. A generalised facies model of the Bagra Formation.

PALÆOCURRENT AND PALÆOSLOPE

The palæocurrent analysis presented here is based on 798 readings of cross-bedding foreset dip azimuths from the Pachmarhi (359), Denwa (201) and Bagra (238) sandstones. The azimuthal data show that the Pachmarhi and Denwa sediments were deposited by river systems draining uniformly from the south-east to the northwest (Fig. 7). During Bagra times, however, debris flows and palæocurrents transported gravelly debris and sand predominantly from a north-northwest direction (Fig. 7). Thus, the Bagra sedimentation demonstrates a reversal of palæo-slope and palæocurrent compared to the Pachmarhi and Denwa Formations. This suggests that the sediments of the two sets of formations, *viz.* Pachmarhi-Denwa and those of Bagra, were derived from different sources situated to the south-southeast and north, respectively.

DEPOSITIONAL FACIES MODELS

Integrated evidence from lithic-fill organisation, characters and palæocurrent patterns suggest that the Early Triassic Pachmarhi sedimentation began by northwesterly flowing stream systems, which continued uninterruptedly throughout the Denwa Formation (Middle Triassic).

The Pachmarhi Formation comprises recurring sequences of multistorey sandstone bodies, which are, by and large, conglomeratic, pebbly coarse-grained and profusely cross-bedded to horizontally bedded in the lower part, with a progressive decrease in thickness, grain size and scale of cross-bedding in the upper part of each cycle. The individual sandstone bodies are commonly elongated and orientated in the direction of depositing streams and locally orientated diagonally/transversely. These may well be attributed to longitudinal/diagonal/transverse sand bars in the channel framework of low sinuosity (bed load) braided streams, most likely akin to the Platte type (Miall, 1977).

The lithofacies assemblage of the Denwa Formation is characterised by recurring fining upward sequences of cross-bedded channel sandstone in the lower part and mud and clays in the upper part. The palæocurrent exhibits a fan-shaped unimodal pattern with the principal mode directed towards the northwest, north, and northeast representing deposition by meandering streams. Overall, the cross-bedded sandy facies is attributed to channel or point bars and overlying fine sandstone, mud and shale to adjoining overbanks and backs-wamps of meandering streams.

The overlying Bagra Formation is essentially a conglomerate and conglomerate sandstone as-semblage. The sequence commences generally with a matrix-supported conglomerate followed by clast-supported conglomerate facies, pebbly coarse sandstone and finally ends up with mudstone and

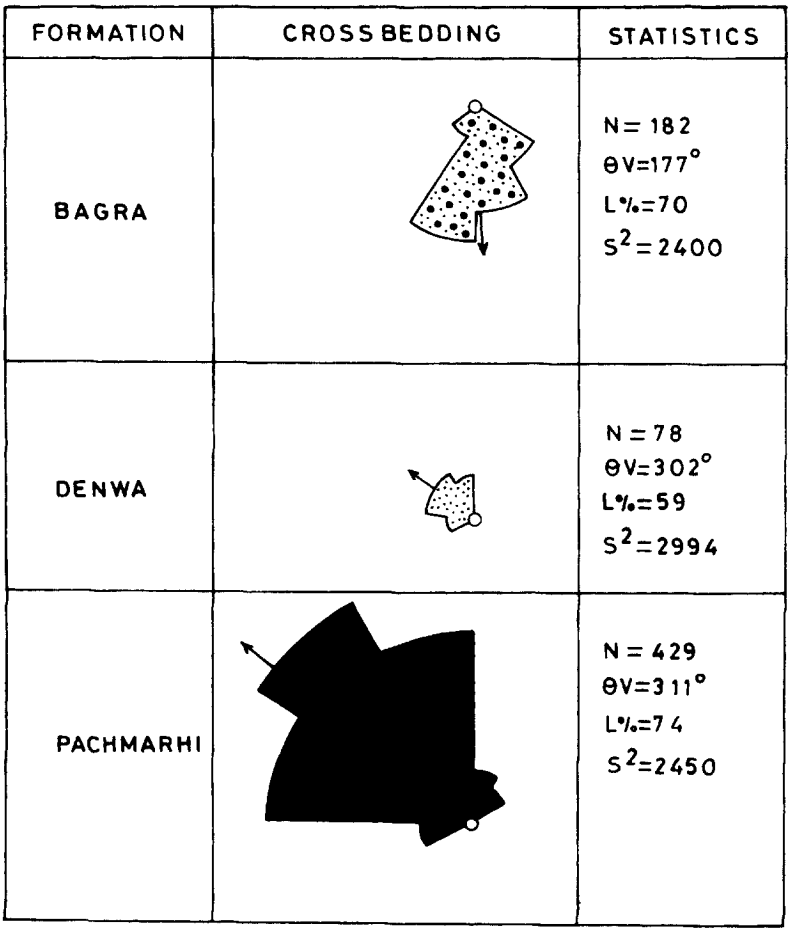

Figure 7. *Rose diagrams showing azimuthal distribution, mean palæocurrent direction and related statistics at the formation level for the Bagra, Denwa and Pachmarhi Formations.*

shale in the upper part. The matrix-supported conglomerate facies, consisting of pebbles, cobbles and boulders up to about 1 m in size of polymictic composition, occurs as coalescing sheet-like bodies. This lithofacies, forming the basal part of the formation and occurring along the northern margin, possibly represents viscous debris flows in the proximal reaches of an alluvial fan. The associated clast-supported conglomerate facies occurs as local interbeds in a matrix-supported conglomerate and gradually as a well-developed assemblage downslope towards the south. This is interpreted as reworked gravels by outflushing waters of an alluvial fan. The clast-supported conglomerate facies is well developed in the medial part of out-spreading fans. The distal facies is characterised by coarse- to medium-grained sandstone, with overlying mudstone and shale forming the upper part of the Bagra Formation (Fig. 8).

The preferred model for the vertical section of the Bagra Formation, comprising conglomerate, sandstone and shale, closely resembles that of a rift basin (half-graben) (Burke, 1977; Burke and Dewey, 1973; Casshyap *et al.*, 1993a, 1993b).

TECTONO-SEDIMENTARY EVOLUTION

The Mesozoic Gondwana rocks in the study area witnessed at least three tectonic events. These events are manifested by tectonic dislocation that caused marginal uplifts, down-warping and flushing of coarse to fine debris across steep to gentle gradients. The occurrence of conglomerates and pebbly gritty sandstones (Fig. 4) in the basal part of the Pachmarhi Formation, compared to the underlying fine clastics of the Upper Permian Bijori Formation, suggests that tectonism heralded the onset of the Pachmarhi sedimentaion refered to as the first tectonic event. Episodic pulses of minor uplifts along the basin margin continued during the early and middle Pachmarhi, as manifested by frequent interbeds of conglomerate and pebbly sandstone. However, seasonal 'cloud bursts' with high precipitation in the hinterland, in otherwise semi-arid and warm climates

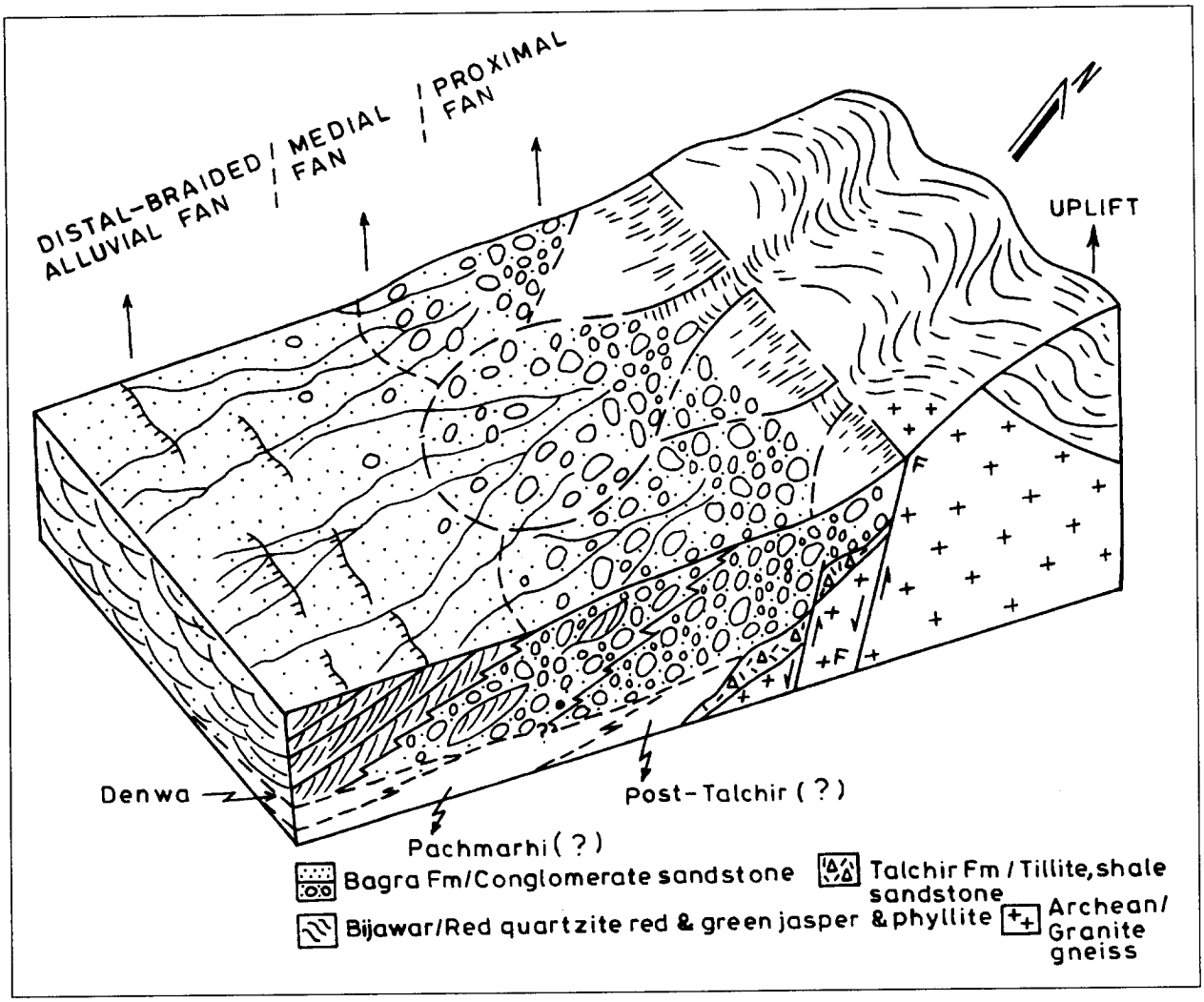

Figure 8. *Schematic alluvial fan model of the Bagra Formation in a downfaulted trough to the south of uplifted highlands of Precambrian granite and metasediments.*

during the Triassic period (Wopfner and Casshyap, 1997), may also account for occasional flushing and deposition of the gravelly debris. The pebbly coarse sands of the Pachmarhi Formation are overlain by a meandering river facies of the Denwa Formation. The progressive change in lithofacies and grain size upward, from dominantly pebbly coarse to medium sandstone in the Pachmarhi to medium to fine sandstone and interbedded shale and mudstone in the overlying Denwa, implies that the source area possibly became peneplained and that the basin became stabilised as sedimentation progressed following uplift. The persistence of northwesterly palæoslope from the Pachmarhi through the Denwa sedimentation also corroborates the contention that general tectonic stability continued uninterruptedly through the Lower to Middle Triassic Denwa Formation in the alluvial basin with gentle slopes. The drainage pattern remained unchanged throughout, from Permian to Triassic, directed dominantly from the southeast to the northwest (Casshyap, 1973, 1979).

Following the Mid-Triassic break in sedimentation after the deposition of the Denwa Formation, there was a prolonged gap of non-deposition during which the Permo-Triassic Gondwana basins of Peninsular India to the south and north of the Narmada-Son Lineament Zone witnessed tectonism by way of widespread faulting, uplift, including selective deformation, and magmatism (Casshyap *et al.*, 1993b; Veevers and Tewari, 1995; Tewari and Casshyap, 1996). This is referred to as the second tectonic event.

A third tectonic event is manifested by the deposition of Late Jurassic-Early Cretaceous Bagra conglomerate and sandstone-shale facies in downfaulted half-grabens along the northern margin of

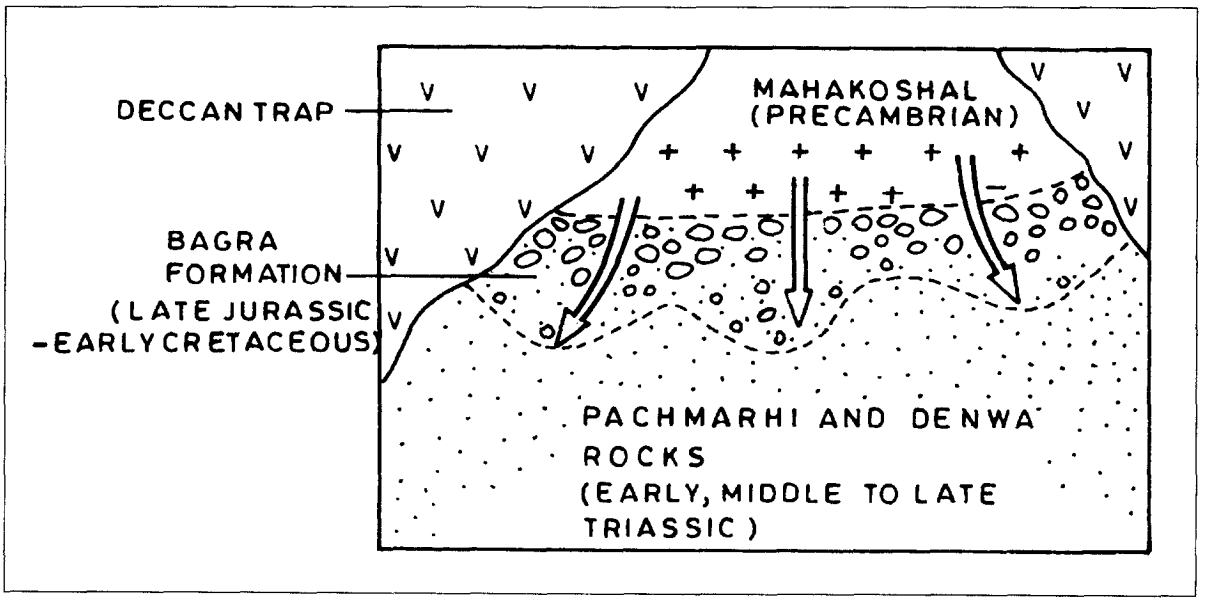

Figure 9. Schematic geological plan of the Pachmarhi, Denwa and Bagra Formations (not to scale).

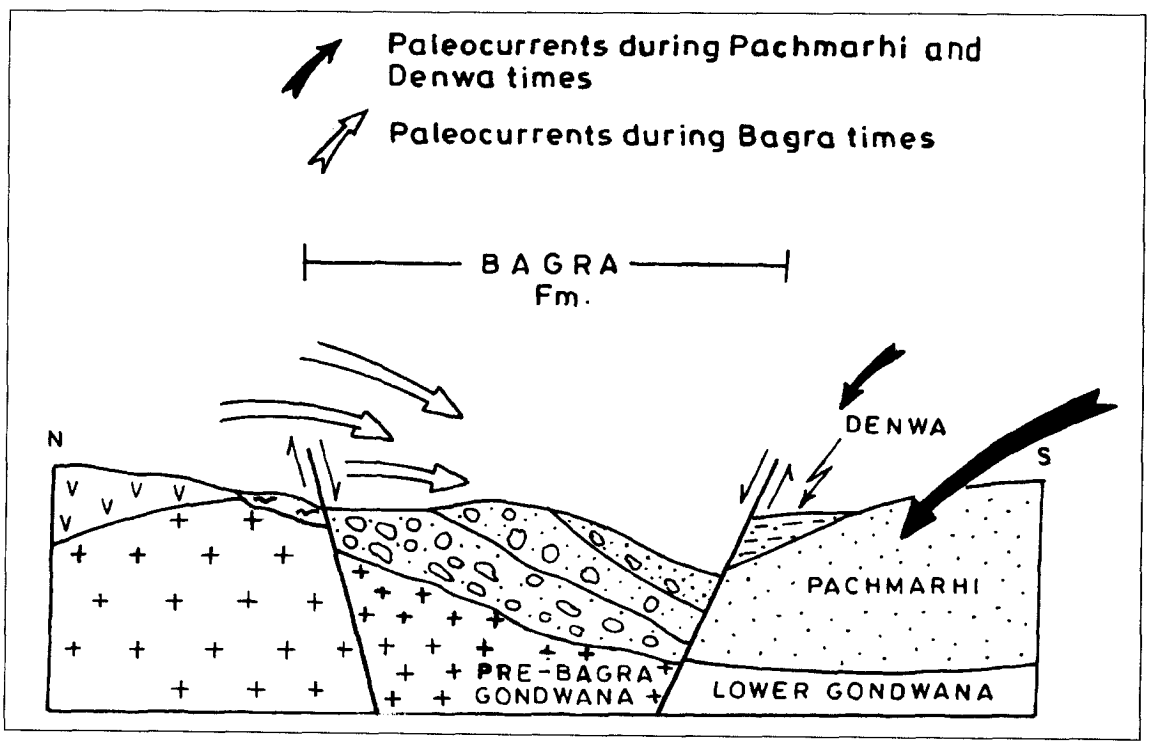

Figure 10. Schematic geological section showing the tectonic setting and palæodrainage during Bagra, Denwa and Pachmarhi sedimentation (not to scale).

the Satpura Basin. The polymictic, coarse, clastic debris and sandy sediments were derived from uplifted highlands to the north and transported southward (Figs 9 and 10). A similar tectonic setting accounts for the deposition of the Early Cretaceous Jabalpur Formation (Casshyap, 1973, 1999; Casshyap *et al.*, 1993b), which conformably overlies the Bagra Formation in the Satpura and adjoining Son Valley Basins. This tectonic event, extending up to the Early Cretaceous Jabalpur Formation, represents the termination of continental Gondwana sedimentation in Peninsular India. The tectonic event, which preceded the widespread eruption of the Deccan Traps (~65 Ma) (Courtillot *et al.*, 1986),

is a significant feature of Gondwana history in India and may well be related to the separatation of the Indian subcontinent from Antarctica in the Late Jurassic/Early to Middle Cretaceous (Casshyap, 1976; Craddock, 1979; Veevers and Tewari, 1995) and doming and rifting prior to eruption of the Deccan Traps (Cassyhap *et al.*, 1993a). As a consequence of this break-up and sea-floor spreading, a northward sloping peninsular craton was tilted southward and small rifted (pull-apart) basins developed in peripheral parts of Peninsular India along the east coast, in the Saurashtra Peninsular in the west and the Narmada-Son Lineament Zone in central India (Casshyap *et al.*, 1993b). To the north of the study area, the doming before the Deccan volcanism and tectonic movement along the Narmada-Son Lineament caused uplift of Palæoproterozoic (Mahakoshal/Bijawar) and the Neoproterozoic (Vindhyan) cratonic blocks. This uplift was accompanied by the reversal of palæoslope and palæocurrent from north to south after deposition of the Pachmarhi and Denwa Formations, but before the Deccan Continental Flood Basalt, as borne out by the alluvial fan-braided complex of the Bagra Formation.

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