Kinematics of the Gondwana basins of peninsular India

Chandan Chakraborty[a,*], Nibir Mandal[b], Sanjoy Kumar Ghosh[a]

[a] *Geological Studies Unit, Indian Statistical Institute, 203 Barrackpore Trunk Road, Calcutta-700035, India*
[b] *Department of Geological Sciences, Jadavpur University, Calcutta-700032, India*

Abstract

The Gondwana successions (1–4 km thick) of peninsular India accumulated in a number of discrete basins during Permo-Triassic period. The basins are typically bounded by faults that developed along Precambrian lineaments during deposition, as well as affected by intrabasinal faults indicating fault-controlled synsedimentary subsidence. The patterns of the intrabasinal faults and their relationships with the respective basin-bounding faults represent both extensional and strike-slip regimes. Field evidence suggests that preferential subsidence in locales of differently oriented discontinuities in the Precambrian basement led to development of Gondwana basins with varying, but mutually compatible, kinematics during a bulk motion, grossly along the present-day E–W direction. The kinematic disparity of the individual basins resulted due to different relative orientations of the basement discontinuities and is illustrated with the help of a simple sandbox model. The regional E–W motion was accommodated by strike-slip motion on the transcontinental fault in the north.

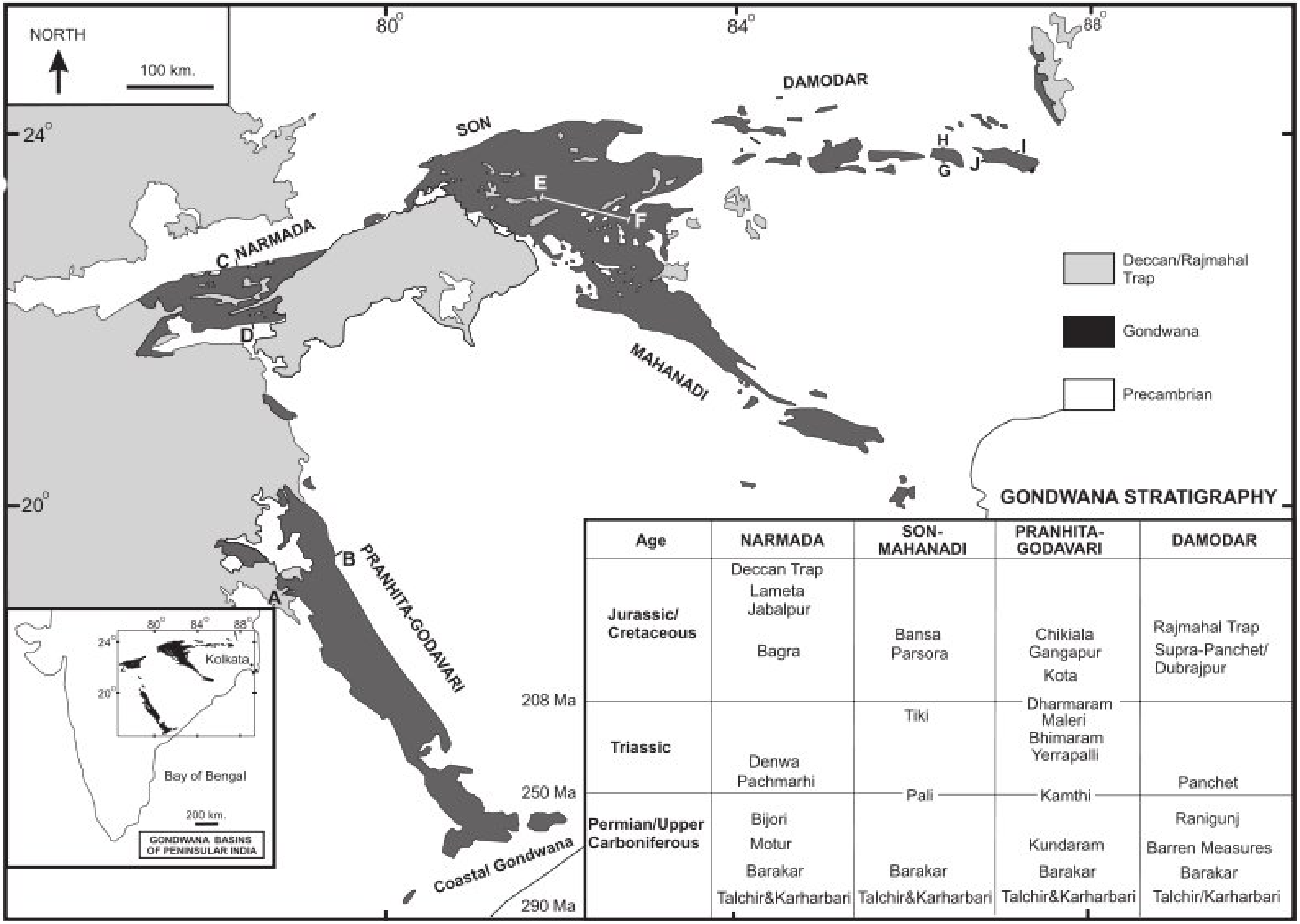
Keywords: Gondwanaland; Permo-Carboniferous; Crustal extension; Sedimentary basins

---

1. Introduction

The sedimentary strata that accumulated in different areas of peninsular India between Permo-Carboniferous and Triassic (290–208 Ma) are referred to as Gondwanas (Fig. 1; Fox, 1931; Robinson, 1967; Venkatachala and Maheswari, 1988; Veevers and Tewari, 1995). The Gondwana deposits mark resumption of sedimentation in the peninsular India in Late Carboniferous after a long hiatus since the Proterozoic. The successions share the faunal and floral characteristics of the equivalent strata of South America, South Africa, Australia and Antarctica—the other constituents of the southern hemispheric part (*Gonddwanaland*) of the Paleozoic supercontinent *Pangea* (Veevers and Tewari, 1995). Evidently, formation of Gondwana basins in India as well as in other continents records a major tectonic event of the earth (Hobday, 1987), which Veevers and Tewari (1995) interpret as driven by the episodic release of Pangean-induced heat.

The Gondwana successions are preserved in a number of discrete basins in the peninsular India (Figs. 1–3). The structural basins are relics of the original depositional master basin that was disrupted during and after deposition (Veevers and Tewari, 1995). The basins define three linear belts along the present-day river valleys of (1) Narmada–Son–Damodar (NSD), (2) Pranhita–Godavari (PG) and (3)



GONDWANA STRATIGRAPHY

Age	NARMADA	SON-MAHANADI	PRANHITA-GODAVARI	DAMODAR
Jurassic/Cretaceous	Deccan Trap Lameta Jabalpur Bagra	Bansa Parsora	Chikiala Gangapur Kota	Rajmahal Trap Supra-Panchet/Dubrajpur
Triassic	Denwa Pachmarhi	Tiki	Dharmaram Maleri Bhimaram Yerrapalli	Panchet
Permian/Upper Carboniferous	Bijori Motur Barakar Talchir&Karharbari	Pali Barakar Talchir&Karharbari	Kamthi Kundaram Barakar Talchir&Karharbari	Ranigunj Barren Measures Barakar Talchir/Karharbari

Fig. 1. Map showing occurrences of Gondwana rocks in the peninsular India. Insets show (a) the relative positions of the Gondwana outcrops in the Indian subcontinent and (b) the Gondwana stratigraphy. Note that the Gondwana rocks occur along the valleys of present-day Narmada–Son–Damodar, Pranhita–Godavari and Mahanadi rivers.

Mahanadi (M) (Fig. 1). The latter two river valleys are subparallel to each other and meet the ENE–WSW trending NSD valley and the present-day eastern margin of the subcontinent at high angles. Regionally persistent dislocation zones of antiquity flank these belts (Narula et al., 2000) (Fig. 3). The basin fills are commonly asymmetric with an overall increase in thickness towards one of the boundary faults, and the strata are also affected by intrabasinal gravity faults reflecting synsedimentary downward displacements (Raja Rao, 1982, 1983, 1987; Ghosh and Mukhopadhyay, 1985; Agarwal et al., 1993; Lakshminarayana, 1994; Casshyap and Khan, 2000; Peters and Singh, 2001; Ghosh, 2002) (Fig. 4). The Bouguer gravity anomaly contours (Fig. 5) as well as drill-hole data again indicate an ~ 4 km thickness of subsurface Gondwana strata, implying synsedimentary tectonic subsidence (Veevers and Tewari, 1995; Mishra et al., 1999). Fault-controlled subsidence had been responsible for the nucleation and evolution of the Gondwana basins of peninsular India (Mitra, 1987; Veevers and Tewari, 1995; Biswas, 1999) under a bulk extensional tectonic regime due to failure of the attenuated crust along preexisting zones of weakness imparted by Precambrian structural fabrics (Chatterjee and Ghosh, 1970; Naqvi et al., 1974; Mitra, 1994; Biswas, 1999; Acharyya, 2000). Permo-Carboniferous glaciogenic deposits at the base of the individual basins demonstrate their development in response to a regional (global) tectonic event (Casshyap and Tewari, 1991; Veevers and Tewari, 1995; Biswas, 1999), so that the kinematics of individual basins ought to be mutually compatible. Earlier studies on a few disparate Gondwana basins revealed their graben-like configuration, so that authors invoked local extensional tectonics (Qureshy et al., 1968; Raiverman, 1985; Ghosh and Mukhopadhyay, 1985; Mishra et al., 1987, 1999; Casshyap and Khan, 2000; Peters and Singh, 2001; Ghosh, 2002). These studies, however, did not consider the constraint that any proposed kinematics of an individual basin ought to be mutually compatible with that of the others. Moreover, no attempt has been made to investigate the mechanism of development of the Gondwana basins maintaining kinematic compatibility in response to a single tectonic regime.

This study analyzes the faults associated with the Gondwana basins and infers the kinematics of individual basins, which differ from basin to basin, in contrast to the existing notion that all these basins are extensional in nature. We show how the kinematic behaviour of individual basins may vary but remain mutually compatible. The study indicates that all the Gondwana basins developed under a single tectonic regime characterized by a roughly E–W motion. The motion-induced strike-slip displacement on an E–W oriented precursor fault lineament and orthogonal extension across two preexisting fault zones disposed at high angle to the direction of bulk E–W motion. This caused preferential subsidence in locales of preexisting discontinuities in the Precambrian basement and led to development of an array of sedimentary basins of varied kinematics along the present-day river valleys of Narmada–Son–Damodar, Pranhita–Godavari and Mahanadi (Fig. 1).

2. Spatial distribution and basinfill characteristics

The Gondwana basins are intracratonic within Precambrian terranes (Figs. 1 and 3). They are disposed along the ENE–WSW trending Narmada–Son–Damodar (NSD) valley, NNW–SSE trending Pranhita–Godavari (PG) valley and NW–SE trending Mahanadi (M) valley (Fig. 1). The basins that occur along the NSD valley from west to east are Satpura, Rewa, Karanpura, Bokaro, Jharia and Ranigunj (Figs. 1 and 3). There are two other basins along the belt, viz., Daltongunj and Rajmahal basins that occur northwest of the Karanpura basin and northeast of the Ranigunj basin, respectively (Figs. 1 and 3). The PG valley is characterized by an elongate basin northward of which occurs the Satpura basin (Figs. 1 and 3). The M valley comprises of three basins known as Hasdo–Arand, Mahanadi and Talchir basins, and at its junction with the NSD valley occurs the Rewa basin (Agarwal et al., 1993; Figs. 1, 3 and 8)). Besides these basins, there are several other small discrete outliers of Gondwana deposits in the peninsular region including those occurring in the east coastal region at the mouths of the Pranhita–Godavari and Mahanadi rivers (Fig. 1), which are not dealt with in this study.

The preserved thickness of the dominantly siliciclastic Gondwana succession ranges between 1 and 4 km (Fig. 2). The glaciogenic Talchir and the overlying coal-bearing Barakar Formations represent the lower part of the Gondwana succession showing uniform characteristics in all the basins. However, the overlying formations have variable lithological and sedimentological attributes in different basins, and their interbasinal correlation is difficult based only on physical characteristics and relative stratigraphic position; consequently, barring Talchir and Barakar, the other formations have been assigned different names in different basins (Robinson, 1967; Figs. 1 and 2). In many of these basins, there are also packages of post-Gondwana (Jurassic/Cretaceous) sedimentary strata that unconformably overlie the Permo-Triassic succession and, in some basins, are intruded and overlain by basaltic trap rocks associated with the Deccan volcanism erupted during Cretaceous period (Robinson, 1967; Figs. 1 and 2).

Traditionally, the Indian Gondwana successions, barring the Talchir Formation, have been interpreted as representing deposition in alluvial settings (Fox, 1931; Robinson, 1967; Raja Rao, 1982, 1983, 1987; Casshyap and Tewari, 1991; Veevers and Tewari, 1995). The Talchir Formation largely comprises of glacial and glacial outwash (glacio-fluvial) deposits along with lithofacies representing subaqueous deposition from mass flows and suspension settlement at depths of a few tens of meters (Smith, 1963; Banerjee, 1966; Casshyap and Qidwai, 1974; Mukhopadhyay and Bhattacharya, 1994; Veevers and Tewari, 1995; Dasgupta, 2002). A few beds containing marine fossils within the Talchir Formation indicate an early Permian marine incursion (Cowper Reed, 1927; Ghosh, 1954, 2003; Ahmad, 1957; Ahmad and Khan, 1993; Dutta, 1965; Chaudhuri, 1985; Venkatachala and Tiwari, 1987; Chakraborty, 1993; Veevers and Tewari, 1995; Biswas, 1999). The rest of the Gondwana succession comprise fluvial deposits and formations have been delineated mainly on the basis of: (1) proportion of

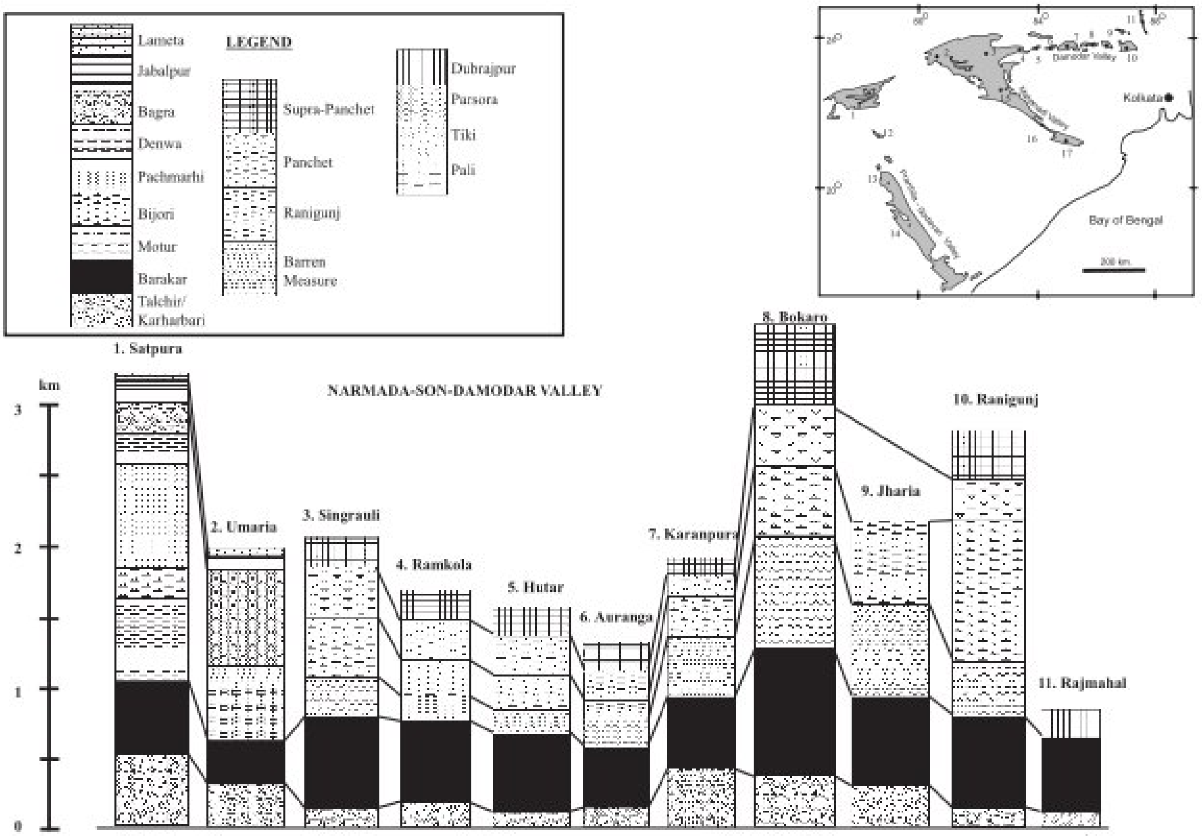


Fig. 2. Stratigraphic successions of the Gondwana Supergroup at different locations shown in the inset.

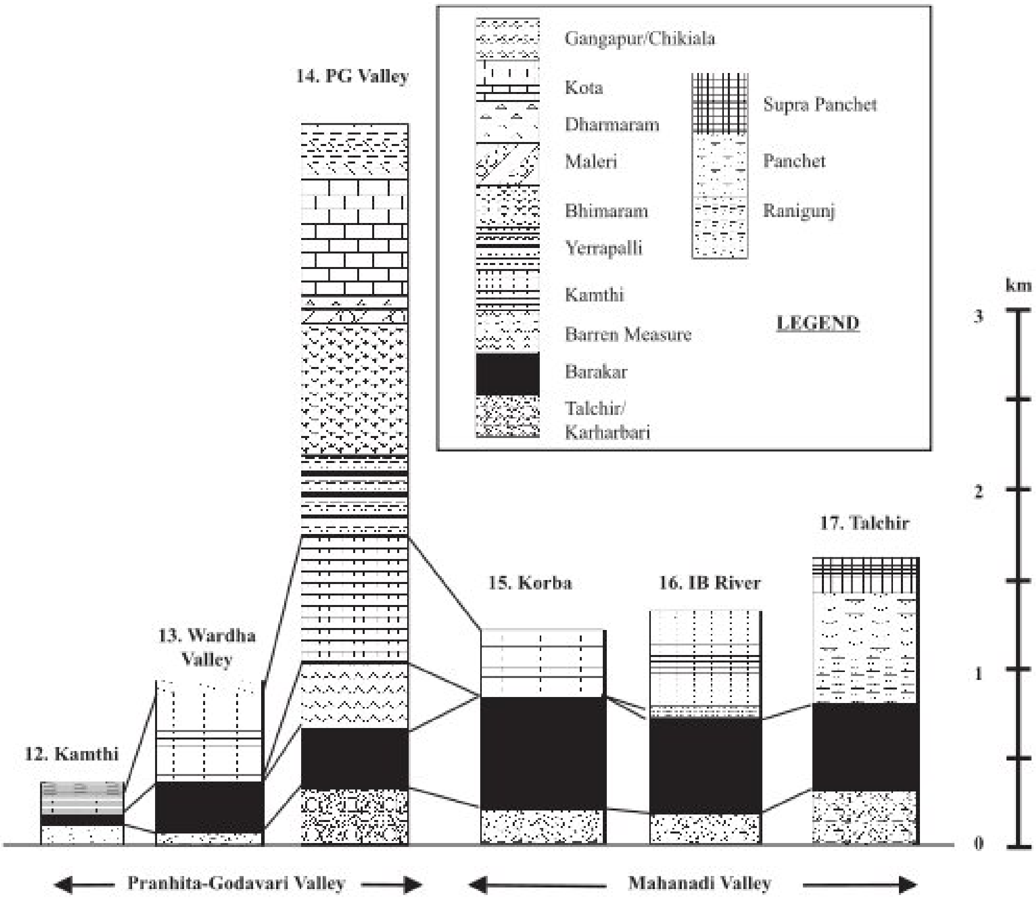


Fig. 2 (*continued*).

channel-belt and floodplain strata, (2) the inferred fluvial style (braided, meandering, anastomosed) and (3) type and maturity of paleosols developed on the floodplain strata (Maulik et al., 2000). Interspersed with these fluvial strata occur sediments representing deposition in subaquatic condition (Ahmad and Khan, 1993; Gupta, 2000; Chakraborty and Sarkar, 2000). The paleoflow is dominantly towards N–NW in all the basins except the Damodar valley (Karanpura, Bokaro, Jharia and Ranigunj) where the flow varies from NNW to W (Casshyap, 1973; Veevers and Tewari, 1995).

3. Structural framework of the basins

The three river belts (NSD, PG and M), along which the Gondwana basins occur (Fig. 1), are flanked by distinct dislocation zones (Fig. 3), many of which are deeply buried and considered to have formed during the Precambrian (e.g. Son–Narmada fault, Tan shear, Godavari valley fault, etc.) and subsequently reactivated (Naqvi et al., 1974; Kaila, 1986; Mitra, 1994; Acharyya, 2000). Demarcation of the Gondwana basinfills by these discontinuities (Fig. 3) suggests their rejuvenation during the development of the basins in Permo-Carboniferous time. It is thus implied that the rigid basement on which the Gondwana basins formed was characterized by preexisting discontinuities that seemingly have controlled the formation of individual basins in response to the bulk tectonic regime. In the following sections, we describe separately the fault patterns observed in the Gondwana basins and infer the probable kinematic conditions for their development.

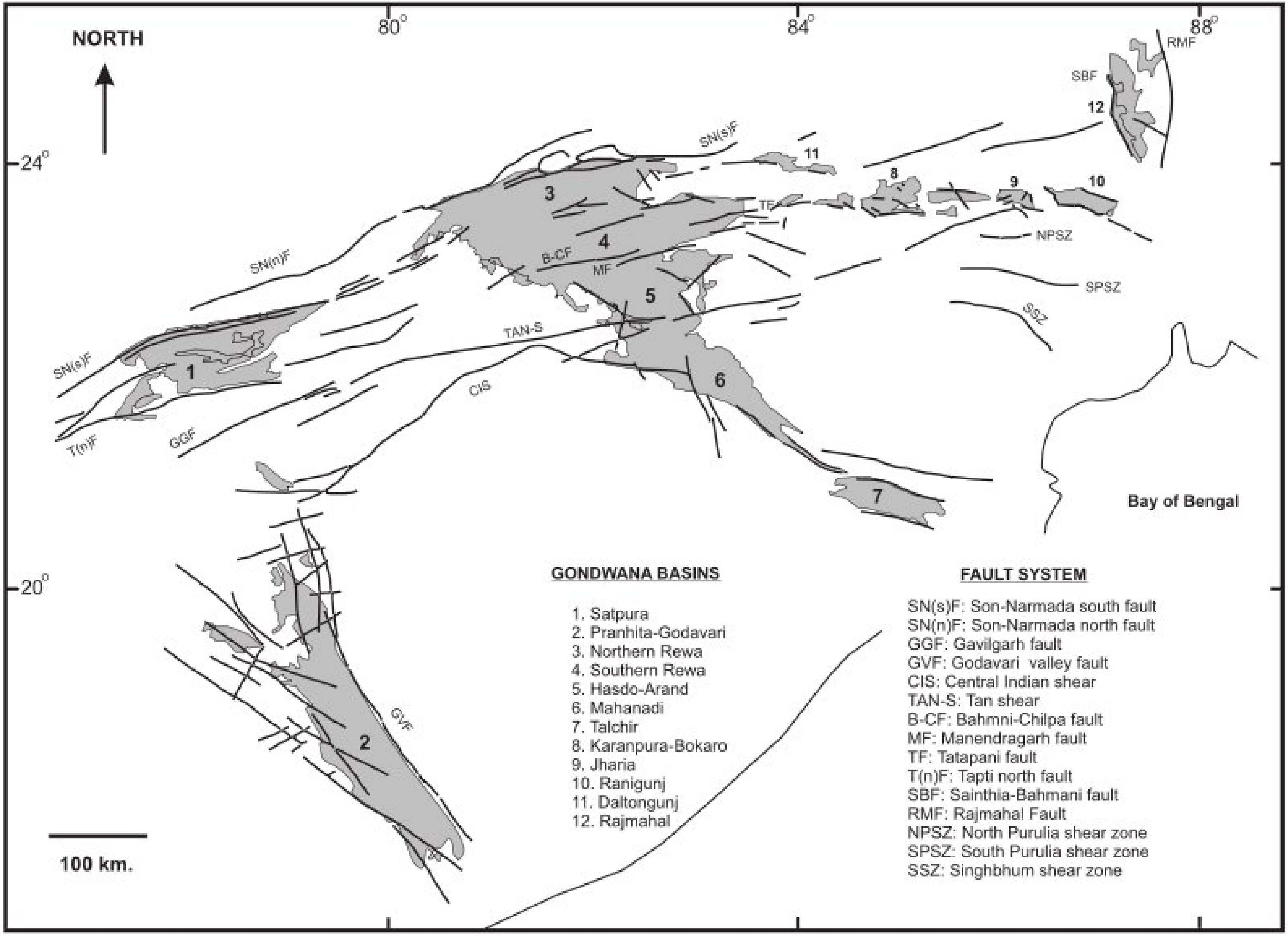
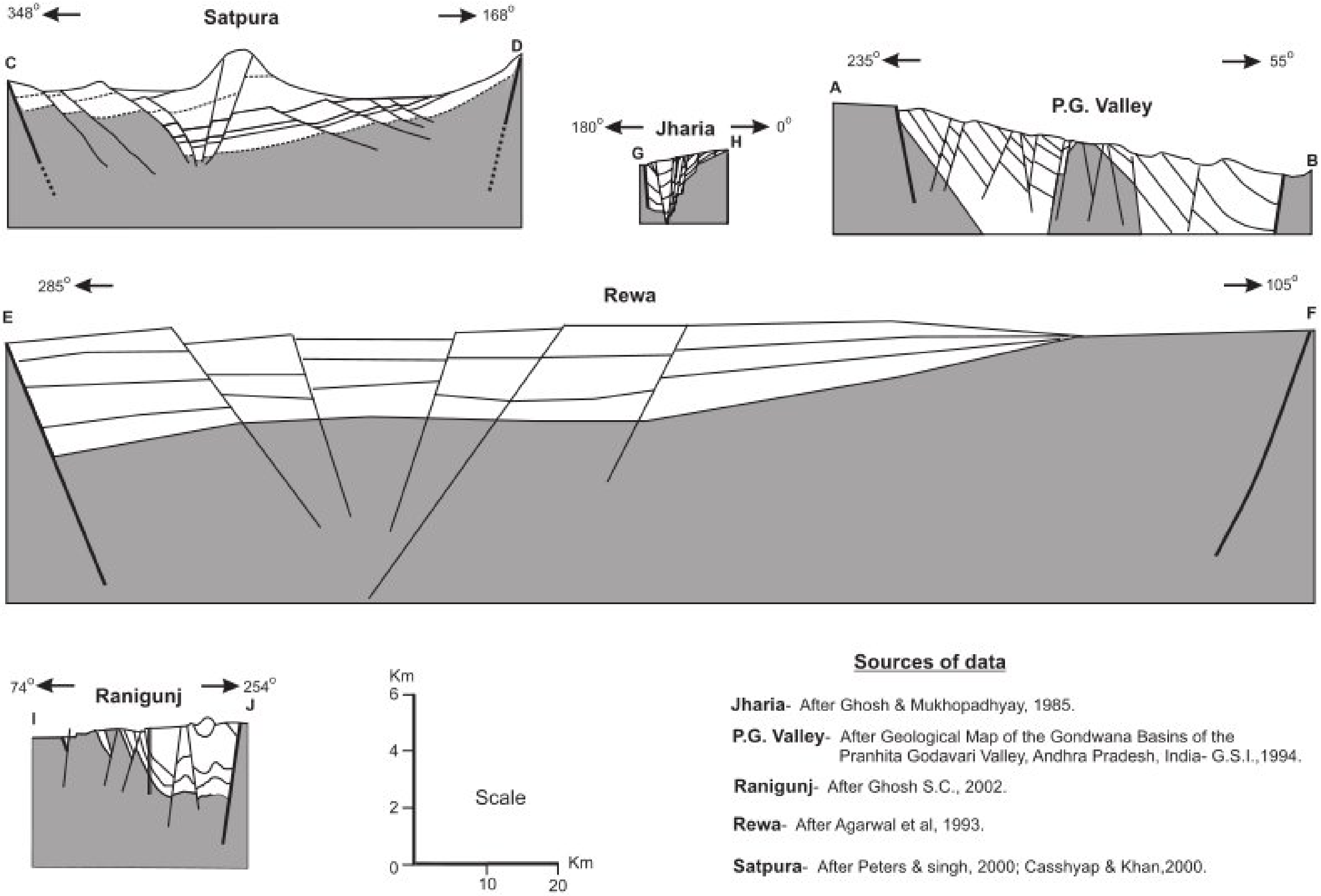


Fig. 3. Layout of the major faults and lineaments associated with different Gondwana basins of peninsular India.



Sources of data

Jharia- After Ghosh & Mukhopadhyay, 1985.

P.G. Valley- After Geological Map of the Gondwana Basins of the Pranhita Godavari Valley, Andhra Pradesh, India- G.S.I.,1994.

Ranigunj- After Ghosh S.C., 2002.

Rewa- After Agarwal et al, 1993.

Satpura- After Peters & singh, 2000; Casshyap & Khan,2000.

Fig. 4. Cross sections of different Gondwana basins of the peninsular India showing the structural architecture. Lines of sections are shown in Fig. 1. Shaded portions represent the basement and bold lines are boundary faults.

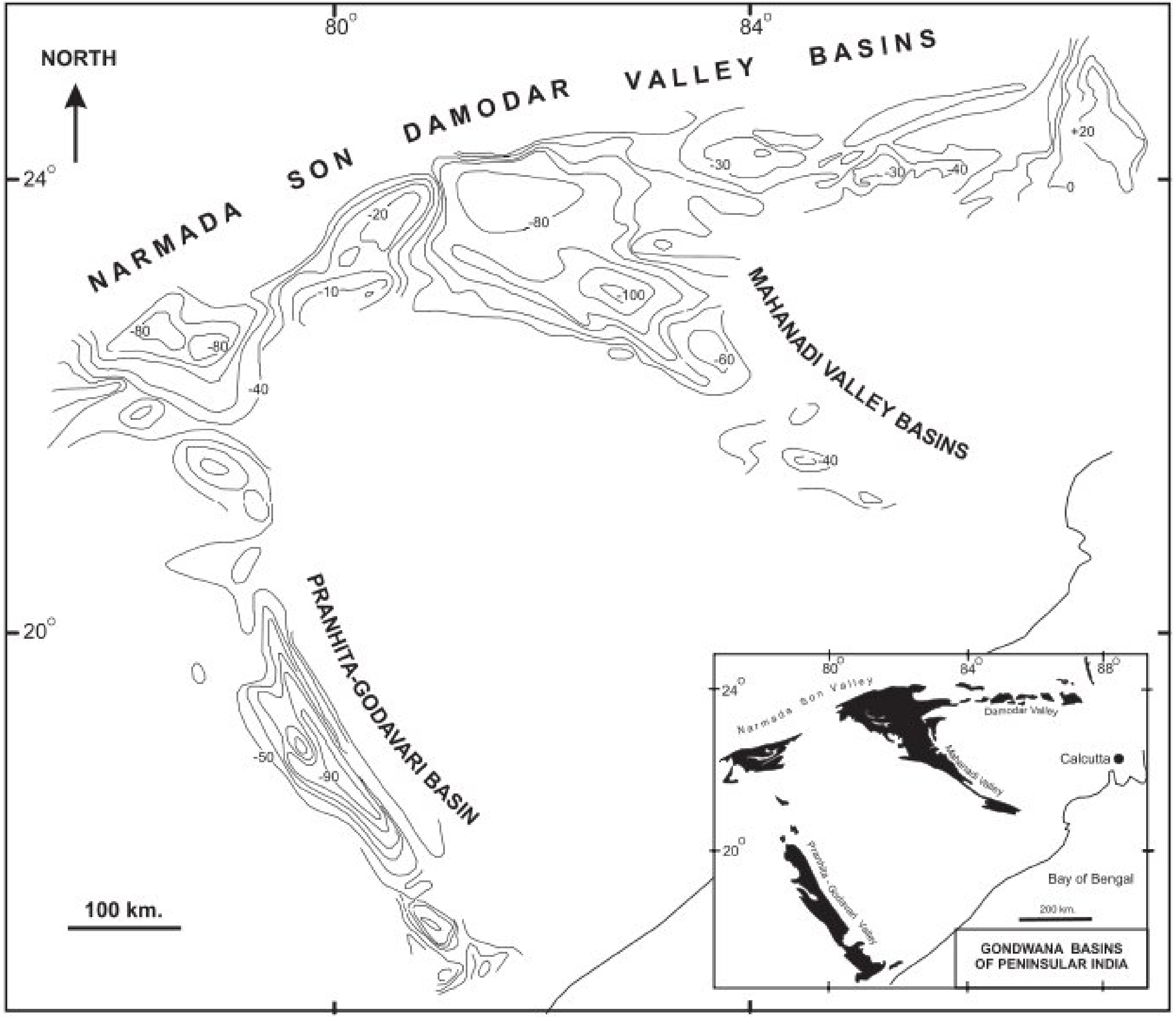


Fig. 5. Bouguer gravity anomaly contours (mgal) of the Gondwana basins of peninsular India (after Narula et al., 2000).

3.1. Pranhita–Godavari basin

The Pranhita–Godavari basin is a NNW–SSE trending elongate basin (400 km long, 75 km wide) and its eastern boundary is marked by the Godavari valley fault trending NNW–SSE, which parallels the strike of the basinfill strata (Fig. 3). The fault dips steeply, while the strata dip easterly indicating that downward displacement of the hanging wall was preferentially localized along this fault leading to a half-graben geometry and led to accumulation of a sediment pile as much as 4 km thick (Figs. 2 and 4). The Bouguer anomaly contours also conform to the shape of the basin and are closely spaced at the eastern margin (Fig. 5). The western margin is also demarcated by faults (Fig. 3). There are numerous intrabasinal normal faults affecting the basinfill strata. Some of these intrabasinal faults may define subsidiary half-grabens within the master basin (Fig. 4). The faults are generally anastomosing in nature and locally branch out making oblique orientation to the basin elongation, which may apparently look like those observed in oblique-type rift setting (McClay et al., 2002). However, their overall orientation is grossly parallel to the length of the basin (Fig. 6). This type of branching fault pattern is also observed in many orthogonal rift basins, e.g. East African rift systems (Lezzar et al., 2002) and Norwegian North Sea rifts (Badley et al., 1984).

In summary, the Pranhita–Godavari basin appears to be a typical rift basin with a master, bounding fault to the east and suffering nearly orthogonal extensional displacement towards WSW (cf. Biswas, 2003). The basin is slightly asymmetrical, showing the depot of thickest sedimentary piles closer to the western margin. The asymmetry has probably developed due to a mode of movement across a basement discontinuity wherein the western block was active and moved westerly, whereas the eastern block remained stationary. Physical experiments show that rift basins that arise due to this type of motion are generally asymmetrical, forming successive new normal faults away from the moving block (cf. McClay and Ellis, 1987a,b; Mauduit et al., 1997; see also Schlische, 1991).

3.2. Satpura basin

The Satpura basin (200 km long, 60 km wide) is rhomb-shaped, relatively long in the ENE–WSW direction and its longer sides are marked by the ENE–WSW trending Son–Narmada south fault and Tapti north fault (Figs. 3 and 7). These faults are subvertical and show evidence of strike-slip movements (Biswas, 1999, 2003). There is also a fault at the western margin disposed at a low angle between the strike-slip faults, tending to link them with an easterly vergence (Figs. 3 and 7). The eastern margin of the basin apparently does not reveal existence of faults perhaps due to burial by Deccan Traps (Fig. 1). The regional strike of the strata is NE–SW, and the regional dip (~ 5°) is northerly. The intrabasinal faults are normal and among them, the dominant set trends along NE–SW, making angles of around 25° with the bounding strike-slip faults. Another set of intrabasinal faults trend NW–SE, making high angles (~ 70°) with the strike-slip faults (Fig. 7). The basin profile also indicates fault-controlled subsidence (Fig. 4).

The rhombohedral shape of the Satpura basin bounded by strike-slip faults and presence of a cross fault linking them at the western margin indicate a pull-apart basin (Crowell, 1974; Aydin and Nur, 1985; Christie-Blick and Biddle, 1985). This basin might have developed on a releasing jog along an ENE–WNW trending transcurrent zone. Easterly vergence of the western sidewall fault indicates development of the basin as a result of sinistral strike-slip movement along a left-stepping fault system. The NE–SW trending intrabasinal faults that are at low angles to the strike-slip faults probably represent the cross-basin fault system commonly observed in natural and experimental pull-apart basins (Dooley and McClay, 1997). The NW–SE trending intrabasinal faults subtending high angles with the strike-slip faults might represent the extensional fault system that commonly form in pull-apart basins as a result of extension across the stepover during strike-slip displacements along side-stepping faults (Dooley and McClay, 1997; Basile and Brun, 1999; Sims et al., 1999). The association of low- and high-angle faults as observed in the Satpura basin has also been reported from several pull-apart basins, e.g. Salina del Fraile strike-slip basin (Dooley and McClay, 1997).

3.3. Rewa basin

The Rewa basin is also rhombic in shape, relatively long in ENE–WSW direction (400 × 150 km; Figs. 3

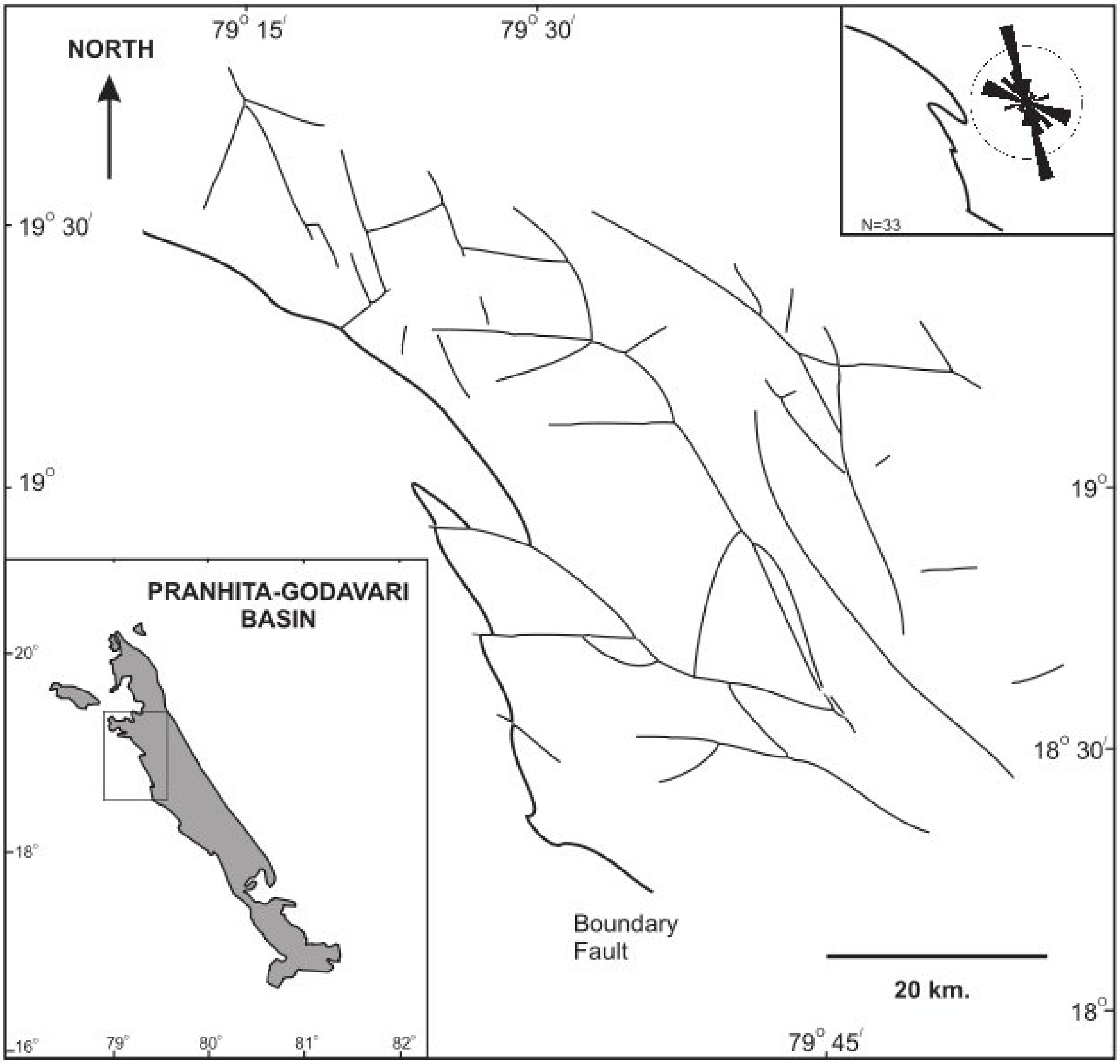


Fig. 6. Disposition of intrabasinal faults within a part of the Pranhita–Godavari basin marked in the inset. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

and 8). A set of faults parallel to and along with the ENE–WSW trending Son–Narmada south fault bound the basin in the north defining the Malwa ridge, which show evidence of strike-slip movement (Raja Rao, 1983; Agarwal et al., 1993). A set of ENE–WSW trending faults run along the middle of the Rewa basin dividing it into northern and southern compartments (Figs. 3 and 8). The basin is separated from the Hasdo–Arand basin in the south by a basement ridge (Manendragarh–Pratappur Ridge) that follows the ENE–WSW trending Bahmni–Chilpa and Manendragarh–Tatapani faults showing evidence of strike-slip displacement (Raja Rao, 1983; Figs. 3 and 8). The basinfill strata generally have low dips (∼ 5°) towards northwest. There are two sets of intrabasinal faults, one making low angles to the basin boundaries in both clockwise and anticlockwise directions, and the other set is at high angles with trends

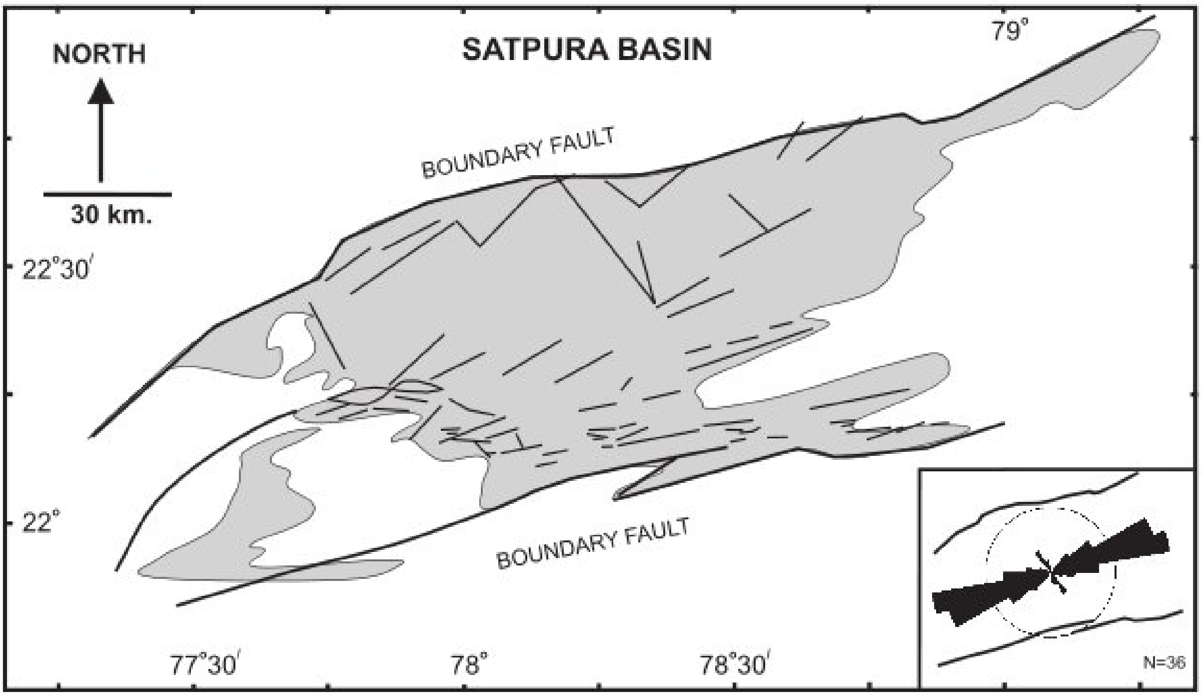


Fig. 7. Disposition of intrabasinal faults within the Satpura basin. Note their relative orientations with respect to the boundary faults. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

varying from NNE–SSW to NNW–SSE (Raja Rao, 1983; Fig. 8). The basin profile indicates fault-controlled subsidence (Fig. 4).

Evidence of strike-slip displacement along the ENE–WSW trending bounding faults of the northern and southern Rewa basins and presence of intrabasinal cross faults suggest that the basins developed due to strike-slip motion. It is also implied that there were relative displacements between the northern and southern blocks of the Rewa basin along the dividing fault.

3.4. Hasdo–Arand basin

This basin is an equant, rhombic basin (80 × 80 km) separated from the northerly occurring Rewa basin by the ENE–WSW trending Manendragarh basement ridge in the north (Figs. 3 and 8). A basement ridge (Naughata Ridge) also marks its southern margin, which is characterized by a set of ENE–WSW trending strike-slip fault zone (Tan shear; Figs. 3 and 8). A NW–SE trending fault zone demarcates the western basin boundary (Figs. 3 and 8). There are also faults at the eastern margin of the basin. The stratal disposition describes a broad synclinal structure. The dominant set of intrabasinal normal faults trends along NW–SE (Fig. 8).

Apparently, sediment accumulation in the Hasdo–Arand basin took place due to subsidence associated with displacements along the normal faults trending NW–SE implying an extension across the NW–SE trending western boundary fault. The extension zone was confined between two parallel transcurrent zones that bound the basin in the north and south.

3.5. Mahanadi basin

South of the Hasdo–Arand basin along the Mahanadi valley (Fig. 1) occurs the NW–SE elongate Mahanadi basin (200 km long, 50 km wide), which is bounded on the southwest by a major fault dipping easterly (Figs. 3 and 8). It is separated from the Hasdo–Arand basin by the Tan shear and the southern extent is limited by a strike-slip fault zone trending WNW–ESE that marks the eastern boundary of the

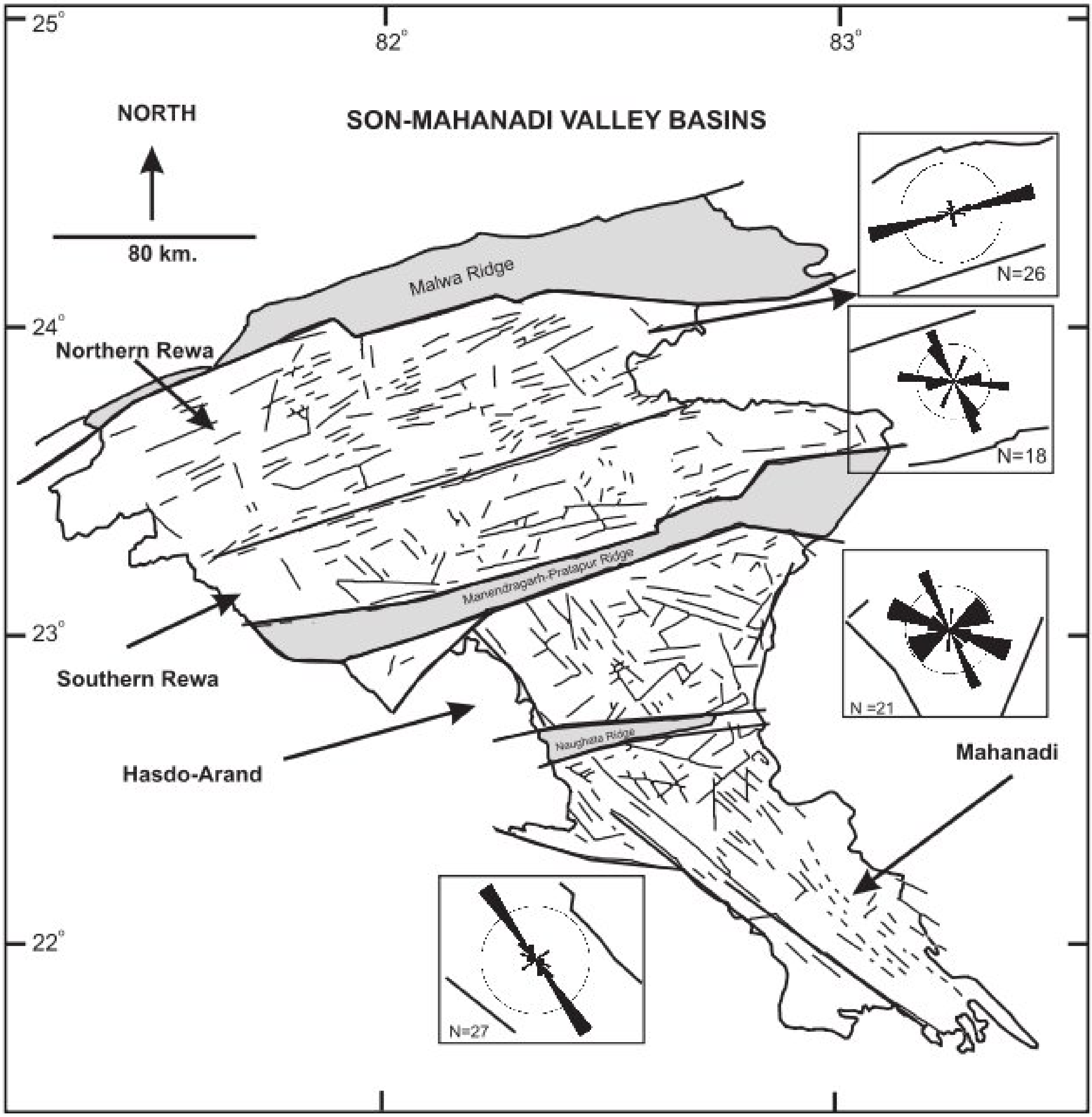


Fig. 8. Structural architecture of the Rewa, Hasdo–Arand and Mahanadi basins as revealed from remote sensing data. Bold lines mark faults observed in the field. Shaded areas represent basement. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

Talchir basin (Fig. 3; see below). The basinfill strata generally strike along the length of the basin defining a broad synclinal structure. The Bouguer gravity anomaly contours (Fig. 5) are closely spaced near the western margin indicating greater thickness of the basinfill close to the boundary fault. Intrabasinal normal faults show trends dominantly along NW–SE with both easterly and westerly dips (Fig. 8).

The structural architecture of the Mahanadi basin resembles extensional basins with a master, bounding fault to the west, suffering an easterly extension confined between two transcurrent zones across the length (cf. Mishra et al., 1999).

3.6. Talchir basin

This is a WNW–ESE elongate, rhombic basin occurring south of the Mahanadi basin (Fig. 3). Its northeastern and southwestern boundaries are marked by major faults (Fig. 3). The regional strike of the strata varies from ENE–WSW to ESE–WNW. Three sets of intrabasinal faults are present, one of which is subparallel to the strike of the strata. The other sets generally have WNW–ESE and NNW–SSE orientations.

The rhombic shape of the basin coupled with the presence of cross-basin faults linking the boundary faults at low and high angles suggest that the Talchir basin is likely be a pull-apart basin (Crowell, 1974; Aydin and Nur, 1985; Christie-Blick and Biddle, 1985; Basile and Brun, 1999; Sims et al., 1999) with predominantly strike-slip displacements along the WNW–ESE trending boundary faults.

3.7. Daltongunj basin

This is a narrow, elongate basin with an overall trend along E–W (80 km long, 15 km wide). The basin describes a conspicuous Z-shaped geometry in plan (Fig. 3). The southern margins are demarcated by prominent faults. Strata dip gently and are intersected by intrabasinal faults, the trend of which varies between NW–SE and NE–SW. The features suggest a fault-bend (lazy Z) basin formed due to dextral shear movement on a strike-slip fault trending roughly along E–W.

3.8. Damodar valley basins

Along the E–W trending Damodar valley, several discrete basins occur that are broadly similar in morphology and structural characteristics (Figs. 1, 3 and 9). They are all rhombic, fault-bound basins with numerous intrabasinal faults making high angles to

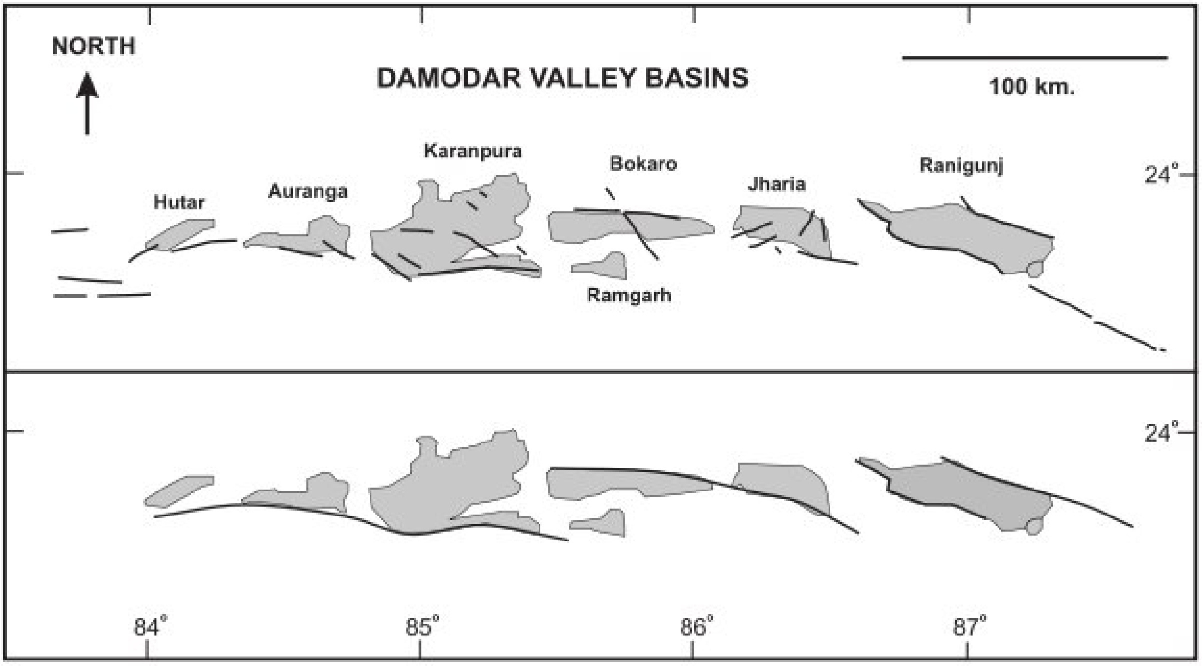


Fig. 9. Arrangement pattern of the bounding faults of the Damodar valley Gondwana basins. Note that the bounding faults are arranged with left stepping as schematically shown at the bottom.

the bounding faults along their longer sides. The structural features of the major basins of the Damodar valley are described below.

3.8.1. Karanpura–Bokaro master basin

The Karanpura and Bokaro basins along with the small outliers of Auranga and Hutar together constitute a sigmoidal master basin (Figs. 3 and 9). The Karanpura basin forms the swollen core of the master basin, whereas the Hutar–Auranga and Bokaro basins represent the narrow wings of the 'S'. A prominent fault zone trending E–W marks the southern margin of the Karanpura basin with evidence of strike-slip movement (Fig. 9, Raja Rao, 1987). The northern margin also shows faults at places. The basinfill strata have low dips and their outcrops grossly conform to the basin margins defining a synclinal structure with centripetal dips. The intrabasinal normal faults dominantly trend along NW–SE. There are also some intrabasinal faults trending E–W (Fig. 10). The Bokaro basin represents the northern wing of the S-shaped master basin and is a narrow, elongate basin trending roughly E–W (Fig. 9). A fault zone marks its northern boundary (Fig. 9). The strata define a broad, gentle synclinal structure with E–W trend. Numerous intrabasinal, normal faults affect the strata, which dominantly trend along NW–SE and NNE–SSW (Fig. 11). The small outliers of Auranga and Hutar together representing the southern wing of the S-shaped master basin also show faults along their southern margins (Fig. 9).

3.8.2. Jharia basin

This is a slightly elongate, rhombic basin (40 km long, 20 km wide) trending WNW–ESE and its southern boundary is marked by a fault zone (Figs.

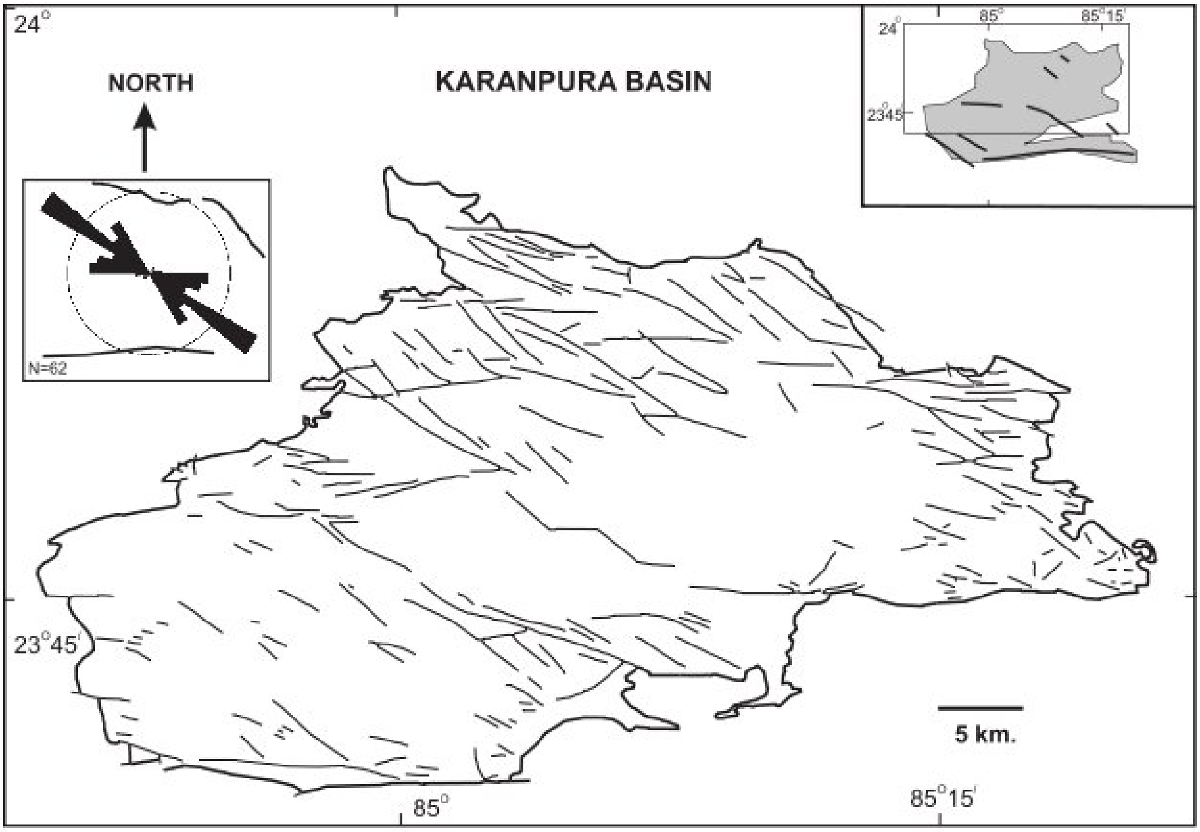


Fig. 10. Disposition of intrabasinal faults within the Karanpura basin. Note their relative orientations with respect to the boundary faults shown in the inset. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

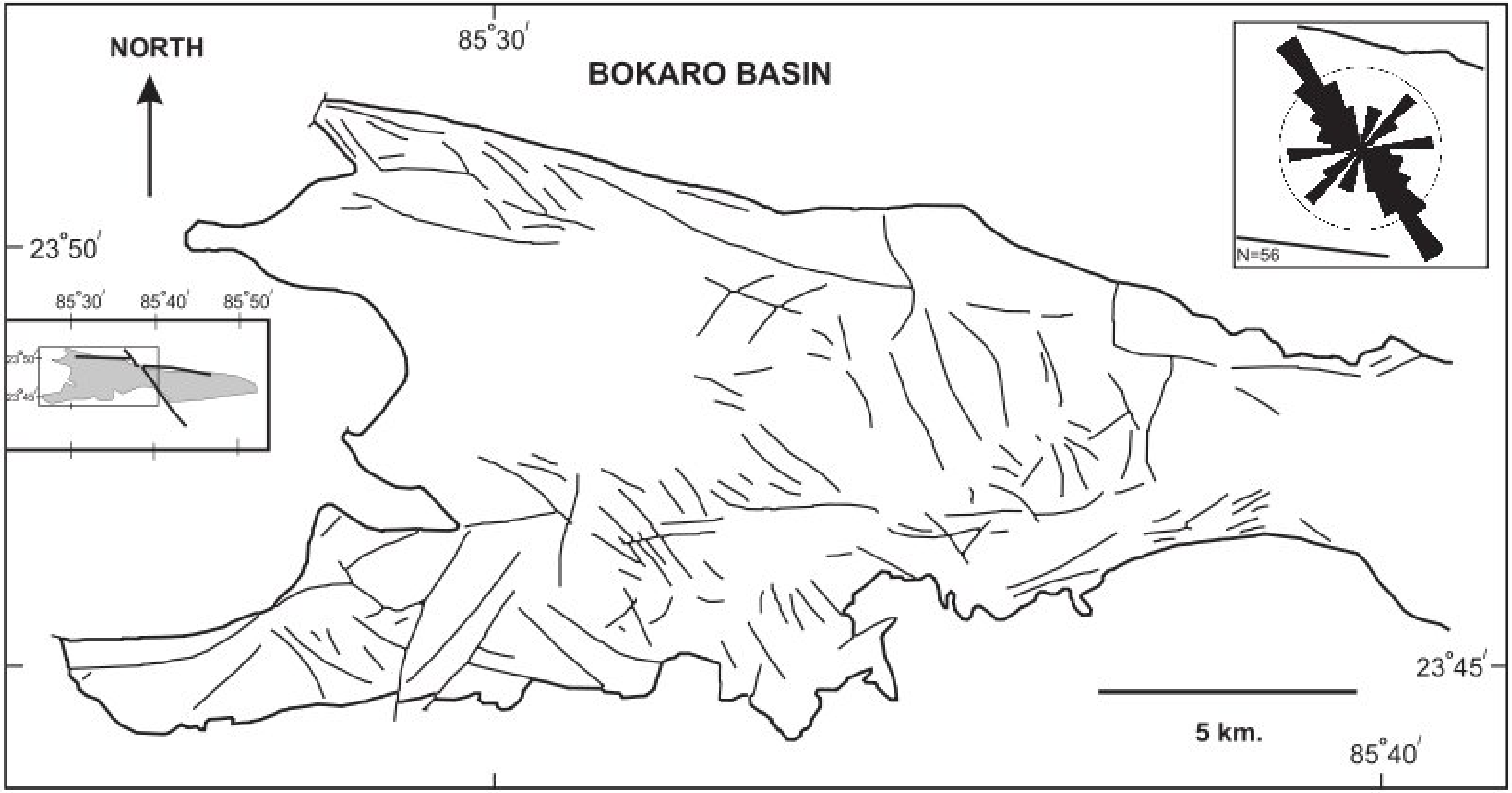


Fig. 11. Disposition of intrabasinal faults within the Bokaro basin. Note their relative orientations with respect to the boundary faults shown in the inset.

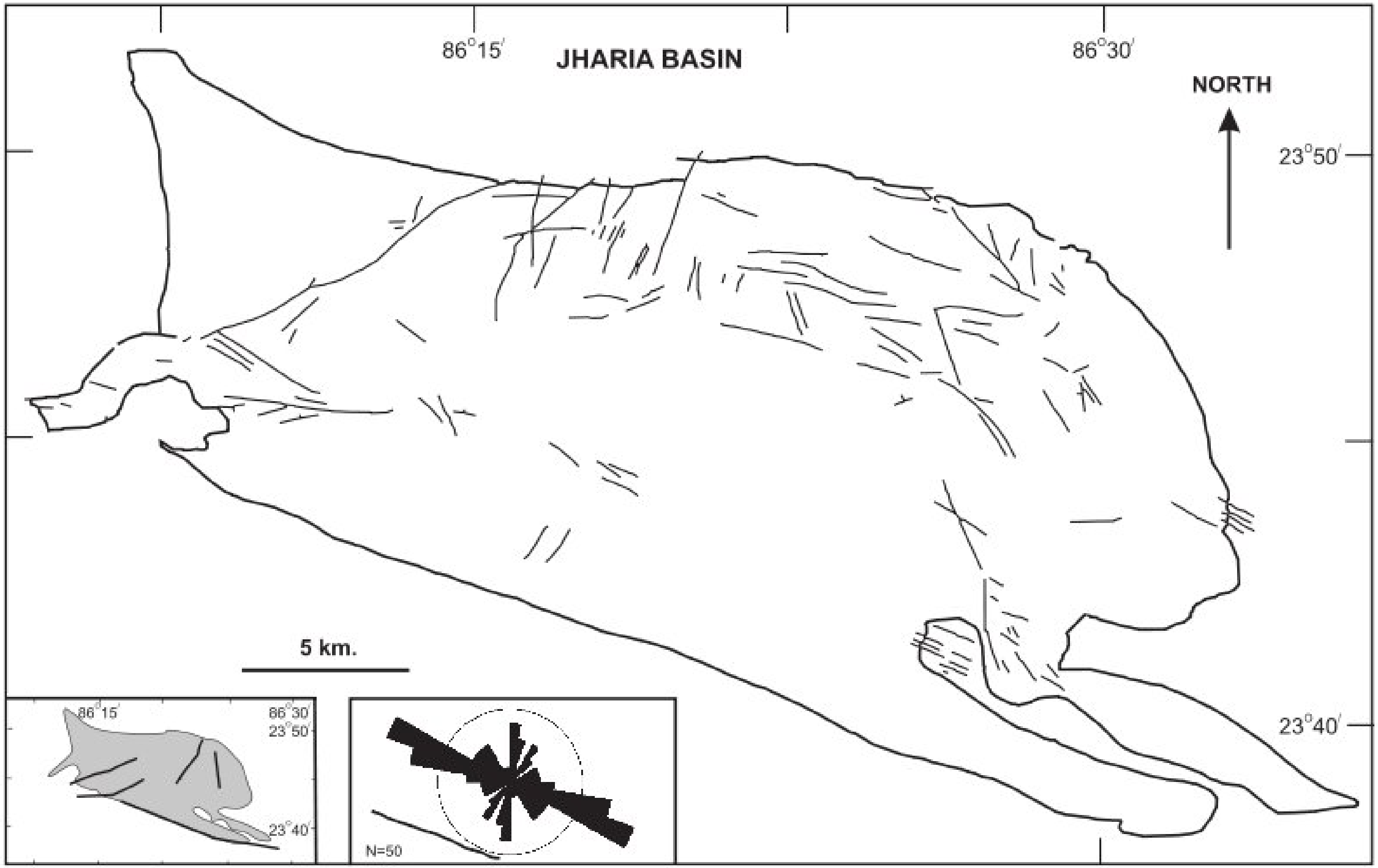


Fig. 12. Disposition of intrabasinal faults within the Jharia basin. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

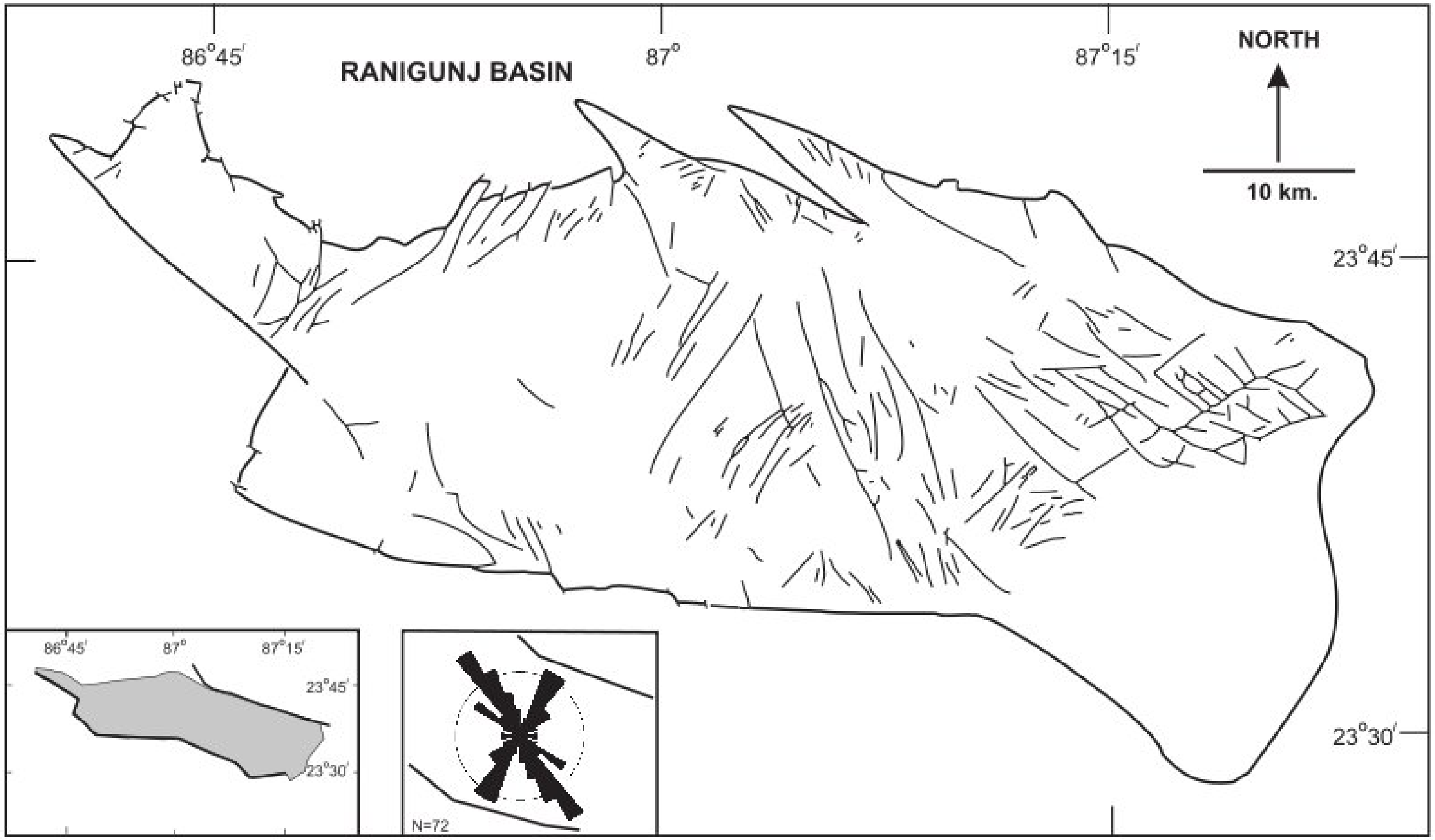


Fig. 13. Disposition of intrabasinal faults within the Ranigunj basin. Orientations of intrabasinal faults are shown by the Rose diagram in the inset in which the bold line represents the boundary fault.

3, 9 and 12). The strata define a broad, gentle syncline plunging towards west. The trends of the intrabasinal, normal faults vary from NW–SE to NNE–SSW (Fig. 12). The basin profile indicates fault-controlled subsidence (Fig. 4).

3.8.3. Ranigunj basin

This is a rhombic basin (70 km long, 20 km wide), relatively long in WNW–ESE direction (Figs. 3, 9 and 13). A prominent fault zone trending WNW–ESE marks its northern boundary. The southern boundary also shows several faults along its trend. The western margin of the basin is demarcated by two major faults trending NW–SE and NNE–SSW. The basinfill strata show broad curvatures and, in general, dip southerly. There are two sets of intrabasinal, normal faults trending NNW–SSE and NNE–SSW (Fig. 13). The basin profile indicates fault-controlled subsidence (Fig. 4).

3.8.4. Implications of the fault patterns of the Damodar valley basins

The boundary faults of the Karanpura, Bokaro, Hutar and Auranga basins together define a fault system with a discernible left-stepping, and at the region of stepover occurs the largest basin (Karanpura) of the belt (Figs. 3 and 9). We thus infer that the fault motion was sinistral, which gave rise to pull-apart basins at the stepovers. The abundant presence of cross faults in the basins also suggests that the basin kinematics were dominated by strike-slip motion (cf. McClay and Dooley, 1995; Dooley and McClay, 1997; Basile and Brun, 1999; Sims et al., 1999). However, sporadic occurrence of E–W trending minor intrabasinal faults implies that the motion was not purely strike-slip, but might have a transtensional component (Tron and Brun, 1991). It may be noted that the vergence of intrabasinal cross faults patterns of the Damodar valley basins is not fully consistent with that expected in pull-apart basins located at a stepover with a neutral geometry (Dooley and McClay 1997). It seems that the stepover probably had large overlap that influenced development of intrabasinal faults with opposite vergence in the Karanpura basin.

The trendline of the northern boundary fault of the Bokaro basin meets the southern boundary fault of the Jharia basin towards east and they are in a left-stepping arrangement with respect to the northern margin of the Jharia basin (Figs. 3 and 9). Again, the northern boundary of the Jharia basin is aligned with the southern boundary fault of the Ranigunj basin and the trend is in left-stepping arrangement with respect to the northern boundary fault of the Ranigunj basin (Figs. 3 and 9).

In summary, it appears that the different basins of the Damodar valley formed along an E–W trending lineament characterized by segments of a master strike-slip fault disposed with left-stepping arrangement (Figs. 3 and 9). The basins were preferentially formed in the regions of stepover as a result of sinistral strike-slip displacements along the major lineament (Figs. 3 and 9). The discrete mode of occurrence of Damodar valley basins defining an array of basins along a lineament resembles pull-apart basins observed in other strike-slip fault zones, such as Anatolian fault zone (Roussos and Lyssimachou, 1991).

3.9. Rajmahal basin

The Rajmahal basin is the eastern most Gondwana basin of peninsular India. This is a N–S elongate basin (70 km long, 40 km wide) largely covered by the Rajmahal Trap rocks (Figs. 1 and 3). A narrow strip of Gondwana strata is exposed along the western margin that is marked by a N–S trending normal fault dipping easterly (Sainthia–Bahmi fault). Another N–S trending fault (Rajmahal fault) delimits the eastward extent of the Rajmahal trap marking the eastern margin of the basin (Fig. 3). The strata strike N–S and dip gently towards east. It is inferred that this basin formed as a result of easterly extension across a N–S trending preexisting discontinuity.

4. Discussion

Traditionally, the Gondwana basins have been considered as extensional, rift basins because of the presence of gravity faults, downward movements along which led to accumulation of thick sedimentary piles. However, fault-controlled subsidence is characteristic not only of extensional basins, but is common also in strike-slip settings (Ingersoll and Busby, 1995). The Gondwana basins are intracratonic in nature, nucleated along preexisting zones of weakness following Precambrian lineaments (Fig. 3) and fault-controlled subsidence was responsible for accumulation of thick continental sediments. Many basin-bounding faults extend away from the basins to run along and meet major, regional faults, lineaments and shear zones among which the E–W trending faults show evidence of strike-slip movements, whereas the N–S trending ones are characterized by dip- to oblique-slip displacements (Fig. 3). Development of the Gondwana basins thus might have been related to a regional E–W bulk motion in the rigid basement containing preexisting weak zones. The E–W bulk motion of the crust was terminated in the north by strike-slip zones along the E–W trending Son–Narmada lineament (cf. Biswas, 1999, 2003). The continental wrench system defined by the Son–Narmada lineament (Fig. 3) is considered to have formed in the Precambrian, reactivated many times subsequently and is still a zone of seismicity (Naqvi et al., 1974; Crawford, 1978; Das and Patel, 1984; Kaila, 1986). The Son–Narmada lineament has been demonstrated as a trans-continental wrench system that in the Gondwanaland assembly extended from Madagascar up to Australia through the Indian subcontinent (Fig. 3; Crawford, 1978; Harris and Beeson, 1993).

The overall motion in E–W direction led to formation of discrete basins due to preferential subsidence in locales of differently oriented preexisting weakness on the basement. The kinematics of these discrete basins varied and they formed either as extensional or as strike-slip basins (cf. Biswas, 1999, 2003) depending upon the initial orientation and pattern of the weak zones with respect to the bulk tectonic movement. In order to illustrate this idea, we replicated the disposition of the Indian Gondwana basins (Fig. 1) in sandbox models (cf. McClay, 1996), which were developed in the following manner.

We took a sheet of rigid cardboard (70 cm long and 35 cm wide) in which cuts were made matching the preexisting discontinuities in the basement (Fig. 14). The configuration of discontinuities was somewhat idealized (Fig. 15) to generate the basins observed in the map (Fig. 3). Lateral displacements of the basal plates produced a number of fault-bound depression zones in the sand layer with a disposition mimicking that of the natural Gondwana basins (Figs. 16 and 17). It was also noticed that basins of both rift and pull-apart types developed simultaneously under a single, bulk horizontal motion of the segmented basal plate (Fig. 17).

The kinematics of the Gondwana basins of peninsular India thus appears to have been controlled by the initial orientation of the preexisting weakness in the basement and can be categorized into the following four types (Fig. 18):

(1) Elongate grabens formed due to near orthogonal, asymmetric extension across preexisting lineaments (Fig. 18). The Pranhita–Godavari basin represents such basins (Figs. 16 and 17). The patterns of basin-bounding and intrabasinal faults of the PG basin (Fig. 6) also indicate extension across the trend of the basin and match with those observed in earlier experimental studies (McClay and White, 1995; McClay et al., 2002).

(2) Rhombic basins resulting from strike-slip movements along preexisting lineaments disposed with releasing steps or bends (Fig. 18). The Satpura, Karanpura–Bokaro, Jharia, Ranigunj, Talchir and Daltongunj basins represent this category (Figs. 16 and 17). Among them, the Talchir basin formed above a step due to dextral strike-slip movement along the basin bounding faults, whereas the Daltongunj basin probably developed on a releasing bend of a strike-slip fault as a result of dextral slip (Fig. 17). The other basins represent strike-slip basins with sinistral sense of shear movement along the basin-bounding faults. The architecture of all these basins (Figs. 7, 10, 11, 12 and 13) resembles that of natural and experimentally produced strike-slip basins (Dooley and McClay, 1997; Basile and Brun, 1999; Sims et al., 1999), and the complex fault patterns observed in these basins are probably the result of stress perturbations and rotation of principal stress axes in the stepover regions of the strike-slip zone (Segall and Pollard, 1980; Maerten et al., 2002).

(3) Rectangular or slightly elongate basins arising due to oblique, asymmetric extension across preexisting weak planes that are bounded on both ends by strike-slip faults paralleling the extension direction (Fig. 18). Their difference with the strike-slip basins mentioned above is that the strike-slip faults are not arranged in steps, but are disposed opposite to each other parallely (Fig. 18). South Rewa, Hasdo–Arand, Mahanadi and Rajmahal

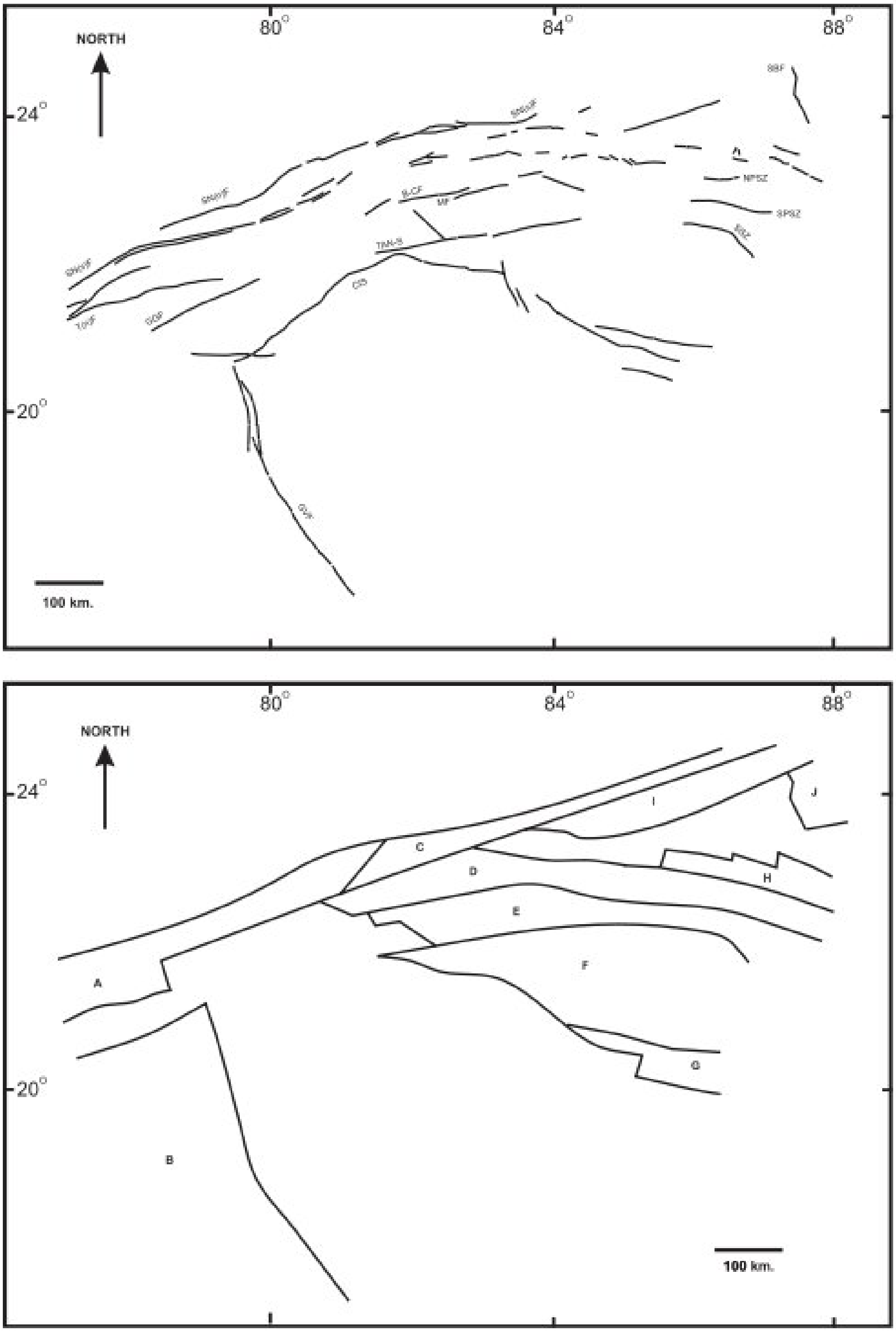


Fig. 14. Diagrams showing the different preexisting basement faults that are inferred to have been reactivated leading to formation of the Gondwana basins (upper half). The lower half shows the reconstruction of the segments of the rigid, Gondwana basement defined by the faults shown in the upper half. Fault names are as in Fig. 3.

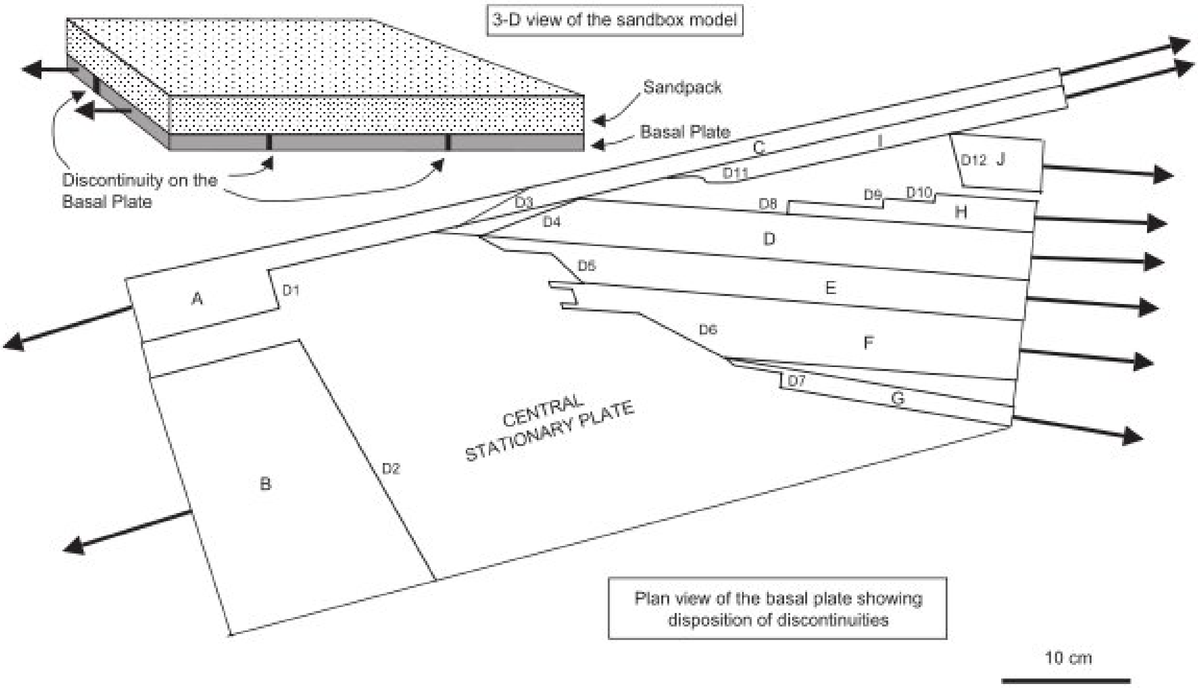


Fig. 15. A schematic sketch of the experimental setup. The basal plate consisted of several segments (A, B,. . ., J) as deduced from the layout of natural basement faults shown in Fig. 14. Discontinuities marked by D1, D2, etc., represent the potential areas of dilation in response to displacement of the segments. Straight, bold arrows show the direction of motion of individual segments of the basal plate. The movement of the segment leads to development of basins in the sandpack as a result of fault-controlled subsidence.

basins represent this category (Figs. 16 and 17). The southern and northeastern margins of the south Rewa basin are marked by prominent zones of strike-slip displacement (Fig. 8). The basin opened over a preexisting weak zone making a low-angle with the strike-slip zone due to extension across it as a result of movement along the strike-slip zones (Figs. 15–17). The intrabasinal faults in this basin formed with alignments grossly parallel to that of the preexisting weak zone. The Hasdo–Arand and Mahanadi basins opened due to extension across preexisting weak zones that were relatively at high angles to the strike-slip zones bounding them (Figs. 15–17). The intrabasinal faults trending at high angle to the strike-slip boundaries probably represent the orientation of the preexisting weak zone (Fig. 8).

(4) Rectangular basins developed due to symmetric extension across preexisting weak planes confined between two strike-slip faults oriented along the extension direction without any stepping (Fig. 18). The northern part of the Rewa basin probably represents such a basin (Figs. 16 and 17).

The present study provides a first-hand basis for understanding the overall development of Indian Gondwana basins under a single tectonic regime. However, there are many local-scale structural complexities in some of the basins, which need to be investigated separately. For example, Ranigunj basin appears to be a strike-slip basin, which is compatible with the regional E–W bulk motion inferred here, and is also reflected in the presence of cross faults. However, the distribution of cross-faults is somewhat more complex (Fig. 13). Further studies are required to explain how a pair of cross-fault sets can develop with opposite vergence in a strike-slip regime. Again, there are also intrabasinal faults parallel to the basin-bounding strike-slip faults, which indicate that the basins were not purely strike-slip in nature, but might have experienced transtensional movement, as documented in physical experiments (Tron

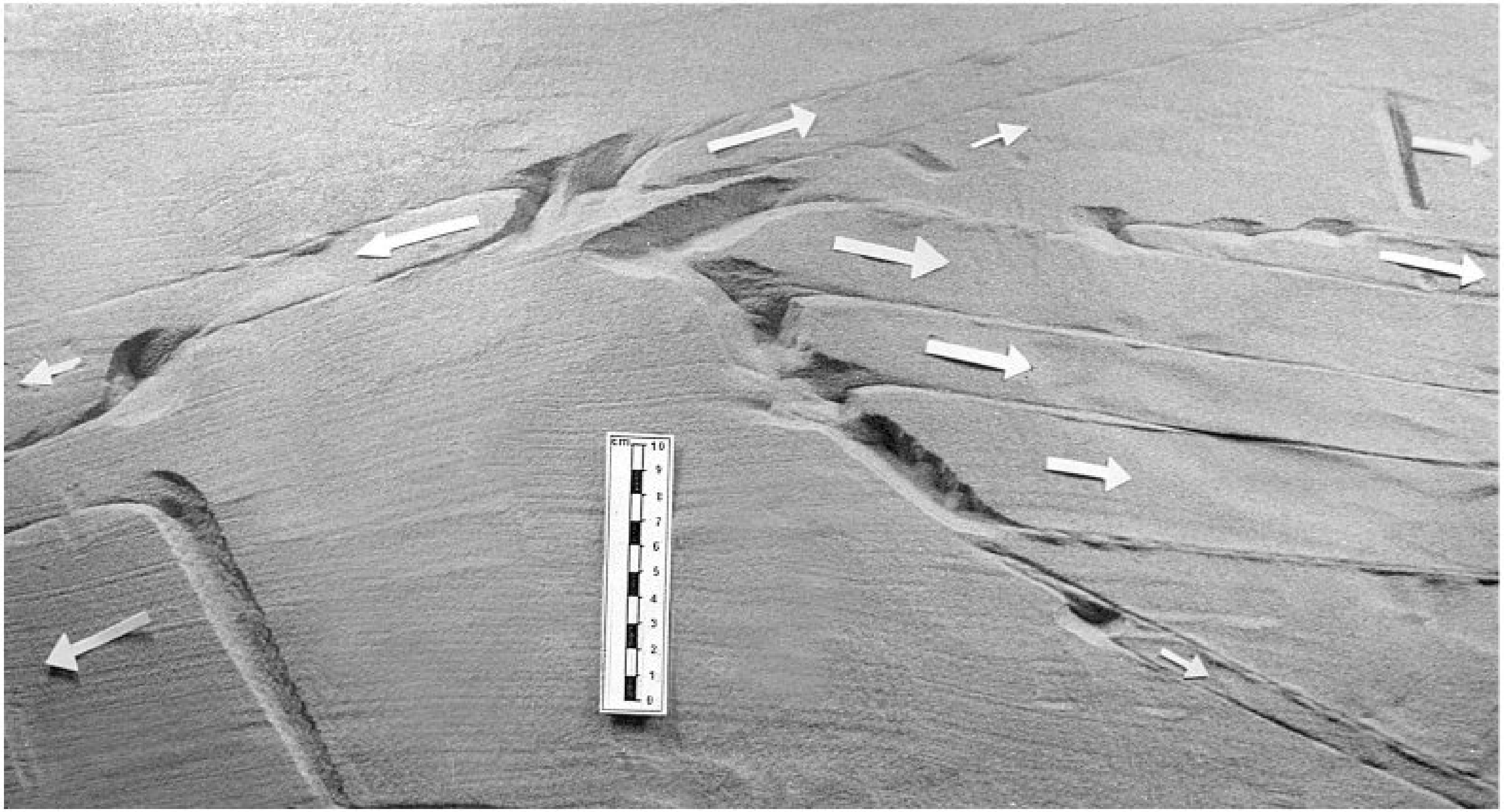


Fig. 16. Plan view of the experimental model after a finite displacement along the arrows. Note fault-bound depressions simulating the Gondwana basins of peninsular India and the transcurrent zones with push-ups. Arrows indicate directions of movement of the segments in the basal plate.

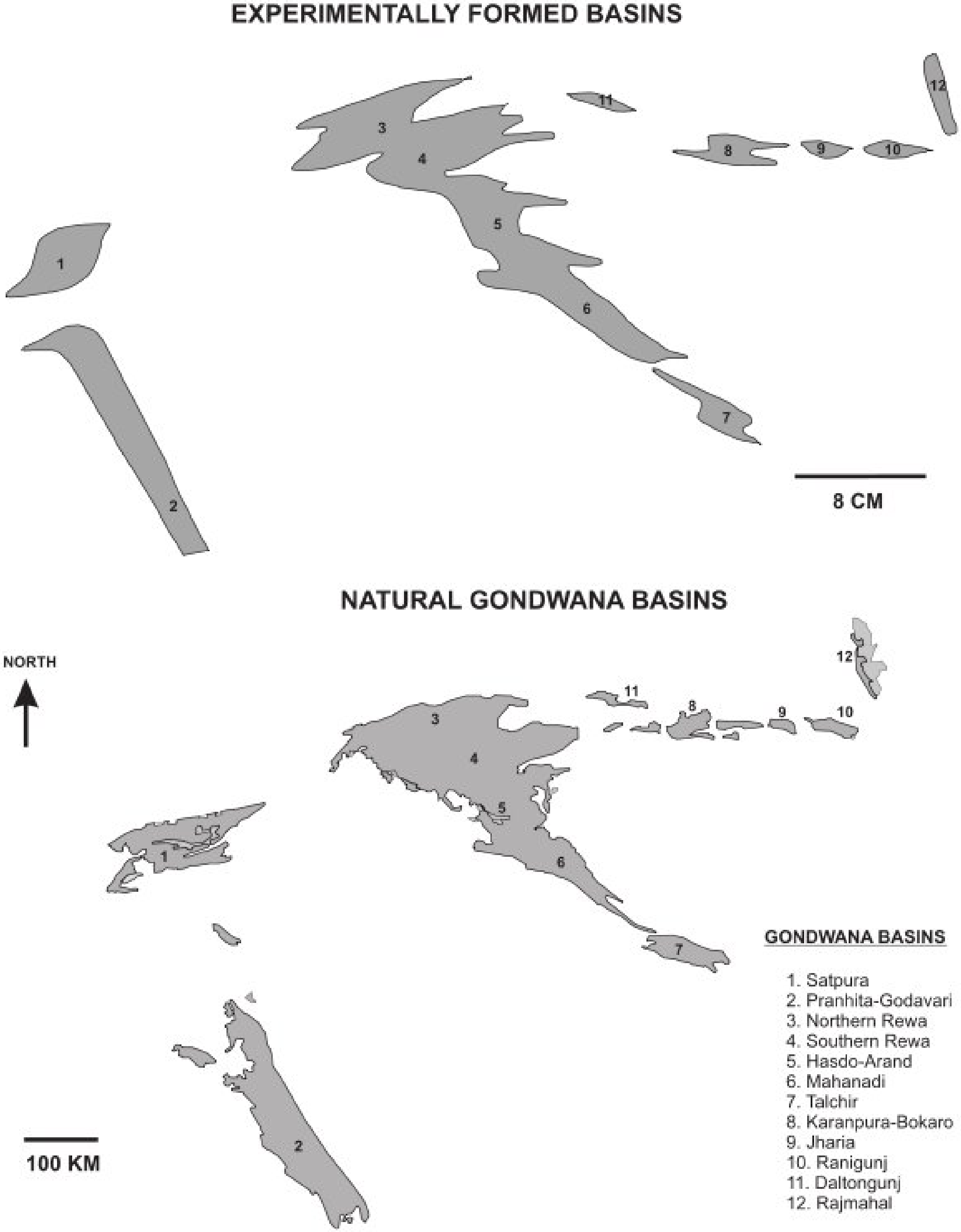


Fig. 17. Comparison of the dispositions of experimentally formed and natural Gondwana basins. 1, 3, 4, 7, 8, 9, 10 and 11 are basins of strike-slip origin, whereas 2, 5, 6 and 12 represent extensional rifts.

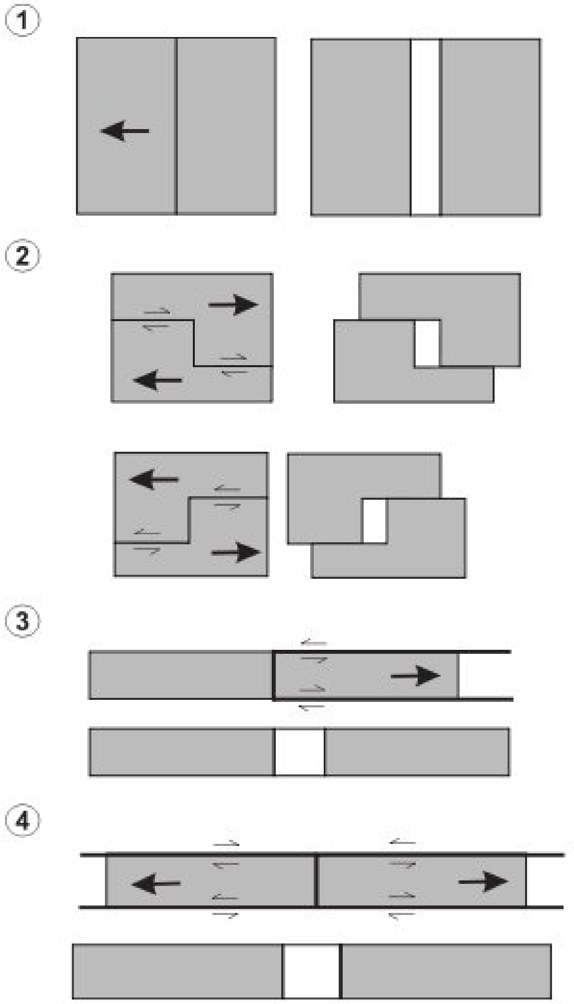


Fig. 18. Kinematic varieties of the Gondwana basins of the peninsular India.

and Brun, 1991). In order to resolve these complexities, kinematic analyses of individual basins need to be studied in detail separately.

5. Conclusions

The principal findings of the present study can be summarised along the following points:

(1) The Gondwana basins of peninsular India nucleated along preexisting zones of weakness in the Precambrian basement.
(2) The basins formed in response to a single regional tectonic event.
(3) The bulk kinematics was that of a horizontal extension grossly along an E–W direction.
(4) Disparate nucleation of the basins resulted due to preferential fault-controlled subsidence at favourable locales.
(5) The kinematics of individual basins varied due to different orientations of the basal discontinuities, but were compatible with one another as well to the E–W bulk motion.
(6) The basins represent both strike-slip and extensional basins.

Acknowledgements

Financial assistance from the Indian Statistical Institute and Department of Science and Technology, India is gratefully acknowledged. Reviews by Prof. J.J. Veevers and an anonymous referee greatly contributed to the improvement of the paper. Prof. Kevin Furlong, the Co-Editor in Chief, is thanked for his perseverance with this paper. We also thank Dr. P. Ghosh, Dr. T. Chakraborty and Dr. S.N. Sarkar for their constructive criticisms of earlier versions of the manuscript. Finally, we would like to acknowledge that we were inspired to look at the Gondwana basins of peninsular India in unity from the works of Prof. Ken McClay, Director, Fault Dynamics Research Group, Royal Holloway, University of London and his colleagues.

References

Acharyya, S.K., 2000. Tectonic setting and nature of the Gondwanic Indian crust. Proc. Vol., Int. Seminar, Precambrian Crust in Eastern and Central India. Geol. Surv. Ind., Spec. Publ., vol. 57, pp. 1–8.

Agarwal, R.P., Dotiwala, S.F., Bhoj, R., 1993. Structural framework of Son–Mahanadi Gondwana basin based on the study of remote sensing data. Gondwana Geol. Magazine, Spec. Vol. Birbal Sahni Centre, National Symposium Gondwana, India, pp. 207–217.

Ahmad, F., 1957. Observations on the Umaria marine bed. Rec. Geol. Surv. India 84, 469–476.

Ahmad, F., Khan, Z.A., 1993. Marine incursions in Lower Gondwana Group in central India. Gondwana Geol. Mag. Spec. Vol. Birbal Sahni Centre Nat. Sympo. Gond., India, pp. 1–7.

Aydin, A.A., Nur, A., 1985. The types and roles of stepovers in strike slip tectonics. In: Biddle, K.T., Christie-Blick, N. (Eds.), Strike-Slip Deformation, Basin Formation, and Sedimentation. SEPM Spec. Publ., vol. 37, pp. 35–45.

Badley, M.E., Egeberg, T., Nipen, O., 1984. Development of rift basins illustrated by the structural evaluation of the Oseberg feature, Block30/6, offshore Norway. J. Geol. Soc. Lond. 141, 639–649.

Banerjee, I., 1966. Turbidites in a glacial sequence: a study from the Talchir Formation, Ranigunj coalfield, India. J. Geol. 74, 593–606.

Basile, C., Brun, J.P., 1999. Transtensional faulting patterns ranging from pull-apart basins to transform continental margins: an experimental investigation. J. Struct. Geol. 21, 23–37.

Biswas, S.K., 1999. A review on the evolution of rift basins in India during Gondwana with special reference to western Indian basins and their hydrocarbon prospects. In: Sahni, A., Loyal, R.S. (Eds.), Gondwana Assembly: New Issues and Perspectives. Proc. Ind. Nat. Sci. Acad. Spec. Issue, 261–283.

Biswas, S.K., 2003. Regional tectonic framework of the Pranhita–Godavari basin, India. J. Asian Earth Sci. 21, 1–9.

Casshyap, S.M., 1973. Palaeocurrent and palaeogeographic reconstruction of Barakar sandstone of peninsular India. Sediment. Geol. 9, 383–404.

Casshyap, S.M., Khan, A., 2000. Tectono-sedimentary evolution of the Gondwanan Satpura basin of central India: evidence of pre-Trap doming, rifting and palaeoslope reversal. J. South. Afr. Earth Sci. 31, 65–76.

Casshyap, S.M., Qidwai, H.A., 1974. Glacial sedimentation of late Paleozoic Talchir diamictite, Pench valley coalfield, central India. Geol. Soc. Am. Bull. 85, 749–760.

Casshyap, S.M., Tewari, R.C., 1991. Depositional model and tectonic evolution of Gondwana basins. In: Venkatachala, B.S., Maheswari, H.K. (Eds.), Indian Gondwana. Mem. Geol. Soc. Ind., vol. 21, pp. 95–206.

Chakraborty, A., 1993. Marine influence during Talchir deposition, Giridih basin, Bihar. Indian J. Geol. 65, 290–292.

Chakraborty, T., Sarkar, S., 2000. Permian lacustrine sediments of the Satpura Gondwana basin: paleogeographic and tectonic implications. Abstract, 31st Int. Geol. Cong., Brazil.

Chatterjee, G.C., Ghosh, P.K., 1970. Tectonic framework of peninsular Gondwanas of India. Rec. Geol. Surv. India 98, 1–15.

Chaudhuri, S., 1985. Marine influence in Hutar coalfield. Palaeobotanist 36, 30–36.

Christie-Blick, N., Biddle, K.T., 1985. Deformation and basin formation along strike slip faults. In: Biddle, K.T., Christie-Blick, N. (Eds.), Strike-Slip Deformation, Basin Formation, and Sedimentation. SEPM Spec. Publ., vol. 37, pp. 1–35.

Cowper Reed, F.R., 1927. The Permo-Carboniferous marine fauna from Umaria coalfield. Rec. Geol. Surv. India, 60.

Crawford, A.R., 1978. Narmada–Son lineament of India traced into Madagascar. J. Geol. Soc. India 19, 144–153.

Crowell, J.C., 1974. Origin of late Cenozoic basins in southern California. In: Dickinson, W.R. (Ed.), Tectonics and Sedimentation. SEPM Spec. Publ., vol. 22, pp. 190–204.

Dasgupta, P., 2002. Architecture and facies pattern of a sublacustrine fan, Jharia basin, India. Sediment. Geol. 148, 373–387.

Das, B., Patel, N.P., 1984. Nature of the Narmada–Son lineament. J. Geol. Soc. India 25, 267–276.

Dooley, T., McClay, K.R., 1997. Analog modelling of pull-apart basins. AAPG Bull. 81, 1804–1826.

Dutta, A.B., 1965. *Fenestella* sp. From the Talchir of Daltongunj coalfield. Q. J. Geol., Min. Metall. Soc. India 37, 133–134.

Fox, C.S., 1931. The Gondwana System and related formations. Mem. Geol. Surv. India 58 (iv), 1–241.

Ghosh, S., 1954. Discovery of a new locality of marine Gondwana formation near Manendragarh in M.P.. Sci. Cult. 19, 620.

Ghosh, S.C., 2002. The Ranigunj Coal Basin: an example of an Indian Gondwana rift. Sediment. Geol. 147, 155–176.

Ghosh, S.K., 2003. First record of marine bivalves from the Talchir Formation of the Satpura Gondwana basin, India: palaeobiogeographic implications. Gondwana Res. (Gondwana Newsl. Sec.) 6/2, 312–320.

Ghosh, S.K., Mukhopadhyay, A., 1985. Tectonic history of the Jharia basin—an intracratonic Gondwana basin in eastern India. Q. J. Geol. Min. Metall. Soc. India 57, 33–58.

Gupta, A., 2000. Role of storm in Ramgarh and West Bokaro coalfields and its implication in adjacent peninsular coalfields, India. Gondwana Res. 3, 529–544.

Harris, L.B., Beeson, J., 1993. Gondwanaland significance of Lower Palaeozoic deformation in central India and SW Western Australia. J. Geol. Soc. Lond. 150, 811–814.

Hobday, D.K., 1987. Gondwana coal basins of Australia and South Africa: tectonic setting, depositional systems and resources. In: Scott, A.C. (Ed.), Coal and Coal-Bearing Strata: Recent Advances. Geol. Soc. Lond. Spec. Publ., vol. 32, pp. 219–233.

Ingersoll, R.V., Busby, C., 1995. Tectonics of sedimentary basins. In: Busby, C.J., Ingersoll, R.V. (Eds.), Tectonics of Sedimentary Basins. Blackwell Scientific Publ., Oxford, pp. 1–52.

Kaila, K.L., 1986. Tectonic framework of Narmada–Son lineament—a continental rift system in central India from deep seismic soundings, reflection seismology: a global perspective. AGU, Geodyn. Ser. 13, 133–150.

Lakshminarayana, G., 1994. Stratigraphy and structural framework of the Gondwana sediments in the Pranhita–Godavari valley, Andhra Pradesh. Ninth Int. Gond. Symp., Oxford & IBH, New Delhi, pp. 311–330.

Lezzar, K.E., Tiercelin, J.-J., Turdu, C.L., Cohen, A.S., Reynolds, D.J., Gall, B.L., Scholz, C.A., 2002. Controls of normal fault array evaluation on the distribution of the major Neogene sedimentary depocenters, Lake Tanganyika, East African Rift. AAPG Bull. 86, 1027–1060.

Maerten, L., Gillespie, P., Pollard, D., 2002. Effects of local stress perturbation on secondary fault development. J. Struct. Geol. 24, 145–153.

Mauduit, T., Guerin, G., Brun, J.P., 1997. Raft tectonics: the effects of basal slope angle and sedimentation rate on progressive extension. J. Struct. Geol. 9, 1219–1230.

Maulik, P.K., Chakraborty, C., Ghosh, P., Rudra, D., 2000. Meso- and macro-scale architecture of a Triassic fluvial succession: Denwa Formation, Satpura Gondwana basin, Madhya Pradesh. J. Geol. Soc. India 56, 489–504.

McClay, K.R., 1996. Recent advances in analogue modelling: uses in section construction and validation. In: Buchanan, P.G., Nieuwland, D.A. (Eds.), Modern Development in Structural Interpretation, Validation and Modelling. Geol. Soc. Lond. Spec. Publ., vol. 99, pp. 201–225.

McClay, K., Dooley, T., 1995. Analogue model of the pull-apart basins. Geology 23, 711–714.

McClay, K.R., Ellis, P.G., 1987a. Analogue models of extensional fault geometries. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.), Continental Extensional Tectonics. Geol. Soc. Lond., Spec. Publ., vol. 28, pp. 109–125.

McClay, K.R., Ellis, P.G., 1987b. Geometries of extensional fault systems developed in model experiments. Geology 15, 341–344.

McClay, K.R., White, M.J., 1995. Analogue modelling of orthogonal and oblique rifting. Mar. Pet. Geol. 12, 137–151.

McClay, K.R., Dooley, T., Whitehouse, P., Mills, M., Khalil, S., 2002. 4D evolution of rift systems: insights from scaled physical models. AAPG Bull. Spec. Issue 86, 935–995.

Mishra, D.C., Gupta, S.B., Rao, M.B.S.V., Venkatarayudu, M., Laxman, G., 1987. Godavari basin—a geophysical study. J. Geol. Soc. India 30, 469–476.

Mishra, D.C., Chandra Sekhar, D.V., Venkata Raju, D.Ch., Vijay Kumar, V., 1999. Crustal structure based on gravity-magnetic modelling constrained from seismic studies under Lambert Rift, Antarctica and Godavari and Mahanadi rifts, India and their interrelationship. Earth Planet. Sci. Lett. 172, 287–300.

Mitra, N.D., 1987. Structure and tectonics of Gondwana basins of peninsular India. In: Singh, R.M. (Ed.), Coal Resources of India. Banaras Hindu Univ., Varanasi, pp. 30–41.

Mitra, N.D., 1994. Tensile resurgence along fossil sutures: a hypothesis on the evolution of Gondwana basins of peninsular India. Abstracts of Proceedings of 2nd Symposium on Petroliferous basins of India. KDMIPE, Dehradun.

Mukhopadhyay, G., Bhattacharya, H.N., 1994. Facies analysis of Talchir sediments (Permo-Carboniferous), Dudhi Nala, Bihar, India—a glaciomarine model. 9th Int. Gond. Symp. Hyderabad, Ind., Oxford & IBH, New Delhi, pp. 737–753.

Naqvi, S.M., Rao, D., Narain, H., 1974. The protocontinental growth of the Indian shield and the antiquity of its rift valleys. Precambrian Res. 1, 345–398.

Narula, P.L., Acharyya, S.K., Banerjee, J., 2000. Seismotectonic atlas of India and its environs. Geol. Surv. India (87 pp.).

Peters, J., Singh, S.K., 2001. Satpura basin—an example of pre-rift, syn-rift and post-rift Gondwana sedimentation in India. J. Geol. Soc. India 57, 309–320.

Qureshy, M.N., Krshna Brahmam, N., Garde, S.C., Mathur, B.K., 1968. Gravity anomalies and the Godavari rift. Geol. Soc. Am. Bull. 79, 1221–1230.

Raiverman, V., 1985. Stratigraphy and structure of Pranhita–Godavari graben. Petroliferous basins of India—III. KDMIPE, ONGC, Dehradun, India 3, 174–189.

Raja Rao, C.S., 1982. Coalfields of India. Vol-II, Coal resources of Tamil Nadu, Andhra Pradesh, Orissa and Maharashtra. Geol. Surv. Ind. Bull. Ser. A, 45.

Raja Rao, C.S., 1983. Coalfields of India. Vol-III, Coal resources of Madhya Pradesh and Jammu and Kashmir. Geol. Surv. Ind. Bull. Ser. A, 45.

Raja Rao, C.S., 1987. Coalfields of India. Vol-IV, Part I. Coal resources of Bihar. Geol. Surv. Ind. Bull. Ser. A, 45.

Robinson, P.L., 1967. The Indian Gondwana formations—a review. First Symposium on Gondwana Stratigraphy, Mar Del Plata, Argentina. UNESCO, Paris, pp. 201–268.

Roussos, N., Lyssimachou, T., 1991. Structure of the Central North Aegean trough: an active strike slip deformation zone. Basin Res. 3, 39–48.

Schlische, R.W., 1991. Half graben basin filling models; new constrains on continental extensional basin development. Basin Res. 3, 123–141.

Segall, P., Pollard, D.D., 1980. Mechanics of discontinuous faults. J. Geophys. Res. 85, 4337–4350.

Sims, D., Ferrill, D.A., Stamatakos, J.A., 1999. Role of ductile decollement in the development of pull-apart basins: experimental and natural examples. J. Struct. Geol. 21, 533–554.

Smith, A.J., 1963. Evidence for a Talchir (Lower Gondwana) glaciation: striated pavement and boulder bed at Irai, central India. J. Sediment. Petrol. 33, 739–750.

Tron, V., Brun, J.-P., 1991. Experiments on oblique rifting in brittle–ductile systems. Tectonophysics 188, 71–84.

Venkatachala, B.S., Maheswari, H.K., 1988. Indian Gondwana—redefined. 7th International Gondwana Symposium, Sao Paulo. BSIPB, University of Lucknow, India, pp. 539–547.

Venkatachala, B.S., Tiwari, R.S., 1987. Lower Gondwana marine incursions: periods and pathways. Palaeobotanist 36, 24–29.

Veevers, J.J., Tewari, R.C., 1995. Gondwana master basin of peninsular India between Tethys and the interior of the Gondwanaland province of Pangea. Mem. Geol. Soc. Amer. 187, 1–73.