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New Insights into the Tectonic Evolution of the Vindhyan Basin revealed by Structural Modelling Studies carried out in Son Valley

Abstract

In the present study, the Son Valley sector of the Vindhyan Basin has been subjected to structural modelling studies using the *MOVE*^{TM} software. An attempt is made to bring out new insights into the tectonic evolution with estimation of amount of erosion suffered, crustal extension and shortening experienced in this part of the basin. Surface seepages and subsurface gas finds in Jabera and Nohta area make these Meso-Neoproterozoic sediments highly prospective. The study is first of its kind undertaken in the Vindhyan Basin.
The structural modelling and tectonic analysis was carried out along a regional profile from the outcropping Bundelkhand Massif passing through Son Valley and extended beyond Son Narmada North Fault upto Central Indian Suture. Cross-section restoration and balancing were carried out along the profile. Sequential restoration carried out revealed SNNF was in existence since Archean time and Son Narmada South Fault came into existence during Bijawar deposition. Several extensional fault systems developed and deposition of the younger sequences continued in these fault blocks. Jabera Dome and Damoh structures evolved as a result of crustal shortening episodes experienced by the basin. The Great Vindhyan Syncline developed during the deposition of Sirbu Shale. The basin experienced cumulative extension to the extent of 1.53% upto Kajrahat Limestone level and thereafter estimated cumulative shortening of 0.73%. The basin underwent erosion estimated to be about 2.4Km in the shortening phase and 0.8Km in the extension phase. The study reveals that the Vindhyan sediments do not extend south of SNNF. It substantiates the existence of compression and fracturing in the southern margin of the Son Valley in the vicinity of SNNF which is highly prospective for hydrocarbon exploration.

Introduction

The Vindhyan Basin is a classic example of Proterozoic intra-continental basin in the central part of the Indian shield and is widely regarded as a high-risk, high-gain frontier area for exploration. The basin continues to be an interesting area for hydrocarbon exploration ever since the first well J-1 was drilled in 1990 and non-commercial gas flowed from the Charkaria Shale and Jardepahar Porcellanite formations in the Jabera Dome and recently in wells drilled in Nohta area within Rohtas Limestone formation and basal part of Kaimur Group in Son Valley. Hydrocarbon indications have been observed in surface as well as in subsurface at several places in Son as well as Chambal Valley, making these Meso-Neoproterozoic Vindhyan sediments to be prospective.

The study is the first of its kind to have been taken up in the Vindhyan Basin using the *MOVE*^{TM} software. It entailed balancing and restoration of a regional geological cross-section in the Son Valley sector of the basin which was extended upto Central Indian Suture (CIS). The balanced cross-sections when restored to their initial configurations provided estimates of crustal extension and shortening. The amount of erosion was also estimated. The balanced sections assume a transport direction parallel to the line of the section and little or no movement of material in or out of the section. A balanced cross section is essentially a model based on incomplete data set and a few assumptions. Like any other type of modelling, the solution we arrive at is most likely to be non-unique. The study has provided inputs for better understanding of the evolutionary history of the Son Valley structures and their relative timings in Vindhyan basin and adjacent areas.

On the basis of orientation analysis carried out, the regional profile was selected for balancing and restoration. The seismic data has been complemented by surface geological data to model the subsurface configuration. The regional profile encompasses seismic lines MP0B-0H, MP0G-01 and MPAI-0G which were depth converted. This profile was extended in the northwest upto Bundelkhand Massif and in the southeast it was extended beyond Son Narmada North Fault (SNNF) up to CIS passing through the Central Indian Tectonic Zone (CITZ) in the peninsular India and its length is 374Km (of which 161Km is in Son Valley, Vindhyan Basin upto Son Narmada North Fault).

Regional Geology

The Indian Peninsula emerged as a large cratonic landmass around 2500Ma at the transition between the Archaean and Proterozoic through accretion and assembly of several smaller Archean cratons (5). The cratonic nuclei that collectively forms Peninsular India comprises of Aravalli-Bundelkhand Cratons, Singhbhum and Bastar Cratons, the Western and Eastern Dharwar Cratons and the Southern Granulite Province. The Vindhyan Basin formed on the Aravalli-Bundelkhand craton. The basin fill, often several kilometers thick, are typically unmetamorphosed, varyingly deformed sedimentary strata that got deposited in an unvegetated landscape. The strata lie unconformably on the Archean–Early Proterozoic gneisses, highgrade rocks, granite-greenstones or meta-sedimentaries of Proterozoic mobile belts (3). SNNF delineates the northern boundary of the Mahakoshal Belt (MB) and separates it from the Vindhyan Basin to the north. The southern boundary, mostly covered by the Deccan Traps, is bounded by the SNSF that separates the MB from the Proterozoic granites of the CITZ.

The CITZ also referred to as the Satpura Mobile Belt (SMB), is a complex Proterozoic orogenic belt that formed during the accretion of the Bastar–Singhbhum Craton to the northern Bundelkhand Craton (2; 10). The mobile belt was originally named after the Satpura Hills and is bounded by the Narmanda-Son North Fault (NSNF) and to the south by the CIS. The CITZ incorporates a system of major shears/faults, with the CIS marking the southernmost boundary of the zone. The gneissic tectonic zone comprises three sub-parallel E–W trending supracrustal belts that are separated from each other by crustal scale shear zones (7). The belts from north to south are the Mahakoshal Belt, the Betul Belt, and the Sausar Belt. The Narmada-Son South Fault (NSSF) separates the Mahakoshal and Betul Belts while the Tan Shear Zone (TSZ) separates the Betul and Sausar Belts (6). The Bastar Craton (Bhandara or Central Indian Craton) comprises the Sausar, Sakoli and Dongargarh Groups which consists mainly of granites and granitic gneisses. The Gavilgarh-Tan Shear Zone (GTSZ) lies in the central part of the CITZ are situated right to the north of the Ramakona-Katangi Granulite (RKG) domain belt. It could therefore be considered as a transpressional fault/shear system that possibly accommodated part of the shortening during oblique convergence of Bastar craton and Bundelkhand Craton. Isotopic and geochronological studies in southern part of CITZ, identified two major tectono-thermal imprints– an Early Mesoproterozoic rifting in BBG and parts of Bastar Craton (~1400Ma), and a Late Mesoproterozoic collision and amalgamation between Bastar and Budelkhand cratons (~1100Ma) along RKG and northern gneisses (1).

Methodology

- Study of available Geoscientific data and geological maps and digitization in Move. Carry out orientation analysis and select the profile.
- Utilizing the SRTM data, prepare a DEM along the selected regional profile in Son Valley sector of the basin.
- Study of seismic data and after depth conversion, interpret the horizons calibrated from well and outcrop data along the selected profile.
- Prepare a regional geological cross-section across the basin incorporating seismic data wherever available and outcrop data and extend to the basin margins to understand the basin configuration.
- Carry out Forward Modeling, validation by Block Restoration and Sequential Restoration of selected depth sections in 2D-Move^{TM}. In the present study, the sequential restoration technique has been applied to analyze the modelled interpretation along the regional profile A-A' and to arrive at inferences regarding the evolution of the structures in Son Valley, Vindhyan basin and adjacent areas upto CIS.
- Estimate the amount of erosion and amount of crustal extension and shortening at different stratigraphic levels along the profile.

Results

Orientation analysis suggested section plane of 143^0 in Son Valley. Section was constructed utilizing well, seismic and digitized surface geological data of Son Valley as well as CITZ area upto CIS. Sequential restoration was carried out and results are presented below from initial basin floor before the onset of Vindhyan sedimentation onwards in Son Valley and also the configuration in the CITZ area. Sequential restoration was carried out for each sequence by reconstructing the amount of erosion, restoring the surface and then decompacting it to get the initial depositional surface. The amount of erosional thickness reconstructed has been estimated based on the maximum thickness of the sediments observed in the undisturbed basinal lows and extrapolated in other parts of the basin along the profile. The intermediate stages of tectonic evolution along the Son-CITZ profile are shown in Fig.2 (A to H)**.**

Inferences and Conclusions

- The Son Narmada North Fault (SNNF) was in existence since the Archaean time. However, the Son Narmada South Fault (SNSF) did not exist during the time of deposition of Mahakoshal Group. The meta-volcano-sedimentary Mahakoshal fold belt presents a lithological sequence evolved in an intracratonic rift, bounded by two major faults, termed as the SNNF and SNSF trending ENE–WSW. The SNNF is inferred to have originated in Archaean times and SNSF was not developed during Mahakoshal Group deposition. In contrast to the dormant tectonic history of the SNNF, the SNSF has witnessed episodic reactivation from Proterozoic upto Phanerozoic. Movement along the SNSF resulted in Mahakoshal belt being uphorsted and as a result this restrained the northward extension of the Gondwana basin into the Vindhyan province.

- The Bijawars were deposited in an extensional set up and later affected by Satpura orogeny. An initial rifting of the Bundelkhand Massif led to the development of small horsts and grabens in which terrigenous sediments, interlayered with mafic volcanics were deposited under shallow, marine conditions. Crustal shortening of around 550m is observed during Bijawar deposition. SNSF came into existence during Bijawar deposition.
- CIS, RKG sutures came into existence and Satpura highlands developed during deposition of Karaundhi Arenite Formation. Several extensional fault systems developed in Vindhyan Basin and Karaundhi Arenite formation deposited in these fault blocks. Extensional set up developed due to lithospheric flexure as a result of southward subduction of Bundelkhand Craton under Bastar Craton. Crustal extension of around 2000m is observed at Karaundhi level. This basal clastic cycle having variable thickness was deposited above the Bijawars in the lows of an undulatory basement.
- The Arangi Shale formation was deposited in an extensional set-up in an inner to outer shelf environment forming part of transgressive systems tract. The SNNF delimited its deposition further south. It is characterized by sandstone-shale intercalations with siltstone. Around 350m of extension has been estimated during this time
- Kajrahat Limestone formation was deposited in an extensional set up and the area between SNNF and SNSF was a high and basinal infill was sourced from north. It predominantly comprises predominantly of limestone which is stromatolitic at places with siliciclastics. Extension of around 750m has been estimated during this time.
- During the deposition of Jardepahar Porcellanite Formation, the area south of SNNF continued to remain a highland. The basin experienced compression due to effect of Satpura orogeny. It consists of porcellanite, shale, and sandstone with occasional claystone, siltstone and argillaceous limestone. The basin experienced minor crustal shortening of around 150m during this time.
- Tectonically stable conditions prevailed during the deposition of Charkaria Olive Shale formation. It is represented by argillaceous limestone with algal matter and sandstone. It was deposited throughout the basin and during this period, the basin experienced cumulative shortening of 100m.
- Damoh structure developed during the deposition of Basuhari Sandstone formation. There was concomitant development of Chhatisgarh Basin south of CIS. It is characterized by dolomitic limestone and fine grained glauconitic sandstone.
- Kaimur deposition was sourced from north and SNNF created a barrier for its deposition further south. Panna Shale deposition was wide spread with marginal sag at the middle and upliftment of fault blocks towards north and southern margin as a result of crustal shortening. Jhiri Shale which was subsequently deposited had its source from Satpura highlands and affected by compression.
- Ganurgarh Shale was deposited in stable tectonic conditions. The basin appears to have been filled up in this stage of equilibrium between basin subsidence and sediment deposition.
- Nagode Limestone deposition was confined towards central part of the basin. The basin underwent compression from south resulting in crustal shortening of 1000m. This also resulted in the development of Jabera Dome structure.
- The Great Vindhyan Syncline developed (GVS) during Sirbu Shale deposition.
- The sediment deposition in the basin was greater than subsidence. 200m crustal shortening is observed at Maihar deposition level.
- The Mandla Low came into existence south of SNSF and Lametas were deposited. Maximum thickness is found in the Mandla Low area of CITZ. The Lameta beds consist of arenaceous, argillaceous calcareous lithofacies and usually occur beneath the Deccan Traps.
- The Deccan Trap effusives enveloped major parts of the Vindhyan Basin and Mandla Low area in CITZ where its maximum thickness is found along the profile. The Deccan Traps also known as Deccan Flood basalts cover and effectively hide the basement rocks (Archean and Proterozoic basement) over large parts of western and central India.
- On the basis of study carried out, it is observed that the basin experienced crustal extension upto the Kajrahat Limerstone level and thereafter underwent crustal shortening at different times. Of the total profile length of 374.6Km, the basin experienced cumulative extension to the extent of 1.53% and cumulative shortening of 0.73%.
- The estimated cumulative cannibalisation of the basin along the SNNF amounted to 695m (0.43%). The profile length is 161Km in Son Valley, Vindhyan Basin.
- The SNL has undergone periodic reactivation throughout the evolution of Vindhyan Basin and also resulted in uphorsting of the Mahakoshal belt. This effectively prevented the extension of the Gondwana sedimentation into the Viindhyan Basin. There was no deposition of Gondwana sediments in the CITZ part of the profile as it remained a positive area.

The results of our study along the Son-CITZ profile for basin evolution in Son Valley are in agreement with Chakrabarti et al. (4). Collision of the Bundelkhand craton occurring to the north and the Bhandara craton situated to the south of the Vindhyan Basin, as seen today, was preceded by a southerly dipping subduction zone resulting in Andean-type arc magmatism. The Vindhyan Basin initiated as a Foreland Basin and sediments in the lowermost Vindhyans including the porcellanites were primarily derived from this now-extinct arc. Initially the SNNF was an upward part of the basement and Vindhyan sedimentation started in the sag created by the extensional forces with the initial transgression of the Vindhyan sea from west and inundated the basement floor. Several extensional fault systems developed in the Vindhyan Basin as a result of lithospheric flexure caused by southward subduction of Bundelkhand Craton under the Bastar Craton. SNNF continued to be active during the deposition of Vindhyan sediments and formed the southern limit of Vindhyan Basin. The basement faults were reactivated concurrent with the deposition of sediments. The deposition of Upper Vindhyans continued with several cycles of regression and transgression.

The CITZ and area upto CIS was incorporated in the profile and modeling was constrained. However, the tectonics of the southern part of CITZ has been debated in the past few decades. Jain et al.(9) proposed a southward dipping subduction model according to which the Bundelkhand Protocontinent (BKC) was subducted beneath the Bastar Protocontinent (BC) producing arc related magmatism in the Sakoli and Dongargarh basins just south of CITZ. Thus, the Vindhyan Basin developed at the end of Delhi-Satpura Orogeny as a post-orogenic (post-collision) peripheral basin on the subducted Bundelkhand craton, receiving sediments from the uplifted fold belts to the south and west.

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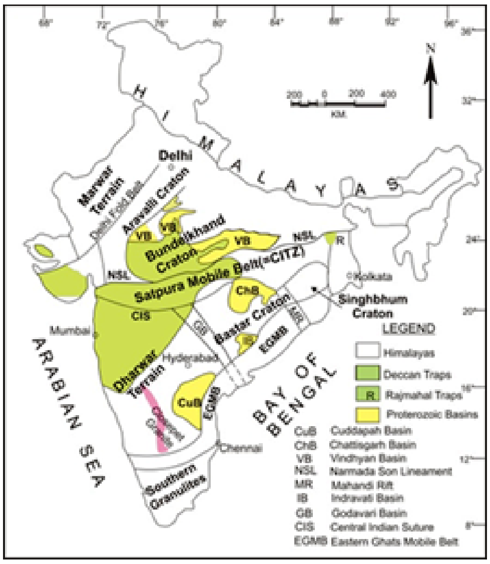

Fig.1 Map of India showing the location of Purana Basins, distribution of cratons and tectonic domains (Modified from 11)

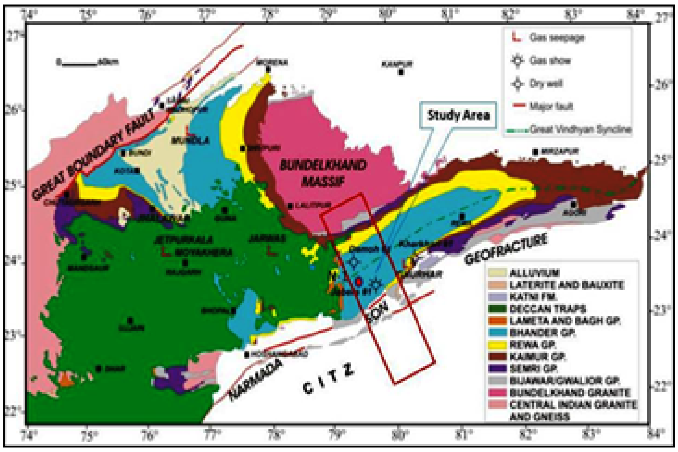

Fig.2 Geological Map of Vindhyan Basin showing the study area

Table-1 Generalised Stratigraphy of Son Valley

SUPER GROUP	GROUP	SUB GROUP	FORMATION	DAMOH-REWA AREA (After Srivastava et.al. 1983)	THICKNESS IN METRES	SUB GROUP	MIRZAPUR-ROBERTGANJ AREA (After Sastri & Mohra 1964)
				LAMETA FORMATION			SUB-RECENT LATERITE
VINDHYAN SUPER GROUP	UPPER VINDHYAN	BHANDER	HAVELI	MAIHAR SST.	87		
				SIRBU SHALE	80		
			BETWA	NAGODE LST	112		
				GANURGARH SHALE	45		
		REWA	ADHES-AR	GOVINDGARH SANDSTONE	55		
				JHIRI SHALE	34		
			ADWA	ASAN SANDSTONE	64		
				PANNA SHALE	34		
		KAMUR	CHURK	DHANDRAUL QUARTZITE	185	KAIMUR	DHANDRAUL SANDSTONE
				SOMAN SCARP SANDSTONE	140		MANGESAR FORMATION
			RAMPUR	BIJAIGARH SHALE	34		BIJAIGARH SHALE
				DOMARKHOKA QUARTZITE	95		GHAGHAR SANDSTONE
							SUSNAI BRECCIA
							SASARAM SANDSTONE
	LOWER VINDHYAN	SEMRI	ROHT-AS	BHAGAWAR SHALE		ROHTAS	BHAGAWAR SHALE
				ROHTAS LIMESTONE	420		ROHTASGARH LST.
			KHENJUA	BASUHARI (GLAUC.) SST.	320	KHENJUA	RAMPUR GLAUCONITE
				MOHANA (FAWN) LIMEST.	207		SALKHAN LIMESTONE
				CHARKARIA (OLIVE) SHALE	561		KOLDAHA SHALE
			CHOPAN	JARDEPAHAR PORCELLANITE	555	DEONAR PORCELL	DEONAR PORCELLANITE
				KAJARAHAT LIMESTONE	335	MIRZAPUR	KAJARAHAT LIMESTONE
							ARANGI FORMATION
				BASAL CONGLOMERATE			DEOLAND FORMATION
				BIJAWAR GROUP			BIJAWAR/ MAHAKOSHAL GROUP
				BUNDELKHAND GRANITE GNEISS			BUNDELKHAND GNEISS

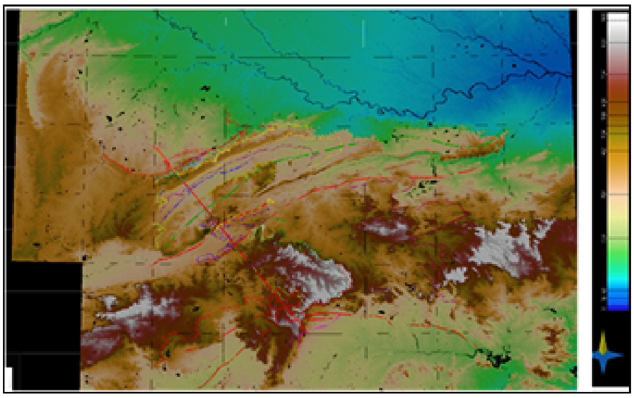

Fig.3 DEM showing the terrain with superimposed digitized geological map of the Son Valley and CITZ area showing the location of the modelled profile A-A'

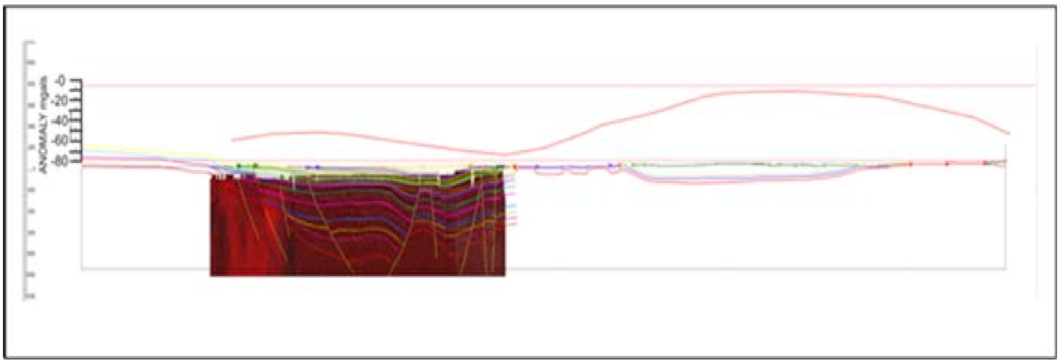

Fig.4 Model of Vindhyan Basin and CITZ based on available Geological Data, Seismic Section Multipanel of Son Valley and Gravity Profile (A-A')

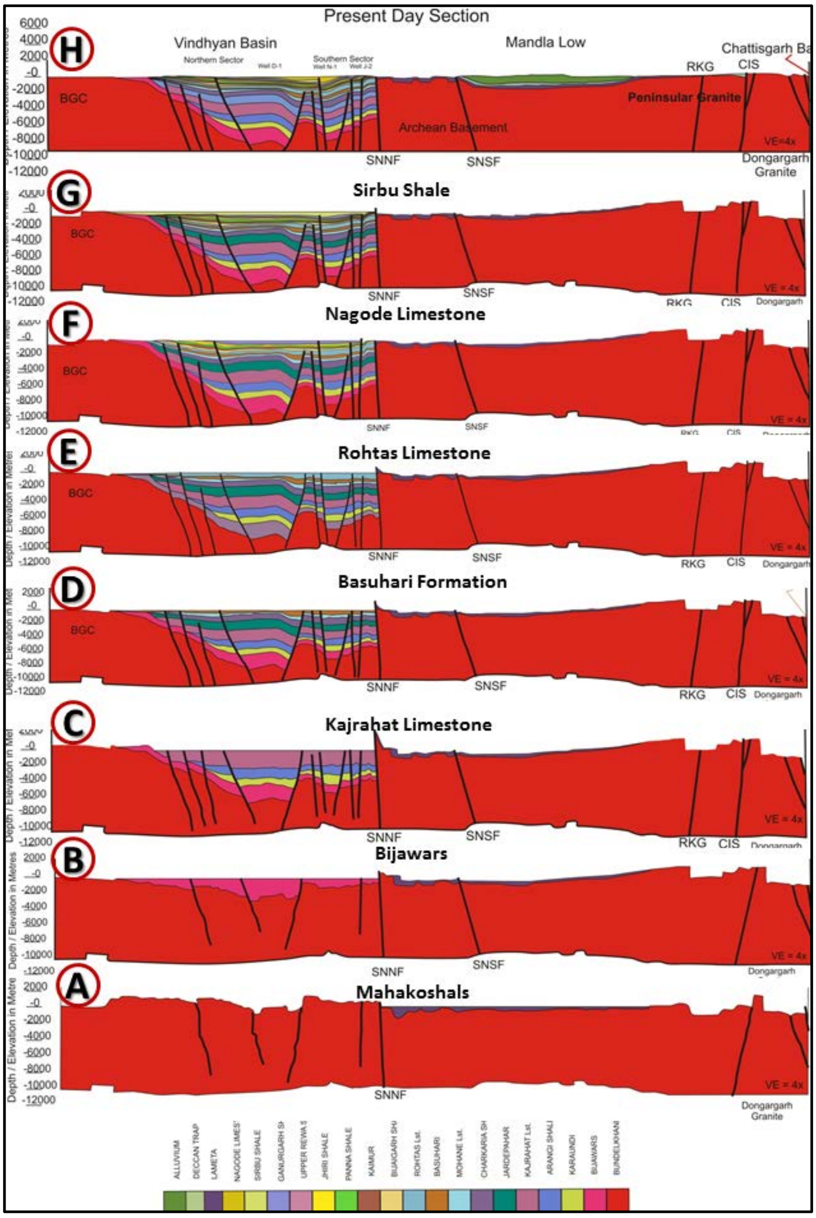

Fig.5 A to H: Sequential restoration along the Son Valley-CITZ profile (A-A') showing stages of tectonic evolution at key stratigraphic levels (Section orientation 143^0)