

# DEEP CONTINENTAL STUDIES IN INDIA



# NEWSLETTER

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## HIGHLIGHTS OF THIS ISSUE

- With the introduction of local earthquake tomography, aftershock seismology has registered a major advance in India in the last decade. **In the first paper Mukhopadhyay and Kayal outline results of detailed aftershock studies carried out after the Bhuj 2004 event and present a picture of the  $V_p$ ,  $V_s$  and  $V_p/V_s$  variations in the 50km depth range of the lithosphere below the meizoseismal and adjoining zones of the event.**
- The DST has in the last year, 2007-2008, supported several research projects on a variety of subjects of relevance in the field of earth sciences and these are enumerated in the next article. **These programmes include projects that aim at generating the much needed geological information from surface outcrops and features in relatively less investigated areas as the NE India that then can help plan more detailed deeper investigations and some mainly in geologically well investigated areas that have an instant relevance to the deep continental structure.**
- The tectonic feature of a triple junction where the Godavari Gondwana graben and the Eastern Ghat strikes meet has received some attention in recent times. **Lakshminarayana and Sivaji present an account of the proceedings of a recent discussion meet held on the initiative of the DST and the Geological Survey of India.**
- **Two recent publications of relevance to the DCS programme of the DST are reviewed.**

## 3D VELOCITY STRUCTURE WITH SPECIAL REFERENCE TO SHEAR WAVE VELOCITY: BHUJ EARTHQUAKE SOURCE AREA, WESTERN INDIA

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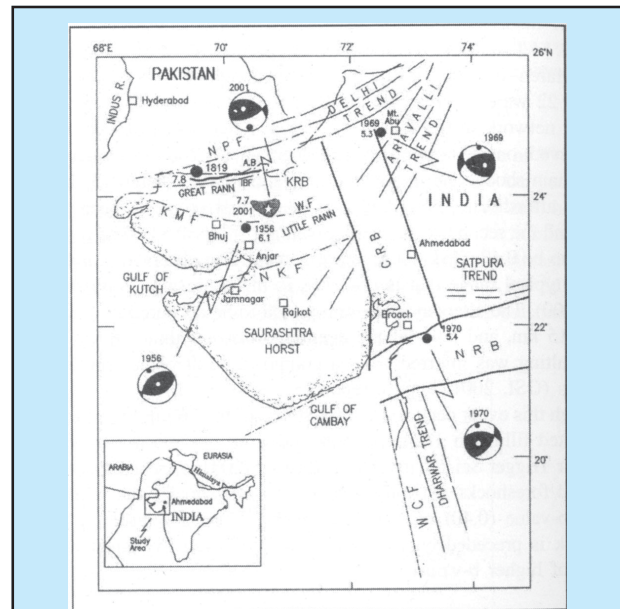
1. Department of Earth Sciences, IIT Roorkee, Roorkee - 247 667. e-mail: sagarfes@iitr.ernet.in
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### Introduction

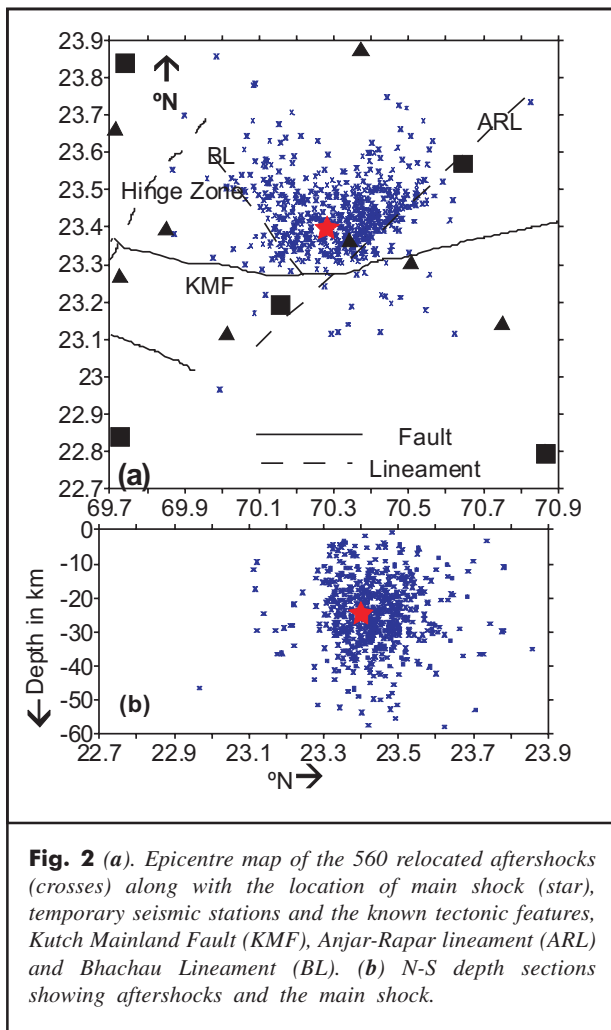
Velocity structure has a vital role to understand seismicity, tectonics and active faults of a seismically active region. The western part of Peninsular India, seismically a very active region, experienced the 1819 great Kutch earthquake ( $M \sim 8.0$ ), the 1956 strong Anjar earthquake ( $M_w$  6.0), and is demarcated as zone V in the seismic zoning map of India. The recent January 26, 2001 Bhuj earthquake ( $M_w$  7.7) caused devastation in the region. Although the Oil and Natural Gas Corporation (ONGC) have made extensive studies on seismic exploration for oil and gas in the region, their studies are mostly confined to a shallow depth of  $< 5$  km. Not much knowledge exists on the seismic structure of the deeper ( $\sim 25$  km) earthquake sources in the region. **The 2001 Bhuj earthquake sequence provided a good data set to shed some light on the deeper seismic velocity structure in the region.**

The 2001 earthquake occurred in the centre of the Kutch rift basin. The Kutch (also called Kuchchh) basin is distinguished by east-west oriented high lands (uplifts) and low lying basins or Ranns (Ranns means uninhabited salt flats that are neither sea nor land, and are flooded periodically). The seismic zone trends northwest, and it merges with the northeast seismicity trends related to the Owen fracture zone and Kirthar range in Pakistan. The Chagos-Laccadive ridge intersects the coastline near this junction. A number of E-W faults control the structural trend of the Kutch Rift Basin (KRB). These are: Nagar Parkar Fault (NPF), the Allah Bund Fault (ABF), Island Belt Fault (IBF), Kutch Mainland Fault (KMF) and North Kathiwar Fault (NKF) (Figs.1 and 2). The NPF is the northern boundary and the NKF the southern boundary faults of the KRB. The basin is filled with

sediments ranging in age from middle Jurassic to Tertiary. The Deccan lava flows separate the Mesozoic and Tertiary stratigraphy of the KRB. After an initial period of extension, the KRB has been subjected to N-S compression at least since 20 Ma (Talwani and Gangopadhyay, *Seism. Res. Lett.*, 72, 336-345, 2001). The Bouguer gravity anomaly in the KRB varies between -20 mgal to 45 mgal and the contours show E-W trend (Mishra et al., *Tectonophysics*, 396, 195-207, 2005). In addition to E-W faults, the basin is transected by N-S to NE-SW and NW-SE tectonic lineaments that include the structural median high (Hinge Zone) to the west of Bhuj, NE-SW Anjar-Rapar lineament, NW-SE Bhachau lineament and a few others. (Biswas, *Tectonophysics*, 135, 307-327, 1987; Talwani and Gangopadhyay, *Seism. Res. Lett.*, 72, 336-345, 2001; Kayal, et al., *J. Geol. Soc. India*, 59, 395-417, 2002a).



**Fig. 1.** Map showing major tectonic features in the study region (Kayal et al., *J. Geol. Soc. India*, 59, 395-417, 2002). **KRB:** Kutch Rift Basin, **CRB:** Cambay Rift Basin, **NRB:** Narmada Rift Basin, **NPF:** Nagar Parkar Fault, **IBF:** Island Belt Fault, **KMF:** Kutch Mainland Fault, **NKF:** North Kathiwar Fault, **WCF:** West Coast Fault, **AB** (Thicker line): 'Allah Bund' ( $\sim 80$  km long and  $\sim 2$  high crustal deformation due to the 1819 great earthquake). Epicenters and fault-plane solutions of the past significant earthquakes  $M > 5.0$  are shown. In fault-plane solutions, the solid circle indicates P-axis in the dilatational zone, and the open circle T-axis in the compressional zone. Epicenter of the 1819 earthquake is given after Rajendran et al. (*Curr. Sci.*, 80: 1497-1405, 2001). The solid star indicates the epicenter of the main shock of 26 January, 2001 and the shaded area the aftershock area.



**Fig. 2** (a). Epicentre map of the 560 relocated aftershocks (crosses) along with the location of main shock (star), temporary seismic stations and the known tectonic features, Kutch Mainland Fault (KMF), Anjar-Rapar lineament (ARL) and Bhachau Lineament (BL). (b) N-S depth sections showing aftershocks and the main shock.

In routine location of earthquakes, a forward inversion is made using a standard crustal model of P-wave velocity ( $V_p$ ), and for S-wave velocity ( $V_s$ ) a normal value of  $V_p/V_s$  is assumed for computation. This simple analysis does not provide high precision locations of the earthquakes, nor help to arrive at the true velocity structure of the crust. Lateral heterogeneity in the Earth's crust has a key role in determining earthquake location and in understanding source processes of earthquakes. Seismologists have tried to solve this problem by seismic tomography study. In seismic tomography study, along with the high precision earthquake locations, the velocity perturbations or deviations (%) from the assumed model are imaged. **In this report, an attempt is made to examine the absolute velocity structures, particularly the detailed  $V_s$  and  $V_p/V_s$  structures in the Bhuj earthquake source zone that may have a key role in the earthquake processes.**

### Seismic Data and Analysis

Large number of aftershocks were recorded by a 12-station temporary seismograph network immediately after the January 26, 2001 Bhuj earthquake (Kayal et al., *J. Geol. Soc. India*, 59, 395-417, 2002a). There were five digital seismographs and seven analog seismographs in the network. About 560 aftershocks ( $M \geq 2.0$ ), that were recorded by the 12-station network for a period of two and a half months, are used in this study. About 5000 seismic phase data, 2876 first P arrival and 2195 first S arrival data, are analysed for joint determination of the hypocentral parameters and 3-D velocity structures. P-wave velocity ( $V_p$ ), S wave velocity ( $V_s$ ) and  $V_p/V_s$  structures in the source area are imaged using the Local Earthquake Tomography (LET) method of Thurber (*J. Geophys. Res.* 88: 8226-8236, 1983) and Eberhart-Phillips (*Seismic Tomography: Theory and practice*, ed. H.M. Iyer and K. Hirahara, Chapman and Hall, London, 613-643, 1993). A critical analysis of the  $V_s$  and  $V_p/V_s$  structures is made by imaging its absolute values to understand its role in earthquake processes.

A high precision timing accuracy of the phase data were maintained by the built-in GPS timing system in the digital recorders. The P- as well as S-arrival time was read with a precision of  $\pm 0.01$  s. Accurate reading of the seismic phase data in analog records, particularly the S phase data, is very tedious. The overall reading accuracy of analog data for P-phase was within  $\pm 0.1$  s and for the S-phase  $\pm 0.2$  s to  $\pm 0.5$  s. To take care of the converted S-phase data, the three component digital records were examined, and the reliable S-phase data were accepted (Kayal et al., *J. Geol. Soc. India*, 59, 395-417, 2002a).

In the preliminary analysis, 800 aftershocks were located by the Hypo71 computer program using 1-D inverted P-wave velocity model and normal  $V_p/V_s$  1.73 (Kayal et al., *J. Geol. Soc. India*, 59, 395-417, 2002). The events were located with an average travel time residuals, root mean square error (rms) 0.5 s, and average location errors 3 km in epicentre and 5 km in depth. **Out of these 800 aftershocks, we selected 560 events with high precision P- and S-arrivals that yielded lower rms values. These 560 events are reanalysed by the LET method for high precision location as well as for imaging the seismic velocity structures of the earthquake source zone. The analysis has produced average rms value of 0.19 s, average errors in epicentre 1 km and in depth 2 km. These relocated events and an N-S depth section are shown in Fig 2. Seismic images of the**

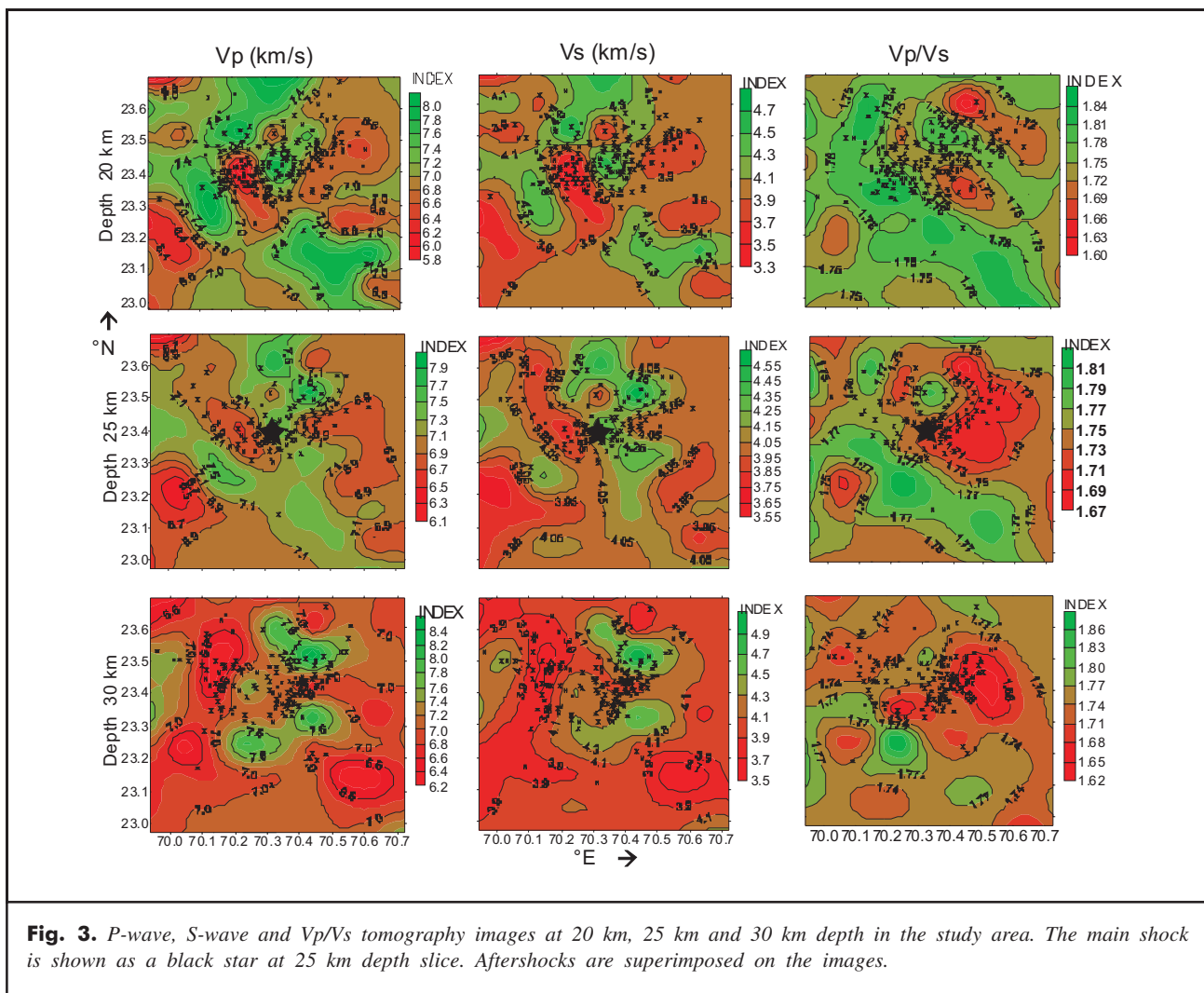
earthquake source zone, depth slices at 20, 25 and 30 km, are shown in Fig 3, and the depth section of the images are shown in Fig 4.

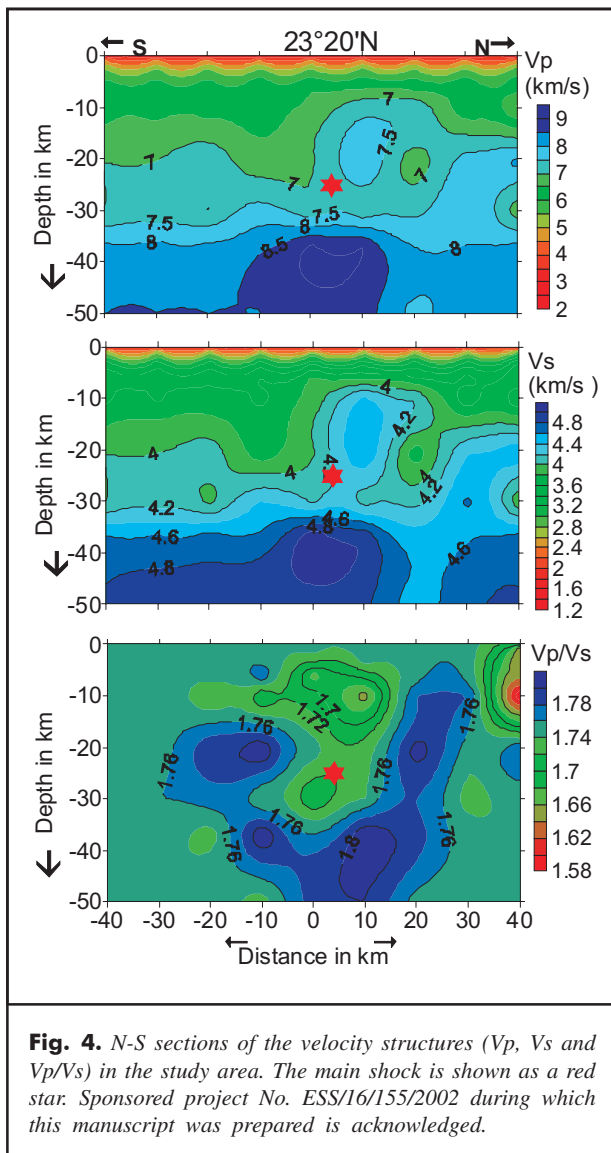
## Results and Discussion

Most of the aftershocks occurred in an area 70 x 35 sq km (Fig. 2a). Intense activity was observed at a depth range 15-35 km (Fig. 2b). The main shock as well as most of the aftershocks occurred to the north of the Kutch Mainland Fault (KMF) and within a V shaped zone, which is delimited by the Bhachau Lineament (BL) to the west and by the Anjar Rapar Lineament (ARL) to the east. Fault plane solutions of the main shock and aftershocks suggest that a south dipping hidden fault caused the main shock (Kayal *et al.*, *J. Geol. Soc. India*, 59, 395-417, 2002a). The N-S

depth section of the well located events in Fig 2b clearly indicates that the main shock and the aftershocks occurred on a steeply south dipping structure.

Seismic images of the source zone of the main shock show lateral heterogeneities in P- and S- wave velocities (Fig. 3). At the 25 km depth slice, in the main shock and aftershock source area, a higher  $V_p$  (~ 7.6 km/s) block is bound by two low  $V_p$  (~ 6.8 km/s) blocks, one low  $V_p$  trends NW and the other NE. These two low velocity structures are also reflected in the  $V_s$  imaging ( $V_s$ ~ 3.9 km/s). These two structures may be representing two fault/shear zones at depth. At the main shock focus zone (25 km depth), the estimated  $V_p$  is 7.2-7.6 km/s,  $V_s$  4.25-4.26 km/s and the  $V_p/V_s$  1.73 respectively. We believe that the heterogeneity in the seismic structure at the 20 and 25 km depth, in the main shock source





zone, caused accumulation of the stress. The seismic images at 30 km depth slice show a prominent zone of high  $V_p$  (7.8- 8.2 km/s) and high  $V_s$  (4.3 – 4.6 km/s). This observation further supports that the higher velocity up-thrown block had been the stress accumulator. The main shock occurred at the boundary of high and low velocity zones, where  $V_p/V_s$  is low compared to its values in the horizontal plane around it. However, its value is higher compared to the high velocity up-thrown block visible in Fig. 4. It may be noted that Kayal et al. (*Geophys. Res. Lett.* 29: 51-54, 2002b) estimated perturbed  $V_p$ ,  $V_s$  and Poisson's ratio  $\sigma$  (in %) at the main shock area. Their studies conform well to the present study. We, however,

estimated the absolute values of  $V_p$ ,  $V_s$  and  $V_p/V_s$  in the source zone. Kayal et al. (*Geophys. Res. Lett.* 29: 51-54, 2002b) found that  $\sigma$  varies from 0.234 to 0.286, which correspond to  $V_p/V_s$  1.69 to 1.82. This is in good agreement with the present study. Mandal et al. (*Bull. Seism. Soc. Am.*, 94, 633-649, 2004) too found a high velocity upraised block in the earthquake source zone. Sarkar et al. (*Geol. Soc. Am.*, SPE425-20, 2007) on the basis of Deep Sounding Survey of this area, finds three strong reflectors within the top 20 km and a northerly dipping Moho with depth varying between 38 to 45 km. The raised block could have led to reflections observed by them in the top 20 km of the crust. We too see the Moho at around 38 km. Besides, there is a high velocity block below the Moho in this region.

Diagnostic seismic images/structures are revealed in the N-S depth section (Fig. 4). An uplifted high velocity block,  $V_p$  7.5 km/s and  $V_s$  4.4 km/s, is well reflected in this section at a depth 15- 22 km, below which the main shock originated (Fig. 4). At the focus, at 25 km depth, the  $V_p$  and  $V_s$  are higher, but  $V_p/V_s$  is lower compared to the surrounding rocks in the same horizontal level (Fig 4). It is further observed that  $V_p$  and  $V_s$  is lower and  $V_p/V_s$  is higher at the focus compared to the material directly above and below this depth level. This implies that the rupture initiated at the weakest point of the up-thrown high velocity rigid block. A Y - shaped higher  $V_p/V_s$  is observed for the surrounding rocks. **We propose that the high velocity rigid block is an asperity and the surrounding low velocity high  $V_p/V_s$  region is a barrier.**

## Conclusions

In routine earthquake location, normally an inverted 1-D P-wave velocity ( $V_p$ ) model is taken, and a normal value of  $V_p/V_s$  is assumed for the whole region for computation of S-arrivals. In 3-D inversion, along with the earthquake locations, lateral heterogeneities in  $V_p$  as well as in  $V_s$  are imaged in terms of % perturbation with respect to the assumed model. **In this report, absolute values of  $V_p$ ,  $V_s$  and  $V_p/V_s$  are illustrated by 3-D inversion, and the role of  $V_s$  and  $V_p/V_s$  is critically examined. These detailed seismic images have shed light on the sheared fault zones and on the role of fluid saturated rock matrix in the source zone of the Bhuj earthquakes.**

## Acknowledgement

We are thankful to Sri T M Mahadevan for kindly inviting this article for the DST News Letter.



## DEEP CONTINENTAL STUDIES IN INDIA : CURRENT RESEARCH PROJECTS AND SCIENTIFIC ACTIVITIES

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The Project Advisory and Monitoring Committee of the DST on Deep Continental Studies in India has, in its 6<sup>th</sup> and 7<sup>th</sup> meetings recently held, examined and recommended for approval a number of research projects and also several connected activities that would enhance the inputs into researches into the deep continental structure of India.

The first of these (the 6<sup>th</sup>) meeting of the PAMC was held **INDIAN INSTITUTE OF GEOMAGNETISM, NAVI MUMBAI – 410 218** on 29-31 MARCH, 2007. **Prof. Archana Bhattacharya, Director, IIG** welcomed the members of the PAMC and assured full participation of IIG in DST activities and DCS Programme in particular.

The seventh meeting of the PAMC was held during 12-14 SEPTEMBER, 2007 at **SRI VENKATESWARA UNIVERSITY, TIRUPATI – 517 502 (A.P.)**. **Prof. S. Jayarama Reddy, Vice-Chancellor, S.V. University** inaugurated the proceedings and offered the support of the University to the research activities being deliberated by the PAMC.

**Several of the projects are now approved in the remote and relatively inaccessible areas in especially Arunachal Pradesh. These now focus on building up a large data base on the surface geology that would then pave the way to formulating detailed geophysical inputs necessary for delving into the deep continental structure. Larger geophysical inputs in various fields, particularly in controlled and teleseismic seismology, are in various stages of formulation and are not included in the list below. DST is also supporting a number of other activities, which include setting up national facilities for application of advanced techniques and generation of new data; training in frontier areas of methodology and modeling; group discussions, field workshops and publications. Some of these activities are outlined in this article.**

### ARUNACHAL PRADESH

(i) **“Integrated tectonic, petrological, geochronological and geophysical investigations, Arunachal Himalaya”.**

PI: Prof. A.K. Jain, Department of Earth Sciences, Indian Institute of Technology, Roorkee – 247 667.

(ii) **“Geomorphology, metamorphism and geodynamic evolution of Kameng, Subansiri and Siang region (Arunachal Pradesh) with special emphasis on Subansiri”.**

PI: Prof. P.K. Verma, Department of Geology, Delhi University, Delhi – 110 007.

(iii) **“Tectono-metamorphic evolution of the higher Himalayan rocks of Western (Kameng Corridor) and eastern Arunachal Pradesh: A comparative study”.**

PI: Prof. Somnath Dasgupta, Department of Geological Sciences, Jadavpur University, Kolkata – 700 032.

(iv) **Project entitled “Exhumation of the Higher Himalayan Crystallines (HHC), Arunachal Himalaya, using fission track thermo-chronology”.**

PI: Dr. R.C. Patel, Department of Earth Sciences, Kurukshetra University, Kurukshetra – 136 119.

(v) **“Granite series evolution along Kameng Corridor of Arunachal Himalaya in terms of magnetic susceptibility of ferromagnesian minerals, whole-rock geochemistry and stable isotopes: Implication for petrogenesis, ore potential and tectonic environment”.**

PI: Prof. Santosh Kumar, Department of Geology, Kumaun University, Nainital – 263 002.

(vi) **“Multiple Geophysical investigations in Eastern Himalayan Syntaxis”.**

PI: Prof. B.R. Arora, Director, Wadia Institute of Himalayan Geology, 33, General Mahadeo Singh Road, Dehradun – 248 001.

(vii) **“Geodynamic evolution of the eastern syntaxis”.**

PI: Dr. N.S. Gururajan, Department of Structure & Tectonics, Wadia Institute of Himalayan Geology, 33, General Mahadeo Singh Road, Dehradun – 248 001.

(viii) **“Structural evolutionary history of the Siang Window based on integrated structural, stratigraphic and metamorphic studies”.**

PI: Dr. S.K. Acharyya, Department of Geological Sciences, Jadavpur University, Kolkata – 700 032

(ix) **“Tectono-stratigraphic configuration around Mayudia-Hunli-Etalin-Anini Traverse of Dibang valley, Arunachal Pradesh, India”.**

PI: Dr. Kali Prasad Sarma, Department of Geological Sciences, Gauhati University, Guwahati – 781 014.



(x) **“Tectonic evolution of the Siang syntaxis in NE Himalaya with emphasis on spatial and temporal pattern of exhumation”.**

PI: Dr. Anand Kumar Pandey, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007.

(xi) **“Geochemical and Rb-Sr isotopic signatures in the litho-units of Lohit Complex, Mishmi Hills, Arunachal Pradesh: Implications for its origin and evolution”.**

PI: Dr. Tapos Kumar Goswami, Department of Geology, J.B. College, Jorhat – 785 001.

(xii) **“Tectonism, magmatism and crustal evolution of the Northeastern Himalayas in parts of Twang and West Kameng Districts, Arunachal Pradesh”.**

PI: Prof. Kali Prasad Sarma, Department of Geological Sciences, Gauhati University, Guwahati – 781 014.

#### SIKKIM

(i) **“Orogenic culmination and evolution of the Teesta Dome in Sikkim Darjeeling Himalaya”.**

PI: Dr. Sumit Kumar Ray, Retd. Dy. Director General (GSI), Emeritus Scientist, Department of Geology, Presidency College, 86/1, College Street, Kolkata-700 073.

(ii) **“Geodynamic evolution of the Main Central Thrust, Himalayas”.**

PI: Dr. Dilip K. Mukhopadhyay, Professor, Department of Earth Sciences, Indian Institute of Technology, Roorkee – 247 667.

(iii) **“The exhumation factor in the genesis of inverted metamorphic sequences – an evaluation from structure, metamorphism, fluid inclusions and earthquakes in the Sikkim Himalaya”.**

PI: Dr. Saibal Gupta, Associate Professor, Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur – 721 302.

(iv) **“Imprint of Himalayan orogeny and neotectonism in sediment, drainage and landform in Sevak-Rongpo transect”.**

PI: Prof. Pradip K. Bose, Professor, Department of Geological Sciences, Jadavpur University, Kolkata – 700 032.

(v) **“Geodynamics of exhumation, uplift and tectonogeomorphologic evolution of Sevoke-Rangpo-Mangan-Chungthang-Lachen-Thangu using 3D techniques and cosmogenic exposure dating”.**

PI: Dr. C.S. Dubey, Reader, Department of Geology, University of Delhi, Delhi – 110 007.

#### MEGHALAYA

(i) **Assessing the role of plume-head for continent-generation in the Khasi greenstone belt of Meghalaya, North Eastern India:**

PI: Dr. Jyotisanakar Ray, Department of Geology, Calcutta University, 35, Ballygunge Circular Road, Kolkata - 700 019.

(ii) **Studies on mafic igneous activity, high-grade metamorphic history and tectonic evolution of Meghalaya, northeast India.**

PI: Dr. J. Mallikharjuna Rao, Geological Studies Division, National Geophysical Research Institute, Hyderabad-500 007

(iii) **“Petrogenesis of mafic rocks of the Precambrian terrains of Meghalaya and Assam, Northeastern India: A record of continental break-up”.**

PI: Dr. Maibam Bidyananda, Lecturer, Department of Geological Sciences, Gauhati University, Gopinath Bordoloi Nagar, Guwahati – 781 014.

#### BAY of BENGAL

(i) **Deep crustal study of Bay of Bengal – deduced from geophysical data”.**

PI: Dr. V. Subrahmanyam, Regional Centre, National Institute of Oceanography, 176-Lawsons Bay Colony, Visakhapatnam – 530 01

#### PENINSULAR SHIELD

(i) **“Chemical petrology of the Archaean high-grade metasediments from Eastern Dharwar craton: Implications for the evolution of Archaean continental crust”.**

PI: Prof. B. Mahabaleswar, Department of Geology, Bangalore University, Bangalore – 560 056.

(ii) **Petrology and geochemistry of synplutonic mafic dykes from the late Archaean granite plutons in the Dharwar craton: implications for magma chamber processes, evolving lithospheric mantle and cratonization of Archaean crust”.**

PI: Dr. M. Jayananda, Reader, Department of Geology, Bangalore University, Jnanabharathi campus, Bangalore – 560 056.

(iii) **Geological, geochemical and isotopic studies in the Sandur and Kadiri greenstone belts: mantle processes beneath the Dharwar Craton”.**

PI: Dr. (Mrs.) C. Manikyamba, Geochemistry Division, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007.



(iv) **“Integrated geological and geophysical studies bearing upon the crustal and lithospheric evolution of the Bastar craton: focus on kimberlites, mafic-ultramafic complexes and major structural units”.**

PI: Dr. Y.J. Bhaskar Rao, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007.

(v) **“Stratigraphic, structural and palaeomagnetic analyses of the volcano-sedimentary successions between Noamundi and Nayagarh, Western Iron basin, Singhbhum craton: implications for the Archaean crustal evolution from the eastern Indian shield”.**

PI: Dr. Gautam Ghosh, Department of Geology, Presidency College, 86/1, College Street, Kolkata – 700 073.

(vi) **“Petrology and geochemistry of mafic dykes in Rewa Basin, Central India: Implications on dispersal and migration of Deccan magma and nature of sub-continental mantle”.**

PI: Dr. D.K. Paul, INSA Senior Scientist, Department of Geology, Presidency College, 86/3, College Street, Kolkata – 700 073.

(vii) **“Geochemical and Fluid Inclusion Studies of Malanjkhanda Granitoid Complex and Associated mineralization: Metallogenesis and Implications for Crustal Evolution”.**

PI: Dr. M.K. Panigrahi, Associate Professor, Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur – 721 302.

(viii) **Reconsideration of the proposal on “Karimnagar Granulite Terrain: Its metamorphic evolution”.**

PI: Dr. D. Prakash, Lecturer, Banaras Hindu University, Department of Geology, Varanasi – 221 005.

(ix) **Petrology of the lamprophyres and related rocks of Bakhatgarh- Phulmal, Panwad-Kawant and surrounding areas and geochemical investigation of these rocks for their Au-Cu, REE and PGE mineralization”.**

PI: Dr. Kirtikumar R. Randive, Lecturer, Post-Graduate Department of Geology, Rashtrasant Tukadoji Maharaj Nagpur University, Law College Campus, Amaravati Road, Nagpur – 440 001.

(x) **Structure and tectonics of the Terrane Boundary Shear Zone, southern part of the Eastern Ghats Mobile Belt, India.**

PI: Dr. T.R.K. Chetty, Geological Studies Division, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007. (Extension for I year up to 31-01-2008).

## MESOZOIC RIFT BASINS

(i) **“Geologic structure, tectonics and origin of the Gulf of Kutch, northwest India”.**

PI: Dr. D. Gopala Rao, Emeritus Scientist, Department of Marine Geophysics, Osmania University, Hyderabad

## DECCAN AND RAJMAHAL VOLCANIC PROVINCE.

(i) **“Mineralogical, petrochemical and isotopic studies on the radial mafic dykes associated with plutonic complexes and continental flood basalts of Saurashtra and Kutch in Western Deccan Volcanic Province”.**

PI: Dr. D.V. Subba Rao, Scientist – EII, Department of Geochemistry, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007

(ii) **“Petrochemistry and petrogenesis of mafic dykes from the eastern part of Deccan Volcanic Province between Narmada-Son and Tapti lineaments”.**

PI: Prof. J.P. Shrivastava, Professor, Department of Geology, University of Delhi, A- II/I, Maurice Nagar, Delhi – 110 007.

(iii) **“An integrated study of the dyke swarms and Deccan Traps of Chhota Udepur province, Lower Narmada Valley.**

PI: Dr. K.R. Hari, Assistant Professor, Department of Geology, Govt. V.Y.T.P.G. Autonomous College, Drug, Chhattisgarh.

(iv) **“Geochemical characterization of the alkaline complexes associated with the Deccan Volcanic Province, in parts of Gujarat and Rajasthan States, India”.**

PI: Dr. N.R. Karmalkar, Department of Geology, University of Pune, Pune – 411 007.

(v) **Petrology, geochemistry and geochronology of distinct dyke rocks of Damodar Valley, East Gondwana Basin, Eastern India”.**

PI: Prof. Rajesh K. Srivastava, Department of Geology, Banaras Hindu University, Varanasi – 221 005.

(vi) **Project entitled “Palaeomagnetic, rock magnetic and low field AMS investigations on the intrusives of Damodar valley coal fields”.**

PI: Dr. S.K. Patil, Reader, Department of Palaeo and Rock Magnetics Laboratory, Indian Institute of Geomagnetism, Magnetic Observatory, Alibag – 402 201.



### PROTEROZOIC BASIN

**(i) Project entitled “Geological and geochemical studies of the Proterozoic Cuddapah basin dykes and their tectonic implications”.**

PI: Prof. R.C. Hanumanthu, Department of Geology, Sri Venkateswara University, Tirupati – 517 502 (A.P.).

### ANDAMAN ISLAND ARC

**i) “Geophysical investigations of the Andaman Island Arc – trench system and back arc basin”.**

PI: Dr. V.K. Gahalaut, National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007.

### OTHER AREAS OF THRUST

**The PAMC has in the two meetings recommended financial and technical support to the following activities.**

**(i) Setting up a laboratory for “Rock properties as A National facility”.**

PI: Prof. P. Rajendra Prasad, Andhra University, Visakhapatnam – 530 003.

**(ii) Training Programme on Diamond exploration in India.**

Coordinator: Dr. R.S. Sawkar, Secretary, Geological Society of India, Bangalore.

**(iii) Training Programme on the Fission Track studies:**

Co-ordinator. Dr. R.C. Patel, Department of Earth Sciences, Kurukshetra University, Kurukshetra 136 119.

**(iv) Field visits and Discussion Meet on Dykes in Dharwar craton.**

Dr. M.Jayananda, Bangalore University and Dr. R.K. Srivastava, BHU.

**(v) Field work and Group Discussion on Nilgiri Granulites along Moyar-Bhavani shear zone.**

Coordinator: Prof. C. Srikantappa, Mysore University, Mysore.

**(vi) Indo-US joint Workshop on “Electromagnetic Induction in the Earth” during 15-17 March, 2008 at NGRI, Hyderabad**

Convener: Dr. T. Harinarayana, NGRI, Hyderabad.

**(vii) Discussion meet on “Shear Zones of India”**

(Coordinator: Dr. S. Sinha-Roy, Birla Institute of Scientific Research, Jaipur - 302 001, Member, PAMC-DCS.

**viii) Publication of the Vision Document on “Metallogeny of Indian Continental Crust”.**

Co-ordinator: Dr. S. Sinha-Roy, Birla Institute of Scientific Research, Jaipur - 302 001, Member, PAMC-DCS

**(ix) Advanced Training Programme on “Modelling of Magmatic and Allied Processes”.**

Course Coordinator: Prof. Santosh Kumar, Department of Geology, Kumaun University, Nainital – 263 002.

**(x) Symposium of the International Geological Correlation Programme : “Geological Anatomy of East and South Asia” (IGCP 516)”**

Organizing Secretary: Prof. Talat Ahmad, Department of Geology, University of Delhi, Delhi – 110 007 at Department of Geology, University of Delhi on 8-9 October, 2007.

**(xi) Publication of the proceedings of the work shop on sutures held at Dehra Dun during 22<sup>nd</sup> – 25<sup>th</sup> November, 2006 at WIHG, Dehradun.**

Co-ordinator : Prof. B.R. Arora, Director, WIHG, Dehra Dun.

**(xii) Publication of the vision document on “Metallogeny, Ore genesis and Crustal Evolution” based on discussions held between 9<sup>th</sup> & 10<sup>th</sup> March, 2007 at IIT, Kharagpur.**

Coordinators: Prof. B. Mishra, IIT (Kharagpur) and Dr. S. Sinha-Roy, member, PAMC-DCS.

## CORRIGENDUM

Caption to Fig.1 of paper by Rajesh K, Srivastava and A.K. Sinha on page 21 of Vol. 17 No. 2 August 2007 of the DST-DCS-Newsletter should read as follows:

Figure 1: Regional geological and tectonic set-up of the Shillong Plateau (modified after Srivastava and Sinha, Mineral. Petrol., 2004).

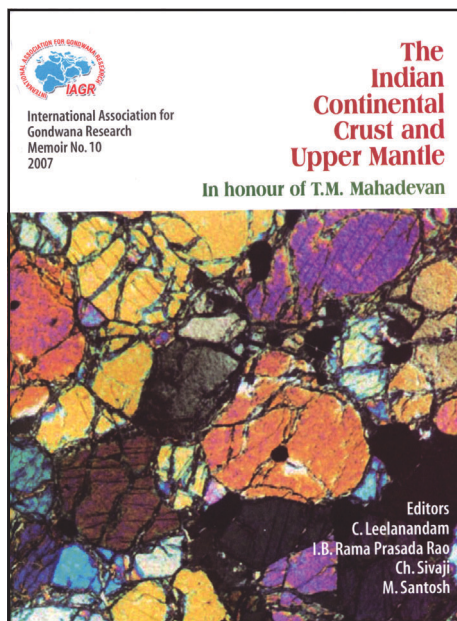
1. Major fault-systems, 2. Archaean gneissic complex, 3. Shillong Group rocks, 4. Mafic igneous rocks, 5. Porphyritic granites, 6. Sylhet basalts, 7. Ultramafic-alkaline-carbonatite complexes [Circled numbers indicate different locations: (1) Sung Valley, (2) Jasra, (3) Samchampi, (4) Swangkre], 8. Cretaceous-Tertiary sediments. Blank portion represents alluvium and recent sediments.

The error is regretted.

Editor.



## NEW PUBLICATION



## Review by A.K. Dubey and B.R. Arora

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A Group Discussion on, "The evolution of the Indian continental crust and upper mantle: Recent advances and future thrust" was organized at Osmania University, Hyderabad in April 2006 to commemorate sixty years of dedicated service to the Earth Science community by Shri T. M. Mahadevan, a person of exceptional qualities. Shri Mahadevan has served in various capacities as scientist, science manager, administrator, advisor, visionary and editor. **A total of 32 lectures were presented and out of these 21 are compiled and presented in the form of a Memoir by the International Association for Gondwana Research, Japan. 9 papers deal with geological structures and the remaining 12 describe the subsurface structures obtained through various geophysical methods. Most of the papers are of review nature and it is nice to have all the disseminated important information at one place.**

An excellent contribution on the major geological provinces of India and continental evolution of the Indian Shield is provided by Mahadevan himself in the first article of the volume. **Models of lithospheric evolution are proposed and the prevalent problems in geophysical and geochemical modelling are highlighted.** The article also provides a comprehensive list of important publications on the subject. In the next article, **Sinha Roy presents a kinematic model for the evolution of the Rajasthan**

**Craton.** The earlier model of the author is modified in the light of recent developments in the field of thrust tectonics. The structural features are interpreted in terms of thin-skinned tectonics and are well supported by seismic profiles of the region. **The evolution of the Central Indian Fold Belts and the Son-Narmada faults are described by Sharma.** The structures are attributed to inversion tectonics in the region. The earlier rift-phase was attributed to a mantle plume below the Rajasthan-Bundelkhand-Bastar protocontinent. The sequence of the fold belts in central India is placed as Dongargarh Fold Belt, Mahakoshal Fold Belt, and Sakoli Fold Belt.

The metamorphism of the Indian Granulite Terrane, which is dissected by a number of intracontinental shear zones, is investigated by **Tsunogae and Santosh.** The terrane is characterized by ultrahigh-temperature (UHT) granulite facies rocks. The peak metamorphic conditions of 900°C – 1000°C and 8 -12 Kbar are obtained for the intermediate Madurai Block lying between the Madras and Trivandrum blocks. **The various mineral assemblages are described and the peak metamorphism is attributed to the continent-continent collision during the final stages of formation of the Gondwana Supercontinent.**

On the basis of field observations and geochronological data, **oblique subduction is proposed along the Shyok Suture Zone and the Karakoram Shear Zone by Jain et al.** The timing of initiation of the compressional phase, based on the SHRIMP U-Pb zircon crystallization ages, is assigned a late Cretaceous age, between 75 and 68 Ma. A large scale strike-slip displacement along the Karakoram Shear Zone is denied because of continuity of the main lithological and tectonic units.

A useful synthesis of textural, mineral-chemical, and whole rock geochemical studies is provided for the Kondapalli layered complex of the Eastern Ghat Belt by **Leelanandam and Kumar.** The study reveals that the felsic granulites, which occur around the Kondapalli layered complex, constitute the plutonic core of a continental magmatic arc, whereas the chromite-bearing ultramafic cumulates form a part of the arc-root complex.

The shear zones of the past orogenic belts are mostly identified by the presence of ophiolite belts with their characteristic association. However from South India, **Ratnakar uses the miaskitic character of the nepheline syenites to characterize the ancient sutures.** The study is also important because the occurrence of nepheline syenite is rare in the central and north India.



Kimberlites have isolated exposures in the Indian subcontinent and they are of significance not only for the occurrence of diamonds but also to understand the deep processes under the continental plates. One such study is presented by **Chalapathi Rao** in which the geochemical characterization of kimberlites from the central and southern India is discussed. It is suggested that the sills and dyke swarms within and around the Cuddapah Basin and basic dykes of the Bijawar of central India should be carefully looked for the occurrence of diamonds. Another important study on the kimberlites (from south India) is performed by **Ravi et al.** **Based on the textural and mineral chemical characteristics, magmatic cumulate origin is proposed for the origin of eclogite xenoliths of the kimberlites. The LREE enrichment in the Wajrakarur kyanite eclogites is attributed to contamination by kimberlite fluids and the positive Eu anomaly to metasomatism by crustal fluid.** A similar study where xenoliths are used to understand the interior of the western continental margin is described by **Karmalkar et al.** in which the **Kutch and Murud-Janjira areas are shown to have different thermal histories.** The Kutch xenoliths reveal less elevated geotherm in comparison to the highly elevated geotherm of the Murud-Janjira area. The large differences in seismic signatures are attributed to differences in the thermal regimes of the two regions.

Deep continental seismic studies provide a useful tool for imaging the two dimensional cross-sections in different orogenic belts. A useful review of the past studies in different parts of India (excluding the Himalaya) is provided by **Rajendra Prasad and Vijaya Rao.** A crustal cross-section along the Kavali-Udipi profile, proposed earlier by Kaila et al. has been incorporated in the study. The cross-section displays a number of steep and deep faults cross-cutting the Moho discontinuity. Similar structures were earlier proposed for the Himalaya by Kaila and his co-workers. **The shift in conceptual model from thick-skin to thin-skin tectonics with a prominent plane of basal decollement (see also Sinha Roy in this issue) is quite evident in the new interpretation of the crustal cross-sections.** Deduced knowledge on basement configuration, crustal and sub-crustal structures is used to trace the geodynamic evolution model of the Indian continental crust from Archean-Proterozoic to Phanerozoic. A similar view on the crustal structure of the Indian Peninsular Shield is provided by **Murty and Reddy.** **The study demonstrates a good correlation between seismicity and structural and velocity inhomogeneities.** The authors also describe

earthquakes along basement and deeper faults although no comment is made on thin vs thick-skinned tectonics.

**Kayal** has described the recent large earthquakes in India including the 2004 Sumatra-Andaman earthquake. **Review highlights the importance of well planned aftershock studies of large event in constraining the seismotectonic model of the stable continental as well as active collision zone of the Himalaya.** In the Himalayan studies, a greater emphasis is provided to earthquakes related to thrusting whereas the aftershock mechanisms of earthquakes dominated by normal and strike-slip faults largely remain uninvestigated by detailed studies.

**Ramesh and Prakash Kumar** in their interesting paper highlight the importance of deciphering mantle stratigraphy (horizontal layering) in depths of 100 to 300 km in modeling continental evolution. They discuss options of evolving suitable methodology and highlight several related geological aspects that can be addressed. The gravity maps are used by **Arora et al.**, to highlight the role of plate tectonics during the Archean (western Dharwar Craton) and Proterozoic (Satpura Mobile Belt) periods. **The mafic / ultramafic intrusives in the Mahakoshal Group are cited as evidence of a rift phase prior to collision and a series of thrust high density lower crustal rocks below the Satpura Mobile Belt as evidence of the later collision tectonics.** The gravity and magnetic data along a 600 km transect from Vasco-de-Gama in the west to Jadcharla in the east are discussed by **Ramadass et al.** Based on the data, **three distinct blocks separated by deep faults and characterized by different average crustal thicknesses are proposed for the Dharwar Craton, in contrast to the existing two.**

An aeromagnetic image map of Dharwar, Bastar, and Singhbhum cratons is presented by **Anand and Rajaram.** **The data helps in understanding the basement, sediment cover and the top trap horizon.**

An Audio Magnetotelluric method is used by **Sinharay et al.** to locate the geothermal source of **Bakreshwar hot spring.** A north-south trending fault close to the hot spring is found to be a shallow feature unable to act as a geothermal source. Hence the source could not be located or identified by the method.

The results of the magnetotelluric Studies undertaken as a part of Deep Continental Studies Programme of the DST, Government of India are summarized by **Harinarayana.** **Resistivity imaging brings out distinctive signature of the shear zone related to the**



**Central India Suture, surface fault of the Narmada-Son Lineament and extended shearing in deep crust resulting from the continent-continent collision of Southern Granulite Terrain and the Bundelkhand craton on the north.** Six traverses in central and southern India reveal a relationship between the upper crustal rocks and seismicity in the region.

The multidisciplinary data obtained from the deep geophysical investigations are used by **Raval and Veeraswamy** to understand the internal constituents of the Dharwar and Bundelkhand proto-continents. **Deviating from the usual path of plate tectonics, mantle plume tectonics is invoked to understand the tectonics of the region. The bimodal hypothesis helps bridging gaps in the earlier suggested Proto-continental evolution model, particularly in the Archean-Proterozoic era.**

**The important types of U-deposits of the Indian subcontinent** along with their ages are discussed by **Dhana Raju** who has a vast experience in the field of U-metallogeny. **The data are used to propose a geochemical evolution model of the Indian continental crust.**

**The rich information emerging from review articles is clear marker that our understanding of basic geological and geodynamic processing operative on Indian shield has matured to a stage where, perhaps, the synthesis of geological and geophysical data can be used to address some of the outstanding problems,** for example, the rheological status of continental lithosphere, role of thick vs thin tectonics, mechanism and source of re-activation of the Narmada-Son Rift and whether Himalayan Arc is primary or secondary. **It is also clear that much of studies so far have focused on Central and South India. The north-east region which appears to be the most complicated part as a result of active tectonics in the syntaxial bend and Shillong plateau largely remains unexplored.**

*The efforts of the editors in compilation of the volume demands liberal appreciation. The publication is very timely as the International Year of Planet Earth is being celebrated. This benchmark publication will definitely help in finding out the future directions of research in India. The print quality including the illustrations is good. The price is not quoted on the volume but looking at the paper back edition, it should be affordable by the Indian standard. We recommend a copy of the volume in all the important libraries dealing with Earth Sciences.*

## A FIELD WORKSHOP-CUM-CONTACT PROGRAMME ON CRUSTAL DYNAMICS IN THE GODAVARI TRIPLE JUNCTION

**G. LAKSHMINARAYANA<sup>1</sup> and Ch. SIVAJI<sup>2</sup>**

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  2. Department of Science and Technology, New Delhi
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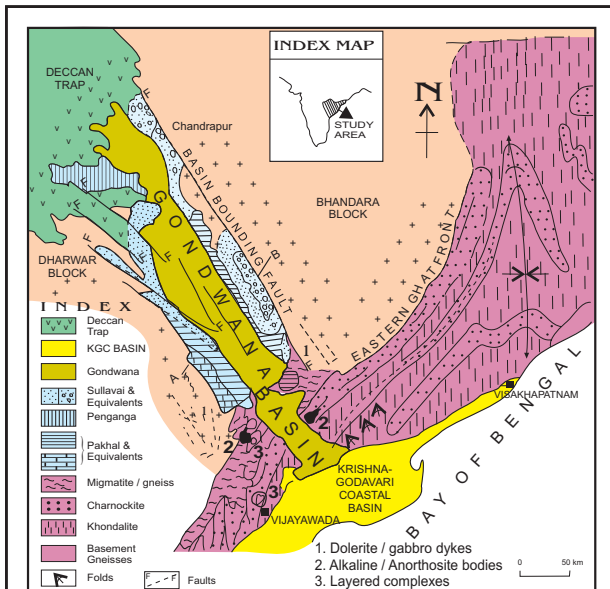
Triple point junctions are contact zones of three armed radial rifts associated with divergent plate margins. One or another arm of such rift system fails early i.e. shortly before or after the development of oceanic crust and then continental separation follows, taking the path of two arms. Failed arm extends at a high angle away from the continental margin. **The Godavari triple junction (Guntur) is one such Phanerozoic triple junction indicated by Burke and Dewey (Jour. Geol. V.81, pp. 406-433, 1973).**

Sedimentary basins formed in the Godavari rift system are unique as they preserve over 10 km thick sediments deposited episodically since middle Proterozoic to the Quaternary. This basin extends over a length of 350 km with an average width of 40 km. The tract is broadly divisible into NW-SE oriented intra-continental Godavari rift (GR) and NNE-SSW to ENE-WSW trending passive continental margin Krishna –Godavari Basin (KGB). The contact between GR and KGB defines the Godavari triple junction whose outcrop expressions are better seen in Kamavarapukota-Zangareddigudem area of West Godavari district, Andhra Pradesh.

Situated at the tectonic join between the Archaean Dharwar and Bhandara cratonic blocks, the GR exposes a 6 km thick lithic fill deposited between Middle Proterozoic and Cretaceous period (Fig.1&2). The middle and late Proterozoic sediments belong to Pakhal Supergroup and Sullavai Group respectively, whereas the Late Carboniferous to Cretaceous sediments belong to the 'Gondwana Formations.' **Development of sedimentary basins along the Godavari valley embodies a testimony to a rare rift-related sedimentary basin development at right angle to the curvilinear Eastern Ghat Mobile Belt (EGMB).**

The KGB, located in the southeastern part of the Godavari valley, exposes NE-SW trending Cretaceous

coastal Gondwana sediments, K/T boundary basalt Trappean succession, Cenozoic Rajahmundry Formation and Quaternary to Recent sediments. The GR and KGB are under active exploitation for Coal and Petroleum-Natural gas respectively.



**Fig. 1.** An outline geological map showing the spatial relationship between the Godavari rift (GR) and the Eastern Ghats Mobile Belt (EGMB). GR is located at the tectonic join between the Dharwar and Bhandara block. (Geology compiled from published literature.

The Gondwana tract of the Pranhita-Godavari valley is an intracratonic fault-bounded composite rift basin. Two transversely oriented structural trends viz. NNW-SSE in the Godavari graben and NE-SW in KGCB are discernible in this tract.

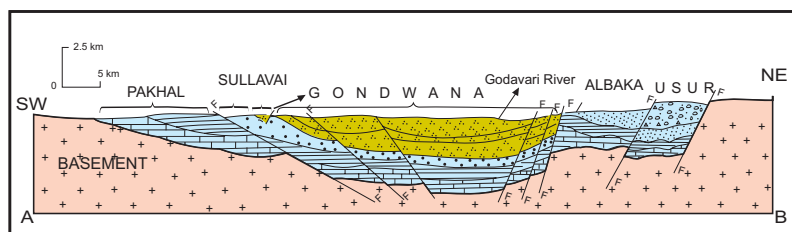
Development of succession of rift basins in Gondwana rift system and pattern of extensional tectonism and *modus operandi* of continental break up can better be deciphered along the Godavari valley. Outcrop evidence exists for reconstruction of intercontinental palaeodrainage during Gondwana deposition in rift basins followed by break-up of India from the unified Gondwana landmass and development of passive continental margin basins during northward drift of India. Variation in Gondwana fluvial regimes of Permian, Triassic, Jurassic and early Cretaceous are better documented than any

other geological terrain in India. K/T boundary basalt volcanism is a classical example for passive continental margin extension related lava eruption. The coarsening-up Cretaceous delta cycle of coastal Gondwana and the Cenozoic estuarine setting of the Rajahmundry Formation provide text book type illustrations.

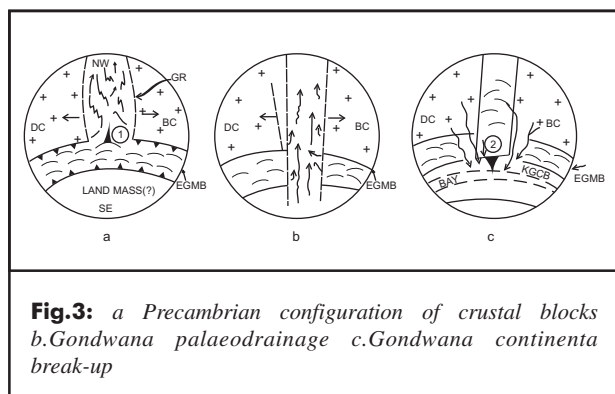
**Salient aspects in the evolutionary pattern of Godavari triple junction (Fig.3) include the following stages.**

- 1) The Gondwana rift (Late Carboniferous to Cretaceous) developed along a pre-existing zone of weakness i.e axial portions of Proterozoic Pakhal and Sullavai basins which are set on continental crust along the contact zone between Dharwar and Bhandara cratonic blocks of the Indian shield.
- 2) During the evolution of the Godavari rift, palaeodrainage was from southeast i.e. somewhere in the landmass that was welded to India (Antarctica or Australia). The onset of the Krishna –Godavari coastal basin owes to Gondwana continental break-up during Cretaceous. Coinciding with this is the termination of basin development along the Godavari rift thereby making it a sort of failed rift
- 3) It is thus the sequential development of rift basins and varying stress regimes in the continental crust and attendant continental separation and drifting that controlled the development of the Godavari triple junction.

With this background information, A Field Workshop cum Contact Programme on “**GODAVARI TRIPLE JUNCTION, A.P., INDIA**” was organized by Geological Survey of India Training Institute under the aegis of Department of Science and Technology from 9<sup>th</sup> to 18<sup>th</sup> July, 2007 in Visakhapatnam-Rajahmundry-Sattupalli area.



**Fig.2:** Schematic geological cross section across the GR. Section line is marked in Figure 1. Index to symbols same as in Figure 1. Eastern margin is fault-bounded whereas the western margin between Pakhal and the basement is unconformable.



**Fig.3:** a Precambrian configuration of crustal blocks  
b. Gondwana palaeodrainage c. Gondwana continental break-up

A total of 27 geoscientists representing, Universities, NGRI, WIHG, ONGC, AMD, GSI, State Government Departments, Reliance and Tata Steel attended the workshop. The Workshop was inaugurated in Geology Department, Andhra University on 09.07.2007. Inaugural function aimed at creating awareness about the DST-GSI Training Institute programmes among the University students, scholars and faculty. About 200 student scholars and faculty of earth science related departments of University attended the function. Shri P.K. Sinha, Dy. Director General, GSI Training Institute, Prof. B. Satyanarayana, Vice-Chancellor-in-charge, Prof. P.Vijaya Prakash, Registrar, Prof P.Veraraju, Principal UCST, addressed the participants and invitees. Prof. Satyanarayana, released a book entitled “**Godavari Triple Junction, A.P, India, explanatory brochure and guidebook**”.

Field visits commenced with the study of present day environments and tectonic setting along the Eastern Ghat (khondalite) tracts flanking Vizag-Bheemili beach. **On day-2.** Participants visited Rajahmundry and sailed along the Godavari River to study fluvial processes viz., flow dynamics, transportation, bar development, over bank deposition, and disposition of sedimentary facies. **On Day-3:** The Bommuru and Lalacheruvu quarries were visited, paying attention to the facies variations of Cenozoic alluvial/intertidal deposits of Rajahmundry Formation and their bearing on evolution of continental margin. **On Day-4,** Godavari Triple Junction zone was visited in Zangareddigudem-Gopalapuram area. Fault patterns and cross trends in basement grain and sedimentary beds are illustrated on outcrops.

*The discussions initiated in this meet, it is hoped, would kindle renewed interest in the tectonic evolution of the region endowed with a rich oil and gas potential.*

## NEW PUBLICATION

**MICROEARTHQUAKE SEISMOLOGY AND SEISMOTECTONICS OF SOUTH ASIA.** By J.R. KAYAL, P. 503, 2008  
CAPITAL PUBLISHING COMPANY,  
NEW DELHI - KOLKATA - BANGALORE.

### Review by T.M. Mahadevan

Microearthquakes (MEQ), the expression of deformation in the earth's crust of a size of  $< 3$  M (in the magnitude scale), fall in three categories. The most intensely monitored and studied are those associated with the sequences of deformation causing a major earthquake, largely in the aftershock sequence. Being associated with the main fault system and the hypocenter of the main event, MEQs throw light on the manner of stress release that characterises the waning phases of the stress fields that generated the major event in the area. These are therefore expected to constrain modeling of the source mechanism that generated the major event. There are also regions generating continuously swarms of MEQ, not necessarily related to any major event. A third category belongs to the not infrequent but episodic deformations in some regions/areas expressed in EQs of largely a size of  $< 5.0$  M. A fourth category is the micro-earthquakes associated with induced seismicity, as exemplified by the events around the Koyna dam. **All the different types of MEQs have the capability to throw light on the style and pattern of stress build up and release through brittle deformation in parts of the earth's crust and in some cases the mantle (as for example the NE Himalaya). They are therefore the most direct tools to understanding the tectonics of a region, essentially an integral part of hazard management.**

MEQ studies received a great impetus in India since the 1993 Killari earthquake, thanks to initiatives taken by several institutions. The Geological Survey of India has since taken major steps to investigate systematically the aftershock sequences in most of the major earthquakes and also the other categories of MEQs. Dr. Kayal who has been one of the leading seismologists to address this



area of seismology has **presented in this book a synoptic and succinct account of the progress made as a result of these and earlier investigations.**

**Understanding MEQs being part of seismology and seismotectonics, all the chapters in this book emphasise this linkage and the book as a whole is both an introduction to classical seismology and seismotectonics of India as it is to the work on MEQs.**

The book comprises seven chapters.

**Chapter 1** projects the application of micro-earthquake network in the background of the classification of earthquakes and the historical development of both seismology and MEQ instrumental network.

**Chapter 2** is an introduction to the seismic wave characteristics that prepares the reader to the mechanism and tectonic setting of MEQs and monitoring them. The chapter outlines earthquake types, magnitude – intensity-energy release relations and hazards, listing world events that caused great damage, a succinct account of the great earthquakes in India, enlisting major events of >7 M or Intensity > VIII; current EQ monitoring stations and currently accepted seismic zonation map of India. The second section of this chapter deals with the types of seismic waves and their characteristics. The chapter presents a useful list of the nomenclature of various seismic phases thus providing a window into the complexities of seismic wave propagation that then provides a large scope to innovate in seismic wave modeling and interpretation in future.

**Chapter 3** provides a lucid introduction to seismometer instrumentation, analogue, mixed and digital recording systems and networks, processing of data and data management, interpretation of the data in relation to earthquake location, computer programmes for location and relocation, seismic tomography, receiver function and seismic waveform inversion and modeling; MEQ magnitude estimation, power law relations, after-shock attenuation and fractal dimensions. The chapter would serve as an introduction to modern seismology, perhaps, more to non-seismologists.

**Chapter 4** provides an introduction to the dynamics of faulting and addresses the classification and the kinematics of faults, the elastic rebound theory and

related aspects of the double-couple hypothesis and the P-wave radiation patterns, fault plane solutions, moment tensor solutions and earthquake mechanisms characteristic of different tectonic environments – the oceanic spreading centres, subduction zones, diffuse plate boundaries and intraplate domains.

**Chapters 5, 6 and 7 present a detailed account of the seismotectonics of the Himalayan – Pamir-Hindukush (H-P-H) Tectonic province, the Assam-Burmese –Andaman tectonic province and adjacent areas and lastly the Peninsular Shield- Sri Lanka Tectonic province.** In each of these chapters, one can find an up-to-date review of the current status of our understanding of the geological features and geophysical characteristics in each of the provinces that helps in understanding the challenges we face in interpreting their seismicity and on going tectonics.

The Chapter on **H-P-H tectonic zone** brings out initially the current models of the lithospheric structure below the region characterised by Collision Tectonics and proceeds to discuss the bearing of several seismotectonic models that have become available through modeling of several recent major earthquakes and the MEQ studies that have followed many of them. Attention is paid to the deep seismicity in the Pamir-Hinukush region, a characteristic feature of this great mountain system, up to depths of 225-250 kms and the seismotectonic perspectives implied in such seismicity. The rest of this chapter provides an illuminating discussion of the lessons learnt from seismological studies, including studies on MEQs, of almost all of the large number and medium scale earthquakes of the Western and Central Himalaya. *The results point to a tectonic heterogeneity along and across the Great Mountain System that defies application of just one or two all encompassing models, steady state or evolutionary, to the whole of the Himalaya. Results of seismic tomography emerging from aftershock seismic monitoring in several earthquakes provide a new dimension to EQ investigations. The chapter concludes with a discussion of Seismic Hazard Potential in this H-P-H tectonic zone.*

The next chapter on **NE India, Myanmar, Bangladesh and Andaman –Sumatra region** brings out the distinctive seismo-tectonic setting arising from a transition from one of collision tectonics in the NE



Himalaya to subduction in the Burmese arc and further south. Studies on regional seismicity in terms of past events have led to a clearer understanding of the Benioff zone below the subducted segment in the south. Results accruing from the temporary and permanent micro-earthquake networks in the region are presented. The seismo-tectonics of the Shillong Plateau and NE region receives pointed attention, tomographic images and fractal dimensions recently developed throwing light on the lithospheric heterogeneities beneath plateau and the fractal nature of the causative faults at different depth ranges. Emerging seismo-tectonic perspectives emphasize how the well defined seismicity in the region at depths between 50 and 100km indicate mantle sources and defy relation to any detachment plane. The rest of the chapter is devoted to discussion of the seismicity of the NE syntaxial zone and subduction zone in the Indo-Burmese arc and proceeds to a detailed presentation of the tectonics and seismicity of the Andaman-Sumatra Arc. This section focusses on the past events and more pointedly on the recent Sumatra Mega Thrust Earthquake of 2004.

The chapter seven presents the characteristics of the seismicity of stable continental region as the Indian Shield and Sri Lanka, the seismicity associated with the Precambrian domains, the Gondwana grabens and the Deccan Volcanic Province and the younger sedimentary basins. In the background of the overall geotectonic setting and the several geophysical parameters, the past seismic activity in the major seismic zones in the Indian Shield are described. MEQ networks in the Koyna region of incessant tremors and quakes and the

swarm activity observed in several parts of the shield have provided insights into source mechanisms. The results of the aftershock investigations in the sites of the 1993 Killari, 1997 Jabalpur EQ, 2000 Idukki EQ, 2001 Bhuj EQ have helped to shed light on intraplate seismic mechanism. Noteworthy are the results of seismic tomography of the Bhuj EQ source area, that has provided images of the  $V_p$ ,  $V_s$  and  $V_p/V_s$  in the source area. This chapter concludes with a brief review of seismicity and tectonic configuration of the Sri Lanka region.

**The need to integrate MEQ studies with general seismological researches imparts to this book a status as a source of introduction to not only to MEQs but seismology and seismo-tectonics in general. One can find here a comprehensive and lucid account of seismicity of a major part of SE Asia shared by a variety of seismogenic environments – Stable continents and Plate Boundaries (collision and subduction zone) and the source mechanisms that are constrained by detailed studies on MEQs. The post –independence Era in India witnessed a thrust given to state of art areas in geophysics and seismology. The standards and quality of seismological studies have undergone a sea change since and this book and its contents stands testimony to the progress achieved. The book is indeed a befitting tribute to the great tradition set in India to seismology, to the great pioneering work of many earlier workers led by the great Oldham in the late 19<sup>th</sup> century. This book will be an asset to all teaching and research institutions in the field of Earth Sciences.**

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