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Imprints of tectonics and magmatism in the south eastern part of the Indian shield: satellite image interpretation

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ABSTRACT
The interface between the Dharwar craton and the southern part of the Eastern Ghats Belt, described here as the Terrane Boundary Shear Zone, is geologically a complex terrane. The zone also hosts many mafic-ultramafic and alkaline plutonic complexes and a recently reported Kanigiri ophiolite mélange. The zone has also been subjected to complex geological processes such as rifting, subduction, accretion and collision between 2.0 Ga and 0.5 Ga. Multi-scale image interpretations has been carried out to identify major structural/ tectonic elements as well as internal magmatic fabric trends of plutonic bodies, followed by detailed geological traverses and structural mapping. The results demonstrate that digitally processed satellite images are much more efficient than the normal satellite images in terms of structural and tectonic interpretations. The study also reveals new mapping results including several dominantly NE-SW, NW-SE and WNW-ESE/ ENE-WSW trending mega- and major- lineaments, consistent with field observations. An attempt is made to correlate genetic and spatial relationship of lineaments with regional tectonics and magmatism.

INTRODUCTION

The south eastern part of the Indian Peninsula is marked by the presence of tectonically contrasting Precambrian geological units. They, from west to east, include the Proterozoic Cuddapah sediments, a tectonic sliver of Nellore greenstone belt, migmatite zone punctuated by a series of plutonic rocks and granites, the southern extension of the Proterozoic Eastern Ghats Mobile Belt (EGMB) and alluvium at the east coast. The zone between the Cuddapah basin and the EGMB is marked by craton-mobile belt interface and is described by several workers (Nagaraju and Chetty, 2005, 2008; Sesha Sai, 2013) as Terrane Boundary Shear Zone (TBSZ) (Fig. 1 inset). Some workers have also described this belt as a suture zone along which many oceanic remnants have been accreted (Dharma Rao et al., 2011; Chetty and Santosh, 2013). The EGMB occurs along the east coast of India for over a length of 1000 km and is well known for its significant linkage with the Rodinia/ Gondwana supercontinental reconstructions (Veevers, 2009; Biswal and Sinha, 2004; Mezger and Cosca, 1999; Ramakrishnan et al., 1998; Rogers et al., 1995; Chetty, 1995). The TBSZ forms a part of southern part of EGMB and hosts a complex tectonomagmatic and metamorphic assemblages (Leelanandam, 1989; Nagaraju and Chetty, 2008; Dharma Rao and Reddy, 2009; Saha, 2011; Dharma Rao, 2011; Sesha Sai, 2013). The kinematics of this interface and its role in the evolution of plutonic complexes were not clearly studied in terms of structure and tectonics. This area provides an excellent opportunity for investigating the significance of crustal scale structures/ lineaments in relation to deformation and magmatism in order to unravel the tectonic history between craton and mobile belt.

The Precambrian terranes in the SE part of the Indian shield preserve important lithostratigraphic records, structural and tectonic history relating to the three major Proterozoic supercontinents – Columbia, Rodinia and Gondwana. The Proterozoic high grade terranes occurring at the southern margins, adjoining the ~3.4 Ga old Dharwar craton (Fig. 1), are of paramount significance and are also relevant to the understanding of the continental tectonics and lithospheric geodynamics. The TBSZ is one such terranes that exposes Precambrian deep continental crust comprising complexly deformed Archaean to Neoproterozoic high grade metamorphic and magmatic assemblages. The zone is also marked by a network of shear zones and a set of

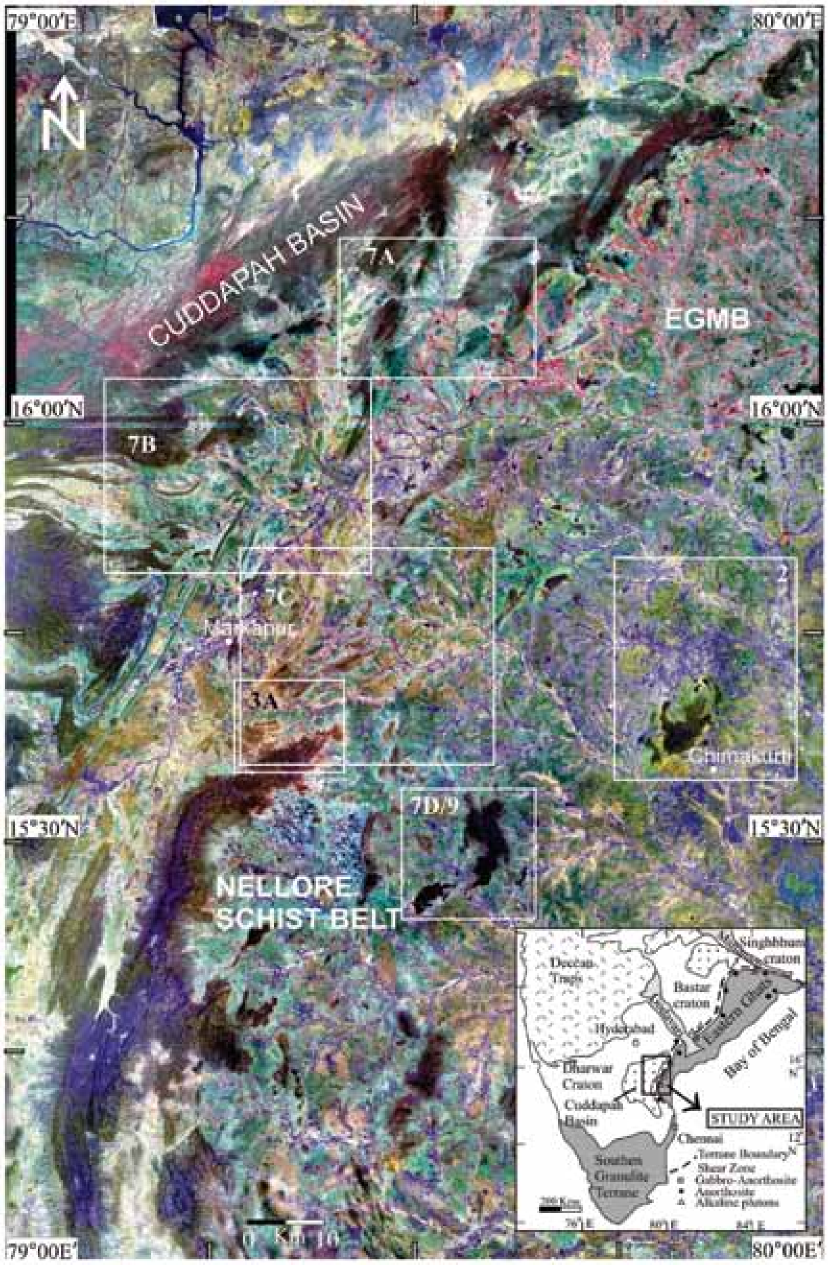

Figure 1. Mosaic of the IRS-1D LISS3+PAN merged digital data of the south easter part of Indian Peninsula on scale 1:250,000 (2 images covering Survey of India (SOI) toposheets nos. 57M and 56P). Boxes with numbers inside refer to the figures that follow. Inset map shows general geology of southern India showing the study area.

younger intrusives. A number of granite plutons of Proterozoic age intrude all along the TBSZ. Their distinct mineralogical association and geochemical characteristics suggest that they are emplaced in a late orogenic to anorogenic tectonic setting (Sesha Sai, 2013).

Remote Sensing is the study of objects by sensing the physical attributes from a distance (Sabins, 1997). It has been increasingly realized that the satellite images and their interpretation form an integral part of all geological/ geophysical investigations, as it provides synoptic coverage and the information from physically inaccessible areas. In particular, satellite images have been widely and successfully used for structural and tectonic investigations in Precambrian high-grade terrains of Indian shield and came out with novel geotectonic concepts, which were not known earlier (Drury et al., 1984; Nash et al., 1986;

Chetty and Murthy, 1993). Remote sensing studies aided by digital image processing (DIP) techniques such as Principal Component Analysis (PCA) and several other image enhancement methods provided encouraging results in geological mapping and structural studies that bear insights into mineral exploration and many tectonic concepts (Gomez et al., 2005; Okada et al., 1996; Ren and Abdelsalam, 2006). The present work involves multi-scale remote sensing lineament/ structural studies with digital image processing approach to understand the relationship between tectonics and magmatism in the area of interest. A comparative study of interpretations between the raw image and digitally processed image has also been made to assess and evaluate the viability of the proposed methodology.

In this contribution, we present the structural architecture of the TBSZ and the adjoining region by attempting multi-scale satellite image interpretations and show that the culminatory Precambrian tectonothermal events shaped the present structural architecture. We also evaluate the available geology from the literature and re-examine the spatial distribution, geometry and kinematics of the shear zones, in conjunction with the recent reports of Precambrian ophiolite suites in the region and evaluate their significance in relation to subduction-accretion-collision tectonics. Our study emphasizes the importance of identifying the large scale structural features from satellite images and their correlation with the regional structural imprints in the rocks of the TBSZ and their utility in understanding the tectonic processes associated with the assembly of the Gondwana supercontinent.

GEOLOGICAL SETTING

The Terrane boundary shear zone (TBSZ), as defined by Nagaraju et al. (2008), occurs between the eastern margin of the Cuddapah basin and the EGMB encompassing the NSB as a tectonic sliver or an accretionary belt. The TBSZ exposes a number of gabbros and granitic plutons of Proterozoic age in association with banded iron formation (Nagaraju and Chetty, 2005). Ophiolite tectonic mélange near Kanigiri was also reported in the area (Dharma Rao and Reddy, 2009).

The study area (60x90 km, Lat 15°00′-16°30′N and Long 79°00′-80°00′E) in south-eastern part of India comprises tectonically contrasting geological terranes, extending in age from Precambrian to Recent. It consists of Paleoproterozoic southern part of Eastern Ghats (termed as Ongole Domain; Dobmeier and Raith, 2003), Marginal Transition Zone (part of Ongole Domain), meta-volcanics of Nellore Schist Belt (NSB) of the Archeaen Dharwar craton and the crescent shaped Proterozoic intra-cratonic Cuddapah supergroup, followed by the TBSZ from east to west, with a Phanerozoic alluvium further east along the East Coast of India (Ramakrishnan et al., 1998). The contact zones of all the terranes are sheared/ faulted (Kaila and Bhatia, 1981; Nagaraju and Chetty, 2008). The TBSZ is perforated by several mafic-ultramafic, syenitic and alkaline granitic plutons ranging in age from ~1650-950 Ma (Prakasam Alkaline Province; Leelanandam, 1989; Prasada Rao et al., 1988; see Vijaya Kumar and Leelanandam, 2008 for sources of age data). These plutonic bodies are conformably aligned with the regional structural trends, i.e., NNE-SSW trend. The tectonic nature of the TBSZ is enigmatic, and several contrasting views like collision/ thrusting (Subrahmanyam, 1978; Singh and Mishra, 2002) to rifting (Leelanandam, 1989; Upadhyay et al., 2006) have been proposed. In the light of recent concepts like DARCs (Deformed Alkaline Rocks and Carbonatites), and the presence of ophiolitic mélanges (Dharma Rao and Reddy, 2009), it is now recognized that the craton-mobile belt interface is a suture zone comprising signatures of Wilson Cycle with several rifting and subduction events during the assembly and break up of Rodinia and Gondwana (Vijay Kumar and Leelanandam, 2008). The major tectonic events in the region can be summarized from the available literature (see Ravikant, 2010; Veevers, 2009; Mukhopadhyay and Basak, 2009; Vijaya Kumar and Leelanandam, 2008; Nanda, 2008; Upadhyay et al., 2006; Dobmeier and Raith, 2003 and Ramakrishnan et al., 1998 for a complete review): (a) Basement ages of about 2800Ma; (b) 2.0 Ga **rifting** (**E1**) - formation of protoliths to NSB meta-volcanics; (c) 1.9-1.8 Ga **convergence** (**E2**) and westward subduction - arc magmatism, enderbitic plutonism, development of back-arc basin and deposition of Cuddapah sediments, followed by UHT metamorphism at 1.65 -1.59 Ga and collision related magmatism; (d) 1.5-1.35 Ga **rifting** (**E3**) - Alkaline magmatism (PAP) as ARCs; (e) 1.25-1.0 Ga **convergence** (**E4**) - Amalgamation of EGMB with the craton, Felsic plutonism, and DARCs, and (f) 0.5 Ga **reactivation of shear zones** (Pan-African signatures are very feeble and are only recorded in Vinukonda and Kanigiri plutons, Dobmeier et al., 2006).

The imprints of structural/tectonic features had been recognized and delineated by interpreting the satellite images with subsequent ground information in the Eastern Ghats Mobile Belt, north of Godavari graben (Prudhviraju and Vaidhyanathan, 1981; Chetty and Murthy, 1994, 1998: Chetty, 2001, 2010) using LANDSAT images and aerial photographs. Detailed structural studies were also carried out in the adjacent Cuddapah basin and the Nellore Schist Belt (Meijerink et al., 1984; Nagaraja Rao et al., 1987; Venkatakrishnan and Dotiwalla, 1987; Saha and Chakraborty, 2003). Our focused and detailed multi-scale image interpretations and their correlation with regional tectonic features reveal the distinct boundaries of different litho units with in the Terrane Boundary Shear Zone (TBSZ) and the adjoining region. Since the plutonic complexes at tectonic boundaries can serve as regional strain markers, the reflections of internal structures within three plutonic bodies intruding the TBSZ viz., Pasupugallu and Chimakurti gabbro-anorthosites; and Kanigiri granite on satellite images, have enabled the authors to take-up a multi-scale structural/lineament analysis to examine and evaluate the relationship between magmatism and regional tectonics.

METHODOLOGY

Image interpretation has been carried out on scales of 1:1 million and 1:250,000 of the study area covering the TBSZ and the regions by utilizing Landsat and Indian Remote Sensing (IRS)-1D LISS-III and PAN merged satellite images. Large scale image interpretation on scale 1:50,000 were also carried out for the selected key areas of by employing IRS-1D LISS-III and PAN merged images (for two layered mafic plutons) and SRTM image for the Kanigiri granitic pluton.

Data sets used

S. No.	Datasets	Toposheet Nos.	Data Type	Scale (resolution)	Source	Mode of Interpretation
1	IRS-1D PAN	56P & 57M	Hard copy transparency	1:250,000 (5.3 m resolution)	NRSA, Hyderabad	Manual by Optical Enlarger
2	Landsat TM	56P & 57M	Hard copy transparency	1:1 million (30 m resolution)	-do-	Manual by Optical Enlarger
3	IRS-1D PAN+ LISS-3	56P & 57M	Raster	1:250,000 (5.3 m resolution)	-do-	Digital Image Processing
4	IRS-1D PAN+ LISS-3	57M/13& 57M/14	Raster	1:50,000 (5.3 m resolution)	-do-	Digital Image Processing
5	SRTM	57M/11	Raster	1:50,000 (90 m resolution)	www2.jpl. nasa.gov	Digital
6	Geology Maps	56P & 57M	Raster	1:250,000	GSI, Hyderabad	For Overlay
7	SOI Topo-sheets	56P,57M, & 57M/11, 13, 14	Raster	1:250,000 & 1:50,000	SOI, Hyderabad	For Geo-referencing

(Abbreviations: IRS - Indian Remote Sensing, NRSA - National Remote Sensing Agency, SRTM - Shuttle Radar Topography Mission, GSI - Geological Survey of India and SOI - Survey of India).

Interpretation of the hard copy transparencies

The prime objective is to view the terrain in a synoptic perspective on different space scales and to decipher planar discontinuities (lithological contacts, lineaments, shear zones, fold forms and structural trends). Further, the area under study is also covered with thick vegetation and the rock exposures are sparse. The hard copies (transparencies) of PAN and Landsat TM images of the study area (SOI toposheets Nos. 57M & 56P) have been interpreted manually with the aid of Optical Enlarger on 1:1 million and 1:250,000 scales, with particular emphasis on major lineaments.

Lineaments can reflect both the exposed as well as the sub-surface fault/ shear zones. Lineaments are very important criteria for understanding major tectonic events and are interpreted using differences/ indifferences of colour, tone, texture, pattern, and association. Regional fold trends were delineated from the images by tracing the trend of the lithounits and gneissic foliations/bedding following the swing along strike. Long, linear or curvilinear belts of distinct topographic and textural expression constituting closely spaced lineaments with well reflected distinct tonal variation on the satellite image were interpreted as shear zones, which were later confirmed by ground checks. Often, circular to elliptical structures representing plutonic bodies were also observed on satellite images due to their variation in shape, tonal variation and differential erosion with the country rocks.

Digital Image Processing

Manipulation and interpretation of digital images with the aid of a computer can be termed as Digital Image Processing (DIP). The digital image fed into the computer is stored as an equation or a series of equations. The results of the computation for each pixel are then stored by the DIP software. DIP carries out several statistical, spatial and spectral operations in the form of matrices and results in a new modified digital image or may it be further manipulated by additional programs. DIP utilizes the image enhancement techniques to increase the visual distinctions between features in a scene in order to effectively display objects in the image. The digital images of the study area (Fig. 1, corresponding SOI toposheets are 57M & part of 56P on scale 1:250,000) and the area selected for large scale interpretation (Fig. 2, corresponding SOI toposheets are 57M/13 & 57M/14 on the scale 1:50,000 for the two layered gabbroic plutons, namely Pasupugallu and Chimakurthi) have been processed with the help of ERDAS Imagine (ver. 9.1) software. For Kanigiri granitic pluton, latest SRTM image was interpreted along with satellite image, as it is of hilly exposed nature.

Processing techniques

The available radiometrically and geometrically corrected images (IRS-1D LISS-3+PAN merged) were combined to prepare mosaics (57M&56P for regional study and 57M/13&57M/14 for large scale study) and were geo-referenced with their corresponding toposheets. The projection used here is polyconic system with the Everest, 1962 datum plane in the northern hemisphere. Subsets of interested areas were made from the two mosaics (N. Lat 15º-16º & E. Long 79º-80º on 1:250,000 scale and N. Lat 15º 30′-16º & E. Long 79º45′-79º55′ on 1:50,000 scale). The following Image Processing and Enhancement Techniques have been applied to the pre-processed images: (i) Raster data scaling, to restrict the stretch of the grey scale so that each pixel shows its original pixel value; (ii) Principal Component Analysis (PCA) to reduce the redundancy in the bands. Linearly stretched PC1 was more useful to highlight the structural trends/ lineaments in the area (Fig. 3 B&E); (iii) Contrast Enhancement Techniques such as image sharpening, finding edge and convolution filtering (5x5 edge detection, 5x5 edge enhancement, 3x3 left diagonal, 3x3 horizontal and vertical filters) were applied (Fig. 3 C&F); (iv) Edge sharpening filters to enhance linear features in different directions present in the image.

Digital processing techniques have greatly enhanced the lineaments and other structural features of the images (Fig. 3 A-F). Linear features and structural trends have been identified on the basis of differences and patterns in colour, tone, texture, abrupt changes in vegetation, long straight stream segments, angular breaks in drainage patterns, land use and moisture patterns, etc. The inferred lineaments related to artefacts, canals and cultural features have been discarded by comparing and checking with the help of toposheets through on-screen swipe and blend options.

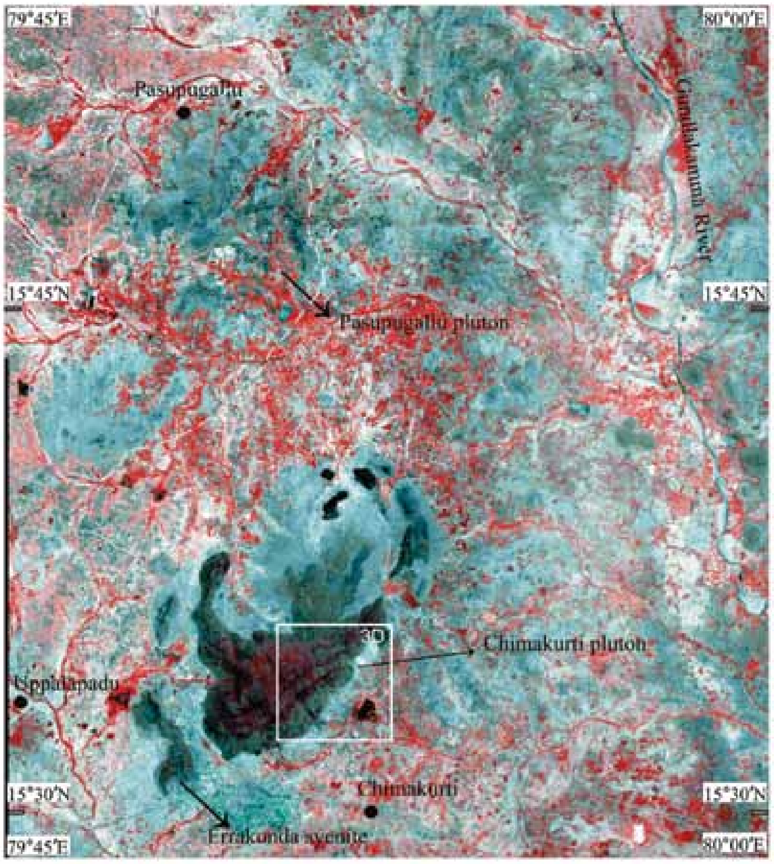

Figure 2. Mosaic of IRS 1D LISS3+PAN images (covering SOI toposheet nos. 57M/13 and 57M/14) of the area selected for detailed interpretation of Pasupugallu (outlined by dashed lines) and Chimakurti mafic plutons on scale 1:50,000. Box refers to Fig. 3D.

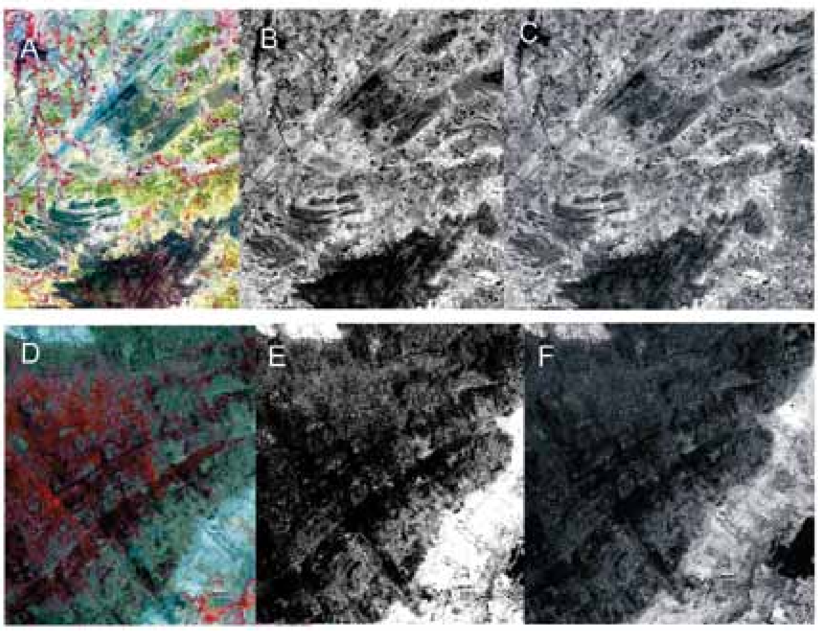

Figure 3. Comparison between the unprocessed digital images (Figs. 3A&D) and the generated PCA1 (Fig. 3B&E) and those (Fig. 3C&F) subjected to further enhancement techniques (edge enhancement, directional filters, etc.). Locations of the blocks are provided in Figs. 1 & 2.

RESULTS OF IMAGE INTERPRETATION

Regional scale mapping (1:1 million and 1:250,000)
The structural interpretation of Landsat TM hard copy transparency (Fig. 4) on scale of 1:1 million reveals several major lineaments, which represent the regional shear zones/ fault zones (surface/ subsurface) and other major tectonic and lithological boundaries. All the lineament trends can broadly be classified as (a) NW-SE, (b) NE-SE to NNE-SSW, and (c) curvilinear with concavity towards east, sub-parallel to the Cuddapah Eastern Margin Thrust (CEMT). The transition zone between the Eastern Ghats and the Dharwar craton is marked by a series of parallel curvilinear major lineaments. The major lineaments (shown with numbers in Fig. 4), which are described as deep crustal fault zones delineated from geophysical surveys (Singh and Mishra, 2002) and were thought to play the significant role in the evolution of Cuddapah basin (Meijerink et al., 1984; Venkatakrishnan and Dotiwalla, 1987). The major lineaments include: (1) Cuddapah Eastern Margin

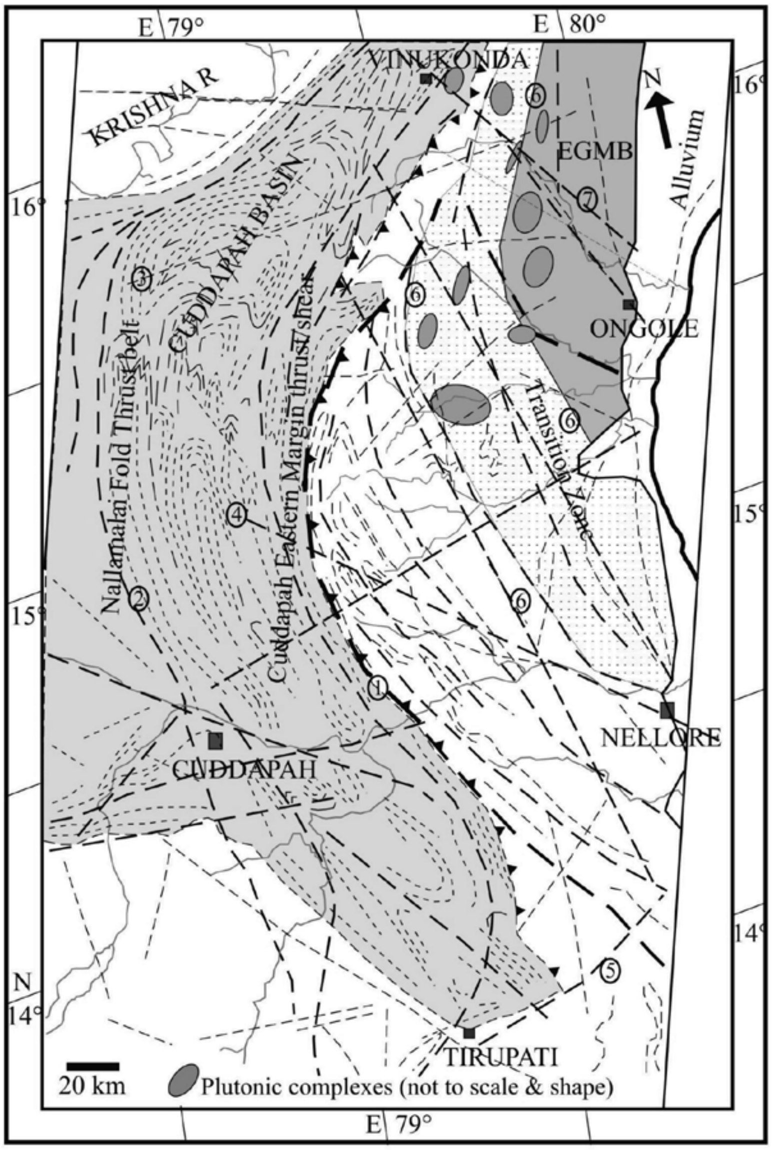

Figure 4. Image interpretation of Landsat TM hardcopy transparency of the study area on 1:1million scale. Several major curvilinear lineaments mimick the Cuddapah Eastern Margin Thrust (CEMT). Some of the major lineaments (shown with numbers) are (1) Cuddapah boundary thrust, (2) Nallamalai/ Rudravaram line, (3) Gani-Kalva fault, (4) Nellore-Badvel fault, (5) Karakambadi fault, (6) Terrane Boundary Shear Zone (TBSZ), and (7) Gundlakamma fault.

Thrust or CEMT (where the older supracrustals of NSB and the basement granitic gneiss were thrusted on to the Nallamalai Group); (2) Nallamalai Thrust/ Rudravaram Line that separates the older Cuddapah and younger Kurnool sediments; (3) NW-SE trending Badvel fault in the southeastern part of the basin; (4) Gani-Kalva Fault, trending NE, at the northern part of the basin; and (5) Karakambadi Fault, trending NE, at the southern tail of the basin. A major curvilinear lineament zone between the CEMT and the western margin of EGMB is well reflected in Satellite images is described here as the Terrane Boundary Shear Zone (TBSZ), which is marked by several major lineaments (No. 6 in Fig. 4) parallel to the CEMT. This shows an arcuate trend from NE-SW in the north, swerving to NW-SE in the southern part of the image.

The plutonic bodies of PAP are conformably restricted to the areas between TBSZ and CEMT and the foliation trends warp around the plutons. Between these lineaments, several large-scale high amplitude isoclinal fold forms with axial planes parallel to the lineaments can be seen in the eastern part of CEMT indicating west-directed compression. The lineaments, trending NW-SE and WNW-SSE that lie parallel to the original Dharwar grain, are also interpreted to represent the younger extensional regime of Gondwana (orientations of Godavari and Mahanadi grabens). These trends are considered as cross-trends (to those of NE-SW trending lineaments in the EGMB and younger succession in Krishna-Godavari basin). One such major lineament lies parallel to the Gundlakamma river, known as

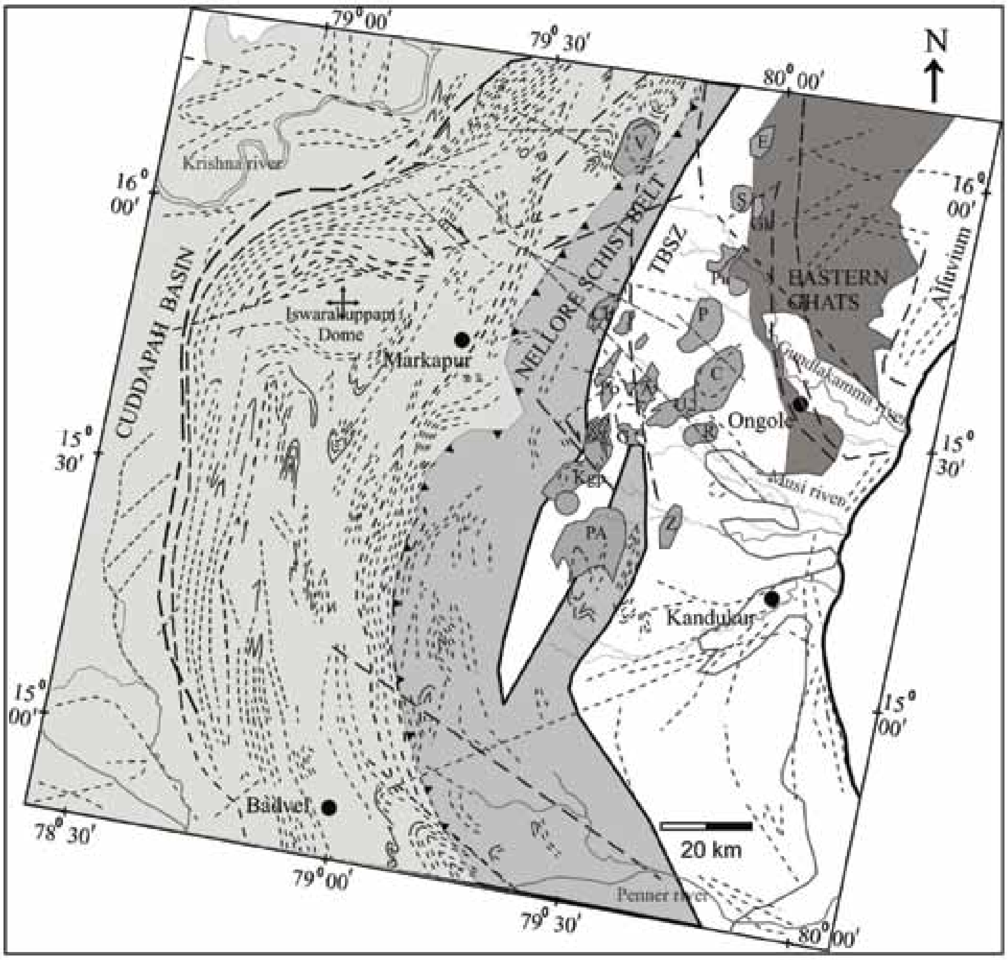

Figure 5. interpretation of IRS-1D PAN hard copy image of the study area on 1:250,000 scale. The transition zone does not display enough information on lineaments and structural trends. Abbreviated plutonic bodies are: syenitic plutons of Elchuru (E), Settupalli (S), Purimetla (Pu), Uppalapadu (U); alkaline granitic bodies at Vinukonda (V), Podili (Po), Kanigiri (Kgp); and gabbro-anorthosite plutons of Gokanakonda (GK), Pasupugallu (P), Chimakurti (C), Chandaluru (Ch), Amudalapalle (A), Ravipadu (R), Pedda Alavalapadu (PA), Zuvvalavaripalle (Z).

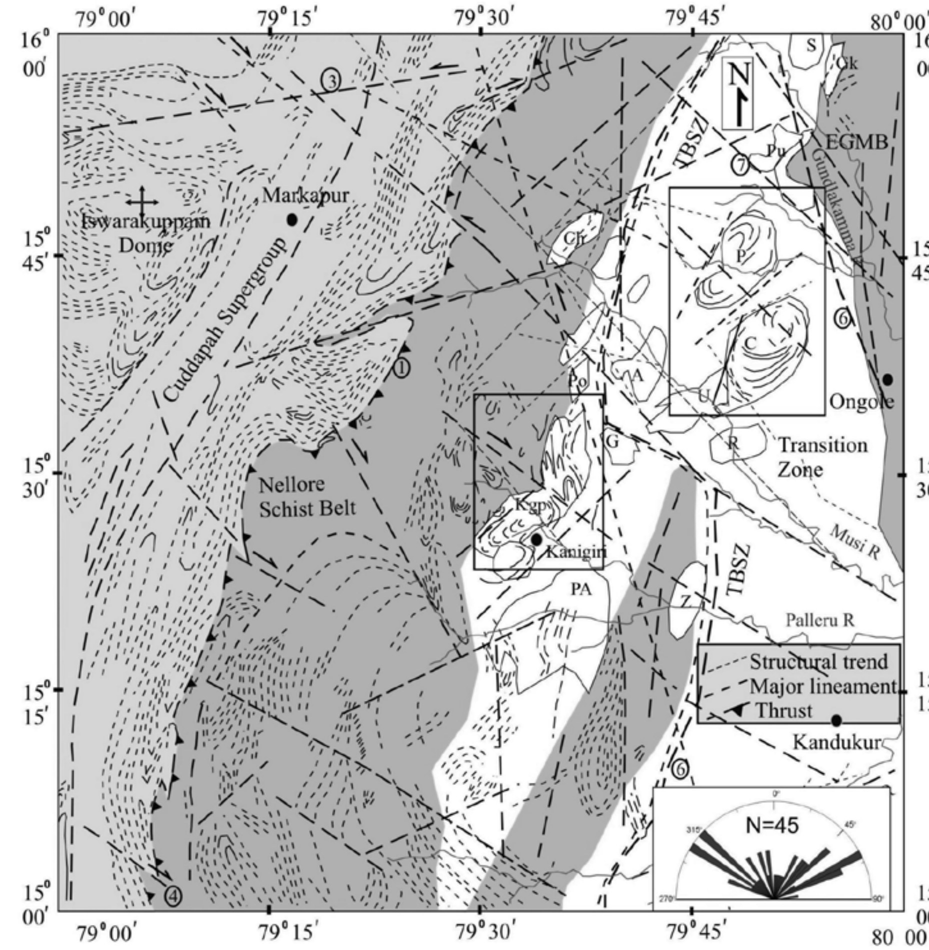

Figure 6. Image interpretation of digitally processed IRS LISS3+PAN merged data (SOI toposheet nos. 56 P and 57M) on 1:250,000 scale. The enhanced data presents much more information in the transition zone along with some plutonic internal fabrics. The inset boxes in the top right corner (Pasupugallu and Chimakurti) & in the centre (Kanigiri) shows the area of plutons selected for detailed study. See Figs. 4 and 5 for the explanation of numbered faults and for the names of the plutons, respectively. Inset: Rose diagram for the major lineaments in the study area.

Gundlakamma Fault (No. 7 in Fig. 4), which extends up to ~200km near Nagarjuna Sagar and beyond traversing the entire northeastern part of Cuddapah basin. The intersection of this fault with several other lineaments at Ongole has been found to be an epicenter of many recurrent mild earthquakes. The drainage system in the study area follows along the NW-SE, ENE-WSE, NNW-SSE lineaments, which can be ascribed to neo-tectonic reactivation of basement faults. The close spatial affinity between the locales of the plutonic bodies and major lineaments suggest the possible control of regional tectonics over the magmatism.

The Landsat-TM and IRS-1D PAN hard copy transparencies were also interpreted on 1:250,000 scale (Fig. 5). Here, the Cuddapah and Kurnool formations clearly exhibit the structural trends, but very few lineaments and structural trends can be identified in the transition zone, west of Eastern Ghats. However, the IRS-1D LISS3+PAN merged digitally processed image has proved relatively more useful for the interpretation, as many new structural trends could be identified in this part. From this image, major faults/ shear zones separating the litho-tectonic units and a few minor lineaments and structural trends in the transition zone could be delineated (Fig. 6). Interestingly, all the lineaments fall into 4 groups (rose diagram in Fig. 6): (i) Curvilinear to arcuate ones swerving from NE-SW in the north to NW-SE in the south, which also

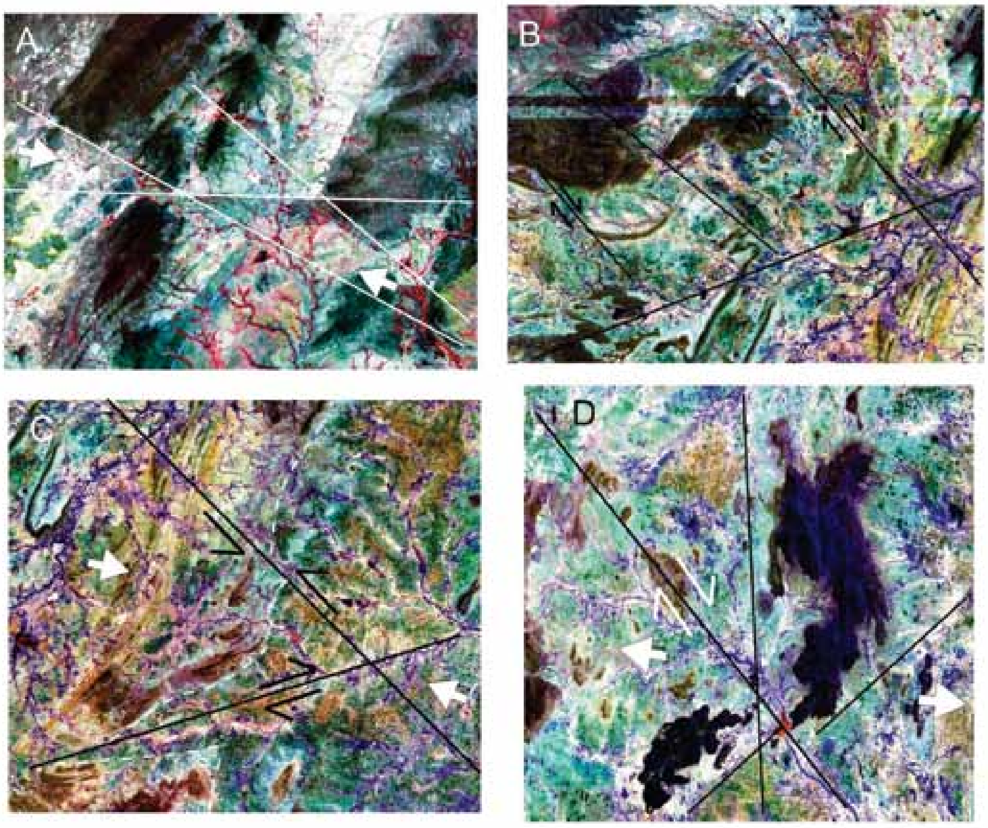

Figure 7. (A) Isoclinal folding of Nallamalai group and the presence of NW-SE & E-W trending conjugate pair of lineaments indicate the NW or West directed principal compressional stress. Streams have been deflected along the lineaments. (B) NW-trending lineaments (right hand shear sense) cross-cut the folded Nallamalai strata along with the NE-trending Gani-Kalva fault. (C) Conjugate pair of lineaments at the Cuddapah margin thrust (dotted lines) and the sense of movements suggest the NW-SE oriented principal compression. (D) Displacement of Kanigiri granite body by the NW-SE and N-S trending conjugate lineaments suggesting E-W extensional stress regime.

represent the major lithotectonic boundaries such as Nallamalai thrust/ Rudravaram line, CEMT and TBSZ; (ii) a set of lineaments trending NW-SE and NNW-SSE; (iii) those trending NE-SW, NNE-SSE; and (iv) those trending ENE-WSW; in the order of their prominence.

The Nallamalai sediments at the eastern part of the Cuddapah basin display spectacular structural, fold trends conformable with the tectonic compression from the east/ south-east (Figs.1 &7 A). These sediments were subjected to low-grade metamorphism and intense deformation, and were described as Nallamalai fold thrust belt (Saha and Chakraborty, 2003). The adjacent 2.7 Ga Nellore schist belt (Ravikant, 2010) is a group of meta-volcanics and meta-sediments displaying similar isoclinal to highly asymmetrical fold forms with their axial planes lying parallel to the tectonic boundaries in the region. Only a few N-S and NE-SW trending structural features could be observed in the EGMB as outcrops are sparse. Several NW-SE and NNW-SSE lineaments were observed to show dextral sense of shear perhaps representing the Dharwar structural grain (Fig.7B&C). Also, some NE-SW trending major lineaments show the dextral sense of shear. Often, some lineaments form conjugate pairs exhibiting opposite shear senses suggesting the E-W/NW-SE oriented compressional and extensional stresses (Fig.7C&D).

The plutonic complexes of PAP display their internal structural fabrics distinctly and are bounded by NE-SW to N-S trending major lineaments. These plutons are further internally traversed by NW-SE, ENE-WSW trending lineaments. The distinct elliptical Pasupugallu and Chimakurti layered mafic complexes exhibit remarkable concentric internal fabrics while the linear Kanigiri-Podalakur granite plutons show highly folded internal fabrics and are

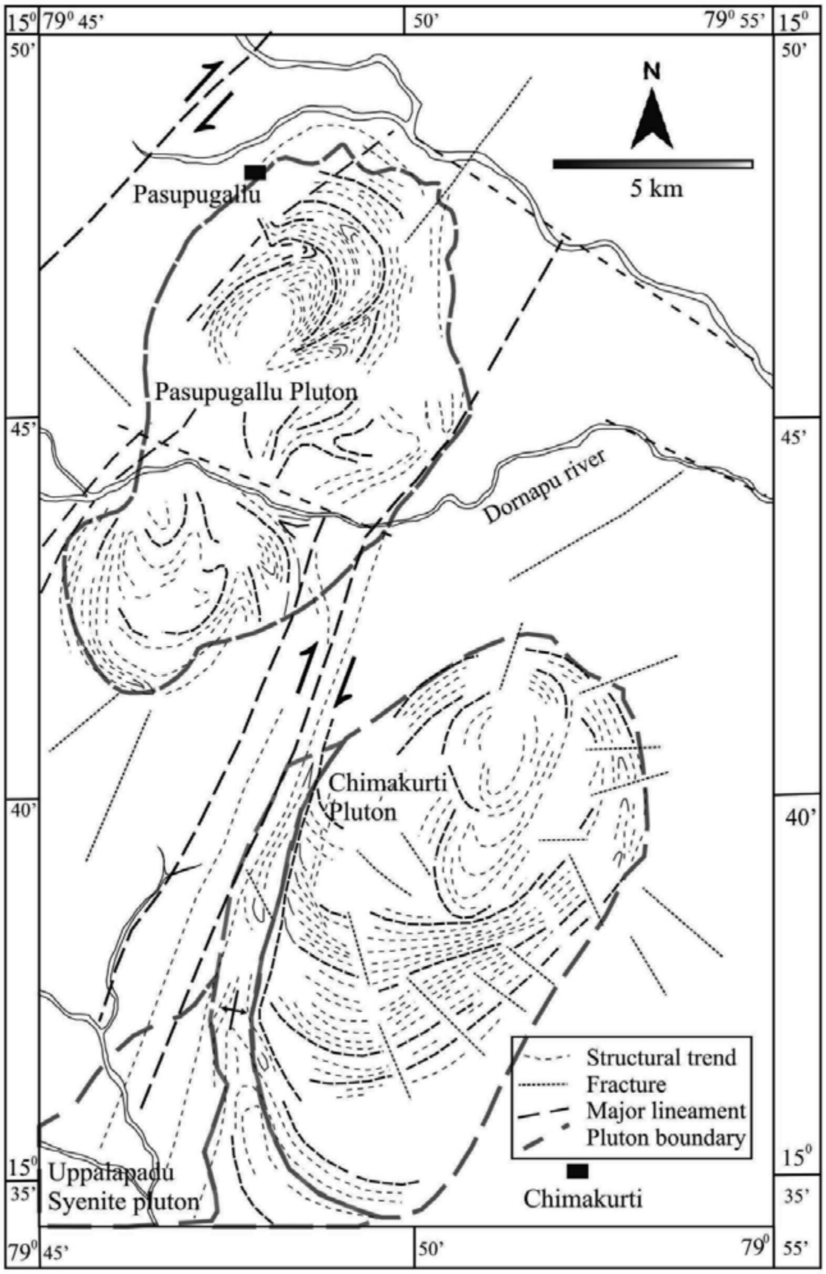

Figure 8. Image interpretation of digitally processed IRS-1D LISS3+PAN merged data of area comprising Pasupugallu and Chimakurti plutonic complexes on 1:50,000 scale.

bounded by two sets of major lineaments trending NE-SW. Some NW-SE trending lineaments cut across the plutons indicating their post-emplacement nature. Based on the proximity with lineaments/shear zones, the alignment and the shape of the plutons, they can be interpreted as the tectonic voids, developed by the regional transpressional kinematics along the TBSZ, which were filled by the magmatic feeders (Nagaraju et al., 2008; Tikoff and Teyssier, 1992).

Large scale mapping of plutonic complexes

Two gabbro-anorthosite layered plutons of Pasupugallu and Chimakurti (N 15°30′-N 16° & E 79°45′-E 79°55′),and one Kanigiri-Podalakur pluton (N 15°26′-N 15°34′ & E 79°30′-E 79° 38′) (see Fig. 1) representing different ages/ tectonic regimes were chosen for the detailed interpretation on 1:50,000 scale in order to study the internal magmatic fabrics and cross-cutting lineaments. Mafic intrusives are elliptical in shape measuring ~13x7 km and ~14x8 km respectively in plan view, whereas granite pluton is a linear body (~18x5km), and all are located in the western margin of Ongole Domain of the Eastern Ghats, Prakasam district, Andhra Pradesh (Prasada Rao et al., 1988). The Pasupugallu gabbro pluton (PGP) consists of gabbro as the dominant rock type along with a few lenses of anorthosite (Nagaraju and Chetty, 2005). The Chimakurti mafic-ultramafic (CMP) pluton is a typical layered mafic complex having gabbro-norite, and gabbro-anrothosite-olivine clinopyroxenite units extending from its margin to centre. Both the plutons are emplaced into the granulite facies rocks and hornblende gneisses of the Eastern Ghats. These are reported to belong to 1634-1698 Ma arc mafic magmatism during E2 event at a convergent margin (Dharma Rao et al., 2012). The digitally processed IRS-1D LISS-3+PAN merged image of the area remarkably displays the boundaries of both the plutons and the internal magmatic structures distinctly (Fig. 8). Kanigiri granite pluton (KGP) is essentially a biotite-granitic body emplaced within sericite-chlorite schists to the west and hornblende gneisses to the east. It might belong to the regional alkaline magmatism of PAP (~1350 Ma, Upadhyay et al., 2006; Dobmeier and Raith, 2003).

The PGP displays two helicoidal, concentric, margin parallel magmatic structural fabrics (Fig. 8) showing consistent correlation with the ground truth from the field observations (Nagaraju and Chetty, 2005). The internal layering seems to have been dragged towards the external major lineaments suggesting possible syntectonic emplacement history. The CMP displays concentric, circular and margin-parallel internal magmatic layering (M1) with remarkable radial fractures indicating that it could be due to magmatic ballooning. The central ultramafic unit is reflected by the light green tone in the original image. The presence of several drag folds in the southwestern part of the pluton indicates differential movement between magma and the host rock substantiating the synchroneity of magmatism and tectonism. The NE-SW trending major lineaments run along the margins of both the plutons. A few NW-SE lineaments traverse across these plutons probably representing post magmatic features (M2). A wide zone of closely spaced lineaments occurs between the two plutons suggest the existence of a shear zone separating the two plutons. Dextral shear sense could be inferred along the shear zone based on the nature of drag folds and the dragging effect of internal magmatic structures. One such dextral shear zone is confirmed along the eastern margin of PGP from the field structural and AMS studies (Nagaraju et al., 2008). It is also possible that the plutons are syntectonically emplaced into the shear zone. The fold forms along the NE-SW axes on the northern and southern tails of the Chimakurti pluton suggests the possible development of dilatational jogs in a transpressional tectonic zone (Fig.10C). Alternatively, the emplacement of plutons in to the hinge zones of regional folds during the development of domal and basinal structures from the combination of field and AMS studies were also suggested (Nagaraju and Chetty, 2006; Nagaraju et al., 2008). All these evidences described above point to the syntectonic emplacement nature of the plutons (Guglielmo, 1993) during a regional deformation event. The NW-SE lineaments seemed to represent post emplacement deformational features and show dextral sense of shear/ faulting. Some other NE-SW lineaments also extend from host rocks to the plutons, which might be due to the reactivation of older shear zones or may be the post-emplacement brittle structures.

In contrast to the mafic plutons, Kanigiri-Podalakur granite pluton (KGP) display linear body with rather internally folded magmatic fabrics, consistent from both image interpretations of both the Landsat (Google Earth) and SRTM images (Fig. 9) as well as from field observations. The long axis of the plutons as well as axial trends of internal folds lies sub-parallel to regional NE-trend of TBSZ. Two major conjugate lineaments trending NE-SW and NNW-SSE along which the internal fabrics have been dragged/ deflected suggesting left-lateral and right lateral kinematic shear senses respectively. The pluton seems to have been bisected by a major NW-SE lineament/ fault in the central part (see Fig.7D), which may be a post-tectonic brittle feature. Several NE-SW trending lineaments in the northern part cross-cut the pluton from host rocks, which were also post-tectonic features indicating the recurrent tectonic activity and deformation of the internal structure of the pluton. The regional extensional stress direction (ENE-WSW) in this part is inferred from the two conjugate lineaments (P, R' shears in a transtensional zone).

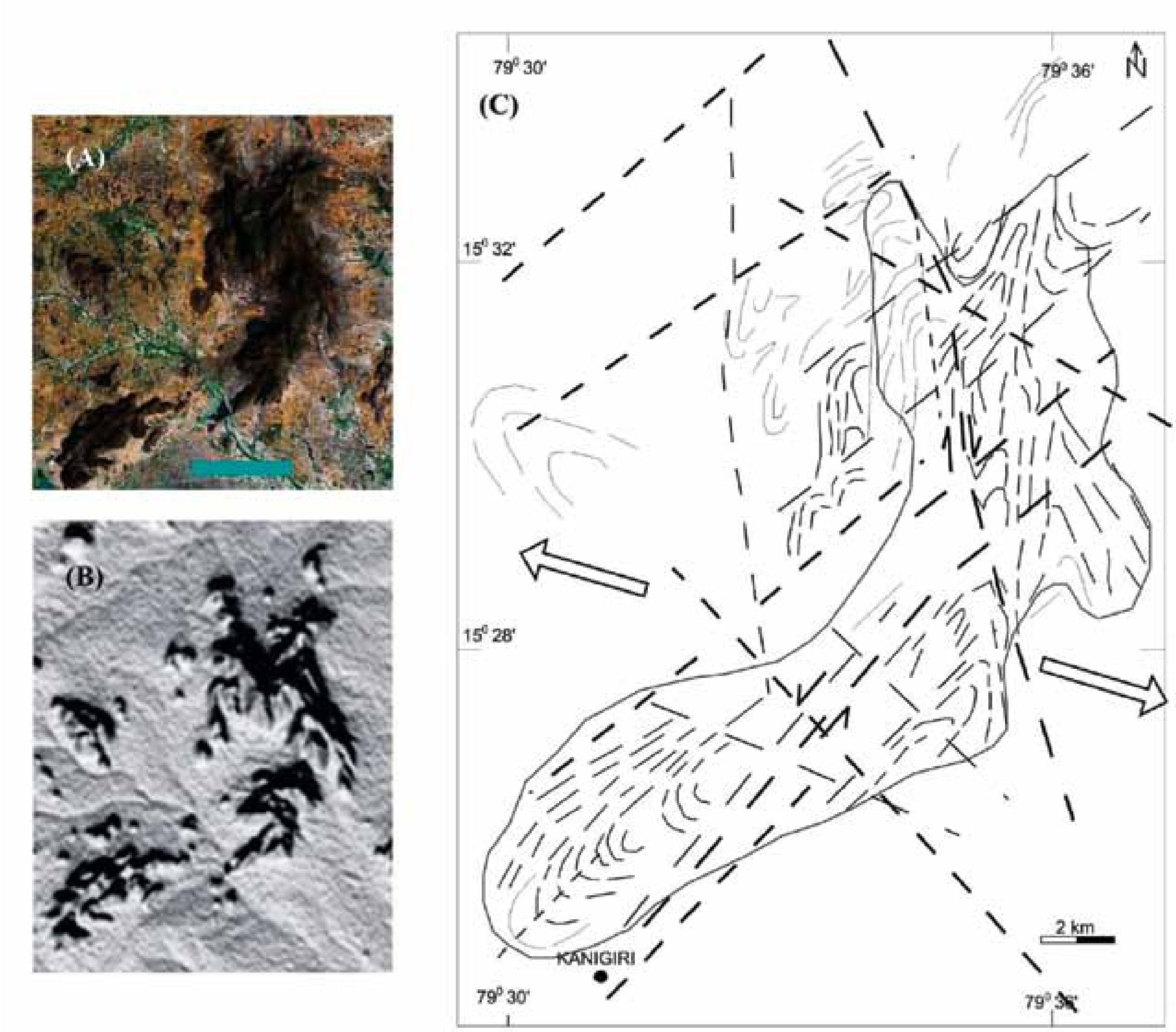

Figure 9. Image interpretation of Kanigiri granite pluton (C) on scale of 1:50,000 along with satellite image (A) and SRTM image (B) of the same. The extensional stress direction (WNW-ESE) is shown with arrows.

DISCUSSION

The correlation of lineaments with the tectonic regimes in a geologically complex terrain, involving several cycles of collision and rifting, is a challenging task. It would be further complicated if the same structures are reactivated/ obliterated associated with inverse tectonics, where normal faults (rift generated) can be switched over to strike-slip or thrust faults during the subsequent younger events. The structural interpretations from multi-scale satellite images and our field observations in conjunction with the available literature show close relationship between tectonism and magmatism from the Terrane Boundary Shear Zone (TBSZ). This is further substantiated by detailed structural analysis of plutons using image interpretations and field observations point to the syntectonic emplacement of plutonic bodies. The Paleostress orientations have been deduced from the stress ellipsoid and acute bisector of conjugate fractures/ faults (Fig. 10 A&B) following Dunne and Hancock (1994).

The curvilinear major shear zones at the litho-tectonic boundaries, which have been reactivated through time with in the TBSZ giving rise to complex structural features that are modeled in terms of Transpressional tectonics (Nagaraju et al., 2008), consistent with the extended transpression model (Ramsay and Huber, 1983; Sylvester, 1988; Tikoff and Saint Blanquat, 1997). This model implies that

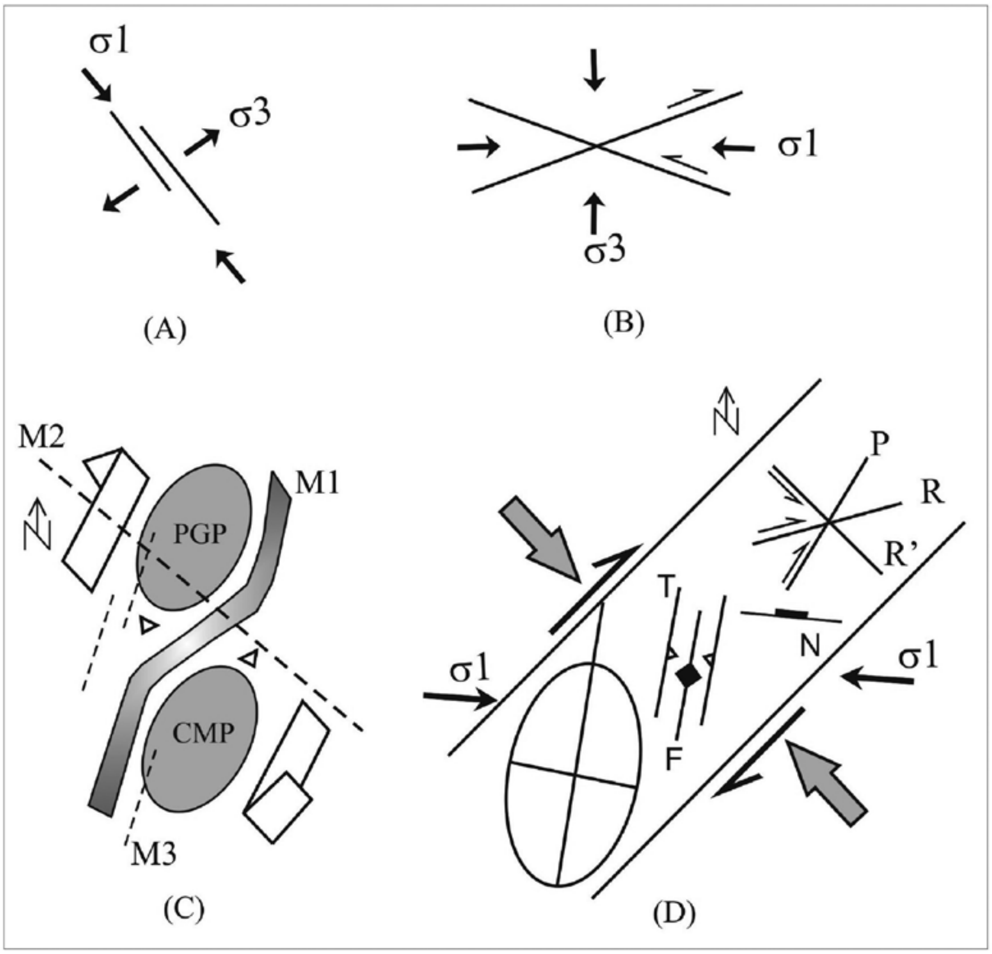

Figure 10. (A) The lineaments related to dikes/extensional fractures are oriented perpendicular the principal extension direction. (B) The Coloumb-Anderson model shows the principal stress axis (compression) is the bisector of the conjugate pair of fractures/shears (Dunne and Hancock, 1994). (C) Cartoon showing the different generations of structures found around the magmatic complex. The triangles at the tails of the plutons are the foliation triple points (see Nagaraju and Chetty, 2005 for field structures). (D) Schematic diagram of transpression (simple shear coupled with boundary perpendicular compression) shows the orientations of P, Riedel (R&R′) shears, thrusts/reverse faults (T), folds (F), normal faults (N) and the finite strain ellipse with respect to the shear zone boundary (modified after Sylvester, 1988 and Fossen and Tikoff, 1998). The M1 structures in fig. 10 (C) can be P/R-shears and the M2 are the reactivated R′, which might have reactivated in a reverse sense (dextral) in the region due to a younger extensional/transtensional event.

several fractures/ shears (P, R, R′), thrusts and folds can be observed within a single zone such as the TBSZ (Fig. 10 D). The major groups of lineaments (NE, N/NNE, NW, E/ ENE), which are interpreted here as mostly ductile and ductile-brittle shear zones with corresponding shear sense, are all in tune with such a tectonic model. It is proposed that all the mafic layered complexes are emplaced along the P and R shears during transpressional event E2 (Fig. 10 C). The NW-trending lineaments (a few with right hand shear sense) cut across all the other structures and plutonic bodies, which can be attributed with the rifting event E3 (possibly reactivated R′ shears of event E2) accompanied by strike-slip tectonics (transtension). Alkaline plutonism may have taken place along the newly reactivated P and R′ shears during this E2 extensional tectonics. The inversion of strain ellipsoid leads to the change in the orientations and sense of the principal axes and the strain was partitioned between P and R shears (tensional and compressional bridges (Tikoff and Teyssier, 1992). Intense folding and the presence of two major conjugate lineaments (NW and NNW) with dextral sense of shear clearly reflect the NW directed compression (E4 convergence). The reactivation/ inversion of E3 rift structures (NW lineaments) might have led to right-hand strike-slip faults at the E4 or the further younger events, along which the major drainage system in the area is aligned. The intersection of NW and N-S trending lineaments (reactivated P and R′ shears) might have triggered the seismicity along the Gundlakamma River at Ongole. Similar set-up can be seen at Kanigiri-Podalakur pluton (Fig. 7 D). It might have been emplaced in a dilatational jog in a NE-trending strike-slip shear zone, which was reactivated later and is evidenced in the form of cross-cutting nature with the plutonic trends (Fig. 9). Our new results and the deformational history suggest that the south eastern part of the Indian shield has witnessed Pacific type orogeny during Proterozoic and the final phases of collision during the amalgamation of Neoproterozoic east Gondwana.

CONCLUSIONS

From our multi-scale remote sensing based structural and tectonic interpretation and field observations, the following conclusions can be arrived at: (i) several digital processing and image enhancing techniques such as Principal Component Analysis directional filters, edge enhancement, etc. are proved to be extremely useful for both regional as well as large-scale structural/lineament mapping of geologically complex terrains. (ii) Tectonic interpretation of multi-scale satellite images have brought out the major lineaments/ shear zones/ faults that separate the distinct lithotectonic domains in the south eastern part of Indian shield. (iii) Our results show a plausible spatial relationship between lineaments with the regional tectonic events and magmatism. (iv) The plutons seemed to have been emplaced along P- and R- shears developed along the NE trending TBSZ during transpressional tectonic regime. (v) Multi-scale structural observations from satellite image interpretation to outcrop scale are found to be essential to have comprehensive tectonic history and our present study indicate that the TBSZ must have been subjected to transpressional tectonics.

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