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Crustal structure and rift architecture across the Krishna–Godavari basin in the central Eastern Continental Margin of India based on analysis of gravity and seismic data

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ABSTRACT

The Krishna–Godavari basin is a rifted passive margin basin that developed orthogonally to the NW–SE trending Pranhita-Godavari graben along the central Eastern Continental Margin of India in response to the continental rifting process and the subsequent seafloor spreading between India and eastern Antarctica during the early Cretaceous period. The 3-D gravity interpretation of both the onshore and offshore sections of the basin integrated with detailed seismic reflection and refraction data provided significant new information about the crustal architecture and the early breakup history of the basin. The gravity-derived crustal models indicate that the crust at the eastern Indian shield margin is 39-41 km thick and thins to as much as 20-23 km at the Ocean Continent Transition (OCT) in the offshore. There is a significant variation in the nature of crust and the configuration along the margin between the three crustal domains encompassing the basin: the Cuddapah basin, Pranhita-Godavari Graben, and the Eastern Ghat Mobile Belt that indicates the lateral segmentation of the margin. A zone of high density (3.0 g/cm³) crustal material at the OCT separates the pure continental and oceanic crusts on either side. The Moho is shallowest along this zone and brought the upper mantle notably close to the surface, which indicates that it could be comprised of Proto-Oceanic Crustal rocks. Furthermore, the present study highlights a major basement structural high in the deep offshore area of the margin. The geophysical signatures over this structure suggest that it is a crustal scale feature that is characterized by intrusive volcanic rocks, comprised of low density crust, and lies close to the OCT towards offshore. Based on the inferred tectonic reconstruction, we believe that this structural high could be a continental fragment that was left behind during the process of breakup between India and the Elan Bank.

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1. Introduction

The East Coast of India is defined by the rifted passive margin that evolved in response to the continental rifting and seafloor spreading processes between India, Antarctica and Australia that occurred during the early Cretaceous period (Powell et al., 1988). It is observed that the Precambrian structural trends, namely, the Godavari and Mahanadi grabens, shear zones and granulite terrains of the Indian shield margin, have close linkages with similar features of the East Antarctica coast (Yoshida et al., 1999). Because of the intrinsic distinctions between different sub-crustal blocks (Radhakrishna, 1989; Lal et al., 2009), the East Coast of India is tectonically and geomorphologically segmented into several peri-cratonic rift basins following the rifting between India and Antarctica, and these basins are the Cauvery, Palar, Krishna–Godavari, Mahanadi and Bengal basins (Fig. 1). Detailed geophysical studies of the East Coast basins (Sastri et al., 1973, 1981; Fuloria et al., 1992; Rangaraju et al., 1993; Prabhakar and Zutshi, 1993; Rao, 2001) revealed NE–SW trending horst-graben structural features in all of the basins formed during rifting.

The Krishna–Godavari (K–G) basin that lies between Visakhapatnam in the north and Nellore in the south (from 14° 30' N and 17° 40' N, including the Pennar river basin) developed along the bite of the East Coast of Peninsular India during the above rifting process (Rao, 2001). The K–G basin is one of the most important petroliferous basins of India (Fig. 1), and it comprises an area of approximately 28,000 km² onshore and 24,000 km²–49,000 km² offshore considering the areas with water depths up to 200 m and 2000 m, respectively (Rangaraju et al., 1993). This basin

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Figure 1. Shaded relief map of the eastern Indian shield margin illustrating the tectonic details of the East Coast of India, the Precambrian geological formations and the disposition of Gondwana rift systems; the Pranhita–Godavari graben (PGG) and the Mahanadi graben (MG) (after Gupta et al., 2001). The inset shows the detailed tectonic elements of the K–G basin (Biswas et al., 1993; Rangaraju et al., 1993). AA' – EE' represent the multi-channel seismic (MCS) profiles in the offshore; the dotted lines (a–d) represent the Deep Seismic Sounding (DSS) profiles in the onshore. P1–P3 are regional transects constructed across the basin by extending the MCS lines into the onshore with a dashed line.

has been classified as a major intra-cratonic rift within the Gondwanaland until the Early Jurassic period (Rao, 2001), and it later transformed into a peri-cratonic rift basin (Biswas et al., 1993). The horst-graben structural configuration and other major basement trends in the onshore and the shallow offshore region of this basin are well-known because of previous geophysical studies and exploratory well drilling data (Sastri et al., 1973; Kumar, 1983; Prabhakar and Zutshi, 1993; Mohinuddin et al., 1993; Rao, 2001; Gupta, 2006; Bastia, 2006). However, the structural continuity in terms of the onshore-offshore tectonic linkages, the rift architecture and the deeper crustal structure has not been comprehensively studied to understand the development of the basin as a whole. Furthermore, the rift-drift history of India and East Antarctica might have left its imprints both at the coast and the adjoining Bay of Bengal (BOB) ocean floor in terms of the structural features in the crust which are not clearly understood. In the present study, we address these issues through an integrated interpretation of the onshore and offshore geophysical data (seismic, gravity and magnetic) across the margin with both 2-D and 3-D constrained potential field modeling. Knowledge of the structural architecture from the onshore to the deep offshore areas of the margin is useful for defining the geometry and structural parameters of the basin and for the delineation of the Continent-Ocean Boundary (COB). These elements contain a record of the early continental rift-drift history and are extremely important for evaluating the deepwater hydrocarbon potential. This study is also expected to provide deeper insight into the variations in structural styles and segmentation of the margin and the role of pre-existing structures during the development of the margin architecture.

2. Regional geotectonic setting

Regional geophysical investigations at the Eastern Continental Margin of India (ECMI) suggest that the margin is a composite with two segments, the northern part (north of 16° N), which has a rifted

margin character, and the southern part, which developed because of shearing during the early stages of continental separation (Subrahmanyam et al., 1999; Chand et al., 2001; Krishna et al., 2009). Different views exist on the timing of the breakup and rifting between India and East Antarctica, and based on magnetic anomaly identifications, it ranges between 132 Ma (Ramana et al., 1994) and ~ 120 Ma (Gopala Rao et al., 1997). Based on the requirement of accommodating the Elan Bank micro-continent (Ingle et al., 2002) that lies on the western margin of the Kerguelen Plateau, Gaina et al. (2003) proposed a two-stage breakup history for the ECMI; first, the India–Antarctica separation during M9°-M2°, and second, the separation of Elan Bank from the present day ECMI at M2, though the times are still not well-constrained. Recent geophysical data of the ECMI favor the above double breakup scenario (Krishna et al., 2009; Radhakrishna et al., 2012) and suggest the possibility of oceanic crust that is younger than M4 in the southern part and younger than M2 in the northern part of the ECMI (Radhakrishna et al., 2012).

The ECMI is characterized by thick sedimentary basins that formed during the rifting, and a portion of these basins prograde into major deltaic basins (Biswas, 1993). The K-G basin is a typical rift basin that initiated during the early Mesozoic period and orthogonally juxtaposed to the NW-SE trending Pranhita-Godavari graben at the central part of the ECMI (Gupta, 2006). This basin is covered by the deltaic and inter-deltaic areas of two major rivers, the Krishna and the Godavari (Biswas, 1993). Both of these rivers and their tributaries feed into the basin and discharge into the deep offshore regions of the BOB (Bastia, 2006). An Archean crystalline basement and the upper Cretaceous sedimentary outcrops define the basin in the northwestern region (Fig. 1), and a significant portion of the onshore area is covered by the Quaternary alluvium (Rao, 2001). The sediment thickness varies from 3 to 6 km in the onshore depressions, and up to 8 km in the offshore regions (Prabhakar and Zutshi, 1993). Two prominent NE-SW trending basement ridges, known as the Bapatla and Tanuku horsts, divide the basin into three major sub-basins: the Krishna, and the West and East Godavari sub-basins (Kumar, 1983; Mohinuddin et al., 1993). Four major NW-SE basement trends/faults (marked as CT1-CT4 in Fig. 1), the Ongole (CT1), Avanigadda (CT2), Chintalapudi (CT3) and Pithapuram (CT4) cross trends, have been identified in the basin (Rao, 1993; Mohinuddin et al., 1993); offshore geophysical data indicates that these cross trends continue into the deepwater areas of the basin (Murthy et al., 1995; Subrahmanyam et al., 2010). The subsurface exploratory well-drilling data indicated the presence of NW-SE trending Gondwana graben sediments in certain parts of the onshore depressions (Mohinuddin et al., 1993).

3. Methodology and data analysis

In the present study, an integrated geological interpretation of various geophysical datasets, such as gravity, magnetic, multi-channel seismic reflection, and refraction data in the onshore and offshore regions of the K-G basin is conducted in terms of the structural setup of the basin. The DNSC08 version of the high-resolution $1' \times 1'$ satellite-derived free-air gravity and bathymetry data (Andersen and Knudsen, 2008) in the offshore and the GTOPO30 topography and Bouguer anomalies (Kumar, 1983) of the onshore region of the basin are considered in the present study. The improved DNSC08 gravity provides better resolution in coastal areas and contains information down to 20 km wavelength (Andersen and Knudsen, 2008). The subsurface basement configuration maps available for the onshore and shelf regions of the basin (Prabhakar and Zutshi, 1993; Rao, 2001; Gupta, 2006) and the time-structure map (in TWT) extending to the top of the basement, which was prepared from a large volume

of offshore seismic data (Bastia et al., 2010a), are used to define the geometry of the sediment body at the margin. To calculate the 3-D gravity effects of the sediments and for modeling the 2-D crustal structure, we utilized seismic velocities obtained from four Deep Seismic Sounding (DSS) profiles at the eastern Indian shield in the K–G basin proper (Kaila et al., 1990; Kaila and Tewari, 1985), and sonobuov refraction data in the northern BOB region (Curray et al., 1982). Furthermore, the DSS profile information has been integrated with the three regional multi-channel seismic (MCS) reflection profiles in the K–G offshore for constructing the crustal transects across the margin and to model the gravity anomalies in terms of the deeper crustal structure. Finally, we proposed a schematic reconstruction model that highlights the breakup history and evolution of the central part of ECMI. The detailed analysis of the above mentioned datasets is presented below with an overall objective of understanding the crustal structure and rift-drift history of the central part of ECMI.

3.1. Topography and gravity

The color coded image of the topography and free-air gravity anomalies at the margin is shown in Figure 2(A and B), respectively. The merged onshore Bouguer gravity and offshore free-air gravity anomalies present an excellent continuity of closures at the coast and their trends into the shelf area. The Bouguer anomalies in the onshore clearly reveal the ridge-depression features of the basement; on this basis, Murty and Ramakrishna (1980) and Kumar (1983) delineated several sub-basins (e.g., Krishna, East Godavari, West Godavari and Pranhita–Godavari grabens) associated with gravity lows separated by ridges (e.g., Tanuku, Bapatla horsts) associated with gravity highs. In the offshore, the free-air gravity anomaly map shows the typical bipolar gravity signature of the shelf-slope region and isolated gravity lows in the inner shelf region. Further seaward into the deep offshore (beyond 3 km depth), a regional free-air gravity low of ~ 30 mGal is observed. From these two maps, we computed the complete Bouguer anomaly map (Fig. 2C) using the Bouguer and terrain corrections by replacing the water layer with an average crustal rock density of 2.80 g/cm³. The resulting map shows a clear inverse relationship with bathymetry, i.e., an increase in the Bouguer anomalies with increasing depths to the seafloor, and reveals two gravity lows $(\sim 20-30 \text{ mGal})$ in the shelf region, one associated with the Kakinada trough, and the other with the Pennar basin. However, the regional free-air gravity low observed in the deep offshore became subdued in the complete Bouguer anomaly map.

3.2. Sediment thickness map

We prepared a compiled depth grid to the basement of the entire K–G basin by merging the basement structure map of the onshore region (Prabhakar and Zutshi, 1993) with the depth converted timestructure (TWT) map (Bastia et al., 2010a) of the offshore region. The TWT map is converted into the depth using few processed regional 2D seismic sections (both time and depth migrated) covering the shelf and the deepwater areas (shown in Fig. 1) of the study region. The time and depth values along these sections resulted in a timedepth parabolic relation $Z = 0.903 + 0.980^*T$ 0.038^*T^2 , which is used to prepare the basement depth map of the K–G offshore. The removal of the bathymetry (Fig. 2A) from the merged basement depth map yielded the sediment thickness map (Fig. 2D) of the entire basin. The sediment thickness map clearly depicts the presence of several ridge-depression features in the onshore and shelf regions and a major depression in the Godavari offshore region that has sediments that are more than 8 km thick. While many of the ridge-depression features are reflected on the



Figure 2. A) Topography map of the K–G basin prepared from the GTOPO30 global relief database in the onshore and the KMS-02 predicted bathymetry data (Andersen and Knudsen, 2008) in the offshore. B) Gravity anomaly map with Bouguer anomalies (adopted from Kumar, 1983) in the onshore and satellite-derived free-air anomalies (Andersen and Knudsen, 2008) in the offshore. C) Complete Bouguer anomaly map of the basin after employing the Bouguer slab correction and terrain correction to the data in (B). D) Sediment thickness map of the K–G basin prepared from vast quantities of industrial seismic data, onshore part compiled from Prabhakar and Zutshi (1993) and offshore part from the present study. Details are discussed in the text.

gravity anomaly map, note that the major depression in the Godavari offshore region is characterized by a subdued gravity field. Further offshore, a localized basement high (2–3 km) on the map is associated with a gravity low.

3.3. Deep seismic imaging of the onshore and offshore areas of the margin

Four DSS profiles that include both refraction and wide angle reflection data (location shown in Fig. 1) available for the K–G basin and the adjoining Cuddapah basin area (a–d in Fig. 3) are utilized for constructing the crustal transects and for constraining the gravity modeling. These profiles are a) Kavali–Parnapalle profile (Kaila et al., 1979; Kaila and Tewari, 1985), b) Alampur–Koniki–Ganapeswaram profile (Kaila and Tewari, 1985), c) Kallur–Polavaram profile (Kaila et al., 1990), d) Paloncha–Narsapur profile (Kaila et al., 1990). The refraction velocities obtained along these profiles resulted in a four-layered velocity structure (Table 1) for the eastern Indian shield crust with a Moho boundary mapped at a depth of 35–39 km in the Cuddapah basin, and 41–43 km in the K–G basin region. The velocity structure below the K–G basin (Kaila et al., 1990) presents an upper

crustal layer with velocities of 5.5-6.2 km/s, two interfaces that have velocities between 6.5-6.6 km/s and 6.7-6.8 km/s below the upper crust, and a velocity jump at the Moho boundary from 6.9 km/s to 8.1 km/s. The crust below the Cuddapah basin is also characterized by a similar velocity structure, except for minor variations in the velocity range for individual layers (Table 1), apart from the presence of a higher velocity layer (>7.2 km/s) in the deeper part of the crust above the Moho boundary. In the K-G basin offshore, we considered five multi-channel seismic reflection profiles (AA' to EE' in Fig. 3, location shown in Fig. 1): three profiles are located across the margin (dip lines AA'-CC') and cover the shelf to deepwater areas, and two of the profiles are located along the margin (strike lines DD' and EE'). The seismic refraction data (Fig. 4A) available for the northern BOB region (Curray et al., 1982) provided further information about the velocity structure of the BOB sediments ranging between 2.0-5.7 km/s and 6.2 km/s for the oceanic basement. The oceanic igneous crust has velocities ranging from 6.2 to 7.5 km/s, where velocities above 7.3 km/s represent the oceanic layer 3. The mapped Moho boundary velocities in the southern part of BOB suggest 8.3-8.5 km/s velocities for the oceanic upper mantle below the BOB.



Figure 3. The seismic profile data used for modeling the gravity anomalies at the margin. The sections in the onshore (a–d) represent the DSS profiles adopted from various previous investigations; a) eastern part of the Kavali–Udipi profile (after Kaila et al., 1979), b) eastern part of Alampur–Koniki–Ganapeswaram profile (after Kaila and Tewari, 1985), c) Kallur–Polavaram profile (after Kaila et al., 1990), d) Polancha–Narsapur profile (after Kaila et al., 1990). The MCS line AA' in the offshore is from Bastia et al. (2010a), and other profiles (BB' – EE') along and across the K–G offshore are from the present study.

Table 1

Crustal seismic velocities and the corresponding density values obtained from the Nafe–Drake relationship for present study region (compiled from Subrahmanyam and Verma, 1981; Kaila and Bhatia, 1981; Kaila et al., 1990). *Indicates that the velocity and the density values of the sedimentary layers increase with depth, as shown in Figure 4, and therefore are not presented here.

Layer			Oceanic crust			
Region	Cuddapah basin & EGMB		Pranhita—Godavari graben		Offshore	
	Velocity range (km/s)	Density (g/cm ³)	Velocity range (km/s)	Density (g/cm ³)	Velocity range (km/s)	Density (g/cm ³)
Sediments	<5.4	*	1.8-5.4	*	1.7-5.0	*
Upper crustal layer	5.5-6.2	2.7	5.5-6.2	2.7	5.0-6.3	2.7
Intermediate crustal layer 1	6.2-6.5	2.75	6.2-6.5	2.75	6.4-6.7	2.9
Intermediate crustal layer 2	_	-	6.5-6.65	2.8	_	-
Deep crustal layer	6.8-6.9	2.85	6.8-6.9	2.85	_	-
Magmatic intrusion	7.2-7.96	3.0	_	-	_	-
Upper mantle	8.1-8.2	3.3	8.1-8.2	3.3	7.9–8.2	3.3

3.4. Densities of the crustal layers and the density-depth relationship for the sediments

From the observed seismic velocities, the density information is obtained using the Nafe–Drake velocity–density relationship, which presents a linear relationship in the velocity ranges between 3.5 km/s to 7.0 km/s and can be used for maximum burial depths of less than 10 km (Nafe and Drake, 1963). Barton (1986) presented the limitations of the above relationship, which result from the

large scatter in the observed densities for a given seismic velocity. We utilized a large number of refraction velocities when assigning an average density for a crustal layer. The densities that were assigned for the different layers in the onshore and their corresponding velocities are as follows: the 2.70 g/cm³ (5.3–6.2 km/s) layer represents the crystalline basement that forms the upper crust, the densities 2.75 g/cm³ (6.3–6.5 km/s) and 2.80 g/cm³ (6.6–6.8 km/s) represent the intermediate crustal layers, and 2.85 g/cm³ (>6.8 km/s) represents the deep crustal layer. In



Figure 4. A) Location of the seismic refraction stations (dots) utilized in the present study. B) Seismic velocity vs. depth plot prepared from the refraction velocities. C) Plot showing the quadratic fit of density contrast with depth obtained with reference to the basement rocks at the margin. D) 3-D sediment gravity effect computed from the above relation in (C) using the sediment thickness map shown in Figure 2D. E) Crustal Bouguer anomaly map obtained after removing the sediment layer effect from Figure 2C.

addition to this gross density layering, the deeper part of crust along the eastern part of the Cuddapah basin above the Moho boundary is characterized by a high density of 3.0 g/cm^3 (>7.2 km/ s) and magmatic intrusions that are related to the Eastern Ghats orogeny (Kaila and Bhatia, 1981). The eastern fringe of the K–G basin is characterized by the presence of rocks typical of the Eastern Ghats Mobile Belt (EGMB), and the density measurements of these rock samples by Subrahmanyam and Verma (1981) indicate average densities ranging between 2.7 and 3.1 g/cm³ with a mean density of 2.85 g/cm³ for the upper crustal layers. For the adjoining oceanic crust, the seismic velocities suggest a two-tier density layering; the oceanic volcanic layer has a density of 2.70 g/cm³ (5.7–6.2 km/s), and the oceanic igneous crust has a density of 2.90 g/cm³ (6.8–7.3 km/s).

In the sedimentary layer, the increase in the seismic velocities with depth results in an exponential variation in the density contrast with respect to the underlying basement because of compaction effects. This variable density contrast with depth in the sedimentary basins can be expressed in terms of a quadratic density function: $\Delta \rho(z) = a_0 + a_1 z + a_2 z^2$, where *z* represents the depth, a_0 represents the extrapolated value of the density contrast at the surface and a_1 and a_2 are the constants of the quadratic function (Bhaskara Rao, 1986). We prepared the density-contrast vs. depth relation for the sediments with respect to a density of 2.80 g/cm³ for the underlying igneous basement by considering the presence of both continental and oceanic crust in the basin. The velocity-depth and the density-contrast depth plots in Figure 4(B and C) indicate a general increase in the seismic velocities and a decrease in the density contrast with increasing depth. The decreasing density contrast with depth (Fig. 4C) is fit with a quadratic density function. Unfortunately, reliable velocity information from the deepest part of the sedimentary layers is not available. Furthermore, Reddy et al. (2002) reported that the velocities of the sediments in the onshore region along the Paloncha-Narsapur profile presented in Kaila et al. (1990) are not well-resolved because they could not map the presence of volcanic formations in the region, which suggests that uncertainties exist in the refraction velocity data. Therefore, large scattering in the velocity values is observed at shallow depths, which could be attributed to the wide variation in the velocities of the unlithified sediments in the offshore regions or the areas covered with thin sediments in the onshore regions. After removing a few distinct outliers, we constructed the density contrast vs. depth relation down to the maximum sediment burial depth of 9 km in the region (Fig. 4C). However, we must keep in mind that in the absence of reliable velocity information on the basin scale, these regional refraction velocity datasets provide the gross velocity structure of the sediments and the underlying crustal rocks from which important insights could be derived.

3.5. Crustal Bouguer anomalies

The Bouguer anomaly reduced to the crust is useful for understanding the deeper subsurface structure and mass heterogeneities after removing the contribution from the water layer and the sediments above the igneous crust. In the present study, the removal of the water layer and the sediments is accomplished by replacing both the water and the sediment layers with an average crustal density of 2.8 g/cm³. The first step involves computing the Bouguer anomaly map, which is already performed (Fig. 2C). During the second step, we computed the sediment gravity effect by considering the sedimentary layer as being a number of juxtaposed regular prismatic bodies that extend down to the basement where the dataset is interpolated onto a regular grid at a grid interval of 5 km. To avoid the edge effects during the gravity calculation, the dataset is extended beyond the study area. The gravity anomaly of these prismatic bodies where the density structure is defined by the quadratic density function (Fig. 4C) is computed at each grid location. The sum of the anomalies at each grid location resulted in the total 3-D gravity effect of the sediments at the margin, which is shown in Figure 4D. The sediment gravity effect is subtracted from the complete Bouguer anomaly map, and the resulting map is called the crustal Bouguer anomaly (CBA) map (Fig. 4E). The crustal Bouguer anomalies primarily reflect the crustal density heterogeneities and undulations in the Moho across the margin. Large positive anomalies indicate the regions where the Moho is shallow and less positive or negative anomalies indicate the regions where the Moho is deeper. The CBA map indicates that the anomalies are largely negative (-60 to -90 mGal) in the shield region and become increasingly positive closer to the basin and further offshore, which generally reflects the isostatic compensation or crustal thinning effects that were manifested by the rising Moho interface across the margin.

Apart from the deeper structural effect, the CBA map will also contain some additional information about the shallow basement structural inhomogeneities/trends; unfortunately, these trends are not clear because of the masking effect of the strong regional gradient due to the crust-mantle interface. To sharpen the shallow anomaly features, we computed the first vertical derivative (FVD) of the crustal Bouguer anomalies. For comparison, we also computed the FVD of the complete Bouguer anomaly map. Both of the FVD maps are shown in Fig. 5(A and B), and as expected, the shallow features have been enhanced in these two maps. In Figure 5A. a clear correlation can now be observed between the different gravity high/low trends with the ridge-depression structural features in the basin that were not distinctly visible in Figure 2C. The map also shows that some of the onshore structure trends continue into the shelf region. However, in Figure 5B, which is free from the sediment gravity effect, the ridge-depression trends are not observed; rather, the major basement trends, such as the Bhadrachalam ridge, the Pithapuram cross trend (CT4) and the Yanam ridge, and the basement faults between the Narsapur depression and Godavari offshore depression are now distinctly visible. In the K-G offshore, a distinct high gravity zone that separates the shelf-slope basement trends closer to the onshore region and the subdued gravity field in the deep offshore region can be clearly identified in Figure 5B. The isostatic residual anomaly map (Fig. 5C) is also prepared by removing the isostatic regional anomaly from the CBA map by assuming that there is Airy isostatic compensation at a compensation depth of 30 km.

3.6. Inferences from the magnetic anomaly map

To further understand the structural features, the global $2' \times 2'$ resolution Earth Magnetic Anomaly Grid (EMAG2) model, which is a compilation of worldwide satellite, aeromagnetic and marine magnetic data (Maus et al., 2009), is used in the present study because it is claimed to be very useful for investigating tectonic/ structural relationships, onshore-offshore tectonic linkages and regional tectonic interpretations. However, to validate this dataset for the present study region, the total field magnetic anomaly map prepared from this dataset is compared with the published aeromagnetic anomaly map of the Peninsular India region (Rajaram et al., 2006) that pertains to the study area (Fig. 6a). We observed that both maps correlate notably well, which may arise from the fact that the EMAG2 model is a collection of huge volumes of worldwide terrestrial magnetic measurements (both aeromagnetic and ship-borne magnetic) (Maus et al., 2009). After gaining confidence that further analysis of the EMAG2 anomaly map may provide certain insights regarding structural information, we



-0.004 -0.003 -0.002 -0.001 0 0.001 0.002 0.003

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Figure 5. The first vertical derivative (FVD) of A) the complete Bouguer anomaly map, B) the crustal Bouguer anomaly map, C) the isostatic residual anomaly map. Details are discussed in the text.

prepared the total field anomaly map and the FVD and tilt derivative (TDR) maps of the EMAG2 dataset (Fig. 6b). The above mentioned edge detection techniques (FVD and TDR) assist in locating the sources on a magnetic anomaly map; while the FVD enhances the shallow sources and is effective in locating the edge of an isolated source, the tilt derivative responds well to both shallow and deeper sources and is useful for identifying the location and extent of the source (Miller and Singh, 1994; Blakely, 1995). From these maps, the boundaries of the Cuddapah basin and the adjoining crystalline rocks of Dharwar and EGMB with the K-G basin could be clearly identified. In the K-G basin, the anomaly trends show that the NW-SE orientation correlates with the Godavari graben and the East Godavari sub-basin, and the NE-SW trends in the west Godavari and the Krishna sub-basins. These trends are observed to be separated or segmented by the NW-SE trending Pithapuram, Chintalapudi and Avanigadda cross trends,

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which indicates that the basement structure has control in defining these anomalies. Note that the surface or subsurface charnockitic rocks, thicker traps below the sediments or supra-crustal rocks are the sources of the magnetic anomalies in the onshore K–G basin (Rajaram et al., 2006). Furthermore, in the offshore area, the change in the magnetic anomaly grain in the shelf-slope region coincides well with a similar change in the gravity anomaly pattern in the FVD of the crustal Bouguer anomaly map (Fig. 5B), which suggests that both of these anomaly trends could be related to change in the crustal characteristics.

3.7. Rift tectonics

In this study, we present eight multi-channel seismic reflection (MCS) profiles and one seismo-geologic section that cover the onshore to the deep offshore areas of the K–G basin to understand



Figure 6. a) Comparison of the EMAG2 total magnetic intensity (TMI) anomalies with the aeromagnetic anomaly map of the study region. b) TMI map of the EMAG2 data in the K–G basin region and its image enhanced maps; the FVD and the tilt derivative (TDR) maps.







further the rift geometry and the deeper basin architecture. Five short seismic profiles across the shelf and slope region (Fig. 7a) reveal various ridges and depressions in the basement. The marginal highs located within the extended crust at \sim 4–5 s TWT suggest considerable post-rift tectonic subsidence of the margin. The seismo-geologic section (Fig. 7b) that is drawn from the well correlations across the margin that cover the onshore to shelf area (after Rao, 1993) shows that there are thick pre-Cretaceous sediments in the onshore depressions and thick Tertiary sediments closer to the offshore. Three deep reflection profiles (dip lines II. III in Fig. 7b and IV in Fig. 7c) in the offshore area have clearly presented the characteristics of rifted and attenuated continental crust: the Mesozoic rift/half-grabens and various sedimentary layers related to different sequence boundaries. Most importantly, in profile IV (Fig. 7c), the continental and oceanic Moho boundaries are mapped as noticeable reflector interfaces. Due to the extreme thinning of the continental crust, the lithospheric mantle appears to have unroofed or exhumed close to the surface and formed a transition zone before the initiation of normal oceanic crust (Nemcok et al., 2012). Deep seismic imaging of the eastern margin of India revealed that this zone represents the Proto-Oceanic Crust (POC) in which the seismic reflection pattern appears to be highly contorted and lacks a distinct seismic signature at the base (Nemcok et al., 2012). Further oceanward, the reflections from the oceanic Moho could be clearly distinguished in the normal oceanic crust area (Fig. 7c). Various aspects of the POC are discussed in detail in the subsequent section of this paper. Figure 8 presents the tectonic/structural features of the basement, which were compiled from previous investigations (Prabhakar and Zutshi, 1993; Biswas, 1993; Choudhuri et al., 2006), as well as from this study, in the onshore and offshore K–G basin.

3.8. Geophysical characteristics of the offshore structural high

Apart from the gravity highs and lows that are associated with the ridge-depression structural features, a prominent localized basement structural high in the deep offshore K–G basin (Fig. 2D) is observed on the free-air anomaly map (Fig. 2B) as a broad circular gravity low. Because the structural high is located seaward of the OCT (Fig. 8) and also in view of its peculiar gravity signature, we decided to further analyze this feature by considering three MCS lines across it (see inset in Fig. 8 for the location). For this purpose, we considered different geophysical datasets, such as the residual geoid anomalies (Krishna et al., 2009) and total field

Figure 7. a) Five short MCS lines (1–5) showing the seismic expression of the rift related ridge-depression features in the shelf-slope region of the K–G offshore. See inset for location of these profiles, b) Seismo-geological section (section I in the inset) showing various depositional sequences in the onshore-offshore part of the Godavari sub-basin (modified after Rao, 1993). Additionally, two regional MCS profiles from the shelf to deepwater area of the margin (II and III in the inset) reveal the rift expression in the basement and various depositional features within the sedimentary layers. c) MCS profile in the southern part of K–G offshore depicting the disposition of continental and oceanic must, as well as the proto-oceanic crust. Both continental and oceanic Moho can be distinctly noticed on this section. Details are discussed in the text.



Figure 8. Map showing the various geological, tectonic and structural features in the onshore and the offshore K–G basin compiled from various sources, as well as from the present study. Geology of the onshore basin was compiled from Ramam and Murthy (1997). Tectonic details in both onshore and offshore are compiled from Prabhakar and Zutshi (1993), Biswas (1993), Venkatarengan and Ray (1993), Choudhuri et al. (2006) and also obtained from the present study. Area marked under square in the deep offshore part of the basin shows the region of basement high and associated gravity low and profiles 1–3 represent seismic lines across this feature.

magnetic anomalies (Ramana et al., 2001) in the area surrounding the structural high along with the gravity anomaly maps (Fig. 9). These maps indicate that the structural high is associated with a residual geoid low, a complex magnetic anomaly and a strong analytical signal high. The anomalies plotted along the three seismic profiles (Fig. 10) suggest that the high is characterized by a mass deficiency zone (low density rocks) and rocks that have strong magnetization.

3.9. 2-D gravity modeling

For the purpose of deriving the crustal structure across the margin, we constructed three regional transects, specifically, P1–P3, by extending the three offshore MCS lines (AA' - CC') into

the onshore up to the crystalline region (see inset Fig. 1). In the onshore region, the profiles were constrained by projecting the regional DSS sections (Fig. 3), and wherever necessary, the basement depth information is considered from the sediment thickness map. The gravity anomalies from the CBA grid (Fig. 4E) were projected along these three profiles for performing the 2-D gravity modeling. The anomalies along the three profiles show a strong regional gradient closer to the offshore region. The gravity modeling is performed using the GM-SYS software and is constrained by crustal layering and the crustal velocity structure (the corresponding density values in Table 1) of the continental crust at the coast. The models identified the geometry of the thinned rifted continental crust and the transition to oceanic crust at the margin (Fig. 11). The higher densities obtained for the EGMB rocks (transect



Figure 9. Geophysical characteristics observed over the offshore basement high region shown in Figure 8. A) Shows profiles 1–3 plotted on the basement depth map. Profiles 1 and 2 are from the present study, while profile 3 is part of MAN-01 section (Pateria et al., 1992). B) Free-air gravity map. C) Complete Bouguer anomaly map. D) Residual geoid low (Krishna et al., 2009). E) Total field magnetic anomaly map (Ramana et al., 2001). F) Analytical signal amplitude map derived from (E).

P3) in the region (Subrahmanyam and Verma, 1981), and the two layered density structure for the oceanic crust were incorporated in the gravity modeling.

4. Discussion

4.1. Crustal architecture

The seismically constrained gravity models that were presented above provided new information about the regional variations in the crustal structure below the K-G basin. The models indicate that the crust at the eastern Indian shield margin is 39-41 km thick. and thins to nearly 20-23 km at the Ocean Continent Transition (OCT) in the offshore area. A sudden rise in the Moho, which is correlated with a significant change in the gradient of the CBA anomaly, is observed. From the crustal models, we also observed that the disposition of crust-mantle interface does not exhibit any spatial relation with the present day coast along the basin. The model along P2 suggests that the crustal structure below the Pranhita-Godavari graben is normal compared to the shield crust, and gradually thins closer to the offshore because of rifting. The modeled structure of the continental crust along the three transects reveals that the nature of crust and its configuration are distinctly different in the three crustal domains that encompass the K-G basin, including the Cuddapah basin (P1) in the west, the Pranhita-Godavari graben (P2) in the center, and the EGMB (P3) in the east. Odegard (2005) suggested that the weakness zones in the continental crust will segment the developing basins by propagating cracks into the lithosphere at angles that are oblique to the spreading. The process oriented modeling of the gravity anomalies across the basin indicate a regionally stronger lithosphere (Te = 30 km) below the K–G basin during rifting (Radhakrishna et al., 2000). Note that the structural and lithosphere strength variations along the margin will influence the development of the rift system, control the breakup process and may eventually lead to segmentation of the margin.

In the offshore part of the basin, the gravity and magnetic data analysis (Figs. 5 and 6) reveal a zone of gravity high and a complex magnetic anomaly signature along the margin. The shelf-slope area landward of this zone shows the basement structural grain of rifted continental crust in both the maps, whereas seaward of this zone, such sharp variation is not observed, and the anomalies smoothly merge. Recently, Nemcok et al., 2012 reported the presence of POC rocks all along the ECMI based on high-resolution seismic reflection imaging. According to these authors, the width of the POC varies in different segments of the margin, and the width is controlled by breakup related tectonics. We compared the authors reported POC corridor with the zone that has distinct gravity and a magnetic signature that we indicated in the K-G offshore area (Figs. 5 and 6). While the boundary between the continental crust and the POC correlates well with the gravity high zone we identified, the boundary between the POC and the oceanic crust located further offshore do not show any marked variation in gravity. It should be kept in mind that the POC rocks identified from the seismic signature require sufficient density/susceptibility contrast (depending on the tectonic setting) to be identified using



Figure 10. Seismic sections (1–3) across the basement high structure in the K–G offshore along with the observed geophysical characteristics.

potential field data. The gravity models (Fig. 11) indicate that the POC rocks are characterized by higher density crustal rocks (3.0 g/cm^3) , and the seismic reflection pattern of one well-resolved section (Fig. 7c) confirmed that Moho is very shallow and brought the upper mantle close to the surface in this zone. Several earlier investigators have interpreted the characteristics of POC rocks in world's passive margins (Rosendahl et al., 1992; Meyers et al., 1996; Whitmarsh et al., 1996; Wilson et al., 2003) and suggested different mechanisms for the POC formation, which explains the seismic signatures or structure. In the offshore region off the west coast of Africa along the north Gabon margin, Meyers et al. (1996) interpreted the POC as being comprised of a combination of dislocated and dike intruded continental blocks (slivers of rifted continental crust), underplated mafic magma, thick volcanic accumulations, unroofed mantle, and sediments that eroded from the uplifted rift flanks, and their disposition was controlled by the regional fracture zone trend. The splitting of the POC body into several segments by the fracture zones was also observed by Wilson et al. (2003) in the offshore region of equatorial Guinea, West Africa; however, these authors proposed different mechanisms for the POC formation at the margin: i) emplacement of the serpentinized upper mantle by the mantle unroofing along the detachment surfaces, or due to oblique slip on transform faults, ii) emplacement of the serpentinized peridotites due to the intense faulting of the anomalous oceanic crust. The density values for the POC crust obtained by Wilson et al. (2003) range from 3.0 to 3.1 g/ cm^3 for the serpentinized peridotites to 2.85 g/cm³ for the anomalous oceanic crust. The above discussion indicates diversities or large variations in the crustal type and the mechanisms for the emplacement of the POC, which may depend on the tectonomagmatic history of individual margin segments during the breakup. Whereas the MCS line IV (Fig. 7c) along the transect P1 presents signatures of an unroofed or exhumed upper mantle, the interpreted POC rocks along the ECMI by Nemcok et al. (2012) indicate that they are composed of slivers of lower crust and unroofed mantle that formed during the rift-drift transition.

4.2. Inferences on the rifting history and basin evolution

It is well-known that the ECMI is composed of northern rifted and southern sheared segments (Subrahmanyam et al., 1999) that are characterized by two stages of continental breakup events; an initial breakup between the southern part of the ECMI with the western Enderby Basin (shearing followed by oblique rifting) when the seafloor spreading (during $M9^\circ-M2^\circ)$ occurred between the Elan Bank and the eastern Enderby Land, and the second breakup between the northern part of the ECMI and the Elan Bank microcontinent (normal rifting) from a northward ridge jump at M2 (Gaina et al., 2007). Recent geophysical studies along the ECMI favor the above mentioned double breakup scenario (Krishna et al., 2009; Radhakrishna et al., 2012) and suggest the possibility of oceanic crust that are younger than M4 in the southern part and younger than M2 in the northern part of the ECMI (Radhakrishna et al., 2012). In the pre-breakup scenario, the Elan Bank is juxtaposed to the EGMB rocks (Fig. 12A) at the central part of ECMI, and the subsequent breakup events stated above (Fig. 12B and C) finally resulted in the development of present-day structural features (Fig. 12D) in the K–G basin in the overall rift-shear setting.

It is relevant to observe the presence of NW–SE trending Pranhita-Godavari graben (PGG) in the central part of the ECMI during the pre-breakup scenario (Fig. 12A). Based on the faulted cross trends mapped from the aeromagnetic data of Enderby Land,



Figure 11. Gravity-derived crustal models for the three regional transects (P1–P3) constructed across the K–G basin. OCT–Ocean Continent Transition, POC–Proto-Oceanic Crust, TR–Tanuku Ridge, GD–Gudivada depression, BR–Bapatla Ridge, UC–Upper crust, CB–Cuddapah basin, EGMB–Eastern Ghat Mobile Belt. Along transect P2, two alternative interpretations are shown in the box (A) and (B). Details are discussed in the text.

Fedorov et al. (1982) suggested the continuation of PGG into Antarctica. It is also known, based on the geological evidence, that both the Godavari and Mahanadi grabens had continuity with the rift-like structures in the Enderby Land and the Lambert rift, respectively (Acharyya, 2000). The northwest-flowing drainage pattern in the late Carboniferous - early Jurassic continental Gondwana sediments of PGG indicates that the source is away from the East Coast of India (Lakshminarayana, 2002) in Antarctica. The subsurface well drilling information and the seismic data indicate the extension of the PGG below the onshore K-G basin (Mohinuddin et al., 1993; Rao, 2001) and the presence of lower and middle Gondwana sediments that rest directly over the Precambrian basement in the offshore Godavari region (Gupta et al., 2001). The subsurface extension of PGG further offshore was previously inferred from the magnetic anomaly trends (Murthy et al., 1995; Rajaram et al., 2000). All these observations indicate the presence of a subsided crust that is characterized by the pre-rift Gondwana basin at the central part of the East Coast of India during the unified continents. Gupta (2006) suggested that during the continental fragmentation, a major NE-SW Jurassic rift basin was created orthogonal to the PGG trend, which accommodated thick late Jurassic sediments. Sarkar et al. (1996) reported late Jurassic – early Cretaceous volcanism in the region where both the structures overlap. During the first breakup event between the southern segment of the ECMI and the Enderby Land (Fig. 12B), the crust in the region of unified India and Elan Bank must have encountered additional thinning and creation of rifts, which ultimately became the zone of future separation. We believe that the Kakinada Trough, which is a half-graben parallel to the coast (Gupta et al., 2001), may be part of this thinned rifted crust. This additional thinning of the crust subsequently became a favorable breakup zone, which occurred because of a northward ridge jump (Gaina et al., 2007) and resulted in the separation of the Elan Bank from India at M2. According to Müller et al. (2001), the proximity of a plume can result in the weakening of zones further inboard from the spreading axis and can eventually force a ridge jump. The proximity of the Kerguelen plume to the ECMI during the breakup period (Coffin et al., 2002) would support the above ridge jump. While the four major cross trends assisted in segmenting and shaping the sediment filled depressions in the K-G basin (Fig. 12C), the Chintalapudi (CT3) and the Pithapuram (CT4) cross trends (Fig. 1), which are the two bounding faults of the PGG (Rao, 2001), continue into the deepwater regions of the margin (Murthy et al., 1995) and created a major accommodation space in the Godavari offshore (Fig. 12C). Subsequently, this region became a major depocenter of the thick Tertiary sedimentary deposition zone.

4.2.1. Offshore structural high – continental fragment or volcanic emplacement?

The invoked crustal model (model P2 in Fig. 11) that passes over the offshore structural high, which is associated with a gravity low, could be modeled as either continental or oceanic crust that have



Figure 12. Schematic representations of the rifting history and the double breakup events between the East Coast of India, Elan Bank and the Eastern Antarctica, and the development of the K–G basin. A) Pre-breakup scenario just before M9 (~130 Ma) showing the sense of future breakup. Area shown in rectangle is already under subsided condition, due to the pre-existing NW-SE trending Pranhita–Godavari graben (PGG) and NE–SW trending Jurassic rift systems developed along the coast. B) Breakup of East Antarctica with the southern part of East Coast of India led to the development of oblique fracture zone trends and generation of late Mesozoic (younger to M4) crust at the margin. Formation of basement highs during the early breakup is indicated as inferred by Krishna et al. (2009). Significant thinning of the crust took place during this time between India and the Elan Bank. C) Ridge jump at M2 gave rise to splitting of Elan Bank from India. Instabilities in spreading segments caused a small portion of the Elan Bank to be left behind with the Indian plate. K–G basin was taking shape, the coastal cross trends helped to further segment the basin. The two cross trends along the PGG created a major accommodation space in the Godavari offshore. D) the K–G basin with its present geological features. SCT–Southern Granulite Terrain, EGMB–Eastern Ghat Mobile Belt, MG–Mahanadi Graben, MR–Mac. Robertson Land, PB–Prydz Bay, LR–Lambert Rift, RG–Robert Glacier, NC–Napier Complex, RC–Rayner Complex, PCM–Prince Charles Mountains.

volcanic rocks emplaced on the surface. The inference of volcanic rocks on the surface of this structure is based on the recent interpretation of high-resolution seismic, gravity and magnetic data that was acquired in the periphery of the regional gravity low by Protacio et al. (2011), who suggested the presence of volcanic intrusive rocks that formed the basement in the region. Many previous investigators have interpreted the magnetic anomaly over this structure in terms of volcanic intrusive rocks/submerged volcano and ascribed its genesis to the hotspot-related volcanism (Venkateswarlu et al., 1992a,b; Murthy et al., 1995). The dimension of the structural high, its associated gravity or residual geoid low, and the magnetic signature (Fig. 9) suggest that it is a crustal scale feature comprised of low density crust that is characterized by intrusive volcanic rocks. This feature lies close to the POC boundary closer to the offshore region (Fig. 5). Krishna et al. (2009) identified five such isolated basement highs along the southern part of ECMI, which are orthogonally juxtaposed between their inferred NW-SE trending fracture zones that formed during the initial breakup. According to the authors, the rises of these structures represent either fossil ridge segments that became extinct during the early evolution or related to the later volcanic activity of the 85° E ridge. However, it can be observed from the gravity and residual geoid anomaly maps (Fig. 3 and Fig. 4a, Krishna et al., 2009) of the BOB that the structural high of the offshore K–G basin is considerably larger in spatial extent and presents a conspicuous gravity/geoid low compared to other basement rises described by the maps. Because gravity interpretation is equivocal and is not capable of resolving the nature of the crust below the structural high, we draw some indirect inferences/evidences from the breakup history of the ECMI to address this issue. Based on the inferred breakup history (Fig. 12), we believe that the structural high in the offshore K-G basin is related to the second breakup event between India and the Elan Bank (Fig. 12C), whereas the other basement rises further to the south could be related to the initial spreading episode (Fig. 12B). As previously stated, this second breakup event that separated the Elan Bank micro-continent from India is due to a northward ridge jump that occurred because of the instabilities in the spreading segments caused by the proximal Kerguelen plume (Gaina et al., 2007). During this process, it may have been possible for a small portion of the continental Elan Bank to have been chipped off, thereby leaving a minor fragment of continental crust that remained attached to the Indian plate in its present position

(Fig. 12C). Such a fragmentation is possible because the western portion of the Elan Bank is associated with the pre-existing rift structures of the NW-SE trending PGG that continue into Antarctica (Fig. 12B). The emplaced volcanic rocks observed on the structure might be related to a volcano that erupted either during the creation of POC or during the post-breakup times. Therefore, one conclusion is that the structural high is a continental fragment that was left behind during the breakup process between India and the Elan Bank. Alternatively, the structure could be described as a thicker oceanic crust that formed during the initial spreading in the K–G offshore. The accretion of thicker oceanic crust is only possible if a highly magmatic spreading segment exists at that location; however, such large-scale isolated magmatism is difficult to explain because the entire rift related structures are well preserved in this part of the margin. This scenario is considerably different from the northern part of ECMI (Mahanadi offshore) in the vicinity of 85° E Ridge, where intense post-breakup volcanism had masked many of the rift related structural features (Bastia et al., 2010b). In the absence of any further constraints, we are inclined to believe that the structural high could be a continental fragment that was separated during the early breakup history at the margin. Detailed seismic refraction data and deep drilling data are required for a better understanding of the structure and to resolve this issue.

5. Conclusions

The combined analysis of gravity and seismic data along the central part of the ECMI provided valuable insights about the crustal architecture and early breakup history of the K–G basin at the margin. Several key results of the study are summarized below:

- Gravity-derived crustal models indicate that the crust at the eastern Indian shield margin is 39–41 km thick and thins to as little as 20–23 km at the Ocean Continent Transition (OCT) in the offshore region.
- Significant changes in the nature of crust and the configuration between the three regions that encompass the K–G basin, including the Cuddapah basin, Pranhita–Godavari Graben, and the EGMB are observed. We believe that these variations along the margin influenced the development of the rift system, control the breakup process and eventually resulted in lateral segmentation of the margin.
- The crustal models also define a zone of high density (3.0 g/ cm³) crustal material that is composed of POC rocks that separate the pure continental and oceanic crusts on either side. The Moho is shallowest along this zone and brought the upper mantle notably close to the surface.
- The analysis of geophysical data over the basement structural high indicates that it is a crustal scale feature that is characterized by intrusive volcanic rocks, is comprised of low-density crust, and lies close to the OCT in the offshore. Based on the inferred tectonic reconstruction, we believe that the structural high could be a continental fragment that was left behind during the breakup process between India and the Elan Bank.

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