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Thrust fault reflections on wide-angle seismics: Modeling by a new approach and implications to Neoproterozoic collision

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Abstract

Collisional events contemporaneous to the global Grenvillian (~1.1 Ga) and the East African (~550 Ma) orogens created a major fold and thrust belt system in the south Indian shield. The Cuddapah basin Eastern Boundary Thrust (CEBT), a significant part of this system, is believed to have evolved by fragmentation and amalgamation of continental blocks in this region. The Cuddapah basin in the eastern Dharwar craton of south India has a long Paleo-Neoproterozoic geological history. Deep seismic near-vertical reflection profiling is the most successful geophysical technique utilized to delineate such complex crustal structures of the orogens. Here we utilize observations on a refraction /wide-angle reflection profile for the first time, to delineate the structure of the CEBT. We developed a novel modeling approach for this purpose utilizing the **'localized phantom horizons'** consistent with the limited-extent discrete reflector segments of the continental crust in the region. A detailed velocity model and geometry of the structure inferred here, by synthetic seismograms modeling of unequivocal seismic reflections, provide clues on the evolution of the CEBT. Another thrust, the Eastern Ghats Thrust (EGT), related to the Eastern Ghats orogen, contemporaneous with the Columbia supercontinent is also identified. Integrating these modeling results, inferred velocity structure, observed steep gradient bipolar gravity anomaly and other geological data, we interpret the CEBT as a collisional suture juxtaposing the Cuddapah basin and the Eastern Ghats mobile belt.

Keywords: Continental crust, Cuddapah basin - south India, Seismic Wide-angle Reflections, Localized phantom horizons modeling approach, Collisional Suture

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Short Summary:

A novel modeling approach of crustal seismics is developed for deep crustal structure and velocity model using **localized phantom horizons**. We model two boundary thrusts at margins of Cuddapah basin and Eastern Ghats Belt formed over the Indian shield during the Rodinia and Columbia supercontinental episodes (1.1Ga and 1.8Ga).The results are significant to continental evolution. Imprints of collisional orogeny revealed as two thrust faults on the margins of the structures involved are modelled.

1. Introduction

Subduction, collision and suturing of crustal blocks, responsible for evolution of the orogens, are the underlying processes for formation of the supercontinents. Collisional tectonics provides the fundamental stress mechanism for the generation of large thrusts at the boundaries of colliding crustal blocks during crustal evolution. Low-angle thrust-faults are the reverse faults having finite length and breadth, dipping at a low-angle of < 45° or even smaller. Variable dipping reverse faults do occur in nature because of variations in the rock properties on a fault surface. Figures 1a and b, illustrate the typical images of prominent thrust faults delineated on seismic reflection profiles in the Indian and the Canadian shields (Cook, 2002; Mandal et al., 2014).

Most of the Precambrian crust of the Indian shield was formed and reworked over several orogenic events since Neoarchean. Many of these events were associated with the assembly and breakup of super-continents. One such area is the southern part of the Indian shield, where the Proterozoic Cuddapah basin spreading across ~ 45,000 km^2 is located (Figure 2). It was subjected to compressional forces leading to the formation of an orogen and a thrust fault at its eastern margin. Here, we use the seismic refraction / wide-angle reflection data acquired along the Deep Seismic Sounding (DSS) profile across the Cuddapah basin by continuous profiling technique with closely spaced 100 m geophone interval. The acquisition geometry by this technique ensured dense overlapping and reverse data coverage on this profile, especially the reflections from the thrust fault. In the present study we model these high-amplitude and high-apparent velocity reflections, significantly observed similar to the Moho reflection phase on this profile, to determine the velocity structure and geometry of the thrust-fault for the first time even in the

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absence of a conventional near-vertical reflection seismic profile. We present detailed modeling of seismic wide-angle reflections, interpreting them due to a collisional low-angle thrust fault on the eastern margin of the Proterozoic Cuddapah basin, referred here as the Cuddapah basin Eastern Boundary Thrust, (CEBT). Delineation of the "Thrust Fault" on the eastern margin of the Cuddapah basin as significantly revealed on a refraction / wide-angle reflection seismic dataset across it, is the main objective of the present study. The results have significance on a global perspective of the continental crustal evolution and correlation as also revealing the potential of dense wide-angle seismic observations and their modelling by novel techniques.

Significant wide-angle reflections from the thrust faults, prominently observed on a few specific favourably oriented refraction profiles, are illustrated in Figures 1c and d. We develop here a new modeling approach to utilize these wide-angle reflections and generate their matching synthetics in order to unravel the geometry and structure of the CEBT with its plausible geodynamic implications. This new approach is also suitable to consider adequately the presence of limited-extent discrete reflectors in the crust inferred earlier in this region from the refraction data. The seismic structure delineated here is further used to infer a viable model of the crustal evolution consistent with other observations in the region. We are of the opinion that this method in a long way may reconcile the differences between the seismic structures derived from near-vertical and refraction data sets.

2. Geology and Tectonics

The Mesoarchean Dharwar craton in south India is one of the largest and oldest cratonic blocks in the world like the Superior, the Yilgaranand the Kaapval cratons. It is divided into two distinct blocks namely, the Mesoarchean Western Dharwar Craton and the Neoarchean Eastern Dharwar Craton (EDC). Among these two crustal blocks, the Western Dharwar Craton was relatively stable, whereas the Eastern Dharwar Craton exhibits episodic growth since Neoarchean; including formation of the Cuddapah basin (1.8 - 0.550 Ga), evolution of fold belts, formation of granulite facies metamorphism, magmatism manifested in the form of mafic dykes (1.8 - 1.1 Ga) and Kimberlite pipes (Kumar et al., 1993; Kale et

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al., 2020; Saha and Tripathy, 2012). Tectonic framework of the Eastern Dharwar craton is shown in Table 1.

The crescent shaped Cuddapah basin located along the eastern margin of the EDC is one of the largest Indian cratonic basins (Figure 2). The N-S trending Cuddapah basin extends for a length of about 450 km along the arcuate eastern margin with ~150 km mean width. It has a long Paleo-Neoproterozoic geological history and hosts a large number of mineral deposits. Based on the sedimentation pattern, spatial distribution and age six sub-basins are suggested within the Cuddapah basin (Ramam and Murthy, 1987), namely, the Palnad, Srisailam, Kurnool, Nallamalai, Chitravati and Papagni- sub-basins (Figure 2). The Nallamalai subgroup located in the eastern part of the basin hosts a thick shallow marine succession that is intensely deformed. It represents a N-S trending fold-and-thrust belt referred as the Nallamalai Fold Belt (NFB).The other subbasins located to its west host relatively undeformed and unmetamorphosed sediments. The Nellore Schist Belt (NSB) and Eastern Ghats Belt (EGB) are the two major tectonic domains located to the east of NFB of the Cuddapah basin.

The Neoarchean Nellore Schist Belt (Ravikant, 2010) is ~300 km long composite tectono-stratigraphic unit comprising greenschist to amphibolite facies volcano-sedimentary rocks intruded by granites and alkaline plutons (Prakasham Alkaline Province). Two small ophiolitic slivers, namely 1.9 Ga Kandra Ophiolite Complex and 1.33 Ga Kanigiri Ophiolitic Melange are also intruded into the NSB during Paleo- and Mesoproterozoic period respectively (Vijaya Kumar et al., 2010; DharmaRao et al., 2011). Multiple cycles of deformation and metamorphism have affected the Nellore Schist Belt (NSB). The Eastern Ghats Belt is a poly-metamorphosed, multi-deformed deeply eroded part of an extensive orogenic belt located along the eastern margins of the Archean cratons of India. The 1000 km long N-S trending Late Proterozoic orogen consists of supracrustals and igneous rocks. It is composed of mafic and felsic granulites (charnokites), anorthosites and alkaline rocks. The Eastern Ghats Belt is subdivided into four lithological zones (Ramakrishnan et al., 1998). Subsequently, based on structural and isotopic data, it is reclassified into four crustal provinces with distinct evolutionary history (Dobmeier and Raith, 2003). It is considered as a orogenic belt that once formed part of Proterozoic mobile belt system within the

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Napier and Rayner complex of East Antarctica and East India (Mezer and Cosa, 1999). It is considered as a segment of the global SWEAT (Southwest-United-States-East-Antarctica) orogen.Based on the constituent crustal blocks, the Cuddapah basin is regarded as a collage of Proterozoic subbasins and terranes (Chetty, 2001; Kale et al., 2020).

The basin has undergone three periods of subduction-collision related orogenic activities contemporaneous with the global supercontinental episodes ~1.8 Ga (Columbia), ~1.1 Ga (Rodinia, Grenvillian orogenic event), and ~550 Ma (Gondwana, East-African orogenic event) episodes as observed from geochemistry and geochronological data and the presence of respective ophiolites (Mezger and Cosca, 1999; Vijaya Kumar et al., 2010; Vijay Kumar and Leelanandam, 2008). This fold and thrust belt thus plays an important role for the fragmentation and amalgamation of continental blocks such as those of Columbia and Rodinia supercontinents (Zhao et al., 2004; Dobmeier and Raith, 2003). The CEBT is formed in response to the amalgamation of the Eastern Ghats - Rayner Province terrane of East Antarctica with the eastern margin of the Cuddapah basin either during the formation of the Rodinia or the Gondwana supercontinent. The low-angle thrust fault, the CEBT, is especially significant as large lateral movements are observed along this thrust fault. These activities make the study of the Eastern Dharwar Craton, especially the structure and tectonics of the Cuddapah basin interesting and significant on a global perspective of the continental crustal evolution.

3. Deep crustal seismic data across the Cuddapah basin

Long-range deep seismic refraction / wide-angle reflection studies were carried out along a 600 km long ENE-WSW trending Kavali-Udipi transect from East coast to West coast in the southern part of the Indian shield (Figure 2, Profile I). Seismic data were acquired using analog instruments with typical 40 km shot point distance and 100 m geophone spacing using explosive as the energy source. A minimum charge size of 50 kg to a maximum of 1500 kg were used for different shot-receiver distances. Thus, the entire profile distance is covered by continuous profiling technique. A large number of Shot Points (SP) are used to delineate the crustal structure down to the Moho and deeper (Kaila et al., 1979). The transect travelled through major geological units such as the Eastern Ghats Belt, Nellore Schist Belt, Cuddapah

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Basin, Closepet granite and Chitradurga Schist belt, thereby covering both eastern and western Dharwar cratons. Deep seismic refraction / wide-angle reflection studies were also carried across the Cuddapah basin, along the Alampur-Koniki profile (Figure 2, Profile II) located ~120 km north of the present transect (Kaila et al, 1987).

The seismic data considered here for modeling the CEBT structure are recordings from the Shot Points (SP) 0, 40 and 80 on the DSS Profile I across the Cuddapah basin (Figure 2). This section is part of the 600 km long DSS refraction / Wide-angle reflection profile (Kaila et al., 1979), with high data density and similar resolution as obtainable by reflection profiling. Deep crustal section was inferred for the eastern part of the Cuddapah basin by detailed analyses of the seismic refraction / wide-angle reflection data on the DSS Profile I. With the aid of a computerised method (Kaila and Krishna, 1979), reversed reflection travel times data from the possible shot-point pairs were converted into the corresponding reflector depth segments (covering the entire crustal section) with their reliable dips and appropriate migrated positions. An initial crustal depth section assembled with those reflector segments displayed the gross features of the crustal structure down to the Moho. Especially a low-angle thrust fault #2 known as the Vellikonda Thrust, referred here as the CEBT, is significantly revealed to mid-crustal depths. Most of the single-sided reflection arrivals data were processed by a analytical migration method (Kaila et al., 1982) and those reflector segments were also included. Refraction data analysis gave some details of the velocity structure, though limited to the shallow layers within the upper to mid-crustal depths, with a slight indication of another low-angle fault #1.The deep crustal depth section thus inferred by detailed analyses of the seismic recordings for the eastern part of the Cuddapah basin is shown in Figure 3a as inferred by Kaila et al. (1979).

It is clear from this migrated depth section (Figure 3a) that the crustal structure in the study region consists of a large number of discrete reflector segments of limited lateral extent and varying dips from very shallow upper crustal depths down to the Moho and deeper. This crustal depth section looks similar to the crustal reflectivity structures revealed by numerous reflection profiling experiments in various regions (Mooney and Meissner, 1992; Cook, 2002). Further, since the seismic profile was chosen with its

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orientation broadly perpendicular to the regional strike, the dips shown for the individual reflector segments are believed to be close to their true dips rather than being apparent. Mereu (2000) in a study on the complexity of the crust and the Moho from seismic refraction and wide-angle reflection data, considered that in the real earth reflectors are randomly located, have random velocity contrasts, and are oriented with dipping trends that have a tectonic origin. As interpreted by Kaila et al. (1979) and Roy Chowdhury and Hargraves (1981), the 600 km long crustal section across the western and eastern Dharwar cratons is divided into several individual crustal blocks by the inferred deep faults, many extending to the Moho depths, and a few thrust faults. Recently, Saikia et al. (2016) used three different approaches including, stacking, inversion, and common conversion point migration of receiver functions computed from teleseismic waveforms, recorded over seismographs located along a profile closely following the DSS profile I to understand the crustal structure. They found that the Moho depths obtained by them are in general consistent with the Moho depths in various crustal blocks bounded by the deep faults given by Kaila et al. (1979).

4. Seismic methodology for delineating complex structures

Deep seismic near-vertical reflection Profiling ("reflection profiling", with higher frequency waves or shorter wavelengths, having vertical resolution ~150 m, and horizontal resolution ~500 m) has been the most successful geophysical technique in resolving the deep structure, tectonics and evolution of the continental crust. The enhanced quality of the reflectivity images provides necessary clues for their interpretation in terms of the deep continental crustal structure and its evolution. Images of paleo-collisional and suture zones as well as detachment zones and notably the low-angle thrusts are well revealed in several studies (Mooney and Meissner, 1992). As their main characteristic, most of the images of the continental crustal structure obtained by this technique in various terranes world-wide, appear to reveal patterns of numerous discontinuous and short reflectors of varying lengths and dips as well as some regions of diffused reflectivity, even down the Moho (Cook, 2002; Mereu, 2000).

Seismic Refraction / Wide-angle Reflection Profiling ("refraction profiling", with lower frequency waves or longer wavelengths) provides complementary datasets traditionally used to derive velocity

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structure and nature of prominent boundaries like the Moho besides other structural / physical characteristics of the deep continental crust. The relatively low frequencies of seismic waves in refraction profiling sample and filter the heterogeneities within the crust in a much different manner in contrast to the higher frequencies of the reflection profiling experiments (Mereu, 2000). Since the longer wavelengths are not suitable to resolve the smaller structures, crustal models derived from those datasets especially with large spacing (1 - 2 km or more) of recorded seismic traces tend to be relatively smooth and layered. Although not so common as observed by reflection profiling, high amplitude low-angle thrust fault reflections are occasionally found in the field record sections acquired with favourable source-receiver geometry and closer spacing of seismic traces on refraction profiles. Figures 1c and d illustrate the wide-angle reflections of low-angle thrusts thus observed on a refraction profile in the southern part of the Indian shield (presented here for the first time with detailed modeling) and the refraction line J of the GLIMPCE experiment of the Canadian shield (Epili and Mereu, 1991). It is interesting to note from these record sections that, the thrust fault reflection signature appears as prominent (with similar high amplitudes and the apparent velocity) as the Moho reflection PmP phase. These typical record sections are both from recordings with close spacing of the seismic traces (50-100 m) and higher frequencies like the reflection profiling and unlike the traditional long-range refraction profiles with 2-5 km spacing. High quality data on such refraction profiles may also reveal some unusual and high energy coherent phases (Krishna and Vijaya Rao, 2011) that can be appropriately processed leading to models of crustal depth sections qualitatively similar to those found by coincident reflection profiling as are being used in the present study.

5. A Novel modeling approach utilizing 'localized phantom horizons' and synthetic seismograms computations

Models of crustal structure inferred from seismic refraction profiles generally appear to be simple with a few layers shown as apparently continuous across the model. It is difficult to derive models of both velocity and the tectonic structure of complex regions as the fold belts with the available processing approaches of either refraction or reflection seismic datasets. A novel modeling approach is developed here to reveal the complex structures like the thrust faults and successfully applied for the first time to a

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closely spaced refraction dataset. This approach provides crustal structure similar to near-vertical reflection profiling and also the velocity structure, which is not obtainable with the conventional reflection data processing technique. Detailed crustal velocity structure modeling and synthetic seismograms matching of the prominent reflection signal of the inferred thrust fault were not attempted (Kaila et al., 1979) earlier in their analysis of this closely spaced DSS profiling data. A recent study (Chandrakala et al., 2015) in the region could neither delineate this distinct thrust fault nor recognize its reflection signal on the seismograms as presented here. Their study identified a normal fault at the boundary of Nallamalai Fold belt and Nellore Schist belt, instead of a thrust fault. Their findings are in contradiction with the geological evidences (Saha and Tripathy, 2012; Kale et al., 2020) which suggest thrusting is responsible for the formation of Nallamalai fold belt region of the Cuddapah basin. As illusrated in Figure 3a, Kaila et al. (1979) have also suggested this thrusting, alhough its fine structure of velocity was not conclusively obtained there. Thus, there is a need to refine and establish the geometry of the CEBT, and obtain a plausible velocity structure in this region. These are achieved by applying our new approach to the present dataset providing insight to the geodynamic evolution and imprints of the global Grenvillian and East-African orogenic events in the region.

In order to refine and establish the geometry and structure of the significant low-angle thrust fault #2 on the eastern margin of the Cuddapah basin (CEBT), and to derive a plausible velocity structure in the region, we propose to use the new approach presented here. Computation of synthetic seismograms compatible with the observed field record sections, especially revealing the thrust fault reflections is primarily considered for this purpose. A computational technique based on the Gaussian Beam method (Cerveny, 1985; Weber, 1986; Rabbel, 1987) is expressly designed for generating the synthetic seismograms in the present study. We present here the digitized (Krishna and Kaila, 1986) seismic record sections from SP0 and SP40 illustrating for the first-time unequivocal reflection signatures of this low-angle thrust fault CEBT (Figures 5a and c).

Considering the migrated crustal depth section (Figure 3a) inferred by extensive data analyses (Kaila et al., 1979), we generate an equivalent data set of the depth section with similar reflectivity fabric

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but represented by a fewer reflector segments, suitable for the computational purpose. The large number of smaller reflector segments in Figure 3a are replaced by a limited number of **'localized phantom horizons'.** These are the lines drawn on the depth section such that they are parallel to as well as coincident with a small group of the reflector segments thus being consistent with the local structural attitude revealed in the earlier section. The large number of the actual reflector segments, which are also not continuous enough to be used in the computations, are thus grouped together and replaced appropriately by fewer number of localized phantom horizon segments. It should be noted here that these individual localized phantom horizons created here are also of limited extent only, similar to the reflector segments in the original section (Figure 3a), and in contrast to much longer phantom horizons usually drawn for interpreting the seismic exploration sections. Figure 3b thus shows the recreated depth section with the new localized phantom reflector horizons replacing the earlier large number of smaller reflector segments. This new depth section while retaining the earlier structural fabric, it also includes all the deep faults and the low-angle thrust faults as given in the original depth section for ray tracing and synthetic seismogram computations.

Figure 3b further illustrates schematically the reflection ray paths that are generated in large number for each of the reflector segments (localized phantom horizons) in the present modeling approach. As shown in this schematic ray diagram, the reflected waves encounter randomly the intervening reflector segments as also some of the deep faults, both in their down-going and the up-coming paths. Ray paths for reflections from each of the localized phantom horizon segments are thus generated for further computation of travel times and synthetic seismograms by the Gaussian Beam method. We thus consider an approach in such a way, various small dipping reflectors are “embedded” in a uniform seismic velocity field and the velocity increases with depth. This is in principle similar to the approach we used earlier (Meru, 2000; Krishna and Vijaya Rao, 2011).

The earlier depth section (Figure 3a) does not give the velocity information at each of the reflector segments as required for ray tracing through this complex crustal model by the approach proposed here. An initial velocity model, with plausible velocity contrasts at each of the localized phantom horizon

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segments, is developed from the earlier models (Kaila et al., 1979; Chandrakala et al., 2015; Kaila et al., 1987; Chandrakala et al., 2013) in the region. The dips as well as locations of all the reflector segments in the section are kept unchanged, in all the computational model input but varying only the velocity contrast across each one of them to generate the reflected waves, starting from reflectors at the shallow to deeper depths. The initial take-off-angles-range from the source downwards to hit a desired reflector is progressively adjusted looking at the interaction of the transmitting rays with the intervening depth segments until a successful hit and the reflection occurs. The final take-of-angle-ranges are fixed to let interactions with all possible depth segments encountered in the up-coming paths. Thus, each of the localized phantom reflector segments (a total of ~100 or more) are ray-traced and the reflection arrival times are checked for possible correlations on the observed records. Any changes of the velocity contrast at the reflectors are made to improve the traveltimes and synthetics fit thus generated. In the present study, we intend to compute the primary reflected wave-field only, besides the refractions, to generate the Gaussian Beam synthetic seismograms matching the CEBT. The same procedure can possibly be extended to generate complete wavefield including other interactions like the multiples, wave-conversions and diffractions but that is not considered necessary and attempted here.

This approach is found efficient and considered suitable for ray-tracing through, and synthetic seismograms modeling of the realistic heterogeneous crustal structures consistently revealed by numerous near-vertical reflection profiles as well. The crustal section considered in the present study (Figure 3a) as well as its recreated version (Figure 3b) also display similarly a large number of discrete reflector segments of limited lateral extent and varying dips. They are also far from being suitable for approximation by a simple layered model with all the interfaces, at times hypothetically, considered to exist end-to-end across the model space possibly missing the actual structural details. It was concluded (Mereu, 2000) that earth models considered with sets of small randomly oriented reflectors embedded in a uniform velocity gradient field will produce wide-angle reflection fields that are very similar to those observed in crustal refraction experiments. The model formulation we considered here is consistent with these findings. Similar conclusions were also made earlier (Long et al.,1994), suggesting that nature of both reflection and refraction profiling data sets has a common cause relating to the basic structure of the

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crust and in particular to the discontinuous nature of crustal reflectors. Those reflectors are modelled as local velocity variations rather than part of large-scale velocity change laterally or vertically. It was also opined (Long et al., 1994) that the crustal models that show existence of velocity discontinuities extending over large distances, as traditionally inferred from refraction profiles, are questionable. The present modeling approach is specifically developed for synthesizing the wide-angle reflection wave-field for the heterogeneous crustal structure consisting of large number of discontinuous reflectors and the low-angle thrust fault which is the major target in the study region (Figures 3a, b).

6. Tectonic imbrication of Proterozoic accretions

The modeling approach developed and used here adequately considers the discontinuous nature of the continental crustal structure consisting of several small and distinct reflector segments clearly revealed in the earlier crustal depth section (Kaila et al., 1979). Such a nature of the continental crustal structure, as also considered earlier (Mereu, 2000; Long et al., 1994) to be more realistic, is consistently supported in several deep seismic reflection profiling experiments in a variety of tectonic regions in the world (Cook, 2002; Mooney and Meissner, 1992). The new modeling approach is used for successful ray-tracings from the CEBT with its fine structure from SP0, SP40 and SP80 as illustrated in Figures 4(a, b and c). Following the ray tracings for the undisturbed structural model as in Figure 3b, and iterating and inferring of the velocities across in the process for all the localized phantom reflector segments, the synthetic seismograms are generated as shown Figures 5 b and d. Especially, the reflections of the low-angle thrust-fault, generated in the synthetics are quite consistent with those found in the observed record sections (Figures 5a and c), thus confirming its geometry (including some inferred layering within) displaying a high velocity (6.8 - 7.3 km/s) structure for it. Thus, it is evident that the CEBT is characterized with a high velocity, and possibly a high-Q (low absorption) structure as well. The P wave velocity structure of the crust and geometry of the thrust-fault is presented in Figure 6a.These structural properties of the CEBT are obtained here for the first time by the new modeling approach developed here. The CEBT is significantly revealed in the seismic record sections of SP0 and SP40 (up-dip recording, as shown here) and it is also seen in record section of SP80 (down-dip recording) on the eastern margin of

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the Cuddapah basin. A similar low-angle thrust fault (like the CEBT) on the eastern margin of the basin was found (Kaila et al., 1987) also on the profile II located ~120 km north of profile I (Figure 2). The CEBT is thus considered as a major tectonic feature of the Cuddapah basin. The CEBT with a stack of reflectors (Figure 6a) is similar to the thrust faults imaged in the deep crustal seismic reflection profiling studies as shown in Figures 1(a, b).

The CEBT demarcates distinctly different velocity structure, lithology and metamorphism (greenschist on the west and granulites on the east) as also reported (Dobmeier and Raith, 2003) earlier. Eastward dipping geometry of the thrust fault suggests that the Dharwar craton subducted to the east and the eastern crustal block was up-thrust to the west. Presence of the Kanigiri ophiolitic mélange (DharmaRao et al., 2011) (~1.3 Ga) in the northern part of the CEBT (Figure 2) suggests presence of an ocean and associated subduction zone in the region during early Neoproterozoic. Further, the geological and geochemical data indicate that the Nellore Schist Belt represents the upper crustal segments of a subduction zone associated with island arc development and closure (Kale et al., 2020; Vijaya Kumar and Leelanandam, 2008; Dharma Rao, et al., 2011; Saha and Sain, 2019). Most of the crustal reflectors from shallow depths to the Moho boundary of the Nallamalai Fold belt domain show consistent eastward dip from SP140 to the CEBT (Figures 3a and b and 6a). These east-dipping reflectors change the dip direction to the west from the CEBT (Figure 6a). These east-west dipping reflectors constitute a bivergent reflection fabric that represents the signature of a collision zone (BABEL Working Group, 1990; Hall and Quinlan, 1994; Vijaya Rao et al., 2000). The uniqueness of the present study is identification of bivergent reflections from DSS refraction / reflection dataset. These bivergent reflections characterize different crustal blocks on either side of the boundary. The collision process has resulted in crustal shortening and thickening as observed from the thickest crust at the CEBT boundary (Figure 6a). Crustal velocities in the upper and middle crust of the NFB are 0.2 km/s greater than those normally found in shield regions. This could be a result of collision which has pushed the deeper rocks towards the surface during the orogenic activity. Similar high velocities are observed from several other orogenic belts, e.g. the Grenville region (Mereu, 2000).

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Beneath the eastern part of Cuddapah basin, the CEBT, Kaila et al. (1979) identified two prominent reflector bands in the deeper part of the crust, one at 40 km and another at 45 km depth (Figure 3a). They referred them as a double Moho-discontinuity. Subsequently, Kaila and Sain (1997) have suggested 42 km thick crust beneath the CEBT. Reanalysis of seismic refraction data using ray methods suggests 47 km thick crust at the CEBT, the Nallamalai Fold Belt-Nellore Schist Belt boundary (Chandrakala et al., 2015). The present study using the Gaussian beam technique has identified the Moho at a depth of ~45 km, which is consistent with the deeper Moho boundary delineated by Kaila et al. (1979). The present results are in conformity with the global compilation study that suggests thicker crust of the order of ~45 km for the Proterozoic and thinner for the Archean regions (Durrheim and Mooney, 1991). A crustal thickness of 47 km was imaged for the Proterozoic Aravalli-Delhi Fold Belt region of NW India (Vijaya Rao et al, 2000; Krishna and Vijaya Rao, 2011). Geological studies also suggest 45-50 km thick crust at the CEBT (Dobmeier and Raith, 2003; Saha and Tripathy, 2019). Thick crust in the region could be due to collisional activity and subsequent magmatic underplating observed in the region (Kaila and Sain, 1997; Chandrakala et al., 2015). Large dyke swarm activities at 1.8 and 1.1 Ga (French et al., 2008; Kumar et al., 1993) observed in the region are manifestations of crust-mantle interaction process that resulted in magmatic underplating. However, the receiver function study identified the Moho at 40 km depth.

Bouguer gravity anomaly map of the region reveals prominent steep gravity increase of ~60 mGals within a 50 km distance, across the collisional boundary (Figure 3a). This gravity anomaly is a regional feature extending all along this 350 km long boundary (NGRI, 1978), and is significant to providing insight for the tectonic evolution of the region. Observations of steep gradient bipolar (low-high pair) gravity anomaly across the CEBT, suggests that this boundary can be a faulted contact of juxtaposed crustal blocks. It is consistent with the gravity high observed over the thrust fault. The gravity low corresponds to the under-thrust block while the gravity high characterises the over-thrust crustal block. This is consistent with the observed seismic signature modelled here as the low-angle thrust fault. Gravity studies from the Canadian, Australian, Indian and other shield regions suggest that a steep

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gradient bipolar gravity anomaly is a characteristic signature of a suture (Gibb and Thomas, 1976; Fountain and Salisbury, 1981; Vijaya Rao et al., 2000; Singh and Mishra, 2002).

Arcuate-basin-pattern and convex-to-the-west thrusted eastern margin of the Cuddapah basin, 'the Cuddapah salient', also indicates east-west convergence and operation of collision tectonics in the region. Based on the seismic reflection signature of the thrust fault and the available geological data, we interpret that subduction and collision are responsible for the crustal evolution and the CEBT in the region. The collision took place between the Dharwar craton in the west and the Nellore Schist Belt-Eastern Ghats Belt-Rayner complex of east Antarctica, a combined continental block to the east forming an extensive orogenic belt contemporaneous with the global Grenvillian orogenic activity at ~1.0 Ga. Earlier geological studies have identified a collision during this period at this boundary (Mezgar and Cosa, 1999; Vijaya Kumar and Leelanandam, 2008).

The geodynamic evolutionary scenario displayed by the seismic structure and consistent with the geological data are presented in the form of a schematic model in Figure 6b. It shows two crustal blocks separated by an ocean and subsequently the western block consisting of the Eastern Dharwar Craton and Cuddapah basin subducted to the east and collided with the Nellore Schist Belt-Eastern Ghats Belt-Rayner complex (eastern Block). The low-angle thrust-fault, CEBT formed during this collisional episode on the eastern margin of the Cuddapah basin acts as a suture by juxtaposing two crustal blocks of different physical properties and evolutionary histories. The collisional activity observed in the region is a marginal segment of a larger orogenic belt during late Proterozoic and related to the assembly of the Rodinia supercontinent (Hoffman 1991; Mezger and Cosca, 1999). Relict-suture zones were identified (Burke et al., 2003) in Africa based on the deformed alkaline rocks and carbonatites. Similar studies have identified the CEBT as a paleo-collision and suture zone (Leelanandam et al., 2006).

Lower elevation in the collision zone (Figure 2) indicates orogenic collapse and operation of post-collisional extensional processes, which might have emplaced several alkaline-granitoid bodies in the region. The high-velocity (6.8 - 7.3 km/s) bodies along the thrust (Figure 6a) indicate such intrusives, namely anorthosites, carbonatites and ophiolitic mélange. The CEBT acted as a channel for the transportation of enriched mineralized fluids from the upper mantle depth to the surface and responsible for the mineralization of the Cuddapah basin, which is recognized as one of the richest mineralized zones in India. The East Gondwana fragments, namely India, Antarctica, Australia and South Africa were amalgamated along the Circum-East Antarctic mobile belts during the assembly of early Neoproterozoic Rodinia supercontinent (Hoffman, 1991). These crustal blocks were reworked during the late Neoproterozoic-early Cambrian East-African orogenic (~550 Ma) activity symbolizing the accretion of East and West Gondwanas with the formation of the Gondwana supercontinent. Based on the later activity, it was suggested (Dobmeier et al., 2006) that the combined Eastern Ghats Belt-Rayner Complex accreted to the Dharwar craton during the East-African orogenic episode.

The present study identified another low-angle thrust fault # 1 extending from the surface to a depth of 20 km to the east of CEBT. It separates distinct geological terranes, namely the Nellore Schist Belt and Eastern Ghats Belt. Similar low-angle thrust fault was also delineated (Kaila et al., 1987) along the seismic profile II, located ~120 km to the north of present transect (Figure 2). It is also located at the eastern margin of Nellore Schist Belt. Thus, the dipping feature can be regarded as a regional feature. The significance of this feature (fault # 1) was not discussed in any one of the earlier works (Kaila et al., 1987; Chandrakala et al., 2013, 2015). Presence of 1.9 Ga Kandra ophiolitic complex representing dismembered Paleoproterozoic supra-subduction zone ophiolite (Vijaya Kumar et al., 2010) at this thrust fault region indicates presence of oceanic crust during late Paleoproterozoic period (Figure 2). We interpret subduction of oceanic crust and collision between the Nellore Schist Belt and another crustal block to the east (Probably East Antarctica) has resulted in the development of Eastern Ghats orogen with the formation of a thrust fault between them. Generally, mountain belts represent regions where oceans might have opened and closed and they are the products of continental collision (Dewey and Bird, 1970). We refer this thrust fault as the Eastern Ghats Thrust (EGT). During the Late Paleoproterozoic period various continental blocks from different parts of the world, including the Eastern Ghats Belt of India were involved in the process of accretion and formation of Columbia supercontinent by subduction and collision processes (Rogers and Santosh, 2002; Vijaya Rao and Reddy, 2002; Vijaya Kumar et al., 2011). The compressional forces developed during this period might also be responsible for the thrusting, collision and formation of Eastern Ghats Belt over this part of the Indian shield. Several geological, geochemical and geochronological studies have suggested the formation of Eastern Ghats Belt during ~1.8 Ga due to subduction and collision between eastern part of the Dharwar craton and probably Rayner complex of East Antarctica (Vijaya Kumar and Leelanandam, 2008; Vijaya Kumar et al., 2010; Dasgupta et al., 2013: Saha and Sain, 2019). The suggested evolutionary model of the region is illustrated in figure 6b.

Seismic structure derived from the present study provides basic constraints for proper correlation of Gondwana fragments and supercontinental formation. It also provides mechanism for the mineralization of the region and crustal evolution during the Proterozoic. Integrating the crustal structure, inferred seismic velocity model specifically of the CEBT, steep gradient bipolar gravity anomaly, presence of the alkaline and carbonatite rocks, geochemical signatures representing the island-arc, subduction zone environment (Vijaya Kumar and Leelanandam, 2008; Kale et al., 2020; Saha and Sain, 2019) and anorthosites, the EGT and CEBT are interpreted as relict subduction-collisional suture evolved during the Late Paleo- and Mesoproterozoic Proterozoic periods.

7. Conclusions

- A new approach is developed for modeling crustal depth sections revealing several limited extent discrete reflector segments in the refraction profiling data. These reflectors are modelled as local velocity variations, and not necessarily part of large-scale velocity changes. The crustal structure derived from this approach closely resembles the images obtained by reflection profiling data as well, closer to the real Earth models. **Localized phantom horizons** approach of refraction data developed here is more useful in understanding the tectonic evolution of the regions of complex tectonic origin compared to conventional layered models inferred by other methods.
- Closely spaced (50-100 m) refraction datasets can be used to delineate both the velocity structure and geometry of the thrust fault regions by this approach as shown in this study.
- Conventional simple layered modeling approach of refraction data, where velocity discontinuities are often assumed to extend over a large distances, is likely to miss the fine structural details.

- Present study suggests the NSB is sandwiched between the EGB toward the east and the Dharwar Craton toward the west during the Late Paleo- and Mesoproterozoic collisional activities resulting in the formation of the EGT and CEBT.

  These events are contemporaneous with the global Columbia and Rodinia or East-African supercontinental episodes.

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Contributions

V.G.K. designed the study, contributed the methodology development and modelled the seismic data. V.G.K. and V.V.R. interpreted the seismic results proposing a plausible geodynamic evolutionary model consistent with the seismic results. V.V.R. examined additional inputs for correlation with the geological data.

Ethics declarations

Competing interests

The authors declare no competing interests.

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Table-1: Tectonic framework of Eastern Dharwar Craton

2.7-2.9 Ga	:	Peninsular Gneisses
2.7-2.55 Ga	:	Formation of a large number of linear Greenstone (schist) belts
2.5 Ga	:	Accretion of western and eastern Dharwar cratons. Wide-spread calc-alkaline to potassic granites
2.3-2.1Ga	:	Mafic dyke swarms
1.8 Ga	:	Mafic magmatism -formation of Paleoproterozoic Large Igneous Province (French et al., 2000)
1.8-0.8Ga	:	Formation of the Proterozoic Cuddapah, Kaladgi and Bhima basins
1.8 Ga	:	Collision between the EDC and Antarctica and formation of Eastern Ghats Orogenic belt. Formation of Granulites.
1.1 Ga	:	Collision between EDC &NSB (Nellore Schist Belt)-EGMB continental block with the formation of Nallamalai foldbelt. Kimberlite Volcanism (Kumar et al., 1993). Alkaline magmatism (Carbonatites) and anorthosites
550 Ma	:	East-African Orogeny related to formation of Gondwana Supercontinent (Dobmeier and Raith, 2003; Meert, 2003; Yoshida et al., 2003).
118 Ma	:	Separation of Australia-Antarctica from the east coast. Evolution of Rajmahal traps and formation of Indian ocean.
90 Ma	:	Kimberlite Volcanism

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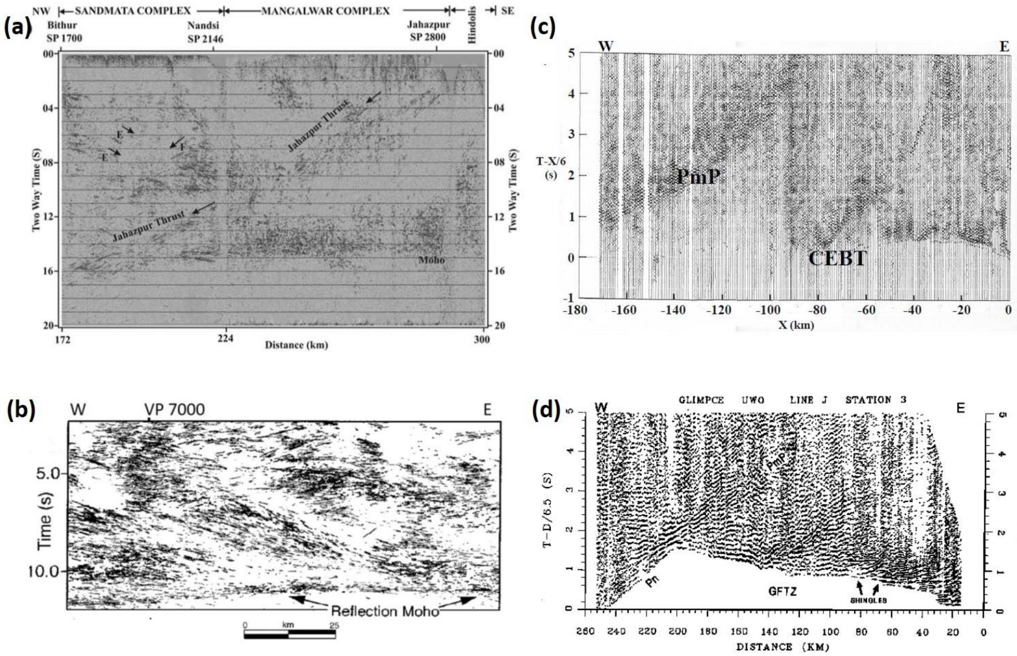

Figures 1 a, b. Typical images of prominent thrust faults delineated on seismic reflection profiles. (a) Jahazpur thrust evolved during the Paleoproterozoic Aravalli orogen of the NW part of the Indian shield (Mandal et. al., 2014), (b) Great Bear arc related to the Wopmay orogen of the Canadian shield (Cook, 2002).

Figures 1 c, d. Significant wide-angle reflection images from the thrust faults observed on a few specific favourably oriented refraction profiles. (c) illustrates the reflection data modelled and interpreted here, (d) illustrates the reflection data across Grenvillian Front Tectonic Zone, GFTZ (Epili and Mereu, 1991).

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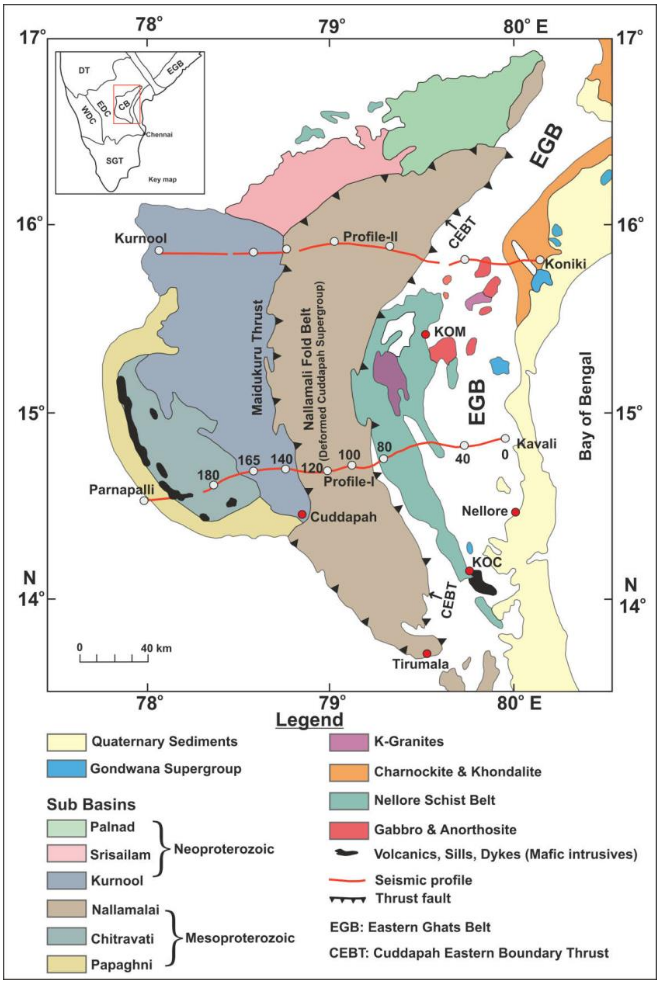

Figure 2. Geological map of the Cuddapah basin (modified after Ramam and Murthy, 1987) showing the distribution of different sub-basins. Locations of the two DSS profiles I and II across the basin are marked. The present study uses the observations from SP0, SP40 and SP80 on the eastern part of the Profile I. NFB: Nallamalai Fold Belt, EGMB: Eastern Ghats Mobile Belt, KOM (Kanigiri) and KOC (Kandra) are the locations of ~1.9 Ga and 1.8 Ga ophiolites. Key map shows the location of the Cuddapah Basin (CB) in the EDC (Eastern Dharwar Craton) and relative to the WDC (Western Dharwar Craton). 0, 40, 80, 100, 120, 140, 165, 180 indicate various shot points operated on the Profile I.

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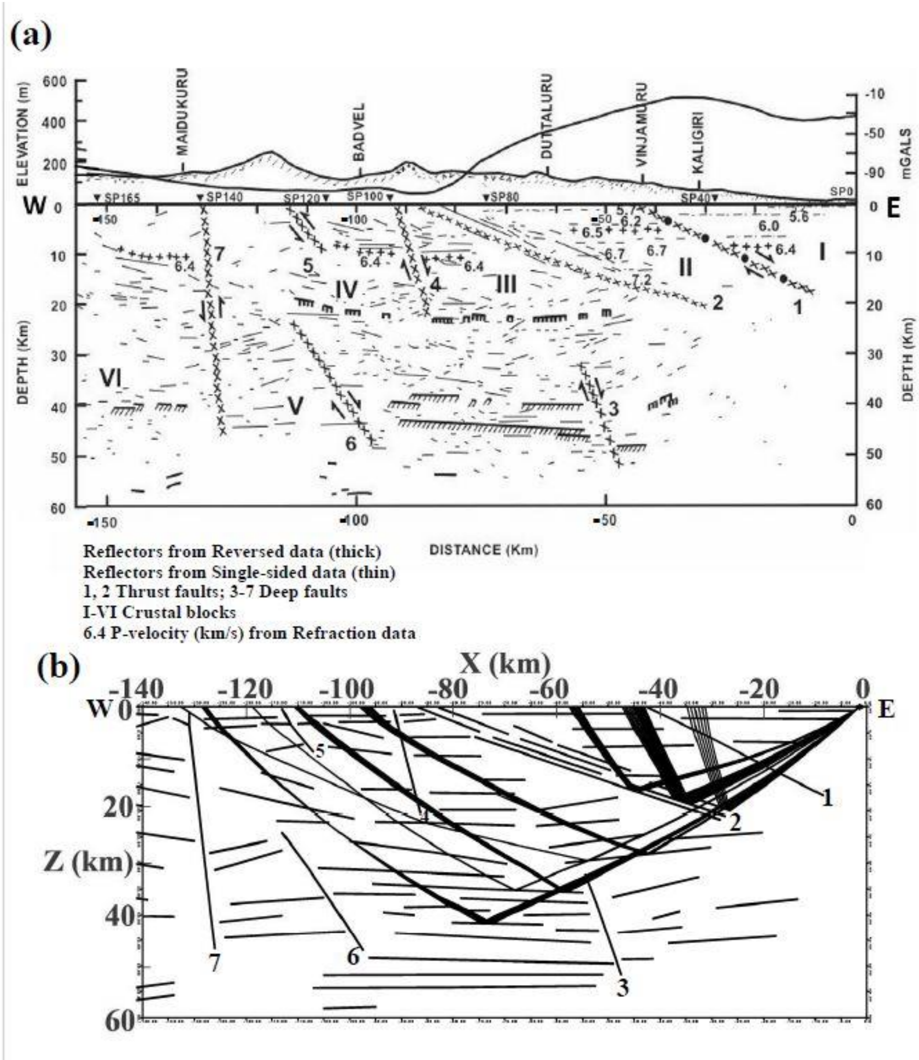

Figure 3a. Deep crustal section inferred (Kaila et. al., 1979) for the eastern part of the Cuddapah basin by detailed analyses of the seismic refraction / wide-angle reflection data on the DSS Profile I. The 600 km long crustal section across the EDC through the WDC is divided into several individual crustal blocks (Kaila et. al., 1979; Roy Chowdhury and Hargraves, 1981) by the inferred deep faults, many extending to the Moho depths, and a few thrust faults.

Figure 3b. An equivalent data set of the crustal section with similar reflectivity fabric represented by fewer reflector segments, suitable for the computational purpose. The large number of smaller reflector segments in Figure 3a are replaced by a limited number of 'localized phantom horizons'. Reflection ray

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paths that are generated in large number for each of the localized phantom reflector segments (a total of ~100 or more) in the present modeling approach are also illustrated schematically. As shown here, the reflected waves encounter randomly the intervening reflector segments as also some of the deep faults, both in their down-going and the up-coming paths.

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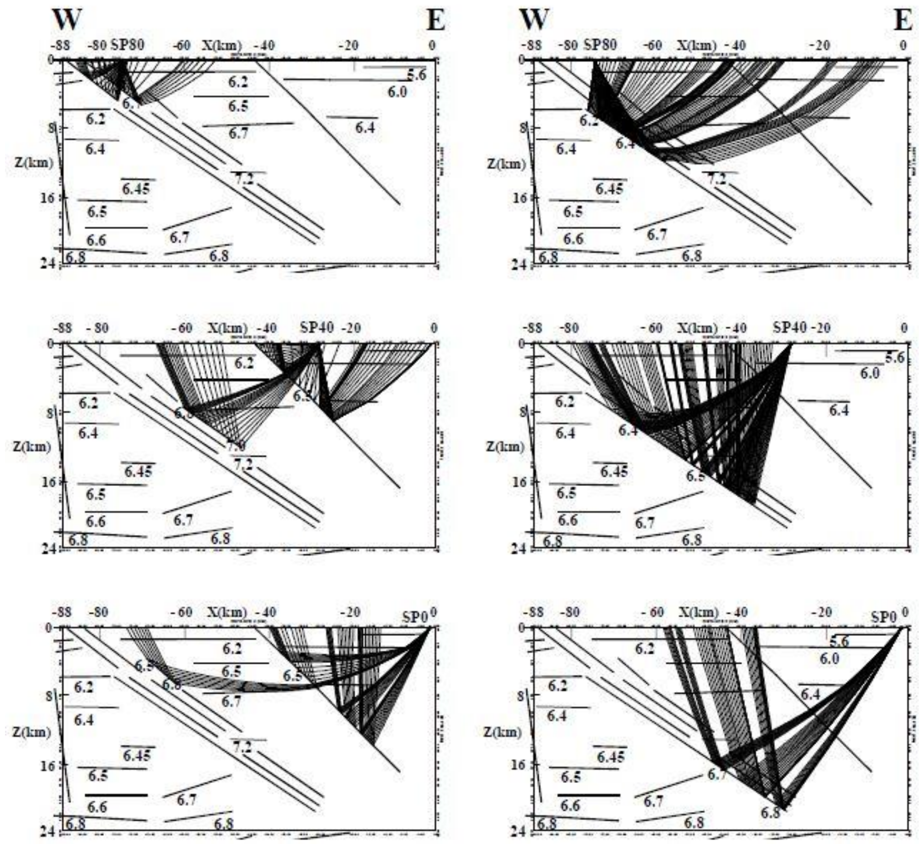

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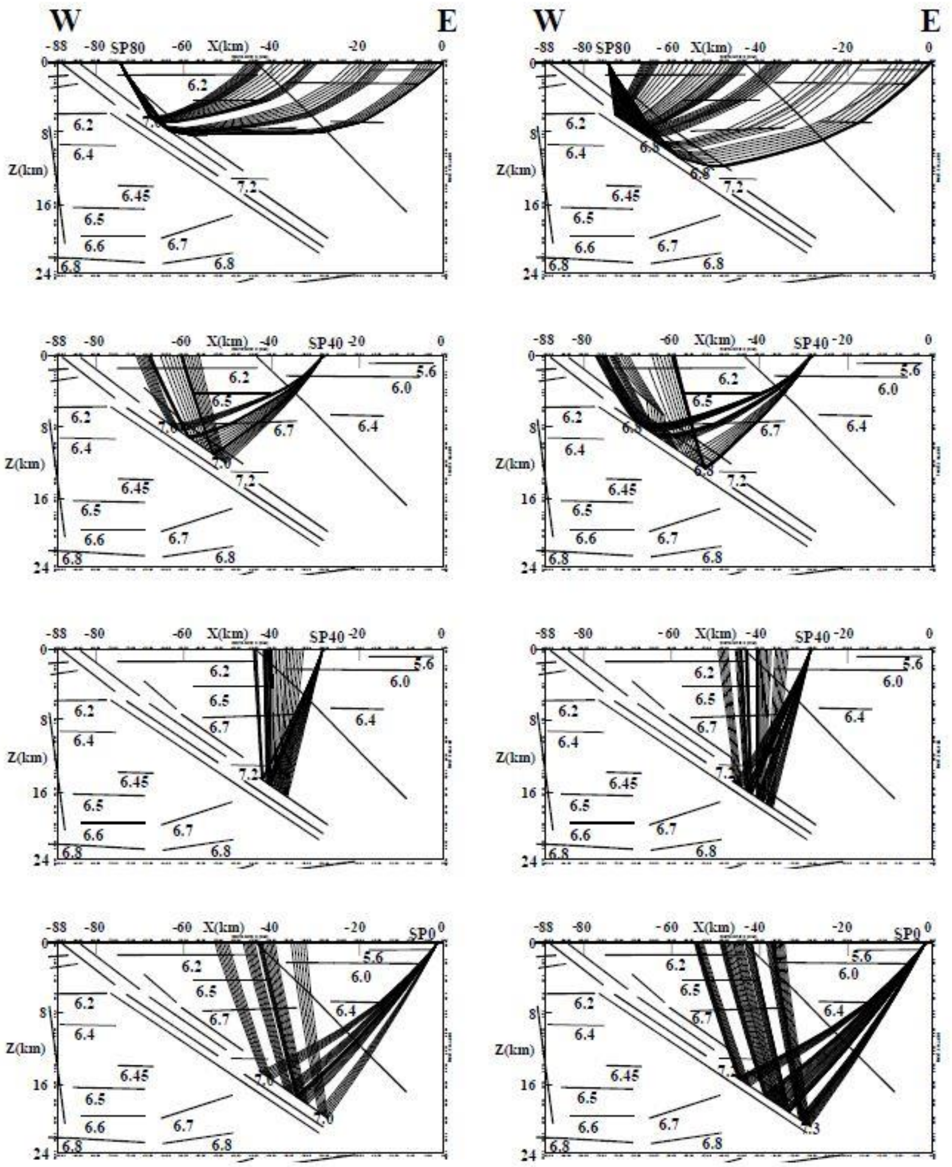

Figure 4b

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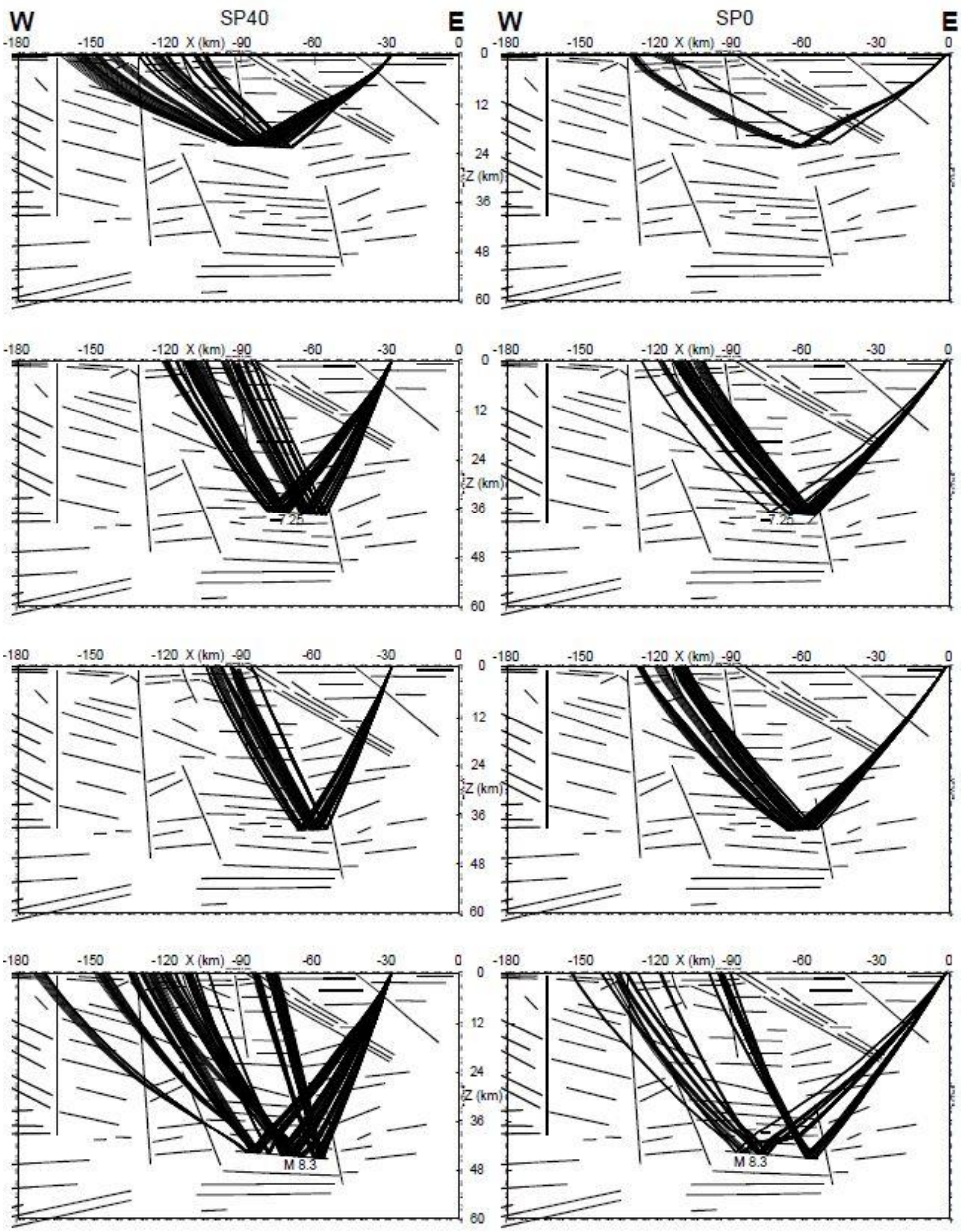

Figure 4c

Figure 4. (a, b). Ray-tracings from the reflector segments of the CEBT with its fine structure generated by our modeling approach from SP0, SP40 and SP80. Ray paths for reflections from each of the localized phantom horizon segments are generated for further computation of travel times and synthetic

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seismograms. The dips as well as locations of all the reflector segments in the section are kept unchanged, varying only the velocity contrast across each one of them to generate the reflected waves, starting from reflectors at the shallow to deeper depths. (c). Ray-tracings from SP0 and SP40 illustrated for a few of the reflector segments in the middle and lower crust as well as the Moho (M) to demonstrate our new approach.

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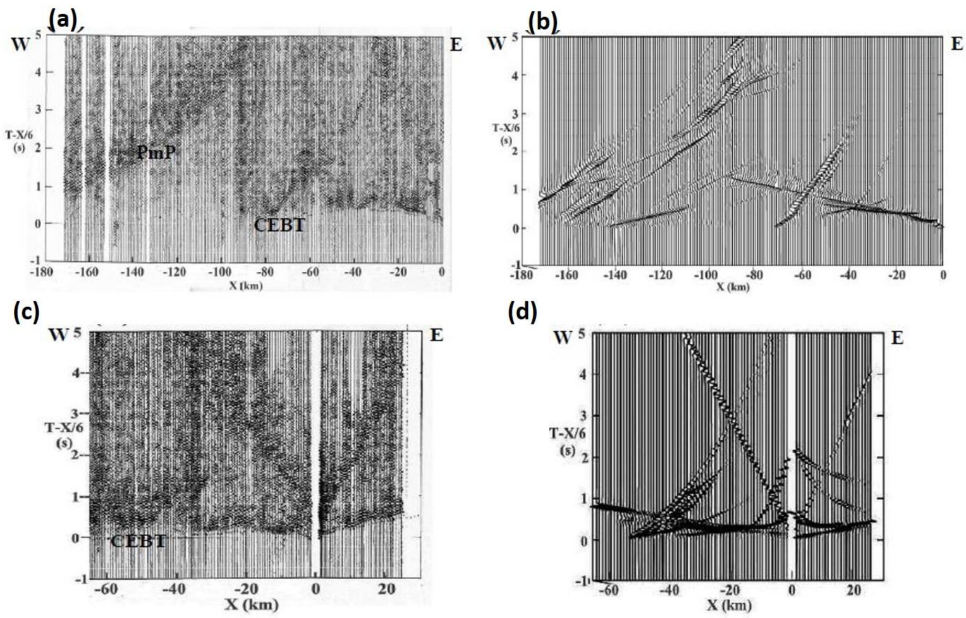

Figure 5. Observed and the Gaussian Beam synthetic seismogram sections especially revealing the CEBT, (a, b) from SP0 and (c, d) from SP40.The original field analog seismic traces were digitized (Krishna and Kaila, 1986) with a sampling rate of 250 samples per second and plotted as record sections using a reduction velocity of 6 km/s. The observed seismic record sections from (a) SP0 and (c) SP40, as well as their synthetics, (b) SP0 and (d) SP40, presented here for the first time, reveal unequivocal reflection signatures of the low-angle thrust fault CEBT. As can be seen from (a), the observed significant high-amplitude and high-apparent velocity CEBT reflection phase is as prominent as the Moho reflection phase PmP.

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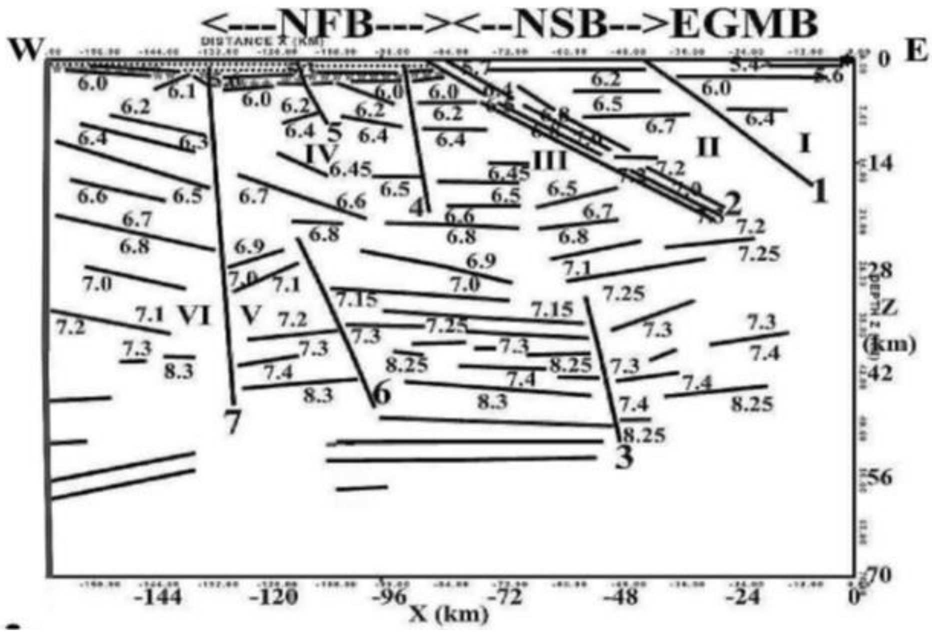

Figure 6a. P wave velocity structural model of the crust and geometry (including some inferred layering within) of the thrust-fault CEBT obtained for the first time by the new modeling approach developed here. This model confirms the high velocity (6.8 - 7.3 km/s) structure of the CEBT. The gross structural features including the deep faults of the continental crust inferred earlier (Kaila et. al., 1979) are retained here, with only the large number of smaller discrete reflector segments (Figure 3a) being replaced by fewer localized phantom horizons (Figure 3b) in the new modeling approach. The deep crustal velocity structure, not obtained earlier, is modelled here by the present approach. NFB: Nallamalai Fold Belt, NSB: Nellore Schist Belt, EGMB: Eastern Ghats Mobile Belt, 6.4 P velocity km/s, 1, 2 Thrust Faults, 3-7 Deep Faults, I-VI Crustal Blocks.

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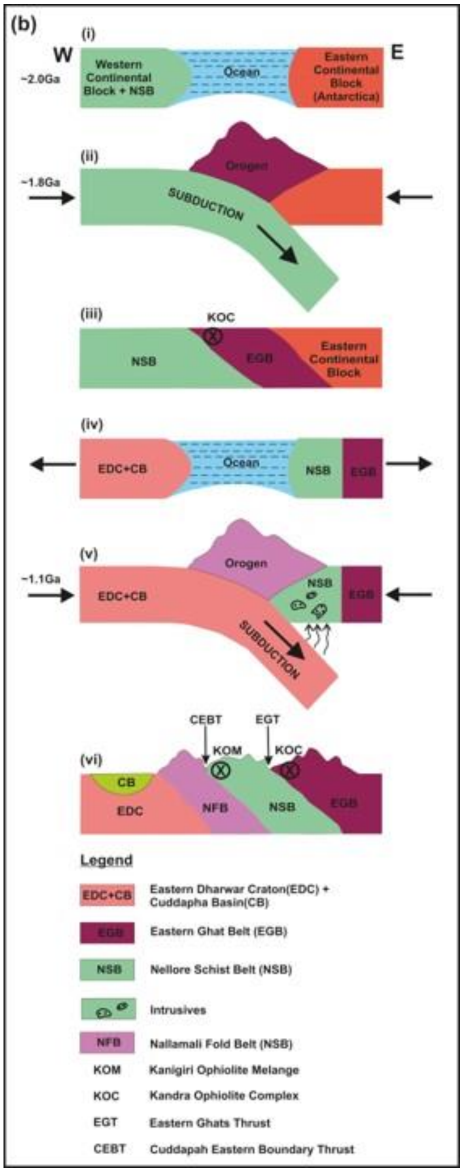

Figure 6b. A schematic model illustrating the geodynamic evolutionary scenario of the Cuddapah basin derived by the seismic structures obtained here and other geological data as discussed in the text. (i) The eastern continental block (Antarctica) was separated by an ocean from the western continental block containing the Nellore Schist Belt (NSB). (ii) The western block was subducted to the east and collided with the eastern block with the formation of Eastern Ghats Orogen at ~1.8 Ga. (iii) Combined continental block showing the Eastern Ghats Thrust (EGT) and Kandra Ophiolite Complex (KOC) located between the Nellore Schist Belt and Eastern Ghats Belt. (iv) opening of an ocean between the combined Eastern

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Dharwar Craton (EDC) and Cuddapah Basin (CB) block and the eastern Continental block consisting of NSB and EGB. (v) Subduction of EDC towards the east and subsequent collision between western and Eastern blocks resulted in the formation of Nallamalai Fold Belt (NFB) at ~1.1 Ga. (vi) Present day structure shows the low-angle thrust-fault, Cuddapah Eastern Boundary Thrust (CEBT), formed during the 1.1 Ga collisional episode on the eastern margin of the Cuddapah basin. Locations of 1.8 Ga Kandra ophiolite Complex (KOC) and 1.1 Ga Kanigiri ophiolite Melange (KOM) are also shown. Evidence for the presence of ocean is derived from two periods of ophiolites and available literature referred in the text.