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DETERMINATION OF THE REGIONAL AND RESIDUAL GRAVITY ANOMALIES TO RECONSTRUCT BASIN STRUCTURES OF THE CAUVERY BASIN

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ABSTRACT

The measured gravity field of the Earth contains two main components of short wavelength residual anomalies and long wavelength regional anomalies. In the petroleum industry, the most important component is the residual anomalies which correlate with the shallow density variations in sedimentary basins. The regional anomalies are caused by deeper density contrasts in the lithospheric mantle and the Asthenosphere. The current study is focused to determine residual and regional gravity anomalies for understanding basin architecture of the Cauvery Basin. In this study, the basement of the Cauvery Basin was determined using two-way-travel time seismic data and well log data obtained from eight exploration wells. Depth data from selected 2D sections were used as input data for a Mathematica® program which developed based on the iterative algorithm to calculate the residual gravity anomaly caused by a 2D polygonal body having a density contrast with the surrounding. The difference of the calculated and the observed gravity was then used to obtain the regional gravity along the arbitrary survey lines. Results show that the regional gravity ranged from about -50 mGal to 70 mGal with having a relatively high gravity anomaly in the central part of the Cauvery Basin. According to the regional tectonic settings, the high gravity anomaly can indicate a crustal thinning process that occurred during the rifting phase of the basin. The residual gravity anomaly of the Cauvery Basin ranged from about -60 mGal to 20 mGal and it follows the horst and graben structures. In summary, several undiscovered sub-basins were identified related to the rifting of (i) East–West Gondwana (ca. 167 Ma, NE–SW trending structures) and (ii) the East India–Antarctica (ca. 137 Ma, NW–SE trending). Therefore, this study can be productively used for mapping the structural elements and architecture in terms of considering the most favorable locations for future hydrocarbon exploration in the Cauvery Basin.

Keywords: *Plate reconstructions, Rift tectonics, Crustal structure, Gravity anomalies, Cauvery Basin*

INTRODUCTION

The fluctuations of the gravity anomaly depend on mainly subsurface geology on the Earth. Sedimentary basins exhibit negative free-air gravity anomalies due to the low density of sediments compared to the density of the surrounding hard rocks. In contrast, ridges and interbasinal highs can record positive free-air gravity anomalies (Rao, 1986; Karner et al., 2005; Watts, 2018). The gravity anomaly is thus a sensitive indicator to determine geological processes for formation and development of sedimentary basins such as rifting, sedimentation, compaction, erosion, crustal intrusions that have shaped the sedimentary basins through time (Granser, 1987; Georgen et al., 2001; Dickson et al., 2003). The gravity modeling considering the geological processes is known as the “process-oriented” model approach. However, gravity measurement can be controlled by several other factors such as mainly latitude and terrain topography (Anderson et al., 1973; Karner and Watts, 1983; Hayling et al., 1996; Watts, 2018). Therefore, gravity corrections are required for the observed raw data.

The latitude and altitude corrected gravity data is known as free-air anomalies which use commonly offshore as air-borne gravity surveys. Bouguer correction is considerably important to determine altitude and topographic effect in the continental regions. The corrected gravity anomalies contain two main components of short wavelength residual anomalies and long wavelength regional anomalies (McKenzie, 1967; Hayling et al., 1996; Tong et al., 2018). The short wavelength residual anomalies can associate with shallow density variations such as sedimentary basins and igneous intrusions. The long wavelength regional anomalies link with the deeper density contrasts in the lithospheric mantle and the Asthenosphere (McKenzie, 1967; Le Pichon and Talwani, 1969; Malengreau et al., 1999; Georgen et al., 2001). The process-oriented gravity modeling in the marine area using the short wavelength residual anomalies and long wavelength regional anomalies have become considerably important in hydrocarbon exploration and oceanography. Petroleum exploration companies use typically gravity data to determine the architecture of frontier offshore sedimentary basins during the reconnaissance survey (e.g., Ravaut et al., 1998; Mammo, 2012; Radhakrishna et al., 2012; Tong et al., 2018).

In this paper, the authors investigated the regional and residual gravity anomalies for a better understanding of the frontier offshore sedimentary basin in Sri Lanka, namely the Cauvery Basin (Figure 1). The Cauvery Basin is the shallowest offshore sedimentary basin in Sri Lanka which covers both onshore and offshore areas. A lot of islands in the Cauvery Basin make it one of the most challenging regions to acquire seismic data for determining subsurface geology and basin architecture. The gravity survey can thus be identified as a potential way to determine geological structures and trends in the region. Besides, the gravity survey can be used to identify potential targets for an optimally designed seismic survey in a later stage.

The main objective in interpreting gravity data of the present study is to investigate (i) the basin structure considering the separating sediments from the interbasinal highs, (ii) the geometry and structural continuity, and (iii) the rift architecture and the deeper crustal structure of the region. The understanding of these objectives is thus important for evaluating the future hydrocarbon explorations in the Cauvery Basin.

STUDY AREA

Sri Lanka consists of three offshore sedimentary basins namely, the Mannar, the Cauvery, and the Lanka Basins (Figure 1). Geological and gravity surveys suggested two small pockets of Jurassic sedimentary rocks in onshore Andigama and Tabbowa Basins (Tanrigoda and Geekiyanage, 1991; Ratnayake and Sampei, 2015), and a considerable gravity depression in the Jaffna Peninsula suggesting that an underlying sedimentary basin (Hatherton et al., 1975, Tanrigoda and Geekiyanage, 1988). The Cauvery Basin is a failed-rift situated in a shallow water environment between Sri Lanka and India. The Sri Lankan part of the Cauvery Basin is located approximately 9º N – 10º N and 79º E – 81º E with an apparent area of 20,000 km^2 (Kularatne et al., 2015).

TECTONIC EVOLUTION

Sri Lanka is composed of amphibolite to granulite facies high-grade metamorphic rocks of Precambrian age (Cooray, 1984; Kröner et al., 1987). The Cauvery Basin has primitively evolved as a failed-rift basin due to the continental rifting and seafloor spreading between East–West Gondwana about 167 Ma (McKenzie and Sclater, 1971; Norton and Sclater, 1979). This tectonic evolution is followed by segmentation of tectonically and geomorphologically distinctions several sedimentary basins in the Indian Plate such as the Cauvery Basin, Krishna–Godavari, Bengal Basin (Figure 1). Geophysical surveys and well log data suggested NE–SW trending horst–graben structures in all sedimentary basins formed during the rifting event of 167 Ma (Rao, 2001; Gupta, 2006; Radhakrishna et al., 2012). The second phase of Gondwana breakup was occurred due to the separation of India/Sri Lanka from east Gunnerus Ridge, East Antarctica (ca. 130 Ma, Sreejith et al., 2008). The oldest magnetic anomaly M11 (134 Ma) about 125 km south of Sri Lanka also supports this idea. According to Desa et al. (2006), the separation of Sri Lanka occurred simultaneously with the rifting of India from East Antarctica. Several investigations have demonstrated that the eastern continental margin of India (Figure 1) developed into two sections of (i) northern rifted part and (ii) southern sheared (transform) part (e.g., Subrahmanyam et al., 1999; Chand et al., 2001). Similarly, Curray (1984) has proposed that the possible continental stretching processes between India and Sri Lanka have contributed to the initiation of the offshore sedimentary basins. Yoshida et al. (1992) also concluded about 30° counterclockwise rotation of Sri Lanka with regard to India during the rifting. The Greater Indian (India–Sri Lanka–Laxmi Ridge–Seychelles–Madagascar) had experienced several continental rifting over geological time (Krishna et al., 2006; Chatterjee et al., 2013). These rifting processes were associated with several episodes of volcanism (ca. 88 Ma, 70 Ma, 65 Ma) in the Indian plate (Sreejith et al., 2008; Tantawy et al., 2009; Chatterjee et al., 2013). The collision of the Indian and Asian plates had played the main role in the formation of the Himalaya and deposition of thick passive margin sedimentary profiles in Sri Lanka and Indian continental margins (Molnar and Tapponnier, 1975). Therefore, in summary, the Cauvery Basin is located at a critical point concerning tectonic evolution in western and eastern continental margins of the Indian plate.

METHODOLOGY

Petroleum Resources Development Secretariat, Sri Lanka (PRDS) repository recorded acquired seismic reflection data over Indian and Sri Lankan sides of the Cauvery Basin during the 1970's and 1980's by different consortia such as Compaigne General de Geophysicque, Western Geophysical, Pexamin Pacific, Cities Services and Petro Canada (Ratnayake et al., 2017). Two-way-travel time (TWT) cross-sections (basement depth maps) were prepared to the basement based on seismic data by a New South Global PTY Ltd. In this study, TWT cross-sections were used as a reference for determining the thickness of sediments over the crystalline basement in the Cauvery Basin.

The digital version of the map was geo-referenced using ArcGIS 10.1 software package by converting the coordinate system from geographic to Universal Transverse Mercator (UTM) projection. The map was then exported as a Tagged Image File Format (.tiff) for compatible with the IHS Kingdom software.

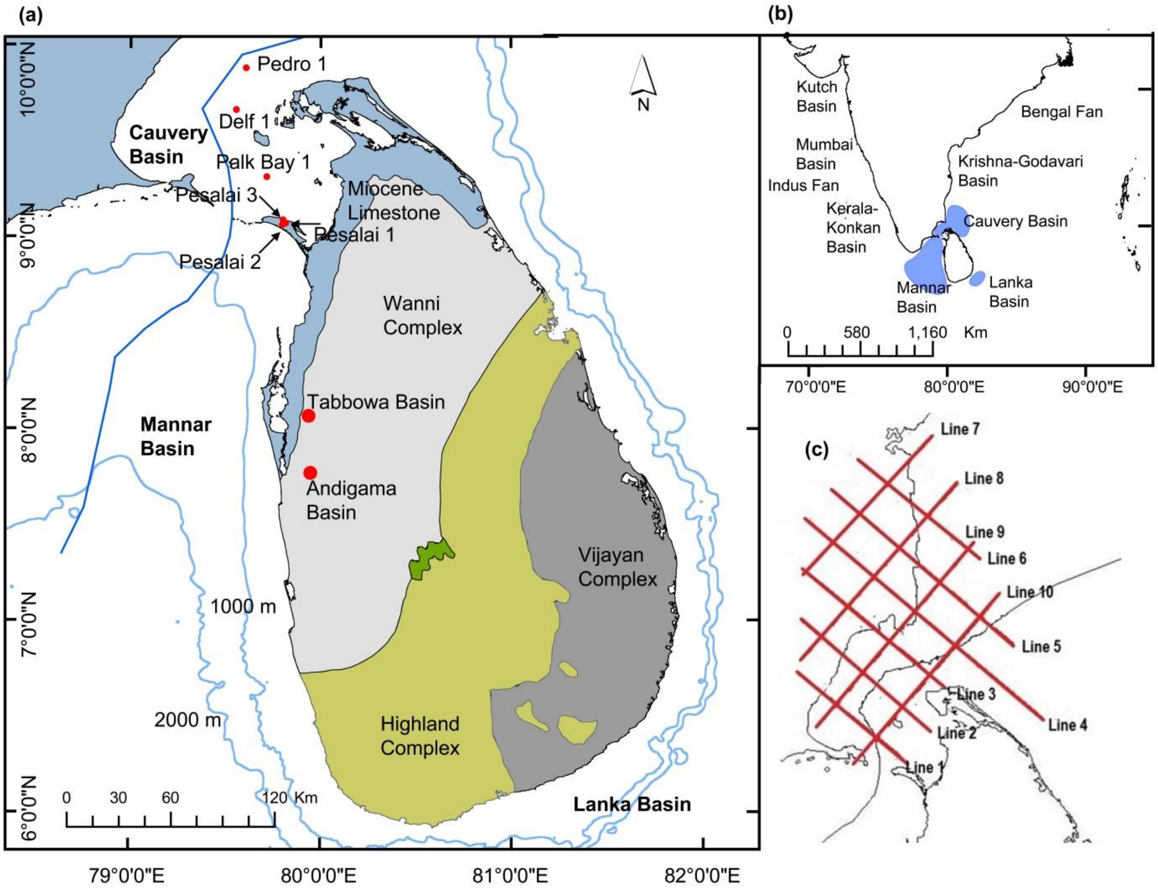

Fig. 1. (a) *Simplified geological map of Sri Lanka showing the Cauvery, Mannar, Lanka Basins and onshore Andigama and Tabbowa Basins, (b) Regional map showing major offshore sedimentary basins in Sri Lanka and India, and (c) Inserted map showing the arbitrary survey lines of the gravity survey.*

After that, the contour lines were digitized with 500 milliseconds contour intervals using the IHS Kingdom software. Major faults were also digitized as well, and then a two-way-travel time grid of the subsurface was created using the flex gridding method of Kingdom software.

The forward modeling of gravity requires actual depth in meters. Therefore, TWT and depth correlations were obtained based on velocity surveys of eight exploration wells in both Sri Lankan and Indian sides of the Cauvery Basin. The well logs data from the Sri Lankan side was obtained from the three exploration wells, named as Palk Bay-1, Delft-1, and Pedro-1 (Figure 1). The well log data of Nagapatnam-1, Mandapam deep-1, Mannar 1-1A, Tirutturaippundi-2, and Karaikkal-9 in the Indian side was obtained from well reports and logs at PRDS data repository obtained through the data exchange program with India in 1976. The data was loaded to the IHS Kingdom software and an average velocity grid was created using the gradient projection gridding algorithm. The determination of the actual depths was carried out by the average velocity map tool in the IHS Kingdom software using a previously prepared velocity model and a time-depth grid (in seconds). The Talwani's algorithm was executed to determine the vertical component of the gravitational attraction. The Wolfram Mathematica® 8 program "calgravity2d.nb" was also written (Appendix 1). The x– and z– coordinates of the vertices of the polygonal body (in km) in a counterclockwise sense were introduced to the program. Data accumulation was carried by 10 arbitrary lines covered the entire Cauvery Basin

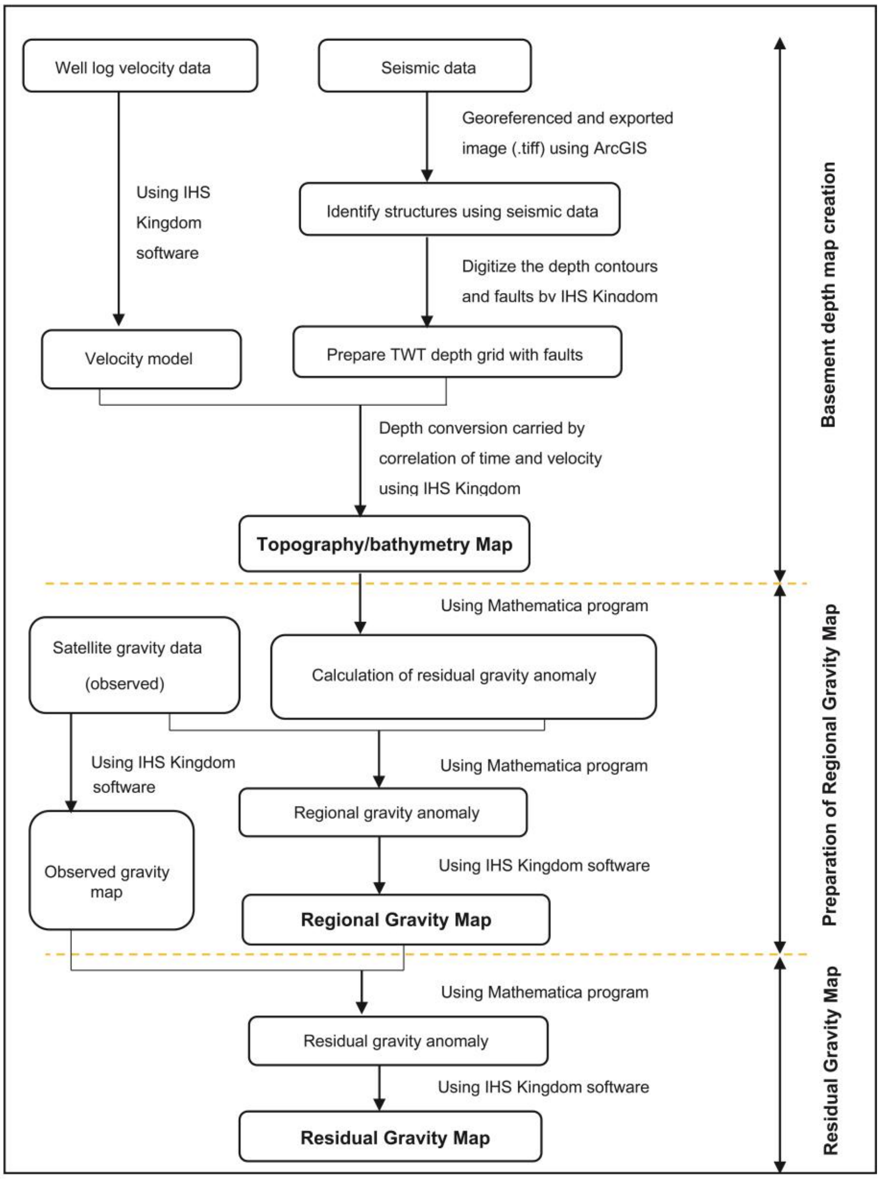

Fig. 2. *The summarized methodology of the study.*

(Figure 1) with extensive knowledge of the subsurface geology.

Satellite-based free-air gravity data from http://topex.ucsd.edu were used in the present study for investigating tectonic/structural relationships and regional tectonic interpretations (e.g., Sandwell and Smith, 1997). The density contrast (in gcm^{-3}), the number of vertices in the polygonal body, number of field points for the calculation of the anomaly and the interval between adjacent field points were also given as inputs. Density contrast was calculated as the difference between the density of the material that had replaced the originally existed material and the density of the originally existed material. Previously calculated residual gravity of the selected lines was then compared with the observed gravity along those lines. The difference of the calculated residual gravity and the observed gravity was then calculated to obtain the regional gravity along the lines. The regional gravity calculated along the lines was then loaded into IHS Kingdom software to create a regional gravity grid of the area of interest. The regional gravity map was then created by interpolating the results obtained above to incorporate the Jaffna peninsula. Therefore, in summary (Figure 2), IHS Kingdom software was used to create a regional velocity model of the subsurface, gridding, contouring, and data extraction and visualizing of gravity and basement data. Wolfram Mathematica software package was used for 2D forward modeling of gravity data, data manipulation, and cross-section visualization.

RESULTS AND DISCUSSION

RECONSTRUCTION OF THE BASIN ARCHITECTURE

Figure 3 shows the generated basement depth map of the Cauvery Basin. The depth of the study area of the Cauvery Basin ranged from 0.06–5.09 km in depth. Different subsurface depths (Figure 3) provided a sense of sub-basins in the study area. The basement depth map is required in the next stage for obtaining depths for residual gravity calculation.

According to the basement depth data, 2D gravity anomaly was calculated along the arbitrary lines (Figure 4). The representative comparison between the calculated residual gravity and the observed gravity anomalies along the arbitrary line 1 is shown in Figure 4b. The depth to the basement and the calculated regional gravity are shown in Figure 4a and Figure 4c, respectively. The basement depth, calculated residual gravity, observed gravity, and calculated regional gravity of other arbitrary lines are shown in Appendix 2. The residual gravity is the result of deducted regional gravity from observed gravity. The regional gravity is thus theoretically the difference between observed gravity and calculated residual gravity as shown in Figure 4c. Therefore, the calculated regional gravity anomalies along 10 arbitrary lines were incorporated to map in Figure 5. The calculated regional gravity anomalies ranged from about -50 to 70 mGal (Figure 5).

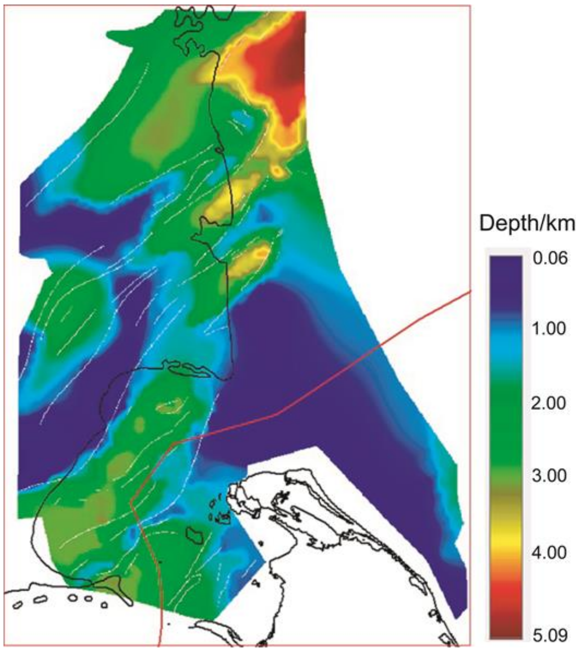

Fig. 3. *Topography/bathymetry map of the Cauvery Basin.*

This regional gravity map was extrapolated for the interesting study area for preparing the residual gravity map (Figure 6) for interpreting subsurface features. The residual gravity anomaly varied from about -60 to 20 mGal in the region, and follows the horst and graben structures trending in the NE–SW direction (Figure 6). Therefore, the variations of residual gravity anomaly indicate the compartmentalization of the Cauvery Basin into sub-basins as demarcated by yellow rectangular in Figure 6. It indicates that the basement structure has controlled the distribution of gravity anomalies (e.g., Dickson et al., 2003; Mammo, 2012; Radhakrishna et al., 2012; Tong et al., 2018).

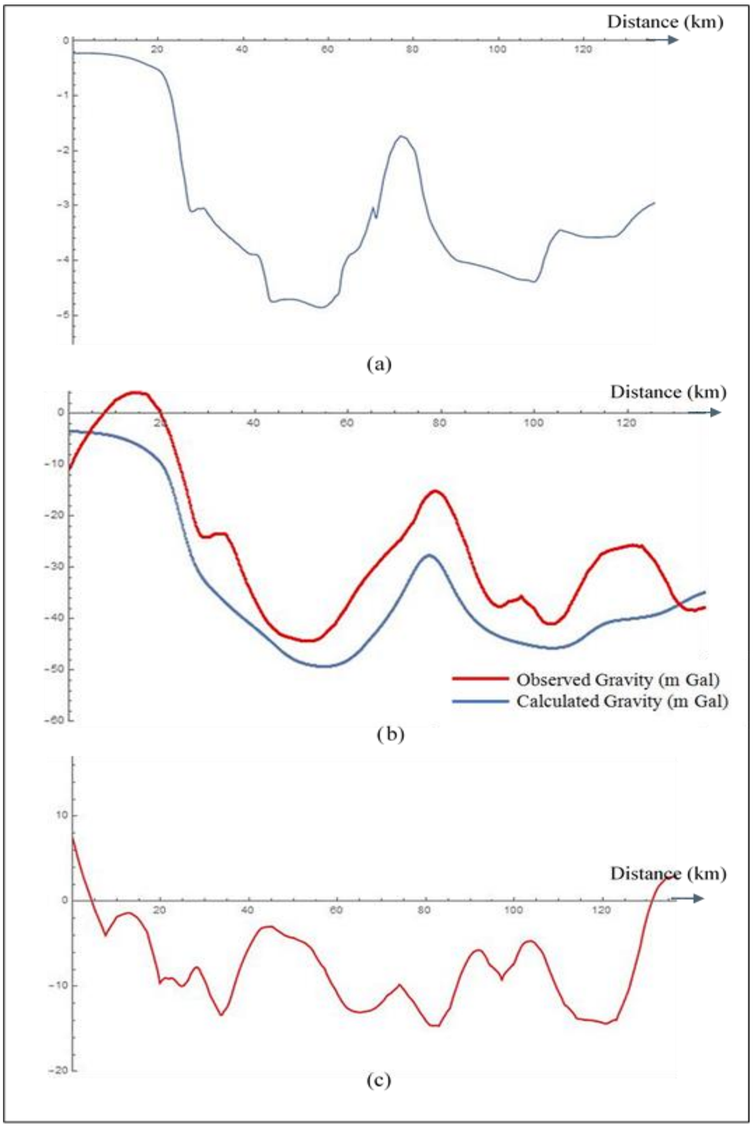

Fig. 4. *(a) Basement depth (b) Comparison of observed gravity and calculated residual anomaly (c) Regional gravity anomaly of along the arbitrary line 1 (m Gal).*

The grey lines represent the margin of the Cauvery Basin and white line for structural highs (Figure 6). The dashed white line can be suggested as the high anomaly impact from high regional gravity (Figure 6) due to the upwelling mantle material when the continental crust thinning process (e.g., McKenzie, 1967; Le Pichon and Talwani, 1969; Malengreau et al., 1999). The negative gravity anomaly over the Jaffna Peninsula has reduced from -70 mGal in the observed free-air gravity to about -30 mGal, after the preparation of residual map based on regional gravity map (Figure 6). Therefore, the orientation of anomalies indicates the extension of a sub-basin towards the Jaffna Peninsula. Another negative anomaly observed in the east of the Jaffna Peninsula as a sub-basin as shown in a dashed yellow rectangular (Figure 6). This sub-basin was separated from the gravity anomaly over the Jaffna peninsula by the N-S trending linear gravity high (Figure 6).

The NW–SE oriented negative gravity anomaly towards the east of Jaffna Peninsula (Figure 6) suggested that the sub-basin is not related to the origin of the Cauvery Basin about 167 Ma (Rao, 2001; Gupta, 2006; Bastia et al., 2010; Radhakrishna et al., 2012). Therefore, it can be related to the rifting of East India–Antarctica about 130 Ma (Sreejith et al., 2008; Bastia et al., 2010; Chatterjee et al., 2013). Therefore, this rifting has happened in a much later stage compared to the rifting episode of the Cauvery and Mannar Basins about 167 Ma (Ratnayake et al., 2018). Besides, the N–S trending linear gravity high can indicate the basin bounding fault of the Cauvery Basin in the Sri Lankan side. However, this interpretation should further collaborate with additional seismic and well data acquired in the future.

ASSUMPTION AND LIMITATIONS

The obtained free-air satellite gravity data consist of low resolution due to the distance of acquisition. Therefore, the regional air-born gravity and gravity gradiometry surveys can provide high-resolution gravity data to further interpret the subsurface features and their trends in higher accuracy. The calculations of Talwani et al. (1959) and Lowrie (2007) assumed that the gravity anomaly is infinitely extended parallel to the strike of the anomalous body. However, the anomalous body occupies a limited volume in the three-dimensional space and its lateral extents are finite. Therefore, the result could have been slightly affected by this assumption. In this study, the low-resolution seismic and well data were used for preparing the basement depth map which was acquired during the 1970's and 1980's (Ratnayake et al., 2017). Therefore, a substantial degree of error can be recorded in the basement depth calculations. The velocity model was prepared using velocity data of eight exploration wells covering a comparatively large area in both Sri Lankan and Indian sides of the Cauvery Basin. Therefore, this velocity model can be further refined in the future by adding additional well logs data.

The gravity can be calculated based on the density contrast of sedimentary rocks and metamorphic basement rock. The average density value of the sedimentary rocks is 2.40gcm^{-3} based on density and sonic logs obtained from the PRDS data repository of Pedro -1, Delft -1, and Palk Bay-1 drilled wells in the Cauvery Basin from 1976 to 1982. According to Woollard and Malahoff (1966), the average density of the metamorphic basement is 2.67gcm^{-3}. This specific density contrast is defined in Mathematica program "calgravity2d.nd" as -0.27gcm^{-3}. In contrast, the density values of the sedimentary rocks can vary based on the buried depth and depositional environment (Granser, 1987; Rao, 1990; Barbosa et al., 1999). The density value for the metamorphic basement in the region can also vary based on its original mineralogical compositions. Therefore, the comprehensive density values considering stratigraphy and facies variations, diagenesis, and tectonic history

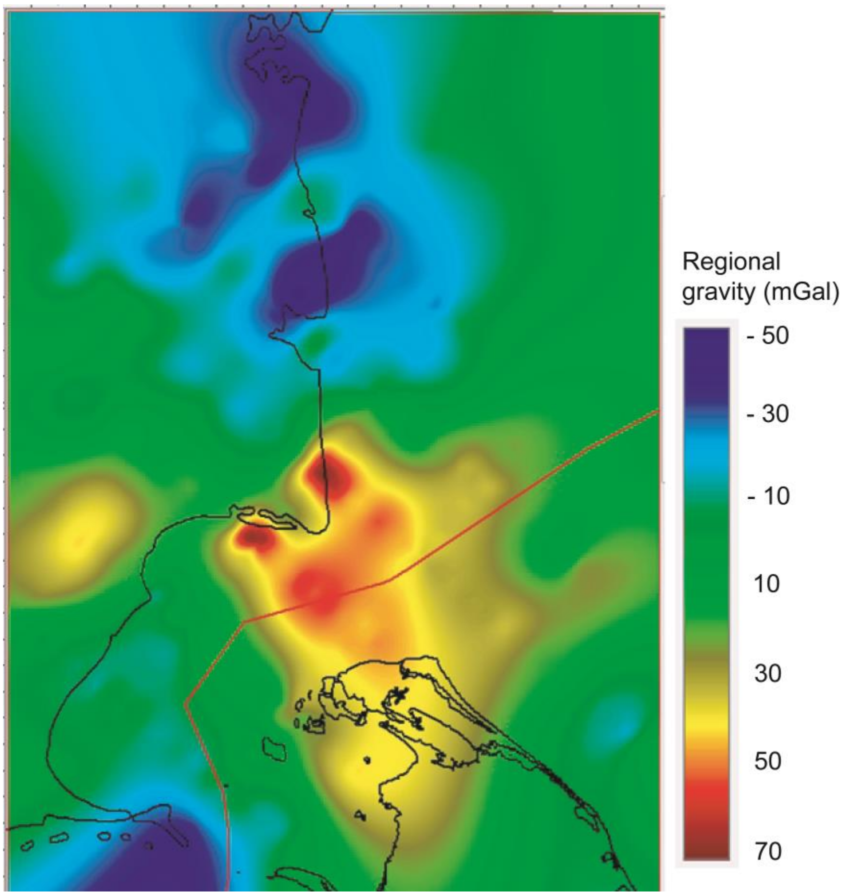

Fig. 5. *Interpretation of regional gravity map of the Cauvery Basin (mGal).*

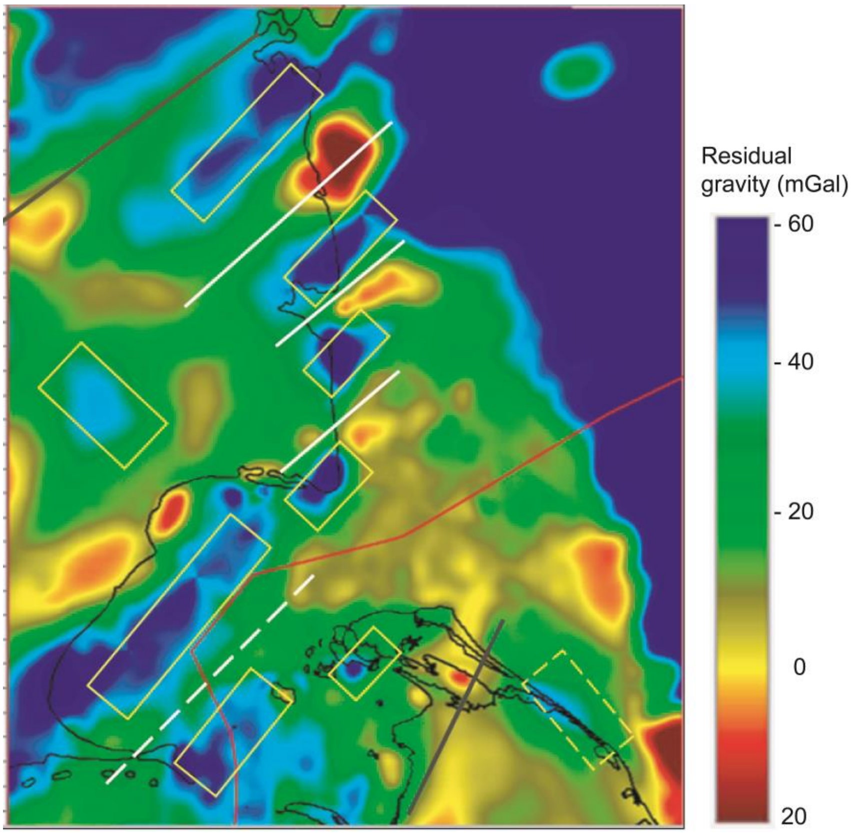

***Fig. 6.** Interpretation of residual gravity map of the Cauvery Basin (mGal).*

are required for understanding in detailed gravity interpretations of the Cauvery Basin (e.g., Granser, 1987; Barbosa et al., 1999).

The water depth values were ignored in the forward modeling of gravity in this shallow water basin. The elevation difference/topography can also contribute to altering in the gravitational field in the terrestrial region of the Cauvery Basin. However, the land area of the Cauvery Basin shows no considerably mass variations/elevation changes and thereby assumed to have a negligible contribution for the calculated gravitational field.

CONCLUSIONS

The present study provided a powerful means for mapping the structural elements and architecture of the Cauvery Basin. The high gravity anomaly of the regional gravity map in the central part of the basin can indicate the crustal thinning process. This process was occurred during the rifting phase of the basin and confirms an upwelling of the mantle into the crust. However, similar to the Mannar Basin, rifting has not progressed up to the formation of an oceanic crust for initiating a new spreading center. According to the regional tectonic setting and NE–SW trending residual gravity map (range from -60 mGal to 20 mGal), the Cauvery Basin can be considered as an extension of the failed-rift Mannar Basin with structural elements of basement highs (horsts), depression of the basement (grabens) and basin bounding faults. The negative gravity anomaly over the Jaffna peninsula (-30 mGal) has suggested the extension of a sub-basin towards the Jaffna peninsula. The negative anomaly of NW–SE trending sub-basin in the east of the Jaffna peninsula can evolve related to the rifting of East India–Antarctica. However, this rifting stage has occurred later stage (ca. 137 Ma) compared to the early rifting episode (ca. 167 Ma) of the Cauvery and Mannar Basins. The boundary of the Cauvery Basin (in the Sri Lankan side) can be recognized using the N–S trending linear gravity high separating over the Jaffna Peninsula.

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