30. Bhattacharya, A., Mazumdar, A. C. and Sen, S. K., Fe–Mg mixing in cordierite: constraints from natural data and implication for cordierite–garnet geothermometry to granulite. *Am. Mineral.*, 1988, **73**, 338–344.

31. Aranovich, L. Y. and Podlesskii, K. K., Geothermobarometry of high-grade metapelites: Simultaneously operating relations. In *Evolution of Metamorphic Belts* (eds Daly, J. S., Cliff, R. A. and Yardley, B. W. D.), Geol. Soc. Spec. Publ., 1989, vol. 43, pp. 45–61.

32. Perchuk, L. L., Derivation of a thermodynamically consistent set of geothermometers and geobarometrs for metamorphic and magmatic rocks. In *Progress in Metamorphic and Magmatic Petrology (A Memorial Volume in Honour of D. S. Korzhinsky)* (ed. Perchuk, L. L.), Cambridge Univ. Press, 1991, pp. 93–111.

33. Nichols, G. T., Berry, R. F. and Green, D. H., Internally consistent gahnitic spinel–cordierite–garnet equilibria in the FMASHZn system; geothermobarometry and application. *Contrib. Mineral. Petrol.*, 1992, **111**, 362–377.

34. Sen, S. K. and Bhattacharya, A., An Opx–Gt geothermometer and its application to the Madras charnockite. *Contrib. Mineral. Petrol.*, 1984, **88**, 64–71.

35. Harley, S. L., An experimental study of the partitioning of Fe and Mg between garnet and orthopyroxene. *Contrib. Mineral. Petrol.*, 1984, **86**, 359–373.

36. Lal, R. K., Internally consistent recalibrations of mineral equilibria for geothermobarometry involving garnet–orthopyroxene–plagioclase–quartz assemblages and their application to the South Indian granulites. *J. Met. Geol.*, 1993, **11**, 855–866.

37. Perchuk, L. L. *et al.*, Precambrian granulites of the Aidam Shield, eastern Siberia. USSR. *J. Met. Geol.*, 1985, **3**, 265–310.

38. Bhattacharya, A., Some geobarometers involving cordierite in the FeO–Al₂O₃–SiO₂ ($\pm$ H₂O) system: refinements, thermodynamic calibration and applicability in granulite facies rocks. *Contrib. Mineral. Petrol.*, 1986, **98**, 387–394.

39. Bohlen, S. R., Wall, V. J. and Boettcher, A. L., Experimental investigation and application of garnet–granulite equilibria. *Contrib. Mineral. Petrol.*, 1983, **83**, 52–81.

40. Perkins, D. and Chipera, S. J., Garnet–orthopyroxene–plagioclase–quartz barometry: refinement and application to the English river subprovince and the Minnesota River Valley. *Contrib. Mineral. Petrol.*, 1985, **89**, 69–80.

41. Bhattacharya, A., Krishnakumar, K. R., Raith, M. and Sen, S. K., An improved set of *a–x* parameter for Fe–Mg–Ca garnet and refinement of the opx–gt thermometer and the opx–gt–plagioclase–qtz barometer. *J. Petrol.*, 1991, **32**, 629–656.

Generation of very high resolution gravity image over the Central Indian Ridge and its tectonic implications

T. J. Majumdar*, R. Bhattacharyya and S. Chatterjee

Earth Sciences and Hydrology Division, Marine and Water Resources Group, Remote Sensing Applications and Image Processing Area, Space Applications Centre (ISRO), Ahmedabad 380 015, India

Satellite altimetry can be used to infer subsurface geological structures analogous to gravity anomaly maps generated through ship-borne survey. In this study, free-air gravity image has been generated over the Central Indian Ridge using very high resolution database as obtained from Geosat GM, ERS-1, Seasat and TOPEX/POSEIDON altimeter data. Isostatically compensated regions could be identified with all fracture zones clearly demarcated in this map.

THE segment of the northern branch of the mid-Indian Ocean ridge system, which lies between Rodriguez Triple Junction and the equator, broadly forming a north–south lineation, is referred as the Central Indian Ridge (CIR)[1] (Figure 1). The Indian Ocean has experienced, along with three main phases of seafloor spreading, two major plate reorganizations from the late Jurassic to the present. The first phase of spreading started in the northwest–southeast direction and resulted in India's movement away from Antarctic–Australia during the early Cretaceous. During the middle Cretaceous, it appears that the Indian plate rotated from its early NW–SE to N–S direction and moved at a slow spreading rate. During the second phase of spreading, India drifted in the north–south direction from Antarctica with a rapid speed of 11 to 7 cm/yr. The Indian and Australian plates merged and formed a single Indo-Australian plate during the middle Eocene. The third phase of spreading was initiated in the northeast–southwest direction, and appears to continue since then. Also, ridge jumps occur as tectonic events and create more complexity to the evolution of ocean floor, besides plate reorganizations. Due to the processes of ridge jumps and frequent readjustment of the ridge segments, the northern part of the present-day CIR came into existence since the past 30 Ma.

The CIR complex has not been sufficiently explored using satellite geoid/gravity data. Satellite altimetry has recently emerged as an efficient alternative for expensive and hazardous ship-borne gravity surveys[2,3]. The averaged sea surface height as obtained from satellite altimeter is a good approximation to the classical geoid, which contains

---

*For correspondence. (e-mail: tjmajumdar@sac.isro.gov.in)

information regarding mass distribution in the entire earth. The anomalies (highs and lows) in geoidal surface are directly interpreted in terms of subsurface geological features, e.g. transform faults, basement highs and lows, etc.[4]. The geoidal anomalies also are converted to free-air gravity anomalies which are particularly useful in the deep sea, where traditional ship-borne geophysical data are either unavailable or scanty. Rapp[5] has developed a method for prediction of gravity anomaly using spherical harmonic coefficients up to degree and order 30 and above. Sandwell and Smith[6] have generated marine gravity anomaly from Geosat and ERS-1 satellite altimetry. Majumdar et al.[4] have developed a brief methodology for offshore structure delineation using altimeter data. Details of the CIR along with mid-ocean ridges and InRidge Programme have been given in Iyer et al.[7].

The major objectives of this study are to develop the methods for generation of satellite-derived geoid/gravity, and then modelling and three-dimensional visualization of the CIR.

The free-air gravity image has been generated using high density database obtained from Geosat GM (Geodetic Mission), ERS-1, TOPEX/POSEIDON, and Seasat altimeter data[8] over CIR System. Due to high density (off-track resolution ~ 3.33 km), sea surface parameters as well as gravity derived from these data are more accurate and de-

tailed. Details of altimeter data and their preprocessing have been discussed elsewhere[4,8]. Part of the CIR which has been studied here, has ranges as follows: lat. 10–35°S and long. 65–85°E. Apart from the CIR, other major features in this region include Southwest Indian Ridge (SWIR), Southeast Indian Ridge (SEIR) and the Rodriguez Triple Junction (RTJ), where these three branches converge. In the plate tectonic framework, these three branches of the mid-oceanic ridges form the boundaries between the Indian, Antarctic and African major plates[1]. Details of data processing and type of adjustments for very high-resolution data were given by Hwang et al.[8]. As far as spatial resolution is concerned, Geosat GM (in the high resolution dataset) is the highest (~ 3.5 km) followed by ERS–1/2 (~35 km), Seasat (~ 100 km), and TOPEX (~ 250 km), whereas in the case of amplitude, TOPEX has more accurate information compared to others. Hwang has done detailed data assimilation using these datasets and Levitus topography utilization for calculation of the deflection of the vertical and then generating 2 × 2 min (4 km × 4 km) grid.

Details of the methodology for obtaining geoid and gravity from altimeter-derived sea surface height have been discussed elsewhere[4,6]. In a simplistic plate model, plate thickness and mean seafloor depth increase with square root of the edge. Geoid anomaly/gravity observed
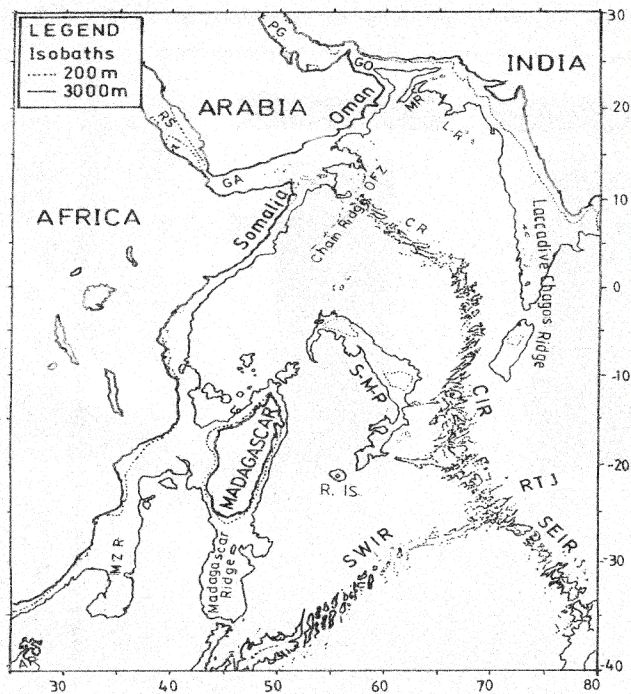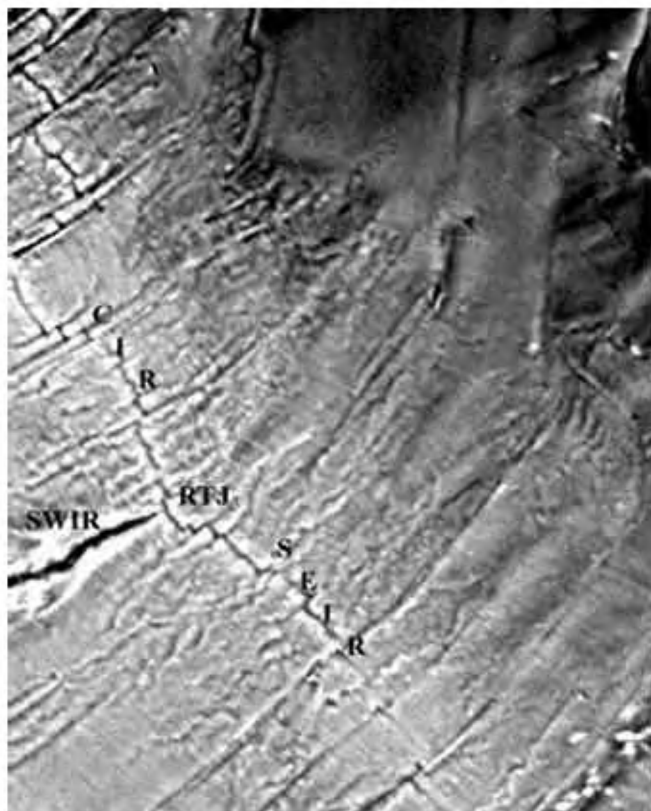

Figure 1. Location of Central Indian Ridge (after Bhattacharya and Chaubey[1]). (CIR, Central Indian Ridge; SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge; RTJ, Rodriguez Triple Junction; R.Is, Reunion Island; CR, Carlsberg Ridge; LR, Laxmi Ridge; OFZ, Owen Fracture Zone; MR, Murray Ridge; MZR, Mozambique Ridge; SMP, Seychelles–Mascarene Plateau Complex; RS, Red Sea; GA, Gulf of Aden; PG, Persian Gulf; GO, Gulf of Oman).
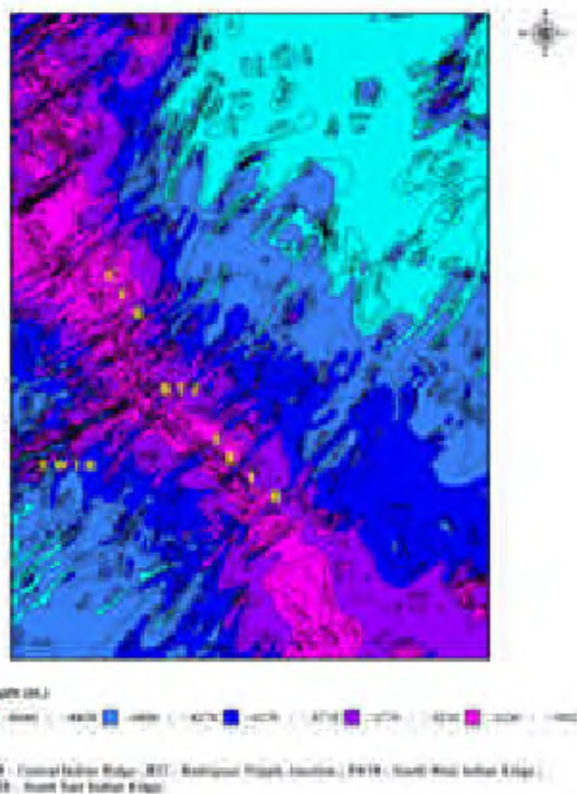

Figure 2. Bathymetry contour map generated from ETOPO5 data over the study area.

over the spreading ridges and fracture zones can be analysed to estimate the age of the seafloor. Since it is reasonable to assume that fracture zones are nearly in isostatic equi-

Figure 3. Free-air gravity image over the CIR as obtained from high-resolution database. (CIR, Central Indian Ridge; SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge; RTJ, Rodriguez Triple Junction).
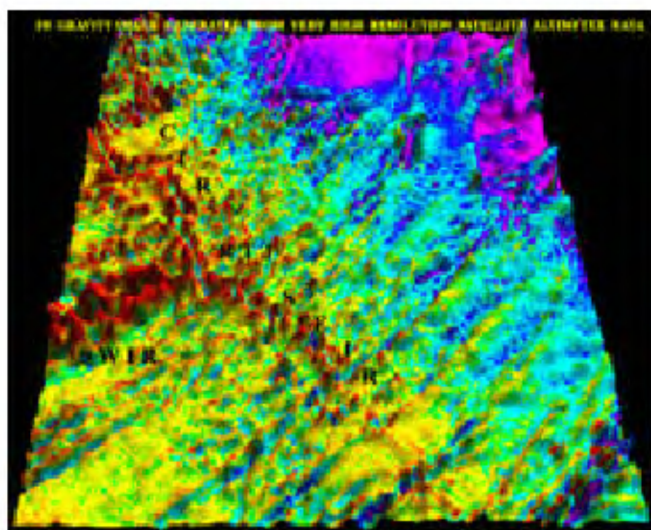
Figure 4. 3D gravity image generated from very high resolution satellite altimeter data over the Central Indian Ridge. (CIR, Central Indian Ridge; SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge; RTJ, Rodriguez Triple Junction).

librium, geoid variation occurs because portions of the lithosphere on each side of the fracture have different thickness and density structure[9]. The geoid/gravity anomaly can thus be directly related to the change in ages of the sea floor and hence can be utilized to estimate the crustal stability of the region beneath the seafloor[3,9].

Geotectonics over the CIR has been discussed in detail earlier[1,7]. The residual geoid undulation was extracted from the observed geoid undulation after removing the deeper earth effects which has been finally used to generate the satellite-derived free-air gravity over the CIR[4]. This residual geoid and the related gravity can be utilized for interpretation of lithospheric changes due to seafloor spreading. A major reorganization of the spreading plate boundaries in the Indian Ocean had occurred during Eocene as a consequence of the hard collision of the Indian plate with the Eurasian plate, which also leads to slow spreading rates of the Carlsberg Ridge and the CIR. In addition, the spreading rates were not found uniform since Eocene, using magnetic anomaly data[10].

ETOPO5 bathymetry image over the CIR is shown in Figure 2. Part of the CIR could be faintly demarcated in the image with bathymetry variation near and around the CIR ranging between 1500 and 3200 m. Figure 3 shows the free-air gravity image over the CIR as derived from the high-resolution database. A three-dimensional image over the CIR has been generated as shown in Figure 4. CIR, SWIR and SEIR along with RTJ can be clearly demarcated and visualized in Figures 3 and 4. In addition, different fracture zones and ridge patterns can be clearly visualized in Figure 4.

Isostatically compensated region could be demarcated with near-zero contour values in the free-air gravity anomaly images over and along the CIR axes and over most of the fracture-zone patterns. However, sharp changes have been found for the free-air gravity values as one shifts away from the ridge axes, showing deficiency in lithospheric compensation[11]. The instability measures can be estimated from the gravity image which vary between −45 to +55 mGal.

A very high resolution free-air gravity image could be generated using various altimeter data including Geosat GM, ERS-1, etc. The present data are of much higher resolution than the Sandwell and Smith[6] data. Enormous amount of data processing and related analysis is required to generate such high-quality satellite gravity images over the CIR. Hence these maps are of high quality than maps usually downloadable from the Internet.

The gravity image and its 3D visualization clearly show the major fracture patterns, seafloor spreading axes and ridge boundaries, etc., which are unique for the study of CIR in mid-oceanic ridge systems. Further studies on estimation of seafloor ages and isostatic compensation zones in the lithosphere of the CIR are in progress. For the prevailing security restrictions, lat./long. coordinates have been omitted in few images.

1. Bhattacharya, G. C. and Chaubey, A. K., Western Indian Ocean – A glimpse of the tectonic scenario. In *The Indian Ocean – A Perspective* (eds Sen Gupta, R. and Desa, E.), Oxford & IBH, New Delhi, 2001, pp. 691–729.
2. Stewart, R. H., *Methods of Satellite Oceanography*, University of California Press, California, 1985.
3. Rajesh, S. and Majumdar, T. J., Generation of 3-D geoidal surface of the Bay of Bengal lithosphere and its tectonic implications. *Int. J. Remote Sensing*, 2004, **25**, 2897–2902.
4. Majumdar, T. J., Mohanty, K. K. and Srivastava, A. K., On the utilization of ERS-1 altimeter data for offshore oil exploration. *Int. J. Remote Sensing*, 1998, **19**, 1953–1968.
5. Rapp, R. H., The determination of geoid undulations and gravity anomalies from Seasat altimeter data. *J. Geophys. Res.*, 1983, **88**, 1552–1562.
6. Sandwell, D. T. and Smith, W. H. F., Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. *J. Geophys. Res.*, 1997, **102**, 10039–10050.
7. Iyer, S. D., Mukhopadhyay, R., Drolia, R. K. and Ray, D., Mid-ocean ridges, InRidge and the future. *Curr. Sci.*, 2003, **85**, 272–276.
8. Hwang, C., Hsu, H. Y. and Jang, R. J., Global mean surface and marine gravity anomaly from multi-satellite altimetry: application of deflection-geoid and inverse Vening Meinesz formulae. *J. Geodesy*, 2002, **76**, 407–418.
9. Haxby, W. F. and Turcotte, D. L., On isostatic geoid anomalies. *J. Geophys. Res.*, 1978, **83**, 5473–5478.
10. Merkouriev, S. A. and Sotchevanova, N. A., Structure and evolution of the Carlsberg Ridge: Evidence for non-stationary spreading on old and modern spreading centres. *Curr. Sci.*, 2003, **85**, 334–338.
11. Watts, A. B., *Isostasy and Flexure of the Lithosphere*, Cambridge University Press, 2001, p. 458.

Absolute gravity measurements in India and Antarctica

V. M. Tiwari*, B. Singh, M. B. S. Vyaghreswara Rao and D. C. Mishra

National Geophysical Research Institute, Hyderabad 500 007, India

A series of absolute gravity measurements have been made at National Geophysical Research Institute, Hyderabad and at Maitri, Indian Antarctic station to establish precise reference gravity stations and also to monitor long-term gravity changes for different geophysical studies. These precise measurements are made with an FG-5 absolute gravity meter, which measures the gravitational acceleration with an accuracy of 20 nm-s^{-2} (2 μGal). Non-tidal time series of measured absolute gravity values at these locations indicate systematic daily and seasonal variation of variable amplitudes. Daily changes are probably caused due to inaccurate global tidal model used in processing of data and suggest a need for better tidal model for the Indian subcontinent. Seasonal changes appear to be mainly caused due to hydrological effects, which can be modelled to derive the aquifer parameters.

THE FG-5 Absolute Gravity (AG) meter records[1] the earth's gravity field to a precision of 1 μGal (10 nn-s^{-2}) and thus allows us to observe very small signals arising due to redistribution of mass and vertical crustal motions caused by various geodynamic processes such as earthquakes, plate convergence, isostatic rebound, etc. Absolute gravity measurements are now widely used to study: the vertical crustal deformation in conjunction with GPS for complimentary verification[2,3], mass and elevation changes due to glacial rebound[4] and actual sea-level rise[5]. Sea-level changes along the Indian coast show a large spectrum[6] and an increasing trend from south to north, which might be caused due to some tectonic and local oceanographic reasons[7]. It appears that some of the tide gauges along the Indian coast are influenced due to vertical ground motions[8] that can be constrained by AG measurements. Furthermore, a reference absolute gravity value is the basic requirement for any gravity survey carried out using a relative gravimeter. In India, absolute reference gravity stations were established during middle of the twentieth century, either with pendulum observations or with relative gravimeters by tying them to known absolute gravity values. Uncertainties in earlier absolute gravity values are rather large and not well defined due to instrumental and environmental problems. Therefore, precise reference absolute gravity value is needed. The Antarctic land mass has few absolute reference gravity stations and none near the Indian station, Maitri. Therefore, the National Geophysical Research Institute (NGRI), Hyderabad in collaboration with the Department of Ocean Development (DOD), acquired an AG meter for addressing the problems of vertical deformation near tide gauges along the Indian coast and establishing the reference gravity stations in India and Antarctica. This communication provides details on precise absolute gravity measurements made in India and Maitri, Antarctica.

An FG-5 AG meter measures the acceleration of the earth's gravity field by precisely recording the time and distance of a free-falling object inside a vacuum chamber (Figure 1). The instrument mainly consists of (i) a dropping chamber, in which retro-reflector corner cube falls freely, (ii) an ion pump that maintains vacuum (10^{-4} Pa) in the

*For correspondence. (e-mail: vmtiwari@ngri.res.in)