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Interpretation of gravity Data from Kutch (India), an intra-plate seismic region using scaling spectral method

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ABSTRACT
The gravity data of the highest seismic risk and tectonically complex region of Kutch (India) is analyzed using scaling spectral method along selected nine gravity profiles. The high-resolution multi-taper method (MTM) is used to calculate the power spectrum. The scaling spectral method provides scaling exponent and depth values, which are useful for describing the heterogeneity of the region. The depth values vary from 1 to 7 km with deeper values in the northern and southern region. The depth values and scaling exponents indicate complex nature of the crust. The calculated β values indicate a heterogeneous shallow crust in the region.

Key Words: Intra-plate Seismicity, Bhuj earthquake, Kutch, Gravity Method, Scaling Spectral Method, Fractals.

INTRODUCTION

The mechanism of intraplate earthquake genesis is poorly understood (Zoback and Richardson, 1996 and references therein). In India, two confirmed cases of intraplate earthquakes with foci in the crust, namely the 1997 Jabalpur and 2001 Bhuj (Kutch region) have been reported. The earthquake of Bhuj (26 January 2001, M_w 7.6) was the largest earthquake since 1819 in the area. There was no surface rupture but, a known tectonic feature was found responsible for the earthquake (Bodin and Horton, 2004). This earthquake was located on a moderately dipping blind thrust fault (Rastogi et al. 2001). Seismicity in the Kutch region, since 2001 Bhuj earthquake, has become central theme of debate and concern for earth scientists, to understand the nature and properties of intraplate earthquakes in the Kutch region (Gupta et al., 2001). The Bhuj earthquake occurred in the Kutch rift region, which has a long history of development from a Precambrian orogeny - referred to as the Delhi trend (Biswas, 1987). The Kutch rift appears to control the tectonics of the basin. Aftershock studies of Bhuj earthquake indicate focal depth range of 10-35 km and an earthquake activity area of 40x33 km (Singh et al. 2004).The activity was associate with an E-W trending south dipping fault zone (Mandel et al. 2004).

In the present article, gravity data is interpreted in terms of depth values and scaling exponents (β). The scaling spectral method (Pilkington et al. 1994; Maus and Dimri, 1994, 1995, 1996; Fedi et al. 1997; Dimri, 2000; Bansal and Dimri, 1999, 2001, 2005a) is applied to gravity data from the Kutch region. The method provides depth values as well as the scaling exponent (β). The β values provide information about the source distribution, which is useful in understanding the statistical properties of source distribution within the crust. These properties are important to know the dynamic processes and evolution of the crust (Wu et al. 1994). Measurements of these properties from boreholes are limited (mainly oil exploration wells) and confined to shallow depth providing only 1-D information. 2-D measurements of these properties have been extracted from surface exposed rocks and geological maps (Holliger and Levander, 1992; Pilkington and Todoeschuck, 1995). The statistical information of heterogeneities derived from the surface rocks provide the information about only surface heterogeneities, the extrapolation of these below the subsurface may not represent the true values at depth. Other means are from indirect information based on geophysical measurements. The commonly used indirect methods are seismic wave scattering, scattering attenuation or transmission fluctuations across an array (Wu et al. 1994). Gravity data can also be a useful tool in providing deeper statistical information of the crustal heterogeneity. Knowledge of crustal heterogeneity is useful in estimation of the propagation of seismic waves, distribution of stress field, fluid flow, rock strength and monitoring hydrocarbon reservoirs (Wu et al. 1994, Marsan and Bean, 1999; Leary, 2002).

The Kutch area has long history of development from the Precambrian and is overlain by number of faults like Kutch mainland fault, South Wagad fault and various lineaments (Fig. 1).The present study will enhance our understanding of the crustal behavior and may also throw light on the dynamic processes in the highest seismic risk zone of Kutch, western India.

Scaling Spectral Method

The scaling spectral method incorporates realistic scaling distribution of sources and calculated depth values are more close to the realistic values (Pilkington et al. 1994; Maus and Dimri, 1996, Bansal and Dimri, 1999). The scaling spectral method provides average depth values of

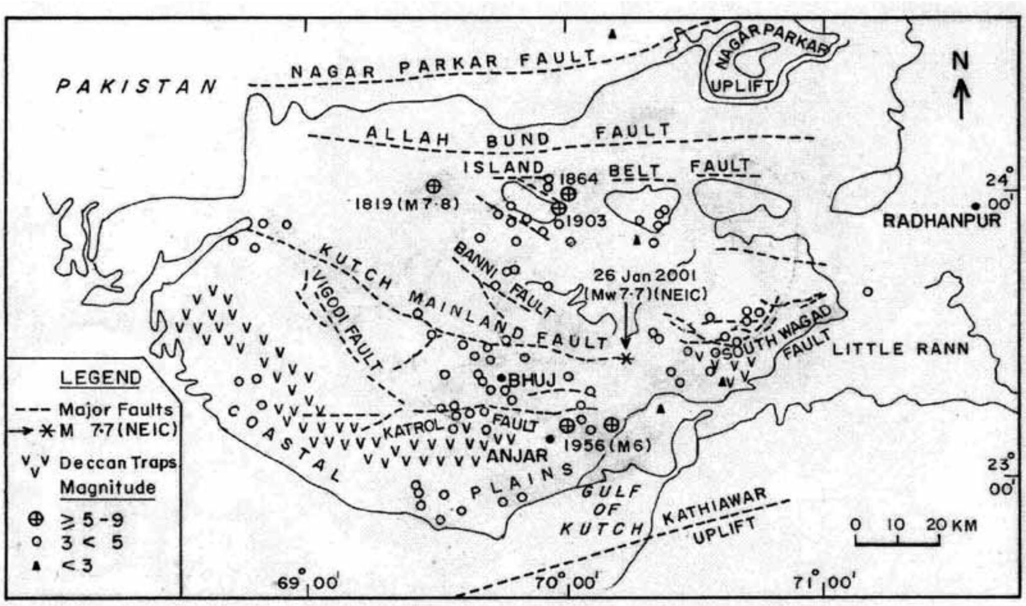

Figure 1. Geology and major tectonic features of the Kutch region showing major tectonic faults and historical seismicity (modified after, Biswas, 1987). Little RUNN (salt pans, low lying area) are the characteristic features of NEO tectonic movements.

anomalous sources and a measure of the distribution of spatial variations of the sources in terms of the scaling exponent (β). In scaling spectrum method the power spectrum of the gravity field can be represented as:

$$P(k) = A\, k^{-\beta} e^{-2kd}$$

Where P(k) is power spectrum, k is wavenumber, A is constant, β is scaling exponent and d is the depth of anomalous source.

In this study, depth values of anomalous sources and scaling exponents are calculated by using least square inverse method. The method is found useful in interpreting the gravity and magnetic data in many parts of the world, including Indian sub continent. For example, interpretation of Bouguer gravity field along the Nagaur – Jhalawar Transect (Bansal and Dimri, 1999), Jaipur – Raipur Transect (Bansal and Dimri, 2001) and Kuppam – Palani Transect (Bansal et al. 2006a) in the western, central and southern parts of the India show a reasonably good match between the depth values from gravity and seismic investigations. The scaling distribution of sources can also be related to the fractal distribution of sources. The fractal distribution is also found suitable for modeling gravity and bathymetry data (Bansal and Dimri, 2005b). The scaling distributions of sources are also implemented in estimation of Curie depth from the aeromagnetic data (Maus et al. 1997; Bouligand et al. 2009; Bansal et al. 2011, 2013). Bansal and Dimri (2014) presented a review of scaling spectral method and its applications.

The high-resolution Multi Taper Method (MTM) is applied to calculate the power spectrum. The MTM was developed by Thomson (1982) to overcome the limitations of the popularly used Fast Fourier Transform (FFT) method, where power spectrum is calculated by applying the orthogonal tapers to the dataset and then average the resulting power spectra (Thomson, 1982; Percival and Walden, 1993). The MTM is also found suitable for finding the scaling exponents from the geophysical data (McCoy et al. 1998, Bansal et al. 2010). McCoy et al. (1998) compared calculated values of scaling exponents using the FFT, maximum entropy method (MEM) and the MTM. McCoy et al. (1998) found less mean square error using the MTM as compared to the FFT and the MEM. Bansal et al. (2010) found more reliable values of scaling exponents from density and susceptibility log of KTB borehole from the MTM. Bansal et al. (2006b) compared the FFT, the MEM and the MTM in calculation of depth values by scaling spectral method.

Geology and tectonics of Kutch

The Kutch basin is a pericratonic rift basin bounded by Nagar Parkar fault in the north and Kathiwar fault in the south (Fig. 1) (Biswas, 1987). Development of faults in the Kutch region was related to the break-up of eastern Gondwanaland from western Gondwanaland in the late Triassic / early Jurassic by a subsidence process between Nagar Parkar fault and Kathiwar fault (Biswas, 2005). The rifting was aborted along Kutch main land fault during the Late Cretaceous due to uplift processes and then became a shear zone with strike-slip movements (Biswas, 1987, 1992). The basin is filled with Mesozoic, Tertiary and Quaternary sediments (Biswas, 2005). In the north,

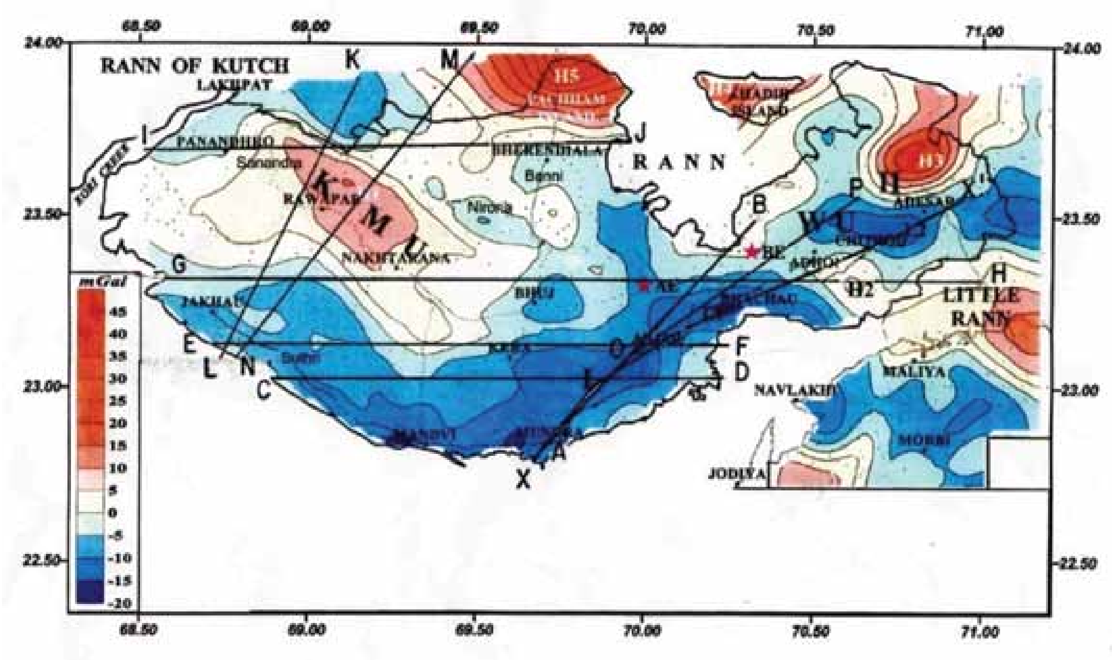

Figure 2. Bouguer anomaly map of Kutch (after Mishra et al., 2005). Nine Profiles (X-X', A-B, C-D, E-F, G-H, I-J, K-L, M-N, O-P) are chosen to compute scaling exponent (β) and depth to anomalous sources in the Kutch region. AE and BE indicate the epicenters of Anjar (1956) and Bhuj earthquake (2001).

Precambrian granitic basement is exposed in the Nagar Parkar Hills and in the south Saurashtra platform, covered by Late Cretaceous sediments and Deccan traps. In the east, basin extends up to north Gujarat plains, where Precambrian rocks are covered by alluvium and in the west it extends to continental shelf. The Kutch basin is under compression stress, due to collision of Indian and Eurasian plates (Gupta et al. 2001).

A transtensional deformation and strike-slip faulting present in the region characterize rifting at old suture zones with mechanical anisotropy. Strike-slip movements are now recognized as a major feature of global tectonics, especially on continents and in later stages of continental collision in ancient orogenic belts (Reading 2000), which may be responsible for heterogeneity/anisotropy in the region.

Application to the gravity data of Kutch region

The gravity data (Fig. 2) was collected using Lacoste-Romberg gravity meter and the elevation of gravity stations are measured by geodetic leveling (Mishra et al. 2005). The Bouguer anomaly map of Kutch region shows several highs and lows indicating heterogeneous nature of the crust (Mishra et al. 2005). Mishra et al. (2005) explained these gravity lows and highs of circular/semicircular nature. They pointed out that these features represent mafic intrusions in terms of basement uplifts and depressions.

Nine profiles (e.g. four East – West, five NE- SW) in the region (Fig. 2) are analyzed to find depth of anomalous sources and scaling exponents in the region. At the outset, a profile X-X' is selected, which is almost parallel to the seismic profile where seismic data was collected (Gupta et al. 2001).

Depth values from scaling spectral method:

The estimated depth values along the profile XX′ are found as 1.3 km, 1.6 km and 3.7 km (Fig. 3) from scaling spectral method. It is interesting to compare these values with the values of Gupta et al. (2001) & Mandal et al. (2004). The depth of trap varies from 1 to 1.3 km (Gupta et al. 2001). Mandal et al. (2004) suggested presence of two layers of depth 0.9 km of low velocity (V_P=2.19km/s) quaternary sediments and 1.1 km (V_P= 4.85 km/s) of Deccan basalts from travel time inversion of P and S waves. Therefore, our first two depth values may be representing the depths of Quaternary sediments and Deccan Basalts with an error of 0.4 km and 0.5 km, respectively. The third depth may be compared to the depth of Jurasic sediments between 3 to 3.4 km (Gupta et al. 2001), whereas Mandel et al. (2004) reported presence of 3.7 km of low velocity (Vp= 3.12 km/s) layer, which is matching with the derived value from present study. Therefore, the depth values along profile XX′ are able to provide good explanation for three layers with some error, particularly in case of first two layers. This could be plausible, as depth estimates using different geophysical methods diverge due to varied applicability and limitation of each method. The E-W striking profiles in the Kutch rift were basically chosen

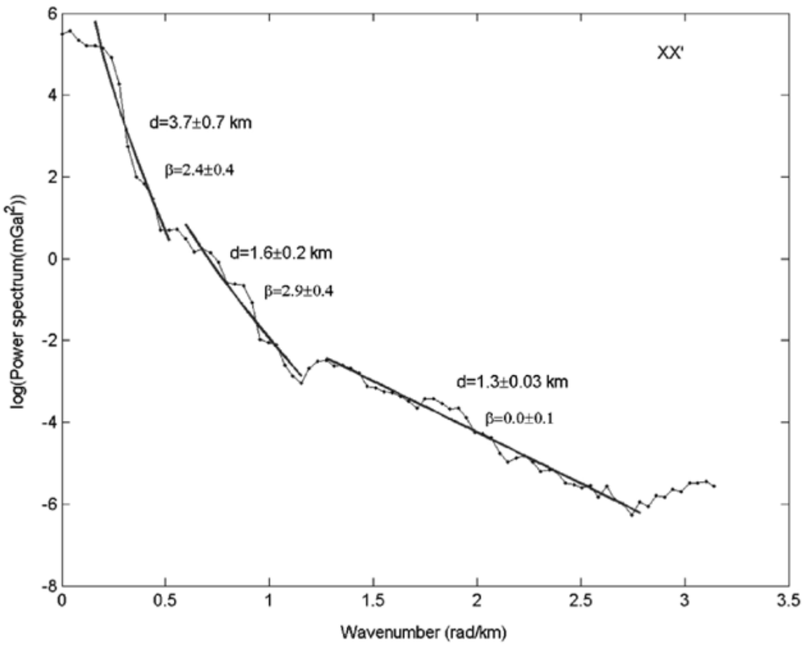

Figure 3. Plot of log power spectrum versus wavenumber along XX′ profile for calculating the depth values and scaling exponents. The depth and scaling exponent values are also shown with standard error of estimation.

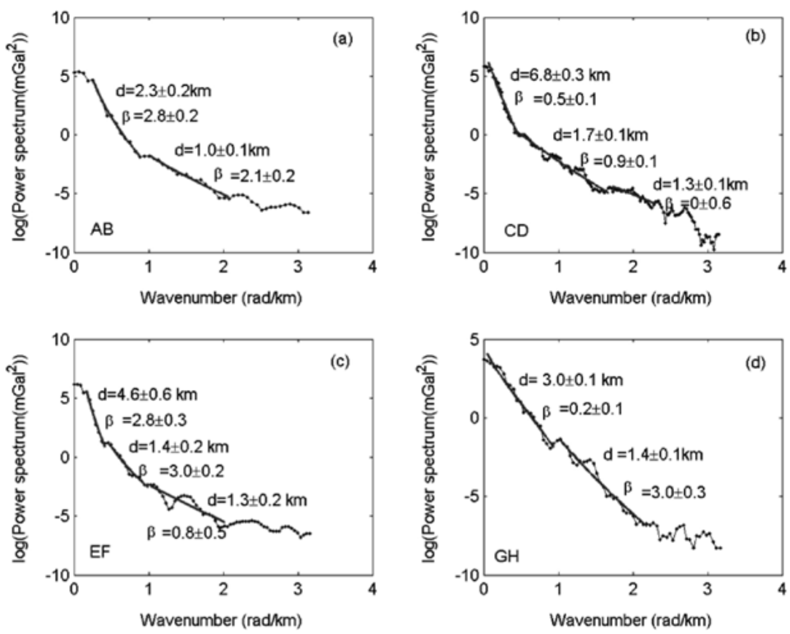

Figure 4. Plots of log power spectrum versus wavenumber along AB, CD, EF and GH profiles for calculating the depth values and scaling exponents.

to see the lateral variation in the N-S direction, which might have been perturbed by various stresses arising due to compressive tectonic forces between the Indian and Eurasian plates. The other stress might have been linked to patches of partial melt providing volatile CO_2 within lower crust of Kutch region (Mandal, 2012). Other profiles (Fig. 2) are across the anomalies, so that some meaningful interpretation can be achieved.

The depth values and scaling exponents (with their standard error of estimation) found from this analysis are presented in Tables 1 and 2. The plot of log power spectrum versus wave-number is shown in Figures 3, 4 and 5, with the calculated depth and β values. In this approach we selected an almost linear portion from the plot of log power spectrum versus wave-number to compute the depth values and scaling exponents from the inversion method.

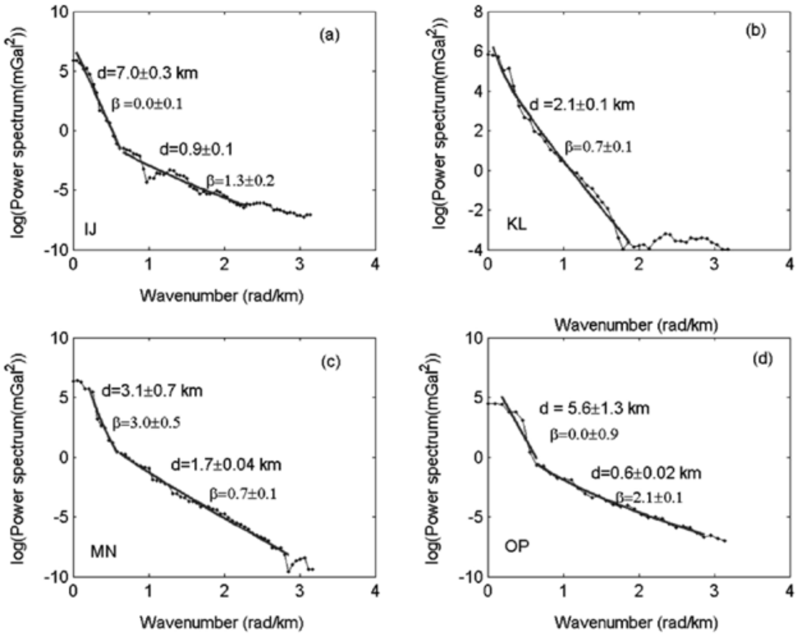

Figure 5. Plots of log power spectrum versus wavenumber along IJ, KL, MN and OP profiles for calculating the depth values and scaling exponents.

Table 1. The depth (km) values calculated along nine profiles in the region. The estimated standard errors of depth are also presented.

AB	CD	EF	GH	IJ	KL	MN	OP	XX′
2.3±0.2	6.8±0.3	4.6±0.6	3.0±0.1	7.0±0.3	2.1±0.1	3.1±0.7	5.6±1.3	3.7±0.7
1.0±0.1	1.7±0.1	1.4±0.2	1.4±0.1	0.9±0.1		1.7±0.04	0.6±0.02	1.6±0.2
	1.30.1	1.3±0.2						1.3±0.03

Table 2. The absolute values of β along nine profiles. The estimated standard errors of β values are also presented.

AB	CD	EF	GH	IJ	KL	MN	OP	XX′
2.8±0.2	0.5±0.1	2.8±0.3	0.2±0.1	0.0±0.1	0.7±0.1	3.0±0.5	0.0±0.9	2.4±0.4
2.1±0.2	0.9±0.1	3.0±0.2	3.0±0.3	1.3±0.2		0.7±0.1	2.1±0.1	2.9±0.4
	00.6	0.8±0.5						0.0±0.1

The depth values in the region vary from 1 to 7 km (Table 1), with deeper values in the northern and southern region. This deepening in north and south may be ascribed to varied basement configuration and fault related subsurface structure. The northern region, south of Allah bund fault, includes many islands surrounded by plains, which is a site of graben/ half graben (Srivastava, 1971), whereas the southern region of the profiles consists of coastal plains. The coastal plain, south of Kutch could be the half graben or depression as the Kathiawar uplift boundary is south of this plain (Fig. 1).

Scaling Exponent (β) values and heterogeneity:

The values of scaling exponents are constrained between 0 and 3. The value of "0" corresponds to the white noise distribution and a value of "3" corresponds to the scaling exponents founds from the other studies (Fedi et al. 1997). The values of scaling exponents are constrained mainly to ensure deriving of reasonable values of scaling exponents and depth values using the inversion method (Bouligand et al. 2009). The plot of depth values versus scaling exponents is presented in Figure 6. The profiles do

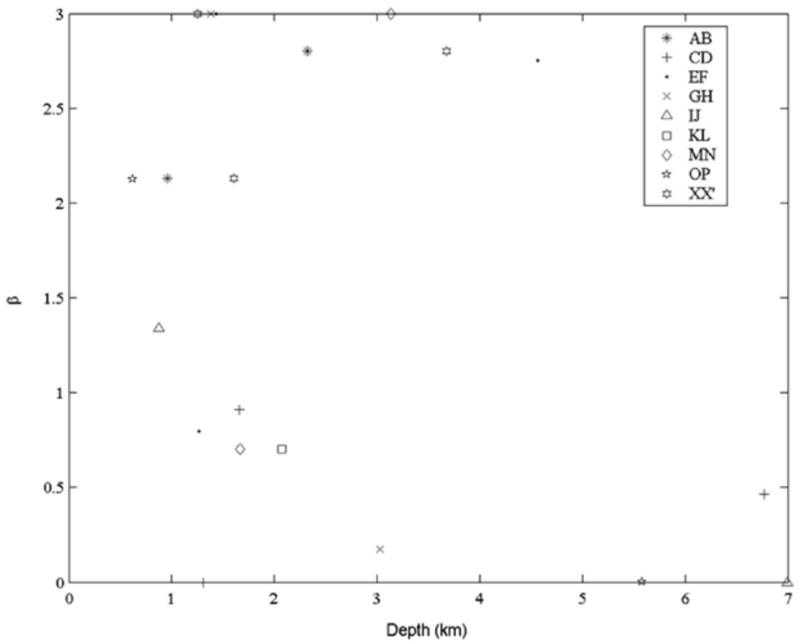

Figure 6. Plot of β values versus depth values for all the profiles (AB, CD, EF, GH, IJ, KL, MN, OP and XX′) shown in Fig. 2.and scaling exponents.

not show any commonality in depth values nor β values. These depths and β values of our study indicate presence of disturbed crustal structure. The variation of β values with depth (Fig. 6) show a decreasing trend with increasing depth. This trend is in conformity with earlier studies (Zhou and Thybo, 1998; Bansal et al. 2010). Different β values indicate the multiscaling nature of the upper crust and heterogeneity. The multiscaling nature of the upper crystalline crust has been reported by Marsan and Bean (1999) by analyzing the sonic velocities from the KTB Main Borehole. The scaling exponent is found to be different for different rock types and is influenced by local geology, lithology, fracturing/ faulting and metamorphic effects (Pilkington and Todoeschuck, 1990; Shiomi et al. 1997; Bansal et al. 2010).

The variation of scaling exponents can be understood in terms of the heterogeneity of the area. Lower values at deeper levels may be related with more homogeneous rock assemblages. The heterogeneities can be mechanical, chemical, lithological, structural, rheological and deformational (Li et al. 2002; Goff and Holliger, 2003; Schweig et al. 2003). The faults and fracture systems are the cases of mechanical heterogeneity and representing the localized concentrations of the strains (Goff and Holliger, 2003).

The present heterogeneity and scaling exponents have probably contributed in shaping the faulting/ lineament pattern, and even the seismo-tectonics of the Kutch region. The Precambrian orogeny - referred to as the Delhi trend in Kutch rift (Biswas, 1987) also inherited tectonic fabric of the upper crust in this region and probably guided the propagation of rift including the mechanical anisotropy that resulted in shear wave splitting (Padhy and Crampin, 2006) and may be the cause of variations in scaling exponent.

The heterogeneity in the crust of the Kutch region is also supported by the study of Schweig et al. (2003). They suggested from a palaeo-seismicity study that the stresses in the Kutch region are controlled by rheological heterogeneities. Mishra et al. (2005) also suggested the presence of shallow crustal heterogeneities based on gravity and magnetic data in the Kutch rift. They suggested that these shallow heterogeneities are main source of stress accumulation in the region. The heterogeneity plays crucial role in the creation of rupture and takes several forms: spatial variation in physical properties e.g. elastic parameters, pore fluid pressure etc. (Aki, 1995). Seismic tomography of Kutch region reveals large variation of Vp and Vs in top one kilometer and few patches of high Vp and Vs between 10 to 30 km depth. This may be attributed to the fluid filled fracture rock matrix (Mandal and Pujol, 2006). Mandal et al. (2005) found the presence of fluid at hypo central depth of 15 km of the Bhuj earthquake, 2001. Mandal (2012) imaged the patches of partial melt. These patches represent volatile CO_2 pathways into the lower crust. The fluids in the lower crust may weaken seismogenic layer present in the upper and middle crust and thus contribute to initiation of large crustal earthquakes (Huang and Zhao, 2004). The other causes of heterogeneity in the Kutch region could be associated with compressive stresses arising from India and Eurasia plate. Similar type of phenomenon is found in the East Los Angles Basin area, California (Yang and Hauksson, 2011). The evidence of blind (Rastogi et al., 2001) strike slip movement (Biswas, 1987) supports presence of the blind thrust strike slip faults and their influence/ association in development of heterogeneity (Roering et al., 1997).

CONCLUSIONS

The application of scaling spectral method to the Bouguer anomaly data of Kutch indicates variations in the depth of sources and scaling exponent (β). The β values in the area indicate heterogeneity in the shallow crust and thus point towards a disturbed nature of crust. The estimated depth values in the region vary from 1 km 7.0 km, representing different anomalies in the region. At the most three layers are observed in the southern and eastern portions of the region. The deepest depth values are found in the northern and southern portions of the region. The variation of scaling exponents and depth values in the region indicate heterogeneity in the shallow crust. The causes of heterogeneities may be lithological / rheological including folds/faults in the area. It is suggested that the presence of fluids, faulting pattern, lithology, stress accumulation due to compressive forces as well as upward movement of volatiles from the lower crust are responsible for weakening of the present crust and heterogeneity in the Kutch region. The understanding of the sources distribution in the region is also useful for the hazard estimation (deterministic / probabilistic) since the heterogeneities influence the propagation of seismic waves.

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