

Quantitative characteristics of the Indian Ocean seafloor relief using fractal dimension

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In this paper spectral technique has been applied for seafloor topographic data analyses from three seafloor provinces of the Indian Ocean. Study sites include West of the Andaman Island (WAT), Western Continental Margins of India (WCMI) and Central Indian Ocean Basin (CIOB). The analyses involved application of suitable gridding techniques to bathymetric data of the multi-beam-Hydrosweep from these sites. Total eleven profiles i.e., three from two sites (A and B) and five from site C were used from varying physiographic provinces. Segmentation method is employed to non-stationary profile into homogenous or stationary segments. Thereafter, estimation of spectral parameters (b) is carried out for thirty-five segmented profiles and amplitude parameter (S) is computed. Also, computation of Fractal Dimension (D) using spectral exponent parameter was carried out and analyses is presented. Current investigation also includes presentation of scatter plot between the b and S value for each site. The computed Fractal Dimension (D) from sedimentary area of the trench side of WAI site revealed very high D values i.e., higher roughness, whereas varying fractal dimension values from remaining areas of this site are indicative of moderate to lower seafloor roughness. Similarly, results from WCMI (site B) area showed variable physiographic provinces from shelf (higher D) to slope morphology which appears to have modified by presence of physiographic highs and slump related features. Highest ' D ' values for summit of the highs indicate sub-aerial erosion and lower ' D ' values for flanks across the highs were also observed. Fractal Dimension (D) values from site C (CIOB) also indicated moderate ' D ' values for E-W and N-S profiles. However, scatter plot, between the b and S values for E-W and N-S profiles show interesting demarcation in terms of clustering. In this work, application of Fractal Dimension is demonstrated for quantitative characterization of the Indian Ocean seafloor roughness.

[Key words: Seafloor relief, multi-beam bathymetry, fractal dimension, spectral techniques, Indian Ocean]

I. Introduction

Dynamic processes related to the ocean floor morphology may well be understood through use of seafloor bathymetry. Accurate description of the seafloor topography using high resolution multi-beam system is important to identify the tectonic and morphological features both qualitative and quantitative way. The seafloor in general is very irregular and changes with the locations and these changes in the topography are due to geological processes active in the region. Therefore, the seafloor topography is a composite of many competing influences and hence it is complex and chaotic. Though it is chaotic there is some order of chaos in topography and has an applicability of fractal statistics. The sea floor topography obeys fractal statistics and there are two main techniques for estimating the fractal dimension: divider/compass method and spectral method. Power & Tullis² has used spectral method along with the many others. In spectral method, the derived amplitude of a Fourier

transformed (one- or two- dimensional) output has power law dependence on wave number³. The power law form seems to represent the best model for describing sea floor topography in the spatial frequency domain⁴. Its simplicity permits the frequency structure of a sample profile to be described using only two parameters (slope and intercept of the power spectral density function). Extensive work by Mandelbrot⁵ has produced a theoretical basis for the consistent relationship between these parameters and formulated it in terms of "fractal dimension". Since spectral techniques have been developed primarily for the treatment of stationary data⁶, a suitable segmentation technique to the profile data may be devised before it is applied to non-stationary data⁷. Generally, topographic profiles were first segmented to delineate areas in which the generated statistics varies minimally. Then for each of this segment, a spectral model is applied to derive the power law parameters and fractal dimensions.

In this study, digitized topography of three Indian Ocean regions is studied (Fig. 1). The study locations include: West of the Andaman Island (WAI), Western Continental Margin of India (WCMI) and Central Indian Ocean Basin (CIOB). The topographic data was collected during the June 1991 and April 2005 using multi-beam echo sounder Hydrosweep system installed on board *ORV Sagar Kanya* for WCMI and WAI areas respectively. However, for CIOB area, multi-beam bathymetric data acquired using the higher version of similar system Hydrosweep DS-II version installed onboard Russian Research Vessel (RV) *Akademik Boris Petrov* during May 2005. The bathymetric data of the seafloor from the WAI region shows the Andaman trench, outer slope, and the inner slope including the accretionary prism forming the Andaman ridge seafloor (site A in Fig. 1). Currently chosen study areas from WCMI include varying seafloor type: continental shelf, slope, isolated bathymetry highs occurring at the upper slope regions and foot of the slope regions (site B). Seafloor topographic data acquired from manganese nodule bearing CIOB consists of various features having orientations from east to west directions and seamounts (site C). Estimation of fractal dimensions from a range of seafloor areas may help to understand the genetic linkages among the area seafloor feature.

II. Materials and Methods

Multi-beam Hydrosweep system used for data acquisition operates at 15.5 kHz frequency. The system installed onboard *ORV Sagar Kanya* utilizes 59 beams covering within the incidence angles between the -45° to 45° angles, i.e., covers the area equivalent to twice its centre beam depth. The MB-System software⁸ and Generic Mapping Tool (GMT)⁹, were used for data processing. However, for bathymetric data acquired through multi-beam - Hydrosweep system (DS II) installed onboard *RV Akademik Boris Petrov* is an improved version. The main characteristics of this system is the coverage angle of $120^\circ - 90^\circ$ for 59 hard beams. In addition to 59 hard beams, high-resolution 240 beams (soft beams) are also acquired. In order to be consistent with the data used for three areas, present analysis uses only 59-beams within the 90° coverage mode systems installed onboard *ORV Sagar Kanya* as well as *RV Akademik Boris Petrov*.

As a part of the Exclusive Economic Zone (EEZ) mapping activity, underway multi-beam sounding

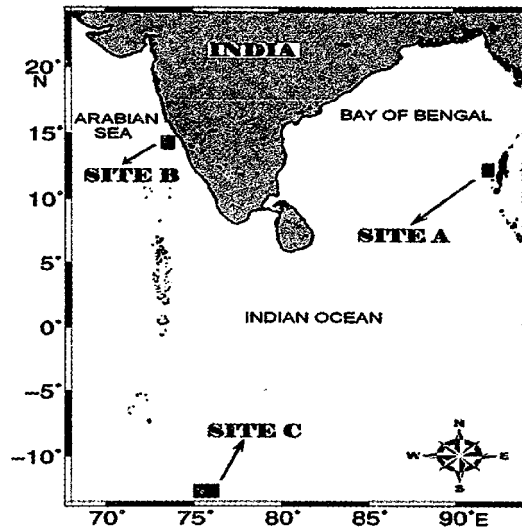


Fig. 1—Three multi-beam bathymetric data acquisition sites.

data were obtained during *ORV Sagar Kanya* expedition (SK 218: 18 March - 16 April 2005) from the Andaman subduction zone in the Bay of Bengal which consists of plain, trench, slope and ridge off the Andaman Islands¹⁰. An area covering 25,000 km² around Andaman subduction zone is used to produce swath bathymetry map of this area. Various geological studies carried out in this area suggest that, the heavier Indian plate is shoving below lighter continental Eurasian plate and causes the subduction morphology and associated structural features. The expedition attempted to characterize the seafloor associated with the trench at the Andaman area in the Bay of Bengal. The detailed survey was made at lat. $11^\circ 30' - 13^\circ 30' N$ and long. $91^\circ - 92^\circ E$, west of Andaman Island. Survey was made from west to east, over the Andaman trench, the outer slope, and then the inner-slope (Fig. 2). The depth values were found to be varying between the 3600 m (western end of the trench side) to ridge areas (towards the Island side) having seafloor depth of 1000 m. Generally, it is difficult to obtain evenly spaced raw data from echosounding system, therefore the raw data was first gridded through spline interpolation using GMT. The selection of the grid cell size depends on the maximum depth of the region. It is known that the swath of the deep sea multi-beam system is twice that of the depth. Since we are dealing with 59 beams, the swath coverage is divided by 59 to get the distance between each beam. Based on this dimension the grid cell size is selected to be slightly greater. In this

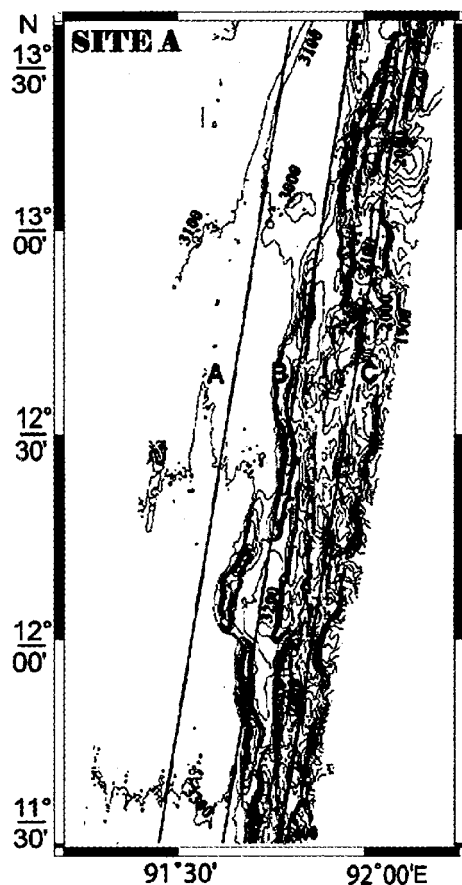


Fig. 2—Bathymetric map of Site 'A' West of the Andaman Island (WAT) (contour interval: 100 m).

region the cell size is taken to be 150 m to carry out gridding. The contour map having contour interval of 100 m (Fig. 2) was prepared. Underway data along three survey tracks (A to C) across the trench were collected to constrain exact physiographic profiles of the trench and the ridge using GMT following Douds¹¹.

About 20,500 km² area was surveyed off the central west coast of India (WCMI)¹². WCMI data (site B) was acquired between Karwar and Kasargod (12° to 14°30' N and 72°30' to 74°15' E) during the *ORV Sagar Kanya* cruise (SK-65: 06 -25 June 1991). As mentioned, the seafloor topography in the area varies from nearly flat continental shelf to lower slopes (Fig. 3). The slope morphology appears to have modified by presence of physiographic highs of varied dimensions and slump related features. In site B (WCMI) depth varies (WCMI) from shallow water (~ 64 m) to deep water (~2200 m). In order to obtain

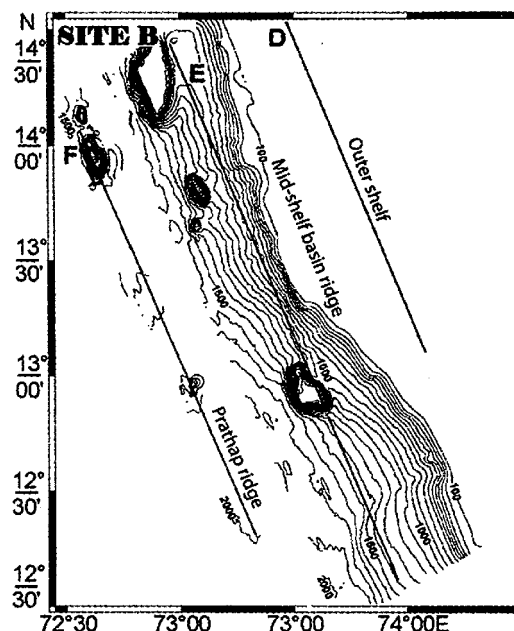


Fig. 3—Bathymetric map of Site 'B' Western Continental Margin of India (WCMI) (contour interval: 100m). Depth ranges for profile 'D' varies between 65-95 m.

evenly spaced data, the raw data was first gridded using the same procedure mentioned above. In site B, 100 m was found to be a suitable grid cell size, later on three bathymetric profiles namely D, E, and F covering outer shelf, Mid- Shelf Basement Ridge upper slope, and Prathap ridge of the basin were extracted respectively. The depth along the profile 'D' varies between 65-95 m. The seafloor depth of the profile 'E' from the Mid-Shelf Basement Ridge varies between the depths of 300 m to 1500 m. Similarly, for profile 'F' from Prathap Ridge the depth varies between 500 m to 2000 m. For profile 'E' the summit height towards the end of the profile is 1300 m. Similarly, profile 'F' is crossing a high towards the northern end having summit height 1500 m, and two closely associated small highs having height of 100 m within the middle part of the profile.

Similarly about, 22,000 km² area from 11°45' to 13°S and 74°45' to 76°30'E in the Central India Ocean Basin (site C, Fig. 1) was surveyed (ABP 06: 31 May -29 June 2005) using multi-beam Hydrosweep DS II system installed onboard Russian Research Vessel *RV Akademik Boris Petrov*. Following the same procedure as that for the earlier two sites, gridding was carried out with a suitable grid cell size of 200 m for this site. Contour map was prepared having

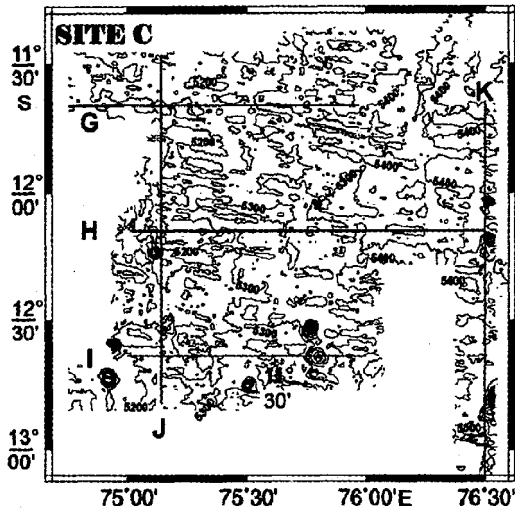


Fig. 4—Bathymetric map of Site 'C' Central Indian Ocean Basin (contour interval: 100 m).

contour interval of 100 m at the water depth varying between 4200 - 5800 m and later on five bathymetric profiles were extracted G-K (Fig. 4). Of these, three E-W profiles (G-I) are situated in the northern and southern end. Other two N-S profiles (J and K) are situated along west and eastern end. It has been observed that, the western region of the site C is comparatively shallower than the eastern side and the seafloor morphology varies from medium to large scale and has E-W trending in the central part of the area. A chain of seamounts trending along N-S direction was also observed in the extreme east region of the study area. Also, few seamounts were observed in the south-west section of the map. The five depth profiles (G, H, I, J and K) from grid data are studied for roughness detail from north, central, south, east, and west of survey area respectively.

III. Data segmentation and spectral parameter estimation

The initial objective in this analysis is to segment the non-stationary profile into homogenous or stationary segments. This is carried out by developing an algorithm that employs to draw of Power Spectral Density (PSD) and in turn to estimate spectral slope 'b' and the amplitude parameter 'S'. Entire data processing and necessary steps related to data analysis is given in block is shown in Fig. 5. The spectral exponent 'b' is estimated at this stage by applying a least square fit over the entire range of the

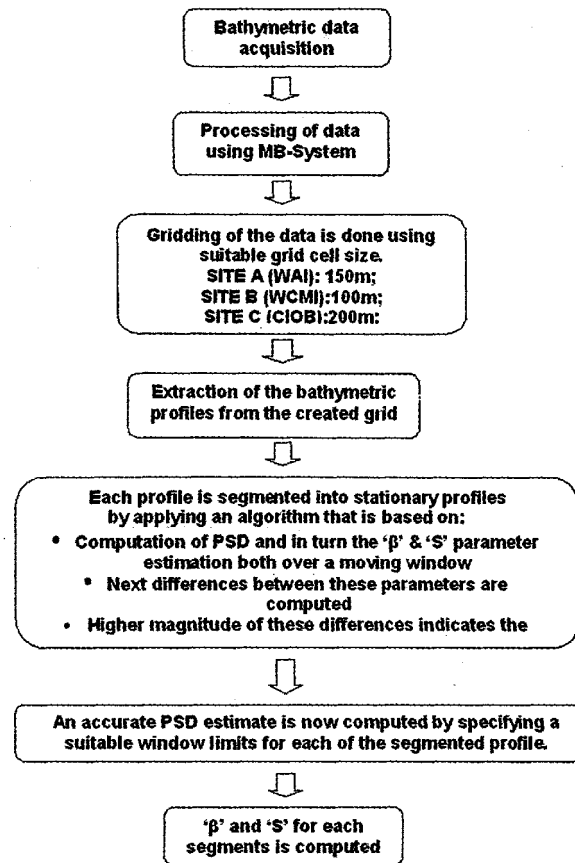


Fig. 5—Flow chart showing the important data processing components.

periodogram and is utilized only for segmentation (detail discussion of spectral exponent 'b' estimation is given in the following subsection). This method is similar to the split moving window technique used by Malinverno¹³. In this, a small window of length $2W$ is moved over the entire profile having $W=50$ points. As this window is moved over the profile, the b and S parameters were estimated for the two sub-profiles that fall in each half (i.e., in the half window width W). Hence we obtain two sets of parameters (b_1, S_1) and (b_2, S_2) for each half, every time the window moves on to the next points in a sequence over the entire profile. If both the adjacent windows fall within a homogeneous portion of the profile, then there will not be much difference between the two points (b_1, S_1) and (b_2, S_2) (we will refer to this as the difference vector hereafter) in the ($b - S$) space. Next when the window moves over from one homogeneous portion to another, it is expected that the difference vector

will start to increase. It would reach its maximum, when the center of the entire window is exactly the boundary between the two homogeneous segments. Since the b and S parameters are estimates drawn for the profiles within each half window, the difference vector plot will be a noisy one. Hence an algorithm is developed to find the regional peaks of the difference vector. These peaks correspond to the boundaries or the segmentation points along the bathymetric profile presented to the algorithm. Once the profile is segmented into stationary profiles a more accurate estimate of the PSD and in turn the spectral slope ' b ' and the amplitude parameter ' S ' were deduced.

Spectral parameter estimation

To estimate the spectral or power law parameter, Welch¹⁴ method was used. In this method, all the input series or the bathymetric profile is first detrended to remove the best fit linear trend of the original profile. Then the first and last 10% of each profile is tapered with a \cos^2 function. This minimizes the edge effects. A Fast Fourier Transform (FFT) algorithm is then applied, and the resulting complex spectrum is squared to obtain a periodogram, which is an unbiased estimator of the true power. The periodogram are presented as a function of wave number k (cycles per kilometer), and the results are then plotted in a \log_{10} - \log_{10} plot. This form of power spectrum was originally suggested by Malinverno¹³ on the basis that the topographic profiles are self-affine and concluded that different depth profiles may be characterized by different fractal dimension (D). Using regression technique⁴, the power law on a logarithmic scale can be written as:

$$\log_{10} PH = (\sim b) \log_{10} k + \log_{10} c.$$

Comparing this equation with the straight-line equation reveals that ' b ' corresponds to the slope of a straight line fitted to the periodogram and ' c ' corresponds to the intercept. At this stage the straight regression line fitting is done for the entire range of \log_{10} (wave number) of the periodogram.

Amplitude parameter

The second parameter that is used to characterize the roughness of the profile is an amplitude parameter S . A robust estimate is the median of the absolute deviation from the sample median¹³:

$$MAD = \text{median} | z(x) - \text{MEDIAN} [Dz(x)] |,$$

where $Dz(x)$ are the first differences of the depth series $z(x)$. An estimate of S from MAD is defined as:

$$S = 1.4826 * MAD.$$

IV. Results and Discussion

Segmentation carried out to nine long profiles from three different physiographic provinces give 35 segments. Three profiles (A, B and C) for site A of WAI region provide 12 segments (Fig. 6a). Our algorithm offers no segmentation to profile A from deeper section of this area having depth range higher than the 3000 m and 225 km of profile length towards the sedimentary provinces of trench side. Four segments were obtained for profile B which lies between the sedimentary trench and ridge area having undulating seafloor at similar depth range. For profile C from relatively shallower depth section of ridge area provides seven segments at depth range 2000 - 2400 m. Similarly, for site B from WCMI the profile D from shallower shelf (depth within the 100 m) present only two segments. Eight topographic segments were obtained for profile E from the Mid-Shelf Basement Ridge. Distinctly different segments for flank parts (E4 and E6) along the bathymetric high E5 of the profile E are seen (Fig. 6b). However, four segments obtained for deeper section of the profile are from sedimentary areas of the Prathap Ridge. For this profile F, two highs having significantly different heights are distinctly segmented. Overall, fourteen segments are made for this part (site B) of the physiographic provinces. For CIOB (site C), five profiles provide only nine segments from the deeper part of the seafloor (~ 5000 m depth) (Figure: 6c). From this basinal part of the seafloor, west to east profiles G and H from northern and middle part of the area do not offer any segment. Interestingly, remaining depth profile (I) from E-W direction provides four segments. Profiles J from western and K from eastern end provide two and one segments respectively.

Once segmentation of the profiles are carried out, the estimation of power law exponent (b) for segmented profiles are important for calculation of fractal dimension. Therefore, a precise or accurate spectral exponent ' b ' is estimated by applying suitable spectral limits for each of the stationary profiles. However, there is an uncertainty in the validity of

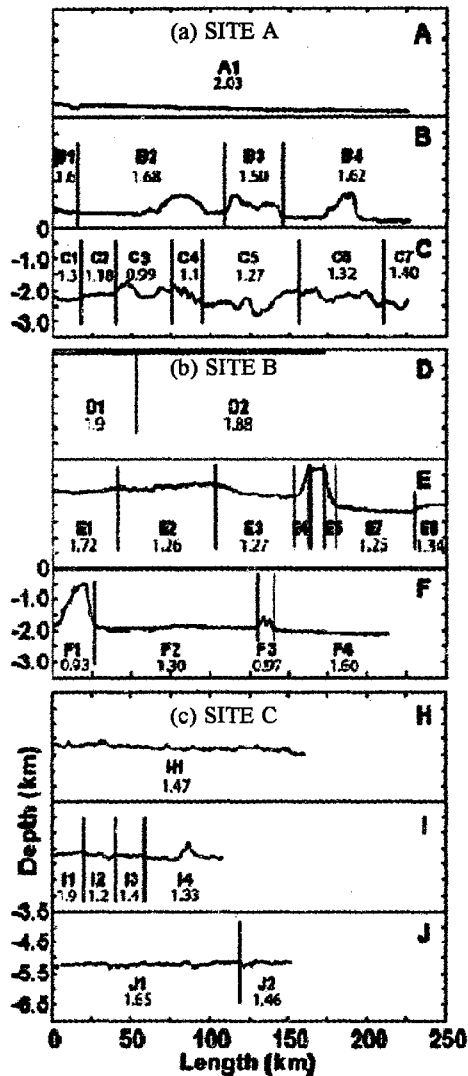


Fig. 6—Segmented sections of the bathymetric profiles from three sites: a) West of the Andaman Island (WAI), b) Western Continental Margins of India (WCMI) and c) Central Indian Ocean Basin (CIOB). Number related to segmented sections are given with the profile number. Also, computed Fractal Dimension (D) values are also printed for each segmented section.

power law, over the wave numbers lower than certain wavelength, wherein it is seen that the spectral exponent b is found to decrease for wavelengths larger than few tens of kilometers. Also, for lower wave numbers there are insufficient data points to confidently estimate the spectral exponent p and therefore we need to restrict or limit the extent of periodogram span towards the lower wave numbers. In the present study, it was seen that maximum

number of segments had a profile length of approximately 20 km, and no bathymetric features are longer than this length. In terms of $\log_{10}(\text{wave number})$ this length turns out to be -1.3 and was considered to be the lower limit of wavenumber for estimating the spectral exponent b .

At higher wave numbers (smaller scale) the periodogram does appear to follow a straight line, whose extent depends on the sampling interval of the profile. As mentioned earlier the bathymetric profiles extracted from the three different sites viz. A, B and C have sampling intervals of 150 m, 100 m and 200 m respectively. Hence, the extent of the periodogram on the higher wave number side in terms of $\log_{10}(\text{wave number})$ is limited to 0.50, 0.65 and 0.40 for site A, B and C respectively. Hence the true drop in power occurs somewhere between the wavelengths ~ 20 to ~ 0.2 km for Hydrosweep operating at 15.5 kHz¹⁵. Hence suitable limits are applied to the periodogram plots while computing the spectral exponent. We employed a window over $\log_{10}(\text{wave number})$ varying from (-1.3 to 0.5), (-1.3 to 0.65), and (-1.3 to 0.4) for sites A, B and C respectively. In Fig. 7, power versus wave number plots for segmented sections (C4, E2, and J1) of the profiles C, E and J are presented respectively as an example. The power law fitted curves and estimated b values are also presented for representative segmented profiles from three sites.

Fractal dimension

For one-dimensional topographic profile, the fractal dimension (D) can be estimated from the spectral exponent b as: $D = (5 + b) / 2$. There exist a limitation on the range of fractal dimensions for one-dimensional profile i.e., $1 < D < 2$ ¹⁶. However, D values computed in this study for 35 segmented profiles are found to be within the given limit except the six values from site A and B corresponding to areas with steep fall and high gain structural rises. Fractal Dimension values are shown in Fig. 6 along with segmented section. For WAI area (site A), deep seafloor profile A towards the sedimentary provinces of the trench side show higher D (2.03) values i.e., higher roughness. Whereas moderate D (1.50 - 1.68) values are obtained for the four segments of profile B interfacing between the sedimentary (profile A) and Ridge areas within the subduction zone adjacent to Andaman Island (profile C). However, undulating depth profile from ridge seafloor 'C' having seven segments provide lower fractal dimension

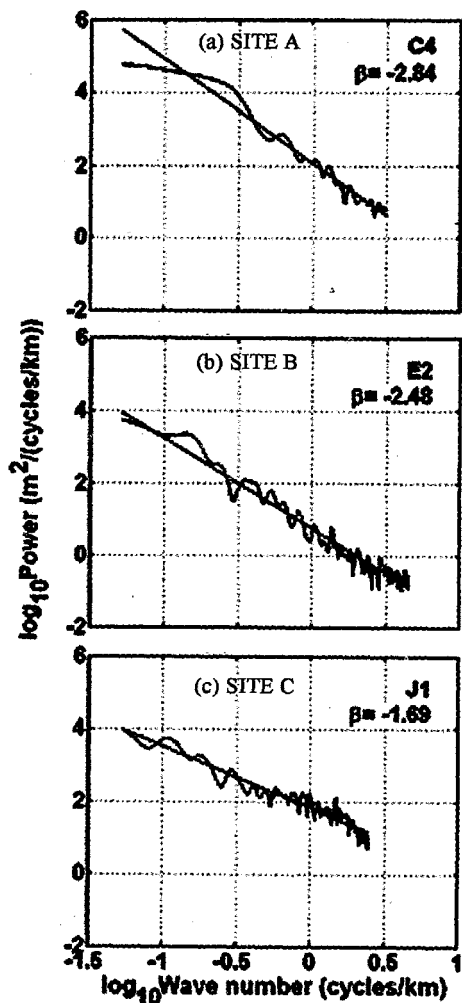


Fig. 7—Relationship between the power spectral density [$\text{m}^2 / (\text{cycles} / \text{km})$] and wave number (cycles / km) are shown for representative segmented sections: 4, 2 and 1 of the profiles: C, E and J respectively.

like: 0.99 to 1.40 i.e., extremely smooth to moderate seafloor roughness.

For site B of WCMI seafloor areas, the estimated fractal dimension (D) parameters show higher values for profile D from shelf seafloor. As mentioned, the estimated fractal dimensions (D) values of several segments along the profiles from various depths of the slopes do not fulfill the required fractal criteria for 1-dimensional data ($1 \leq D \leq 2$). In fact for this site, areas with steep fall and high gain structural rises do not lie within the fractal limits. The fractal dimension value of the largely even eastern basin (i.e., devoid of flanks and highs), by contrast lie well within the

fractal limits. Higher D values (higher roughness) are seen for two segments D1 (1.90) and D2 (1.88). Extreme D values (2.05-0.72) are obtained for twelve segmented seafloor profiles of E and F of the physiographic provinces like: Mid- Shelf Basement and sedimentary basin in the Prathap Ridge respectively. Towards the N-E side of the profile E, segment of the Mid-Shelf Basement Ridge, E1 shows moderate D values (1.72). Fractal dimension (D) values become lower for segments E2, E3 and E7 (1.27 - 1.25). Though, the fractal dimension values for the flanks (E4 and E6) across the high (E5) show lower values. The fractal dimension (D) of summit high segment (E5) indicates highest value (2.05) i.e. higher roughness, which may be attributed due to the sub aerial erosion¹². Profile F along the Prathap Ridge provides four segments. Segments F1 and F3 represent highs having different morphology than the highs from Mid-Shelf-Basement Ridge. No separate segments for flanks of the highs from profile F was observed as in the profile E. Moreover, similar to the summit highs of Mid-Shelf Basement Ridge no separate segments for flat summit highs of the profile F (Prathap Ridge) was observed. Interestingly, segments of the two highs (F1 and F3) showed lower fractal dimension values (0.93 and 0.97 respectively). However, fractal dimension values of the plains between the highs showed moderate values i.e., 1.30 and 1.60 for F2 and F4 respectively which is similar to the profile E of Mid-Shelf Basement Ridge area.

For CIOB site C, fractal dimension (D) for E-W profiles like northernmost G and centrally located H show similar values: 1.50 and 1.47 respectively. However, four segments of the southernmost E-W profile I indicate higher to moderate D values varying from 1.90 -1.15. Westernmost segment II possesses higher D value (1.90) and lower values for centrally located segments I2 and I3 (1.2 and 1.4) and moderate value for easternmost I4 (1.33) segments covering seamount of 500 m summit height. Similarly, for two segments from western end of the N-S profiles: J1 and J2 provide moderate fractal dimensions (D) i.e., 1.65 and 1.45 respectively. Eastern end of the N-S profile K has similar value of 1.62.

Fine scale analyses using 'b' and 'S' parameters

The estimated 'D' and 'b' values of the thirty-five segmented sections are found to vary between (2.05 and 0.72), and (-0.90 and -3.56) respectively. D values: 2.05 and 0.72 are computed for seafloor

segments E5 and E6 respectively, which could not be showed in the (Fig. 6b) due to presentation difficulty. Overall, the 'b' values are always negative and having large magnitudes indicating low 'D' values, representing terrains which are relatively rough at large and smooth at smaller scales. Conversely, lower magnitudes of the 'b' parameter (and higher 'D' value) represent terrains which are smoother at large scales than at small scales. Occasionally, the estimated fractal dimension (D) values of several segments from the physiographic provinces do not fulfill the required fractal criteria for 1-dimensional data ($1 \leq D \leq 2$). In fact, areas with steep fall and high gain structural rises do not lie within the fractal limits. However, fractal dimension value of the largely even seafloor areas (i.e., devoid of flanks and highs), by contrast lie well within the fractal limits. This fact is clear in the work of Malinverno¹³. However, Malinverno¹³ has successfully characterized the seafloor using two parameters (b and S), detailed study on similar ground was employed by Chakraborty *et al.*¹² to multi-beam bathymetric data from WCMI.

The scatter diagram between the power spectral exponent (b) and amplitude (S) parameters offer interesting results (Fig. 8a). Overall variations in the roughness of these study areas may group in distinct clusters. For WAI physiographic provinces, the seafloor along profile A from sedimentary provinces of the trench side possesses b and S values: -0.93 and 3.55 respectively. As mentioned, high b corresponds to rough seafloor, while S quantifies amplitude (overall energy) of an area. For example, profiles having similar p but higher S will correspond to rough profile. Scatter diagram (Fig. 8a) for this physiographic province indicates an isolated point (A1) for a rough seafloor from trench side. However, four segmented profiles (B1- B4) between the trench and ridge side provide (b= -1.87 and S= 6.50), (b= -1.64 and S= 10.20), (b= -2.00 and S= 8.86) and (b= -1.77 and S= 13.90) respectively. Similarly, for seven segmented sections of profile C from adjacent ridge area from Andaman Island provide variations of spectral parameter (b) value between (-2.19 to -3.02) and amplitude parameter S value (15.20 to 3.20). A critical analysis of these results indicate significantly lower b in comparison with the segments of the profile B i.e., smooth seafloor than the segments from the profile B. No clear cut cluster formation is seen in WAI region. Moderate to higher amplitude (S)

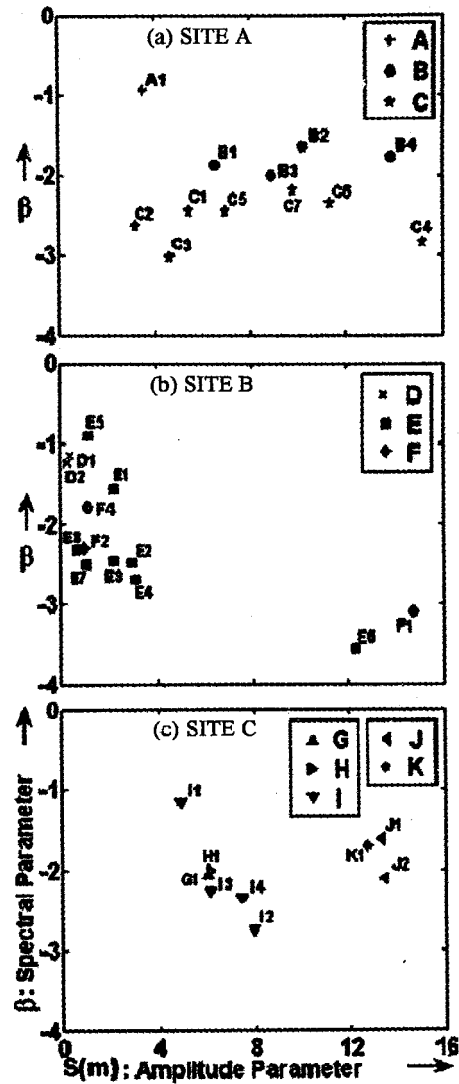


Fig. 8—Relationship between the power spectral p and amplitude S parameters for thirty-five bathymetric segments. Note two cluster for the sites B and C.

parameters for profile B and C data and relatively higher b value for profile B are indicative of higher seafloor roughness. The observations related to WAI seafloor region made in this section are well supported by interpretation made by using fractal dimension (D) values presented in previous section.

For site B of the WCMI, estimated 'b' and 'S' values of fourteen segmented sections are found to vary between (-3.56 and -0.90), and (0.24 and 22.28) respectively. The scatter diagram between the power spectral exponent (b) and amplitude (S) parameters offer interesting results (Fig. 8b). The overall

roughness observed in the study area groups in two distinct clusters¹². One cluster includes segments from structural rises like: E6 (flank related to Mid-Shelf Basin Ridge), F1 (highs related to the Prathap Ridge) and F3 (S=22.28 consisting of two small closely associated highs and not included in Fig. 8b). These areas show high S and low to medium b values, suggesting seafloor roughness on a large scale. In contrast to this, another cluster comprises the remainder of the areas, including gently sloping outer shelf and part of the western shelf margin basins. The seafloor here shows low S and moderate to higher b value, suggesting dominantly small-scale undulations. A comparison of the clustering of the structural rises with that of the outer continental shelf and basin regions (Fig. 8b) indicate differences in their mode of origin (volcanic and plutonic, respectively). For example, the Mid-Shelf Basement Ridge and the Prathap Ridge are believed to have been formed by emplacement of volcanic material during the separation of India and Madagascar in mid-Cretaceous times. Detailed tectonic and other aspects of these areas in terms of clustering are well covered by Chakraborty *et al.*¹².

The analyses based on the spectral and amplitude parameters in the study site 'C' having seafloor depth vary between 4200 m and 6000 m depth. The estimated 'b' and 'S' values of the E-W profiles (G, H and I) are found to be varying between (-1.14 and -2.70) and (7.44 and 4.87) respectively (Fig. 7c). Also 'b' and 'S' values of N-S profiles are found to vary between (-1.70 and -2.083) and (13.33 and 12.75) respectively. If we remove data points related to the southernmost E-W segmented sections (I2, I3 and I4) of the profile I, the b parameter becomes comparable (-1.70 and -2.10) with N-S profiles (J and K), though, the amplitude parameter (S) are higher for N-S oriented profiles varying between (12.75 and 13.49) than the E-W profiles (4.9 and 7.9). Though we observe most of the profiles / segmented sections are similar, as far as b is concerned, however, show clear-cut existence of two clusters due to variation in amplitude parameter. The amplitude parameters show difference between the E-W and N-S profiles i.e., the amplitude (S) for N-S oriented profiles are higher than the E-W profiles. For similar b values towards the E-W and N-S direction with higher amplitude for N-S profiles than the E-W indicate dominant large scale roughness for N-S profiles whereas E-W profiles indicate dominant small scale roughness. This

fact is prominently clear in the report of the Malinvemo¹³ (see Fig, 5 therein).

V. Conclusion

Overall, results from site A indicates moderate seafloor roughness except the profile A from sedimentary trench part of this site. Similarly, results from WCMI (site B) area show variable physiographic provinces from shelf to slope morphology appears to have modified by presence of physiographic highs of varied dimensions and slump related features. Analyses based on fractal dimension values identify these features. Highest fractal dimension (D) values on summit of the highs indicate sub-aerial erosion and lower 'D' values for flanks across the highs are also observed. Moreover, scatter plot between the (b) and amplitude parameter (S) indicate two clusters which clearly demarcate the differences among the large / small scale rough and smooth seafloor features. Fractal dimension (D) values from site C (CIOB) also indicates similar values except for southernmost E-W profile (I). Scatter plot between the p and S values for E-W and N-S profiles show interesting demarcation in terms of clustering. N-S profiles show larger seafloor roughness in terms of greater S values. However, b values are observed to be possessing similar values with different ranges of S value for both the profiles (except for few segments from southernmost E-W profile I). Current study indicates clear demarcation in the seafloor roughness parameters between the E-W and N-S bathymetric profiles.

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