TECTONIC INTERPRETATION OF DIGITAL TERRAIN DATA THROUGH MORPHOMETRIC ANALYSIS OF THE REGION AROUND LANJA, DISTRICT RATNAGIRI, INDIA.

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ABSTRACT

The presence of geomorphic features such as regional anisotropy, tilted terrain, linear valleys, ridgelines slope breaks and steep slopes of uniform aspect reflects tectonic movement in the region. Numerical analysis of Digital Elevation Models (DEM) helps characterise tectonics in the area quantitatively. This study investigates numerical geomorphometric methods for tectonic geomorphology of the southern region of Deccan Traps in the Konkan Coastal Belt (KCB). The essential geometric attributes (elevation, slope, aspect and curvatures) complemented the automatic extraction of ridge and valley lines and surface-specific points. Evans' univariate and bivariate methodology of general geomorphometry extended with texture (spatial) analysis methods, such as trend and autocorrelation analysis. Terrain modelling implemented with the integrated use of (1) numerical differential geometry; (2) digital drainage network analysis; (3) digital image processing; and (4) statistical and geostatistical analysis. the Lanja area is tectonically controlled, wherein N-S tectonic lineaments are more active than NW-SE, ENE-WSW and NE-SW lineaments. The present landscape is the result of the interplay between tectonic activity and fluvial response to it.

KEYWORDS: digital terrain modelling; tectonic geomorphology; digital drainage analysis; morphometry

1. INTRODUCTION

The analysis of DEMs allows quantifying land surface geometry in terms of elevation and its derivatives. The basic geometric properties that characterise the terrain surface at a point are (1) elevation; (2) terrain aspect; (3) surface curvature, (4) convexity; and (5) local maxima (peaks), minima (pits), saddle points (passes), inflexion points, break-lines, ridge and valley lines. The relationship between geometric point attributes and tectonic structures such as slope-breaks and fractures is often straightforward (Siegal and Gillespie, 1980; Drury, 1987; Prost, 1994; Salvi, 1995). For example, steep slopes of uniform aspect over an area related to faulting. Linear valleys, ridgelines and slope-breaks are morphological features commonly associated with faults (Prost, 1994). On the other hand, complex structures, such as folds and curving fault lines, are difficult to capture by geometric analysis.

In contrast to local geometric analysis, numerical geomorphology studies the statistical and spatial characteristics and relationships of point attributes (Evans, 1972, 1980). Relationships between point attributes are used to characterise the terrain further (Evans, 1980). The present tectonic geomorphology study investigates the most superficial relationships. The elevation-average slope curve was used to study slope conditions. Aspect-average slope curve and aspect-slope were used for investigating if slopes in a given direction tend to be steeper.

By fitting a trend surface to the study area or its parts, the overall tilt due to tectonic activity can be studied (Doornkamp, 1972; Fraser et al., 1995). Autocorrelation and spectral analysis methods can reveal anisotropy and periodicity present in the DEM. Both features often result from tectonic control on terrain morphology (Harrison and Lo, 1996). In addition to autocorrelation analysis, directional variogram analysis was carried to investigate patterns in the terrain studied.

This study aims to investigate the use of geomorphometric methods to identify tectonic activities in the study region. This paper presents the geomorphometric analysis that combines numerical differential geometry, digital drainage network analysis, digital image processing and statistical and geostatistical analysis. Univariate and bivariate methods of general geomorphometry were complemented with texture (spatial) analysis methods such as trend, autocorrelation, spectral and network analysis. Furthermore, a technique to generate artificial DEMs using drainage lines to study anisotropy and periodicity.

2. THE STUDY AREA

The study of surficial geomorphic, structural and morphometric evidence of long– and short–term tectonic activity is morphotectonics. The endogenous mechanism operates and controls the tectonic activities represented by relative movements, such as uplifting, subsidence, and translation of the crust. Multi-sensor digital images and DEMs and advanced digital image processing techniques, supported by field evidence, are handy for observing and mapping morphotectonic features. The analysis of these morphotectonic indicators gives a synoptic view of the (neo)tectonic activities. Most of the tectonic activities date current or geological recent times, which can be considered neotectonic activities. Bedrock joints mainly indicate the relationship between geomorphometric elements and neotectonic landscape in the area of questions.

Fig.1: Location map of the study area

The continental-scale passive west coast margin of India, representing one of the world's rifted margins, has attracted many researchers because of its unique spatial position and its significant role in shaping the tectonic characteristics of India. Still, there is ample scope to dive into the research in the tectonics of the west coast margin of India. The northern part of this west coast margin of India is covered by voluminous Deccan basaltic lava flows, covering an area of about half a million square kilometres erupted 65Ma representing K-T boundary, marked by mass extinction on a global scale. Coast parallel precipitous escarpment (Western Ghat Scarp) trending nearly about N-S direction recedes eastward due to intense weathering and generates a narrow low-land at its west and a plateau at its east (Fig.1). This geomorphic setting forms three distinct morphotectonic units from west to east: Konkan low-land (Konkan Coastal Belt), Western Ghat Scarp (called Sahyadri in local Indian language), and Deccan plateau. The formation of these morphotectonic units, their evolution, seismic events, view of mantle plume theory in its formation, and recent trends in remote sensing are the source of this research.

3. METHODOLOGY

For geomorphometric studies of landscape, the five basic parameters calculated are elevation, slope, aspect, profile and tangential curvatures according to Evans' general geomorphometric method (Evans, 1972, 1980). This study complements these basic geometric attributes by automatically extracting surface-specific points and ridge and valley lines. In addition, univariate and bivariate methodology extended with texture (spatial) analysis methods such as trend and autocorrelation analysis. Four significant fields of terrain modelling were used in integration in this paper: (1) elevation analysis (relative relief and cross-sectional view); (2) digital image processing which includes, histogram manipulation and terrain generalisation); (3) Numerical differential geometry (slope, aspect and curvature); and (4) digital geomorphometry includes analyses such as univariate, bivariate, trend, autocorrelation and spectral.

The present investigation started with elevation analysis by calculating frequency histograms of point attributes and their moments, such as mean, range and standard deviation, over the whole area or its parts. Next in the analysis, bivariate and multivariate relationships between variables (derivatives and moments) were studied. Plotting average slope against aspect showed if steeper slopes tend to face in a specific direction. Steep slopes with the same orientation can be associated with faulting. The average slope plotted against elevation was used to identify flat planation surfaces. Finally, terrain texture was studied utilising spatial statistical methods and network analysis techniques. For the whole area and its elements (basins only, for example), trend analysis, autocorrelation, and spectral analysis were carried out. Trend surfaces were fitted to all data points or surface specific points to estimate regional dips, such as peaks or valley lines.

Autocorrelation and spectral analyses reveal lineation (anisotropy) and periodicity of landscape due to faulting or folding. The autocorrelation property can also study by calculating semivariograms in different directions (Curran, 1988). Valley lines are delineated using the generalisation of DEM developed by Leonowicz et al. (2010), which is freely available software called 'terrain sculptor'. A binary image of the extracted channel network is used to create an artificial elevation model of valleys. Terrain sculptor is a new algorithm that removes unnecessary details and preserves the prominent landform. In this method, successive raster operations divide the terrain into mountainous and low-land areas, generalise these major morphological areas in different raster operations, and recombine them into one elevation model. Imhof, (1982) has formulated this principle for accentuating ridgelines in high mountain areas and river valleys on the flat plains.

Digital image and terrain analysis usually use image processing techniques applied to grey-scale images for lineament extraction. This paper proposes using the more realistic digitally extracted ridge and valley lines with spatial statistics to these networks. For example, digitally extracted drainage network, drainage channel orientation, length and density.

4. RESULT AND DISCUSSION

3.1 Elevation analysis: Elevation analysis was carried with the help of colour-coded DEM, digital cross-section, superimposed cross-sections, shaded relief images, relative relief map and TPI images to recognise morphotectonic features. Digital image processing is achieved by the study of images generated using the terrain generalisation technique. The task of numerical differential geometry was implemented to understand morphotectonic features associated with altimetry, slope, aspect and curvature maps. The aspect map was further processed for the autocorrelation and anisotropy (lineation) to understand the aspects trend and classify aspects of the study region.

The colour-coded DEM (Fig. 2) nicely dictates the bare physiographic setting of the study area. The main physiographic features that stand out from this model are upland, the Western Ghat escarpment (Sahyadri), KCB and the West coast. Other features are; scarp, drainage divides, major rivers, local relief, incised streams, degree of dissection, plateaux, ridges, valleys, planar surfaces and lineaments. This model also shows that the entire area is sloping towards the west. Westerly flowing major rivers namely Kajali, Machkundi, Kodavli, Vaghotan and their tributaries, are traversing the region.

The DEM exhibits N-S and NW-SE trending valleys controlled by lineaments. The difference and spatial distribution of ridges, eroded hills and plateaux are highlighted. The western region of the area dominates by plateaux deeply incised by rivers and streams. It also exhibits linear coastal segments in the form of cliffs. The eastern region adjacent to the escarpment exhibit numerous valley heads originating at the scarps. A relic part of the projected upland is distinct, west of Vishalgad, separated by N-S trending deep valleys. The elevations of E-W oriented ridges decrease towards the west and terminate against the curvilinear lineaments. A very narrow region between the western plateau and eastern E-W ridges exhibit levelled to undulating topography. Based on relief, degree of dissection, type of landforms in the region, the study area can be divisible into three geomorphic domains, from east to west are 1) Escarpment and Foot Hills (EFH), 2) the middle Low Relief Lowland (LRL) and 3) Dissected Tableland (DTL).

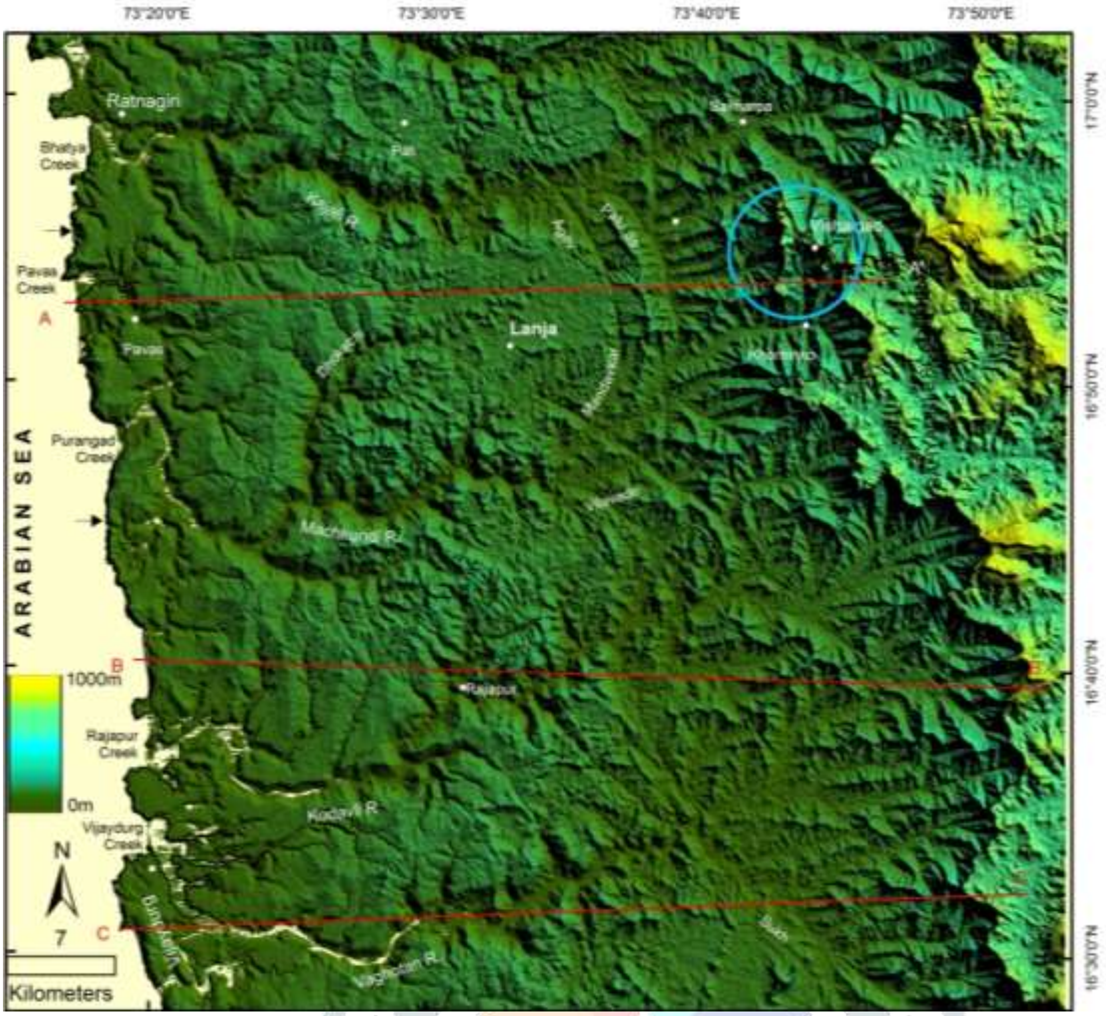


Fig. 2. Digital Terrain Model of the study area with colour coded elevations. Arrows show lineaments. The relic part of upland, Vishalgad is in the blue circle. A-A’, B-B’ and C-C’ are lines of profiles

3.1.1 Profiles: Three profiles (Fig. 3.2 A, B and C) represent E-W profiles of the study area’s northern, middle and southern parts, respectively. The profiles exhibit major topographic features such as western plateaux, middle featureless low land and high relief near escarpment. Superimposed profiles (Fig 3.1 A and B) exhibit more than one planar surface in the coastal plains and the upland region. Coastal plains exhibit four major planar surfaces: the low-level lateritic surface at the top and the deeply incised surface. The bottommost represent the oldest and youngest surfaces, respectively. The bottommost planar surface is nearly at sea level, indicating deep incision as a result of uplift. Thus, these major planar surfaces support the rejuvenation of the region. The middle planar surface appears inclined and wavy, possibly reflecting the differential uplift across the area. These also indicate that the incision depth is more in the western plateau region, which has reached very near sea level. Similarly, the profiles also exhibit the increase in incision depth towards the south in the western plateau region. Both these observations highlight that the uplift is more in the western plateau region wherein it also increases in the south.

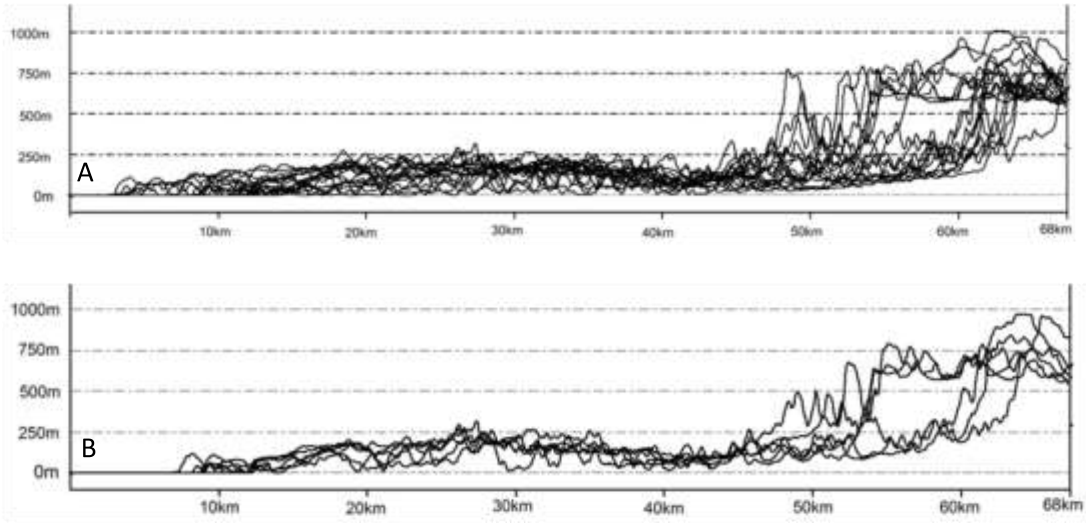
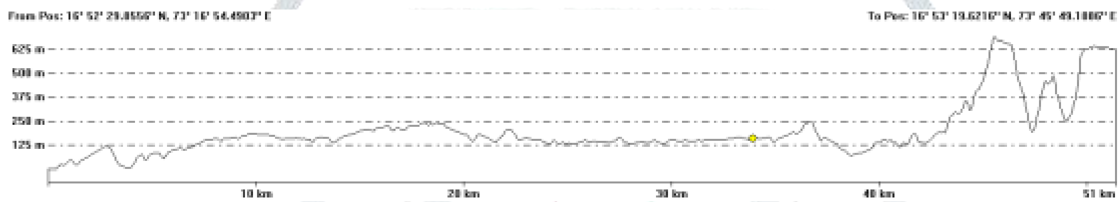
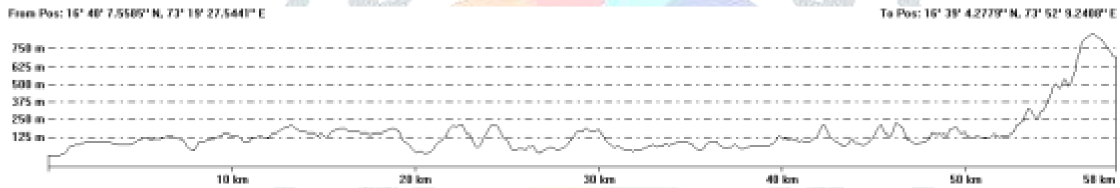


Fig. 3.1: Superimposed digital profiles through E-W direction, from Lat $16^0$30’ to Lat $17^0$00’ at 2’ intervals. A) Superimposed Profiles of complete study area. B) Profiles of middle part, latitudes from $16^0$41’ to $16^0$50’.

Profile A



Profile B



Profile C

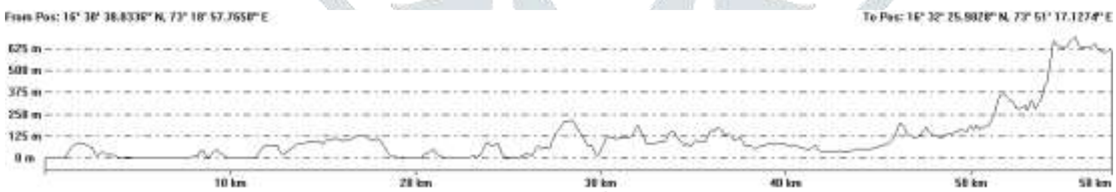
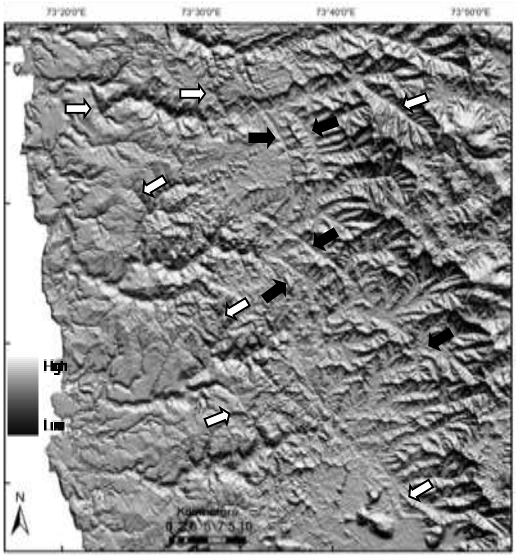
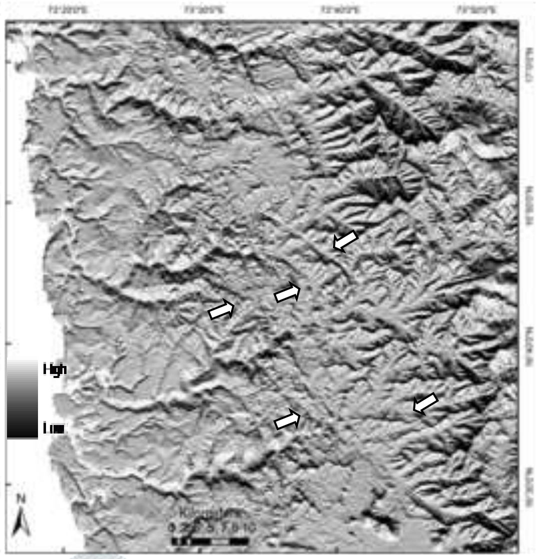


Fig. 3.2: E-W digital profiles in northern (A), middle (B) and southern (C) of the area.

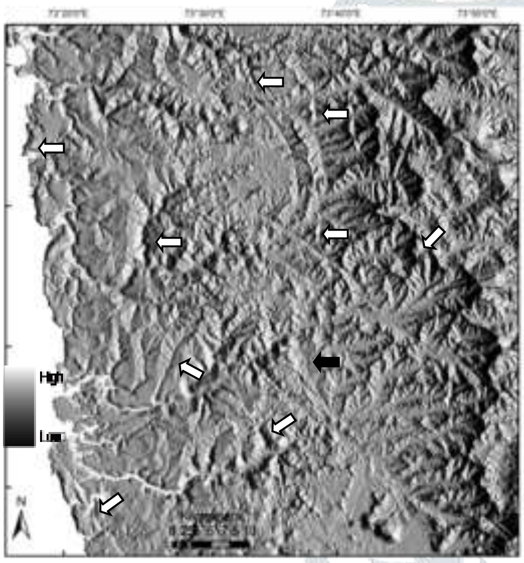
3.1.2 Shaded relief model: The grey-scale raster images (Fig. 4 A, B, C and D) depict topographic and tectonic features. Structural discontinuities, lineaments, slope breaks, linear stream segments, linear and curvilinear valleys, tonal and topographic contrasts are prominent. Major lineaments are easy to identify visually from each shaded relief image.



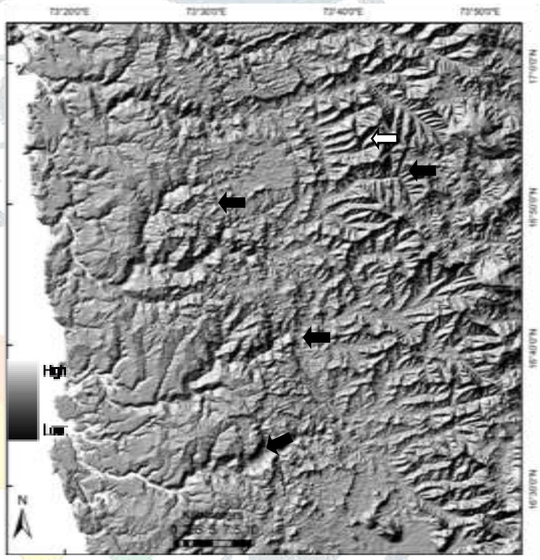
A. Image illuminated from north



B. Image illuminated from south



C. Image illuminated from east



D. Image illuminated from west

Fig. 4: Shaded relief images of the study area. Images illuminated from (A) north, (B) south, (E) east and (D) west at 45^0 Sun's azimuth. Arrows show significant lineaments. A bold black arrow in the images shows enhancement of lineaments indistinct in remote sensing and colour coded images.

3.1.3 Relative relief map: The relative relief map (Fig. 5) shows very high values of relative relief along the escarpment and its foothills. A group of higher relative relief values occurs in the middle part of the area. Relative relief is lower in the N-S trending middle narrow, and elongated track. The relative relief map also nicely expresses the major lineaments trending in N-S, NW-SE directions. The obscure N-S linear and ENE-WSW lineaments (arrows in Fig. 5) and planar surfaces in the western plateau region of the area are recognisable in the relative relief map.

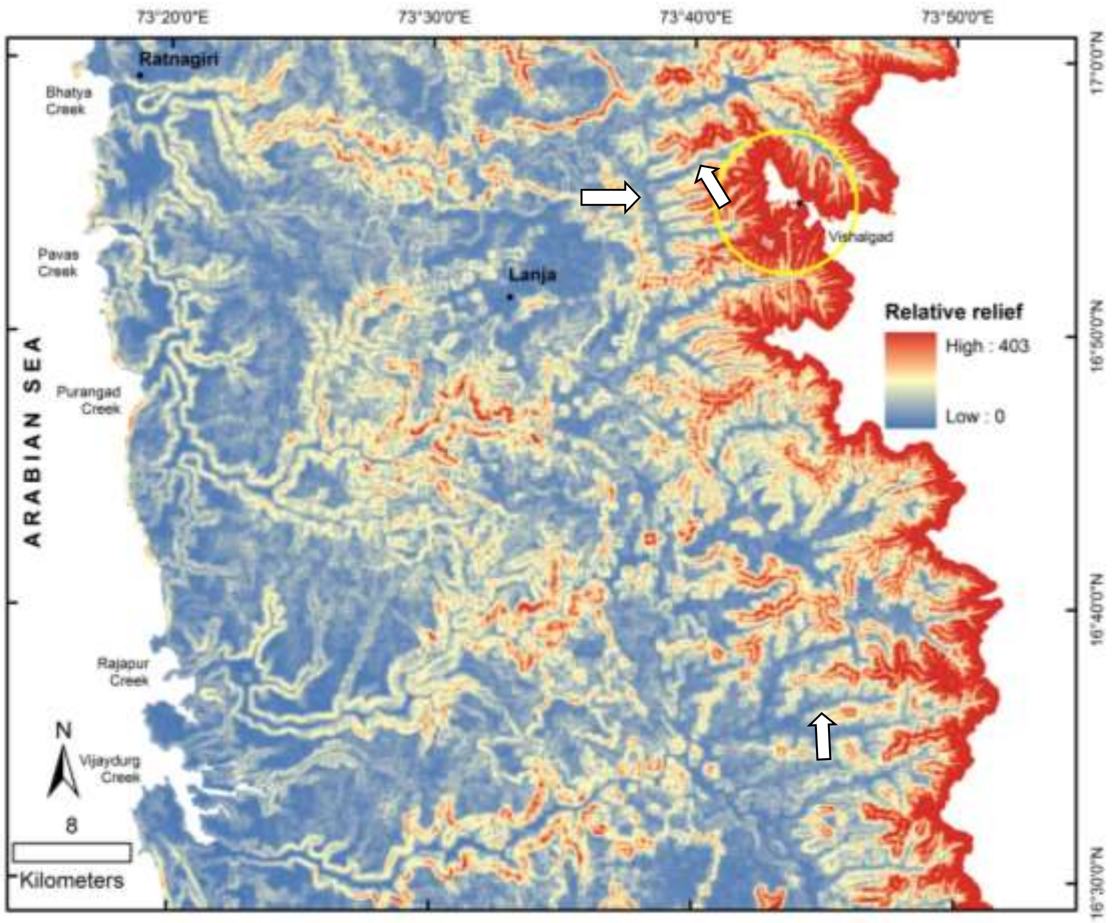


Fig. 5: Relative relief map of the study area. Arrows show the appearance of indistinct lineaments. The relic part of the upland is in a yellow circle.

3.1.4 Topographic Position Index map: The TPI map (Fig. 6) discriminates and shows the distribution of landforms such as ridges, steep slopes, plain areas, incised 'V' shaped and 'U' shaped valleys. (Dikshit and Patil, 2012). This map also enhances major lineaments trending N-S, NW-SE and ENE-WSW. Deeply incised 'V'-shaped valleys in the western dissected plateau areas, whereas 'U'-shaped valleys and ridges are prominent in the escarpment region and its foothills. The plain surfaces represent planar surfaces in the dissected plateau region. Dominating ridges are trending in the E-W direction, and the N-S curvilinear ridge between Agav-Mandavkar and Palu river indicates the structural control. The abrupt break across the prominent ridges (Fig. 7) supports the weak zones along the lineaments. The middle region between the western plateau and escarpment foothills shows a number of hillocks and small ridges (Fig. 8B).

3.2 Digital Image Processing: The digital image processing was achieved by a terrain generalisation algorithm. These images exhibit valleys, ridge lines, triangular facets, and enhancement of lineaments. Image (Fig 7A) produced using a low pass filter exhibits the west-facing escarpment and major river basins. Sharpened and exaggerated images (Fig. 7B) exhibit enhanced ridgelines, valleys in foothills of escarpment and incised deep valleys in plateaux. This image isolates the areas of alternating ridges and valleys in the east from western plateaux. This image also helps to depict the narrow region of low relative relief located between the western plateaux and ridges and valleys in the east. This narrow zone constitutes numerous hillocks all along the eastern edge of the plateaux region. The rivers and streams of the plateaux region show higher degree incision. Exaggerated and smoothened ridge slopes (Fig. 7C) depict most ridges trending in E-W direction, while structurally controlled curvilinear ridge is associated with curvilinear lineaments. The rose diagram of the azimuth of ridge lines (Fig. 8B) shows the dominating N-S trend. The other trends of ridgelines are E-W and NE-SW.

The mountainous and low-land combination model also shows enhanced indistinct N-S lineaments (Fig. 8, shown by arrows) and helps to recognise the line of triangular facets (Fig. 8A) along the eastern valley side of the Palu stream. The association of triangular facets with N-S trending curvilinear Palu lineament indicate the presence of a fault. The termination of E-W ridges supports the presence of fault along Palu lineament. Two short N-S linear lineaments terminate at Palu lineament (Black arrow in Fig. 8) indicate that these curvilinear lineaments are older while linear N-S lineaments are younger. The topographic expression in very low relief, associated with indistinct curvilinear lineament (at X in the image), indicates fault's presence.

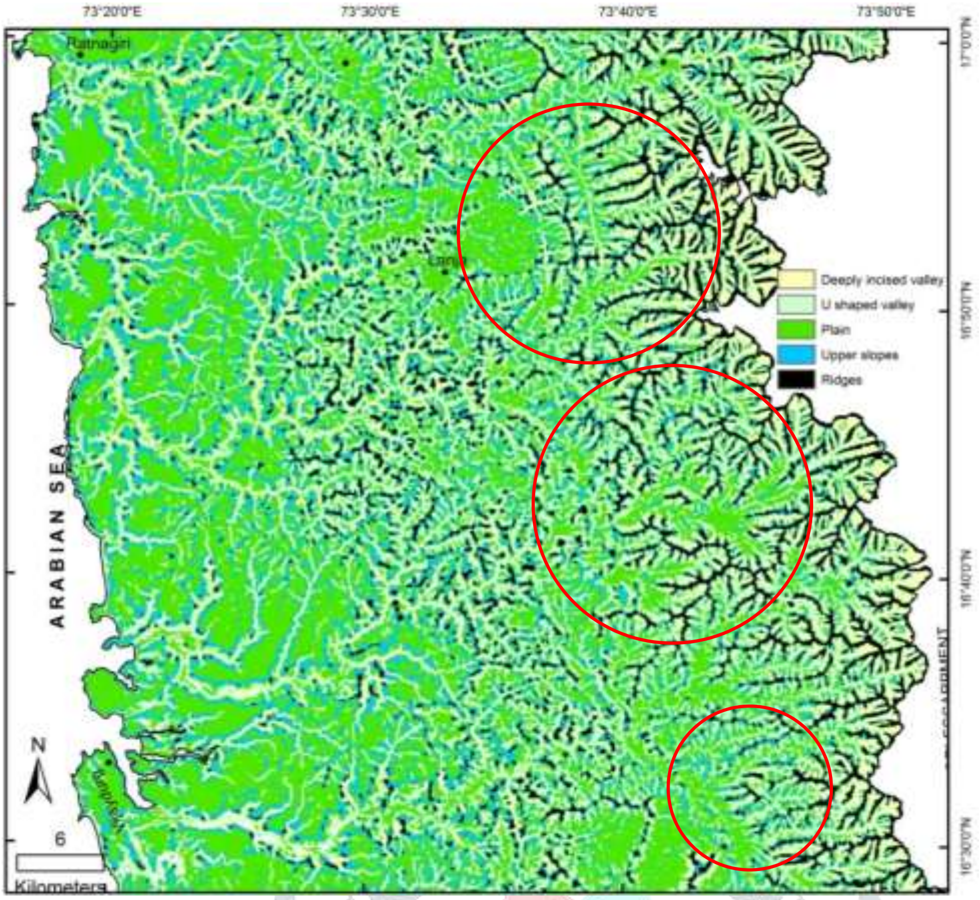


Fig. 6: Topographic Position Index (TPI) map of the area. Abrupt breaks in ridges are shown in red circles.

3.3 Numerical Differential Geometry Analysis: The histogram (Fig. 9) represents an automatic analysis of the area, revealing the number of planar surfaces and slope breaks. Planar surfaces in the study area are at 620m, 580m, 160m, 123m, 75m and about 5m asl. The most prominent planar surfaces are at 160m, 123m and 75m asl, whereas slope breaks are at 560m, 250m and 10-15m asl. The last four planar surfaces below 250m asl are related to the western coastal plateau region. The presence of these four planar surfaces supports superimposed profiles and reveals polycyclic evolution. The presence of sharp slope breaks at about 250m and 10-15m on either side of the planar surfaces in the western coastal plateau region infers faults.

The slope map (Fig. 10) shows that the precipitous and very steep slopes are mainly associated with the escarpment. However, steep slopes also occur along the coast and eastern edges of dissected plateau and along deeply incised valley sides. Changes in the colour tone and presence of steep linear slopes (18^0-30^0) helps to recognise slope breaks and lineaments along the curvilinear valleys indicating weak zones. Level to gentle slopes occurs in the coastal plateau region and east of Lanja, which represent tilt of flats, and according to Keller and Pinter, (1996), such flats are bounded by the fault zone.

The classified aspect image (Fig. 11) is independent of illumination parameters and, therefore, helps locate valley lines, slope breaks and ridges, occur along with Palu, Agav and other streams controlled by lineaments. Thus, the dominance of N-S and NW-SE lineaments is expressed in this image (arrows). The rose diagram (inset in Fig. 11) displays two significant directions: one facing SW (190^0-220^0) with the high frequencies and the other pointing in the WNW direction (270^0-290^0) with lower frequencies. The rose diagram is strongly asymmetric, having higher frequencies and dispersion between the SE (150^0) and W (270^0) and lower frequencies between NW (310^0) and ESE (120^0). The pronounced lack of landscape facets facing NW and ESE indicates that NE-SW oriented morphological features are not characteristic of the area or subordinate. Large petal in a rose diagram shows that a more significant number of pixels have an aspect in a preferred orientation, but these pixels are scattered all over the area and does not show linear orientation. At the same time, the number of pixels oriented to the west and northwest directions are less number but are present closer together, forming a large area with linearity and uniformity. Slopes of dominating uniform aspects are W and NW edges, suggesting structural control possibly in the NNW-SSE direction.

The high and linear profile curvatures in figure 11A and the plan curvature map (Fig.11B) show the deeply incised valleys of rivers and tributaries in the escarpment region and in plateaux, where streams are eroding the substrate at higher rates. The arrows shown in the profile curvature map depict the streams flowing over the higher gradient and generating valleys of higher curvature by eroding substrate. The profile curvature map also helps to delineate lineaments. The plan curvature map exhibits curved valleys of Palu, Agav and a ridge in between them.

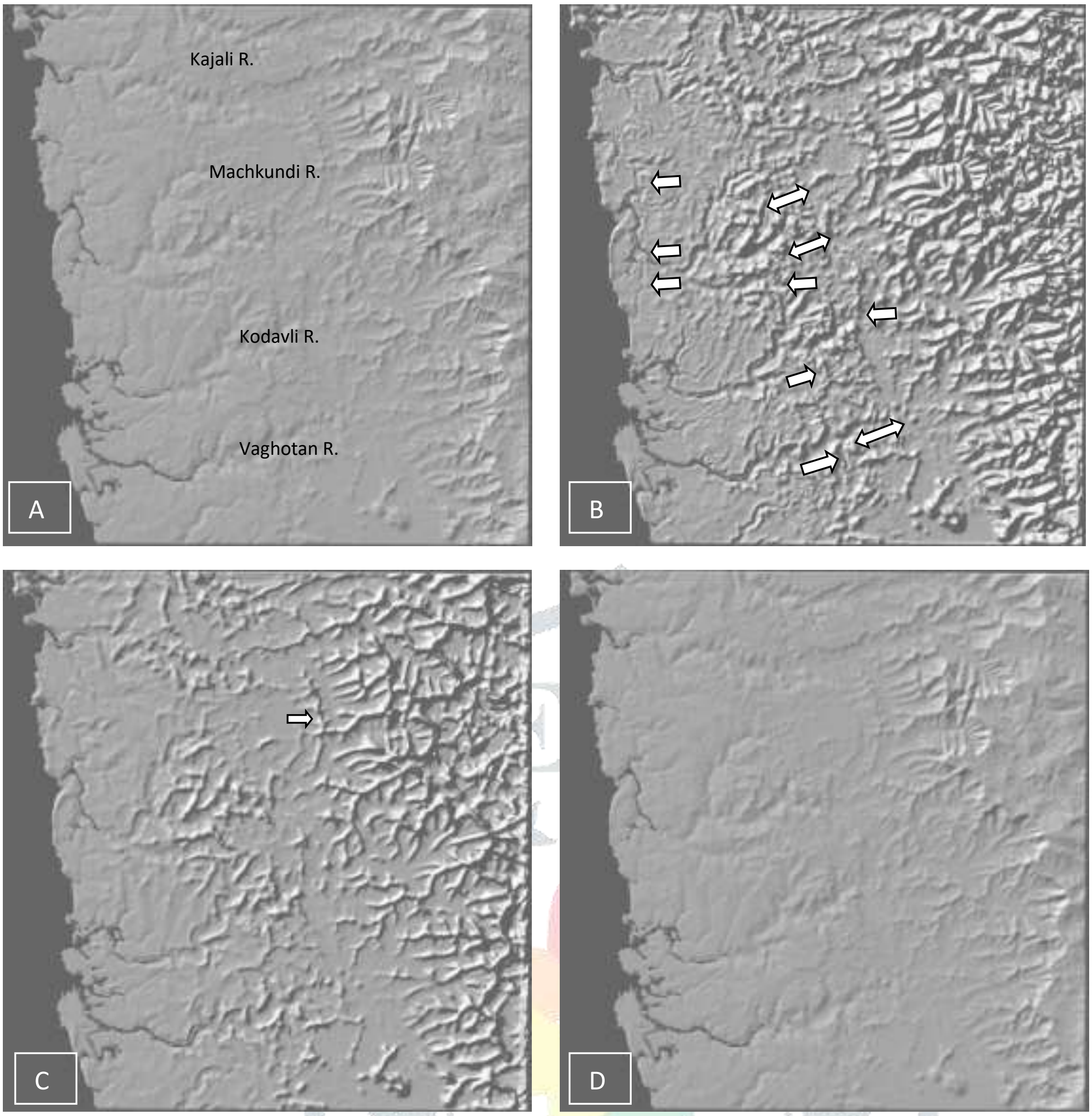
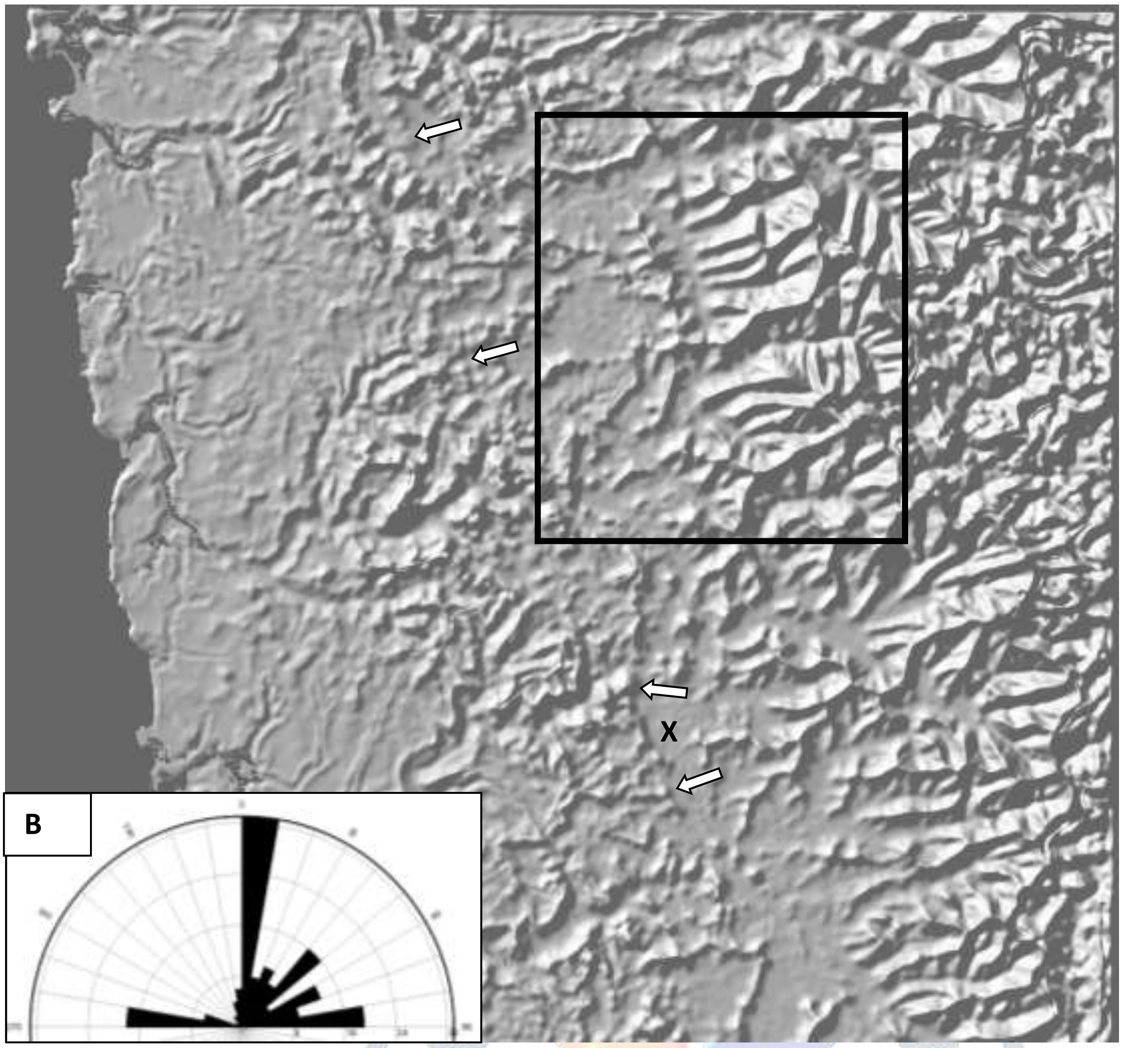


Fig. 7 Images generated by generalisation methods. A: low pass mean filtered image, B: ridges exaggerated and sharpened image, arrows show enhanced lineament and N-S zone of deformation, C: ridges exaggerated image, ridge details removed and valleys deepened, arrows show N-S oriented curvilinear ridges, D: low-land image, valleys deepened and widened to generalise low areas.

The anisotropy value derived by semivariogram analysis is 331.8^0 (Fig. 14), indicating that most aspects are oriented in NNW-SSE direction ($N28.2^0W$), and their slopes are oriented perpendicular to this anisotropy that is in the WSW or ENE directions. Thus, NNW-SSE lineation has the most significant impact on the morphology, which coincides with the Dharwarian trend of south India.

Figure 15 illustrates a classified aspect image generated by autocorrelation analysis of the study area, indicating that the prominent aspects (gray shaded areas) oriented in NW-SE direction and curvilinear aspects. Related aspects bounded by sharply defined linear hillslope edges (bold black lines) oriented in NW-SE direction and curvilinear. The autocorrelation analysis generated the NNW-SSE lineation regional trend of the area while its classification brought out different linear and statistically correlated aspects of NW-SE and curvilinear N-S trend.



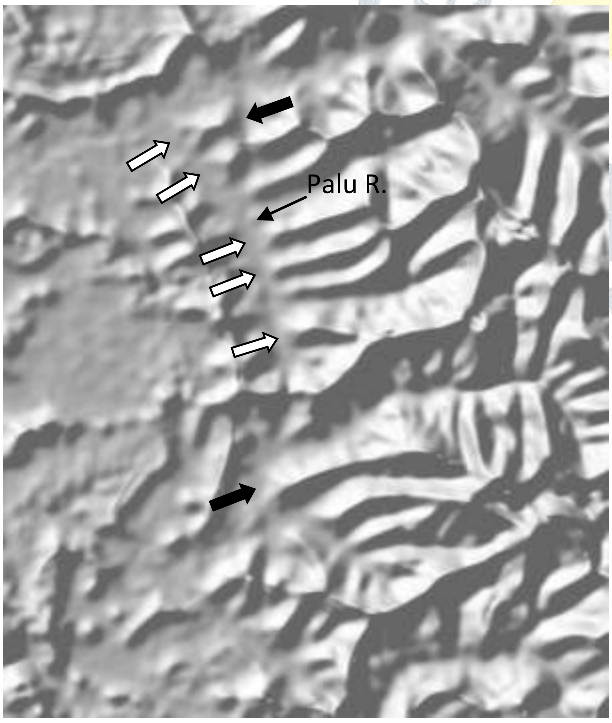


Fig. 8: Combination of mountain model (exaggerated ridges) and lowland model (deepened valleys). Arrows in the main figure show enhanced lineaments due to image generalization. Rectangular portion of the image is zoomed in and presented in A.

A) Arrows shows triangular facets at mountain front emerged due to generalization of image. Black arrows show Palu lineament intersecting N-S lineaments.

B) Inset shows the N% rose diagram of ridge line's azimuth.

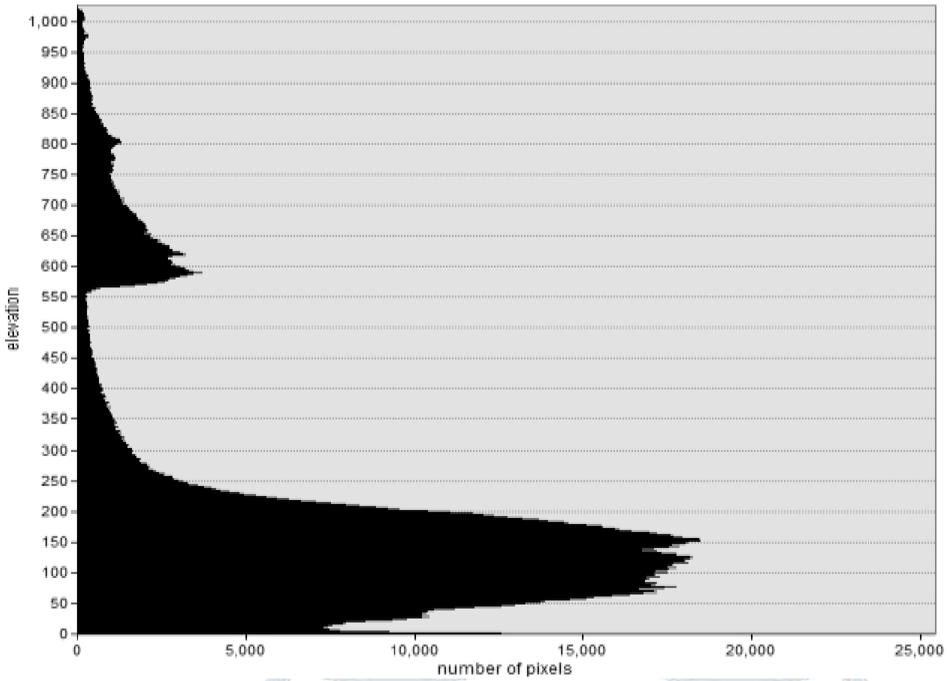


Fig. 9: Histogram of DEM.

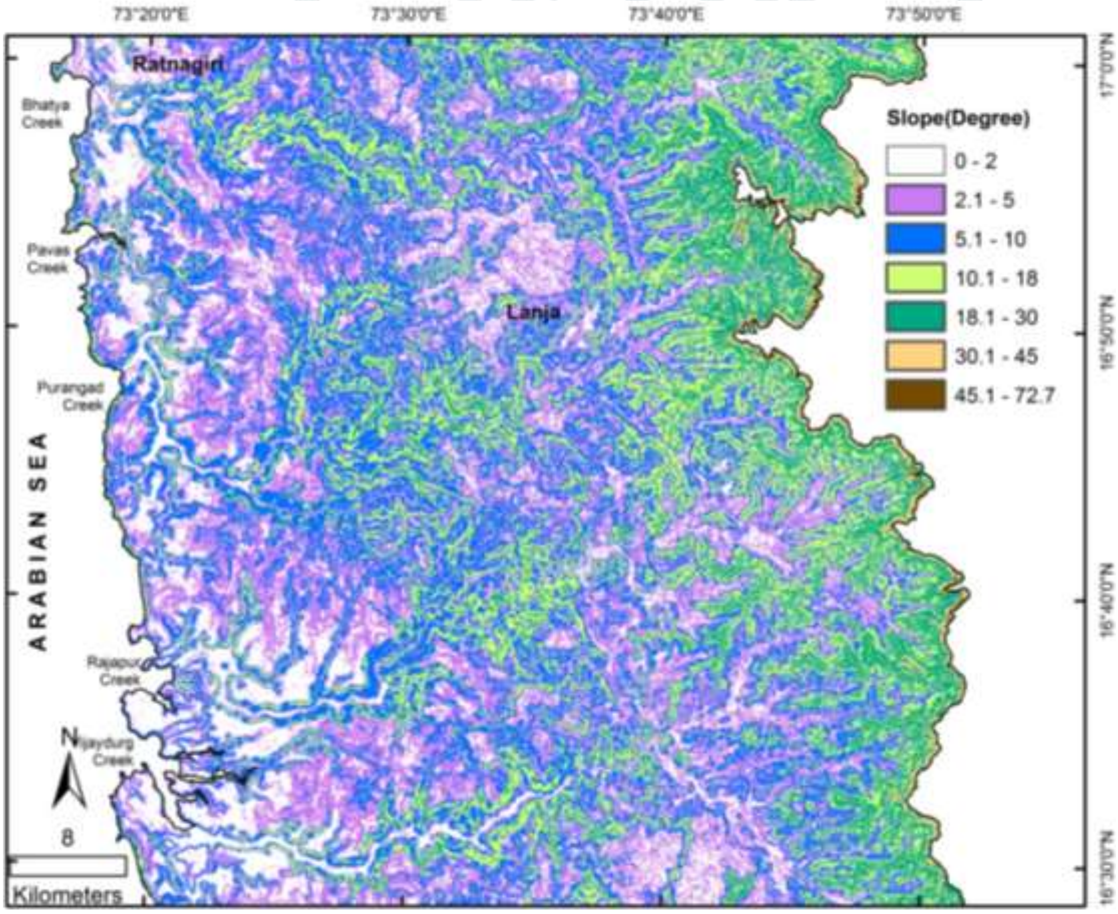


Fig. 10: Classified slope map of the study area.

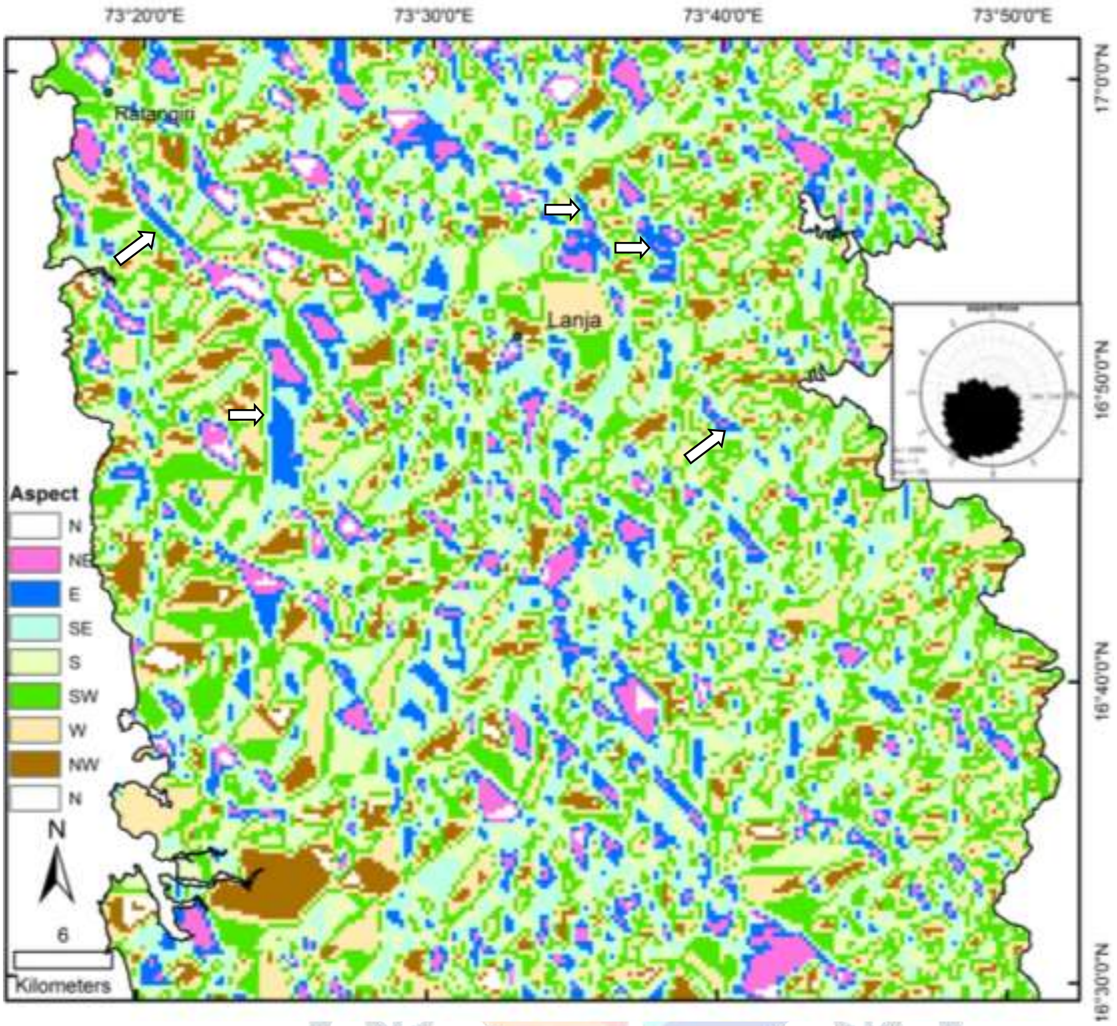


Fig. 11: Classified aspect image of the area. (Inset – Rose diagram of aspect) Arrows show N-S and NW-SE lineaments.

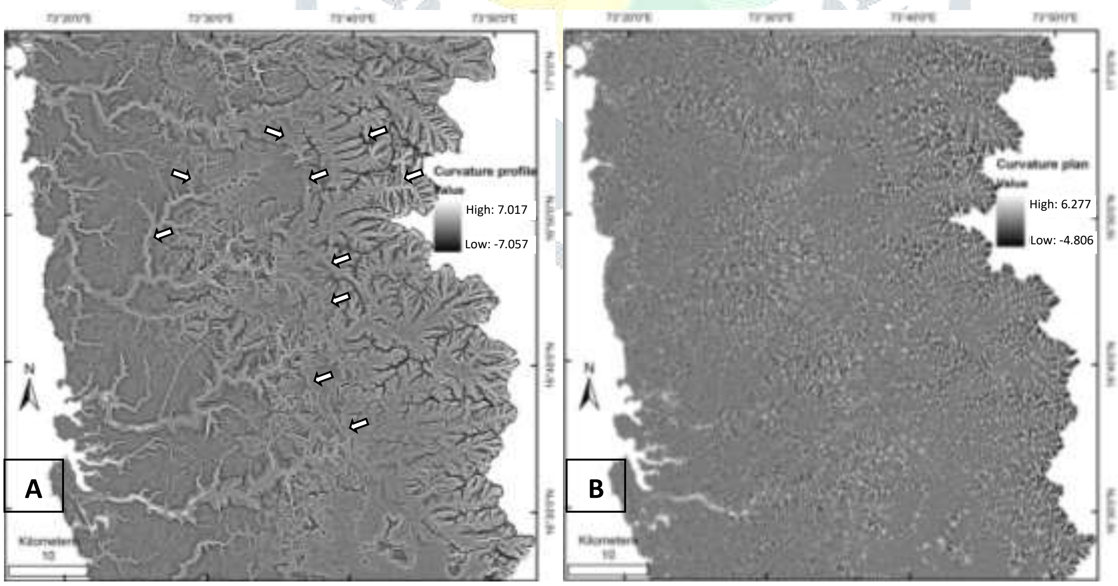


Fig. 12: Curvature map of the area. A) Profile curvature map B) Plan curvature map. Arrows indicate high and linear profile curvatures.

3.4 Digital Geomorphometry: Figure 12 illustrates the trend of lineation of aspects in the area, generated by autocorrelation analysis. Most of the aspect entities are oriented in the NNW-SSE direction (arrows in the figure).

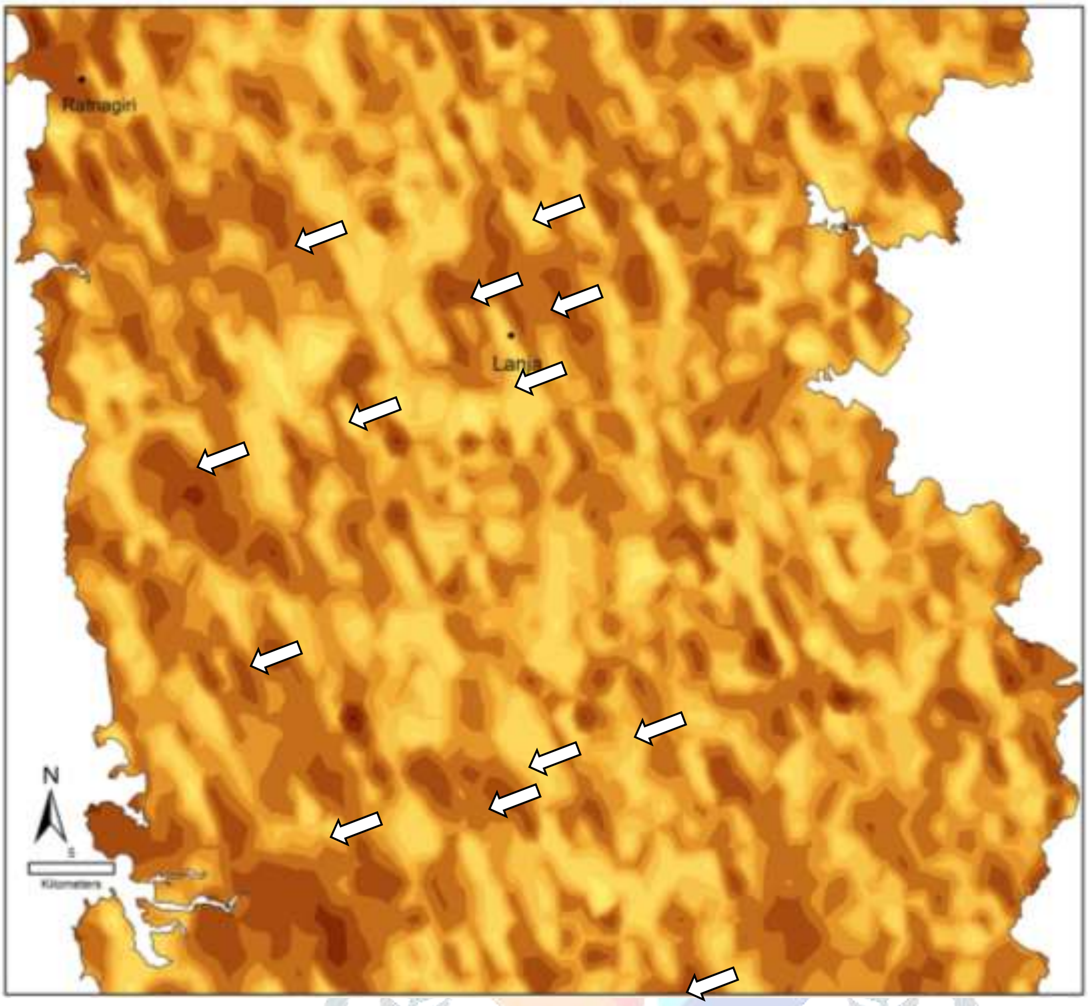


Fig. 13: Autocorrelation analysis of the study area. (Darker areas indicate most correlated entities of aspect) Arrows indicate linear and correlated aspect entities.

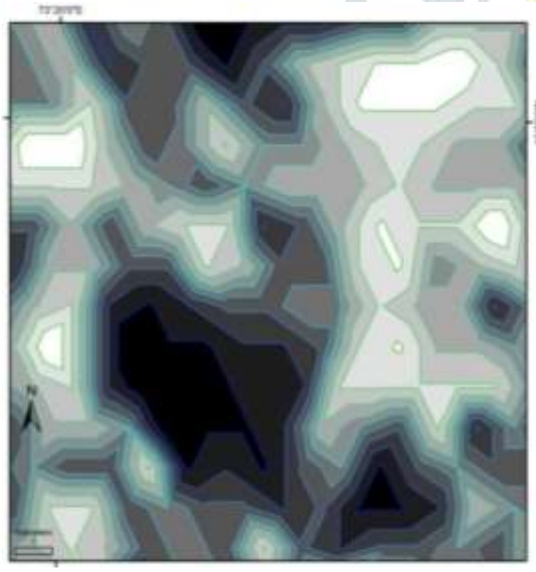


Fig. 14: Autocorrelation Contour lines show correlation values. Large values are emphasized with darker tones. White arrow indicates NNW-SSE anisotropy direction (part of study area).

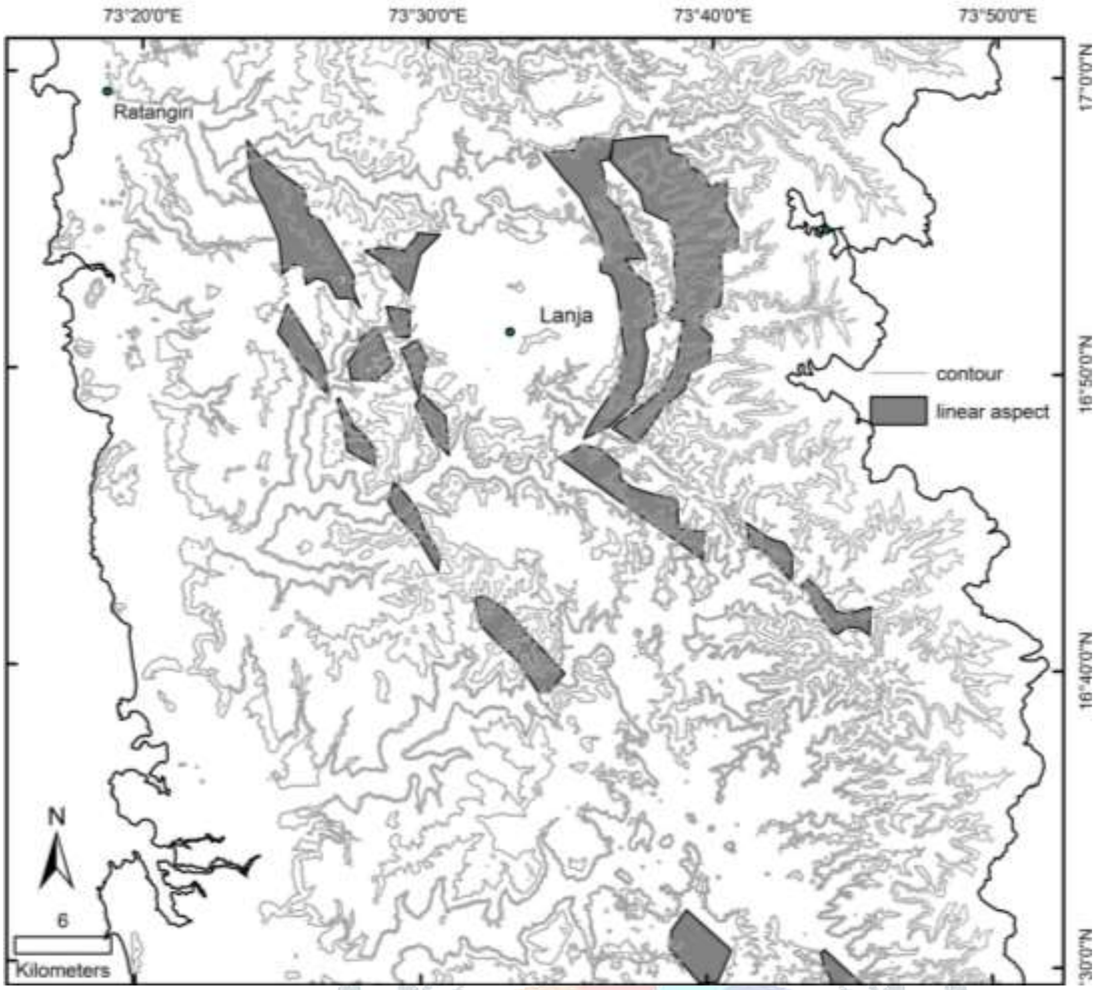


Fig. 15: Classified aspect map based on spatial autocorrelation and anisotropy (lineation) of the study area. Dark shaded areas are aspects in NW-SE and N-S directions. Lines are drawn to highlight edges of the hill slopes. Elevation contours of 80m, 100m, 180m and 240m are also shown to delineate ridges and slopes.

5. CONCLUSION

The DTA algorithm suggested by Jordan et al (2003) helps decipher morphotectonic features and the region's tectonic setting. Colour coded DEM, shaded relief map and aspect map were utilised to recognise regional and local morphotectonic features. The regional features recognised are Western Ghat scarp, upland, west coast and the Konkan plain. The local features recognised are drainage patterns, linear valleys and ridges, mesas and plateaux, planar surfaces, break in slopes, triangular facets, relative relief etc. Shaded relief models generated by illuminating DEM from north, south, east and west were helpful in enhancing lineaments. The autocorrelation of aspect data gave distinct linearity of orientation of tectonic trend in NNW-SSE.

The study area exhibits four lineaments; of these, N-S dominates more than NW-SE and ENE-WSW, while NE-SW lineaments are least. N-S lineaments are distributed all over the region, whereas NW-SE and ENE-WSW lineaments are associated with the eastern part of the study region. The N-S lineaments are of two types, linear and curvilinear. The relationship between linear and curvilinear lineaments indicates that linear N-S lineaments in the NE region of the area are younger than the curvilinear lineaments. L_5 lineaments coincide with the linear coastal segments. L_4 lineament represents the deformation zone and coincides with a line of hot springs indicating its deep-seated structure. The L_3 lineament is a weak zone across the relic part of upland and foothills near Vishalgad and Khorninko. The concentration of lineaments is more in the northeastern Khorninko block and suggests it is more active than other blocks. The NW-SE and ENE-WSW lineaments express as a conjugate pair. The compressive palaeo maximum principal stress (σ_1) determined from this pair is the WSW-ESE direction. Thus, the pattern of the lineaments in the study area reveals complex tectonic activity.

The colour-coded DEM and other models helped to demarcate three geomorphic subzones from east to west are; I) Escarpment and adjacent Foot Hills (EFH), II) Low Relief Lowland (LRL) and III) Dissected Tableland (DTL). N-S lineaments separate these subzones. E-W oriented ridges and valleys are dominating in the EFH subzone. The DTL is a highly dissected plateau region with deep rivers and tributary streams to form many plateaux and mesas. Absolute relief in the DTL decreases towards the south. However, the degree of incision increases in the southern region and reaches nearly sea level. The LRL subzone is relatively low-land with very gentle to moderately undulating topography. Very gentle to gentle slopes of the plateaux in the DTL and northern LRL represent few numbers of major planar surfaces. The curvature analysis reveals a high rate of erosion and incision in DTL and EFH subzones compared to the

LRL subzone. The altimetric studies showed the levels of planar surfaces viz., 620m, 580m, 160m, 123m, 75m and about 5m asl in the study area. The last four planar surfaces are dominating in DTL.

The DTA emphasised secondary tectonic landforms such as deep incised linear and curvilinear valleys, trellis and asymmetric drainages, sharp bends of stream channels, meandering rivers, ridge lines, and slope break whereas, triangular facets along Palu valley represent a primary tectonic feature. The automated delineated drainages using TauDEM module are in good agreement with the drainages of topographic maps. The Khorninko block exhibits structurally controlled parallel, asymmetrical and trellis younger drainage patterns. The region exhibits numerous secondary landforms in linear, deeply incised valleys, indicative of fault-line valleys (Altunel and Hancock, 1993). According to Stewart and Hancock (1994), deeply incised valleys are fault line valleys, and they opined the parallel curvilinear valleys are of the listric type of normal fault and strike parallel axial (subsequent) streams and associated trellis pattern develop as a result of active tectonics. Thus, the deep valleys of Palu, Agav-Mandavkar and Khorninko are fault lines.

In brief, it concludes that the Lanja area is tectonically controlled, wherein N-S tectonic lineaments are more active than NW-SE, ENE-WSW and NE-SW lineaments. Linear N-S lineaments mainly control the coastline, while the zigzag escarpment controls NW-SE and NE-SW lineaments. The N-S deep valleys in the northeastern region are fault lines responsible for developing asymmetrical and trellis drainage patterns. The deep incision along the major rivers, tributaries and elevated lateritic planar surfaces in the DTL region indicate a lower base level due to strong uplift and change in sea level. The three subzones result from tectonic adjustment and fluvial erosion. The deep valleys in the DTL subzone are strong indicators of uplift. The DTL and northern EFH appear to be tectonically more active than LRL and southern EFH. Thus the present landscape is the result of the interplay between tectonic activity and fluvial response to it.

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