Mapping and analysis of tectonic lineaments of Pachamalai hills, Tamil Nadu, India using geospatial technology

A. Prabhakaran and N. Jawahar Raj
Department of Geology, National College, Tiruchirappalli, India

ABSTRACT
In the present study an updated tectonic lineament database for Pachamalai hill, a resource-rich hill of central Tamil Nadu state of India has been generated and analysed. Digital Elevation Model generated from CARTOSAT-1 satellite data have been the data source. Lineaments extracted from eight different azimuth angles were compiled together towards the generation of the lineament database, which has been subsequently analysed for their number, length, density and spatial distribution using ArcGIS software. In addition, their orientations were analysed using Rockworks software. Of the 561 lineaments of the study area, about 90% are very short and short lineaments. The total length of the lineaments is 680 sq. km and their density ranges from 0 to 3.4 km/sq. km. The diversely oriented lineaments of the hill reflect the multiple deformation events that have affected the region through geologic time. In about 30% of the hill, the lineament density is high to very high which implies higher degree of deformation, fracturing, shearing and permeability of rocks besides higher soil erodibility and groundwater yield. These high to very high density areas render themselves unsuitable for the construction of dams and reservoirs as the possibility of water leakages into the subsurface, slope and dam failures and rate of sedimentation would be higher. Further, the analysis of the lineaments clearly underlines the need to extract lineaments from different azimuth angles instead of the widely adopted practice of mapping lineaments from single azimuth angle.

1. Introduction
The term lineament refers to mappable linear or curvilinear features on the Earth's surface which maybe the expression of a fault or other linear zones of weakness. A number of studies have demonstrated the utility of the knowledge about lineaments of an area in various fields of geosciences such as mapping of geological structures, exploration for minerals, hydrocarbons and groundwater, identification of areas prone for seismicity, volcanic eruption, landslides, soil erosion, detection of hot springs, sites suitable for the construction of dams, tunnels, bridges, roads especially in hill areas, etc. The advent of remote sensing data and the demonstrated capabilities of mapping lineaments from them have led to increasing number of studies pertaining to lineaments. Aerial photographs which were widely used for the study of lineaments have now been replaced by satellite images. The availability of variety of freely downloadable satellite images, advancements in digital image processing and automated lineament extraction techniques have made satellite data as the main data source for extracting lineaments. The rapid advancements made in the field of Geographical Information System (GIS) has made this technique a powerful and indispensable tool especially towards the analysis of the identified lineaments in view of its ability to process quickly, store the results quantitatively and also to generate maps. Thus, the advancements made in the field of geospatial technology and the demonstrated utilities of the study of lineaments in various fields of geosciences have led to the spurt in the studies pertaining to lineaments.

Pachamalai hills, the study area is a natural resource-rich area, inhabited by tribals. For formulating strategies towards sustainable development of the hills, it is essential to have thorough knowledge about the lineaments of the hills. Lineaments specifically of Pachamalai hills have not been studied so far. Existing information about the lineaments of the study area are of regional nature (Balaji, 2000; Cenki & Kriegsman, 2005; Chetty, 1996; Drury & Holt, 1980; Drury, Harris, Holt, Reeves, & Wightman, 1984; Grady, 1971; Rakshit & Prabhakar Rao, 1989; Ramasamy, 1989; Ramasamy, 2006; Ramasamy & Balaji, 1993; Ramasamy, Balaji, & Kumanan, 1999; Reddy, Mathew, Singh, & Naidu, 1988; Srinivasan, 1974; Subrahmanya, 1996; Subrahmanyan, 1978; Sugavanam, Venkata Rao, Simhachalam, Nagal, & Murthy, 1977; Tirukumaran, 2013; Valdiya, 2016; Vemban, Subramanian, Gopalakrishnan, & Venkata Rao, 1977)
and are not specific to Pachamalai hills. Furthermore, these lineaments have been mapped from small scale satellite data which is sufficient only for regional level studies. Detailed investigation into the lineaments of this hill has not been attempted so far. The present study attempts to study the lineaments exclusively of the Pachamalai hills using large-scale data. The study area is located in the central part of Tamil Nadu state of southern India, between north latitudes 11°8’52”–11°28’39” and east longitudes 78°29’34”–78°39’29”, and forms part of the Survey of India’s topographic sheets 58 I/11, 12 and 15 of 1:50000 scale (Figure 1). The maximum north–south stretch of the hills is 37 km and along the east–west it is almost the same (36 km). The areal extent of the study area is 507.52 sq. km and is spread over three districts of the central Tamil Nadu state; while the northern and southern halves lie within Salem and Tiruchirappalli districts, respectively, a small portion on the eastern side lies in Perambalur District (Figure 2).

The objectives considered for the present study includes the extraction of lineaments of the study area (from CARTOSAT satellite data) from eight different azimuth angles and their compilation to generate lineament database for the study area, evaluation of number, length, orientation, lineament density variations and a comparative analysis of the lineaments obtained from the eight different azimuth angles considered with that of the final lineament output.

2. Geology of the study area

The study area forms part of the geologically well-known southern Granulitic Terrain of Tamil Nadu state which has experienced multiple episodes of crustal deformation (Chetty & Bhaskar Rao, 2006; Chetty, Vijay, Narayana, & Giridhar, 2003; Drury & Holt, 1980; Ramasamy et al., 1999) because of which the rocks are highly deformed and metamorphosed to granulite facies. Geochronological and isotope studies have shown crustal growth of the terrain during the period 3400 Ma. to 2500 Ma. (Geological Survey of India [GSI], 2006). The granulitic facies metamorphism that occurred in the region has resulted in the formation of charnockites of the region and concomitant anatexis of earlier rocks (GSI, 2006). Information relating to the rock types of the study area obtained from the geology map published by the Geological Survey of India in the year 2014 and ascertained by field checks reveals that the study area comprises predominantly of the rocks of Charnockite Group (mostly charnockites intruded by ultrabasics rocks and granites, and pyroxene granulites) and Bhavani Group (Fissile hornblende biotite gneiss and basic dykes) of Archaen and Archaen to Proterozoic age respectively (Figure 3). Of these rocks charnockites are widespread and they occupy most part of the study area (93%), the typical mineral assemblages being orthopyroxene + quartz + K-feldspars + biotite ± garnet. Geochemically the charnockites of this region has been characterized as Tonalite with high Na₂O and Al₂O₃ contents, and the charnockitic magma of the region is found to be generated due to crustal recycling process at the mid-crustal region (George & Sajeev, 2015). Similar view has been expressed by Rajesh (2012) who attributes the origin of these charnockites to subduction process. Rest of the 7% of the study area is occupied by pyroxene granulites, hornblende biotite gneiss, granite, basic dykes, ultrabasics and garnetiferous gabbros. The pyroxene granulites of the study area occur as linear bands trending in an almost NE–SW direction confining to the northern part of the study area especially to the Gangavalli, Pulambadi and Vedambiyam Reserved Forests. The mineral assemblage of this rock includes quartz + clinopyroxene + orthopyroxene and K-feldspar.

Hornblende biotite gneiss is restricted to the foot hills of the study area especially to the eastern and south eastern parts. The mineral assemblage of the rock is quartz-hornblende-biotite-K-feldspar-plagioclase. Granites are confined to the northern part of the study area especially to the Vedambiyam and Pulambadi Reserved Forests and are seen as enclaves within charnockites. These small plutons were emplaced as culmination of migmatization that occurred in the area during the Late Archaean-Early Proterozoic Periods (George & Sajeev, 2015). The basic dykes of the study area are seen transecting the charnockites and are exposed in three locations. One of them occurs in the northern part of the study area (near Vedambiyam) trending in a NNE–SSW direction while the other two are found in the eastern part of the study area (near Nagur and Sikkadu villages) trending in ENE–WSW to nearly E–W direction. A small patch of ultrabasic rocks occurs in the western part of the study area within the Sengattuppatti Reserved Forest.

The strike direction of the foliation of the major rock type of the study area, the charnockites, is predominantly NE–SW. Two prominent synform structures are found on the western part of the study area, one of which is in the Periyasolai Reserved Forest and the other in the north eastern side of Sengattuppatti Reserved Forests. A prominent antiform structure is found in the south eastern side of the Sengattuppatti Reserved Forests. Two prominent NNE–SSW trending shear zones pass through the Manmalai Reserved Forest in the north western part of the study area (Figure 3).

3. Methodology

Literature relevant to the present study which include those relating to the various aspects of lineaments and those pertaining to the rocks, geological structure and geological history of the study area were collected, compiled and reviewed in order to have a thorough understanding of the theme under study and the geology of the area. In the next stage, lineaments of the study area
were extracted from Digital Elevation Model (DEM) generated from CARTOSAT-1 satellite data (P143 R52) by the National Remote Sensing Centre (NRSC) which is freely downloadable (http://bhuvan.nrsc.gov.in/data/download/index.php). Topographic features which represent lineaments such as straight valleys, continuous scraps, straight streams segments and rock boundaries, systematic off set of streams, sudden tonal variations and alignment of vegetation were identified and digitized on screen. Lineaments were extracted from eight different...
Figure 2. Administrative divisions. Source: Published Survey of India’s Open Series Map.
Figure 3. Rock types. Source: Geological Quadrangle Map of Salem District Published by Geological Survey India.
azimuth angles (45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°) to ensure unbiased mapping of all lineaments of the area under study as demonstrated from a number of studies (Hubbard, Mack, & Thompson, 2012; Muhammad & Awdal, 2012; Tahir, Garba, & Hassan, 2015). Furthermore, interpretation of lineaments at each of these azimuth angles was done at two different scales (1:50000 and 1:80000 scales) to ensure mapping of lineaments of all sizes. The extracted lineaments from each azimuth angle were compared with other data sources such as topographic maps and high resolution Google images to eliminate non-geological lineaments. This elimination of non-geological lineaments was performed for all the eight lineament maps extracted from the eight different azimuth angles. After this elimination process, the remaining lineaments in each of the eight different azimuth angles were stored in eight different separate GIS shape files.

This was followed by combining all the lineaments obtained from these eight different shape files into a single shape file. From this output the redundant/duplicate lineaments were eliminated and the final lineament map of the study area was generated. In the next stage, the final lineament map was analysed for number of lineaments, length of lineaments, lineament density from the computations made using ArcGIS software 10.2 version. Orientation of lineaments of the study area were also analysed for which rose diagrams generated using Rockworks software 2016 version were made use of. This was followed by compilation of results based on which conclusions have been made.

4. Results and discussion

Lineaments extracted from each of the eight azimuth angles considered for the study (45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°) and the final lineament output (generated by compiling the lineaments from all the eight azimuth angle outputs) are shown in Figures 4a–4h and 5, respectively. These lineament data-sets were made use of to estimate their numbers, length and orientations besides spatial variation in lineament density. The salient findings from these estimations are discussed in the following section.

The total number of lineaments of the study area, estimated from the final lineament output is 561. However, lineaments extracted individually from various azimuth angles were far lesser in number and it varied from 116 (at 225° azimuth angle) to 223 lineaments (at 45° azimuth angle). Among the eight azimuth angles, greater number of lineaments (223) were extractable from the 45° azimuth angle. However, even from this seemingly most favourable azimuth angle data for lineament extraction, the number of lineaments extracted (223) was only about 40% of the lineaments extracted from the final lineament output (561 lineaments) (Table 1).

The total length of lineaments of the study area is 680.89 km. However, the length of lineaments estimated from the eight individual azimuth angles were far lesser, varying from 154.30 km (at 225° azimuth angle data) to 261.21 km (at 45° azimuth angle output), which is reflection of variation in the extractable lineaments at different azimuth angles discussed earlier.

Based on the length, lineaments of the study area (Figure 5) were classified as very short (<1 km), short (1–2 km), medium (2–3 km), long (3–4 km) and very long (>4 km). Estimation of the number of lineaments in each of these classes shows that of the 561 lineaments of the study area, 291 are very short and 211 are short lineaments. These two lineament classes together constitute about 90% of the lineaments of the study area. Dominance of such smaller lineaments have also been reported from Adwa river basin of Vindhyan plateau (Nagal, 2014). Medium sized lineaments are lesser in number and they constitute only 7% of the lineaments of the study area. Long and very long lineaments are fewer in number and they constitute just about 2% each of the lineaments of the study area (Table 2).

Lineament density, the total length of lineaments per unit area was estimated and analysed in order to demarcate geologically weaker zones. For understanding the spatial variation of lineament density, a grid of cells 1 sq. km each was overlaid over the final lineament map of the study area and the length of lineaments in each grid was estimated. Based on the range of such estimated lineament density values of the grids, the various lineament density classes such as low (<.5 km/sq. km), moderate (.5–1.5 km/sq. km), high (1.5–2.5 km/sq. km) and very high (>2.5 km/sq. km) were demarcated (Figure 6) using ArcGIS software. In the study area lineament density ranges from 0 to 3.24 km/sq. km. In most part of the study area (57%), the density of lineaments is moderate. The density is found to be high and very high in about 30 and 2%, respectively, and are restricted to the reserved forests such as Palamalai extension, Nakkasalem, Solaimatti and Gangavalli, besides the villages of Thenpurananadu and Vadapuranadu. Studies have shown that areas of high lineaments density reflects high degree of rock fracturing (Edet, Okereke, Teme, & Esu 1998), shearing (Chandrasekhar, Martha, Venkateswarlu, Subramanian, & Kamaraju, 2011), intensity of deformation (Hung, Batelaan, San, & De Smedt, 2004), permeability (Masoud & Koike, 2011), higher groundwater yield (Sener, Davraz, & Ozcelik, 2005), mineral occurrences associated with hydrothermal alteration zones (Kiran Raj & Ahmed, 2014; Rameshchandra Phani, 2014), higher soil erodibility (Jawahar Raj, 2001) and slope failures (Kiran Raj & Ahmed, 2014), etc. Thus based on the above established relationship of high lineament density with the above described factors, it can be inferred that in the high and very high lineament density zones of the study area, the degree of rock fracturing, shearing, intensity of deformation, rock permeability, groundwater yield and soil erodibility, would be
Figure 4a. Lineaments extracted by 45 degree azimuth angle.
Figure 4b. Lineaments extracted by 90 degree azimuth angle.
Figure 4c. Lineaments extracted by 135 degree azimuth angle.
Figure 4d. Lineaments extracted by 180 degree azimuth angle.
Figure 4e. Lineaments extracted by 225 degree azimuth angle.
Figure 4f. Lineaments extracted by 270 degree azimuth angle.
Figure 4g. Lineaments extracted by 315 degree azimuth angle.
Figure 4h. Lineaments extracted by 360 degree azimuth angle.
Figure 5. Final output.
Figure 6. Lineament density. Source: Generated from Cartosat-1 Satellite’s DEM Data.
Table 1. Number of lineaments and length from various azimuth angles.

| Sl. No. | Azimuth angle (in degrees) | Number of lineaments | Min. length | Max. length | Total length of lineaments (in km) |
|---------|-----------------------------|-----------------------|-------------|-------------|-----------------------------------|
| 1.      | 45                          | 223                   | 0.30        | 3.36        | 261.21                            |
| 2.      | 90                          | 201                   | 0.48        | 3.96        | 253.12                            |
| 3.      | 135                         | 155                   | 0.46        | 6.95        | 215.39                            |
| 4.      | 180                         | 165                   | 0.20        | 5.11        | 225.13                            |
| 5.      | 225                         | 116                   | 0.41        | 6.61        | 154.30                            |
| 6.      | 270                         | 148                   | 0.26        | 5.90        | 180.83                            |
| 7.      | 315                         | 183                   | 0.38        | 5.12        | 234.86                            |
| 8.      | 360                         | 178                   | 0.52        | 5.43        | 241.04                            |
| 9.      | Final output                | 561                   | 0.20        | 6.95        | 680.89                            |

Figure 7. Rose diagrams depicting orientation of lineaments at various azimuth angles.
higher. These areas render themselves unsuitable for the construction of dams and reservoirs as the possibility of water leakages into the subsurface, slope and dam failures, rate of sedimentation are higher.

Rose diagrams were constructed for the finalized lineament output (to understand the orientation of lineaments in the study area), lineament outputs of eight different azimuth angles (to understand the existence of preferred orientation(s) of lineaments, if any, in different azimuth angles) and outputs of various lineament length classes (to understand the existence of size-wise preferred orientation(s) of lineaments) using the Rockworks software – 2016 version (Figure 7(a)–(h)) (Table 2).

Rose diagrams constructed for the final lineament output shows that though the lineaments of the study area are diverse in orientation, those oriented in N–S, ENE–WSW and NE–SW directions are predominant (Figure 7(i)). The diverse orientations of the lineaments of the study area reflect the multiple episodes of deformation events that have occurred in the region through...
Table 2. Number of lineaments and length of various lineament length classes.

| Sl. No. | Lineament length class (in km) | No. of lineaments | No. of lineaments |
|---------|--------------------------------|-------------------|-------------------|
|         |                                | (in Nos.)         | (in %)            | (in Nos.) | (in %) |
| 1.      | <1                             | 291               | 51.87             | 213.73    | 31.39  |
| 2.      | 1–2                            | 211               | 37.61             | 282.95    | 41.55  |
| 3.      | 2–3                            | 37                | 6.60              | 90.38     | 13.27  |
| 4.      | 3–4                            | 13                | 2.32              | 45.29     | 6.65   |
| 5.      | >4                             | 9                 | 1.60              | 48.54     | 7.13   |
|         | Total                          | 561               | 100.00            | 680.89    | 100.00 |

Figure 7. (Continued)
features of the study area such as the trend of the prominent regional Gangavalli Shear Zone that passes through the study area, trend of basic dykes and pyroxene granulitic bands which are all oriented in almost NE–SW direction.

The analysis of orientation of lineaments of different sizes (Figure 8(a)–(c)) shows distinct size-wise preferential orientation. North–south direction is found to be the predominant orientation of very short and short lineaments in addition to NE–SW direction of the later. Moderate-sized lineaments are oriented predominantly

geologic time as reported by Anderson (1951), Drury and Holt (1980), Bartlett, Dougherty, Harris, Hawkesworth, and Santosh (1998), Ramasamy et al. (1999), Chetty et al. (2003), Bhaskar Rao et al. (2003), Chetty and Bhaskar Rao (2006) and Tirukumaran (2013). The predominant orientation of the lineaments of the study almost corroborates with the results of several regional studies on lineaments (Balaji, 2010; Rakshit & Prabhakar Rao, 1989; Subramanian & Mani, 1979; Tirukumaran, 2013) and with the orientation of a number of prominent geological

Figure 8. Rose diagrams depicting orientation of lineaments at various lineament length classes.
This data can serve as a valuable input in evolving strategies towards developmental and management planning of this natural resource-rich hill which is facing threats from anthropogenic activities. Furthermore, the analysis of lineament number, length and predominant orientation from eight different azimuth angles and the compiled final lineament output clearly shows that extraction of lineaments from any single azimuth angle, which has been the widely followed practice, is inadequate to provide a reliable account of the lineaments. The study further underlines the need to extract lineaments from varied azimuth angles and their compilation, for getting a reliable database of lineaments.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**5. Conclusion**

The present study has helped to derive a comprehensive lineament database, generated by compiling lineaments extracted from eight different azimuth angles.
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