Geomorphic pattern recognition of SRTM data applied to the tectonic interpretation of the Amazonian landscape

Delano Menecucci Ibanez a,b,⇑, Fernando Pellon de Miranda b, Claudio Riccomini c

⇑ Corresponding author. Address: Petróleo Brasileiro S.A., Centro de Pesquisas e Desenvolvimento (CENPES), Av. Hordício Macedo, 950, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, RJ, Brazil. E-mail addresses: dibanez@petrobras.com.br (D.M. Ibanez), fmiranda@petrobras.com.br (F.P. de Miranda), riccomin@usp.br (C. Riccomini).

1. Introduction

For many years, the Amazon region was presented as uniform and monotonous, not organized in compartments and lacking physiographic and ecological diversity (Ab’Sáber, 1992). However, the substratum of the world’s largest tropical forest is not as homogenous as it may first appear. Countless ecosystems that interact and change over space and time make up an infinite number of scenarios instead of a single one (Val, 2009). The Amazon landscape, a mosaic of islands, plateaus, streams, colossal rivers and lakes, may exert important controls over this ecological diversity (Magalhães et al., 1998). Nevertheless, the Amazon landscape can reveal fundamental information about the underlying geology (Hayakawa et al., 2010).

In the Uatumã River region (Fig. 1), the relief variation is admittedly subtle (Nascimento et al., 1976). The morphological features qualitative descriptions, such as floodplains, fluvial terraces as well as tabular and hilly surfaces, reveal that the terrain is affected by different degrees of dissection and incision (Pellin et al., 2010). The dense vegetation cover and limited access, make geomorphological/geological field mapping very difficult to carry out. Therefore, data from remote sensors, such as the Shuttle Radar Topography Mission (SRTM), have great potential in studying this region, as demonstrated by Almeida-Filho and Miranda (2007) and Hayakawa et al. (2010). In addition, this subtle topographical variation can be studied by quantitative approaches using geomorphometric techniques applied to the SRTM DEM, such as a fractal dimension (Wallace et al., 2006), drainage network density (Luo and Stepinski, 2008), and semivariogram (Bishop et al., 2003).
Furthermore, the topography of the Amazon region portrays a variable morphology/texture (imprinted for instance, by fault scarps and rivers), which results in landscape anisotropy. To also evaluate the anisotropy of each geomorphometric variable and, consequently, the relief, this study focused on topographic roughness and relief elevation, respectively. Each geomorphometric parameter is interpreted in relation to spatial distribution and semivariance anisotropy.

The topographic semivariance anisotropy from semivariogram analysis has been widely used in the Earth Sciences (e.g., Lyew-Ayee et al., 2006). It indicates altimetry variations in preferential directions. The other two techniques were developed in this research and are based on fractal properties. One uses the fractal property of self-affinity, which was extracted from topographic profiles (Wilson and Dominic, 1998) in different orientations, seeking to identify the direction with the most pronounced degree of complexity (roughness). Similar methods were used to study the textile surfaces roughness (Militký and Nováková, 2004) and coral topography (Zawada et al., 2010).

The drainage network density anisotropy evaluates the hydrographical network spatial distribution in different directions by means of the self-similarity fractal property. The direction with the highest value indicates an increased drainage network scattering, while the direction presenting the lowest value denotes a greater agglomeration. This approach was adapted from the fractal anisotropy method developed by Gerik and Kruhl (2008) to study magmatic and deformational features of rock surfaces.

This study seeks to use geomorphometric parameters to quantify the landscape of the Uatumã and Urubu River region and to discuss the relationship between these parameters and structure and the area tectonics. The geomorphometric parameters include the drainage network density, fractal dimension and semivariogram, obtained from the SRTM DEM to evaluate the dissection, roughness and relief elevation, respectively. Each geomorphometric parameter is interpreted in relation to spatial distribution and anisotropic trends. These quantitative parameters facilitated the evaluation of the geologic factors influence on the Central Amazon geomorphologic features.

2. Geology

The Uatumã River region is situated within the Amazon Sedimentary Basin boundaries, which includes continental, marine, shallow marine and fluvial sequences, in addition to intrusive rocks. The stratigraphic column spans from Ordovician to Recent time (Cunha et al., 2007). In the studied area northwesternmost portion, there are three Paleozoic outcropping lithostratigraphic units of the Trombetas Group (Nogueira and Sarges, 2001; Cunha et al., 2007): (a) the Nhamundá Formation, which combines neritic and glaciogenic Silurian sandstones; (b) the Pitinga Formation, which includes Silurian marine shales and diamictites; and (c) the Manacapuru Formation, made up of shales and subordinate sandstones ranging in age from Upper Silurian to Lower Devonian.

The studied area remaining surface is largely occupied by Alter do Chão Formation rocks (Fig. 5b), which is made up of quartz arenites coarse to medium grained, locally conglomeratic, red to variegated, kaolinitic, poorly sorted and with low consolidation. Subordinately, red mudstones and siltstones are found (Costa, 2002). This unit development is associated with a high-energy river system developed from Paleocene to Miocene (Caputo, 2011). It is also worth noting that throughout the region’s main rivers alluvial plains, there are Quaternary deposits formed by clay and sand rich sediments with plane-parallel and crossed stratification, derived from the floodplain, levee and abandoned channel, overlying the Alter do Chão Formation rocks (Latrubesse and Franzinelli, 2002).

The studied area has two main structural directions, NE–SW and NW–SE, which are representative of reverse, transcurrent and normal faults affecting the Paleozoic section and linked to Mesozoic age tectonic and magmatic events (Gonzaga et al., 2000). In addition, normal faults with a similar strike are found in the Cenozoic package, which are associated with two extensional pulses: Miocene–Pliocene and Pleistocene–Holocene (Riccomini et al., 2012). Apparently, these structures control the erosion and dissection processes, as observed in drainage and lineament maps (e.g., Sternberg, 1950). The region’s current stress field is characterized as compressional with the maximum horizontal stress (SHmax) in the NNW–SSE direction (Assumpção, 1992; Lima et al., 1997).

3. Geomorphology

The geomorphological framework conceived by Nascimento et al. (1976) for the Uatumã River region almost entirely forms the Trombetas-Negro River Dissected Plateau. In the studied site’s northwesternmost portion areas surrounding Presidente Figueiredo town are related to the Amazon Sedimentary Basin Plateau, while the southeasternmost part is associated with the Amazon Plain (Fig. 2a).

Subsequently, this region was included in a larger geomorphological unit known as the Amazon Depression or the Amazon
Depression Low Plateaus due to its modest altitudes (with elevations ranging from 100 to 180 m) and the low amplitude of its relief, which are incompatible with a plateau area (Ross, 1991).

Thus, the investigated site relief predominantly consists of an extensive and monotonous domain of low dissected plateaus that are sustained by Alter do Chão Formation rocks affected by different intensities of incision (Pellin et al., 2010). However, a morphological configuration detailed analysis of these low plateaus reveals surprising internal variability, mostly expressed by the differential dissection intensity. This fact led Pellin et al. (2010) to identify five morphological units, summarized as follows:

- **Floodplain**: it represents a set of aggradation forms produced by modern river sedimentation, consisting of seasonally flooded areas that fill the valleys of the main channels.
- **Fluvial terraces**: they represent old floodplains that, due to the channel base lowering, reached an elevation above the seasonal flooding. Thus, these areas became hydrologically inactive and began to be dissected, mainly by fluvial erosion.
- **Sandy plains**: they constitute flat surfaces developed above an extremely sandy substrate and covered by more stunted vegetation (prairies and savannahs), which are found around valley bottoms and interfluvies.
- **Tabular surfaces**: they form a group of relief shapes that are generally found at an interfluvial position and underwent denudation of a low to moderate intensity. They exhibit a diversified morphological character, which vary from a flat top to gently rolling features and steep slopes. Sometimes, they generate significant rugged areas with incised or extended valleys. Furthermore, there are numerous waterfalls, rapids and caves in the mid-upper portion of the Urubu River course. This region is made up of Paleozoic sandstones of the Nhamundá, Pitinga and Manacapurú Formations (Nogueira and Sarges, 2001). It also displays low to medium drainage density, altimetry amplitude between 20 and 50 m, and incised valleys with gentle to steep slopes with gradients between 5° and 20°.
- **Hilly surfaces**: they bring together a set of landforms that are characterized by more intense morphodynamic activity and by a more marked dissection than others of the region. They exhibit morphological features with strong carving, short and steep slopes, rounded tops and incised valleys with alluvial sedimentation, as well as the highest density of the drainage network.

The drainage network distribution pattern presents a subtle variation in the studied area (Fig. 2b). Based on the classification proposed by Deffontaines and Chorowicz (1991), the drainage network is generally classified as dendritic to sub-dendritic (Nogueira and Sarges, 2001). A pinnate pattern is also observed, especially in the main river tributary channels (Ibanez, 2006). It is related to the Alter do Chão Formation clayey-sandy composition, which is broadly distributed, and to the colluvium deposits (Silva, 2005). Trellis drainage, characteristic associated with fault zone areas (Deffontaines and Chorowicz, 1991), is commonly observed in the tributaries on both Preto da Eva and Urubu River banks, tributaries on the Anebá River left bank, and Uatumã River banks (Silva, 2005; Ibanez, 2006).

Finally, rectangular drainage is generally associated with portions of the Urubu River headwater and some Uatumã and Sana-bani River tributaries (Silva, 2005). Annular and radial patterns map drainage anomalies mainly in the Anebá and Sanabani River surroundings region (Almeida-Filho et al., 2010).

### 4. Materials and methods

The SRTM digital elevation data was used for the geomorphometric analysis. The SRTM DEM, produced by NASA originally and subsequently processed by CGIAR Consortium for Spatial Information (SRTM version 4; CGIAR-CSI, http://srtm.csi.cgiar.org), was generated for South America with a 3 arc-seconds (~90 m) spatial resolution. A C-band synthetic aperture radar system, operated in the interferometric mode collected the data (Rabus et al., 2003). In dense vegetation coverage areas, such as the Amazon, the SRTM wavelength (~5.6 cm) radar return signal is controlled by several vegetation canopy components (trunks, branches and leaves). Therefore, the SRTM elevation model in such areas reflects the terrain morphology and the vegetation mean height combination (Hayakawa et al., 2010). Because the vegetation mean height normally follows the terrain undulations, the SRTM data are capable of highlighting changes in the gradients not recorded in other topographic databases available for the region (Almeida-Filho and Miranda, 2007). Some studies for the Amazon region (e.g., Santos et al., 2006; Oliveira and Paradella, 2008; Miceli et al., 2011) indicate that the SRTM DEM planimetric quality has a 12 m root-mean-square elevation error (RMSE) that fulfilled the 1:100,000 topographic mapping requirements. Thus, this scale was adopted in this study.

The geomorphological variables: roughness (fractal dimension), drainage network density (horizontal distance from the cell to the nearest downstream channel) and elevation (semivariogram) were analyzed to characterize the SRTM spatial and anisotropic topographic data. First these variable spatial properties were defined, followed by qualitative comparisons with geological and geophysical information to assess possible lithological and structural influences on the topography. Subsequently, the structural relief tendencies were confirmed by analyzing the variables’ anisotropy and a directional comparison with the structural geological information available in the literature. These procedures were achieved by combining the ArcGis 10.0, TauDEM 5.1 and Matlab R2010a programs.
4.1. Topographic roughness

The self-similarity fractal dimension was used to characterize the SRTM DEM roughness. In doing this the relief maintains the same statistical characteristics over a wide range of scales (Mandelbrot, 1975; Grazzini and Chrysoulakis, 2005), and there is a direct relationship between the fractal dimension and the surface spatial complexity (roughness) (Pentland, 1984). Although the topography has not been recognized as self-similar (e.g., Mark and Aronson, 1984), this property is useful to statistically describe geomorphological attributes such as roughness. Consequently, spatial complexity knowledge aids to better understand the processes that shape the land surface (Huang and Turcotte, 1990; Clarke and Schweizer, 1991; Taud and Parrot, 2005). In addition, the fractal dimension extracts pieces of information about roughness that are not captured by traditional geomorphometric parameters. In fact, it provides a theoretical description of roughness independent of sampling, contrary to other measurements (Xu et al., 1993).

For the SRTM DEM fractal analysis, the eight-pixel method developed by Sun (2006) was adopted, which is a modified triangular prism method conceived by Clarke (1986). This method used sliding windows measuring 33 × 33 pixels to generate squares with 32 × 32 pixels (Clarke, 1986). The 32 × 32 size corresponded to the smallest data matrix, which provides a good fractal dimension estimate for natural surfaces at any scale (Cheng et al., 1999; Sung and Chen, 2004). The window was progressively moved from the SRTM studied area image upper left to the lower right corner by shifting 16 × 16 pixels each time. A final 2.0736 km² area (corresponding to the SRTM data 16 × 16 pixels sliding window) was obtained to estimate the relief’s fractal dimension values.

4.2. Topographic roughness anisotropy

One way to check the fractal characteristics of relief self-affinity is to analyze topographic profiles. However, because many topographic profiles behave as a self-affine time series similar to a Brownian motion (e.g., Turcotte, 1997), this study applied the same procedures used in a real time series analysis.

The R/S analysis (Rescaled Range Analysis) method estimated the self-affinity fractal dimension. This approach, proposed by Mandelbrot and Wallis (1969), is based on hydrological studies performed by Hurst (1951) to calculate the Nile River water reservoir size. From the Hurst exponent calculation, the long-range dependence intensity was classified by measuring in a time series (Cameirão, 2005).

The Benoit 1.31 program provided the R/S analysis calculations. Here, the time series was divided into intervals or windows with a length w. For each interval, R was calculated for the range or amplitude from the least to the greatest value found, along with the standard deviation S. The rescaled range is defined by R/S. This is the Hurst exponent (H) calculation (Turcotte, 1997):

\[ H = \frac{\log (R)}{\log (w)} \] (1)

The H exponent ranges from 0 to 1. Values greater than 0.5 imply a persistent series in which elevation values maintain an increasing or decreasing tendency along the analyzed profile. Values less than 0.5 indicate anti-persistence, i.e., a trend from positive to negative or vice versa along the profile. For H values equal to 0.5, the elevation is a random series and is uncorrelated. The fractal dimension is calculated by this Hurst exponent relationship, i.e., \( Drs = 2 - H \).

To study the elevation roughness and persistence behavior in different directions, the R/S analysis was applied in 20-km topographic profiles centered on the same point and extracted in 36 directions, which varied from 0° to 360° with a 10° spacing. Notably the topographic profile extraction direction affects the R/S analysis. For example, a N–S topographic profile has a Hurst exponent different from an S–N profile, despite presenting the same direction. In addition, their elevations exhibit a different persistence depending on the orientation measurement being considered. Nevertheless, the different H profile values with the same orientation, but running in opposite directions, were not sufficient to reclassify them from anti-persistent to persistent or vice versa.

After the complete R/S analyses, the direction versus the fractal dimension values were plotted and an ellipse fitted to the data. The major ellipse axis indicates the topography direction with the greatest roughness and least persistence.

4.3. Drainage network density

Developed by Horton (1932, 1945), the drainage network density is a fundamental concept in river basin morphometric analysis that represents the topographic dissection degree in landscapes determined by the fluvial activity or the available quantity of flow channels (Strahler, 1964; Christofolleti, 1979). This morphometric variable is computed for a land surface unit as the sum of all channel lengths divided by the total area. Normally, this unit is defined for the entire drainage basin or for sampling areas with pre-established dimensions. This variable is a studied unit attribute and because it cannot describe density changes within the unit, it is not a good spatial variability dissection measurement (Luo and Stepiński, 2008). An improved spatial resolution method to determine the dissection variability is to consider the closest channel horizontal distance, a spatial variable introduced by Tucker et al. (2001). This concept calculates the shortest horizontal distance to the closest downstream channel for each cell. The variable has lower values where the drainage network is dense and higher values where there is little network distribution (Luo and Stepiński, 2008; Wechsler et al., 2009).

Due to the complex land surface morphology, obviously two neighboring cells may have different distance values (e.g., when on the border between adjacent drainage basins). Therefore, distance alone is not an adequate dissection measurement because of the noisy result (Luo and Stepiński, 2008). As an alternative, Tucker et al. (2001) suggested using a spatial mean established...
by a circular filter with an autocorrelation analysis selected size. For the SRTM DEM, this study’s filter diameter was 2500 m (Fig. 3).

### 4.4. Drainage network density anisotropy

The drainage network density anisotropy method evaluated differences in the drainage network spatial distribution. This approach, developed for Structural Geology, uses the capacity dimension to demonstrate the spatial distribution anisotropy of fractures and/or lineaments may be related to any particular zone stress field (Pérez-López et al., 2005, 2007). However, some studies (e.g., Odling, 1997; Bour and Davy, 1999) suggest the correlation function, used to calculate the correlation dimension, best characterizes natural spatial distribution patterns than the box-counting technique (capacity dimension). The correlation dimension describes how object parts are spatially related to others (Bonnet et al., 2001). This dimension was used to evaluate the drainage network spatial distribution anisotropy.

In this method, the drainage lines were extracted from the SRTM DEM using the D8 method of Jenson and Domingue (1988), available in the program PCI Geomatica 9.1. Subsequently, the channels were sampled with 20 km diameter windows, as used in the semivariogram analysis sampling procedure being more than sufficient for a statistically significant analysis (Lyew-Ayee et al., 2006). Next, a set of parallel, 50 m-spaced lines were superimposed on the circular windows (Fig. 4a). According to Gerik and Kruhl (2008), the target region’s circular shape ensures a high degree of the results comparability based on different angles, thus minimizing the geometry opening influence. Indeed, the line spacing only remains constant with a circular opening. From its initial horizontal position, the set of lines experiences a subsequent counterclockwise rotation that follows an angle, $\beta$ (10°), around a fixed central point. The procedure is repeated while the total rotation angle $\beta$ is less than 180°.

This procedure generates intersection points between the profiles and the drainage network elements, which are subsequently used to calculate the correlation dimension. This measurement is based on the correlation function between two points (Munier, 2004), as follows:

$$C(r) = \frac{1}{N} N_d(r)$$

where $N$ is the number of points (intersections) and $N_d$ is the number of point pairs with separation distances less than radius ($r$). Subsequently, $C(r)$ is plotted in a log–log diagram against the distance $r$. When the data form a straight line in the log–log diagram, the distribution follows a power law, and the slope calculated by a linear regression may be equated with the correlation dimension ($D_c$) (Fig. 4b). The calculated slope values can then be plotted in a direction versus slope diagram. This correlation–orientation dimension diagram is presented in Fig. 4c, along with the ellipse that best represents the majority of the data. The major ellipse axis is $a$, and $b$ the minor and $\gamma$ refers to the $b$ axis orientation in relation to 0°. The axial ratio is $a/b$, referred to as the fractal dimension anisotropy by Volland and Kruhl (2004). Whenever $a/b$ is close to 1, the ellipse almost becomes a circle with respect to the statistical inaccuracy. Consequently, the analysis correctly reflects the pattern isotropy (Gerik and Kruhl, 2008).

### 4.5. Topographic semivariance

According to the procedures adopted by Al-Kouri et al. (2010) and Lyew-Ayee et al. (2006), spatial variation in the relief elevation value was also used for the geostatic topography characterization. First, a semivariogram is generated in ArcGis 10.0 (Johnston et al., 2001). Basically, the semivariogram measures the spatial structure degree between neighboring points, with the expectation that closer points will present a greater influence on their magnitude value.
compared with those separated by longer distances. Therefore, more distant points would have a smaller influence until the observed difference can be attributed to chance alone. The elevation ($'gamma'$) semivariogram is defined by Lyew-Ayee et al. (2006) as the following:

$$\gamma(s_i - s_j) = \frac{1}{2\sigma} |Z(s_i) - Z(s_j)|,$$

where $\sigma$ is the elevation variance and $Z$, the elevation, while $s_i$ and $s_j$ are the analyzed point pairs. After removing the directional trend from the data, the k-Bessel model (Chilès and Delfiner, 1999), also known as the Matern (1960) model, was fitted to the experimental points based on the semivariogram cloud shape and on the predictive cross-validation model (Lyew-Ayee et al., 2006).

5. Results and discussion

5.1. Terrain geostatistics

The studied region self-similarity fractal image, calculated with the eight-pixel method, exhibited different textural characteristics, as shown in Fig. 5a. This image highlights zones with low fractal dimension values that are mainly associated with the main rivers' floodplains. The high value areas correspond to the interfluves and occupy more than 2/3 of the investigated area. Compared with the geological map (Fig. 5b), the lowest value zones are mostly related to Quaternary alluvial sediments. In contrast, the high value zones correspond to Alter do Chão Formation rocks, except in the studied region extreme northeast, which consists of outcropping Paleozoic rocks. However, the high value zones feature distinct shapes and distributions, suggesting they reflect not only a lithology control, but also have a structural component. Furthermore, the main rivers (where the alluvial deposits accumulate) are predominantly NW–SE aligned, indicating structural control in the drainage network installation and, consequently, in the sediments distribution corroborating previous observations of Sternberg (1950).

The high fractal dimension value regions were visually separated into six domains for a subsequent statistical analysis. They were named according to their geographic location, as follows: Urubu, Puraquequara, Presidente Figueiredo, Preto da Eva, Silves, and Uatumã (Fig. 5a). Besides the distinct terrain roughness spatial distribution, visual interpretation took into consideration each domain's geomorphologic characteristics. In the Silves region, hilly surfaces were found with rounded peaks in addition to drainage network annular and radial patterns (Silva, 2005; Almeida-Filho et al., 2010). In Presidente Figueiredo, there were tabular surfaces with many waterfalls and rapids (Nogueira and Sarges, 2001).

The other domains display subtler variations with the combined presence of hilly, tabular, sandy plains and fluvial terrace features. In Puraquequara, more undulated shapes stand out, characterized by U-shaped valleys and elongated depressions. In the Preto da Eva domain, the shapes are smoother, with an emphasis on fluvial terraces in the main rivers' tributaries (Billacrê's et al., 2010). Urubu and Uatumã domain geomorphologic descriptions are scarce. Therefore, their geomorphologic features, perhaps indicative of tectonic control, were considered to distinguish them. For Uatumã, the Abacate River capture should be mentioned, as well as its waterfalls (Nelson et al., 2010) and interfluves orientated WNW–ESE. For Urubu, the interfluve orientated NW–SE between the Uatumã and Urubu Rivers was taken into account, which coincides with the magnetic discontinuities mapped by Miranda et al. (1994), as suggested by comparing Figs. 5a and 8b. Despite the Mesozoic age of this subsurface feature (Gonzaga et al., 2000), its rejuvenation expression can be represented by block tilting zones associated with extensioinal events that have been affecting the Central Amazon region since the Miocene (Ibanez and Riccomini, 2011; Riccomini et al., 2012).

In the statistical analysis, both the highest and lowest fractal dimension values are recorded in the Silves domain. The Uatumã domain exhibits the highest mean, while the Puraquequara domain has the lowest standard deviation. Table 1 summarizes the descriptive statistics for each domain. To test the hypothesis that all the domains have the same mean fractal dimension, the Kruskal–Wallis test (Wallace et al., 2006) was used. This test provided a small $p$ value ($3.14 \times 10^{-4}$), which is strong evidence to reject this hypothesis. However, the Tukey's honestly significant difference method (Perry et al., 2008), which determines the domains that are significantly different from each other, showed that the fractal dimension distinguishes neither the Presidente Figueiredo from the Urubu and Silves regions nor the Puraquequara from the Preto da Eva and Uatumã domains (Fig. 6a). Nevertheless, President Figueiredo, Urubu, and Silves domains coincide spatially with the magnetic discontinuity mapped by Miranda et al. (1994) in the Uatumã and Urubu Rivers' interfluves, which may point to a possible structural control over the region's fractal dimension distribution (Fig. 6b).

Using the semivariogram analysis, all the domains, even those where it was not possible to make a distinction using the fractal dimension, displayed significant differences. For this analysis, 400 km$^2$ sampling areas were selected for each domain. Depending on the domain size, more than one sample was taken. This was the Silves case, which had three samples, and also for Uatumã and Preto da Eva, with two samples each. To distinguish one sample from another in the same domain, they were named according to their location. For example, in the Silves domain, the samples were named Silves East, Silves South and Silves West (Fig. 7).

In the analyzed samples (Table 2), the highest threshold or sill value, indicative of the spatial variation degree in the elevation, was found in Presidente Figueiredo, and the lowest value in Preto
The Presidente Figueiredo samples exhibited the greatest range, indicating spatial autocorrelation occurs at increased horizontal distances, i.e., the elevation spatial dependence is maintained for longer distances in this region. In contrast, the Silves samples exhibited the smallest range values. These results indicate the differences between Silves and Presidente Figueiredo could be expressed by means of Geostatistics, in contrast to these domains’ mean fractal dimensions. In the Urubu domain, the range value is less than half of that observed in Presidente Figueiredo, showing a narrow interval of spatial correlation for Urubu when compared to Presidente Figueiredo. Despite not being spatially adjacent, the small difference between the Puraquequara and Uatumã regions range values and sill values confirm the geostatistical similarity between the two regions.

The topographic variability was also confirmed by the drainage density map (Fig. 8). The result of this analysis, indicative of the dissection pattern, showed no relationship with the geological map (Fig. 5b). In contrast, it has a strong correlation with subsurface and surface geological features. In the Silves domain, for example, Almeida-Filho et al. (2010) found many drainage anomalies and associated them with subsurface faults. The density circular pattern in this region may also reflect this structural control. In addition, lineaments extracted from the map in Fig. 8a are related to strong magnetic gradients. This spatial association is evident in Fig. 8b, where the drainage density map is compared with the anomalous magnetic field reduced to the pole (Miranda et al., 1994). This is also the case for the interfluves between the Uatumã and Abacate rivers, where a high drainage density zone (A1) is aligned with this morphological WNW–ESE direction feature and with a strong magnetic gradient. This configuration may reflect a fault zone, and this interpretation is supported by the Bela Encantada Waterfall at this location. Drainage density use to indicate subsurface faults has already been suggested by Marple and Talwani (2000) and Han et al. (2003) for the southeastern United States and northern China, respectively.

Also evident in Fig. 8 is the lineament (A2) that is defined by a NE–SW oriented low drainage density zone; it also coincides with the Morenas Waterfall and with the Uatumã River floodplain expansion area (Fig. 9a). The topographic profiles (Fig. 9b) that cross the Uatumã River reveal an abrupt change in their

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### Table 1

Descriptive statistics for the domain fractals.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Area (km²)</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Mean</th>
<th>Stand. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presidente Figueiredo</td>
<td>814</td>
<td>2.284</td>
<td>2.694</td>
<td>0.410</td>
<td>2.487</td>
<td>0.081</td>
</tr>
<tr>
<td>Preto da Eva</td>
<td>2535</td>
<td>2.240</td>
<td>2.757</td>
<td>0.516</td>
<td>2.512</td>
<td>0.083</td>
</tr>
<tr>
<td>Puraquequara</td>
<td>1748</td>
<td>2.267</td>
<td>2.810</td>
<td>0.543</td>
<td>2.538</td>
<td>0.079</td>
</tr>
<tr>
<td>Silves</td>
<td>5958</td>
<td>2.000</td>
<td>2.836</td>
<td>0.837</td>
<td>2.501</td>
<td>0.097</td>
</tr>
<tr>
<td>Uatumã</td>
<td>2525</td>
<td>2.242</td>
<td>2.820</td>
<td>0.578</td>
<td>2.544</td>
<td>0.100</td>
</tr>
<tr>
<td>Urubu</td>
<td>2645</td>
<td>2.233</td>
<td>2.743</td>
<td>0.511</td>
<td>2.486</td>
<td>0.091</td>
</tr>
</tbody>
</table>

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### Table 2

Summary of geostatistical results.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Sill (m)</th>
<th>Range (m)</th>
<th>Major range (m)</th>
<th>Minor range (m)</th>
<th>Anisotr.</th>
<th>Anisotr. direc. (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puraquequara</td>
<td>393.29</td>
<td>3180.26</td>
<td>4356.33</td>
<td>2692.24</td>
<td>1.62</td>
<td>152.23</td>
</tr>
<tr>
<td>Presidente Figueiredo</td>
<td>589.62</td>
<td>5506.98</td>
<td>7549.69</td>
<td>3705.50</td>
<td>2.04</td>
<td>13.18</td>
</tr>
<tr>
<td>Preto da Eva North</td>
<td>284.13</td>
<td>2040.57</td>
<td>3042.95</td>
<td>1813.10</td>
<td>1.68</td>
<td>37.62</td>
</tr>
<tr>
<td>Preto da Eva South</td>
<td>254.82</td>
<td>3350.71</td>
<td>4608.07</td>
<td>2596.76</td>
<td>1.77</td>
<td>34.63</td>
</tr>
<tr>
<td>Silves East</td>
<td>492.66</td>
<td>1961.73</td>
<td>2819.36</td>
<td>1868.45</td>
<td>1.51</td>
<td>2.81</td>
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<tr>
<td>Silves West</td>
<td>468.50</td>
<td>1612.19</td>
<td>1693.03</td>
<td>1568.96</td>
<td>1.08</td>
<td>168.40</td>
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<td>30.59</td>
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<td>4714.44</td>
<td>2312.45</td>
<td>2.04</td>
<td>23.73</td>
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<td>Uatumã West</td>
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<td>5770.01</td>
<td>3068.24</td>
<td>1.88</td>
<td>123.40</td>
</tr>
<tr>
<td>Urubu</td>
<td>373.41</td>
<td>2120.44</td>
<td>3061.31</td>
<td>1931.79</td>
<td>1.58</td>
<td>29.71</td>
</tr>
</tbody>
</table>
cate that the ellipse minor axis has the following directions: relative uplift, as postulated by Marple and Talwani (2000).

This modification, combined with the increase in the drainage network of the Morenas Waterfall leading to a wide floodplain downstream. geomorphologic characteristics, with a V-shaped valley upstream shows annular density pattern in the region of Silves (see the text for more details).

A1 indicates that the lineament coincides with the interfluves of the Uatumã and Abacate rivers; A2 indicates the lineament that crosses the Uatumã River; C1 indicates the Bela Encantada Waterfall; C2 indicates the Morenas Waterfall; S shows annular density pattern in the region of Silves (see the text for more details).

5.2. Anisotropic trends analysis

To analyze the drainage network spatial distribution anisotropy, features corresponding to the channels were sampled by circular windows centered on the variography investigated areas. This procedure shows the studied region has weak anisotropy, with the ellipses almost becoming circles (a/b ranging from 1.002 to 1.008). There is also a preferential NE–SW major axis direction of the Presidente Figueiredo, Uatumã East, Preto da Eva South and Silves West samples. For the Preto da Eva North, Urubu and Silves East and South samples, the major axis direction is WNW–ESE, while for the Puraquequara and Uatumã West samples, the direction is NE–SW. Table 3 displays the major axis (axis a) values in degrees for all samples.

The standard deviation (s) normalized by the major axis (a) length was employed to confirm the points fit to the ellipse (Gerik and Kruhl, 2008). A good data likeness was obtained for the ellipse, with a 0.339–0.474% variation (Table 3). The drainage network density anisotropy may be related to the stress field (Pérez-López et al., 2007). In addition, the ellipse minor axis may be parallel to the SHmax (maximum horizontal stress). Thus, even with a small difference in the lengths between the axes (a/b), the results indicate that the ellipse minor axis has the following directions:

- NW–SE for the Presidente Figueiredo, Uatumã East, Preto da Eva South and Silves West samples; NNE–SSW for the Preto da Eva North, Urubu and Silves East and West samples; and NE–SW for the Puraquequara and Uatumã West samples (Fig. 11).

When compared to the target region current stress field, the NW–SE direction is linked to the compressive stresses SHmax resulting from the scattering along the Mid-Atlantic Ridge on one side and the resistance imposed by the Nazca and Caribbean plates on the other (Mendiguren and Richter, 1978; Assumpção and Suárez, 1988). Alternatively, the NNE–SSW direction is associated with the local effects generated by the Amazon Basin Paleozoic Rift (Assumpção, 1992; Zoback and Richardson, 1996). In contrast, the NE–SW direction has no link with the data representing the current stress field. However, it is possibly linked to the old NW–SE structures formed during Mesozoic tectonic events (Miranda et al., 1994) which control the direction of the studied area main rivers. Furthermore, these old structures apparently were reactivated by extensional pulses, which have occurred in the region since the Miocene (Riccomini et al., 2012).

For the topographic roughness anisotropy analysis, the topographic profiles were centered on the same circular sampling area used in the drainage network density anisotropy analysis. The only example that displayed persistence (H > 0.5) was Presidente Figueiredo, which is displayed in the WNW–ESE direction (Fig. 11). The other domains were classified as anti-persistent. Low, or even a lack of, persistence may be a characteristic of gentle elevation landscapes, as found by Rice-Snow and Russell (1999) in a topographic profile R/S analysis of the United States Continental Divide.

In addition to the persistence, the R/S analysis also indicated the anisotropy degree and the greatest roughness direction (Table 4). The highest anisotropy degree (1.15) was found in the Presidente Figueiredo sample (a/b), and the lowest degree was found in the Uatumã East sample (1.08), while both had greatest roughness directions that were approximately N–S (Fig. 11). The highest roughness value (1.72) was found in the Uatumã East sample, and the lowest (1.65) in the Preto da Eva North sample. Fig. 10 shows the comparison of the topographic profiles from the highest to the lowest roughness for the Presidente Figueiredo and Uatumã East samples, respectively. However, the most common sample direction was E–W. This is the highest roughness direction in the Urubu, Puraquequara, Silves West and Uatumã West samples. The NE–SW direction is predominant in the Preto da Eva South and Silves South samples, while NW–SE appeared in the Silves East sample (Fig. 11).

Using the semivariogram, the highest elevation spatial variation direction was confirmed, i.e., to measure the anisotropy of these data, as shown in Table 2. Generally, the anisotropy degree may be estimated by means of the difference between the maximum and minimum ranges. However, the ratio between them was used in this study as a standardization method with other anisotropy measurements. The Presidente Figueiredo and Uatumã East sampling areas have the highest anisotropy degrees (2.04), while Silves West exhibits the smallest (1.08). The predominant directions are NNE–SSW and NE–SW, except for Puraquequara, Silves West and Uatumã West, which feature a NW–SE direction most likely influenced by the direction of the Puraquequara, Anebá and Abacate river valleys, respectively. Additionally, the topographic semivariance anisotropy exhibits strong relationships with the roughness and drainage network density anisotropy. The samples with the highest degree of topographic semivariance anisotropy tend to display less than 20° differences among the directions with the highest roughness and elevation, while the difference between the highest elevation direction and the highest density agglomeration is close to 90°.

Fig. 11 shows the comparison of the anisotropy analysis with seismic interpretations available for the region (Neves, 1990;
Miranda et al., 1994). Using this comparison, the Silves East and Silves South samples, located between the Lucas Borges lineament and the normal fault defined by Neves (1990), display an approximately N–S direction for the highest drainage network agglomeration and the highest elevation range. Another example of possible subsurface structure control over the region’s anisotropy patterns is observed in the Uatumã domain, specifically in the Uatumã East sampling area. There, both the semivariance and roughness anisotropy exhibit a main direction that is similar to the reverse faults orientation mapped with seismic data (Miranda et al., 1994) in the Paleozoic sedimentary piles. Also in this region, the direction with the highest drainage network agglomeration is almost

Table 3

<table>
<thead>
<tr>
<th>Domain</th>
<th>a</th>
<th>b</th>
<th>s/a (%)</th>
<th>a/b</th>
<th>Direc. axis a (°)</th>
<th>Direc. axis b (°)</th>
<th>Stand. dev. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presidente Figueiredo</td>
<td>1.574</td>
<td>1.570</td>
<td>0.394</td>
<td>1.002</td>
<td>63.059</td>
<td>333.059</td>
<td>0.006</td>
</tr>
<tr>
<td>Preto da Eva North</td>
<td>1.590</td>
<td>1.578</td>
<td>0.440</td>
<td>1.008</td>
<td>278.575</td>
<td>8.575</td>
<td>0.007</td>
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<tr>
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<td>1.582</td>
<td>1.572</td>
<td>0.474</td>
<td>1.006</td>
<td>54.086</td>
<td>324.086</td>
<td>0.008</td>
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<tr>
<td>Piraquequara</td>
<td>1.573</td>
<td>1.568</td>
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<td>321.260</td>
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<td>0.006</td>
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<tr>
<td>Silves East</td>
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<td>0.367</td>
<td>1.002</td>
<td>291.653</td>
<td>21.653</td>
<td>0.006</td>
</tr>
<tr>
<td>Silves West</td>
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<td>1.560</td>
<td>0.339</td>
<td>1.003</td>
<td>19.388</td>
<td>289.388</td>
<td>0.005</td>
</tr>
<tr>
<td>Silves South</td>
<td>1.571</td>
<td>1.568</td>
<td>0.363</td>
<td>1.002</td>
<td>270.463</td>
<td>0.463</td>
<td>0.006</td>
</tr>
<tr>
<td>Uatumã East</td>
<td>1.581</td>
<td>1.577</td>
<td>0.348</td>
<td>1.002</td>
<td>25.165</td>
<td>295.165</td>
<td>0.006</td>
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<tr>
<td>Uatumã West</td>
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<td>1.572</td>
<td>0.417</td>
<td>1.007</td>
<td>310.195</td>
<td>40.195</td>
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<tr>
<td>Urubu</td>
<td>1.579</td>
<td>1.575</td>
<td>0.361</td>
<td>1.003</td>
<td>286.922</td>
<td>16.922</td>
<td>0.006</td>
</tr>
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</table>

Fig. 9. Change in the shape of the Uatumã River, which may be related to tectonic movements. (a) Region geological map where there is a floodplain expansion of the Uatumã River (Miranda et al., 1994). (b) Topographic profile A–A0, which is located upstream from the Morenas Waterfall, with the embedded valley in a “V” shape. (c) Topographic profile B–B0, which is located downstream from the Morenas Waterfall, with the broad expansion of the floodplain. AD = Alluvial deposits, AC = Alter do Chão Formation, Mp = Manacapuru Formation, and Nh = Nhamundá/Pittinga Formation. The arrow indicates the location of the Uatumã River. See Fig. 8a for the location of lineament A2.
perpendicular to the roughness and topographic semivariance anisotropy. These facts indicate subsurface structures exert a strong control over the anisotropic relief trends. This also indicates these structures have been reactivated by Miocene to Holocene age tectonic events, as demonstrated by Riccomini et al. (2012).

**Fig. 10.** Topographic profiles: Presidente Figueiredo, major (a) and minor (b) roughness; Uatumã East, major (c) and minor (d) roughness.

**Fig. 11.** Anisotropy analysis comparison. In the rose diagram, arrows indicate the direction with the greatest drainage network agglomeration; the green line represents the topographic semivariance anisotropy; and the orange shows the greatest roughness. In the SRTM image, red lines indicate reverse faults mapped in the Palaeozoic section; blue lines indicate normal faults; and rose-colored lines indicate transcurrent faults (Miranda et al., 1994). The yellow line delineates the fractal domains. For the structures mapped from seismic surveys (Neves, 1990), the numbers are indicative as follows: 1 = Urubu lineament; 2 = Normal fault; 3 = Lucas Borges lineament; 4 = Jatapu lineament; and 5 = Northern hinge line of the Amazon Basin. The sampling areas were abbreviated as follows: PF = President Figueiredo; PS = Preto da Eva South; PN = Preto da Eva North; PU = Puraquequara; SE = Silves East; SW = Silves West; SS = Silves South; UE = Uatumã East; UW = Uatumã West; and UR = Urubu. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Similarly, in the areas surrounding Presidente Figueiredo, normal faults and fractures, formed by extensional events during Holocene–Miocene times (Riccomini et al., 2012) and associated with waterfalls and rapids, show a preferential NNE–SSW direction (Nogueira and Sarges, 2001). These structures' orientations coincide with the major axis directions indicated for the roughness and elevation anisotropies.

For the drainage density anisotropy, the NNW–SSE direction, which features the highest agglomeration, corresponds to the normal faults and fractures orientations. These structures are also associated with rapids and waterfalls (Nogueira and Sarges, 2001; Silva, 2005). The Urubu River WNW–ESE upper course direction is most likely embedded in normal faults. On the left bank, scarps with triangular facets (Fig. 12) suggest a tectonic valley, characteristic of extensional regimes, similar to those recognized by Salvador and Riccomini (1995) in the Taubaté Basin.

The approximately 70° change in all anisotropy directions for Paraquequara, Preto da Eva North and Preto da Eva South may be indicative of structural control. The Paraquequara region is characterized by NW–SE orientated normal faults located in the main river valleys (Ibanez and Riccomini, 2011). This is the same direction for the elevation and roughness anisotropies. In Preto da Eva South, Riccomini et al. (2012) mapped NE–SW direction normal faults and fractures, which cut Miocene to Holocene age sediments. Presumably, these structures also influence the semi-variance and roughness anisotropy, as well as the Preto da Eva and Paraquequara River tributaries.

6. Conclusions

The Amazon region has been posing a continuous challenge to those devoted to understand the intricate relationships between geology, geomorphology, hydrology and biology in such a unique scenario. The ability to infer geology and geomorphology, or at least some of their aspects, automatically from topographic data provide affordable means to survey large regions, such as Central Amazonia, where this information is not yet available. The proposed methods properly address the questions raised by surface phenomena in a rainforest environment related to processes such as differential dissection and resulting roughness. Our results demonstrate a framework to infer contrasts in geology and geomorphology from DEM data, which are readily available from remote sensing (e.g., SRTM data) for the Amazon region that is limited by physical access. Furthermore, it may serve as an aid in Amazon forest biodiversity studies, given that the region's live biomass spatial distribution may be associated with relief variations (Castilho et al., 2006).

These methods also proved the Amazon landscape is more compartmentalized than shown in the available geomorphological map. Similarly, the spatial coincidence between geomorphometric and magnetic features demonstrate the adopted methodology potential to identify geological structures in the Amazon context. In addition, landscape trends are apparently controlled by a present-day stress state and subsurface geologic structure. Therefore, this work contributes to support the interpreter by providing suitable tools to unravel the Amazon region unique geomorphological framework, and an aid to tectonic studies.

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References


