Trend-surfaces analysis of morphometric parameters: A case-study in southearstern Brazil.

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Abstract

Trend-surface analysis was carried out on data from morphometric parameters isobase and hydraulic gradient. The study area, located in the eastern border of Quadrilátero Ferrífero, southeastern Brazil, presents four main geomorphological units, one characterized by fluvial dissection, two of mountainous relief, with a scarp of hundreds of meters of fall between them, and a flat plateau in the central portion of the fluvially-dissected terrains. Morphometric maps were evaluated in GRASS-GIS and statistics were made on R statistical language, using the *spatial* package. Analysis of Variance (ANOVA) was made to test the significance of each surface and the significance of increasing polynomial degree. The best results were achieved with 6th-order surface for isobase and 2nd-order surface for hydraulic gradient. Shape and orientation of residuals maps contours for selected trends were compared with structures inferred from several morphometric maps, and a good correlation is present.

Keywords: Trend-surface analysis, Morphometric Analysis, Geographic Information Systems, GRASS-GIS, R statistical language, Analysis of Variance.

1. Introduction

Trend-surface analysis is the mathematical method used separate map data into components of regional nature from local fluctuations (Agterberg, 1974; Davis, 1986). Regional trends are computed as polynomial surfaces of successive powers; residual values, corresponding to local fluctuations, are the arithmetic difference between original data and trend surface. Residuals maps play an important role in trend-surface analysis given that they can favour on identify or accentuate features of interest. This technique has been widely used by petroleum geologists, to predict structural behaviour of stratigraphic units in search for traps, geographical features, or to recognize structural "breaks" between successive units (Merriam and Harbaugh, 1963; Merriam and Lippert, 1966; Sutterlin and Hastings, 1986; Davis, 1986).

Morphometric maps are important tools in studies related to neotectonics and geomorphology, where the answers of natural landscapes to planet's interior dynamics is often masked by fast action of weathering, and the presence of drainage network anomalies and relief pattern discontinuities may be related with recent terrain movements (Zuchiewicz, 1991; Rodriguez, 1993; Salvador and Riccomini, 1995; Hiruma and Riccomini, 1999; Hiruma *et al*, 1999).

This work presents trend-surface analysis of the morphometric parameters hydraulic gradient (Rodriguez, 1993) and isobase (Filosofov, 1960 cited in Jain, 1984; Golts and Rosenthal, 1993), with integrated utilization of free software GRASS-GIS (U.S. Army CERL, 1993) and R statistical language (Ihaka and Gentleman, 1996), in the Serra do Caraça region, eastern border of Quadrilátero Ferrífero, southeastern Brazil.

2. Geological and geomorphological context

The Quadrilátero Ferrífero region, south São Francisco Craton, is characterized by Archaean granite-gneiss domed complexes coeval to Rio das Velhas greenstone belt (Machado *et al,* 1992), engaged to south and east in a Paleoproterozoic metamorphic belt (Mineiro belt, Teixeira and Figueiredo, 1991) defined as an acrescionary orogen of ca. 2.1 Ga (Fig.1).

The study area presents four main geomorphological units (Fig.2): *Serra do Caraça Range*, with average altitudes of 1400-1600m and maximum at 2064m; *Serra do Pinho Range*, in the eastern side of the area, with N-S trend; *Chapada de Canga Plateau*, in the central region of the study area, leveled at *ca.* 900m; *Minas Gerais center-south and east Highlands*, characterized by fluvial dissection. The scarp that limits the Serra do Caraça from the other units has hundreds of meters of fall, and leads to believe that not only erosional processes, but also post-Cretaceous tectonic movements contributed in the morphological evolution.

According to Varajão (1991), remains of planation surfaces in the Quadrilátero Ferrífero have close relations with lithostructural domains. Reactivations with vertical displacement

of ancient faults would be responsible for present day altimetric differences (King, 1956; Barbosa, 1980).

Evidences of Cenozoic tectonics in the Quadrilátero Ferrífero are observed in several sedimentary deposits and indicate three deformational events with distinct tension fields. The first event, extensive, oriented NNE-SSW and probably related with horsts and grabens oriented ESE-WNW. A second, and more expressive event, mainly compressive NW-SE. The third event is considered to be the relaxing of previous event structures. (Lipski *et al*, 2001).

In the study area, the Quaternary Chapada de Canga Formation consists of a flat plateau formed by a succession of continental itabiritic ironstone pebble conglomerates and directly overlies the Eocene Fonseca Formation and the Precambrian basement (Sant'Anna and Schorscher, 1995). Cenozoic deposits are cut by NE and NW brittle faults and joints, related to reactivation of pre-existing structures in Precambrian basement, process that strongly influenced the development of present day landscape morphology and drainage network (Sant'Anna *et al*, 1997).

3. Methods

The GIS used was the Geographic Resources Analysis Support System - GRASS 5.0.3 (U.S. Army CERL, 1993; Neteler, 1998; Neteler and Mitasova, 2002; GRASS Development Team, 2002), an open-source project, freely available on the Internet [1], which offers an integrated environment for raster and vector analysis, image processing and maps/graphics creation.

Statistical analysis were carried out on R, a system for statistical computation and graphics (Ihaka and Gentleman, 1996; Grunsky, 2002; R Development Core Team, 2003), through an interface with GRASS (Bivand, 2000) that allows raster maps and points files to be treated as variables for analysis. The R core package and extensions, as well as related documentation, can be obtained from CRAN (The Comprehensive R Archive Network [2]). Morphometric parameters were developed in GRASS according the propositions of Grohmann (2004).

Isobase lines (Filosofov, 1960 cited in Jain, 1984; Golts and Rosenthal, 1993) draw erosional surfaces; hence isobase surfaces are related to erosional cycles, mainly the most recent ones. The map of isobase (Fig. 3A) was made from interpolation of the intersections of contours with 2nd and 3rd-order stream channels (drainage orders according to Strahler, 1952a,b).

The map of hydraulic gradient was elaborated to determine areas with similar hydraulic behaviour (Fig. 4A). This parameter is calculated for each 2nd-order stream channel as the ratio of the altimetric difference between head and mouth with the plan length; the value is attributed to the mid-portion of the stream and point's values are interpolated.

Points files were imported into R as data frames; trend surfaces were computed using the R

package *spatial*, which allows the fit of a polynomial surface up to 6th degree, and inserted back into GRASS as raster maps; residual surfaces were obtained by subtracting trends from the original surface.

A problem that can affect not only trend surfaces, but also contour maps, moving-average and other forms of fitted surfaces is the presence of "edge effects", which occur when there are few (or no) control points on the map boundary, so there are almost no constraints on the form of the surface (Davis, 1986; Landim, 1998). In order to avoid these effects, the area used for analysis is smaller than the area of the morphometric maps, assuring the presence of a "buffer", in which edge effects are concentrated (Figures 3A, 3B, 4A, 4B).

The goodness-of-fit of trend surfaces can be statistically tested by analysis of variance (ANOVA), comparing the variance of regression to the variance of deviations (residuals). When a series of equations of successively higher degree are fitted to the data, this analysis can be expanded to analyse the contribution of additional partial regression coefficients and measure the appropriateness of increasing the order of equations (Davis, 1986). The general ANOVA table for test the significance of increasing degree of polynomial surface is presented in Table (1).

The number of observations is very important in trend-surface analysis, due its influence on the F test; if a large number is used, any test may present statistical significance. Since the original datasets for morphometric data analysed has 4512 points for isobase and 453 points for hydraulic gradient, 50 points were randomly selected from each dataset for analysis (Fig. 3B, 4B).

ANOVA data for evaluated morphometric parameters is presented in Table (2) for isobase and Table (3) for hydraulic gradient. All F-values for isobase are very high, and the best correlation is of 6th-order surface (Fig. 3C), with a R^2 of 0.794. The best F-values for hydraulic gradient were achieved with 2nd-order polynomial (Fig. 4C), with R^2 of 0.146.

4. Discussion

Morphometric analysis of the study area were carried out by Grohmann and Campos Neto (2003), where several parameters were employed to infer structures that can be related with landscape configuration; a morphological scenario was proposed, with a depressed central area enclosed by uplifted hills (Fig. 5). The presence of these structures can be seen on residual maps for the analysed parameters (Fig. 3D, 4D), in the change of shape and orientation of contours.

The 2nd-order residuals for hydraulic gradient show a fast transition to higher values in the eastern region, with a strong alignment of contours in NW-SE and NE-SW directions, which mark the scarp of Serra do Caraça. The 6th-order residuals for isobase also have good agreement with inferred structures; in this map, a region of very negative deviations marks the scarp.

There is a nearly E-W structure in the central portion of the study area, admitted as a

normal fault (Sant´Anna *et al*, 1997) associated with a morphological step of the Chapada de Canga plateau, which is well marked in swath profiles (Fig. 6) made by Grohmann (2004).

Despite the fact that the Chapada de Canga plateau is a very distinctive topographic feature, it does not show much expression on morphometric maps, what can be explained by the fact that it is an area of very low drainage density, and that evaluated morphometric parameters are based on the relations of topography with drainage network.

5. Conclusions

Trend-surface analysis was applied to morphometric data, and analysis of variance was used to determine the most representative polynomial surface. The residuals maps were compared with a proposed morphological scenario, and there is a good correlation between inferred structures with shape and orientation of contours. In the central portion of the area, there is a flat plateau, which has little expression in morphometric maps, although it represents a distinct topographic feature. This can be seen as a result of low drainage density in the flat area, since most morphometric methods are based on relations of topography with drainage network.

The fit of trend surfaces with very different orders (6th and 2nd) for morphometric parameters of the same area, may be explained by the spatial behaviour of these parameters. The isobase method tends to produce a smooth surface across the area, while hydraulic gradient is more sensitive to local fluctuations, and creates a surface with bigger variability, which could be better studied with frequency analysis methods, such as Fourier series.

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[2] The Comprehensive R Archive Network. http://cran.r-project.org

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Square	*F* Test
Regression of Degree p	SS_{RP}	k	MS_{RP}	MS_{RP}/MS_{DP} (a)
Deviation from Degree p	SS_{DP}	$n - k - 1$	MS_{DP}	
Regression of Degree $(p+1)$	SS_{RP+1}	m	MS_{RP+1}	MS_{RP+1}/MS_{DP+1} (b)
Deviation from Degree $(p+1)$	SS_{DP+1}	$n - m - 1$	MS_{DP+1}	
Regression due to Increase from p to $(p+1)$ Degree	$SS_{RI} = SS_{RP+1} - SS_{RP}$	$m - k$	MS_{RI}	MS_{RI}/MS_{DP+1} (c)
Total Variation	SS_T	$n - 1$		

Table 1 – General ANOVA for the significance of increasing the degree of a polynomial trend from p to $(p+1)$ degree; polynomial equationof degree p has k coefficients, not counting the b_0 term; equation of degree $(p+1)$ has m coefficients, not counting the b_0 term; number of observations is n.

(a) test of significance of the p-degree trend surface. (b) test of significance of the $(p+1)$-degree trend surface. (c) test of significance of increase in fit of the $(p+1)$ degree over p degree.

degree	Source of Variation	Sums of Squares	Degrees of Freedom	Mean Square	R^2	F	$F_{(0.05)}$
1st	Regression	8.15×10^5	2	4.1×10^5	0.242	8.823	3.195
	Deviation	21.7×10^5	47	0.5×10^5	0.758		
2nd	Regression	14.8×10^5	5	3×10^5	0.438	8.652	2.427
	Deviation	15×10^5	44	0.3×10^5	0.562		
Regression due to Increase		*6.6×10^5*	*3*	*2.2×10^5*		*6.477*	*2.816*
3rd	Regression	18.5×10^5	9	2.0×10^5	0.535	7.266	2.124
	Deviation	11.3×10^5	40	0.3×10^5	0.465		
Regression due to Increase		*3.7×10^5*	*4*	*1.0×10^5*		*3.285*	*2.606*
4th	Regression	22.9×10^5	14	1.6×10^5	0.676	8.32	1.986
	Deviation	7.0×10^5	35	0.2×10^5	0.324		
Regression due to Increase		*4.4×10^5*	*5*	*0.9×10^5*		*4.498*	*2.485*
5th	Regression	24.9×10^5	20	1.2×10^5	0.719	7.258	1.945
	Deviation	4.9×10^5	29	0.2×10^5	0.281		
Regression due to Increase		*1.9×10^5*	*6*	*0.3×10^5*		*1.874*	*2.432*
6th	Regression	27.1×10^5	27	1.0×10^5	0.794	8.008	2.071
	Deviation	2.7×10^5	22	0.1×10^5	0.206		
Regression due to Increase		*2.2×10^5*	*7*	*0.3×10^5*		*2.523*	*2.464*

Table 2 - General ANOVA for the significance of increasing the degree of isobase trend surfaces from 1st to 6th degree.

degree	Source of Variation	Sums of Squares	Degrees of Freedom	Mean Square	R^2	F	$F_{(0.05)}$
1st	Regression	0.014	2	0.007	0.016	1.400	3.195
	Deviation	0.241	47	0.005	0.984		
2nd	Regression	0.060	5	0.012	0.146	2.680	2.427
	Deviation	0.195	44	0.004	0.854		
Regression due to Increase		*0.045*	*3*	*0.015*		*3.391*	*2.816*
3rd	Regression	0.070	9	0.008	0.108	1.659	2.124
	Deviation	0.190	40	0.005	0.892		
Regression due to Increase		*0.010*	*4*	*0.002*		*0.5267*	*2.606*
4th	Regression	0.097	14	0.007	0.133	1.540	1.986
	Deviation	0.158	35	0.004	0.867		
Regression due to Increase		*0.028*	*5*	*0.005*		*1.235*	*2.485*
5th	Regression	0.114	20	0.006	0.063	1.167	1.945
	Deviation	0.142	29	0.005	0.937		
Regression due to Increase		*0.016*	*6*	*0.002*		*0.563*	*2.432*
6th	Regression	0.157	27	0.006	0.140	1.294	2.071
	Deviation	0.099	22	0.004	0.860		
Regression due to Increase		*0.043*	*7*	*0.006*		*1.367*	*2.464*

Table 3 - General ANOVA for the significance of increasing the degree of hydraulic gradient trend surfaces from 1st to 6th degree.
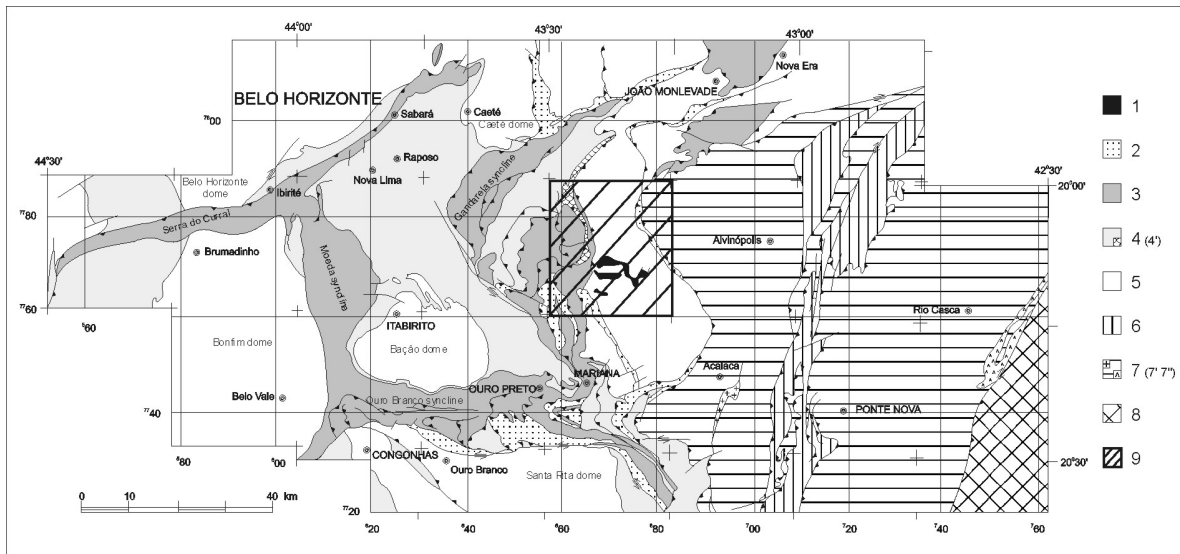
Fig. 1 – Simplified geological map of southeast São Francisco craton (modified from Campos Neto *et al.*, 2004). 1 - Cenozoic Chapada de Canga and Fonseca Fms.; 2 -Itacolomi/Espinhaço Gr.; 3 - Minas Supergroup; 4 - Rio das Velhas Supergroup (4'- komatiitic unit); 5 - SE São Francisco craton gneiss; 6 - Dom Silvério Gr.; 7 - Mantiqueira gneisses (7'-amphibolite, 7''- granulite); 8 - Juiz de Fora granulites; 9 - Study area.
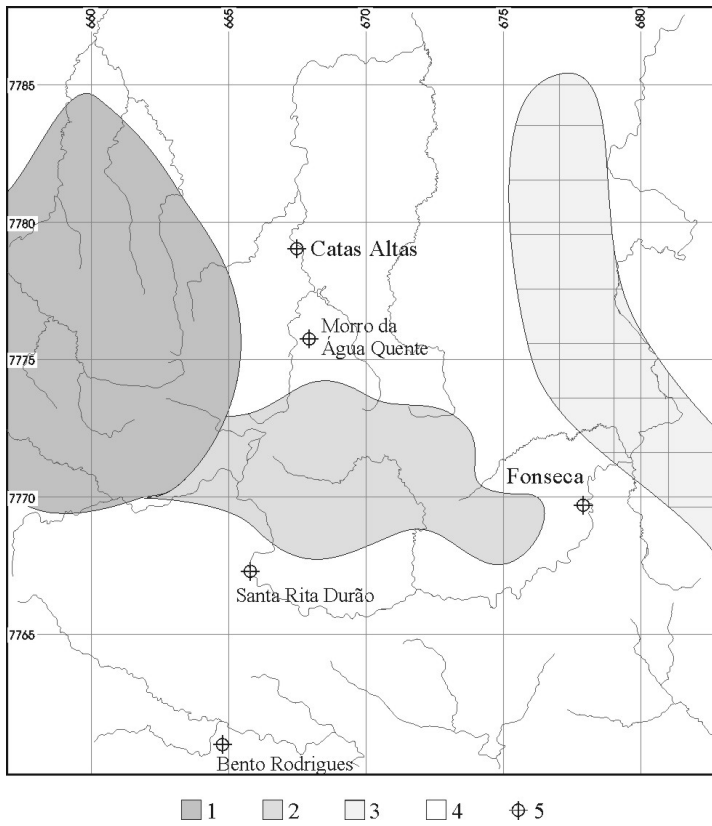
Fig. 2 – Main geomorphological units in the study area. 1 – Serra do Caraça Range; 2 – Chapada de Canga Plateau; 3 – Serra do Pinho Range; 4 – Minas Gerais center-south and east Highlands; 5 – Cities.
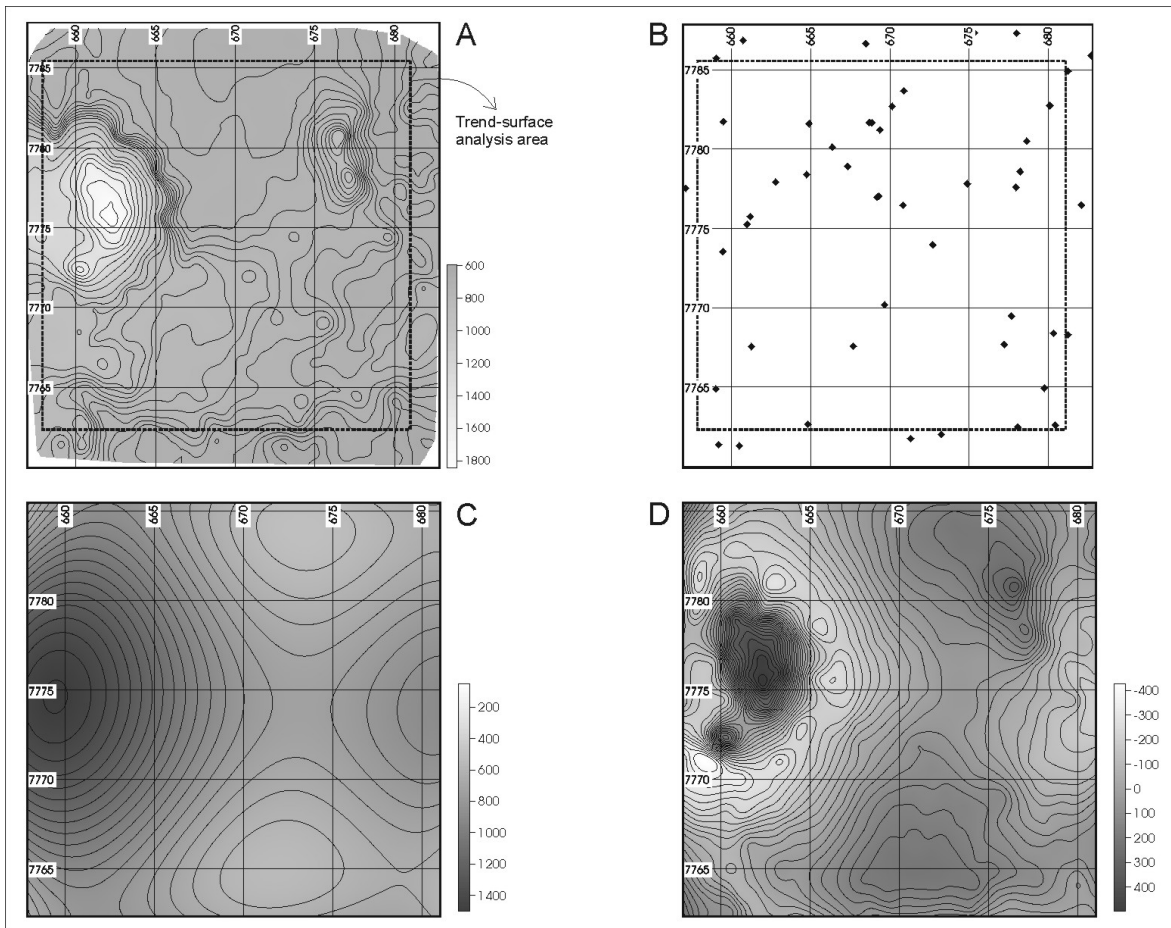
Fig. 3 – A: Original isobase surface, with area used for trend-surface analysis in dotted line; B: Data points, n=50; C: 6th-order trend surface; D: Residuals of 6th-order.
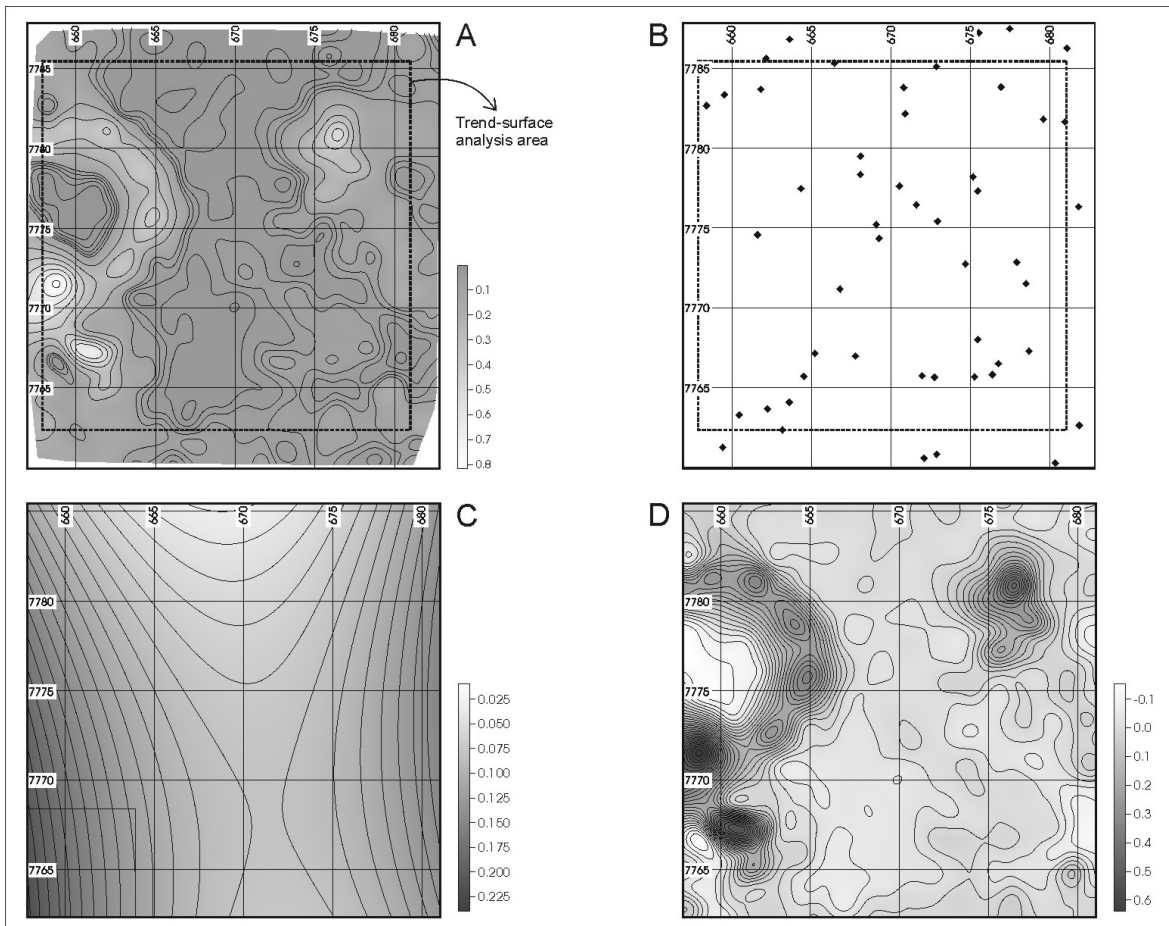
Fig. 4 – A: Original hydraulic gradient surface, with area used for trend-surface analysis in dotted line; B: Data points, n=50; C: 2nd-order trend surface; D: Residuals of 2nd-order.
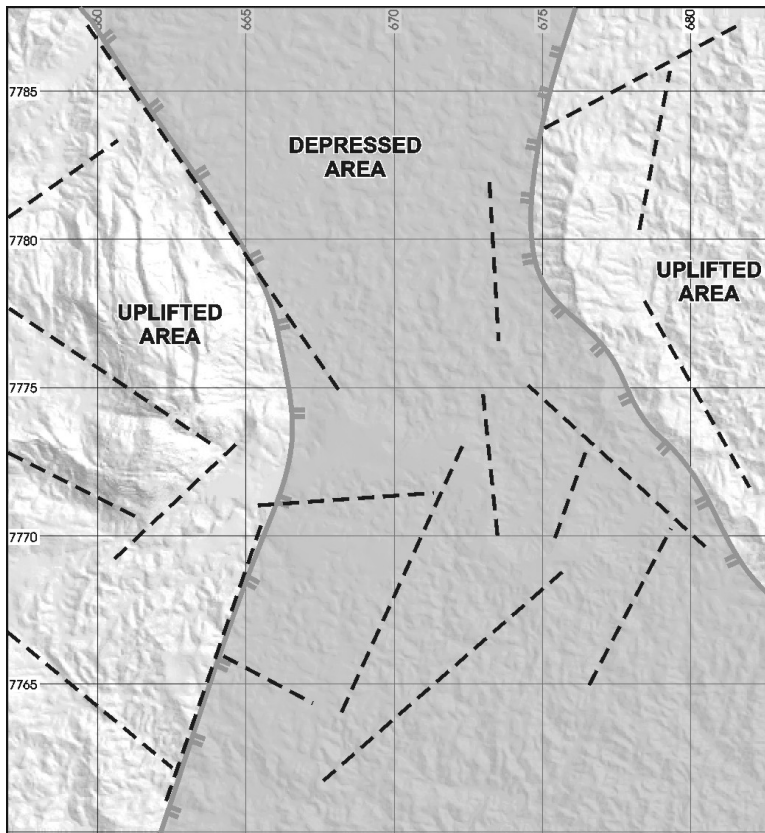
Fig. 5 – Morphological scenario and inferred stuctures for the study area, according to Grohmann and Campos Neto (2003).
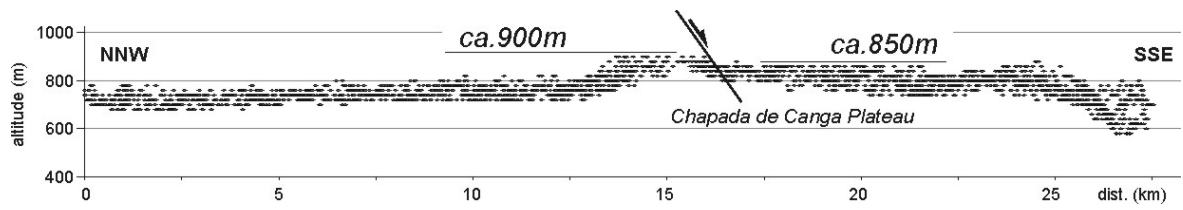
Fig. 6 – Swath profile oriented NNW-SSE through the center of the study area (Grohmann, 2004).

Note the step of the flat plateau in its mid-portion, associated with a normal fault.