Hydrol. Earth Syst. Sci. Discuss., 8, 89–110, 2011
www.hydrol-earth-syst-sci-discuss.net/8/89/2011/
doi:10.5194/hessd-8-89-2011

Hydrology and Earth System Sciences Discussions

Regional scale analysis of landform configuration with base-level maps

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Received: 26 November 2010 – Accepted: 13 December 2010 – Published: 10 January 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Base-level maps (or “isobase maps”, as originally defined by Filosofov, 1960), express a relationship between valley order and topography. The base-level map can be seen as a “simplified” version of the original topographic surface, from which was removed the “noise” of the low-order streams erosion. This method is able to identify areas with possible tectonic influence even within lithological uniform domains. Base-level maps are usually applied in semi-detail scale (e.g., 1:50 000 or larger) morphotectonic analysis. In this paper, we present an evaluation of the method’s applicability in regional-scale analysis (e.g., 1:250 000 or smaller). A test area was selected in Northern Brazil, at the lower course of the Araguaia and Tocantins rivers. The method provided results consistent with the scale of the data used as topographic base and with the drainage network (1:1 000 000). Some of the base-level anomalies interpreted correspond to important faultlines and geological contacts present at the 1:5 000 000 Geological Map of South America. Others have no correspondence with mapped structures and are considered to represent more recent morphotectonic features. The E–W inflexion of the lower Tocantins is considered as a major drainage capture, originated by an E–W, southward-dipping normal fault. The base-level map also presented a good correlation with anomalies in geophysical data, which shows that the method is sensitive enough to detect features with little topographic expression.

1 Introduction

The concept of base level was defined by Powell (1875) as a level “below which the dry lands cannot be eroded”. Although the sea level remains as the ultimate base level, several authors have acknowledged that local base levels can be defined according to different geological/temporal conditions across regions or even within the same watershed (e.g., Powell, 1875; Davis, 1902; Mackin, 1948; Penck, 1953; Quirk, 1996).

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Base-level maps (Dury, 1952; Filosofov, 1960; Pannekoek, 1967) express a relationship between valley order and topography. The valley order refers to the relative position of stream segments in a drainage basin network, where streams of similar orders relate to similar geological events and are of similar geological age (Horton, 1945; Strahler, 1952; Golts and Rosenthal, 1993). Each base-level surface is related to similar erosional stages, and can be considered a product of erosional-tectonic events, mainly the most recent ones (Golts and Rosenthal, 1992, 1993).

The concept of base-level map, as used in this paper, is the same as the "isobase map" of Filosofov (1960, 1970, 1975) and Golts and Rosenthal (1992, 1993), and is similar to the "Thalweg" of Annaheim (1946), the "Reliefsockel" of Louis (1957), the "streamline surface map" of Dury (1952) and Pannekoek (1967), the "subenvelope map" of Hack (1960) , or the "Sloping Local Base Level" of Jaboyedoff et al. (2004, 2009). The main goal of this method is to be able to identify areas with possible tectonic influence even within lithological uniform domains.

Given that in Earth Sciences the term "isobase" is used in the sense of a "line of equal uplift" and is commonly applied to marine terraces and shorelines raised in the Holocene (e.g., Leverington et al., 2002), we think that "base-level map" should be used instead of "isobase map" in morphotectonic studies, even though the latter has been used recently in this sense (e.g., Golts and Rosenthal, 1993; Grohmann et al., 2007).

When interpreting base-level maps, some details must be taken into account. Abrupt deviations, compression and spreading of the base-level lines can be indicatives of structures associated to tectonic movements, extreme lithological changes or important geomorphological features. Considering that recent tectonic movements provoke instability on the erosional surface defined by streams of similar order, the method provide the possibility to identify geological structures associated to the stabilization process of this new surface, even within lithological uniform domains.

Base-level maps are usually applied in semi-detail scale (e.g., 1:50 000 or larger) morphotectonic analysis (Golts and Rosenthal, 1993; Modenesi-Gauttieri et al., 2002;

Grohmann et al., 2007; Jaboyedoff et al., 2009). In this paper, we present an evaluation of the method's applicability in regional-scale analysis (e.g., 1:250 000 or smaller). A test area was selected in Northern Brazil, at the lower course of the Araguaia and Tocantins rivers (Fig. 1).

2 Base-level maps

2.1 Construction

Base-level maps are constructed from an initial map of valley orders, classified according to the Strahler (1952) system, which is based on the number of tributaries upstream of a valley segment. Streams without tributaries are assigned first order (headwater streams). A second-order stream is the segment downstream the confluence of any two first-order streams and a third-order segment is formed by the junction of any two second-order streams and so on (Fig. 2).

The points where individual thalwegs are crossed by contours of the same elevation are connected by smooth lines (isobases). These lines should cross the thalwegs at right angles and are plotted in a similar manner of topographic contours (Zuchiewicz, 1989) (Fig. 3). Several base-level maps can be made for a given region. For instance, in the 2nd-order base-level map, all valleys except those of 1st-order will be used for plotting. The 3rd-order base-level map is constructed from all valleys except those of 1st- and 2nd-order, and so on. The base-level map can be seen as a simplified form of the original topography, where the relief above the base-level surface is disregarded.

Disregarding 1st-order streams intends to eliminate the "noise" that could prevent the identification of a scarp or other significant feature of the topographic surface. In Fig. 4, a schematic scenario is presented for the geomorphological evolution of a fault scarp. The initial condition (Fig. 4a) is disturbed by a fault and knickpoints indicate the break-of-relief (Fig. 4b). As erosion progresses, new 1st-order streams appear and a segmentation of the the fault scarp into trapezoidal facets can be observed

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(Fig. 4c,d). These facets will evolve into triangular forms (Fig. 4e) and will eventually be suppressed, when the clear identification of the fault may be hard or impossible. A time span of about 10^5 years would be sufficient to degrade a fresh fault scarp to a point where all remnants of the tectonic surface were removed (Stewart and Hancock, 1990). A base-level map, constructed from the elevations of 2nd and 3rd-order channels, although smoother and simpler than the original topography, would show an inflexion in the faultline area (Fig. 4f).

2.2 Applications

In this section, some applications of base-level maps ("isobase maps" of Filosofov, 1960) in morphotectonic studies are presented.

Golts and Rosenthal (1993) derived a morphotectonic map from base-level lines for an area of approximately 1100 km^2 in Northern Arava, a part of the Jordan-Dead Sea Rift Valley. They conclude that in young sedimentary basins characterized by flat and weakly incised relief, the base-level map was useful as structural background for designing detailed investigations, such as seismic surveys.

The influence of the geological structure on the geomorphology of an area of the Basin and Range Province (NE Utah, USA) was analysed by Zuchiewicz and Oaks (1993). From an original topographic data at 1:100 000 scale, base-level maps of 1st-, 2nd- and 3rd-order were made. The maps of 1st- and 2nd-order were considered to closely resemble the original topography, but the map of 3rd-order showed the dominant faults and folds undulations.

Sant'Anna et al. (1997) studied the Cenozoic tectonics of the Fonseca Basin region, in the Quadrilátero Ferrífero (Southeastern Brazil). The morphostructural map confirmed the existence of major tectonic discontinuities with N–S and, less frequently, E–W, NE and NW directions. The same area was studied by Grohmann (2004), who compared manually created base-level maps with automatic processing of digital elevation data in a GIS environment and concluded that both products were similar.

The morphotectonic analysis of a high plateau on the northwestern flank of the Continental Rift of Southeastern Brazil showed that fault reactivation along Precambrian shear zones were responsible for drainage captures and segmentation of the plateau into smaller blocks, which could be identified in the 2nd-order base-level map (Hiruma and Riccomini, 1999; Modenesi-Gauttieri et al., 2002).

Ribeiro et al. (2006) applied base-level maps in a morphotectonic analysis of an area at the top of the Serra do Mar coastal range of the State of São Paulo, Brazil. A 2nd-order base-level map was manually created from 1:10 000 topographic maps and showed that the drainage of the Guaratuba river basin is controlled by NW-trending faults, which were responsible for drainage capture and subsequent isolation of this sub-basin from the upper Tietê river. Since the fish species occurring in the upper Guaratuba river are identical to the ones that occur in the upper Tietê river, the river piracy event is of young geological age and was inferred to be of Late Pleistocene-Holocene.

The Pocos de Caldas Alkaline Massif is a 33 km-diameter Late Cretaceous collapsed volcanic caldera located in Southeastern Brazil. The massif's main morphology is a semi-circular plateau with average altitude of 1300 m rising up to 400 m above surrounding flatlands (Poços de Caldas Plateau), with elevations up to 1500–1600 m in its borders. A 2nd-order base-level map of the massif showed a partial coincidence of a lithologic change in the northeastern portion of the massif with a strong NE–SW base-level anomaly, which turns abruptly to NW–SE in the central area of the plateau, without any associated variation in lithology. The large NE–SW anomaly was related by Grohmann et al. (2007) to a faultline previously identified by Almeida Filho and Paradella (1977) while the NW–SE smaller anomaly was considered a result of recent tectonic activity.

The Sloping Local Base Level (SLBL) of Jaboyedoff et al. (2004) is a generalization of the base level concept applied to landslides. It is very similar to the original isobase surface of Filosofov (1960) and allows the definition of a surface above which a rock mass is assumed erodible. Jaboyedoff et al. (2009) used the SLBL method to estimate

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the present unstable volumes in the main scar of a 30 M m^3-rockslide in the eastern slope of Turtle Mountain (Alberta).

3 Methods

Manual production of base-level maps is a time-consuming process. Classification of valley orders and interpretation of base-level lines demands topographic maps of good quality and in a proper scale. Using SRTM (Farr et al., 2007) digital elevation models (DEMs) for automatic extraction and classification of stream channels allows the data to be obtained faster, from a single data source, without cost (Grohmann et al., 2007).

All data processing was carried out with GRASS-GIS version 6.4 (Neteler and Mitasova, 2008; GRASS Development Team, 2009). As topographic base, we used SRTM30_PLUS V3 DEMs (Becker and Sandwell, 2007), with spatial resolution of $0°0'30''$ (~1 km). Drainages were extracted using an A^T least-cost search algorithm designed to minimize the impact of DEM data errors (Ehlschlaeger, 1989). This algorithm provides more accurate results in areas of low slope and also on DEMs where canopy top might be mistaken as ground elevation, such as SRTM (Kinner et al., 2005). Water flow was calculated using a multiple flow direction (MFD) method, where the water flow is distributed to all neighboring cells with lower elevation using slope towards these cells as a weighing factor for proportional distribution, a convergence factor of 5 as recommended by Holmgren (1994) and a minimum size of an exterior watershed basin of 25 cells. The extracted drainage network is compatible with a 1:1 000 000 scale.

The base-level maps were constructed with an adaptation of the methods proposed by Grohmann (2004). First, the drainage network (in raster format) was classified according to Strahler's system. Raster algebra was then used to produce maps where values of SRTM30 elevation were assigned to selected stream orders. These maps were converted to 3-D vector points and interpolated into a continuous surface with

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Regularized Splines with Tension (RST – Mitasova and Mitas, 1993; Mitas and Mitasova, 1999; Hofierka et al., 2002). Base-level maps were constructed according to the following valley orders combinations: 2nd + 3rd, 3rd + 4th, 4th + 5th. The resulting maps are presented in Fig. 5.

4 Results and discussion

Regarding the interpretation of regional-scale morphostructures, the map constructed with 2nd and 3rd-order valleys (Fig. 5b) presented the best results. In the map of 3rd and 4th orders (Fig. 5c), the large structures still can be identified, although with less detail. The map of 4th and 5th orders (Fig. 5d) is oversimplified and does not provide useful information.

The base-level anomalies interpreted for the study area are presented in Fig. 6a. Some anomalies correspond to the present-day valley of Tocantins river or with geological contacts and Pre-Paleozoic faults present in the 1:5 000 000 Geological Map of South America (Schobbenhaus and Bellizzia, 2001). Anomalies without a clear correspondence with the geological map area oriented mainly at NE–SW or NW–SE.

Although none of these mapped structures have ever been connected to recent tectonic events, we must note that some of them, such as the NNW–SSE-trending thrust north of the rivers major inflexion (Fig. 6a), correspond to the physical limits of the Parnaíba Sedimentary Province. Therefore, we cannot rule out the possibility that these structures were active during or after the sedimentation of these rocks.

A strong E–W orientation of the base-level lines over the inflexion of the Araguaia and Tocantins rivers (Fig. 6a), previously identified by Costa et al. (1996) as a right-lateral transcurrent fault zone, suggest a major drainage capture. The Tocantins river flows in a North-Northeast path before this sudden inflexion, and it would seem more natural for it to continue in its lower course towards the sea following the Gurupí river valley, which also has a NNE–SSW orientation (see Figs. 1 and 6b).

Topographic swath profiles (or projected profiles, Baulig, 1926; Tricart and Cailleux, 1957) are those were intersections of contours with equally spaced profile lines are marked within a swath, or band. This kind of profile can provide a broader view of altimetric behavior, and help to determine inclination of large topographic features (Meis et al., 1982). Figure 7 shows a N–S swath profile constructed in a band of 2° with a 10′ interval between individual profiles. There is a general trend of lowering the elevation towards north, which is interrupted at about halfway the profile length by a strong increase in elevation and subsequent gradual decrease. The general topographic pattern can be interpreted as a southward-dipping normal fault (lower right inset in Fig. 7). Given that the abrupt change of elevation correspond to the E–W inflexion of the Tocantins river, this adds to the hypothesis of a major drainage capture in the lower Tocantins and of tectonic influence in the landform configuration of the study area.

In Fig. 8, the base-level lines are overlaid over geophysical data available for the study area (the cyan solid line represents the limits of the Parnaíba Sedimentary Province). Figure 8a shows the magnetic total field intensity anomaly corrected from IGRF in a 1 × 1km grid (CPRM, 2004), and Fig. 8b shows gravimetric Bouger anomalies (Petersohn, 2007). In both maps there is a good correlation between the base-level anomalies shown in Fig. 6a and geophysical anomalies. Both the NE–SW and NW–SE trend are easily identified in the magnetic data and some correspond to sharp changes in gravimetric values.

The NW–SE anomaly in the southeast of the study area corresponds to the northern border of the Mosquito lava field, of Jurassic age (Marzoli et al., 1999). Moreover, the NW–SE anomaly traced in the northeastern sector of the study area can be interpreted as the Picos-Santa Inês lineament (Cunha, 1986), which has little topographic expression, but can be identified in the geophysical maps.

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5 Conclusions

Base-level analysis have been successfully applied to semi-detail scale morphotectonic studies. In this paper we presented an example of the applicability of the method to regional-scale investigations. The method provided results consistent with the scale of the data used as topographic base and with the drainage network (1:1 000 000). Some of the base-level anomalies interpreted correspond to important faultlines and geological contacts present at the 1:5 000 000 Geological Map of South America. Others have no correspondence with mapped structures and are considered to represent more recent morphotectonic features. The E–W inflexion of the lower Tocantins is considered as a major drainage capture, originated by an E–W, southward-dipping normal fault. The base-level map also presented a good correlation with anomalies in geophysical data, which shows that the method is sensitive enough to detect features with little topographic expression.

Acknowledgements. This study was supported by the State of São Paulo Research Foundation Grants FAPESP 04/06260-5 and 09/17675-5 to Carlos Grohmann. Claudio Riccomini is a Research Fellow of the National Council of Scientific and Technological Development, CNPq Grant 304649/2005-8. Marlei Chamani has a MSc scholarship from CNPq.

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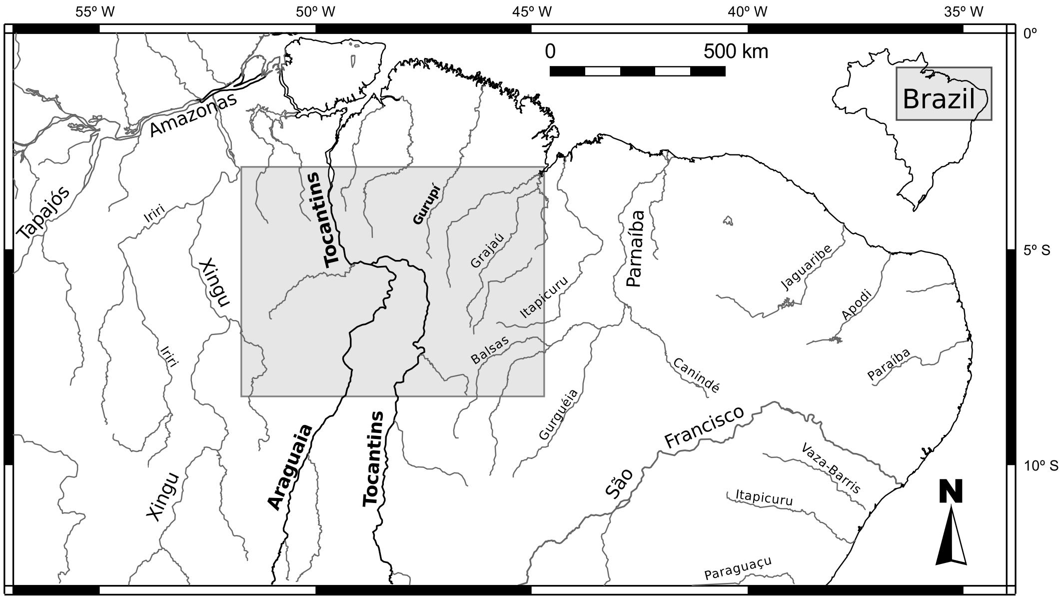

Fig. 1. Location of study area.

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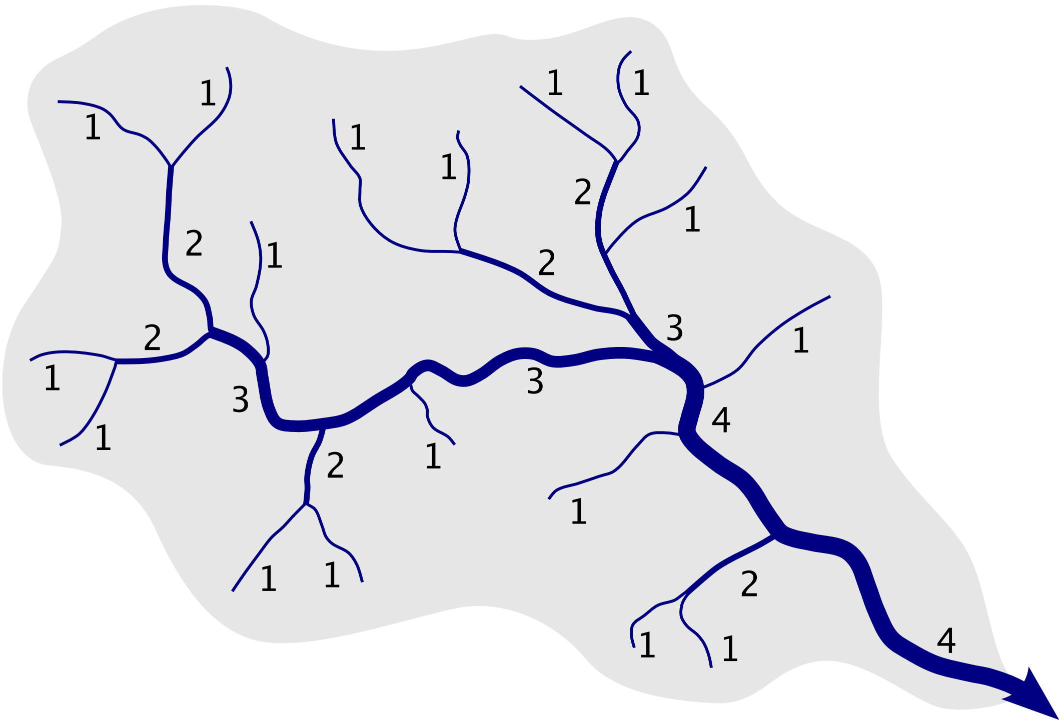

Fig. 2. Stream ordering in a watershed, according to Strahler (1952). After FISRWG (1998).

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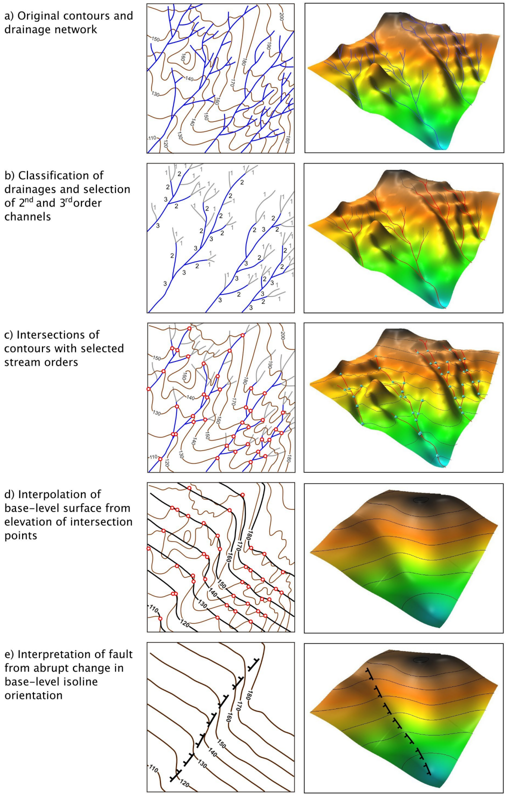

Fig. 3. Development of a 2nd-order base-level map. **(a)** Original topography (contours) and drainage network. **(b)** Classification of drainage network and selection of 2nd and 3rd-order channels. In this case, 1st-order streams are discarded. **(c)** Determination of intersection points of contours and selected stream channels. Elevation of contour is assigned to each point. **(d)** Interpolation of base-level lines (or surface) from elevation of intersection points. **(e)** Fault traced according to deviations of base-level lines. Modified from Golts and Rosenthal (1993).

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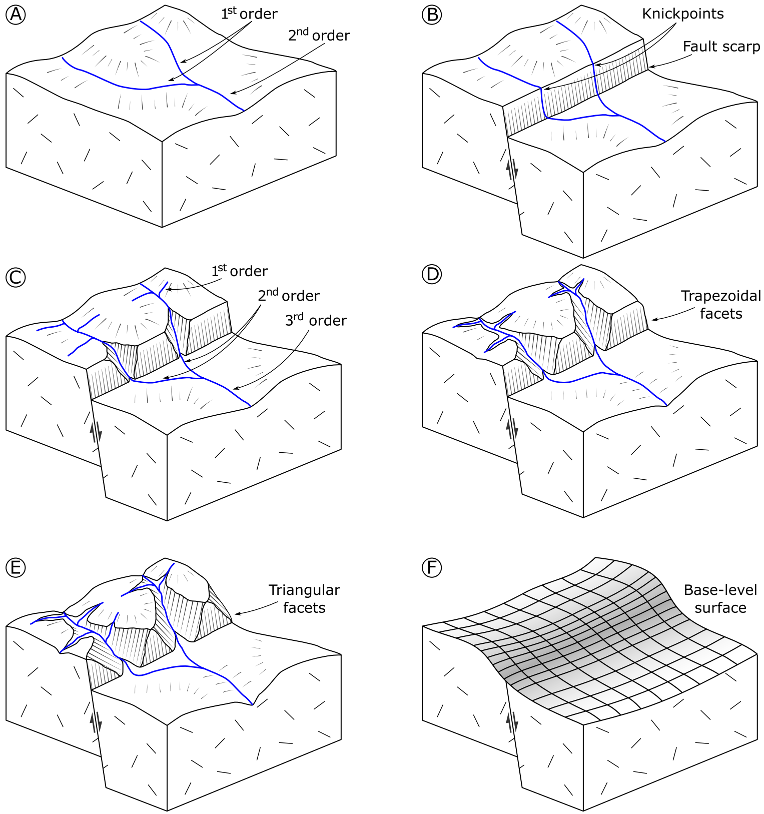

Fig. 4. Schematic evolution of a fault scarp, with development of knickpoints and new 1st-order streams. The scarp will be segmented into a series of trapezoidal facets, which will became triangular and will be progressively eroded, until the original morphology cannot be recognized. A base-level map, constructed from the elevations of 2nd and 3rd-order channels, shows an inflexion in the faultline area.

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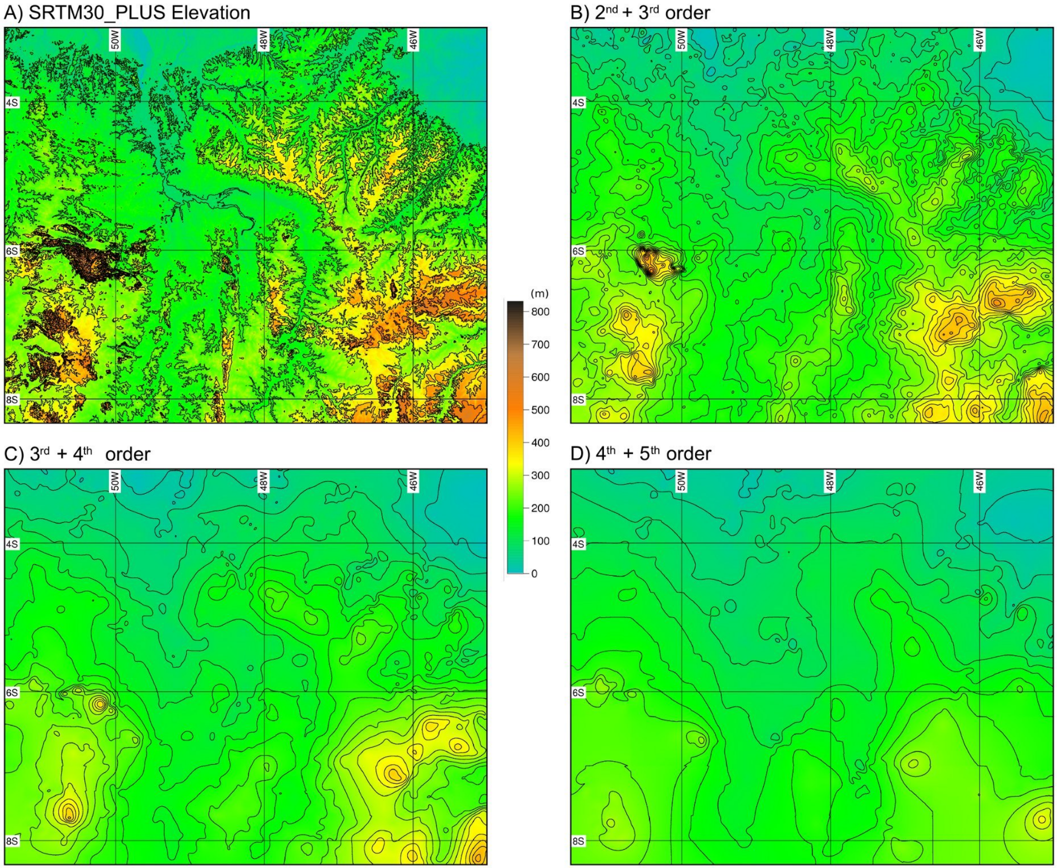

Fig. 5. Base-level maps constructed for the study area. See text for details.

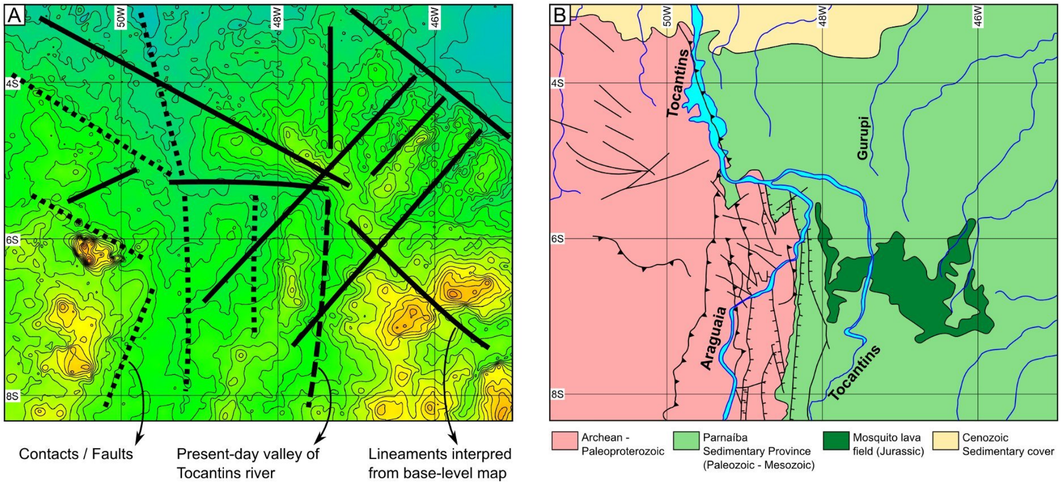

Fig. 6. **(A)** Interpreted structures for the base-level map constructed with 24nd and 3rd valley orders. **(B)** Simplified geological map of the area (modified from Schobbenhaus and Bellizzia, 2001).

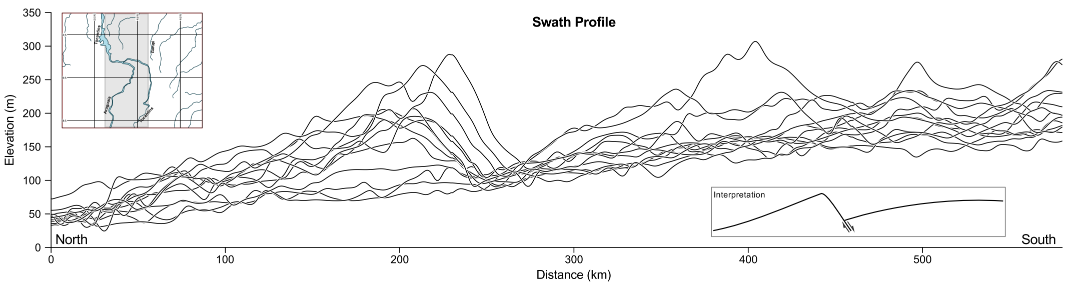

Fig. 7. N–S swath profile of 2nd-order base-level map (Fig. 5b). Swath location is the gray area in upper left map. Lower right inset shows the interpretation as a southward-dipping normal fault.

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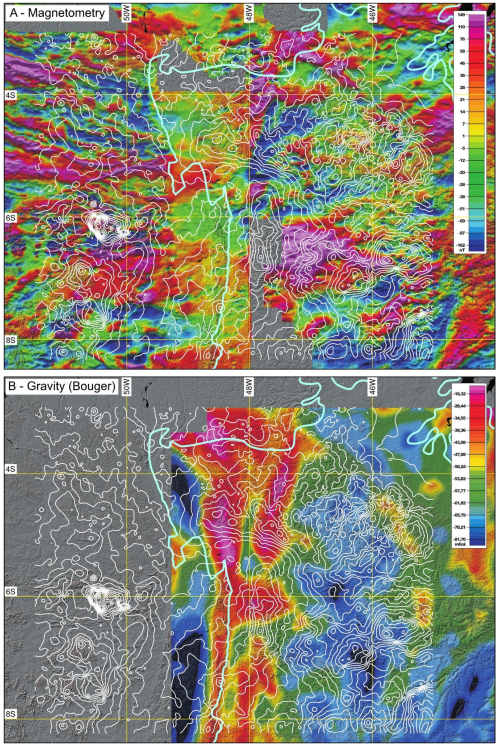

Fig. 8. (A) Magnetic total field intensity anomaly (IGRF corrected), 1 × 1 km grid (CPRM, 2004). **(B)** Gravimetric Bouger anomalies (Redrawn from Petersohn, 2007). The cyan solid line represents the limits of the Parnaíba Sedimentary Province.

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