ARTICLE IN PRESS
GEOMOR-03968; No of Pages 11
Geomorphology xxx (2012) xxx–xxx
Contents lists available at SciVerse ScienceDirect
Geomorphology
journal homepage: www.elsevier.com/locate/geomorph

Remote sensing analysis of depositional landforms in alluvial settings: Method development and application to the Taquari megafan, Pantanal (Brazil)

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ARTICLE INFO

Article history:
Received 12 September 2011
Received in revised form 20 March 2012
Accepted 4 April 2012
Available online xxxx

Keywords:
Megafan
Quaternary
Digital elevation model (DEM)
SRTM
Pantanal

ABSTRACT

Traditional Shuttle Radar Topography Mission (SRTM) topographic datasets hold limited value in the geomorphic analysis of low-relief terrains. To address this shortcoming, this paper presents a series of techniques designed to enhance digital elevation models (DEMs) of environments dominated by low-amplitude landforms, such as a fluvial megafan system. These techniques were validated through the study of a wide depositional tract composed of several megafans located within the Brazilian Pantanal. The Taquari megafan is the most remarkable of these features, covering an area of approximately 49,000 km^2. To enhance the SRTM-DEM, the megafan global topography was calculated and found to be accurately represented by a second order polynomial. Simple subtraction of the global topography from altitude produced a new DEM product, which greatly enhanced low amplitude landforms within the Taquari megafan. A field campaign and optical satellite images were used to ground-truth features on the enhanced DEM, which consisted of both depositional (constructional) and erosional features. The results demonstrate that depositional lobes are the dominant landforms on the megafan. A model linking baselevel change, avulsion, clastic sedimentation, and erosion is proposed to explain the microtopographic features on the Taquari megafan surface. The study confirms the potential promise of enhanced DEMs for geomorphological research in alluvial settings.

1. Introduction

Megafan environments have received much attention in recent years due to their capacity to transport and retain large volumes of sediment, often forming the largest clastic sediment sinks in continental foreland basins (DeCelles and Cavazza, 1999; Barnes and Heins, 2009). Given their large dimensions (>10^3 km^2), orbital remote sensing has provided essential data for the study of modern megafan environments (e.g., Assine, 2005; Assine and Silva, 2009; Blechschmidt et al., 2009; Chakraborty and Ghosh, 2010; Hartley et al., 2010; Weissmann et al., 2010; Bernal et al., 2011; Buehler et al., 2011). Recently, these kinds of depositional systems have generated substantial debate in literature because of their complex dynamics in space and time (Nichols and Fisher, 2007; North and Warwick, 2007). Modern examples of fluvial megafans are found on many continents, with the best known examples being the Okavango system in Africa (Stanistreet and McCarthy, 1993; Gumbricht et al., 2001, 2005), the megafans of Kosi, Tista and Gandak in the Ganga plains (Wells and Dorr, 1987; Gupta, 1997; Sinha et al., 2005; Roy and Sinha, 2007; Chakraborty and Ghosh, 2010; Chakraborty et al., 2010), and the megafans of the Chaco plains (Horton and DeCelles, 2001; Latrubesse, 2003; Wilkinson et al., 2006). These examples are all located in tectonically active basins marked by strongly seasonal rainfall patterns and recurrent sedimentation during the Quaternary (Leier et al., 2005).

The Brazilian Pantanal is one of the largest wetlands in the world (Alho et al., 1988), with an area of ~135,000 km^2. The Paraguay River is the trunk collector of flowing water in the wetland, and it can be considered the regional baselevel for the whole Pantanal (Assine and Soares, 2004). The Pantanal mega-geomorphology is characterized by the occurrence of low-relief fluvial megafans (Assine and Soares, 2004) and seven active megafan systems can be recognized in satellite images (Fig. 1). However, little is known about the morphodynamics of these systems, and studies linking sedimentary landforms with recent depositional processes could therefore lead to a better understanding of megafan environments. With recent advances in remote sensing, new products have allowed unprecedented investigations of inaccessible regions such as the Pantanal in great detail. In this context, the Shuttle Radar Topographic Mission (SRTM) can be highlighted for generating a high resolution global digital elevation model (DEM), which now constitutes a major source of data for geomorphological studies and also partially fills the need for topographic data in regions that lack detailed surveying.

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doi:10.1016/j.geomorph.2012.04.003

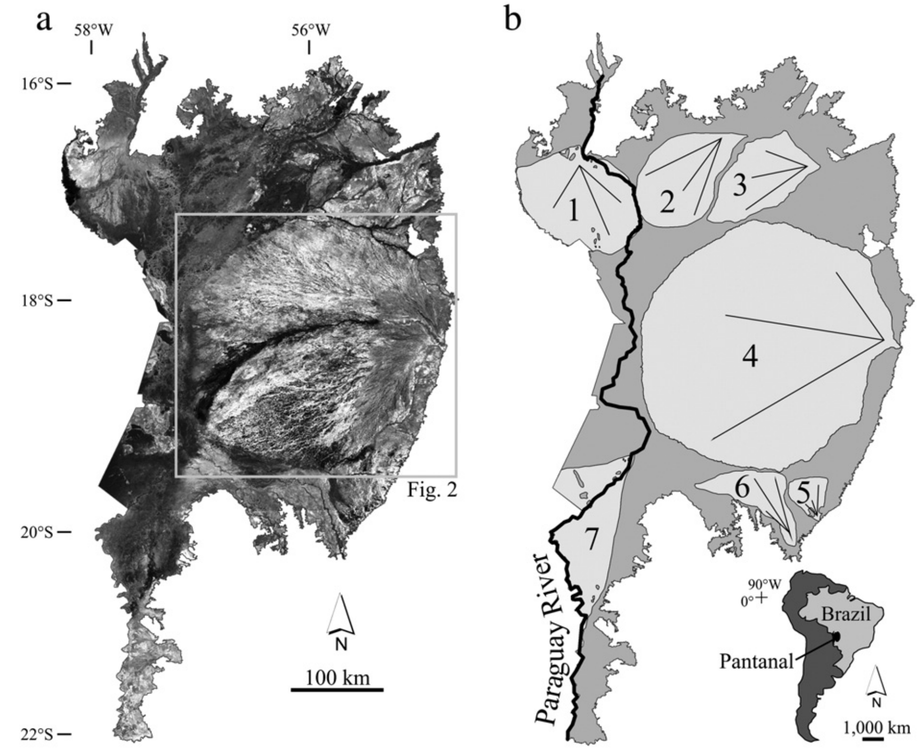

Fig. 1. Limits of the Brazilian Pantanal and the megafans that characterizes its mega-geomorphology. (a) Mosaic of Landsat TM4/5 images in 1990, band 7. (b) Megafans of (1) Paraguai, (2) Cuiabá, (3) São Lourenço, (4) Taquari, (5) Taboco, (6) Aquidauana and (7) Nabileque.

This paper applies the SRTM-DEM to the Taquari megafan in the Brazilian Pantanal and introduces a novel series of techniques designed to enhance the identification and analysis of low-relief landforms. A thorough characterization of meso-scale sedimentary landforms produced by the DEM enhancement process is presented and the processes responsible for their genesis are discussed. Finally, a model is proposed to explain the observed dynamics.

2. The Taquari megafan

The Taquari megafan is set in the morphotectonic context of the Pantanal sedimentary basin. The Neoproterozoic basement of the Pantanal basin is composed of low-grade metamorphic and magmatic rocks (Assine, 2003). The Pantanal basin has an elliptical shape and is considered seismically active (Assine and Soares, 2004), with its origin related to the geological events that formed the Andes mountains (Horton and DeCelles, 1997; Ussami et al., 1999). According to Ab'Sáber (1988), the sedimentary processes responsible for filling the Pantanal have been active since the Pleistocene, with the basin depocenter possibly located in the lower course of the Taquari River (Ussami et al., 1999).

The Taquari River catchment is situated on the western portion of the Brazilian Plateau and its headwaters dissect Paleozoic sandstones within the Parana basin (Assine, 2005). After flowing for ~220 km in the highlands (plateau top average elevation is ~800 m a.s.l.), the Taquari River crosses a steep escarpment and enters the Pantanal wetland (average elevation of ~120 m a.s.l.), forming a megafan that spreads up to 49,000 km^2 with an apex-to-toe length of ~253 km (Fig. 2). The altitude in the Taquari megafan varies from 190 m at its apex to 85 m at its toe, resulting in a very low average gradient of 0.36 m km^{-1}.

Alluvial fan types are distinguished by the dominant depositional process (Stanistreet and McCarthy, 1993). In this broad spectrum, the Taquari can be classified as a river dominated fan characterized by low sinuosity and meandering (i.e., *losimean*) channel patterns. This generic model states that the sedimentary landforms are constructed by fluvial processes occurring along very low slopes, which is in accord with observations for the Taquari and also for the rest of Pantanal megafans. Assine (2005) proposed that the Taquari megafan is composed of three main geomorphological units: (1) the 3 to 6 km wide meander belt, where the upper part the Taquari River is entrenched within sediments of Pleistocene fan lobes; (2) the modern fan lobe, located downstream of the intersection point (i.e., where stream-power abruptly decreases), where the stream discharge progressively diminishes and crevasse splays are active; and (3) the abandoned lobes, which are areas without active sedimentation processes today.

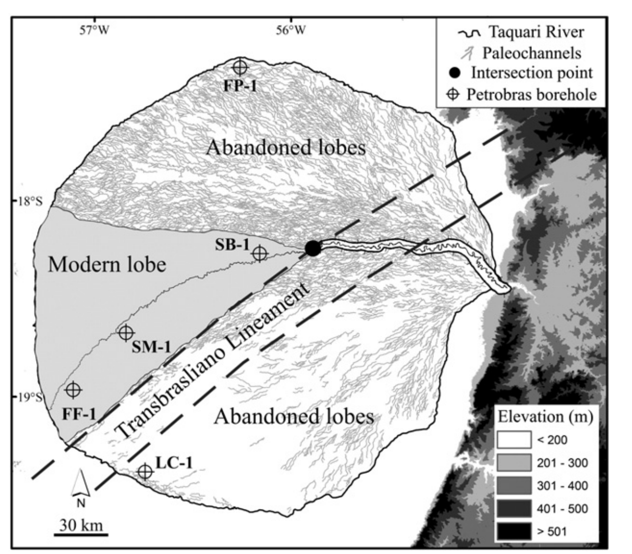

Fig. 2. Main geomorphological units of the Taquari megafan (after Assine, 2005). Paleochannels and modern drainage network from Zani and Assine (2011).

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A drilling program carried out by Petrobras (the Brazilian state oil company) in the 1960s created five wells inside the Taquari megafan. Two of these boreholes reached basement (FF-1 and LC-1; Fig. 2), at an average depth of ~200 m in the megafan toe. The deepest well (SB-1) coincides with the Taquari modern lobe (Fig. 2), which may be located in the Pantanal basin depocenter (Ussami et al., 1999). This well penetrated 412 m of Cenozoic sediments, but it did not reach the basement. More recently, interpretation of seismic reflection data suggests a maximum sediment thickness of 550 m in the area of the basin depocenter (Assine and Soares, 2004). Despite the absence of geochronological analysis, some researchers have suggested that most of the landforms exposed on the fan surface, including deflation pans, lunettes, and depositional lobes, were formed during the late Pleistocene under drier conditions compared to the Holocene (Klammer, 1982; Tricart, 1982; Assine and Soares, 2004).

A remarkable aspect of Taquari geomorphology is a dense and well preserved network of paleochannels, which indicates that the river has shifted during the Quaternary (Fig. 2). Rapid changes in the Taquari channel are attributed to fluvial avulsions (Assine, 2005; Buehler et al., 2011), commonly triggered by alluviation at a specific point in the main channel. Alluviation processes tend to decrease channel slope and the capacity to transport sediment, which causes progressive in-filling and a reduction of channel depth. Natural levees are formed at the same time, growing vertically by aggradation during floods. The disruption of levees during a flooding episode and the establishment of a new course characterize the avulsion process. With the aid of remote sensing, the entire paleochannel network was mapped in detail (Zani and Assine, 2011) and the most recent avulsions events were documented (Padovani et al., 2001; Assine, 2005; Buehler et al., 2011). Alluviation and avulsion are well known processes affecting alluvial systems (Slingerland and Smith, 2004) and have likewise been observed in most megafans (Hartley et al., 2010). However, the short recurrence interval (i.e., high frequency) for rapid changes verified in the Taquari are not observed in other well studied megafans, such as the Kosi in the Ganga plain and the Okavango in Africa.

There is abundant evidence of Quaternary syn-sedimentary tectonism in the Pantanal wetlands. The Transbrasiliano Lineament is the main active fault trend crossing the Taquari megafan (Fig. 2). With an NE–SW orientation, the Lineament is an old crustal structure associated with the Pan-African orogeny in the Neoproterozoic (Cordani and Sato, 1999). However, geomorphic evidence suggests that the feature has been reactivated by Phanerozoic tectonic activity. Morphological lineaments identified in false-color satellite images with an NE–SW trend in the southern portion of the Taquari megafan (Assine, 2003; Zani, 2008), as well as abrupt deflections of some segments of the Paraguay River (Assine and Soares, 2004), are the best known evidence of neotectonics. In addition, bathymetric surveys conducted in some of the largest Pantanal lakes (McGlue et al., 2011) suggest that neotectonics may have played a role in creating accommodation space for recent sediment deposition, as lake basins deepen in close proximity to margin-coincident topography. Further evidence for neotectonism can be found in the historical catalog of seismicity, which shows earthquake epicenters broadly distributed along the strike of the Pantanal basin. The magnitudes of earthquakes in the Pantanal are variable and in some instances exceed $mb = 5.0$ (Assumpção et al., 2004).

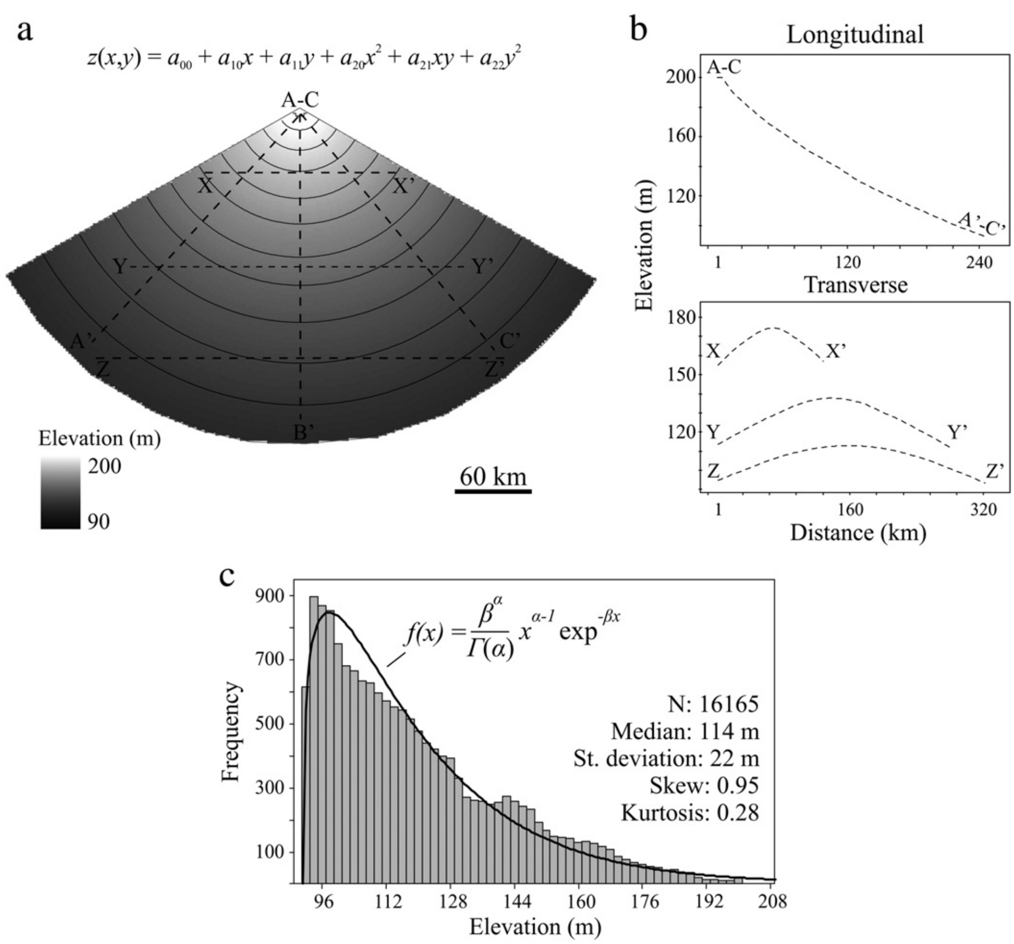

Fig. 3. Idealized megafan environment represented by a DEM. (a) Archetype modeled by a second order polynomial equation, with concentric contour lines (10 m interval) irradiating from the apex. (b) Longitudinal and transverse cross-profiles exhibiting the typical geomorphometry of this kind of depositional system. (c) Gamma distribution (solid line) fitted to the observed elevation values (columns), with basic statistical descriptors.

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Due to its low latitude position, the climate of the Pantanal is strongly influenced by the seasonal shifts of the Intertropical Convergence Zone (ITCZ). The mean annual temperature is ~25 °C, with two distinct seasons based on the rainfall regime: (1) a dry season, occurring during the austral winter (May to September, mean precipitation of 180 mm); and (2) a wet season, occurring during the austral summer (October to April, mean precipitation of 855 mm). Vegetation is characterized by an association of species derived from three tropical ecoregions (Prance and Schaller, 1982): (1) *cerrado*, composed by a savanna-like vegetation with open canopies species and isolated forest patches; (2) Amazonia, with semi-deciduous forest; and (3) Chaco, composed of seasonal dry forests and open vegetation. In the Taquari megafan, the distribution of plant species is controlled by the temporal variations of surface water (Pinder and Rosso, 1998), a factor that is controlled by topography.

3. Materials and methods

3.1. SRTM-DEM

The SRTM-DEM is the main remote sensing dataset used in this research. The Shuttle Radar Topography Mission produced the first high resolution global DEM, with 3″ resolution (nominally 90 m). According to Rodríguez et al. (2006), the SRTM-DEM has an absolute vertical accuracy of ± 9 m, and in areas of gentle slope, such as floodplains and megafans, this error decreases to ± 5 m, when considering a confidence interval of 90%. This dataset was considered a major advance over the previous global DEMs (van Zyl, 2001) and it has been extensively used in geomorphological studies (e.g., Verstraeten, 2006; Grohmann et al., 2007; Rossetti and Valeriano, 2007; Ehsani and Quiel, 2008; Hashimoto et al., 2008; Reinhardt et al., 2008; Ghoneim, 2009; Hayakawa et al., 2010; Rossetti et al., 2011; Andrades Filho and Rossetti, 2012). Detailed technical information about SRTM is presented by van Zyl (2001) and Farr et al. (2007).

For Brazilian territory, the original SRTM-DEM was refined from 3″ to 1″ in the scope of the Topodata Project (Valeriano and Rossetti, 2012). This topographic database was prepared through a kriging interpolation, with geostatistical coefficients related to the geomorphological characteristics. After several preliminary tests, we verified that the original SRTM-DEM was significantly improved after the interpolation of Valeriano and Rossetti (2012). The data utilized here were downloaded from the Topodata website (www.dsr.inpe.br/topodata), totaling 10 tiles corresponding to the 1:250,000 quads (1° × 1.5°) of the Brazilian Cartographic System.

3.2. Modeling the megafan topography

General evidence indicates that megafan systems exhibit remarkably smooth surfaces, characterized only by very low amplitude changes in superficial relief within a global topography trend theorized as a simple conical surface where concentric altimetric isolines radiate from the highest altitudes (i.e., megafan apex; Gumbricht et al., 2001). This surface can be represented by a generic polynomial algorithm, with the altitude (z) in function of geographic coordinates (x,y):

$$z = \sum_{i=0}^{N} \sum_{j=0}^{N} d_{ij} x^i y^i \quad (1)$$

where N is the polynomial degree; i and j are variables of interaction; and d is the regression coefficient.

The most appropriate degree for Eq. (1) is commonly selected in a process known as trend surface analysis (Davis, 2002). However, for large geomorphic features like megafans, a lower polynomial is notionally preferable, because macro-scale processes at the Earth's surface tend to be poorly represented by complex polynomial equations (Agterberg, 1974; Jones et al., 1986; Swan and Sandilands, 1995). In this manner, a second order equation is satisfactory to describe the megafan global topographic trend (Fig. 3a), and potentially other kinds of depositional systems as well, such as deltas and deep-sea fans that occur on the continental shelf. This archetype follows the basic geomorphometry identified both in alluvial fans (Bull, 1977; Blair and McPherson, 1994) and megafans (Stanistreet and McCarthy, 1993; Gumbricht et al., 2001, 2005; Assine, 2005; Chakraborty and Ghosh, 2010), exhibiting a concave longitudinal profile and a convex transverse profile (Fig. 3b). The statistical distribution of the elevation data shows a positively skewed histogram (Fig. 3c), due to the high frequency of low areas located along the megafan toe. The observed values can be fitted to the Gamma distribution:

$$f(x) = \frac{\beta^a}{\Gamma(a)} x^{a-1} \exp^{-\beta z} \quad (2)$$

where α and β are the parameters for the shape and scale of the theoretical distribution, respectively. The parameters can be used as morphological descriptors because they are closely related to the size and shape of the analyzed megafan deposit.

Identification of the megafan global topography (Eq. (1)) is the critical first step to highlight low amplitude landforms in the DEM. Notionally, most accommodation space (i.e., the potential volume of space available for sediments to accumulate) exists below the global component of topography, modulated by the location of sediment routing pathways. On the other hand, features above the megafan trend surface are indicative of depositional landforms produced by non-random clastic sedimentation (Gumbricht et al., 2005). Therefore, to enhance these features a simple subtraction of the original DEM from the modeled megafan global topography can be performed. After this operation, the altimetric trend is completely removed, and low amplitude features are enhanced on a new DEM

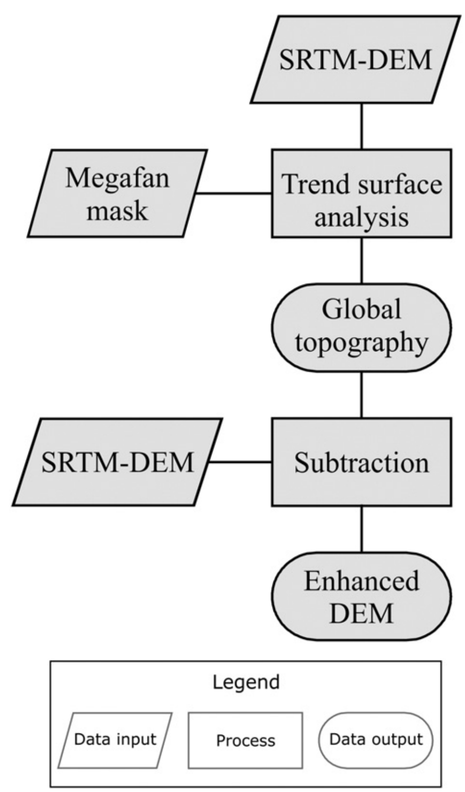

Fig. 4. Techniques applied to enhance the Taquari megafan landforms.

product. In this new DEM, the elevation is expressed as residuals, where the positives values are related to landforms such as depositional lobes and levees. Recognizing these features in the megafan environment is of great value, as several studies have demonstrated that they represent the dynamics of the most recent depositional events (e.g., Assine, 2005; Gumbricht et al., 2005; Fontana et al., 2008; Chakraborty et al., 2010).

3.3. Processing steps

Almost all steps explained here can be performed with geographical information systems (GIS), and only tools for data interpolation and vector manipulation are required. Here we describe the routines using ArcGIS 9.2, considering that it is one of the most-widely used GIS packages and contains all the tools required to implement the process in straightforward manner. The procedure to enhance the Taquari megafan landforms with the SRTM-DEM is illustrated in Fig. 4.

After downloading the SRTM-DEM, a polygon covering the megafan boundary was built by means of a visual interpretation. This was used to mask the SRTM-DEM, because of the sensitivity of Eq. (1) to outliers (Davis, 2002), and to limit the influence of high topography adjacent to the Taquari which is not related to the depositional system. Following the creation of a megafan mask, Eq. (1) was applied to extract the global topography and tested from 1° to 9°. The most representative polynomial degree was selected in accordance with standard trend surface analysis. In ArcGIS 9.2, Eq. (1) is implemented using the Geostatistical Analyst extension and is named Global Polynomial Interpolation.

The interpolation procedure generates a new raster that constitutes the simplified megafan surface, e.g., the global topography. Lower polynomials tend to produce smother surfaces (Swan and Sandilands, 1995), like the one represented in Fig. 3. The next step was a subtraction of the raster representing the global topography from the SRTM-DEM. In ArcGIS 9.2 this procedure can be done with the Minus tool, located in the Spatial Analyst extension, or alternatively by manually entering the expression in the Raster Calculator. This simple operation removes the large scale trend in the Taquari megafan topography, generating a DEM with the altitude values referenced to the global topography, where positive residual elevations are above the large scale trend and negative elevations are below. As a result, all depositional lobes and other landforms, which have low relief but are discordant from the global topography, are highlighted.

3.4. Product assessment

The results of the proposed technique may vary according to the study area, since each megafan has a unique shape and altimetry range (Hartley et al., 2010). This variability will certainly be reflected in the statistical transformations and consequently in the final product. To determine the fidelity of the enhanced DEM in highlighting landforms, we used datasets independent of the SRTM-DEM, including: (1) oblique aerial photos, captured in October 2003 (i.e., wet season); (2) control points and georeferenced photos, collected during field campaigns in June 2003 and July 2007 (i.e., dry season); and (3) optical satellite images, from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and China–Brazil Earth Resources Satellite (CBERS-2B) platforms. These datasets were used to evaluate the identified landforms and also for visual analysis.

4. Results

Nine trend surfaces were generated from the application of Eq. (1) to the SRTM-DEM. The first three surfaces are presented with their respective equations in Fig. 5. Histograms show that the distributions of altitudes become positively skewed with an increasing polynomial

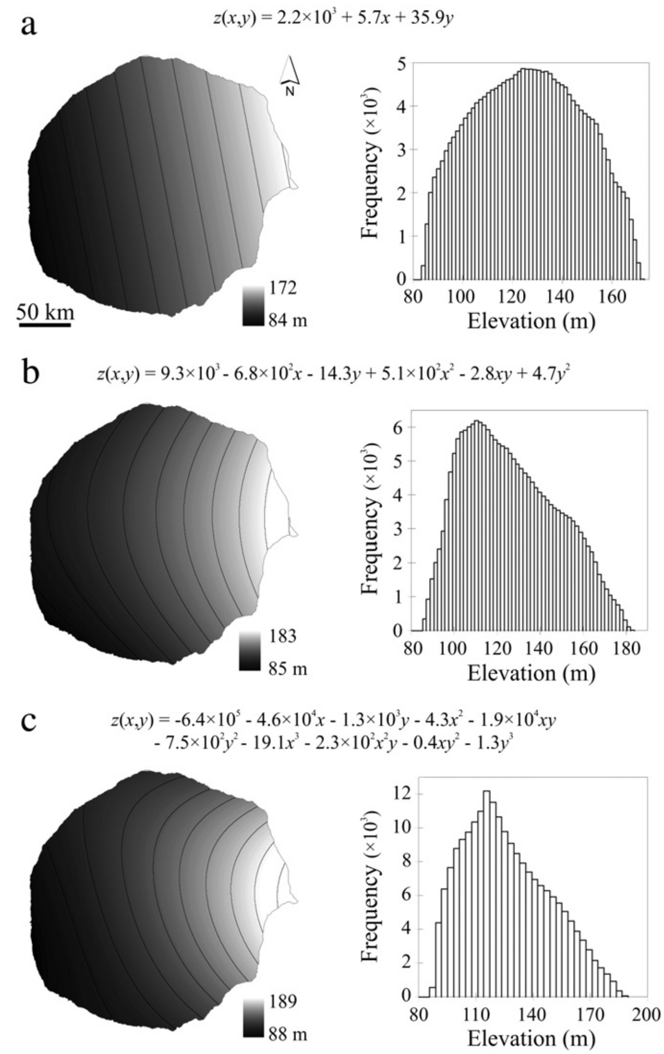

Fig. 5. Three trend surfaces generated to represent the global topography of the Taquari megafan. (a) 1st order polynomial. (b) 2nd order. (3) 3rd order. Note that more complex surfaces are generated with the increase of the order. The histogram skewness tends to be higher as the modeled surface becomes progressively more complex.

order (Fig. 5). Also discernible is the reduced variability of the datasets as trend surfaces become more complex; this is likely due to the better fit of the equations in these cases.

Visualization of the generated surfaces, as well as its goodness of fit (R^2) analyses, suggest that a second order polynomial equation is satisfactory to represent the global topography of the Taquari megafan (Fig. 6). Note that the adjustment between the SRTM-DEM and the quadratic trend, representing the global topography, is better after the apex region (Fig. 6a). This is due to the Taquari megafan geometry, which almost approximates a regular circle. The goodness of fit is generally improved as the order increases, but this improvement is only substantive up to the second order (Fig. 6b). Small gains achieved after the second order are too small to be representative. Moreover, studies from other regions suggest that high order polynomial equations are poorly suited to represent macro-scale processes (Agterberg, 1974; Jones et al., 1986; Swan and Sandilands, 1995), and thus they are not considered here. The trend surface analysis confirmed the initial assumption for using a low order polynomial to represent the megafan global topography.

The subtraction of the global topography (modeled by a second order polynomial) from the SRTM-DEM resulted in a new DEM, which considerably enhanced the landforms in the Taquari megafan. A side-by-side comparison of the raw and enhanced data illustrates

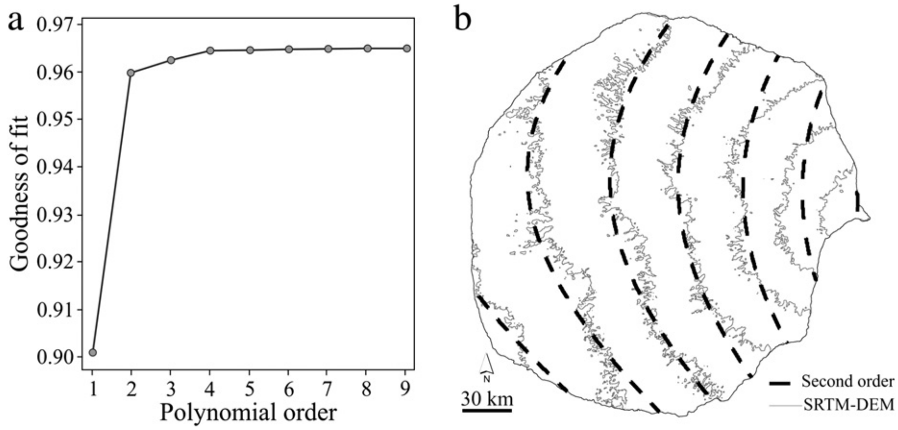

Fig. 6. Taquari megafan global topography. (a) Overall agreement between the second order trend surface contours with the SRTM-DEM, both with an equidistance of 15 m. (b) Goodness-of-fit plotted against polynomial order, showing low increase after the second order trend.

the results of the applied methods (Fig. 7). A descriptive statistical analysis on both datasets reveals that after the enhancement, the frequency of the data is increased, and these values approach a normal distribution. The new DEM exhibits strong contrasts in elevation values, whereas values in the raw DEM are heavy tailed.

The highest residual elevations in the enhanced DEM occur close to the megafan boundary. However, no evidence of these features was found in the field, and they reflect a limitation in the method (so-called "edge effect"; Swan and Sandilands, 1995; Davis, 2002). Commonly, the impacts of edge effects are diminished by including data well beyond the area of interest. However, given the different geologic context of the regions bordering the Taquari megafan, this procedure is not feasible for the study area. Intrinsic artifacts to the SRTM-DEM were also enhanced by the applied methods, but these do not impact on interpretations of the modern fan surface. For instance, the highly linear features observable in the northeastern portion of Fig. 7b are not real landforms. This striping pattern results from artifacts related to the SRTM-DEM production, and is commonly observed in low-relief areas (e.g., Bhang et al., 2007; LaLonde et al., 2010).

5. Discussion

5.1. Influence of vegetation on the enhanced DEM

Prior work has recognized vegetation as a potential source of error affecting the SRTM-DEM accuracy (e.g., Bourgine and Baghdadi, 2005; Bhang et al., 2007). The sensitivity of the C-band sensor to land cover could artificially lead to an increase of surface heights (LaLonde et al., 2010) or alternatively work as a smoothing blanket over local relief

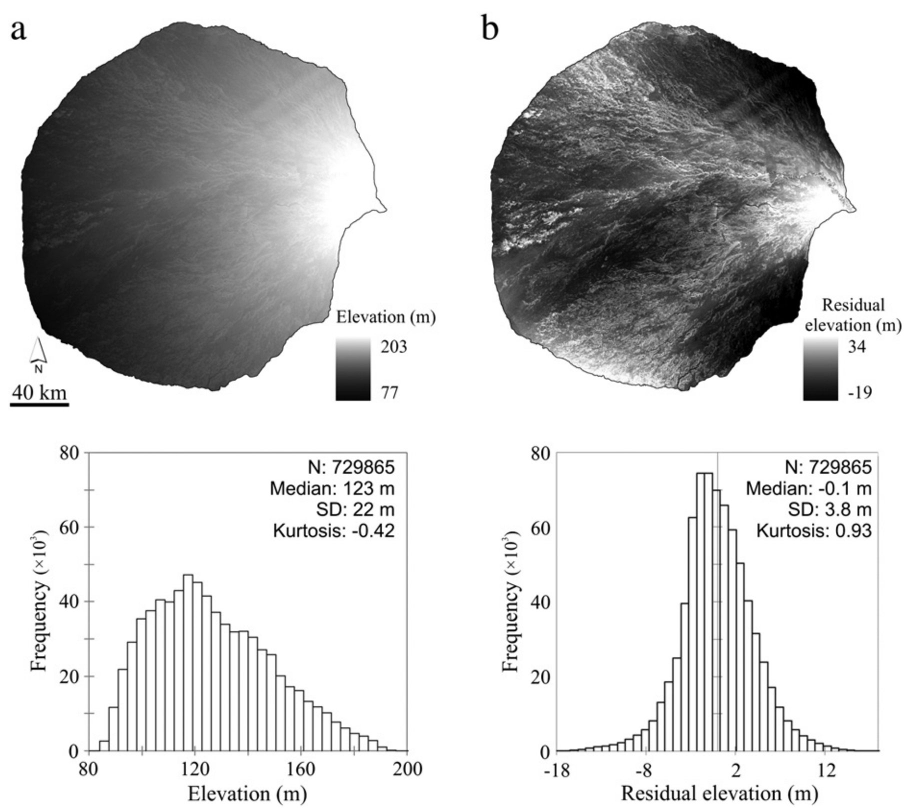

Fig. 7. Comparison between (a) the SRTM-DEM and (b) the detrended DEM. Note that the histogram of the detrended DEM presents higher frequency and lower standard deviation (*SD*) after the subtraction of megafan global topography.

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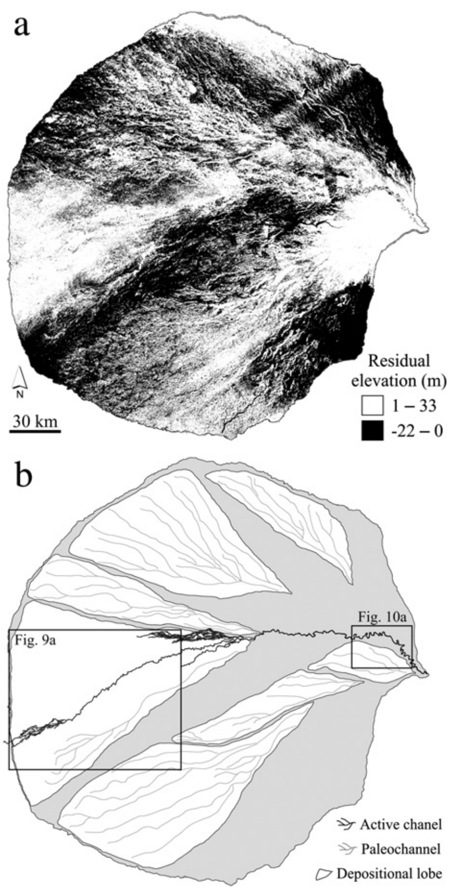

Fig. 8. Taquari megafan depositional landforms. (a) Enhanced DEM after positive residual elevation slice, showing sedimentary landforms related to positive residual elevation. (b) Depositional lobes extracted by visual analysis and their respective distributary paleochannels.

and landforms in densely forested areas (Valeriano et al., 2006). On the other hand, vegetation type is intimately connected with fluvial processes (Osterkamp and Hupp, 2010) and using optical satellite images as collateral data prevents misinterpretations.

Clearly, caution must be taken when interpreting an SRTM-DEM in low-relief terrains, particularly after applying the methods described here aimed to enhance low amplitude features. LaLonde et al. (2010) observed that in areas with extremely low topography, such as alluvial plains, the land cover can induce an inverted terrain model. In this situation, low-lying vegetated riparian areas tend to be represented higher than surrounding bare ground. This artifact poses significantly limitations to modeling studies and affects the calculation of terrain derivatives (Zandbergen, 2008). However we verified in the field that riparian vegetation causes the opposite effect in the Taquari. Dense and tall vegetation (wooded savanna) is usually located in elevated areas with well-drained soils, and these are correctly represented by even higher elevations in the enhanced DEM. Therefore we conclude that intrinsic errors and inaccuracies induced by land cover do not impact the analysis presented here.

5.2. Enhanced landforms and underlying processes

The most impressive landforms revealed by the enhanced DEM are several abandoned depositional lobes, appearing with a distinctive positive relief (Fig. 8a,b). In landscapes dominated by sedimentary processes like the Taquari megafan, local positive relief is interpreted as a kind of gradational feature, formed due to differential rates of sediment accumulation. Gumbricht et al. (2005) showed that the local positive relief in the Okavango megafan is a direct product of non-random clastic sedimentation in distributary channels, which creates landforms higher than the surrounding areas. This is a plausible explanation for the landforms enhanced in Fig. 8, since processes that occur in the Okavango are similar to those observed in the Taquari.

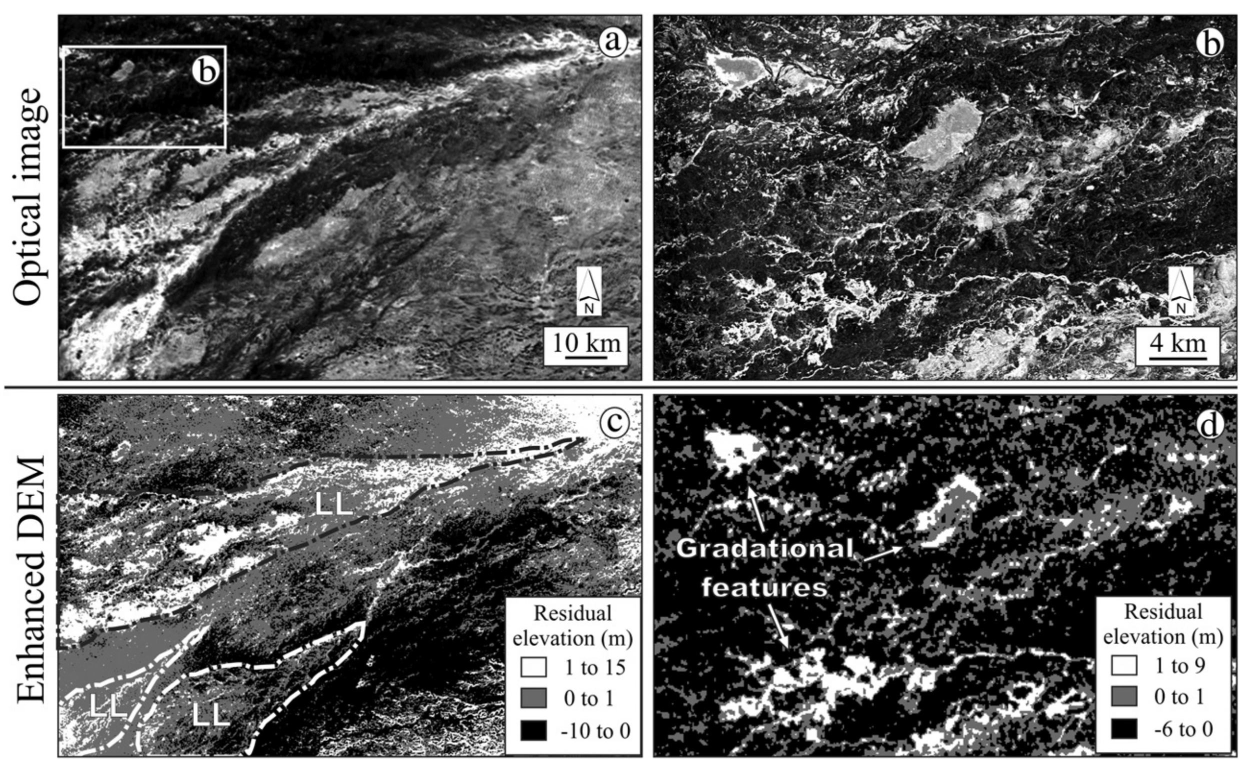

Fig. 9. Satellite images showing that areas with high residual elevation are not flooded in the rainy season. (a) CBERS-2B WFI imagery, band 2, on 07 June 2008. (b) ASTER imagery, band 1, on 28 July 2006. (c) Enhanced DEM covering the same area of (a). LL = lobed landforms. (d) Enhanced DEM covering the same area of (b).

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Depositional lobes are common features of alluvial fans (Bull, 1977; Blair and McPherson, 1994). In megafan environments, depositional lobes are characterized by elongate and asymmetric geometries that are produced by distributive channel networks. In the Pantanal, the networks that produce these sandy deposits are referred to as avulsion belt complexes (Assine, 2005). The widespread occurrence of depositional lobes implies that this is the dominant sedimentation pattern in the Taquari megafan. This evidence, combined with observations in other megafan environments, (e.g., Fontana et al., 2008; Assine and Silva, 2009; Chakraborty et al., 2010) suggests that the processes of construction and subsequent abandonment of depositional lobes are the primary mechanisms of megafan construction. An analog can also be drawn with deep-sea fans, as some processes (e.g., avulsion and aggradation) and forms (e.g., levees, lobes, and crevasses) reported in the literature for submarine systems (Curray et al., 2002; Jegou et al., 2008) are very similar to what is observed in the Taquari. Observations at several scales reveal that there is a continuum interface between small gradational features (~20 km^2) forming lobate landforms (~1500 km^2), which in turn make up the depositional lobes (~3000 km^2). The importance of deciphering these landforms relies on their origin associated with distinct sedimentation events, responsible for shaping the Taquari megafan.

On the modern distributary lobe, active sedimentary processes are responsible for the production of high local relief, which are barely discernible in the SRTM-DEM but are clear on the enhanced DEM (Fig. 7). Satellite images acquired from the region lend support to this hypothesis (Fig. 9a,b), as high relief areas typically escape inundation during the rainy season. They are located on terrains higher than 5 m relative to the regional surface trend, whereas flooded areas always occur below 0 m (Fig. 9c,d). Observations of the region during an airplane reconnaissance trip confirmed the existence of small cattle ranches and settlers occupying these high terrains areas, confirming they are dominantly dry.

Apart from depositional landforms, the enhanced DEM also highlighted both neotectonic and erosional features. A major lineament with 45° NE–SW orientation, enhanced by a low residual elevation zone (Fig. 8a), follows the deduced location for the Transbrasiliano Lineament (Fig. 2; Assine and Soares, 2004). Several depositional lobes seem to be truncated by this feature (Fig. 8b) and we interpret this as striking morphological evidence for active tectonics in the Pantanal. The enhanced DEM also highlighted the contrast with the Taquari meander belt and the surrounding areas (Fig. 10a). The mean residual elevation verified for this unit is under 0 m, attesting the prevalence of erosional processes. Along the megafan apex, abandoned fan lobes are being eroded and exposed (Fig. 10b). Experiments conducted by Rachocki (1981) with miniature models showed that drastic falls in the baselevel produces similar features. This process is discussed in detail in the next section.

5.3. Controls of avulsion processes

As previously stated for alluvial fan environments (Fernández et al., 1993; Florsheim et al., 2001; Harvey, 2002; Viseras et al., 2003), baselevel is thought to be the main mechanism controlling accommodation space, which determines the total volume available for sediment deposition. Tectonics and climate are commonly held as the main controls regulating baselevel in a regional context (Harvey, 2002). Tectonics can create accommodation space through subsidence in the depositional basin, whereas climate change can raise the baselevel with a long term increase in precipitation, affecting the water level of distal streams or water bodies. Although the baselevel hypothesis has seldom been tested in large systems such as megafans, the landforms observed here combined with previous reports (Assine, 2005; Zani and Assine, 2011) opens a new opportunity to discuss the relationship between baselevel fluctuations and avulsion processes in such environments.

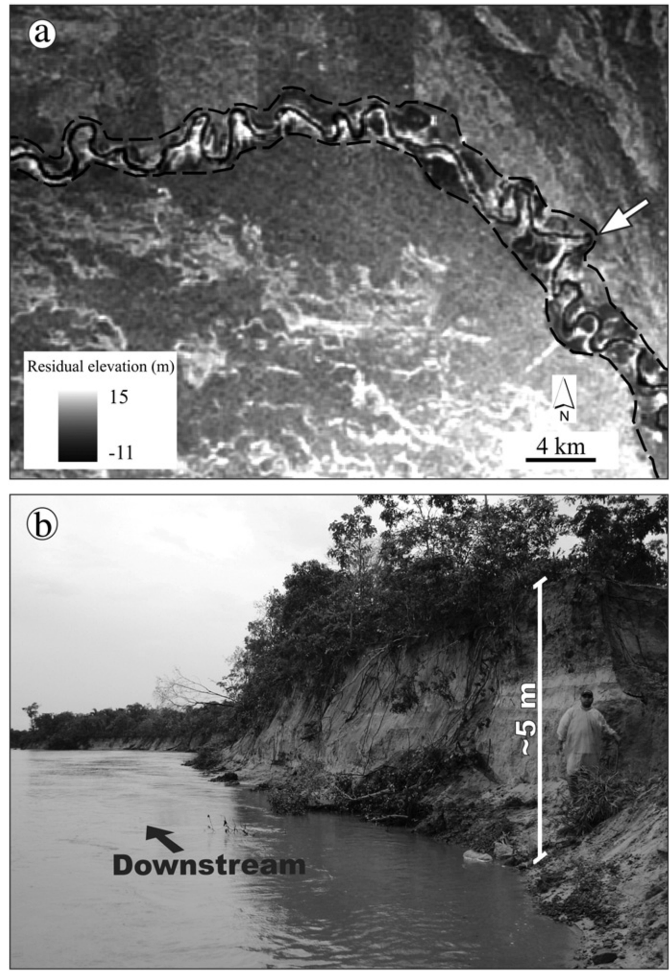

Fig. 10. Upper Taquari meander belt. (a) Residual elevation showing that the Taquari has been eroding deposits of abandoned lobes in the megafan apex. The arrow indicates the location of (b). (b) Main channel entrenched in a 5-m meander belt.

Although there is no consensus on the causes that initiate the avulsions in the Taquari megafan (Assine, 2005; Buehler et al., 2011), it is clear that recent events are occurring progressively closer to the apex (Fig. 11a). A single and relatively confined channel without crevasses or distributaries existed only until 1977 (dashed line on Fig. 11a). In the mid-1980s, several crevasses formed in the lower Taquari, which evolved into a complete avulsion in 1990. From this period until 1997, the river maintained a stable position, when a new crevasse started to form in 2000 close to the intersection point. Unfortunately satellite time series are still limited to just a few decades, and therefore trends in processes directed towards the upstream region cannot be conclusively confirmed. However, the short temporal evolution shown in Fig. 11a may be an indication of a progressive shift in the intersection point, suggesting that the system is being filled in a toe-to-apex direction. In fluvial systems, particularly in low gradient rivers, a continuous baselevel rise would cause backfilling in the main channel (Schumm, 1993). This has been described for Spanish fans by Viseras et al. (2003) and may be the main control of avulsion process in the Taquari megafan.

Based on the previous observations, a simple conceptual model is proposed to explain the influence of baselevel, both on the erosive character of the Taquari in its upper zone and the dominance of depositional processes in the modern lobe (inner box in Fig. 11a). This model follows the guidelines established by Schumm (1993) for alluvial rivers. In the upper zone the baselevel is below the river profile, and low preservation potential is expected. After the intersection point, accommodation space is available for sedimentation as the

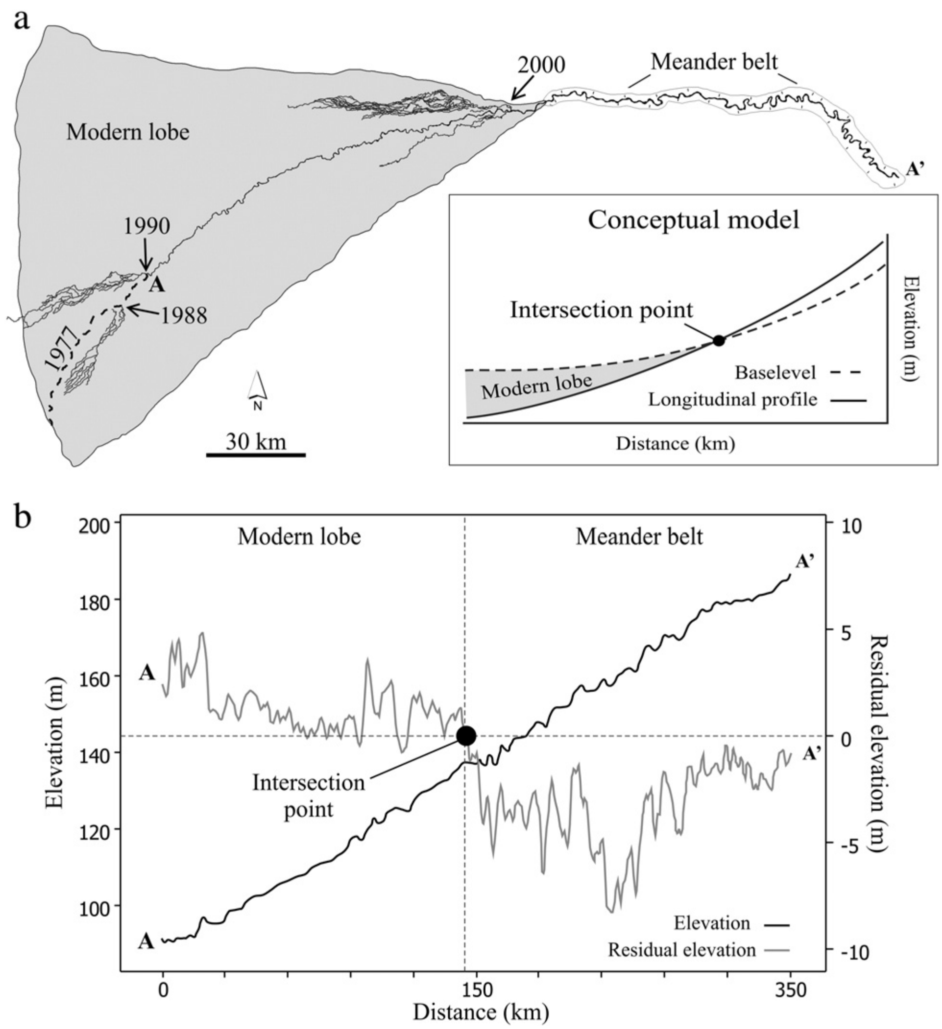

Fig. 11. Avulsion processes and baselevel. (a) Present conditions for the Taquari River and its conceptual longitudinal profile, with active distributary channels and crevasses splays restricted to the modern lobe. (b) Longitudinal profile and residual elevation along the segment A–A′ shown in (a). Note the positive residual elevation downstream the intersection point indicative of aggradation processes.

baselevel is above the longitudinal profile. The enhanced DEM illustrates the model concepts very well (Fig. 11b). A longitudinal profile collected over the Taquari River shows the meander belt with negative residual elevations, as a result of erosional processes related with a low baselevel. Field observations have revealed that in this area, the Taquari River is confined and forming lateral erosional terraces (Fig. 10b). When the river reaches the intersection point (~155 km), the average of residual elevations becomes higher than the baselevel. As a result of sediment aggradation downstream of this point, the river shoals and the main channel divide, causing lobe formation and switching within the floodplain. Avulsion processes are common and the drainage assumes a broadly distributary pattern within the modern depositional lobe.

6. Conclusions

In this paper we applied a series of techniques to the SRTM-DEM in order to enhance landforms in the Taquari megafan. The results led to the following conclusions:

- The global topography of the Taquari megafan can be well represented by a second order polynomial equation applied to the SRTM-DEM.
- Subtraction of the global topography from the second order SRTM-DEM polynomial surface produced an enhanced DEM, which revealed landforms not clearly recognizable in the original SRTM-DEM.
- Lobate landforms are features that stand out above their surroundings and comprise the main depositional landforms in the Taquari megafan.
- Fluctuations in baselevel and lobe aggradation and switching play an important role in the avulsion processes, which are responsible for the dynamics of construction and subsequent abandonment of depositional lobes.

Our case study of the Taquari megafan demonstrates that remote sensing products such as the SRTM-DEM can be used to effectively characterize a modern fluvial megafan that might otherwise be inaccessible for study due to its vast size and remote location. This method is also valuable for studying other types of broad terrain and can be used to guide subsequent investigations, including the development of landscape evolution models.

Acknowledgments

We acknowledge the financial support of the São Paulo Research Foundation—FAPESP (grants 2006/02381-8 and 2007/55987-3) and the National Council for Scientific and Technological Development—CNPq (grant 305108/2009-3). We are grateful to Dr. Márcio de Morisson Valeriano for suggestions and discussions regarding the manuscript structure and figure layout. Dr. Martin Thorp and an anonymous reviewer are thanked for their suggestions and comments that helped to improve an early draft of this paper.

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