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Application of morphometry in neotectonic studies at the eastern edge of the Paraná Basin, Santa Catarina State, Brazil

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ABSTRACT

The neotectonic evolution of the eastern edge of the Paraná Basin in the Santa Catarina State, Brazil was investigated using field data and detailed morphometric analysis along an east–west section. Analysis included generation of maps of isobase, hydraulic gradients, hypsometry, incision of drainage basins, drainage asymmetry and anomalous morphological features. All these maps generated results that agreed with field data and helped define recent faults in directions close to N–S and E–W, both probably reactivated faults of the Paraná Basin and the basement. Geomorphological features identified in topographic maps, possibly related to neotectonism, have a close agreement with our observations in the field. The asymmetry of basins as analysed by the T-Index method proved to be compatible with the influence of a E–W compressive tectonic regime and showed a movement from W to E. Application of the hypsometric integral technique helped establish a correlation between the younger basins with structures trending N–S (±30°). The N–S faults were related to a compressional stress field ($SH_{max)}$ close to E–W and SH_{min} (stress minimum) around N–S, thereby establishing a tectonic context of structures developed in a transpressive regime. The compressional field was caused by the subduction of the Nazca tectonic plate below the South American plate, whereas the transcurrent component exploited pre-existent E–W structures when the Atlantic Ocean was opening.

1. Introduction

Morphometric maps were first used in tectonic analysis by Filosofov (1960), and since then methods for the construction and assessment of morphometric parameters have been constantly improved with the development of new techniques (Zuchiewicz, 1991; Golts and Rosenthal, 1993; Rodriguez, 1993; Cox, 1994; Salvador and Riccomini, 1995; Grohmann, 2004; Garrote et al., 2008). Particularly in this last decade, remotely-sensed data coupled with Geographical Information Systems (GIS) have promoted significant improvement of these methods, giving them greater agility and precision in interpretation (Jordan et al., 2005; Guth, 2006; Valeriano et al., 2006; Grohmann et al., 2007). Structural analysis (geometric and kinematic) of brittle faults and prioritization of these structures are essential tools for the interpretation of palaeostress fields, which are responsible for the generation of brittle structures, and validation of the models obtained in a GIS environment.

The term 'neotectonics' is used here in the same original sense introduced by Obruchev (1948, in Suguio, 1999, p. 113), who describes it as the study of "tectonic movements which took place at the end of the Tertiary and in the Quaternary periods, which have had a decisive role in the current topographical configuration of the earth's surface…". Based on this initial concept, the term was redefined by several different authors, mainly in relation to the geological time involved in the process. However, the Neotectonics Commission of INQUA (International Union for Quaternary Research) does not use any time limits in the study of movements related to neotectonics but mentions that they could have had any duration ranging from one instant, produced by earthquakes, up to 10^7 years (Mörner, 1989).

The present study characterizes the neotectonic development of the eastern border of the Paraná Basin, Santa Catarina State, southern Brazil (Fig. 1A), based on the analysis of the morphometry and structural parameters. Neotectonic studies which involve Santa Catarina State are not easily found in the literature, being restricted largely to Saadi (1993), Assumpção (1998), Reis and Tomazzoli (2010) and Assumpção et al. (2011). It is important to emphasize the significance of neotectonic studies in the area as it is representative of a passive margin intraplate setting and is limited by the edge of the Paraná Basin. This study aims to: (1) evaluate the results obtained by different morphometric techniques and test them with field data; (2) define the systems of faults that were reactivated in the study area; and (3) establish direction of the current maximum horizontal stress (SH_{max}) in the study area.

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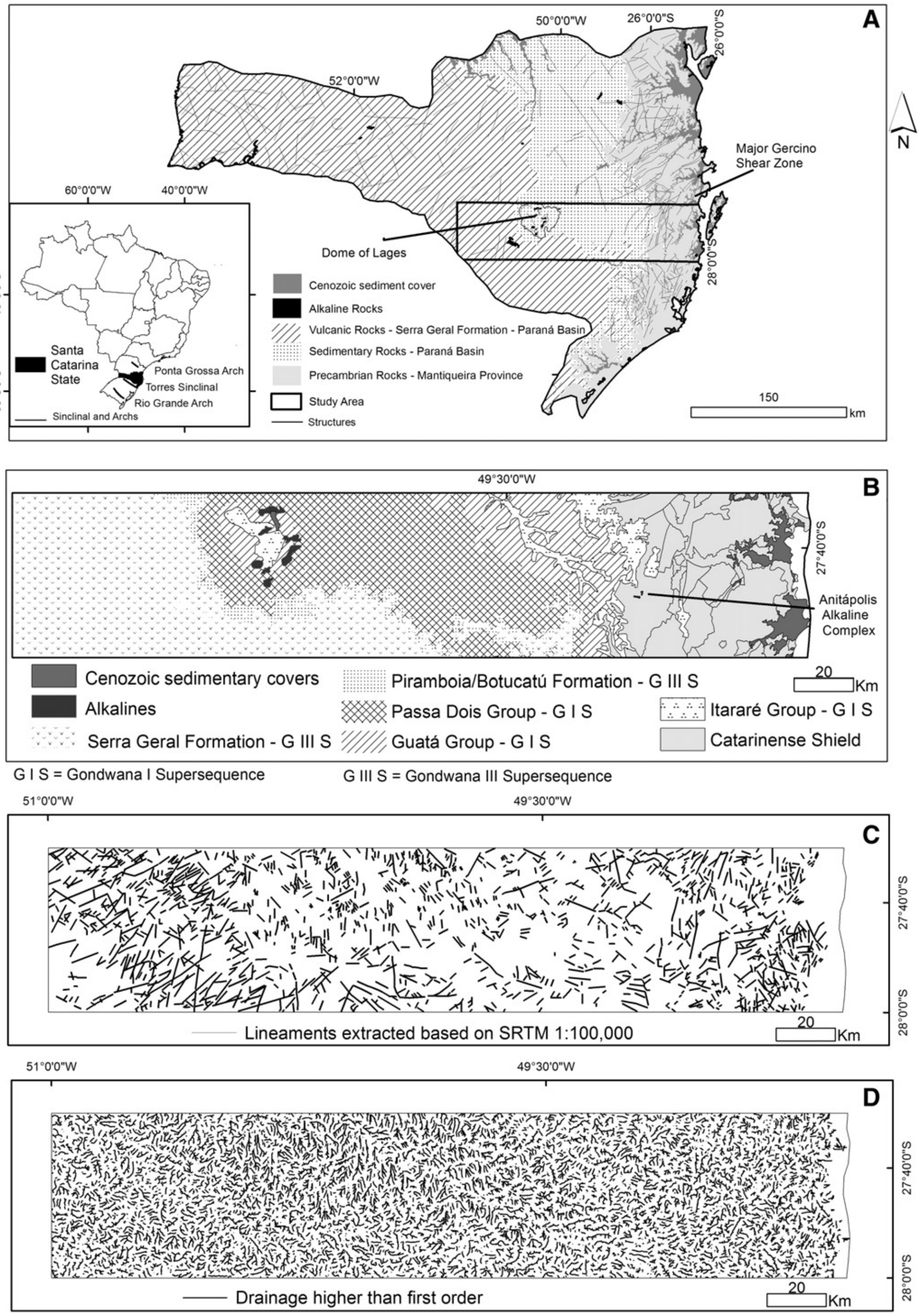

Fig. 1. A—Location of the study area based on the Geological Map of Brazil (1:1,000,000 scale) (Perrota et al., 2004; Ramgrab et al., 2004). B—Detail of lithological units in the study area. C—Lineaments extracted from SRTM images (1:100,000 scale) (Jacques et al., 2010, 2012). D—Drainage obtained for the construction of isobase and hydraulic gradient maps.

2. Study area

The study area (Fig. 1A,B), located in south-central Santa Catarina State, is part of the Mantiqueira and Paraná tectonic provinces (Almeida et al., 1977, 1981) and is located between two important regional tectonic structures of the eastern margin of the Paraná Basin: the Ponta Grossa Arch, in the north, and the Torres Syncline, in the south (Fig. 1A). Regionally, the Mantiqueira Province encompasses Precambrian rocks exposed in the eastern part of the South American Platform. With an approximate area of 700,000 km^2, it stretches out from the Espírito Santo State in Brazil to Uruguay. According to Hasui (2010) the Mantiqueira Orogenic System had its final process of accretion between 500 Ma and 460 Ma. The trend of the main structures (NE/SW) is related to dextral transcurrent/transpressive shear zones (Heilbron et al., 2004).

The Paraná Province is one of the major tectonic provinces in Brazil and encompasses Paleozoic sedimentary rocks of the Paraná Basin, with an approximate area of 1.6 million km^2. It is situated entirely within the South American Platform and covers seven Brazilian states and three neighbouring countries: Uruguay, Argentina and Paraguay. The stratigraphic framework of the basin consists of six supersequences, corresponding to the tectono-sedimentary phases (Milani, 1997;

Milani et al., 1998; Milani, 2004; Milani et al., 2007). The firsts three supersequences are correlated with major transgressive–regressive cycles of sea-level oscillation in the Paleozoic: Ivaí (from Ordovician to Silurian); Paraná (Devonian) and Gondwana I (Carboniferous to Early Triassic). The three younger supersequences are associated with Mesocenozoic sediments of continental origin and volcanic rocks (Milani et al., 2007): Gondwana II (Triassic to Upper Triassic), Gondwana III (Upper Jurassic to Early Cretaceous) and Bauru (Upper Cretaceous).

Zalán et al. (1987, 1990) highlight, within the structural framework of the basin, three structural trends: N45–65°W, N50–70°E and E–W. According to the authors, the NW and NE directions are the oldest and originated from the reactivation of the weak zones present in the framework of the basin, which were reactivated during the Phanerozoic. These weak zones had a strong influence on paleogeography, sedimentation and the distribution of facies in the basin, as well as the development of tectonic sedimentary structures including liquefaction related to seismites, as described in relation to the Corumbataí Formation in the State of São Paulo (Riccomini et al., 1992, 2005). The E–W lineaments were developed during the break-up of Gondwana, and therefore have been active since the Triassic period, as have many of the NW-trending faults, whereas the NE-trending faults have apparently remained inactive (Zalán et al., 1987, 1990).

Jacques et al. (2010, 2012), studying the structural lineaments along the eastern margin of the Paraná Basin and its basement in Santa Catarina by means of digital products (LANDSAT and SRTM images on 1:100,000 and 1:500,000 scales), defined the directions as follows: N–S and NNE–SSW (basement), NW–SE and N–S (Gondwana I Supersequence) and NE–SW and NW–SE (Gondwana III Supersequence - Serra Geral Formation) and concluded that SRTM 1:100,000 has the best results for the extractions of brittle lineaments (Fig. 1C).

In the present study, a transverse segment (E–W) in the southeast of the Paraná basin was selected (Fig. 1B), including Precambrian rocks of the Mantiqueira Province (the eastern part of the area) and Paleozoic and Mesozoic rocks from the Paraná Province, respectively in its central and western parts, in order to assess the continuity and the reactivation of structures of the Santa Catarina Shield on the edge of the basin. There are five main geological domains present in the study area:

a) Catarinense Shield (age older than 550 Ma)—consisting of granulites, metavolcanic and metasedimentary rocks and granites.
b) Paraná Basin sedimentary rocks (between 500 and 180 Ma)—these sedimentary rocks are part of the Gondwana I Supersequence and comprise three stratigraphic groups: Itararé (bottom), Guatá (middle) and Passa Dois (top) (Fig. 1B).
c) Paraná Basin Igneous Rocks (±130 Ma)—constituted mainly, in the study area, of volcanic rocks of the Serra Geral Formation (Gondwana III Supersequence).
d) Alkalines Complexes (Anitápolis ±130 Ma and Dome of Lages ±65–70 Ma)—the Anitápolis Alkaline Complex is located in the Catarinense shield (eastern part of the study area) and it can be associated with the tholeiitic magmatism in the Paraná basin and related with an initial rifting, during the Early Cretaceous (~132 Ma), before the opening of the Atlantic Ocean (Comin-Chiaramonti et al., 2002). The Dome of Lages (Fig. 1A) is intruded into the rocks of the Paraná Basin, with major axis near NW–SE, and is composed of Neocretacic alkaline rocks, which age (Rb/Sr, K/Ar and Ar/Ar) is around 75 Ma (Scheibe et al., 1985; Scheibe, 1986; Machado and Teixeira, 2008).
e) Cenozoic sedimentary covers—located in east of the study area, near the coast, and characterized by Quaternary sediments accumulated by diverse environments as rivers, lagoons, wind and sea.

3. Material and methods

The assessment of the influence of Cenozoic tectonics on the current landscape of the study area was based on the analysis of the correlation between morphometric maps of isobase, hydraulic gradient, hypsometry, the incision of drainage basins, drainage asymmetry, lineaments and geomorphological features supported by structural data collected in the field. The main source of information and data for the preparation of the morphometric maps was the DEM, with a horizontal spatial resolution of 90 m, available at the Consortium for Spatial Information (CGIAR-CSI) and produced based on original SRTM data (Shuttle Radar Topography Mission, Farr et al., 2007). A synthesis of the morphometric techniques applied in this study is presented in Table 1.

Geomorphological features, related to neotectonic events, were identified from topographical maps at 1:50,000 and 1:100,000 scales produced by the Brazilian Institute for Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE) between 1974 and 1980. In addition, optical remote sensing images (LANDSAT ETM + and ASTER—Table 2) were useful in the extraction of linear features related to relief and geomorphology. Further information about the image processing applied in LANDSAT ETM + and SRTM images can be find in Jacques et al. (2012).

The Isobase map is a ‘simplified’ version of the original topographic surface without the influence of the first order stream erosion (Grohmann et al., 2007, 2011) and the abrupt deviations in isobase values may reflect tectonic dislocations or severe lithological changes (Golts and Rosenthal, 1993). It was generated following the concept described by Filosofov (1960) and Golts and Rosenthal (1993), which assumes that the isobase lines delimit erosional surfaces related to tectonic–erosional events, mainly the most recent ones. The isobase map used in this paper can be regarded as the same as ‘Base-level maps’ (Dury, 1952; Filosofov, 1960; Pannekoek, 1967) which express a relationship between the base-level surface and erosional stages. First-

Table 1
Synthesis of the morphometric techniques applied.

Morphometric parameter	Significance	Restriction	Selected sources
Isobase	Abrupt deviations in isobase values may reflect tectonic dislocations	It can reflect lithological changes too. It is important to observe together with other information (lithology, faults, fractures).	Golts and Rosenthal (1993), Grohmann et al. (2007, 2011)
Hydraulic gradient	Height values indicate nick points which can be associated with neotectonic.	Nick points can be associated with changes in lithology.	Rodriguez (1993), Modenesi-Gauttieri et al. (2002), Grohmann (2004, 2005)
Hypsometry	Most tectonically active areas show value >0.6.	It is sensitive to the erosional resistance of different lithological units and is scale dependent.	Strahler (1952), Walcott and Summerfield (2007)
T-Index	Preferential direction of asymmetry can be associated with tectonic forces.	If the directions are random, the pattern is associated with fluvial process.	Cox (1994), Cox et al. (2001), Salvany (2004), Garrote et al. (2008), Ibanez and Riccomini (2011)
Features	Suspended basins (hanging valley), interrupted drainage alignments, structural highs, significant breaks in drainage with angles close to 90°, abnormal routes taken by the drainage network	Important to minimize the subjectivity of the manual interpretation	
Data field	Observations of faults on soil (pedogenetic)	It is not easy to find soil with slickensides.	

Table 2
Scenes and date of Landsat and Aster images used in this study.

Landsat	Aster
220_079 (10/Mar/2002)	17730, 17732 (9/Dec/2003)
221_079 (16/Mar/2002)	17905 (21/Oct/2000)
	18141 (13/Apr/2006)
	17894 (04/Feb/2007)

order drainage (with characteristics of more recent river incision) was eliminated to reinforce and allow the analysis of characteristics controlled by recent structures. Grohmann et al. (2011) disregard 1st order streams with the aim of obliterating the effects that may mask the identification of a scarp or other topographic features related to erosional–tectonic events. The automatic extraction of the drainage network (Fig. 1D), based on DEM, was done using D8 method (O'Callaghan and Mark, 1984) in ArcGIS software with a threshold higher than 100 (related to flow accumulation), which according to the spatial resolution of SRTM produces a drainage network compatible with a 1:100,000 scale (Grohmann et al., 2007). The establishment of the hierarchy followed the concept proposed by Strahler (1952). The values of the altitude from the SRTM–DEM were incorporated into the drainages of the second and higher orders, generating a file with points that were interpolated using the inverse distance weighted (IDW) method (Philip and Watson, 1982), at the second power, with a variable search radius and considering the 12 closest points. According to Binh and Thuy (2008)

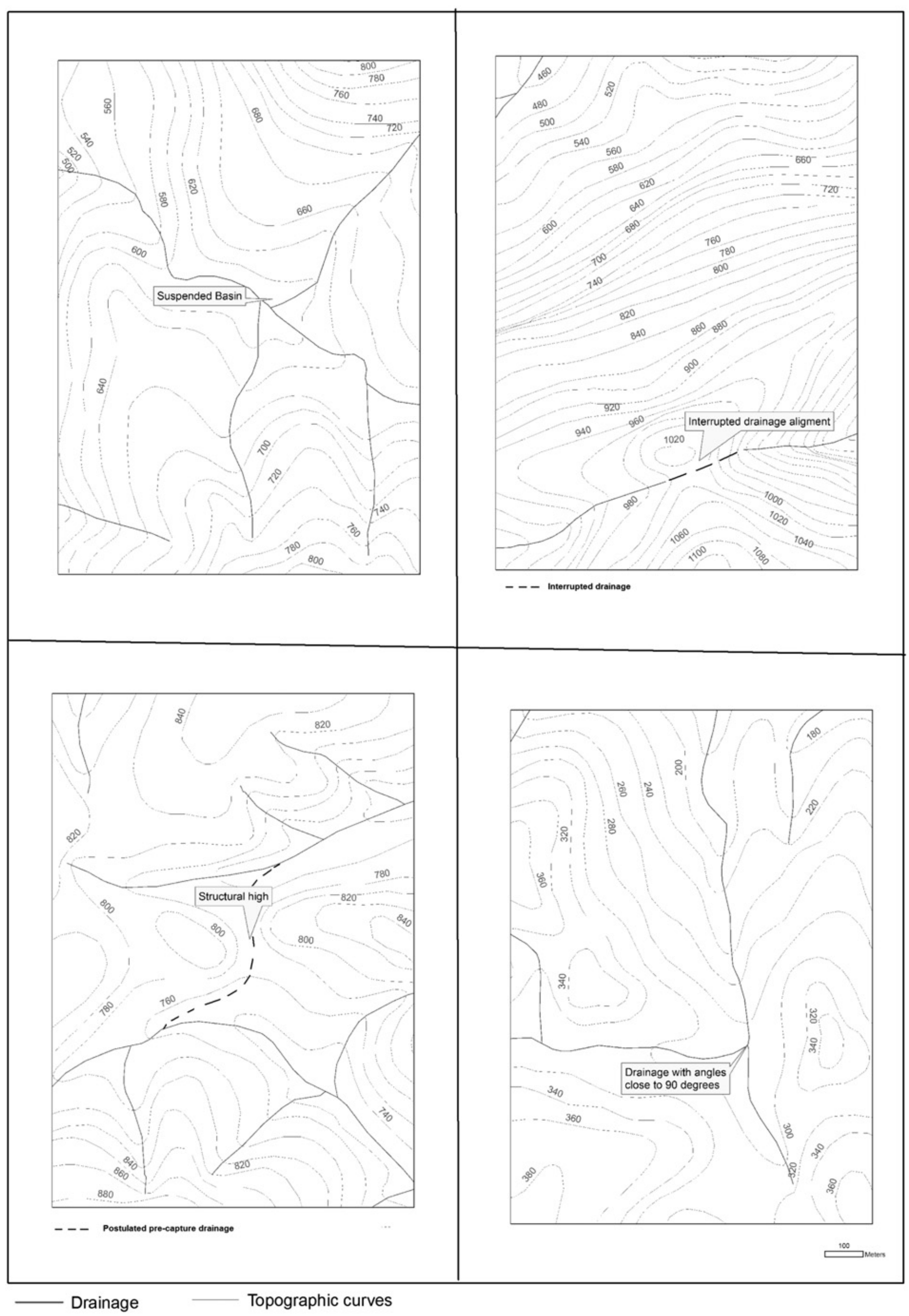

Fig. 2. Geomorphological features that could be related to recent tectonics: suspended basin, interrupted drainage alignment, structural high with possible deviation and capture of drainage and significant break in drainage, with an angle close to 90°. Dashed lines denote pre-capture drainage.

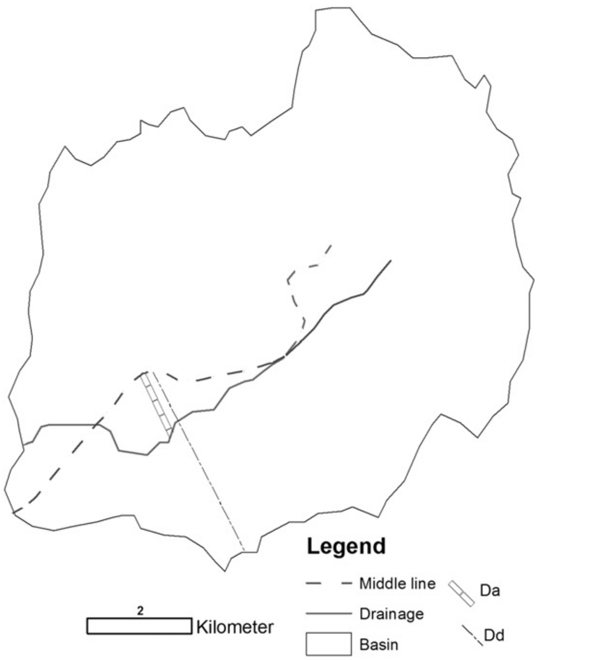

Fig. 3. An example of TecDEM in obtaining the T-Factor. Da = Distance from the basin bisector to the current drainage. Dd = Distance from the basin bisector to the border of the basin. Distances are measured perpendicular to the trunk drainage channel.

for hilly and flat areas, IDW or ordinary kriging with an exponential model variogram are recommended, however the IDW is much faster than kriging.

The Hydraulic Gradient (HG) map (Rodriguez, 1993; Modenesi-Gauttieri et al., 2002; Grohmann, 2004, 2005) was generated to determine areas with similar hydraulic behaviour with the aim of relating them to structural lineaments. It was constructed based on drainage of second and higher orders (as indicated by Grohmann, 2004) and for each component a pair of points was assigned, at the source and at the drainage mouth, which combined with DEM allowed the generation of a network with the values of the different altitudes. Each drainage section had its length calculated, and then the value of the hydraulic gradient was calculated using Eq. (1) and assigned to its midpoint. The midpoints were then interpolated, considering the 12 closest points and a variable search radius using the IDW method at the second power, thereby generating the HG map.

$$HG = [(h_c - h_f)/d] * 100 \quad (1)$$

where:

HG hydraulic gradient
h_c height at source
h_f height at mouth
d distance from source to drainage mouth.

The extraction of brittle linear relief features was done manually based on the visual interpretation of shaded relief images, with the application of artificial lighting to the SRTM DEM at a scale of 1:100,000 (Jacques et al., 2010, 2012). These data were compared with the features obtained by the isobase and HG maps, and the common lineaments to both types of data (SRTM × isobase or SRTM × HG) were interpreted as possibly associated to recent tectonic events.

Geomorphological features that suggest possible neotectonic activities have been identified on digitized topographical maps at scales of 1:50,000 and 1:100,000 and features were considered corresponding to: (1) suspended basins (hanging valley); (2) interrupted drainage alignments; (3) structural highs responsible for the deviation and capture of drainages; (4) significant breaks in drainage with angles close to 90°; and (5) abnormal routes taken by the drainage network (Fig. 2).

Exploring the correlation of these features with the lineaments extracted from the morphometric maps, buffer maps showing distances from the lineaments were generated, considering both the total lineaments and the lineaments grouped into six range direction classes: NNE (1° to 30°), NE (31° to 60°), ENE (61° to 90°), WNW (91° to 120°), NW (121° to 150°) and NNW (151° to 180°). Due to the different information sources used in this study, with a variety of scales and hence associated location errors, we considered that features up to 1 km away from the linear structures can be correlated.

The analysis of the drainage asymmetry (Cox, 1994), known as Transverse Topographic Symmetry (T-index), has been applied in several different works related to studies of neotectonic deformations in the Quaternary (Cox et al., 2001; Salvany, 2004; Garrote et al., 2008; Ibanez and Riccomini, 2011). The T-index method (Fig. 3) allows the quantification of the direction of the average migration of drainage

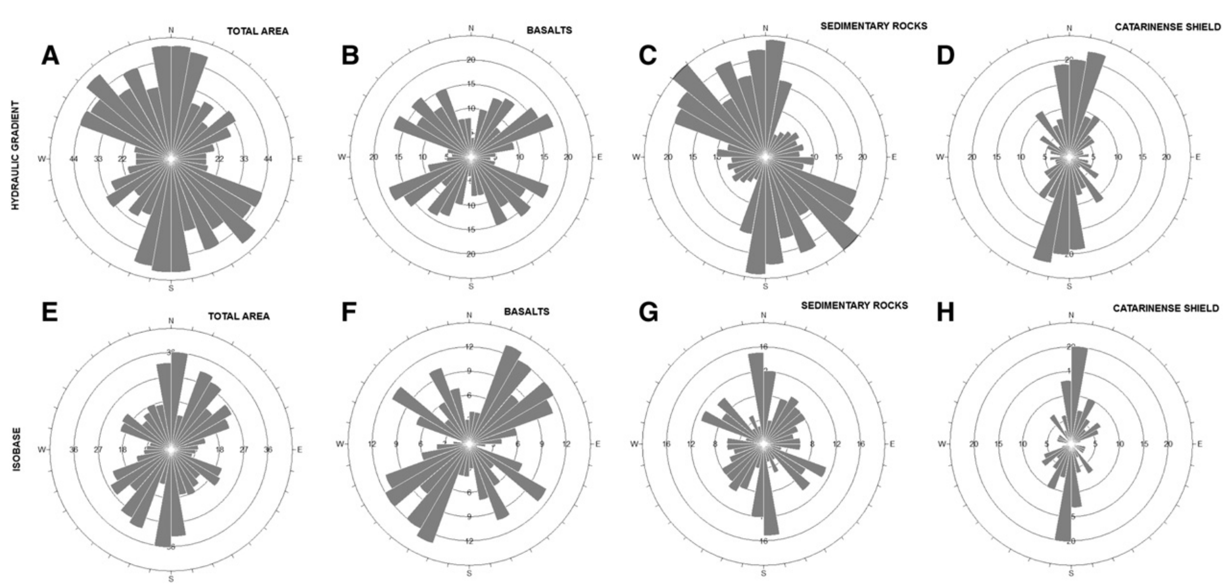

Fig. 4. Rose diagrams of the lineaments obtained from hydraulic gradient (A–D) and isobase (E–H) of the study area.

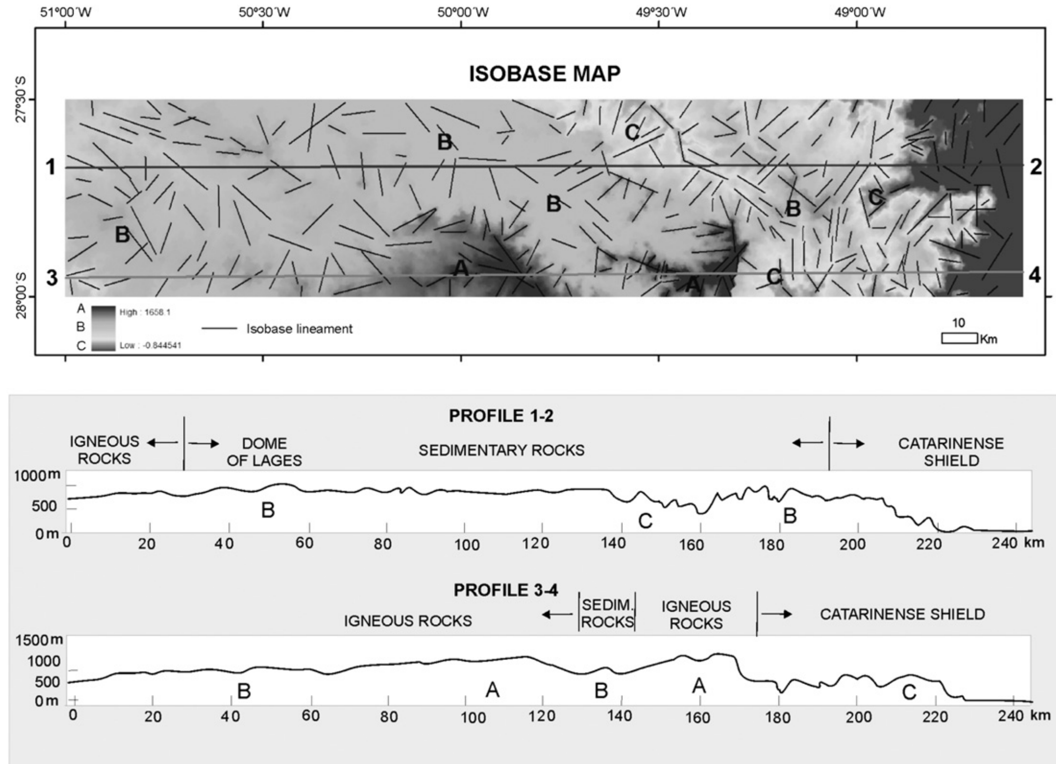

Fig. 5. Isobase map, interpreted lineaments and domains: (A) High, (B) Medium and (C) Low. Two morphological profiles show the relation between the isobase domains.

courses and also the discovery of the cause of this migration, which can be a consequence of fluvial processes (the asymmetry drainage pattern is random) or due to external tectonic forces (imposing a preferential direction to the asymmetry). In drainage basins of higher orders, this asymmetry reflects regional morphological and structural trends, while in basins of lower orders they reflect more recent tectonic movements (Garrote et al., 2008). The T-index results may reflect deep crustal blocks bounded by active faults or flexures and can reflect the regional subsurface structural grain (Garrote et al., 2006). For this analysis, 417 second-order drainage basins were used, distributed in the area as to represent the geological domains that have been studied. The basins were calculated automatically in the software TecDEM

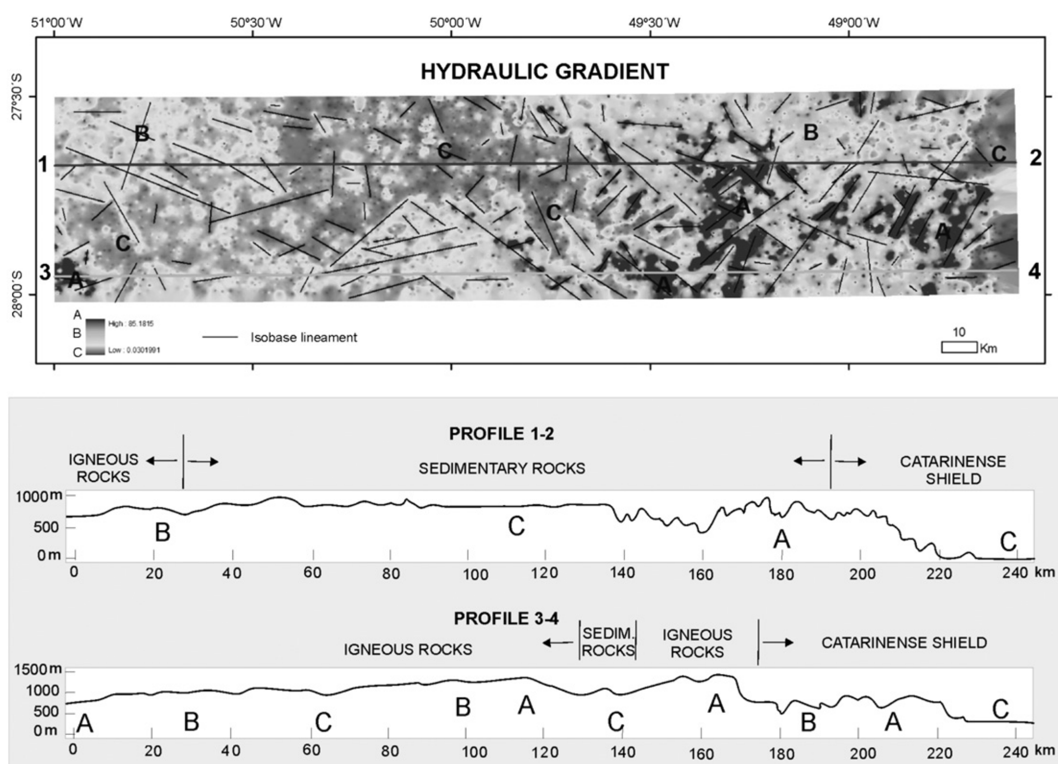

Fig. 6. Hydraulic gradient map, interpreted lineaments and domains: (A) High, (B) Medium and (C) Low. Two morphological profiles show the relation between the domains.

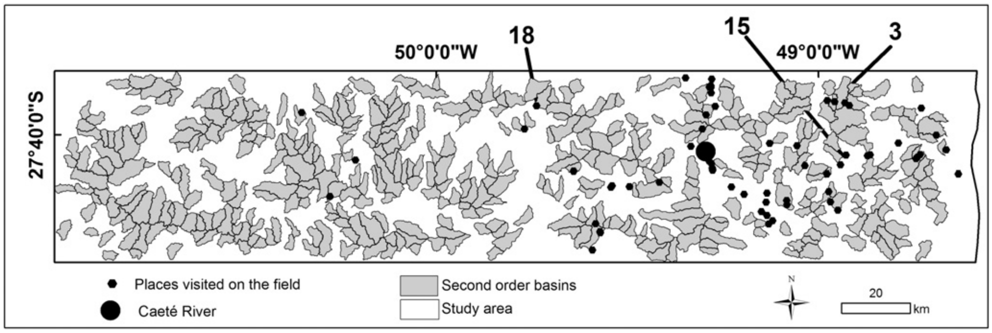

Fig. 7. Location of the points showing drainage anomalies confirmed in the field indicated by numbers, when they are referred to in the text, and second-order drainage basins analysed by the T-Index method.

(Shahzad and Gloaguen, 2011) for the whole study area, based on second-order drainage and resulting in 417 basins. The mean T-index and also the direction of the asymmetry were calculated for each basin using TecDEM, based on segments of about 2 km (Cox et al., 2001; Salvany, 2004).

The hypsometric integral (Strahler, 1952) was calculated for the selected 417 drainage basins, with the purpose of analysing the different stages of maturity (younger, mature and older). The hypsometric integral (Eq. (2)) is obtained through the integral of the absolute hypsometric curves (X,Y) where the elevations (h) and areas (a) are relative to the maximum height (H) and the total area (A) of each basin:

$$\int_0^1 = X.dY \qquad (2)$$

where: $X = a / A$ and $Y = h / H$.

Values close to one (100%) represent younger terrain, in apparent imbalance, whose declivity undergoes rapid transformation; values close to 0.5 (50%) are mature terrain, with an erosion balance; and values close to 0 are older areas, where erosion is dominant. The value of the Hypsometric Integral (HI) was extracted automatically through the program Cal-Hypso (Pérez-Peña et al., 2009) and the results were classified according to the limits proposed by Strahler (1952), in the following manner: young basins with HI values > 60%, mature basins with 35% ≤ HI ≤ 60% and old basins with values of HI < 30%.

4. Analysis and results

In this study the morphometric data obtained were analysed in order to relate them to neotectonic structures. These results were compared to structural data obtained in the field for the confirmation of the areas affected by recent tectonic movements (neotectonics) and the tectonic processes involved. The preferential structural trends as obtained from the isobase and HG maps can be seen in the rose diagrams shown in Fig. 4.

4.1. Isobase map

The isobase map, constructed based on second and higher order drainages, allowed depiction of the features controlled by recent structures as an inflexion in the fault line area or a lineament (Fig. 5). As a first analysis, it shows three large domains in the study area: High (A), Medium (B) and Low (C), and isobase lineaments were interpreted over this map (Fig. 5).

High isobase values occur in the central-southern portions of the area and include mainly igneous rocks of the Serra Geral Formation. Isobase lineaments in this domain have NW and NE directions (Fig. 4F). Medium values occur in the central-west part of the area, over sedimentary rocks and alkaline intrusions (Dome of Lages). Isobase lineaments in the sedimentary rocks have a N–S orientation (Fig. 4G), whereas in the Dome of Lages area lineaments are oriented to the NW, according to the main axis of the dome. Low isobase values occur over metamorphic and igneous rocks of the Catarinense Shield, as well as on the coastal Cenozoic cover, in the eastern part of the area. Isobase lineaments have a NNE orientation (Fig. 4H).

The main morphological difference between the isobase (Fig. 5) and the original topographic surface is the removed of the noise of the low-order streams, which allows the identification of possible tectonic influence.

4.2. Hydraulic gradient

The distribution pattern of the hydraulic gradients values in the study area allows the identification of three major domains (Fig. 6). High hydraulic gradients occur mainly in the eastern area, related to the Catarinense Shield. Lineaments in this domain are oriented NE and NW in the basalts (Fig. 4B), NW in the sedimentary rocks (Fig. 4C) and NNE in the Catarinense Shield (Fig. 4D). Medium HG values are associated mainly with the Catarinense Shield, with NNE lineaments, and with sedimentary rocks, with NE lineaments. Low values occur in coastal areas (east) and in sedimentary rocks (centre). The transition to

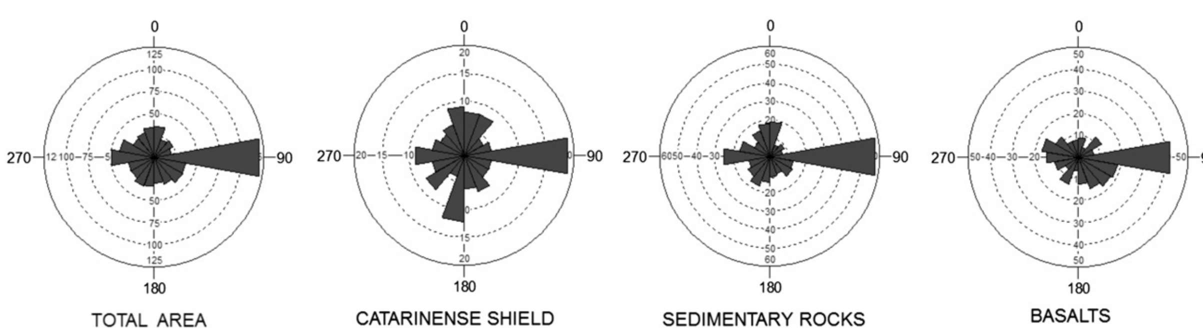

Fig. 8. Rose diagrams for drainage asymmetries from left to right: Total area, Precambrian rocks (Catarinense Shield), Paleozoic sedimentary rocks (Paraná Basin) and Mesozoic igneous rocks (Serra Geral Formation - Paraná Basin).

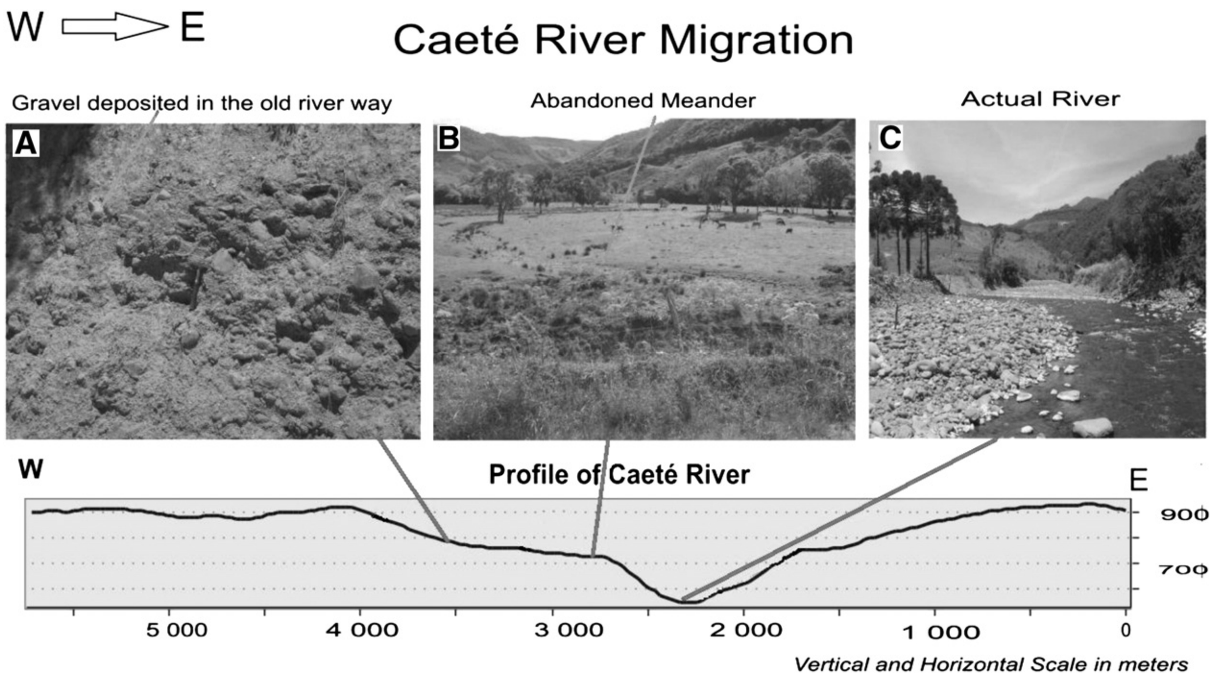

Fig. 9. Migration of the Caeté River drainage (shown in Fig. 7) from West to East. A) Conglomerates of the old river channel. B) River plain with an abandoned meander. C) Current channel of the Caeté River. Location of photographs shown on profile.

medium hydraulic gradients is associated with NW and NNE structures (Fig. 4C,D, respectively).

The main morphological difference between the hydraulic gradient map (Fig. 6) and original topographic surface is the value of the hydraulic gradient map, since it is calculated from the ratio of the difference between altitude of the source and the mouth of each second order drainage, with the length indicating possible nick points.

4.3. Basin asymmetry

The T-Index method identified a main direction of fluvial migration and a possible cause of this migration. An analysis of 417 second-order hydrographical basins (Fig. 7) showed drainage asymmetry in the ESE direction, with average T-Index of dislocation being 0.25 and largest asymmetry indices of the basins (T-Index > 0.5) well distributed between the units of the different geological domains (Fig. 8). The combined analysis of these basins with the structures selected from the isobase and HG curves shows a good correlation with structures oriented N–S $\pm 30°$ (46% for isobase and 41% for HG). Fig. 9 shows the migration of the Caeté River Basin from west to east. Being a fourth-order basin, it was not considered in the analysis of basin asymmetry but the migration is clearly visible, with deposits in terraces and coarse-grained conglomerates from the old river bed located in the west, and those of the current river bed in the east. The coincidence of the migration from west to east of the Caeté River and in the T-index draws attention to a possible tectonic cause.

4.4. Hypsometry

The results of hypsometric integral were compared against the structures selected from isobase and HG maps. Basins with younger hypsometric profiles are located mostly in the domain of igneous and sedimentary rocks of the Paraná Basin. Only two of these basins, out of a total of 41 classified, are within the domain of Precambrian rocks. These young basins seem to be related to ENE, NNE and WNW structures, which control the isobase and HG curves (Fig. 10). Mature basins occur mainly on Catarinense Shield rocks and on igneous rocks of the Serra Geral Formation. There is no correlation between these basins and preferential directions of isobase or HG lineaments. Older (senile) basins in the study area are mainly in the domain of Paleozoic sedimentary rocks of the Paraná Basin and show a good correlation with NNE and NE isobase lineaments and with NW and NNW HG lineaments.

4.5. Geomorphological characteristics

Geomorphological features that can be related to recent tectonic activity were identified and compared against isobase and HG lineaments (Fig. 11). The quantification of this data shows that, out of a total of 129

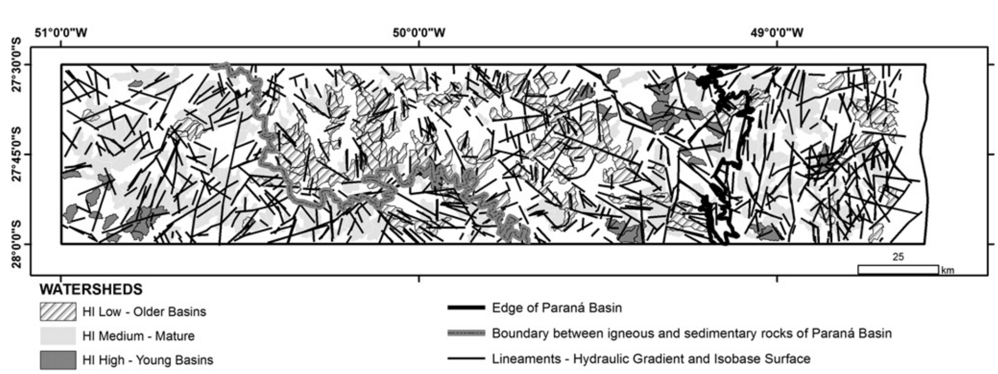

Fig. 10. Hydrographical basins considered old, mature and young, based on hypsometric integral values overlaid by isobase and HG lineaments.

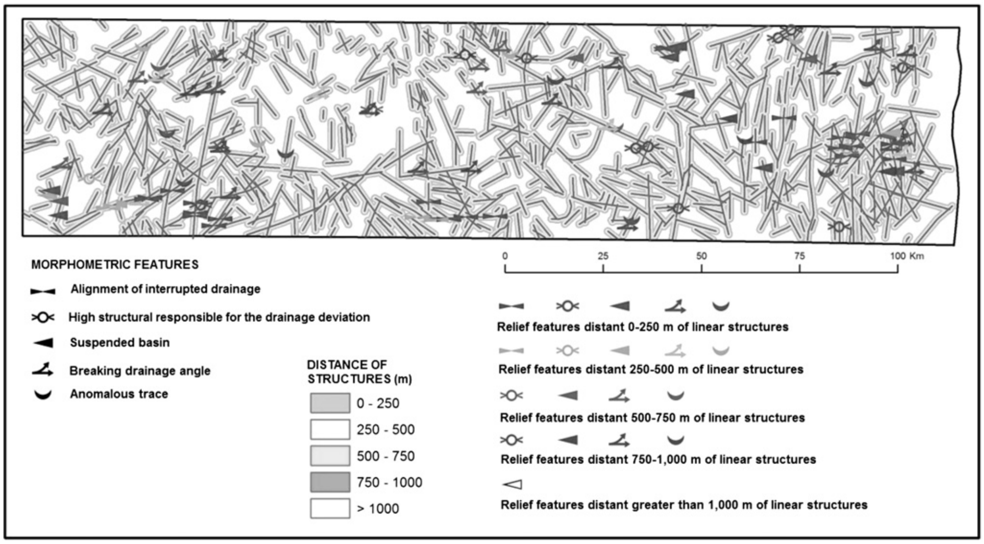

Fig. 11. Geomorphological features suggesting recent tectonic activities and their relationship with selected isobase and hydraulic gradient lineaments.

features indicated on the map, 81% of these are related to some lineament direction, considering a distance of up to 1 km. Out of these, 37% are related to the ENE direction and 31% to the NNE direction. It is important to observe that most of those anomalies are located in the same lithologies and sometimes they are aligned, showing they are not related to the differences in resistance of bedrock but with recent structures.

In an additional analysis relating these features to hypsometric data, out of 129 morphometric anomalies identified 17% occur in the basins with younger profiles, 67% in mature basins, and 16% in older basins. Considering that the area of occurrence of younger basins is only 9% of the total area and that 17% of the anomalies occur in these basins, the probability of occurrence of features related to neotectonic activities in these younger basins is 1.9 (17/9 = 1.9), whereas it is 1.1 (67/63 = 1.1) for mature basins and 0.6 (16/28 = 0.6) for older basins.

4.6. Structural and geomorphological field data

In the field, were observed fractures and faults with the presence of striations (slickensides) in soil (pedogenetic profile) at two different locations (3 and 15, Fig. 7). Those fractures (total of 35) are represented in Fig. 12A and the faults in Fig. 12B. Although the numbers of faults presents in soil are very small, only 5, they show a maximum main stress (σ1) near E–W (285°/10°) (Fig. 12C).

In the field, priority has been given to identify and characterize extensional structures (for example, T-Fractures or tension fractures), as these fractures are formed parallel to the maximum main stress (σ1) and perpendicular to the minimum main stress (σ_3). At outcrop 18 (Fig. 7) transcurrent, normal and oblique faults, with directions close to E–W were observed, along which there is oil migration (evidence of extensional structures). These structures affect sedimentary rocks of the Serra Alta Formation (Paleozoic - shale) and also a Mesozoic basic dyke. In the same outcrop were observed N–S faults but it was not possible to determine the relative chronology between the E–W structures and the N–S faults, as they cross-cut each other. These opposing relationships were interpreted as the result of reactivation of both families of faults and allow the suggestion of the presence of T-Fractures in the E–W direction.

Field work also confirmed the existence of morphometric anomalies previously identified on topographic maps. All 40 morphometric features selected for field inspection were coherent with the initial interpretation.

5. Discussion

Brittle deformations in transcurrent and extensional regimes present vertical traction (T) fractures. In compressional regimes, these same structures are horizontal and strike parallel to the main maximum stress (σ1) and perpendicular to the main minimum stress (σ3) (Fernandes, 2008). The probable E–W T-fractures within the Paraná Basin rocks, including those with oil migration, are coherent with a horizontal E–W maximum compressional axis σ_1 and a N–S minimum extensional stress σ_3, also horizontal. In the field the oil migration planes

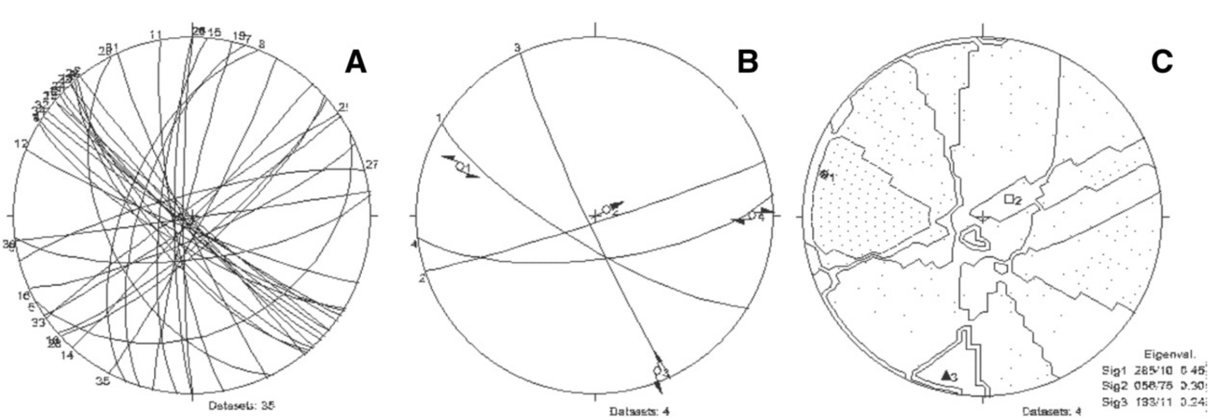

Fig. 12. (A) Great circle plots of fractures present in soil. (B) Angelier plots of five faults observed in soil. (C) Principal stress calculation based on five faults.

(E–W) are vertical, a situation which is compatible with tectonics developed in a transcurrent or extensional regime.

Prevalence of N–S structures observed in rose diagrams of isobase lineaments may be associated with the reactivation of the structures present in the basement rocks in the Catarinense Shield and which are reflected, partially, in the Paraná Basin sediment (Fig. 4). Dispersion of isobase and HG lineaments observed in the rocks of the Serra Geral Formation can be related to the columnar joint pattern of the basalts.

Analysis of hypsometric integral shows that the younger basins are mostly located in the western part of the study area within the domain of the igneous rocks of the Serra Geral Formation, and also in the central region within the domain of the sedimentary rocks of the Paraná Basin (Fig. 10). The main linear structures related to isobase and HG which affect these basins strike N–S (±30°), suggesting a compressional stress with an E–W (±30°) main axis. Another main direction is E–W (±30°) that could be associated with T-fractures.

The Transversal Topographic Symmetry method (T-Index) proved to be an excellent technique for analysing the origin of the asymmetry of the basins, whether of tectonic origin or caused by internal river processes (Fig. 8). In the studied region, there was an indication of asymmetry of the hydrographic basins from W to E, caused by tectonic movements, which were confirmed in the field by observing the migration of river channels eastwards.

The eastern portion of the study area, in the Catarinense Shield, shows a strong element of drainage asymmetry pointing ESE, also shown in the Paraná Basin rocks. However, the rose diagrams (Fig. 8) show greater dispersion for the rocks of the Catarinense Shield than for those of the Paraná Basin, a factor that could be related to the greater proximity of the eastern part of the area with the passive margin of the South American Plate which would have a stronger influence on the drainage network configuration.

The data collected in this study revealed the role played by compressive stresses in the area oriented E–W, suggesting a transpressive tectonic model. The compressive component could be related to the subduction of the Nazca plate under the South American Plate (Riccomini and Assumpção, 1999; Lithgow-Bertelloni and Guynn, 2004; Assumpção et al., 2011; Cogné et al., 2013).

According to Assumpção et al. (2011) all earthquakes in the sub-Andean region show reverse fault mechanisms, with the principal major compression (σ1) near E–W. The authors presented an updated compilation of earthquake focal map in Brazil and sub-Andean region and the few earthquake focal mechanisms near the study area are related to a compression near E–W.

6. Conclusions

Based on the data as discussed in this study, particularly when comparing the results obtained by morphometric techniques and those obtained in the field, the conclusions are:

1) Structures taken from isobase maps are coherent with a tectonic model of reactivation of N–S (±10°) structures, possibly related to the compression from west to east caused by the subduction of the Nazca Plate under the South American Plate;
2) Selected structures from the hydraulic gradient maps, representing the rocks of the Catarinense Shield, are coherent with this same model;
3) Geomorphological features identified in topographic maps have proved to be very useful as 'a guide to points to be visited in the field' and the index of correspondence between them and the observations in the field was 100%; this showed a correlation of 37% with ENE-trending structures and 31% with NNE-trending structures, occurring with greater frequency in the basins with younger hypsometric profiles;
4) Asymmetry of basins as analysed by the T-Index method proved to be compatible with the influence of an E–W compressive tectonic regime. This can be confirmed by the migration of river beds from west to east, and also by the greater dispersion of the asymmetry of the shield rocks, interpreted as a greater tectonic influence related to the passive margin of the South American Plate when compared to its active margin, where there is prevalence of a compressive tectonic regime;
5) Application of the hypsometric integral technique helped establish a correlation between the younger basins with structures trending N–S (±30°), suggesting the reactivation of the N–S, NE and NW trending structures of the Paraná Basin, and structures trending close to N–S of the Santa Catarina Shield.

It is also possible to suggest for the study area a modern stress field with SH_{max} oriented close to E–W, with a sub-horizontal compression axis and N–S SH_{min} also sub-horizontal. Faults close to N–S are attributed to the compressive tectonic interaction between the Nazca and South American plates, and the faults around E–W are interpreted as extensional structures reactivated by the expansion of the Mid-Atlantic ridge, configuring a tectonic context of structures developed in a transpressive regime.

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