Jurassic–Cretaceous deformational phases in the Paraná intracratonic basin, southern Brazil

Abstract

This paper examines the domes and basins, regional arcs and synclines, and brittle structures in upper units of São Bento Group (of the Paraná Basin) flood volcanism to characterize the deformational phases in its Jurassic to Cretaceous history. Geometric, kinematic and dynamic structural analyses were applied to define. First-stage fieldwork revealed brittle structures, extensional joints, and strike-slip faults, and second-stage fieldwork investigated the connections of the brittle structures to both open folds and dome-and-basin features. Fault-slip data inversion was performed using two different techniques to distinguish local and remote stress/strain. Geometric and kinematic analyses completed the investigations of the deformation, which characterized two deformational phases for the Jurassic to Cretaceous periods in the Paraná Basin. Both developed under regional bi-directional constrictional ($\sigma_1 \geq \sigma_2 >> \sigma_3$) stress regimes that produced a number of non-cylindrical folds. The D1 deformational phase produced the N–S and E–W orthogonally oriented domes and basins. The D2 arcs and synclines are oriented towards the NW and NE and indicate a clockwise rotation (35–40°) of both horizontal principal stress tensors. Stress/strain partition in elongated domes or basins controls lower scale structural elements distribution. The extensional joints and strike-slip faults characterize the local stress field in the outer rim of the orthogonally buckled single volcanic flow, whereas the inner rim of the buckled single flow supported constriction and thus, developed the local arcuate folds. Fault-slip data inversion was performed using two different techniques to distinguish local and remote stress/strain. The strike-slip is then a local scale stress regime, resulting from stress drop after the onset of extensional joints (orthogonal dykes patterns) in the outer rim of domes or basins.
1 Introduction

The Paraná Basin is located in the South America Plate (Fig. 1) and is characterized as a huge Paleozoic to Mesozoic intracratonic depression filled by sedimentary and volcanic rocks (see Zalán et al., 1991; and Zalán, 2004 for a revision on stratigraphy and tectonic subjects). The upper stratigraphic sequences (São Bento and Guará groups) occupy c.a. 80% of the basin area. The São Bento Group is mainly composed by Serra Geral Formation, which contains the volcanic rocks of the well-known Paraná–Etendeka Flood Basalt Province (Wilson, 1989).

However, the regional stratigraphic correlation and facies change for the uppermost sequences in the Paraná Basin (São Bento Group) remain controversial, since Scherer and Lavina (2006) correlated the Pirambóia Fm. with Neo-Permian sedimentary units, while Soares et al. (2008a) correlated it with Neo-Triassic to Jurassic sedimentary units. The regional isopach maps for the Mesozoic sedimentary sequence (Artur and Soares, 2002; Soares et al., 2008b) fit well with the results presented here. Thus, the proposition by Soares et al. (2008a) is adopted to characterize the Jurassic–Cretaceous stratigraphic interval of the Paraná Basin. As a result, the São Bento Group is considered to comprise the Pirambóia and Guará (Eo to Meso-Jurassic), Botucatu (Neo-Jurassic), and Serra Geral (Cretaceous) formations (Soares et al., 2008a). The Serra Geral Formation is mainly composed of volcanic rocks, well known as the Paraná–Etendeka Flood Basalt Province (Wilson, 1989).

The main structural features of the Paraná Basin were recognized using satellite imagery lineaments and fault plane trends (e.g., Soares et al., 1982; Zerfass et al., 2005; Reginato & Strieder, 2006; Strugale et al., 2007; Machado et al., 2012; Nummer et al., 2014; Jacques et al., 2014), geophysical lineaments (e.g., Ferreira, 1982; Ferreira et al., 1989; Quintas, 1995), or isopach maps developed for each sedimentary sequence (e.g., Northfleet et al., 1969; Artur and Soares, 2002). The main findings include regional lineaments, arcs, and flexures (Fig. 1) that have been summarized by Almeida (1981), Zalán et al. (1991), and Zalán (2004). These
authors also highlighted the influence of the basement on the development of these structural features in the Paraná Basin. These regional-scale structural features deform the entire Paraná Basin sequence and do not depend on the stratigraphic interpretation of the uppermost sequences.

Riccomini (1995) conducted the first paleostress investigation of the uppermost stratigraphic units of the Paraná Basin by applying the method of Angelier and Mechler (1977). Due to the large predominance of the lateral fault-slip data, Riccomini (1995) adopted a strike-slip stress regime to distinguish a number of deformational phases from the Permian units of the Paraná Basin through to the Holocene continental margin rift basins (Table 1) by applying the method of Angelier and Mechler (1977). The main criterion used to distinguish the deformational phases was, then, to separate fracture direction families with compatible sense of movement. These assumptions and procedures, Riccomini (1995) interpreted these deformational phases by considering transcurrent regimes, mainly due to the large predominance of striae parallel to the fault strike and were based on propositions suggesting differential movements during South American and African plate rotation after Gondwana rifting (Morgan, 1983; Chang et al., 1992; Riccomini, 1995).

Recent publications also adopted a strike-slip stress regime, following the proposition of Riccomini (1995). Strugale et al. (2007) distinguished two deformational phases in the Jurassic and Cretaceous of the Ponta Grossa Arc region. These deformational phases can be correlated to D_{n+1} and D_{n+2} described by Riccomini (1995). Similarly, Machado et al. (2012) and Nummer et al. (2014) distinguished three deformational phases in the high hills of the Torres Syncline. These phases can also be correlated with the D_n, D_{n+1}, and D_{n+2} phases proposed by Riccomini (1995).

Heemann (1997, 2005), Reginato (2003), Acauan (2007), and Amorim (2007) also applied the Angelier and Mechler (1977) method to fault slip data from volcanics and interlayered aeolian
sandstones of the Serra Geral Fm. **However, these works**, which involved a geometric and symmetry analysis of fault slip data, enabled deformational phases to be distinguished. Consequently, Heemann (1997, 2005), Reginato (2003), Acauan (2007), and Amorim (2007) distinguished two deformational phases: i) a NS and EW oriented stress field, and ii) a NW and NE oriented stress field; however, they could not determine which of these was the first. **However, some of the observed structural features do not equate for a strike-slip stress regime.** Strieder and Heemann (1999) and Reginato and Strieder (2006) highlighted the NS–EW orthogonal pattern of the sandstone dikes and mineralized veins emplaced into the basalts. Heemann (1997, 2005), Reginato (2003), Acauan (2007), and Amorim (2007) also identified areas with opposite positioning of the maximum and minimum stress axes (Table 2), although their findings were difficult to interpret. Therefore, these results **were under evaluation** need to be investigated further using additional fieldwork for fault slip data, and fault geometry analysis and arcuate fold analysis were carried out. The present paper aims to demonstrate that a bi-directional constrictional stress state regime was active during Jurassic (Botucatu Fm.) and Cretaceous (Serra Geral Fm.) periods in the Paraná Basin. This study aimed to report the results of a large-scale structural analysis survey conducted within the Serra Geral and the underlying Botucatu formations. An analysis of the brittle structures focused mainly on stress inversion techniques applied to fault slip data from volcanic rocks in order to distinguish the different phases of deformation and evaluate the paleostress field during the Jurassic to Cretaceous periods. The paper presents a geometrical and kinematical analysis of mesoscale faults (10–100 m long) investigated at 42 sites ( quarries and large road cuts) located within the central region and eastern border of the Paraná Basin. This stress state regime was determined by means of structural analysis techniques from e symmetry, geometric, kinematic and dynamic
analysis incorporate to constrain their times of occurrence, a number of local and regional structural elements used to characterize these deformed phases: fault plane, slip direction and sense, type of kinematic indicator, fault splay geometry, fracture opening and infilling, large-scale folding and dome and basin features, and the basal contact of the Botucatu and Serra Geral formations.

The structural analysis follows Turner & Weiss (1963, p. 3-11). The geometric analysis is developed for outcrop and regional scale folds, domes and basins, and also for fractures (joints and faults). The kinematic analysis is based on paleostress inversion, but its results are reconciled with geometry and symmetry of fractures. The dynamic analysis of the deformation integrates geometric and kinematic analyses for both folds and fractures, in order to define the deformational regime, the structural relationships between folding and fracturing, and, finally, stress drop and tensor permutation, and the development of orthogonal joint pattern.

The paper also discusses the stress state regime tectonic conditions within which the paleostress axis inversion operated and the orthogonal joint pattern developed. In this way, the dynamic analysis discusses the operation of local and far (remote) stress field in development of the structural elements. Orthogonal joint formation and its associated stress inversion remain subjects of discussion, and a number of mechanisms have been proposed to account for the local and regional deformational features (see Caputo, 1995; Caputo and Hancock, 1999; Bai et al., 2002). Based on these elements, the mesoscale fault geometries and fault-slip data of the rocks of the Serra Geral Fm. have been shown to be reliable indicators of the distribution of the local paleostress state in the Paraná Basin during the Jurassic to Cretaceous periods.
2 Fieldwork and structural analysis methods

The fieldworks were carried out in three research stages to The regularities of the preliminary paleostress fields recorded structural features in the volcanic rocks and intertrap sandstones of the Serra Geral Fm., and in the Botucatu Fm. sandstones, mainly at the contact of these formations. The investigated structural features include: fault plane, slip direction and sense, type of kinematic indicator, fault splay geometry, fracture opening and infilling, fold of different scales and dome-and-basin features, and the basal contact of the Botucatu and Serra Geral formations—at different sites inspired a second stage of fieldwork, which involved both revisiting previous sites to obtain a more complete structural study and surveying new sites in the southern Paraná Basin.

A third stage of fieldwork was performed to characterize the gentle folds and dome-and-basin structures developed within the Botucatu and Serra Geral formations. The procedure for characterizing such structures involved their identification from satellite imagery or aerial photographs, followed by fieldwork to measure the sandstone–basalt contact orientations, or the basal surface of a given basalt flow. The significance of fault-slip data on this study makes necessary to show explicitly i) the field analysis for splaying Riedel fractures geometry and symmetry and the recorded type of striae, and ii) the paleostress technique used for fault-slip data inversion.

2.1. Fieldwork methods for brittle structures

The structural-geological studies were undertaken brittle structural features were investigated in open-pit quarries, underground openings, and large road cuts (mesoscale faults: 10–100-m long). This investigation were carried out of the brittle structures from the in 42 sites, and involved analysis of the slip direction and sense of movement of more than 800 fault planes.

To ensure the confidence of the results, only those records with a clearly defined slip sense
were sampled for the computation of the paleostress fields. Brittle structures were recorded in basalts, andesites and dacites of the Serra Geral Fm., since kinematic indicators are best preserved in these lithologies. Field investigations also included geometrical data records based on fracture splaying (Fig. 2). Fracture splaying shows patterns similar to synthetic and antithetic fractures developed during shear experiments (e.g., Tchalenko, 1970; Tchalenko and Ambraseys, 1970). Most fracture patterns exhibit open spaces and at least one of those fractures is mineralized. Mineralization is composed of carbonate, chalcedony, and zeolites, or a combination of carbonate + chalcedony + celadonite. The fracture patterns, and mineralization of dilatational spaces and sandstone dikes can be observed on different scales, but their geometric relationships are more easily distinguished on the outcrop scale. A field diagram was developed to compile and record different fracture patterns (Fig. 3).

Kinematic indicators include a variety of types, but frictional steps and the accretionary growth of crystal fibers (Hancock, 1985), and RM and TM types of secondary fracture steps (Petit, 1987) largely predominate (Fig. 4). Some fault planes display different slip striations and movements, and occasionally crosscutting (truncation) relations could be recorded (Fig. 4B). The truncation between different striations in the same plane suggests their age relation (Table 3). A rare melted and polished fault plane with slip striae is shown in Fig. 4C and ductile drag deformation of the horizontal joints can be observed in Fig. 4D in the basaltic rock with the development of a fracture cleavage.

2.2. Methods for evaluation of deformational phases in the Serra Geral Fm.

The first approximations for paleostress regimes in the volcanic rocks of the Paraná Basin used the graphical method described by Angelier and Mechl (1977). This graphical method superposes P and T dihedrals for each element of fault-slip data, which allows paleostress
regimes to be distinguished by grouping compatible fracture splay geometries and fault slip data.

In the second phase of the paleostress analysis, the above graphical method was combined with two numerical stress-inversion techniques (Žalohar and Vrabec, 2007, 2008), by means of the T-TECTO 3.0 program (http://www2.arnes.si/~jzaloh/t-tecto_homepage.htm) developed by Dr. Jure Žalohar. The Gauss method is an inverse-method that is applied to define paleostress (Žalohar and Vrabec, 2007), whereas the MSM is used as the direct kinematic paleostrain method (Žalohar and Vrabec, 2008). The parameters for stress inversion by MSM are shown in Table 4.

The Gauss method was applied site-by-site to limit the fault-slip data numbers and to evaluate local heterogeneities in the paleostress regimes of the Paraná Basin volcanic rocks. It is important to note that the Gauss method can distinguish between heterogeneous fault-slip data, as is the present case (two superposed deformational phases). The separation of paleostress regimes from heterogeneous fault systems is tedious. In the present case, the complete fault-slip data sets were tested by applying the Gauss method described by Žalohar and Vrabec (2007). This method defines a Gaussian compatibility function based on the adjustment measure between the angular misfit and the normal to the shear stress ratio on the fault plane. The Gauss method proposed by Žalohar and Vrabec (2007) can distinguish between heterogeneous fault-slip data, as is the present case.

Then, the Gauss method was applied site by site to limit the fault-slip data numbers and to evaluate local heterogeneities in the paleostress regimes of the Paraná Basin volcanic rocks. In order to obtain numerically stable results, the fault-slip data of some sites were merged based on their proximity, fault-slip consistency, geometry, and fault pattern. The merged fault-slip data represent small areas of the Paraná Basin under homogeneous stress/strain...
conditions. These fault-slip data were then reprocessed and the results used for the structural analysis discussion.

The stress inversion was performed using the T-TECTO 3.0 program (http://www2.arnes.si/~jzaloh/tecto_homepage.htm) developed by Dr. Jure Žalohar. The paleostress/paleostrain regimes were determined using the Gauss method and kinematic multiple-slip method (MSM) (Žalohar and Vrabec, 2008). The MSM calculates weighting factors for moment tensor summation based on the number and orientation of parallel faults of the same size range, direction of slip along them, and the mean rock properties. The parameters for stress inversion by MSM are shown in Table 4.

The reduced tensors calculated by these methods can be interpreted either as the stress or strain tensor. The Gauss method is an inverse method that is applied to define paleostress (Žalohar and Vrabec, 2007), whereas the MSM is used as the direct kinematic paleostrain method (Žalohar and Vrabec, 2008).

3 Regional structural features in the Jurassic–Cretaceous units of the Paraná Basin

Figure 1 shows some structural features that affect the stratigraphic units of the entire Paraná Basin; however, some are of particular interest with regard to the Jurassic–Cretaceous interval because it will be shown here that they were developed during the deformational phases.

The most prominent structures are the large-scale anticlinal and synclinal gentle folds in the eastern border of the Paraná Basin (Fig. 5), which show NW-dipping hinges (see Zalán et al., 1991). Erosion of the anticlines created the area in which the volcanic and sedimentary rocks of the Paraná Basin are exposed towards the NW, and gave rise to the Rio Grande and Ponta Grossa arcs. However, the folds are not cylindrical, but produce elliptical domes and basins (details in Fig. 5).
The presence of large domes in the Serra Geral volcanics has long been reported (e.g., Lisboa and Schuck, 1987; Schuck and Lisboa, 1988; Rostirolla et al., 2000). Similar structures were also described for underlying sedimentary sequences (Riccomini, 1995). Close examination of these structural features reveals that they are an association of gentle domes and basins, which can be classified into two groups based on orientation: a) those with N–S or E–W orientation, and b) those with NW or NE for the longest axis direction orientation. Some examples of such domes are indicated in Fig. 5: a) Quaraí Dome, b) Rivera Crystalline Island, and c) Aceguá Crystalline Island. The longest axis of these domes is <100 km. The Quaraí Dome shows a NE orientation of its longest axis, while the Rivera and Aceguá crystalline islands exhibit EW orientation. Aboy and Masquellin (2013) presented some structural and sedimentary evidence supporting the uplift of the Rivera Crystalline Island from the Permian period onwards.

The basal contact of the Serra Geral Fm. volcanic rocks was measured in a number of outcrops to constrain the deformation related to the NW-dipping anticlines–synclines (Fig. 5A). Figure 5B shows that the axes of these continental-scale gentle folds are oriented towards 06/308. A balanced SW–NE structural section (Fig. 6) illustrates the relationships between the anticlines–synclines from Uruguay to São Paulo (Brazil). This regional cross section was balanced as concentric folds (Marshak and Mitra, 1988; pp. 269–302).

Structural mapping was conducted in the Quaraí Dome area, close to the Brazil–Uruguay border (Fig. 7A). In this area, the erosion of volcanic flows over the Botucatu Fm. sandstones allows a number of domes and basins with different orientations to be recognized. The most important of these is the Quaraí Dome, because it has the greatest amplitude and it exposes the underlying Botucatu Fm. sandstone. Measurements of the sandstone–basalt contact show that the Quaraí Dome is oriented towards 02/043 (Fig. 7B).
North and northwest of the Quaraí Dome, two elongated basins (N–S and E–W, respectively) can be recognized (Fig. 7A). The attitudes of the thin volcanic flows are shown for the E–W-dipping (Fig. 7C) and N–S-dipping (Fig. 7D) long axes for both basins. The N–S-oriented folds were also recognized on the outcrop scale (Fig. 7E). This fold is developed upon the Botucatu Fm. sandstone and it was identified in the inner part of the Quaraí Dome along the BR-293 road. The eolian stratification was deformed around an 11/176 folding axis (Fig. 7F).

The map in Fig. 7A shows that the domes and basins with the same orientation do not interfere with each other. The folds are described as non-cylindrical and arcuate in map view. The fold tightness varies from gentle (interlimb angle: 170° for small domes and basins, 151° for the Quaraí Dome, and 159° for regional arcs) to open fold (interlimb angle: 120° for the N–S outcrop fold).

4. Paleostress tensors in the Serra Geral Fm. volcanic rocks

The results of the fault-slip data processing are presented in a sequence of figures for each site/area (Figs. 8 and 9). The figures include the Wulff projection (lower hemisphere) of the brittle fault-slip data, misfit angle histogram, unscaled Mohr diagram for resolved stress on the faults, and a diagram relating the values for the object function (M) and shape of the strain ellipsoid (D). The object function depends on the parameters defined in Table 4, and relates the standard deviation (s) of angular misfit between the direction of slip along the faults (striae) and the shear stress produced by a given tensor. Therefore, its value is used to determine the best orientation of stress tensor for those fault-slip data (Žalohar and Vrabec, 2007).

The structural analysis performed on the Serra Geral Fm. volcanic rocks (Paraná Basin) distinguished two different paleostress fields:
a) Predominantly N–S-oriented maximum horizontal stress with permutations to the E–W;

b) Predominantly NE–SW-oriented maximum horizontal stress with permutations to the NW–SE.

In both cases, the intermediate principal stress ($\sigma_2$) is subvertical, which explains the prevalence of strike-slip faulting. The crosscutting relations between striations (Table 1) indicate that the N–S maximum horizontal stress is older than the NE–SW stress. This interpretation is also consistent with other structural features such as the elliptical domes.

These general orientations for the NE–SW (NW–SE) stress tensors agree with those presented by Riccomini (1995), Strugale et al. (2007), Machado et al. (2012), and Nummer et al. (2014). They differ, however, on processing methodology and kinematic analysis. It should be noted that the area studied by Riccomini (1995) and Strugale et al. (2007) is heavily influenced by the NW–SE Ponta Grossa faults and dikes. Despite final results that are difficult to reconcile, it seems that the D1 faults (deformation) defined by Strugale et al. (2007) correspond to the D2 deformational phase discussed here.

4.1. Predominantly N–S-oriented maximum horizontal stress with permutations to the E–W

The maximum ($\sigma_1$) and minimum ($\sigma_3$) compressive paleostresses are subhorizontal (Fig. 8). These main paleostress axes are oriented close to the N–S and E–W directions and in most cases, the stress ratio ($\Phi$) ranges from 0.10–0.30. The mean misfit angle of the fault-slip data for each site/area is $<15^\circ$ (see Fig. 8), while the standard deviation is $<20^\circ$ (see Table 5). These conditions suggest a strike-slip regime and the observed fault-slip data indicate the presence of conjugate patterns of faults (Fig. 8).
This group of tensors shows the permutations of the maximum ($\sigma_1$) and minimum ($\sigma_3$) compressive paleostress axes between the N–S and E–W directions. In Fig. 8(A, B, E, and G), the maximum compressive ($\sigma_1$) paleostress axis is close to the E–W direction, whereas in Fig. 8(C, D, F, H, and I), the maximum compressive ($\sigma_1$) tensor is close to the N–S direction. Such results, recorded in the CODECA quarry (Fig. 6G and 6H), were initially intriguing and demanded a careful re-investigation of the fault-slip at this site. The alternated orientation of the maximum paleostress axis was observed at other sites/areas within the Paraná Basin volcanic rocks. Furthermore, the alternation of the stress tensor occurs in some tectonic regimes (Angelier, 1989) and this aspect will be considered later.

4.2. NE–SW maximum horizontal compression

This group of paleostress tensors is also related to the subhorizontal maximum and minimum compressive stresses, while the intermediate stress axis ($\sigma_2$) is subvertical (Fig. 9). The maximum horizontal compressive stress is oriented close to NE–SW and the stress ratio ($\Phi$) ranges from 0.10–0.30. These conditions also suggest a strike-slip stress regime and the presence of a conjugate pattern of faults (Fig. 9).

The mean misfit angle of the fault-slip data for each site/area is close to 15° (see Fig. 7) and the standard deviation is <18° (see Table 6). Table 6 summarizes the results of the stress inversion for this fault-slip data set.

The paleostress tensors also indicate the permutations between the maximum ($\sigma_1$) and minimum ($\sigma_3$) compressive stress axes from the NE–SW to NW–SE directions in some sites/areas (Santa Rita quarry) (see Fig. 9A–F).

5. Geometric and kinematic analyses of deformational structures in the volcanic rocks
The regional-scale folds (Fig. 5) and the domes and basins (Fig. 7) discussed in the previous sections show systematic relationships with the fracture patterns (Figs. 8 and 9). Thus, the deformational structures developed within the volcanic rocks of the Serra Geral Fm. are analyzed considering the fracture patterns.

The geometric and kinematic analyses of fracture patterns use rose diagrams to classify conjugated and splay fractures observed in each site/area, because the strike-slip stress regime developed subvertical to vertical fractures. This procedure makes it possible to distinguish the synthetic and antithetic fractures and to determine the mean \( \phi \) (internal friction angle; see Jaeger, 1969; Angelier, 1989).

### 5.1. Fracture patterns of N–S paleostress tensors

The fracture patterns developed in the N–S maximum horizontal compression clearly indicate conjugate geometry, as can be seen in Fig. 10. However, it is clear that dextral and sinistral conjugate sets show different spatial distributions (orientations) and frequency.

The rose diagrams in Fig. 10 show fracture orientations according to the synthetic Riedel fracture criteria (Tchalenko 1970) and reinforce the field observations (Fig. 2). The rose diagrams indicate the predominance of R-type fractures and some diagrams illustrate the presence of fractures at angles lower than 15–20° relative to the main compressive stress axis \((\sigma_1)\). These fractures are classified as hybrid joints (Hancock, 1985).

R-type fractures usually merge with C-type fractures to develop splay or duplex fracture patterns, and hydraulic breccia are often associated with such dilatational spaces. The dilatational space is filled by a zeolite ± quartz ± chalcedony ± calcite ± celadonite paragenesis.

The geometric and kinematic analyses of the N–S-directed paleostress field also consider the occurrence of tabular dykes of thermally metamorphosed sandstone emplaced into the
vesicular basalts (Fig. 11A) of the Serra Geral Fm. sequence. A detailed field survey of their orientation was undertaken in the Salto do Jacuí region. Figure 11B shows that these tabular dykes are predominantly subparallel to the maximum compressive stress axis ($\sigma_1$) when it is oriented either to the N–S or to the E–W.

In the Caxias do Sul region, the thermally metamorphosed sandstone tabular dykes were measured cutting across the massive basalts of the Serra Geral Fm. Figure 11C shows that such dykes are also oriented to the NE–SW; however, they still show the main distribution in the N–S and E–W directions. In the Caxias do Sul region, a large number of mineralized veins were measured. Figure 11D shows that opened fractures are mainly oriented in the N–S, E–W, and NW–SE directions.

The orientation of metamorphosed sandstone dykes in the Salto do Jacuí and Caxias do Sul regions are slightly different. For the Salto do Jacuí region, the preferred orientation is N10E, whereas in the Caxias do Sul region, it is N10W. However, such differences are in accordance with the local stress field orientations, as can be seen in Fig. 8(C, D, E, G, and H).

The sandstone dykes and mineralized veins cutting across the basalts are controlled by an orthogonal pattern of fractures. This observation agrees with the permutations of the maximum ($\sigma_1$) and minimum ($\sigma_3$) compressive paleostress axes between the N–S and E–W directions, as reported above.

This orthogonal pattern (N–S and E–W) is also observed in the Cerro do Jarau giant intertrap dune (Remde, 2013). The orthogonal pattern in the Cerro do Jarau area (Fig. 7A), however, is defined by centimeter-scale veins in the basalts (Fig. 12A), and mainly by millimeter-scale deformation bands in the intertrap Botucatu Fm. sandstone (Fig. 12B). The centimeter-scale veins in the basalts display a “ladder” pattern, or an H-shaped abutment (Hancock 1985), where the N–S veins are longest. In contrast, the deformation bands display a “grid” pattern with mutual crosscutting relationships (Rives et al., 1994). The orthogonal deformation bands...
are crosscut by shear deformation bands (Fig. 12C), suggesting an initial onset of extensional joints, followed by shear. Figure 12(D and E) shows the rose diagrams for the orthogonal patterns in the basalt and sandstone, respectively, in the Cerro do Jarau area.

5.2. Fracture patterns of NE–SW-directed paleostress field

The geometry of the fractures formed in the NE–SW-directed paleostress field shows an asymmetric distribution for the dextral and sinistral conjugated branches (Fig. 13). This asymmetric distribution of fracture orientation frequency allows them to be classified according to the Riedel shear criteria. However, the fault-slip data for the NE–SW paleostress field show that higher frequency Riedel fractures vary between sites, being classified as either R-type, C-type, P-type, or even hybrid fractures.

The rose diagrams for the NE–SW paleostress field are in accordance with field observations of fracture splaying. The R- and C-type fractures usually merge into one another to produce both dextral or sinistral splayed fractures and duplex strike-slip patterns. Such fracture patterns are the locus for mineralization. Fracture surfaces and open dilatational spaces are coated by celadonite ± chalcedony ± calcite. Hydraulic breccias are also recognized, but with minor frequency.

Some rose diagrams in Fig. 13 indicate the presence of extension to the hybrid joints (Hancock, 1985) and additionally, Fig. 13(E and F) suggests the development of the orthogonal fracture pattern in this second deformational phase. In the Cerro do Jarau giant intertrap dune (Fig. 7A), the N–S orthogonal deformation bands are also superposed by “grid” patterns of orthogonal NE–SW deformation bands (Fig. 14A). Careful measurement and evaluation of the orthogonal patterns at a number of outcrops permitted the construction of a rose diagram for this second generation of deformation bands (Fig. 14B). The dispersion of
the orthogonal NE–SW deformation bands also suggests the interplay of extensional and hybrid joints.

6. Stress/strain regime

Analysis of the deformational phases

The paleostress analysis distinguished two different deformational phases in the upper units of the São Bento Group Serra Geral Fm. volcanic rocks (Paraná Basin). The relative ages of the deformational events were established from field observations (Table 1), regional-scale folds (Fig. 5), and domes and basins (Fig. 7). The N–S-oriented stress field was assessed as being older than the NE–SW-oriented stress field deformational phase during the Jurassic to Cretaceous periods.

The regional-scale folds and the dome-and-basin features (Figs. 5 and 7) were shown to pertain to two distinct groups: i) those with N–S and E–W elongations, and ii) those with NE and NW elongations. These directions are closely related to that determined for the orthogonal fracture patterns and faults in the previous sections. Considering Figs. 5, 7–10, 12, and 13, it can be established that a relationship of symmetry exists between the fractures, faults, and folds of the elongated domes and basins. Thus, the association between buckling processes and brittle deformation will be further analyzed to define their relationships and role in each deformational phase.

6.1. Folds vs fracture patterns relationships

The presence of gentle domes and basins with their longest axes oriented in orthogonal directions (Section 3) suggests a regime of bi-directional compression ($\sigma_1 \sim \sigma_2 > \sigma_3$). Gosh and Ramberg (1968) and Gosh et al. (1995) performed experimental investigations into the development of domes and basins under constrictional deformation. The Serra Geral Fm. field data recorded for São Bento Group upper formations do agree with experimental results in
that: i) domes and basins are elongated in orthogonal directions (Fig. 7A); ii) domes and basins of the same deformational phase do not interfere with each other, but merge or abut without crossing (Fig. 7A); and iii) the orthogonal fracture patterns and deformation bands are set parallel and perpendicular to the elongated fold hinge (Fig. 15).

Figure 15 summarizes the symmetry relationships between local and regional scale arcuate folds and fractures (joints and faults). It includes field records and results (Figs. 7–14) for the entire investigated area. These symmetry relationships support the development of fractures as consequence of arcuate fold formation in a bi-directional stress state regime.

6.2. Stress/strain analysis for deformational phases

A constrictional deformation regime is usually characterized by a stress difference ratio close to 1 ($D = \Phi \sim 1$). It is common practice to evaluate the stress state from the stress ratio ($D = \Phi$; Angelier, 1989) and Fig. 16A shows a histogram based on the results of the linear inversion method (Gauss method; Žalohar and Vrabec, 2007). It can be seen that the D ratio shows a wide dispersion for the first deformational phase, varying from 0.8 (area C), to 0.0–0.3 in most of the studied sites.

The stress state for each deformational phase can also be evaluated on the diagram proposed by Lisle (1979). This diagram (Fig. 16B) shows that the stress tensors for each site/area are distributed in a linear pattern. This pattern suggests that the main stress difference ($\sigma_1 - \sigma_3$) remains approximately constant, while $\sigma_2$ encompasses most of the variation. The N–S-oriented stress field varies from a multidirectional stress field ($\sigma_1 > \sigma_2 >> \sigma_3$), towards a field where the major stress tensor is greater than the other two ($\sigma_1 >> \sigma_2 \geq \sigma_3$). The NE–SW-oriented stress field, however, is constrained to the field where the major compressive tensor is greater than the other two.
The Morris and Ferril (2009) diagram analyzes the slip tendency of rock mass discontinuities in terms of effective stress; i.e., the diagram can distinguish the influence of fluid pressure (Fig. 16C). The first deformational phase (N–S paleostress) plots in two separate parallel lines of constant slip tendency (Ts = 1.3 and 1.5). These two parallel lines suggest the varying influence of the intermediate stress tensor (σ₂) on the deformation. However, the second deformational phase (NE–SW paleostress) data correlate with a linear equation whose angular coefficient is >-1.0, which shows the influence of variations of both the σ₁ and σ₂ tensors on the deformation.

The fault-slip data inversion also allows the strain condition of the deformational phases to be evaluated (e.g., Marrett and Allmendinger, 1990; Cladouhos and Allmendinger, 1993; Žalohar and Vrabec, 2008). Figure 17 shows the logarithmic diagram for strain ratio derived from the Gauss Method (Žalohar and Vrabec, 2007), and from the MSM (Žalohar and Vrabec, 2008). The MSM allows the strain ratio to be determined from the total displacement gradient tensor of all measured fault sets, weighted by the number of faults in each set, number of fault sets (their symmetry), and resolved shear stress (Žalohar and Vrabec, 2008).

The MSM strain values were defined by varying slightly the coefficient of residual friction (φ₂) in the T-Tecto program. Such a procedure brought closer adjustment of the stress (Gauss) and strain (MSM) tensors, because the axis of rotation is closer to a main tensor. Tables 5 and 6 show that the coefficients of residual friction (φ₂) determined from both the Gauss and MSM inversion techniques are largely similar. The greatest difference in friction coefficient (7–10°) is related to those sites/areas with a small number of fault-slip data, or asymmetric fault-slip sets.

Figure 17A represents the strain derived from the linear inversion technique and shows that deformation was developed under constrictional conditions. This result is consistent with the remote stress field, as discussed above. However, the strain ratio determined from the MSM
shows that both deformational phases could be distinguished based on this parameter, but follow a flattening strain path (Fig. 17B). This flattening strain path results from a local stress field, because most of the investigated sites for fault-slip data inversion represent a single outcrop. However, it must be noted, on the other hand, that the flattening strain path (Fig. 17B) is consistent in the volcanic rocks of the Paraná Basin, even for sites combining two or more outcrops (see Žalohar and Vrabec, 2008). The highest \( (\varepsilon_2 - \varepsilon_3) \) MSM strain ratio is achieved in those sites where conjugated faults or symmetric fault sets are best developed (see Fig. 13). Additionally, the flattening strain path is best developed for the second deformational phase, which could be a consequence of the higher degree of fractures inherited from the original basalt flows and the first deformational phase.

The strain–ratio diagrams indicate a bi-directional constrictional deformation of the Paraná Basin for both phases. However, a deformational model must be developed to account both for the remote and local stress/strain fields and for the observed fracture patterns.

### 6.3. Deformational model and the orientation of main horizontal stress tensors

The deformational structures under investigation were developed upon both upper formations of the São Bento Group the basalts to dacites of the Serra Geral Fm. (Paraná Basin). The volcanic flows are dominantly massive, show large lateral extensions and are usually more than 20 m thick (>20 m) (Heemann, 1997, 2005; Reginato, 2003; Acauan, 2007; Amorim, 2007). Thus, the buckling deformation must have been produced by a tangential longitudinal mechanism (Ramsay, 1967, p. 391–415) and the neutral surface must have played an important role in local strain partitioning and the development of the local scale structures. Figure 18, based on the discussion by Lisle (1999),
summarizes a geometric model relating bi-directional constrictional domes and basins, orthogonal fracture patterns, deformation bands, and conjugated faults.

The relations of symmetry of joints and faults to folds have long been investigated (e.g., Stearns, 1978; Hancock, 1985; Cosgrove and Ameen, 1999). The geometry of the domes and basins in the Paraná Basin volcanics (Fig. 7) has to consider bi-directional constriction in which both the major and intermediate (σ₁ ≥ σ₂) remote tensors are horizontal. The buckling mechanism operating simultaneously in the orthogonal direction gave rise to a local flattening strain field in the outer part of the single flows, and open orthogonal extensional joints (Fig. 18). The fault-slip data, orthogonal joints, veins, and deformation bands were measured at the outcrop scale and then developed to the outer buckled rim of each single volcanic flow of the Paraná Basin Serra Geral Fm.

The elongation ratio and orientation of the greatest axis of the domes and basins (arcuate folds) control stress/strain partition and orientation at this scale. Then, at domes and basins scale, σ₁_{db} orient parallel to the shortest axis, while σ₂_{db} orient parallel to major axis. The local flattening field in the outer rim of dome and basin, however, implies a third order stress/strain partition (σ₁_{lo} \gg σ₂_{lo} \geq σ₃_{lo}). Both these conditions explain the main stress/strain tensor permutation recorded in Figures 8 and 9 (Section 4): a) NS and EW (D₁), and ii) NW and NE (D₂).

Their gentle interlimb angles of folds do not suggest large departures between the orientations of the remote (upper order) and local tensors. Thus, even though the magnitudes and spatial distributions of the remote and local tensors differ, the extensional joints closely parallel the main tensors and the axes of the domes and basins (cross bc and ac joints: Hancock, 1985). This deformational model accounts for the square (Fig. 2F) or rectangular (Fig. 12A) symmetry of the orthogonal veins, and for the “grid-type” deformation bands (Figs. 12B and 14A).
The regional distribution of veins and dykes (Fig. 11) is in accordance with this deformation history for the Paraná Basin volcanics. The emplacement of the thermally metamorphosed sandstone dykes could be attributed to the mobilization of the still unconsolidated sands from the underlying Botucatu Fm., or from the Botucatu sands interlayered (intertrapped) between the sequences of lava flows, into orthogonal extensional joints opened in the outer rim of the buckled volcanic flows.

The shear fractures (hybrid joints and faults) display a conjugated arrangement with regard to the extensional joints (Figs. 10, 11, 13), but they started to develop just after the orthogonal fractures. The symmetry of the hybrid joints and faults is related to hk0 patterns in acute or obtuse angles to the elongated fold axis (Hancock, 1985).

6.4. Local scale Strike-slip stress regime and the stress drop

The strike-slip stress field determined from the fault-slip data (Sections 4 and 5) for both the first and second deformational phases appears to be inconsistent with the local flattening strain field in the outer part of the buckled volcanic flows. The fault-slip data showed that rather than the major compressive tensor being vertical (σ1L), it was the local intermediate compressive tensor (σ2L) instead. However, the onset extensional joints induce local stress release in the σ1L direction and a permutation between the local σ1L and σ2L tensors. This stress drop explains why the main stress difference (σ1 – σ3) remains approximately constant (Fig. 16).

The stress/strain main tensor positioning after local stress release (σ1sd > σ2sd > σ3sd, intermediate tensor now in vertical position) characterize the strike-slip stress state, and generates controls strike-slip faults (hk0 fault symmetry pattern) in the Jurassic to Cretaceous formations of the Paraná Basin. These deformational conditions explain the connection of extensional joints and hybrid to shear fractures, as shown in Figs. 2 and 11A.
The bi-directional constrictional deformation in the Paraná Basin during the Jurassic to Cretaceous periods, then, accounts for the outcrop-scale alternation of $\sigma_3$ ($\sigma_{3sd}$) position, i.e., either N–S or E–W in the first deformational phase, or NE or NW in the second deformational phase. In fact, the different $\sigma_1$ and $\sigma_2$ orientations distinguished in Figs. 8 and 9 are not related to local $\sigma_1$- and $\sigma_2$-permutations on the outer rims of the folded volcanic flows. It should be noted that $\sigma_1$ ($\sigma_{1sd}$) and $\sigma_3$ ($\sigma_{3sd}$) orientations alternate between different investigation sites. Thus, it can be concluded that $\sigma_1$ ($\sigma_{1sd}$) and $\sigma_3$ ($\sigma_{3sd}$) orientations, inverted from fault-slip data, are related to the elongation of the dome-and-basin structures developed in each area. The bi-directional constrictional ($\sigma_1 \geq \sigma_2 > \sigma_3$) stress regime gave rise to orthogonally oriented domes and basins, as shown by Gosh and Ramberg (1968) and Gosh et al. (1995), which controlled the local distribution of extensional joints and strike-slip faults. These deformatonal conditions explain the connection between extensional joints and hybrid to shear fractures, as shown in Figs. 2 and 11A. The extensional joints and their splays to hybrid and shear fractures frequently have hydraulic breccia (Fig. 2). Such a feature points to supra-hydrostatic conditions ($P/P_{\text{grav}} > 0.4$) during the deformation, which favor the development of extensional joints. Veins and associated hydraulic breccia are also developed on fractures related to the second deformational phase, i.e., the supra-hydrostatic conditions remained active during this deformational phase. This structural model of the constrictional deformation in the Paraná Basin also accounts for other important features observed in the volcanic flows. Small-scale folds, similar to that in Fig. 7E, are recorded on basal horizontally jointed portions of the volcanic flows (Fig. 19). These small-scale folds are frequently truncated by fracture zones at their limbs. These folds, however, are developed in the inner zone of the dome-and-basin structures, which is the locus for the local constrictional stress/strain in the tangential–longitudinal mechanism (Fig. 19C). Thus, it can be concluded that buckling of a single lava flow gave rise to the distinguishing
deformational structures on either side of its neutral surface. At the outer rims, orthogonal
extensional joints developed and sandstones dykes were emplaced, while at the inner rims,
non-cylindrical folds developed.

6.5. Time constrain to deformation

The fault-slip and structural data for this investigation derive from the Botucatu and Serra
Geral formations (upper units of São Bento Group) of the Paraná Basin. The deforma-
tional structures of the volcanic rocks of the Serra Geral Fm. were developed during the Jurassic to
Cretaceous periods. Lava flow stratigraphy differs in each of the studied sites/areas
(Heemann, 1997, 2005; Reginato, 2003; Acauan, 2007; Amorim, 2007), and it is still not
possible to correlate the studied quarries to specified time intervals taking into account
stratigraphic elements. However, the investigated structural elements (folds, joints and faults)
can be time constrained based in some regional features. This time intervals will certainly be
refined in future detailed investigation, the fault-slip investigations were constrained to the
Serra Geral Fm. volcanics and intertrap sediments, which left the exact time of onset of the
first deformatonal phase to be defined.

The onset of the first deformatonal episode, however, is not constrained by the volcanic
flows and underlying Botucatu Fm. The analysis of the thickness distribution for the
underlying Meso-triassic sequence (Artur and Soares, 2002), and also for the Pirambóia–
Guará and Botucatu formations (lower units of São Bento Group, Soares et al., 2008b) shows
a series of N–S elongated and circular structures. These results suggests that the stress field
for the first deformatonal episode might have operated from at least the Triassic (lower
bound) to the Early Jurassic period (upper bound) onwards.

For structural purposes, geochronological data produced in association with palaeomagnetic
studies for volcanic rocks related to the Paraná Basin can improve structural analysis, because
it introduces better differentiation between the relative timings of volcanic structures (flows, dykes, and sills).

Palaeomagnetic data and precise absolute ages for Mesozoic basic rocks related to the Serra Geral Fm. volcanism clearly distinguish three groups (see Ernesto, 2006, 2009, for a revision):

a) Serra Geral flows, b) Ponta Grossa Arc and Serra do Mar basic dyke swarms, and c) Florianópolis Dyke Swarm. While some overlap of apparent ages and virtual geomagnetic poles (VGPs) exists, it should be noted that the Serra Geral flows are older (time span 135–132 Ma) and show VGPs oriented to 83/090. The Ponta Grossa Dyke Swarm (PGDS) shows ages spanning from 132–129 Ma and has a mean VGP directed towards 82/059. The Florianópolis dykes have a time span in the interval 127–121 Ma and a VGP oriented to 88/003.

Ponta Grossa Arc and its Dyke Swarm (PGDS) are one of the main structural feature of the Paraná Basin (Fig. 5). The mean axial planes (305/84) and arc axes (06/307) of these structures are all compatible with a mean compressive stress field directed to 035–040 (D2 deformational phase). The mean direction for the basic dykes of the Ponta Grossa Arc is 300–310 (e.g., Strugale et al., 2007). These structural relationships indicate that the PGDS was emplaced in extensional fractures developed at the outer hinge zone in an anticlinal fold (Fig. 6) including Paraná Basin basement. The PGDS crosscut the basement rocks, and sedimentary and volcanic rocks of the Paraná Basin (e.g., Strugale et al., 2007). In this scenario, the PGDS cannot be regarded as an aborted rift arm, as it has previously been interpreted (e.g., Morgan, 1971; Chang et al., 1992; Turner et al., 1994).

The emplacement of the Ponta Grossa dykes (PGDS), then, can be taken as the upper age limit for the onset of the second deformational episode (ca. 132 Ma). And, thus, the first (D1) deformational phase can be constrained, in a first approximation, to ca. 200–132 Ma interval.
An upper age limit to D2 deformation can be taken from the emplacement of the Florianópolis dykes. Raposo et al. (1998) related them to extension of the South America crust just prior to the Atlantic oceanic crust expansion. Thus, the second (D2) deformational phase can be preliminary constrained to ca. 132–121 Ma interval.

7. Conclusions

The geometric and kinematic and dynamic analyses of the field data permitted to characterize a regional bi-directional constrictional ($\sigma_1 \geq \sigma_2 > \sigma_3$) stress state regime two deformational phases during the Jurassic to Cretaceous periods to be distinguished of the Paraná Basin. Two Both deformational phases were developed under these regional bi-directional constrictional ($\sigma_1 \geq \sigma_2 > \sigma_3$) stress regimes and gave rise to a number of non-cylindrical folds. These structures are characterized as domes and basins, and regional anticlines and synclines. Consequently, both deformational phases produced similar local-scale structures. However, these deformational phases can be distinguished both by the orientation of their structures and by some other particular structural features. The first deformational phase shows elongated domes and basins oriented both N–S and E–W. The second deformational phase also shows elongated domes and basins, but these are oriented NW–SE and NE–SW, according to the most expressive Ponta Grossa and Rio Grande arcs, and the Torres Syncline in the eastern border region of the Paraná Basin. These conditions indicate a clockwise rotation (35–40°) for both horizontal principal stress tensors ($\sigma_1 \geq \sigma_2$) during the Cretaceous period.

The stress/strain partition at different scales was responsible for structural features recorded at decreasing scales in the Paraná Basin. The orthogonal orientation of the major axis of domes and basins controls alternated orientation of stress/strain tensors ($\sigma_{1db} \geq \sigma_{2db}$) at this scale.
The tangential longitudinal buckling mechanism supported by massive, thick volcanic layers enabled local scale stress/strain partition between outer and inner arcuate folds. The outer rim developed orthogonal patterns of the dykes and veins, and also deformation bands, retaining symmetric relationships with the fold axes of the elongated domes and basins. The inner rims of the buckled volcanic flows, however, developed local arcuate folds, whose local stress axes are close to the regional ones. It should be noted that local-scale folds could reproduce the regional bi-directional constrictional regime. Further investigations are needed to address this point in the future.

These orthogonal extensional joints are developed in the outer rims of the folded volcanic flows; however, the strike-slip faults follow the development of extensional joints. The strike-slip faults are the result of the stress drop after the onset of the extensional joints, which enabled a local permutation between $\sigma_1$ and $\sigma_2$. The $hk0$ symmetry for the strike-slip faults in the arcuate folds is in accordance with field observations.

The stress/strain condition in the outer rim of arcuate folds (flattening) governs outcrop-scale alternation of the $\sigma_{3\text{sd}}$ position, either N–S or E–W (D1 phase), or NE or NW (D2 phase), is not related to after stress drop due to extensional fractures onset. These conditions are supported by the fact that the different $\sigma_1$ and $\sigma_2$ orientations distinguished in Figs. 8 and 9 are mainly reported in different investigation sites and result from the orientation of the arcuate fold minor axis. Thus, the $\sigma_3$ position depends on the orientation of the orthogonal elongated domes and basins. Thus, further investigation is in progress to determine the regional (remote), rather than local stress/strain field in the Jurassic to Cretaceous periods of the Paraná Basin.

These orthogonal extensional joints are developed in the outer rims of the folded volcanic flows; however, the strike-slip faults follow the development of extensional joints. The strike-slip faults are, then, the result of the stress drop after the onset of the extensional joints, which
enabled a local scale permutation between $\sigma_{1o}$ and $\sigma_{2o}$. The hk0 symmetry for the strike-slip faults in the arcuate folds is in accordance with field observations.

The paleostress-inversion-based distinction of fracture orientation families introduces biased results in some previous papers. The field-based data (fault slips, fracture patterns, dykes, and contact attitudes) and data derived from paleostress inversions and kinematic analyses are in agreement with each of the deformational phases.

The paleostress orientation derived from fault-slip data, however, is related to the local stress field developed upon the buckled single volcanic flows of the Serra Geral Fm. after stress drop episodes.

The se general orientations for the NE–SW (NW–SE) stress tensors agree with those presented strike-slip stress state regime proposed by Riccomini (1995), Strugale et al. (2007), Machado et al. (2012), and Nummer et al. (2014), then, is a local scale stress field. This strike-slip stress state regime—differ, however, was applied on specific way for data processing methodology and kinematic analysis by those authors. Then, the deformational phases discriminated. It should be noted that the area studied by Riccomini (1995),—and Strugale et al. (2007), Machado et al. (2012), and Nummer et al. (2014) are hard—is heavily influenced by the NW–SE Ponta Grossa faults and dikes. Despite final results that are difficult—to reconcile with results obtained in this study without introducing biased interpretation, it seems that the D1 faults (deformation) defined by Strugale et al. (2007) correspond to the D2 deformational-phase discussed here.

The Gauss and MSM paleostress inversion methods (Žalohar and Vrabec, 2007, 2008) were applied to fault-slip data for 42 sites in the southeast border and central regions of the Paraná Basin (Brazil). A number of fieldwork campaigns were undertaken to map the important structural features of the Paraná Basin that developed during the Jurassic to Cretaceous periods.
**Author contribution**


**Acknowledgments**

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Table 1 Deformational phases distinguished in the uppermost units of the Paraná and in the continental rift basins of Southeast Brazil (Riccomini 1995)

<table>
<thead>
<tr>
<th>Def Phase</th>
<th>Time interval</th>
<th>Main geological features</th>
<th>Interpretation</th>
</tr>
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</table>
| Dₙ       | Permian to Lower Cretaceous | Deformational event previous to Gondwana rupture  
NE-oriented basalt and clastic dikes  
Geophysical alignments                                                                                                               | NW-oriented minimum stress ($\sigma_3$) axis                                    |
| Dₙ₊₁     | Upper Cretaceous       | NW-oriented basalt dikes in the Ponta Grossa Arc region  
Final stages of the Serra Geral volcanism  
Jacupiranga Alkaline Intrusion  
Anticlinal dome structures                                                                                           | NE basalt dikes and NW Ponta Grossa dikes were indicated to represent a triple junction remnant  
NE-oriented minimum stress ($\sigma_3$) axis  
**Dextral transcurrent system**                                      |
| Dₙ₊₂     | Paleocene to Eocene    | Bauru Basin structural development  
Rift (graben) basins at the continental margin  
NE-oriented lamprofiric dikes                                                                                          | NW-oriented minimum stress ($\sigma_3$) axis  
**Sinistral transcurrent system**                                      |
| Dₙ₊₃     | Eocene to Oligocene    | Jaboticabal Alkaline Intrusion  
Hydrothermal silification contemporaneous to sedimentation of Itaqueri Fm.                                                                                         | NNW-oriented maximum stress ($\sigma_1$) axis  
**Dextral transcurrent system**                                      |
| Dₙ₊₄     | Miocene                | Ultrabasic flows in Volta Redonda and Itaboraí  
Deposition of Itaquaquecetuba Fm.                                                                                     | Maximum stress ($\sigma_1$) axis alternating from NS and EW according the balance between South Atlantic drifting and Nazca Plate subduction  
**Dextral EW transcurrent system**                                      |
| Dₙ₊₅     | Pliocene               | NS-oriented grabens  
Extensional WNW-ESE regime                                                                                             |                                                                                                                                           |
| Dₙ₊₆     | Pleistocene to Holocene |                                                                                                                             |                                                                                                                                           |

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<td><strong>Heemann (1997,2005), Heemann and Strieder (1999)</strong></td>
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<td>80-248</td>
<td>02-158</td>
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Table 3 Summary of crosscutting relations of different striations observed in the same fault plane

<table>
<thead>
<tr>
<th>Site</th>
<th>Relative age</th>
<th>Fault plane</th>
<th>Striae orientation</th>
<th>Sense of movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedreira Quarai</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>359/73</td>
<td>20/173</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>359/73</td>
<td>14/006</td>
<td>Dextral</td>
</tr>
<tr>
<td>Pedreira SF Assis</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>066/72</td>
<td>27/236</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>066/72</td>
<td>27/077</td>
<td>Sinistral</td>
</tr>
<tr>
<td>Pedreira Painel</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>166/72</td>
<td>09/343</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>166/72</td>
<td>10/169</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>034/74</td>
<td>13/039</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>034/74</td>
<td>60/185</td>
<td>Normal</td>
</tr>
</tbody>
</table>
Table 4 Parameters for stress inversion using multiple-slip method (Žalohar and Vrabec 2008).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion ($s$)</td>
<td>20</td>
</tr>
<tr>
<td>Threshold ($\Delta$)</td>
<td>40–50</td>
</tr>
<tr>
<td>Shear strength ($\phi_1$)</td>
<td>50–65</td>
</tr>
<tr>
<td>Angle of residual friction ($\phi_2$)</td>
<td>20–35</td>
</tr>
<tr>
<td>Stress parameter</td>
<td>40–50</td>
</tr>
<tr>
<td>Andersonian regime set</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The shear strength and angle of internal friction data for volcanic rocks of Paraná Basin are from fresh rock test (Meirelles 2008).
Table 5 Summary of principal stress axes in the N–S and E–W orientations computed for sites within the volcanic rocks of the Paraná Basin.

<table>
<thead>
<tr>
<th>Site Description</th>
<th>Standard deviation of s</th>
<th>Linear inversion</th>
<th>MSM inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ₁, σ₂, σ₃</td>
<td>Relative values</td>
<td>D, σ₁, σ₂, σ₃</td>
</tr>
<tr>
<td>A Compilation from PR (Ped Registro) and PQ2 (Ped Quarai)</td>
<td>13 02/260 84/009 06/170</td>
<td>-0.56 -0.24 -0.33</td>
<td>0.10 25 01/264 87/011 03/174</td>
</tr>
<tr>
<td>B Pedreira SF Assis 2 (BR377)</td>
<td>20 02/273 72/176 18/003</td>
<td>-0.58 -0.24 -0.34</td>
<td>0.10 25 12/275 78/104 02/006</td>
</tr>
<tr>
<td>C Compilation from sites Estr Velha, Sobradinho1, and Saltinho1A</td>
<td>14 02/174 84/283 06/084</td>
<td>0.99 0.16 0.07</td>
<td>0.78 0.63 0.06</td>
</tr>
<tr>
<td>D Compilation from sites Angico and Poço Grande</td>
<td>17 12/184 76/030 06/275</td>
<td>-0.48 -0.11 -0.37</td>
<td>0.30 35 01/190 83/094 07/280</td>
</tr>
<tr>
<td>E Compilation from sites Sobradinho2, Saltinho2, Gar Zubi, and Pedra Funda</td>
<td>17 02/260 84/152 06/350</td>
<td>-0.94 0.35 0.09</td>
<td>0.94 0.27 0.10</td>
</tr>
<tr>
<td>F Compilation from sites Gar Ametista, Pedr Fred Westph, and Caicara2</td>
<td>20 02/177 72/283 18/096</td>
<td>-0.57 -0.29 -0.29</td>
<td>0.00 20 06/187 83/342 03/097</td>
</tr>
<tr>
<td>G Compilation from sites Pedr Guerra, CODECA1, Aflor Tega, and Veranopolis</td>
<td>11 02/076 84/328 06/166</td>
<td>-0.59 -0.25 -0.34</td>
<td>0.10 25 01/072 88/324 02/162</td>
</tr>
<tr>
<td>H Pedr CODECA1</td>
<td>9 13/184 76/030 06/275</td>
<td>-0.50 -0.12 -0.38</td>
<td>0.30 40 02/001 82/105 08/270</td>
</tr>
<tr>
<td>I Pedreira Painel</td>
<td>10 13/002 76/208 06/094</td>
<td>0.95 0.33 0.07</td>
<td>0.52 -0.17 -0.35</td>
</tr>
</tbody>
</table>

Results for the linear and multiple-slip methods of inversion are calculated by the T-TECTO 3.0 program, according to Žalohar and Vrabec (2007, 2008).
Table 6 Summary of principal stress axis in the NE–SW orientation computed for sites within the volcanic rocks of the Paraná Basin.

<table>
<thead>
<tr>
<th>Site</th>
<th>Standard deviation of s</th>
<th>Linear inversion</th>
<th>MSM inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ₁, σ₂, σ₃</td>
<td>Relative values of λᵢ</td>
<td>D</td>
</tr>
<tr>
<td>A  Compilation from Pedr Sta Rita 1 + BR293 + Pedr Quarai 1</td>
<td>02/027 84/135 06/297</td>
<td>0.62 : -0.27 : -0.36</td>
<td>0.10</td>
</tr>
<tr>
<td>B  Pedreira Sta Rita 2</td>
<td>02/309 84/201 06/040</td>
<td>0.65 : -0.27 : -0.37</td>
<td>0.10</td>
</tr>
<tr>
<td>C  Pedreiras BR290 + BR377</td>
<td>02/223 72/320 18/133</td>
<td>1.10 : 0.18 : 0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>D  Compilation from sites Barragem M Filho and Gar Ralph</td>
<td>02/236 84/127 06/326</td>
<td>1.06 : 0.30 : 0.11</td>
<td>0.30</td>
</tr>
<tr>
<td>E  Pedreira Dacito</td>
<td>13/142 76/296 06/051</td>
<td>0.65 : -0.28 : -0.39</td>
<td>0.10</td>
</tr>
<tr>
<td>F  Compilation from sites Pedreiras FrWestph1, Caçaral1, RodBon1, and Planalto-Alpestre</td>
<td>02/125 84/234 06/035</td>
<td>1.11 : 0.18 : 0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>G  Pedreria Rodeio Bonito 2</td>
<td>13/058 76/264 06/150</td>
<td>0.52 : -0.12 : -0.39</td>
<td>0.30</td>
</tr>
<tr>
<td>H  Rota dos Canions (RS)</td>
<td>02/039 84/148 06/309</td>
<td>0.57 : -0.19 : -0.38</td>
<td>0.20</td>
</tr>
<tr>
<td>I  Compilation from sites Pedreiras BJSerra and Painel2</td>
<td>12/212 76/057 06/303</td>
<td>0.52 : -0.12 : -0.39</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Results for the linear and multiple-slip methods of inversion are calculated using the T-TECTO 3.0 program, according to Žalohar and Vrabec (2007, 2008).
Figure 2 Fracture patterns in the Serra Geral Fm. volcanic rocks. A) Fracture splay and a triangular zone showing hydraulic breccia (weathered). B) Extensional joint terminating into R shear and hydraulic breccia. C) Extensional joints terminating into either dextral or sinistral shear. D) Different generation of extensional joints and hydraulic breccia. E) Orthogonal extensional joints filled by thermally metamorphosed sandstone. F) Orthogonal extensional joints filled by metamorphosed sandstone (the sandstone dykes were laterally delineated). R, C, and P are synthetic shear fractures; R’ indicates antithetic shear; T indicates extensional
joints; s or d indicate sinistral or dextral fracture sense of movement, respectively. Notation for fracture orientation follows Fig. 3.

Figure 3 Field diagrams of fracture patterns in the volcanic rocks of the Serra Geral Fm. A) Riedel-type fractures, as reported by Tchalenko (1970) and Tchalenco and Ambraseys (1970). B) Dextral patterns of shear fractures. C) Sinistral patterns of shear fractures. D) Conjugated shear fractures and combinations of tension joints and shear fractures. Hatched areas represent transtensile dilatational spaces developed by shearing. R, C, and P are synthetic shear fractures; R’ indicates antithetic shear; T indicates extensional joints; s or d indicate sinistral or dextral fracture sense of movement, respectively.
Figure 4 Geological features of the fault planes in the volcanic rocks of the Paraná Basin. A) RM-type striation. B) Overprinting of TM striation on former striation with mineralization in the same fault plane. C) Frictional striae and steps in a polished fault plane. D) Sub-centimeter fracture cleavage dragging the horizontal joints of basalt.
Figure 5 Regional folds developed by NE–SW paleostress tensors. A) Map showing the location of synclines and anticlines (arcs), and also the domes and basins in the southern part
of the Paraná Basin. B) Lower hemisphere, equal area stereogram of the basal contact of the Serra Geral Fm. along the Rio Grande Arc and Torres Syncline (dashed line is the best-fit great circle to poles). 1) Quaternary sediments. 2) Cenozoic sedimentary rocks. 3) Cretaceous to Paleogene sedimentary rocks. 4) Paraná Flood Basalts. 5) Paleozoic–Mesozoic sedimentary rocks of Paraná Basin. 6) Basement rocks. 7) Main rivers, lakes, and lagoons. 8) Main NW-oriented arcs and synclines. 9) Elongated domes (red circles do highlight): a) Quaraí Dome (see Fig. 7 for a detailed map), b) Rivera Crystalline Island, c) Aceguá Crystalline Island.

Based on South America Geological Map (Schobbenhaus and Bellizzia 2001). Small open dots represent outcrops where fault-slip data were measured and analyzed.

Figure 6 Balanced SW–NE cross section from Uruguay to São Paulo (Brazil) showing the gentle anticlines and synclines dipping NW in the eastern border of the Paraná Basin. The cross section is perpendicular to the fold hinge. 1) Cretaceous to Paleogene sedimentary cover. 2) Serra Geral Fm. 3) Paleozoic–Mesozoic sedimentary rocks of the Paraná Basin. 4) Basement. The structural section was built upon the South America Geological Map (Schobbenhaus and Bellizzia 2001), and structural field data. The vertical exaggeration is 13×.
Figure 7 Dome and basin structures in the Quarai Dome area. A) Geological sketch indicating the main structural features in the region. B) $\pi$ diagram for sandstone–basalt contact in the...
Quaraí Dome. C) $\pi$ diagram for a basalt flow contact along the E–W basin. D) $\pi$ diagram for the basalt flow contact along the N–S basin. E) South-dipping fold in Botucatu Fm. sandstone. F) $\pi$ diagram for sandstone in the road cut outcrop. (Dashed lines in stereograms are best-fit great circle to poles; continuous lines are axial plane to folds).
Figure 8 Paleostress results for the N–S and E–W tensors observed in the volcanic rocks of the Paraná Basin. Each area/site is identified by a capital letter. The graphics for each area/site
include: lower hemisphere, equal area stereogram of brittle fault-slip data; misfit angle histogram; Mohr diagram for resolved shear stress; and biplot of the value for object function (M) vs. shape of the strain ellipsoid (D). Open circles and open squares in the stereograms represent stress direction determined using the Gauss and MSM methods, respectively. The sizes of the open circles and squares relate to the magnitudes of the stress tensors. The stereograms show the fault planes and their respective striae and sense of movement. Red and blue areas of stereograms represent P and T fields according Angelier and Mechler (1977), respectively.
Figure 9 Paleostress results for NE–SW tensors observed in the volcanic rocks of the Paraná Basin. Each area/site is identified by a capital letter. The graphics for each area/site include: lower hemisphere, equal area stereogram of brittle fault-slip data; misfit angle histogram;
Mohr diagram for resolved shear stress; biplot of value for object function (M) vs. shape of the strain ellipsoid (D). Open circles and open squares in the stereograms represent stress direction determined using the Gauss and MSM methods, respectively. The sizes of the open circles and squares relate to the magnitudes of the stress tensors. The stereograms show the fault planes and their respective striae and sense of movement. Red and blue areas of stereograms represent P and T fields according Angelier and Mechler (1977), respectively.
Figure 10 Rose diagrams of fault-slip data for N–S tensors. Circular histograms from A to I correspond to the sites/areas described in Table 3. Blue and yellow arrows represent maximum and minimum stress tensor orientation from Fig. 8.

Figure 11 Tabular dykes emplaced into basalts of the Serra Geral Fm. A) Photograph of the tabular dykes emplaced into the vesicular basalts of the Salto do Jacuí region. B) Rose diagram of orientation of sandstone dykes in the Salto do Jacuí region (N = 135). C) Rose
diagram of orientation of sandstone dykes in the Caxias do Sul region (N = 24). D) Rose
diagram of orientation of mineralized veins in the Caxias do Sul region (N = 85).
Figure 12 Orthogonal pattern features recorded in the Cerro do Jarau intertrap megadune. A) Centimeter-scale orthogonal “ladder-type” veins in the basalt of the Cerro do Jarau hills. B) Millimeter-scale orthogonal “grid-type” deformation bands in the Botucatu Fm. sandstone in the Cerro do Jarau intertrap dune. C) Superposed shear deformation bands on orthogonal bands. D) Thin section of thermally metamorphosed sandstone showing the orthogonal deformation bands. E) Rose diagram of the orthogonal veins in basalts (N = 134). F) Rose diagram of deformation bands in sandstones (N = 28).
Figure 13 Rose diagrams of fault-slip data for NE–SW tensors. Circular histograms from A to I correspond to sites/areas described in Table 4. Blue and yellow arrows represent maximum and minimum stress tensor orientation from Fig. 9.
Figure 14 Orthogonal patterns associated with second deformational phase in the Cerro do Jarau area. A) NE–SW orthogonal deformation bands superposed upon the N–S bands. B) Rose diagram of the NE–SW orthogonal deformation bands (N = 36).

Figure 15 Lower hemisphere stereograms showing the symmetry relationships between domes and basins and fractures in the Paraná Basin volcanics. A) Fold axis (red squares), extensional dykes and veins (blue squares), and deformation bands (black dots) of the first deformational phase in the Quaraí Dome area. B) Fold axis (red squares) for NW regional arcs, Quaraí Dome, extensional dykes and veins (blue squares), and deformation bands (black dots).
dots) of the second deformational phase. Dashed great circles are axial planes of folds and arcs.


Figure 17 Strain-ratio log diagrams for volcanic rocks of the Paraná Basin. A) Results from the linear inversion method (Žalohar and Vrabec 2007). B) Results from multiple-slip method.
Green triangles represent the first deformational phase and blue diamonds the second.

Figure 18 Bi-directional dome-and-basin model structures for the Serra Geral Fm. volcanics (Paraná Basin). A) Regional sketch for orthogonal elliptical non-cylindrical folds. B) Detail for local-scale stress/strain distribution in the tangential–longitudinal buckled volcanic layer; stippled line distinguishes the neutral surface. The principal curvature directions (contour lines for domes and basins) parallel to the principal strain directions give rise to orthogonal joints in the outer rims of non-cylindrical folds (Lisle 1999).
Figure 19 Small-scale fold on basal horizontally jointed basalt flow. A) Outcrop-scale fold at base of a basalt flow. B) Lower hemisphere stereogram for folded horizontal joints of the basalt flow (Dashed lines in stereograms are best-fit great circle to poles; continuous lines are axial plane to folds). C) Tangential–longitudinal buckle model distinguishing structural features developed at the outer and inner rims of a buckled single layer flow.