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GEOSCIENCES

Mesozoic/cenozoic strike-slip tectonics in the catarinense shield and its correlation with structures associated with the continental rift in southeastern Brazil

RÔMULO MACHADO, PATRÍCIA D. JACQUES & ALEXIS R. NUMMER

Abstract: Structural studies carried out on mesoscopic scale of planar and linear brittle structures from quarries in Precambrian rocks of the central-southern portion of the Catarinense Shield led to a characterization of four main fault directions: NE-SW, NW-SE and some around N-S and E-W. The older dextral (~ N-S) and sinistral (~ E-W) strike-slip faults are explained through a paleostress field approximately NE-SW oriented. The younger dextral (NE-SW) and sinistral (NW) strike-slip faults are compatible with an approximately E-W oriented paleostress field. The oldest event fits between the Cretaceous and Cenozoic and the younger event fits between the Neogene and Quaternary.

Key words: Catarinense Shield, brittle deformation, structural analysis, strike-slip tectonic, paleostress fields.

INTRODUCTION

The structural framework of the Catarinense Shield presents two conspicuous tectonic domains: (i) one domain with a dominant NE-SW trend, situated north of Florianópolis, and (II) a second domain with a dominant NNE trend, situated south of Florianópolis (Fig. 1).

The first domain mainly comprises rocks belonging to the Brusque (or Metavolcanics Sedimentary Belt or Schist Belt) and Camboriú metamorphic complexes, intrusive granite suites (São João Batista, Valsungana and Nova Trento), the Itajaí Basin and Santa Catarina Granulite Complex (Basei et al. 2000, Bitencourt et al. 2008).

The Brusque Metamorphic Complex corresponds to a NE-SW trending domain, extending for about 75 km, with a maximum width of 45 km, separated into two segments by the Valsungana Batholith (Basei et al. 1994). Its tectonic limits are to the northwest with the Itajaí-Perimbó Strike-slip Shear Zone (IPS-SSZ; Fig. 1), and to the southeast with the Major Gercino Shear Zone (Philipp et al. 2004). They are high-angle ductile shear zones, with strong deformation, and dextral kinematics (Passarelli & Basei 1995, Passarelli 1996, Philipp et al. 2004, Bitencourt et al. 2008, Passarelli et al. 2010). The IPTS-SSZ corresponds to a 10 to 15 km thick strike-slip zone, developed under ductile and brittle-ductile conditions from granulite and metavolcanics sedimentary rocks, which generated mylonites, ultramylonites and phyllonites (Bitencourt 1996).

The second domain comprises rocks of the Florianópolis Batholith (or Granitic Belt) and, in its northern part, are found small portions of the Camboriú Metamorphic Complex.

The Florianópolis Batholith corresponds to a spatial extension of the Pelotas Batholith that

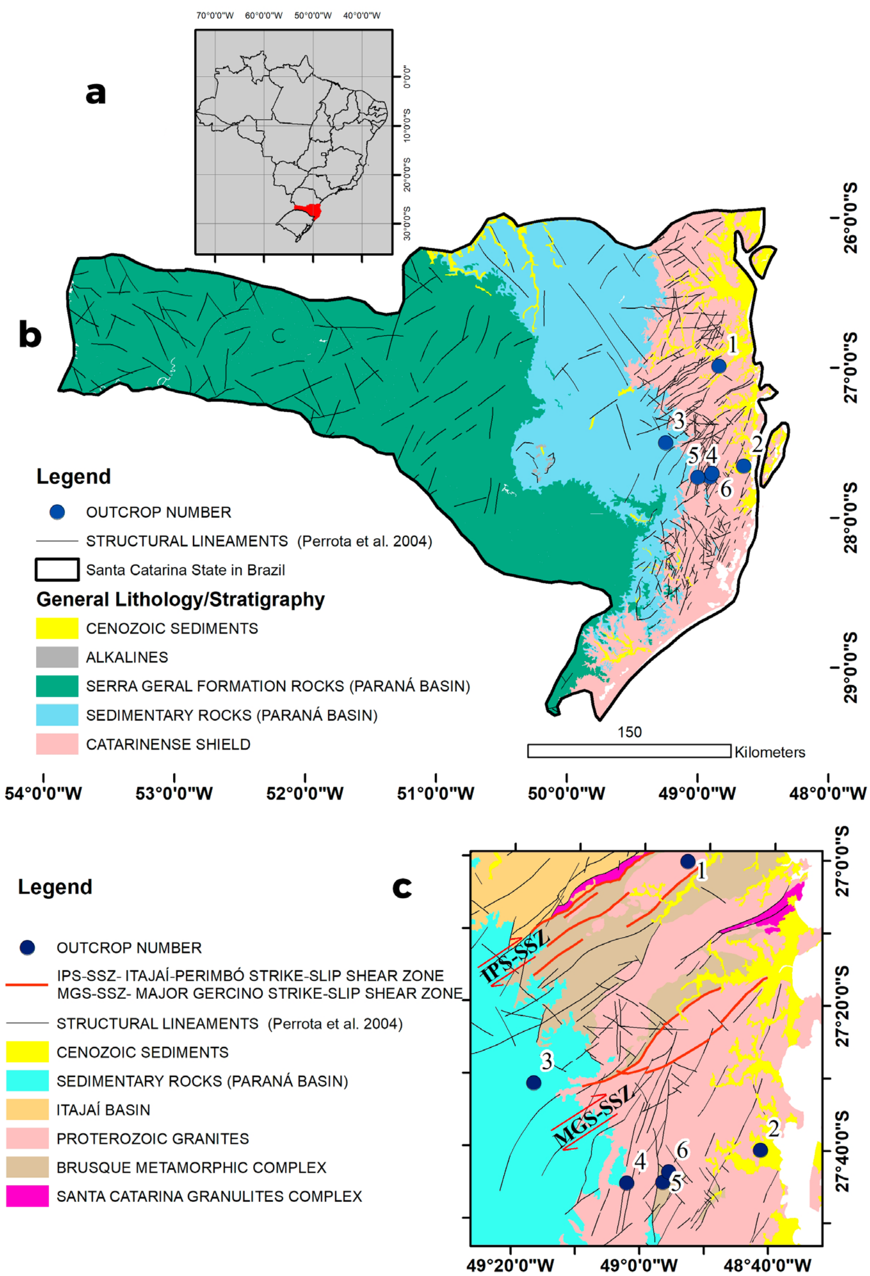


Figure 1. a – Location in Brazil. b – Santa Catarina State. c - synthesis of the main geological units that appear in the studied area and structural lineaments (modified after Perrota et al. 2004). The area object of this study is highlighted with the transversal E-W section. The numbers correspond to the outcrops that were selected for structural analysis (UTM, zone 22, south, Datum WGS-84).

outcrops to the south in the eastern portion of Rio Grande do Sul State trending towards Uruguay and known as the Aiguá Batholith. In Santa Catarina State, this batholith is divided into three main suites: Águas Mornas, São Pedro de Alcântara and Pedras Grandes. In the Águas Mornas suite deformed granites (Paulo Lopes) are found, including protomylonites and *augen* granites with dominant N10º-30ºE/45º-50ºSE foliation (Basei et al. 2000).

The Precambrian ductile structures present in the NE and NNE portions of the Catarinense Shield were recurrently reactivated during the Phanerozoic and its consequence can be evidenced through the pattern change for the isopach maps of the Paraná Basin lithostratigraphic units (see Northfleet et al. 1969, Zalán et al. 1990), as well as the brittle structures (lineaments and faults) that deform the Basin's stratigraphic succession and its basement, as described by several authors (amongst others, Soares et al. 1982, 1996, Ferreira & Almeida 1989, Zalán et al. 1990, 1991, Riccomini 1995a, Rostirolla et al. 2000, Castro et al. 2003, Freitas et al. 2007 are mentioned). There are brittle structures resulting from reactivation that present the same orientation of the basement framework, and there are other structures with different orientations as well, suggesting that their development was independent from previous structures. The youngest brittle structures are a result of the Gondwana continental rupture along the Jurassic-Cretaceous.

Due to the absence of Phanerozoic stratigraphic markers in the Catarinense Shield, which would allow to establish a more precise age positioning for the structures studied in this work, the aim was to establish a correlation, in stratigraphic terms, with similar and better known structures in the Paraná Basin. This is the reason why it will initially be presented a brief introduction of the basin's geological evolution and a synthesis of the main structural orientations that affected the Gondwana sequence and volcanic rocks of the Serra Geral Formation, and the tectonic process related to the Continental Rift development in Southeastern Brazil.

This paper presents results of the structural studies (geometry and kinematics), carried out on mesoscopic scale of planar (joints and faults) and linear (striae and fibers of mineral growth) brittle structures from quarries in Precambrian rocks of the central-southern portion of the Catarinense Shield, extending approximately between the cities of Joinville and Florianópolis (Figure 1). Concurrently, an attempt was made for positioning those structures on a time basis using the geologic correlation of similar structures (orientation, geometry and kinematics) described on the edge of the basin, particularly where the Lages Dome (Santa Catarina State), the Ponta Grossa Arch and the Quatiguá Dome (Paraná State) are situated, since such structures are relatively well-known in terms of age, due to the existence of stratigraphic markers from the Upper Cretaceous to Tertiary (Rostirolla et al. 2000, Freitas & Rostirolla 2005, Roldan 2007, Roldan et al. 2010, Machado et al. 2012, Jacques 2013, Jacques et al. 2014, 2015, Santos et al. 2019). An additional correlation was established related with the evolution of the Serra do Mar Rift System (Almeida 1976) or the Continental Rift in Southeastern Brazil (Riccomini 1989).

REGIONAL TECTONIC STRUCTURE

Catarinense Shield

Initially, the brittle structures of the Catarinense Shield were assigned as post-Paleozoic (Putzer 1952). Two groups of fractures were identified: the first one N0-30E and N60W oriented, named as the *Riograndense System*, and the second group N60E and N30W oriented, called *Catarinense System*. Later studies carried out in the fluorite district of Santa Catarina confirmed such structures, since basic dikes cutting Paleozoic rocks (Horbach & Marimon 1980). Three main lineaments are regionally recognized: Garopaba (NE-SW), Urussanga (NW-SE) and Canela Grande (NE-SW). Cataclastic and acid subvolcanic rocks, quartz veins and diabase dikes are associated with the first two lineaments (Jelinek et al. 2003). Figure 1 shows the main geological units and structural lineaments of the Santa Catarina State. Two major geologic domains are distinguished: (a) Catarinense Shield and (b) Paraná Basin. The first domain is made up of the following geological units: Archean migmatites and granulites, metasedimentary and Proterozoic metamorphic rocks, besides some Cenozoic sediments that are found along the coast. The second domain is made up of Paleozoic sedimentary and Mesozoic volcanic rocks (Serra Geral Formation) of the Paraná Basin, besides Mesozoic-Cenozoic alkaline rocks which are also seen in the previous domain.

The main tectonic unit of the Catarinense Shield is the Dom Feliciano Belt (DFB), dated as Neo-Proterozoic/Cambrian, with the Luis Alves Microplate (Granulite Complex) as a foreland in its northern portion (Basei et al. 2000). The DFB, in Santa Catarina State, is divided into three crustal segments (from SE to NW): Granite Belt (Florianópolis Batholith), Metavolcanic Sedimentary Belt or Schist Belt (Brusque Metamorphic Complex) and Foreland Basin (Itajaí Basin). The Brusque Metamorphic Complex is limited to the northwest by the Itajaí-Perimbó Strike-Slip Shear Zone (IPS-SSZ; see Figure 1), and to the southeast by the Major Gercino Strike-Slip Shear Zone (MGS-SSZ; see Figure 1), both SSZ are Neo-Proterozoic, with dextral kinematics (Passarelli 1996, Bitencourt et al. 2008, Passarelli et al. 2010). The contacts to the south and to the west are with Paleozoic rocks of the Paraná Basin. In the domain of the Florianópolis Batholith (southern part of the shield) predominates a NNE structural trend (~N20°E), whereas in the Brusque Metamorphic Complex domain a NE structural trend (~N55°E) predominates, and that is also the same orientation of the granitic bodies, whose age is between 650 and 580 Ma (Bitencourt & Nardi 2000, Basei et al. 2000, Philipp et al. 2004, Bitencourt et al. 2008).

In the ocean portion frontal to the studied area there is an extensive E-W lineament, defined as the Florianópolis Fracture Zone (Asmus 1978). This structure is parallel to the São Paulo Plateau and marks its southern limit, continuing seawards, where it is considered as the northern limit of the Rio Grande Plateau. In the continental area, the alignment of the Uruguay River would represent the continuity of this structure. A structural and magmatic feature of the continental edge – the Florianópolis Structural Platform - would correspond to the connection between the two above described structures, and concurrently it is the limit between the Santos and Rio Grande basins (Asmus 1978).

Four main lineaments are identified between the Major Gercino and Itajaí-Perimbó strike-slip shear zones: (1) N00°-05°E, (2) N65°-75°E, (3) N70°-85°W and (4) N40°- 45°W (Castro et al. 2003). These authors emphasize that the first three directions are also identified in the Paraná Basin, with the first of them being concordant with the basic dikes and the fluorite and barite mineralization in the southern part of Santa Catarina State, whereas the last direction (NW) is approximately parallel to the swarm of basic dikes of the Ponta Grossa Arch. Studies with Fission Traces in apatite and fluid inclusions, carried out in the Santa Catarina Fluorite District, show the presence of a regional thermal anomaly with an age of approximately 70 Ma, which was responsible for a regional hydrothermal activity and formed the fluorite deposits found therein (Horbach & Marimon 1980, Jelinek et al. 2003). These data indicate a typical event of regional denudation whose commencement was around 90 Ma ago, with the main ages varying from 67 to 46 Ma. Shortly before that occurrence, at the beginning of the Upper Cretaceous (Cenomanian), an uplift of the southeastern continental edge of Brazil, accompanied by an intense erosive process would have occurred, and that flattened the then emerged relief, with the Japi Surface being considered as the final episode of that process (Almeida & Carneiro 1998).

Studies carried out about the structural lineaments on the eastern edge of the Paraná

Basin and in its basement in Santa Catarina State, based on satellite images (Landsat, SRTM) and geophysics (aeromagnetic results), enabled to define the following structural directions: (1) N-S and NNE-SSW (in the basement); (2) N-S and NW-SE (Gondwana Sequence), and (3) NE-SW and NW-SE (Serra Geral Formation) (Jacques et al. 2010, 2014). The magnetic data highlighted deeper NE-SW structures of the Paraná Basin substratum, which reflect a framework of the ductile structures belonging to the Catarinense Shield that continue under the basin. The structural NNE pattern appears to the south of the Major Gercino Strike-Slip Shear Zone, and the NE pattern appears to the north of this structure. In the Lages Dome, some of these structural directions were characterized as strike-slip faults (NNE-SSW, NE-SW and E-W), affecting the alkaline rocks associated with the dome, whose age is assigned between the end of the Cretaceous and beginning of Paleogene (Roldan 2007, Roldan et al. 2010, Machado et al. 2012, Jacques 2013).

Structures of the Paraná Basin

The Paraná Basin is an elongated depression following the NE-SW direction, according to the Precambrian framework of the substratum, which was a reactivated weakness zone under the compressional field, originated on the edge of the continent by the Oclóyica Orogeny in Late Ordovician, with the basin undergoing cycles of accelerated subsidence induced by orogenic episodes (Assine 1996, Milani & Ramos 1998, Milani et al. 2007). A new cycle of subsidence took place in Late Permian as a result of the Sanrafaelic Orogeny (Milani & Ramos 1998). When analyzing the sedimentary register of the basin, three transgressive-regressive cycles connected with oscillations of the relative sea level in Paleozoic time are recognized. They are re-covered by continental sedimentary packages with associated igneous rocks (Milani et al. 2007).

The last subsidence cycle in the basin evolution history occurred during the Late Cretaceous, with deposition of continental sediments covering volcanic rocks of the Serra Geral Formation, related with the Bauru Group or Bauru Supersequence (Milani 2004, Milani et al. 2007).

The tectonic deformation of the Paraná Basin was also connected to strike-slip faults in the intraplate environment, whose origin is a subject still under debate.

During the Gondwana rupture, that occurred along the Jurassic-Cretaceous, the structures of the Paraná Basin basement were strongly reactivated and injected with a colossal volume of basic magmatism, such as dikes and sills in the Paleozoic units or it reached the surface as flows (Milani et al. 2007). This tectonic reactivation was also responsible for the structuring of arches and flexures, particularly in the proximity of the eastern edge of the basin, such as the Ponta Grossa and Rio Grande arches, the Torres Synclinal, the Lages Dome amongst others (Almeida 1983, 1986, Zalán et al. 1987, 1990, Machado et al. 2012, Jacques 2013, Strieder et al. 2015).

Structural studies carried out on the Lages Dome, in the Santa Catarina Plateau, and also on the eastern portion of Rio Grande do Sul Plateau, allowed to define several directions of strike-slip (and oblique) faults, which were grouped into three deformational events/phases (D1, D2 and D3): D1 underwent maximum paleostress ($\sigma 1$) oriented around the NS direction, D2 is NE-SW oriented, and D3 is approximately E-W oriented (Roldan 2007, Roldan et al. 2010, Machado et al. 2012, Jacques 2013, Jacques et al. 2014, 2015, Nummer et al. 2014). The first deformational phase was related to Early Cretaceous, whereas the second and third phases were respectively related to the Upper Cretaceous and Paleogene

Table I. **Summary chart of the previous paper regarding the deformational pulses/phases that occurred from Cretaceous to Quaternary.**

Region	Event/ Fase/	Tectonic regime	Faults		Stress field (σ1)	Deformation age	Analized lithology	Ref
			Type	Orientation				
Cananéia Alkaline Massif (SP)	1 2	Transcurrent Transcurrent	Strike-slip (s); Nornal Strike-slip (s); Nornal Strike-slip (d)/normal Strike-slip (d)	E-W; NW (trachyte dikes) E-W; NE(lamprophyre dike) NS NNE (younger)	NW-SE NE-SW	Late Cretaceous Paleogene (Eocene)	Alkaline rocks	(1) (2)
Quatiguá Dome (PR)	1 2	Transpressive Transtensional	Strike-slip (s) Strike-slip (d)	NE-SW NW-SE		Permian-Triassic Mesozoic	Paleozoic sequence of Paraná Basin	(3)
Curitiba Basin (PR)	D1 D2 (D2', D2'')	Extensional Compressive Transtensional** Transpressive***	Nornal Strike-slip (d)/ oblique reverse	NE-SW NE-SW, NNE and NW (secondary)	Vertical* EW, NW and NNW; EW and WNW NNE	Cretaceous/ Paleocene Neogene/ Quaternary	Sedimentary rocks and basement	(4)
Ponta Grossa Arch (PR)	D1 D2	Extensional Transtensional	Strike-slip(d) and (s) Strike-slip (s) and (d)	N40-55W****, N40W (s) and S30E (d) conjugates N45-60W (ssfSBGs) and N60E (dafSBGs); N50W(dbbr)	N45W to N10W (crSBGs) and N10W to N10E(SBbr) N10W to N20E (crSBbr)	Early Cretaceous Late Cretaceous/ Paleogene	Serra Geral, Botucatu and Piramboia formations	(5)
Lages Dome (SC)		Compressive	Strike-slip(d) and (s)	NS (NNE to NNW) EW (ENE to WNW)	~NE-SW	Late Cretaceous Paleogene	Alkaline rocks	(6)
	D1 D2 D3	Compressive Compressive Compressive	Strike-slip(d) and (s) Strike-slip(d) and (s) Strike-slip(s) and (d)	NNW and NNE NNE and ENE NW and NE	~NS ~NS ~EW	Early Cretaceous Late Cretaceous/ Paleogene Paleogene/Neogene	Serra Geral Formation	(7)
Rio Grande do Sul Plateau (RS)	D1 D2 D3	Transcurrent Transcurrent Transcurrent	Strike-slip(d) and (s) Strike-slip(d) and (s) Strike-slip(d) and (s)	NE and NW NS to NNE and ENE-EW NE and NW	~NS ~NS ~EW	Early Cretaceous Late Cretaceous/ Paleogene Paleogene/Neogene	Serra Geral Formation	(8)

References: (1) Riccomini 1989, 1995; (2) Riccomini et al. 2004; (3) Rostirolla et al. 2000; (4) Salamuni et al. 2003; (5) Strugale et al. 2005; (6) Machado et al. 2012); (7) Jacques et al. 2015, 2016; (8) Nummer et al. 2014. ***Abbreviations*****: (d) - dextral; (s) - sinistral; (*) – basement and basin; (**) – in the basin; (***) – in the basement; (****) – dyke intrusion directions; (crSBGs) - clockwise rotation in the São Bento Group sandstones; (crSBbr) - clokwise rotation in the São Bento basic rocks; (ssfSBGs)- sinistral synthetic faults in the São Bento Group sandstones; (dafSBGs) dextral antithetic faults; (dbbr) deformation bands in the basic rocks.**

and between the Neogene and Quaternary (see Table I).

After recent studies (structural data and satellite images) performed on the eastern edge of the Paraná Basin, in Santa Catarina State, it was possible to define three deformation phases/pulses that occurred between the Cretaceous and Upper Pleistocene: the first pulse (pulse A) with a NNE-SSW oriented main paleostress field; the second pulse (pulse B) with a NNW-SSE oriented main paleostress field, whilst the third pulse (pulse C) presents an E-W oriented main paleostress field (Santos et al. 2019). These three events reactivated part of strike-slip faults from the basement and deformed the volcanic rocks of the Serra Geral Formation (Santos et al. 2019).

The main NW-SE regional structures of the southeastern portion of the Paraná Basin, domes or arches and basins, also called synclines and anticlines, more recently have been interpreted as resulting from a deformation phase (D2 phase) with a NE-SW oriented stress field, that took place during the Jurassic to Cretaceous periods (Strieder et al. 2015).

Zalán et al. (1991) highlighted three preferential directions in the structural framework of the basin: N50-70E, N45-65W and E-W. The first two directions are also those presenting the highest conformable index (Soares et al. 2007). These structures probably are older. Along the coast of São Paulo State, younger (Paleocene/Eocene or Neogene - Miocene) sinistral strike-slip faults with this same direction were characterized. Such faults affect the alkaline rocks of the Cananéia Massif and the sedimentary rocks of the Taubaté Basin and were also responsible for control and development of smaller sedimentary basins, such as the Itaquaquecetuba Basin (Riccomini 1989, 1995a, Riccomini et al. 2004). This tectonic event was preceded by a crustal distension, with NNW-SSE direction, that took place along the Paleocene and Oligocene causing the installation of the Taubaté Basin and other tectonic basins associated with the Continental Rift in Southeastern Brazil (Riccomini 1989, 1995b, Riccomini et al. 2004).

Rift System in Southeastern Brazil

The Serra do Mar Rift System (Almeida 1976) or the Continental Rift in Southeastern Brazil named by Riccomini (1989) is a tectonic entity of the immerse continental area, extending along the southeastern coast of Brazil, encompassing a complex of tectonic depressions, including mountainous blocks, the Paraíba do Sul Graben and small Cenozoic sedimentary basins with a tectonic origin. Opposite vertical movements that took place in this region since Late Jurassic were of great magnitude, causing a displacement between the highest mountains and the Santos Basin basement that exceeds 11 km (Almeida 1976).

Riccomini (1989), based on structural studies in the central part of the rift, also considered the following succession of deforming events: (1) E-W sinistral strike-slip, with NW distension and, locally, a Neogenic (Miocene?) NE-SW compression, (2) dextral strike-slip with NW compression dated as Quaternary (Upper Pleistocene to Holocene), (3) Holocene WNW-ESE distension and (4) N-S faults with inverse reactivation and generation of conjugated joints by shears in colluvial/alluvial deposits, caused by E-W compression (Salvador & Riccomini 1995). A sinistral strike-slip deforming event probably preceded an extensional NNW-SSE event, causing the installation of the basins.

Geomorphologic and geologic studies accomplished along the southeastern Brazilian coast suggest a Paleocene origin for the mountain ranges of Serra do Mar and Serra da Mantiqueira, and that the escarpment of Serra do Mar was farther east than its present geographic position, it sloped backward mainly due to differential erosion conditioned by the Precambrian structures and lithologic units (Almeida & Carneiro 1998). However, Zalán & Oliveira (2005) thought in a different way, they consider that the present recessive escarps must be very close to the Cenozoic transtensional normal faults that originated them. They argue based on the rectilinear pattern and the abrupt difference in levels of the Serra do Mar. They point out that all the above faults were the reason for the sinking of the entire basement situated between the scarps and the Cretaceous hinge line, right in front of the Santos Basin, closer to the coast line than the continental slope. This structure, with a difference in levels of up to 5 km between the high and low blocks, is evidenced by the anomalies on the magnetic maps, as well as by the main lithologic variations of the basement (Zalán & Oliveira 2005).

The presence of a surface affected by regional erosion that smoothed and leveled all the Atlantic Plateau area, called the Japi Surface (Almeida 1958), shows evidences in many regions in Southeastern Brazil, and its age is reasonably well known, since it levels the Upper Cretaceous (Cenomanian) alkaline intrusions to the west of Minas Gerais State, southeast of Goiás State, and on Serra da Mantiqueira, where the alkaline massifs (Itatiaia and Passa Quatro, dated as to the final Cretaceous) were partially eroded and stood up 800 m above of the referred surface (Almeida 1983, Almeida & Carneiro 1998, Riccomini et al. 2004). A great amount of this eroded material was deposited in the receiving troughs of the Santos/Campos/Espírito Santo basins (Zalán & Oliveira 2005).

A tectonic event that had its beginning during the Paleocene and was more expressive during the Eocene (Zalán & Oliveira 2005) deformed - by flexure and rifting - the Japi Surface causing the taphrogenic southeastern basins and formed the Serra do Mar and Serra da Mantiqueira mountain ranges. The Serra do Mar established itself in the area of the present continental shelf, which through the raise of the western block of the Santos fault and subsidence of the eastern one, was filled by Cenozoic marine sediments (Almeida & Carneiro 1998). Concomitant with this process occurs the fracturing and gravitational collapse of the Serra do Mar in the Cretaceous (between 58-20 Ma, climax between 48-40 Ma happened in a staggered form, from Serra da Mantiqueira up to the Cretaceous hinge line of the Santos Basin (Zalán & Oliveira 2005). This tectonic feature has even caused the reactivation of the onshore alkaline magmatic chambers (ankaramite lava and phonolite dikes), between 55-40 Ma (Zalán & Oliveira 2005).

Ab'Sáber & Bigarella (1961) set apart, in Paraná State, two distinct geomorphologic compartments: (1) the Iguaçu High Surface (Maack 1947, Almeida 1955), that corresponds to the Lower Tertiary South American Surface of King (1956), and (2) the Curitiba Surface, that corresponds to the leveled surfaces (altitude between 750 and 980 m) of the First Paraná Plateau (Bigarella et al. 1965, Salamuni et al. 2004). It was in the later geomorphologic compartment – situated between the Devonian scarp of the Paraná Basin to the west and Serra do Mar to the east - that the Curitiba Basin was developed along the Miocene and Oligocene, according to two events: an extensional D1 event, with generation of NE-SW faults, and a D2 event, transtensional (D2') to transpressional (D2''), that reactivated previous structures such as strike-slip faults and oblique inverse faults (Salamuni et al. 2003). Such events began during the Paleogene and defined the basin's geometry, it firstly was a half graben, and was later reactivated as a pull-apart type basin. During the Miocene there was an alteration in the context of the regional paleostress, it changed from extensional - D1 (between the Cretaceous to Paleogene) with vertical paleostress field (σ1) to compressional - D2 (since the Neogene) with E-W paleostress field (σ1) (See Table I).

The morphostructural feature of the Serra do Mar, in Paraná State, was generated along the Cenozoic during deformational events superimposed over older tectonic events (Nascimento et al. 2016). The geometric analysis of strike-slip faults related with the paleostress direction, were identified in adjacent areas affected by Neogene tectonic activity (Paranaguá Graben, Sete Barras Graben and Curitiba Basin). The authors recognized six important escarpments limited by geologic structures, and mapped eight morphostructural units and four morphostructural domains, designed as: (1) Antonina; (2) Morretes; (3) Guaratuba and (4) Guaraqueçaba.

Neotectonic studies performed on the edge of the Santa Catarina Plateau, based on the drainage morphometric analysis and other geomorphic parameters, show that the structures with N-S and E-W orientation were responsible for the control and development of the drainage catchments and regional relief (Jacques et al. 2014, De Sordi et al. 2015, 2018). These structural orientations probably represent reactivation of older structures existing in the basement of the Paraná Basin. Drainage morphometric analysis coupled with denudation rates derived from in-situ-produced 10Be cosmogenic nuclide or low-temperature chronological data indicates tectonic influence in the relief morphogenetic evolution and drainage pattern rearrangement (De Sordi et al. 2018).

N-S structures and NE-SW strike-slip, and NW faults that affect Precambrian rocks (Atuba Complex) and basic and lamprophyre dikes in the surroundings of Curitiba, are attributed to a Neogene N-S ntraplate compression, with alternation of the E-W principal stress induced in the South American Plate (Chavez-Kus & Salamuni 2008). According to the authors, this type of configuration can also be expected in other regions with a similar tectonic context.

Zalán & Oliveira (2005), consider that in the Neo-Cretaceous, between 89 and 65 Ma (climax between 85-65 Ma), the crystalline basement was raised, indicated by a wide extension of the alkaline intrusive centers (dikes, plugs and stocks), dated from 82 Ma and 70 to 60 Ma, coincident with the areal distribution of the present major mountain ranges whose peaks were leveled by the Japi Surface (final of the Cretaceous). That is corroborated not only by the thick sedimentary rock packages of the Upper Cretaceous (Coniacian/Maastrichtian) adjacent to such raise, respectively deposited in the Paraná Basin (on one side) and the Santos Basin (on the other side), as well as they precisely date the formation of an extensive Neo-Cretaceous plateau.

According to these authors, the Cenozoic tectonic regime was extensional, predominantly perpendicular (deformation mechanism caused by pure shear) to slightly oblique (deformation mechanism by 15° simple shear), that installed a slight sinistral transtension that formed rift-grabens slightly staggered to the right the easternmost and the offshore grabens.

E-W sinistral strike-slip faults have been related to an E-W strike-slip regime, installed in the southern portion of the São Francisco Craton connected with the westwards drift of the South American Plate, with the deformation divided into the morphotectonic, directional, transpressive and transtensive domains (Morales 2005, Hasui et al. 2000, Hasui 2010).

The fission track data show that rocks of the coastal plain in Southeastern Brazil have been exhumed from temperatures of > 110-120 °C since the passage from Lower to Upper Cretaceous up to Quaternary, while the basaltic plateau was in lower temperatures at < 50 °C since the eruption of volcanic rocks of the Serra Geral Formation in the Lower Cretaceous at ~130 Ma (Gallagher et al. 1995). The reactivation of the SE Brazilian margin has been described in three phases related to the rift and the post-rift evolution: the first phase from Early Cretaceous, the second one between Late Cretaceous and Paleogene, and the third phase dated as Paleogene (Eocene, ~40 Ma to Miocene, ~20 Ma) (Franco-Magalhães et al. 2010). The authors also divided these ages into two groups: a younger group (NE of Curitiba) with ages around 20 Ma, and an older group (NW and SW of Curitiba) with ages around 50 Ma.

More recent low-temperature thermochronology data recognized for the Brazilian Southern coast three cooling episodes that accelerated the relief formation: they were dated as Lower Cretaceous, Upper Cretaceous and Paleogene-Neogene episodes (Jelinek 2019). During the late episode the denudation rates augmented, and this was related with the formation and reactivation of high angle fault blocks that moved in response to intraplate stresses. According to the authors, the Ponta Grossa Arch presents the younger relief of all continental margin, and the final cooling reaching surface temperatures was in the Cenozoic. However, according to Oliveira et al. (2016), the onshore and offshore basement show an early thermotectonic event during the Late Cretaceous, which was linked to the uplift and denudation of the Serra do Mar and Serra da Mantiqueira.

MATERIALS AND METHODS

Data discussed in this work were obtained from field analyses (geometric and kinematics) of brittle structures (joints and faults), carried out in six quarries in the Catarinense Shield (Figure 1), following the procedures described and summarized in several papers and text books on the subject (Mercier & Vergeley 1992, Vialon et al. 1976, Petit 1987, Doblas 1998, among others). The paired structural data (plain and striae), measured on site, were organized in Excel™ spread sheets and later analyzed in Angelier diagrams, based on the graphical approach of the Straight Dihedrons method (Angelier & Melcher 1977). Diagrams were generated based on the Tectonics FP™ program and determined the compressive (maximum stress - σ_1) and distensive (minimum stress - σ_3) fields for each fault family. During the fieldwork, 366 measures of grooves and striae and mineral growth in fault plans were taken.

Initially, faults and fractures used for definition of the paleostress were hierarchized into different fault families, according to the geometric criteria and associated genetic aspects, namely: system architecture, symmetry, morphology of the surface, dihedral angle and microscopic characteristics in thin sections (Hancock 1985). Based on the Riedel model, several authors considered the criteria for the kinematic determination of faults to be associated with the deformation mechanism by simple shear (Petit et al. 1983, Petit 1987, Petit & Laville 1987, Fossen 2010). Such criteria are based on the geometric relation between the main displacement/rupture surfaces (Y or M surfaces) and associated secondary surfaces (P, T, R and R´ structures). Doblas (1998) summarizes the previous classifications and adds new parameters for kinematic analysis and establishes three reliability levels: good, acceptable and weak. These parameters were used in this work.

In parallel, an attempt for temporal positioning those structures was made, based on geologic correlations of structures developed in a similar crustal level (orientation, geometry and kinematics). Such structures are relatively well-known, and were studied on the eastern edge of the Paraná Basin, in the Tertiary sedimentary basins and the Cretaceous alkaline rocks associated with the Serra do Mar Rift System or the Continental Rift in Southeastern Brazil (Almeida 1976, Riccomini 1989). In terms of age, such structures are relatively well-known, since they affect clearly known stratigraphic units of these basins, as an example there are studies accomplished in the areas of the Ponta Grossa Arch and the Quatiguá Dome in Paraná State, on the Lages Dome in Santa Catarina State, and in the Taubaté and Itaquaquecetuba basins in São Paulo State, in Resende and Volta Redonda in Rio de Janeiro State, and the Alkaline Massif of Cananéia, in São Paulo State (Almeida 1976, Almeida & Carneiro 1998, Riccomini 1989, 1995b, Riccomini et al. 1983, 2004, Zalán & Oliveira 2005, Rostirolla et al. 2000, Freitas & Rostirolla 2005, Roldan 2007, Roldan et al. 2010, Machado et al. 2012).

RESULTS

Figure 2 shows a synoptic chart regarding the structural data of the analyzed faults in each quarry, comprising the stereograms, the orientation of maximum, minimum and intermediate stress axes, the diagram of the Straight Dihedrons method and the observed fault type. The six analyzed quarries belonging to the Catarinense Shield generally present the predominant directions to NNE (strike-slip, oblique with WNW thrust, and normal), NE (dextral strike-slip to slightly oblique, with inverse and normal movements), and NW (sinistral strike-slip). In addition, there are secondary strike-slip faults approximately trending E-W, with the predominance of sinistral kinematics, as well as faults with dextral kinematics. Such structures can be alternatively explained, according to two distinct tension charts: one of them with the main tension axis oriented close to NE-SW (sinistral to E-W), and the other one oriented around NW-SE (dextral to E-W).

Point 1 (see Figure 1), located in the Britagem-Barracão Quarry, it is part of the geologic context of the Valsungana Intrusive Suite, hosted by metamorphics of the Brusque Metamorphic Complex (or Belt) (Basei et al. 2000, Philipp et al. 2004, Bitencourt et al. 2008). There are faults with the main direction close to N-S and, secondarily, ENE-WSW. Generally, the N-S faults are cut by the ENE-WSW ones, and can be explained in the same tension chart as suggested above for the E-W sinistral strike-slip faults (Figure 2a).

Point 2, located in the granite outcrop of the Gabiruba Suite, shows two granite facies: one is coarse-grained, nondeformed, and the another is finer grained, deformed, with cataclasite containing plagioclase and hornblende porphyroclasts immerse in a recrystallized very fine matrix. The main fault family trends E-W with sinistral strike-slip kinematics. This same situation was observed in points 3 and 6, located near the contact of the Catarinense Shield with the Paraná Basin (Figure 1), suggesting that such faults are young structures, certainly developed in the Phanerozoic, since they cut the sedimentary units of the basin and, on the contrary of other fault directions described herein, they have not reactivated Precambrian structural directions.

At the outcrop of the contact of the Catarinense Shield with the Paraná Basin (Point 3) only few (8) data regarding faults were collected, however it was enough to suggest a transtensional regime with NW compression, evidencing a tectonic contact.

At Points 4 and 5, one close to the other, faults were identified with general ESE-WNW orientation and steep to moderate dips to

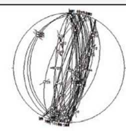
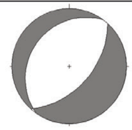
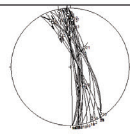
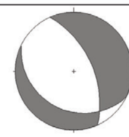
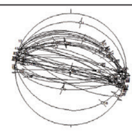
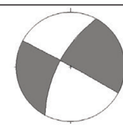
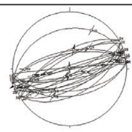
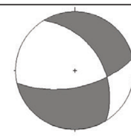
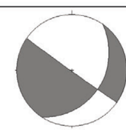
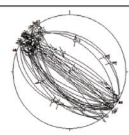
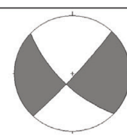
Orientation / Measurements number	Stereograms	Orientation of the axes of maximum, intermediate and minimum tension	Straight dihedral diagrams	Type of faults
(A) NNE-SSW 50		σ1 – N130/14 σ2 – N220/03 σ3 – N321/75		Strike-slip, oblíque and normal
(B) NNW-SSE 25		σ1 – N51/16 σ2 – N146/19 σ3 – N282/65		Strike-slip to oblíque
(C) ESE-WNW 41		σ1 – N72/12 σ2 – N303/72 σ3 – N165/14		Sinistral strike-slip to slightly oblíque and normal
(D) ENE-WSW 29		σ1 – N200/09 σ2 – N102/43 σ3 – N299/45		Sinistral strike-slip to slightly oblíque and normal
(E) NE-SW 48		σ1 – N248/31 σ2– N126/42 σ3 – N01/33		Dextral strike-slip to slightly oblíque
(F) NW-SE 46		σ1 – N90/09 σ2 – N210/73 σ3 – N357/15		Sinistral strike-slip

Figure 2. Synoptic chart of the faults outcropping in the Catarinense Shield. The gray area in the diagrams indicates the orientation of the maximum paleostress field (σ1).

the north. At Point 5, represented by mylonitic gneiss, faults are preferably NW-SE oriented, with steep dips to NE and SW (Figure 2f). Point 6 is at an outcrop where there are faults with direction close to N-S, with dextral and sinistral strike-slip kinematics. Additionally, there are NE-SW faults with dextral kinematics and E-W faults with sinistral kinematics.

DISCUSSION

The structural studies (geometric and kinematics) carried out on brittle structures (faults and fractures) that affect rocks of the Catarinense Shield (granites and metasediments) allowed to establish the following fault directions: N-S, NE-SW, E-W and NW-SE.

Results obtained with this work are compatible with the regional kinematic context considered for the development of the faults of the Jurassic-Cretaceous to the Paleogene to Quaternary on the eastern edge of the Paraná Basin in Southeastern Brazil, described by several authors (Ferreira & Almeida 1989, Riccomini 1989, 1995a, b, Rostirolla et al. 2000, Castro et al. 2003, Riccomini et al. 2004, Morales 2005, Freitas & Rostirolla 2005, Roldan 2007, Roldan et al. 2010, Hasui 2010, Machado et al. 2012, among others).

Dextral NNE oriented strike-slip faults, attributed to the Mesozoic (post- Passa Dois Group), are described in the southern part of the Catarinense Shield, in the Morro da Fumaça Fluorite District, city of Criciúma, Santa Catarina State (Ferreira & Almeida 1989). These faults follow the same direction of the Garopaba Lineament described by Horbach & Marimon (1980). In the Lages Dome, strike-slip faults with this same orientation and kinematics are also described. Such structures affect alkaline rocks associated with the dome, whose age is considered to be between the Final Cretaceous and the Paleogene (Roldan 2007, Roldan et al. 2010, Machado et al. 2012, Jacques 2013, Jacques et al. 2014, 2015). The authors relate these strike-slip faults to a compressive stress field with NE-SW oriented axis of the main paleostress (σ1), that was also probably responsible for the dome structuring and continued after the intrusion and cooling of the alkaline rocks. This same paleostress field would have also generated E-W (ESE to ENE) sinistral strike-slip faults. The presence of alkaline rocks and lamprophyre dikes with dominant NE-SW direction is compatible with the above mentioned paleostress field orientation (Roldan 2007, Machado et al. 2012). In the Santa Catarina Fluorite District WNW-ESE lineaments (Urussanga Lineament) are characterized, associated with cataclastic rocks, quartz veins, acid subvolcanic rocks and diabase dikes (Horbach & Marimon 1980, Jelinek et al. 2003). In the oceanic area, the Florianópolis Lineament and the São Paulo High are prominent, both are E-W oriented, with the latter separating the Pelotas and Santos basins.

The first deformation pulse taken under consideration herein is slightly younger than the σ1-I or D2 event characterized in the Ponta Grossa Arch, whilst the second event has the same age of the σ2-I (or D2) deformational event defined in the same region (Strugale 2002, Freitas 2005, Strugale et al. 2007). The third pulse, dated between the Neogene and Quaternary (Upper Pleistocene), shows the same stress field orientation that was subjected the eastern edge of the South American Plate (Jacques et al. 2014, 2015, Nummer et al. 2014, Santos et al. 2019). The sinistral strike-slip faults with direction around E-W, characterized in three studied outcrops (points 1, 3 and 6) - two of them (points 3 and 6) situated on the contact of the Paraná Basin with the basement - show the same orientation of the existing structures/lineaments in the basin (see Figure 1). Such structures were probably already active during the Triassic and certainly were active in the Cretaceous, with continuous activity in the Neogene, persisting until the Quaternary (Zalán et al. 1987, 1990, Zerfass et al. 2005, Morales 2005, Hasui et al. 2000, Hasui 2010). Normal faults with this same direction affected the Triassic Sanga do Cabral Supersequence, in the Santa Maria region, in Rio Grande do Sul State (Zerfass et al. 2005). On the other hand, sinistral strike-slip faults with similar direction affected the alkaline rocks associated with the Lages Dome, dated as being ~75 MA, positioning this tectonic event between the final Neo-Cretaceous and the Paleogene (Roldan 2007, Machado et al. 2012).

Sinistral E-W strike-slip faults were also registered in the Cananéia Alkaline Massif and the Taubaté Basin, dated between the Paleocene and Miocene (Riccomini 1989, 1995a, b, Riccomini et al. 2004). This tectonic event deformed the Japi Surface and the staggered formation of the taphrogenic basins (continental and offshore) plus the mountain system (Serra do Mar and Serra da Mantiqueira) in Southeastern Brazil. In addition, it was responsible for the reactivation of alkaline magmatic chambers onshore and formation of ankaramite lavas and phonolite dikes during the Eocene (Almeida & Carneiro 1998, Zalán & Oliveira 2005). In accordance with the authors, these structures were also responsible for the control and installation of small sedimentary basins, such as the Itaquaquecetuba Basin, located in the surroundings of São Paulo city. A similar age, between the Neogene and Quaternary, was attributed to the E-W strike-slip regime that was installed in the southern portion of the São Francisco Craton connected with the South American Plate westward movement (Morales 2005, Hasui et al. 2000, Hasui 2010).

The NW-oriented strike-slip faults described in this paper are coincident with the structural lineaments seen on satellite images (Landsat and Radar) and on magnetic maps of the Ponta Grossa Arch region and the structural alignments associated to them: Guapiara, São Jerônimo-Curiúva, Rio Alonso and Rio Piquiri (Ferreira 1982). This orientation corresponds to the Médio Ivaí fault (N45W ± 5) described by Soares et al. (1982). NW basic dikes of the Upper Cretaceous and small alkaline bodies, including kimberlites, are found throughout faults and fractures in the central region of the Rio Grande Arch, affecting both Precambrian and sedimentary rocks of the Paraná Basin, showing that this structure was active in the Mesozoic (Almeida 1986). A similar regional situation is described in the Alto Paranaíba Arch, where diabase dikes extending for over 20 km, some of them N40W oriented, fill fractures and present the same direction of the linear magnetic anomalies extending for up to 400 km (Almeida 1986). In this domain, the NW structures are regionally more expressive and appear as long lineaments extending for tens of kilometers (20 to 80 km). These lineaments reactivated structures which had already been reactivated during the Jurassic-Cretaceous (Zalán et al. 1987, 1990).

Sinistral NW-oriented strike-slip faults, considered as reactivation of previous structures, were registered in several areas in southeastern Brazil, with some of them being associated with domic structures, for example the structural highs of the Quatiguá Dome in Paraná State, Pitanga Dome in São Paulo State, and Lages Dome in Santa Catarina State (Soares et al. 1996, Riccomini 1995a, Rostirolla et al. 2000, Souza 1997, 2002, Roldan 2007, Machado et al. 2012, Jacques 2013). In Paraná State, in the Quatiguá Dome and the Ponta Grossa Arch, the strike-slip faults are related with two tectonic events: D1, beginning in the Early Cretaceous, controlled the emplacement and deformation of basic dykes, and D2, from the Late Cretaceous to Paleogene, with a main paleostress field ($\sigma 1$) NW to NNE (N10-15W to N10-15E) oriented. However, in the basic dikes of the Serra Geral Formation, this paleostress field is oriented between N40-45W to N15-20W, whereas in sandstones of the Botucatu and Piramboia formations, the orientation is around E-W (between ENE to ESE, respectively) (Rostirolla et al. 2000, Freitas & Rostirolla 2005, Strugale 2002, Strugale et al. 2007). Two tectonic events with similar orientation stress fields are also characterized in diabase sill in the surroundings of the Mauá Hydroelectric Power Plant, located on the Tibagi River, central portion of the Paraná State, but both events dated as post-Cretaceous (Rivas et al. 2019).

The NW-oriented Lages Dome is one of the most spectacular tectonic structure on the eastern edge of the Paraná Basin in Santa Catarina State. The structures, beyond exerting control of the alkaline intrusion associated with the Upper Cretaceous, were initially reactivated as strike-slip faults, probably during the Paleogene, and later as normal faults at the final Miocene, what generated the great Rio Canoas Lineament and promoted the inversion of the main drainage towards the interior of the continent and begun the dissection of the flattened surface (Roldan 2007). In the Catarinense Shield there are NW structures filled by basic dikes that cut the Paleozoic rocks (Putzer 1952). As mentioned before, the NW structures are well-known in the Ponta Grossa Arch with some of them characterized as dextral strike-slip faults that would have been active during the emplacement of the dikes (Strugale 2002, Strugale et al. 2007).

According to what was mentioned, it is shown that NE and NW brittle structures, associated with fractures/faults, are expressive in the studied area, and N-S and E-W structures subordinately occur, with associated faults and fractures, also found on the edge of the Paraná Basin in Santa Catarina State, both in the domain of the Paleozoic sedimentary rocks and in the domain of the volcanics of the Serra Geral Formation.

The results obtained with the tectonic studies for the Catarinense Shield highlight four main directions of brittle strike-slip structures: (1) NE-SW, dextral; (2) NW-SE, sinistral; (3) ESE-WNW and ENE-WSW, sinistral, and (4) NNE-SSW and NNW-SSE, dextral. The first fault system (dextral NE and sinistral NW) is compatible with a compressive event with an axis of maximum main paleostress ($\sigma1$) oriented around E-W. This same orientation of the paleostress field, defined in the Ponta Grossa Arch and the Paraná Basin – bounding line between Paraná and Santa Catarina states, was related to an event of the Upper Cretaceous to Paleogene (Strugale 2002, Freitas 2005, Freitas et al. 2007, Strugale et al. 2007). However, this event may be of late occurrence and related with the E-W compression, imposed on the southeastern edge of the South American plate (Assumpção 1998, Riccomini & Assumpção 1999). The second strike-slip fault system (dextral NNE and sinistral ESE) can be explained through a paleostress field with maximum main axis ($\sigma1$), around NE-SW, analogous to what was considered for the structuring of the Lages Dome, and for a strike-slip fault system affecting its own alkaline rocks, whose age has been situated between the Upper Cretaceous and Paleogene (Roldan 2007, Roldan et al. 2010, Machado et al. 2012, Jacques 2013, Jacques et al. 2014).

The neotectonic reactivation of faults oriented around E-W (ENE-WSW and ESE-WNW) and N-S (NNE-SSW and NNW-SSE) was responsible for the evolution of the Serra do Mar escarpment in Santa Catarina State, and additionally for the rearrangement of the drainage patterns and processes related with the relief denudation (Jacques et al. 2014, De Sordi et al. 2018). Drainage morphometric analysis coupled with denudation rates derived from in-situ-produced ^{10}Be cosmogenic nuclide data indicating that the Serra Geral escarpment is retreating westward at a significantly lower rate than showed in advance by evolutionary models (De Sordi et al. 2018). According to these authors, on the highlands, samples yield weighted means of 3.1 ± 0.2 and 6.5 ± 0.4 m/Ma at the Caçador and Araucárias plateaus; meanwhile an 8-fold higher denudation rate was determined along the escarpment, 46.8 ± 3.6 m/Ma, being compatible with values that occur in an old stable passive margin. The results obtained by these authors indicate that there was stability on the Araucárias Plateau at least during the last 30 Ma.

The age of the cooling episodes defined from the low-temperature thermochronology in Southeastern coast of Brazil is compatible with the age of the deformational events associated with the development and deformation of sedimentary basins and alkaline intrusions arranged along the Continental rift in Southeastern Brazil, and of domic structures that occur on the eastern edge of the Paraná Basin (see Riccomini 1989, 1995a, b, Salamuni et al. 2003, Riccomini et al. 2004, Franco-Magalhães et al. 2010, Machado et al. 2012, Jacques 2013, Jacques et al. 2014, 2015, Nascimento et al. 2016, Jelinek 2019, among others).

CONCLUSIONS

The structural studies (geometric and kinematic), accomplished in a mesoscopic scale in rocks from the Catarinense Shield, identified four main fault orientations, developed in a brittle deformation regime, namely: NE-SW, NW-SE, N-S (NNE to NNW) and E-W (ENE to ESE). These faults are of high to intermediate dip, with slightly oblique directional component, dextral (NE and NNE) and sinistral (NW, NNW and E-W), with the majority of these directions showing reactivation evidences as normal faults.

The structural data presented herein show that strike-slip (to slightly oblique) faults are present and affected Proterozoic rocks in the central part of the Catarinense Shield. Such faults were developed in depths where the processes of brittle deformation predominate, thus contrasting with the Proterozoic strike-slip faults that affected rocks of the above mentioned shield, such as Major Gercino and Itajaí-Perimbó, that were developed in depths compatible with the ductile deformation regime. Additionally, these data present the same characteristics (geometry, kinematics and stress fields) of the strike-slip faults studied on the edge of the Paraná Basin.

In addition, the structural data show the relation between the here characterized faults - in terms of orientation, geometry, kinematics and stress fields - and faults of post-Cretaceous age that affect the edge of the Paraná Basin in Southeastern Brazil, suggesting that they are of the same age, and were developed through the same events of regional brittle deformation. Such events were triggered by the continental rupture of Gondwana and the opening of the South Atlantic in the Jurassic-Cretaceous. This process continued during the rotation of the South American plate from east to west, mainly as a result of the stress field active on the plate edge for the expansion of the Mid-Ocean Ridge.

The strike-slip faults characterized along this work are related to two distinct deformational events: an older one, with axis of maximum main paleostress ($\sigma1$) oriented around NE-SW that was responsible for generation of the dextral NNE, and sinistral oriented around E-W strike-slip faults (between ENE and ESE). This event coincides with the orientation of the paleostress field of the D2 deformational event, suggesting that it has contributed for the formation of NW-SE elongated domes and basins in the Paraná Basin (Strieder et al. 2015), although they are of slightly different ages. The most recent event, with axis of maximum main paleostress field ($\sigma1$) approximately E-W, was responsible for the reactivation of the NE (dextral) and NW (sinistral) strike-slip faults.

The above discussed first deformational event has the same stress field orientation considered for the E-W strike-slip faults that affected the alkaline rocks of the Cananéia Massif (São Paulo State), the volcanic rocks of the Serra Geral Formation on the eastern edge of the Paraná Basin, Santa Catarina State (region of the Lava-Tudo and Pelotas rivers) and the Lages Dome (in Santa Catarina as well), respectively dated from the Paleogene to Neogene (Miocene?) or even of later occurrence (Upper Pleistocene), and from the pre-Cretaceous to Paleogene (Riccomini 1989, 1995b, Riccomini et al. 2004, Roldan 2007, Machado et al. 2012, Jacques et al. 2014, 2015, Nummer et al. 2014, Santos et al. 2019). This event affected the central part of the Continental Rift in Southeastern Brazil and was also responsible for the installation of small basins connected to the mentioned rift (Riccomini 1989, Riccomini et al. 2004).

The second event that was characterized presents a paleostress field very similar to the one of the most recent event (σ1-II or D2), developed along the pre-Cretaceous to Paleogene, described in the region of the Ponta Grossa Arch (Strugale 2002, Freitas 2005, Freitas et al. 2007, Strugale et al. 2007). However, this event may have taken place later than considered by these authors, and may be related with the E-W compression linked with the westward movement of the South American Plate, that established itself in the South of the São Francisco Craton, with Neogene to Quaternary age, as considered by several authors (Riccomini 1989, Assumpção 1998, Morales 2005, Hasui et al. 2000, Hasui 2010), or even related to the subduction of the Nazca Plate, underneath the South American Plate (Riccomini & Assumpção 1999, Lithgow-Bertelloni & Guynn 2004, Cogné et al. 2013, Jacques et al. 2014). Small sedimentary basins, such as Itaquaquecetuba, developed during the tectonic evolution of the Continental Rift in Southeastern Brazil (Riccomini 1989, 1995b, Riccomini et al. 2004) are dated with this same age as well. The E-W compression, considered here as the second brittle deformational event that affected rocks of the Catarinense Shield, caused the inverse reactivation of faults with a direction around N-S, and additionally reactivated NNE and NNW structures such as oblique faults to dextral and sinistral strike-slip faults, respectively. The NNE faults were developed in transpressive regime, whereas the NNW faults were developed in a transtensional regime. These structural directions successively reactivated older structures of the Catarinense Shield and of the Paraná Basin, particularly at the final Cretaceous, during the Paleogene and Neogene and, probably, until the Quaternary.

The conclusion is that the NE-SW paleostress field (Figure 2a, 2b and 2c) is older than the E-W paleostress field (Figure 2d, 2e and 2f), it is possible that it established itself at the final Late Cretaceous and probably remained active until the Paleogene, whereas the E-W paleostress field can be dated between the Neogene and Quaternary (Paleocene?). In the latter event, the stress field was accompanied by a clockwise (30-45°) movement from ENE-WSW to ESE-WNW, which initially triggered the nucleation of sinistral strike-slip faults and later with the movement inversion to dextral, both presenting slightly oblique components. E-W and N-S-direction faults were responsible for controlling the evolution and retreat of the Serra do Mar in Santa Catarina State, plus the rearrangement of the drainage patterns, as well as for the modeling of the regional relief between the Neogene and Quaternary.

Finally, the tectonic events here discussed show a good age correlation with the regional cooling episodes, recorded by low-temperature thermochronology related to the rift to post-rift evolution and formation of the relief along the Southeastern continental margin of Brazil, and the development of domic structures on the edge of the Paraná Basin.

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RÔMULO MACHADO[1,2]
https://orcid.org/0000-0002-9448-8937

PATRÍCIA D. JACQUES[2,3]
https://orcid.org/0000-0003-1491-7138

ALEXIS R. NUMMER[4]
https://orcid.org/0000-0001-8741-7826

[1]Universidade de São Paulo, Instituto de Geociências, Rua do Lago, 562, 05508-900 São Paulo, SP, Brazil

[2]Universidade de São Paulo, Instituto de Geociências, Programa de Pós-Graduação em Geociências (Recursos Minerais e Hidrogeologia), Rua do Lago, 562, 05508-900 São Paulo, SP, Brazil

[3]Serviço Geológico do Brasil-CPRM, Divisão de Geoprocessamento, Av. Pasteur, 404, 22290-240 Rio de Janeiro, RJ, Brazil

[4]Universidade Federal Rural do Rio de Janeiro, Instituto de Geociências, Antiga Rio São Paulo, Km 47, 23897-000 Seropédica, RJ, Brazil

Correspondence to: **Rômulo Machado**
E-mail: rmachado@usp.br

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