

Brecha tectônica da área de Cabo Frio - RJ, intrudida por dique máfico do Eocretáceo: evidência do tectonismo rúptil do Pan-Africano?

Tectonic breccia of the Cabo Frio area, State of Rio de Janeiro, Brazil, intruded by Early Cretaceous mafic dyke: evidence of the Pan-African brittle tectonism?

Akihisa Motoki

Departamento de Mineralogia e Petrologia Ígnea, Universidade do Estado do Rio de Janeiro
rochasornamentais@yahoo.com.br

Thais Vargas

Departamento de Mineralogia e Petrologia Ígnea, Universidade do Estado do Rio de Janeiro
thais@uerj.br

Woldemar Iwanuch

Departamento de Mineralogia e Petrologia Ígnea, Universidade do Estado do Rio de Janeiro
woliwa@itelefonica.com.br

Susanna Eleonora Sichel

Departamento de Geologia, Universidade Federal Fluminense
susanna@igeo.uff.br

Alex Balmant

Departamento de Mineralogia e Petrologia Ígnea, Universidade do Estado do Rio de Janeiro
alexbalmant@yahoo.com.br

José Ribeiro Aires

Abastecimento, Petróleo do Brasil S.A. (ABAST/PETROBRAS)
aires@petrobras.com.br

Resumo

Esse trabalho apresenta as descrições de campo e observações petrográficas de uma brecha tectônica no embasamento gnáissico das áreas de Cabo Frio e Arraial do Cabo, RJ, e seu contato intrusivo com um dique máfico do Eocretáceo. Na proximidade da ilha do Japonês, ocorre um excelente afloramento de contato entre esses litotipos. A zona da brecha tectônica tem 10 a 20 m de largura e tem direção de N30°E. Os clastos da brecha são angulosos e caracterizados pela textura de auto-brechação, sendo similares aos de brecha tectônica. A matriz é firmemente consolidada por hidrotermalismo e silicificação. O dique máfico tem 7 a 10 m de largura e N45°E de direção. Ao longo do contato, observa-se a margem de resfriamento do dique, caracterizada por basalto de granulometria fina e disjunções prismáticas. Na Praia das Conchas e Arraial do Cabo, ocorrem quatro afloramentos de contato, demonstrando a intrusão dos diques máficos nas brechas tectônicas consolidadas. Esses afloramentos comprovam que as brechas tectônicas silicificadas são mais antigas do que os diques toleíticos do Eocretáceo. As brechas poderiam ter sido formadas durante a fase hidrotermal e tal processo estaria associado ao tectonismo rúptil do estágio final da Orogenia Pan-Africana, sem atividades magmáticas. A existência dos clastos constituintes da brecha, que são compostos de brecha, sugere que os movimentos de falha e atividades hidrotermais ocorreram repetidamente.

Palavras-chave: Brecha tectônica, Dique máfico, Contato intrusivo, Cabo Frio, Arraial do Cabo, Orogenia Pan-Africana.

Abstract

This paper presents the field descriptions and microscopic observations of a tectonic breccia in the basement gneiss of the Cabo Frio and Arraial do Cabo areas, State of Rio de Janeiro, Brazil, and its intrusive contact with the Early Cretaceous mafic dyke. At the sea cliff close to the Ilha do Japonês, there is an excellent contact outcrop between them. The tectonic breccia zone is 10 to 20m wide and has N30°E direction. The breccia clasts are angular and characterized by auto-brecciation texture, and composed of breccia with similar aspect of the host tectonic breccia. The matrix is firmly consolidated by hydrothermalism and following silicification. The

mafic dyke is 7 to 10m wide and of N45°E direction. Along the contact, the dyke chilled margin featured by fine-grained basalt and prismatic joints can be observed. At the Conchas Beach and Arraial do Cabo city, there are four outcrops demonstrating the mafic dyke intrusion into the consolidated tectonic breccias. These outcrops prove that the tectonic breccias are older than the Early Cretaceous tholeiitic dykes. The fault breccias could have been formed during the brittle-phase tectonism of the last stage of the Pan-African Orogeny by hydrothermalism without magmatic activities, namely tectonic hydrothermalism. The existence of the clasts constituent of the breccia that are composed of breccia suggests that the fault movement and following hydrothermalism occurred repeatedly.

Keywords: Tectonic breccia, Mafic dyke, Intrusive contact, Cabo Frio, Arraial do Cabo, Pan-African Orogeny.

1. Introduction

In the State of Rio de Janeiro, Brazil, there is a large number of silicified tectonic breccia zones. They are generally sub-vertical and have NE-SW-ward strike ranging between N30°E and N60°E. Most of them are narrow, 50cm to 5m wide, but some of them are more than 200m wide. The examples are found at Rio de Janeiro city, Canaã village, Tanguá area, Cabo Frio area, Arraial do Cabo area, Carapebus

rural zone, Macaé area, etc. (e.g. Zimbres et al., 1989).

Among them, the breccia of Tanguá is considered to be associated with the hydrothermal activities related to Early Cenozoic nepheline syenite magmatism (Ferrari & Riccomini, 2003). The research documents for the tectonic breccias are scarce and the relative age between the tectonic breccia and the Early Cretaceous mafic dykes based

on the field observations was not reported.

The authors have found some contact outcrops of the mafic dykes intruding into the tectonic breccias in the Cabo Frio and Arraial do Cabo areas, State of Rio de Janeiro (Figure 1). This paper reports the contact outcrops observations and petrographic descriptions of the tectonic breccia and considers the origin and formation of the tectonic breccias.

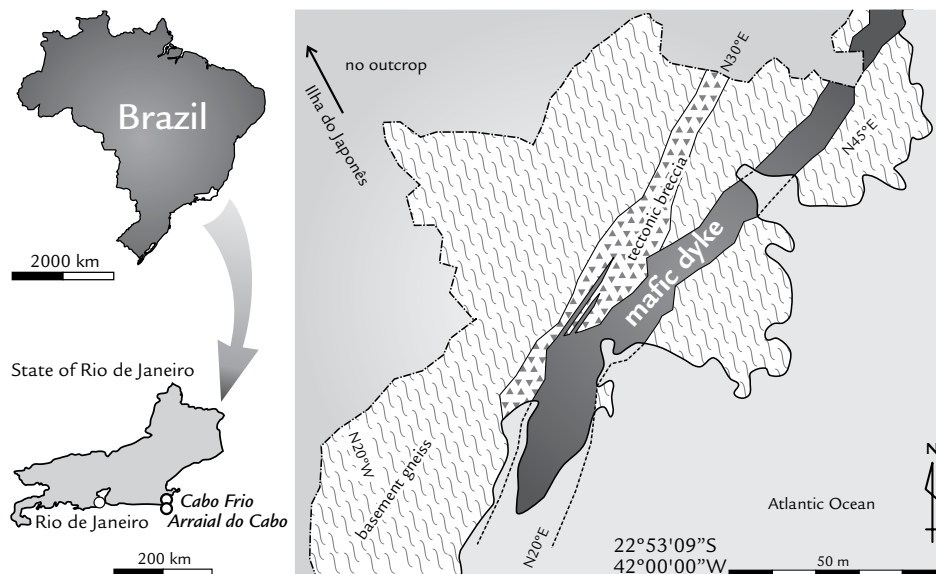


Figure 1
Local geologic map for the outcrop situated at about 500m to the SSE of the Ilha do Japonês, Cabo Frio municipal district, State of Rio de Janeiro, Brazil, at the coordinates of at 22°53'09"S, 42°00'00"W, showing intrusive contact of the mafic dyke into the silicified tectonic breccia.

2. Basement rocks

The areas of Cabo Frio and Arraial do Cabo, State of Rio de Janeiro, are underlain mainly by felsic granitic orthogneiss and mafic amphibolitic gneiss. The gneiss of this region strikes N15°W, being widely different from the other areas, N45°E a N55°E, and therefore it is considered to be a part of the Congo Craton (Heilbron et al., 2000; Heilbron & Machado, 2003), regionally called the Cabo Frio Block. The granitic gneiss is the main component and called the Região dos Lagos Unit. The mafic gneiss

is made up mainly of amphibolite and intercalated by the granitic gneiss. It is called the São Mateus Unit (Schmitt et al., 2008a).

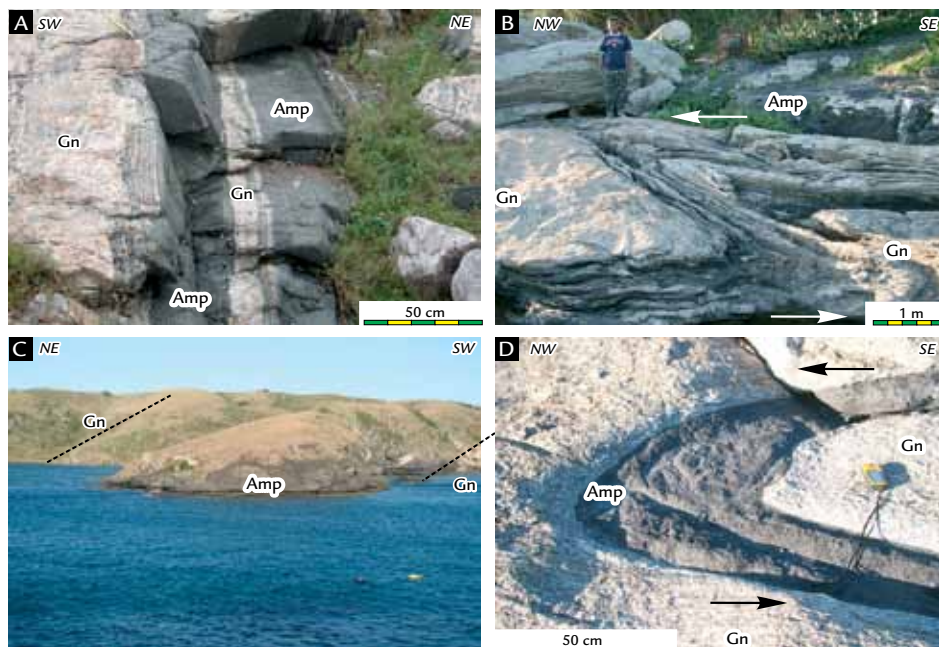
Both of the gneisses were submitted to the Pan-African Orogeny with metamorphic age of about 530Ma according to recent U-Pb zircon spot age (Motoki & Orihashi, 2009, unpublished data). The felsic gneiss has original intrusion age of about 1950Ma (Zimbres et al., 1990; Schmitt et al., 2008b; Motoki & Orihashi, 2009, unpublished data). The

contact between both types of gneiss are relatively sharp and the transition zone is less than 1m wide.

The geologic relation between the felsic and mafic gneiss before the Pan-African metamorphism is unclear. The mafic gneiss is 100 to 200m thick and occurs as an intercalation in the granitic gneiss (Figure 2C). It dips about 30° to the northeast and the upper block slides to the northwest (Figure 2B, D). This unit could be originated from gabbroic intrusion into the host granite.

Figure 2
Basement rocks of Cabo Frio area,
State of Rio de Janeiro:

- A) Contact zone between the felsic gneiss and the mafic one.
B) Plastic deformation observed at the contact zone.
C) Mafic gneiss body intercalated by the host granitic orthogneiss.
D) Tectonically deformed mafic gneiss.
Gn - felsic granitic orthogneiss,
Amp - mafic amphibolitic gneiss.



3. Tectonic breccia of the outcrop close to the Ilha do Japonês

To the south-southeast of Ilha do Japonês, Cabo Frio, State of Rio de Janeiro, at the coordinates 22°53'09"S, 42°00'00"W, there is a coast outcrop exposing a well-defined contact between the tectonic breccia and the mafic dyke. The tectonic breccia zone is sub-vertical and 10 to 20 m wide. There is complex branching of small breccia zones. They are 10 cm to 1 m wide and configured in parallel to the main breccia zone.

The tectonic breccia has cataclastic texture characterized by angular clasts (Figure 3). This texture is due to brittle fracturing and is widely different from that of the mylonite of the Paraíba do Sul shear zone (e.g. Egydio-Silva & Mainprice,

1999; Riccomini & Assumpção, 1999; Al-Mishwat, 2001).

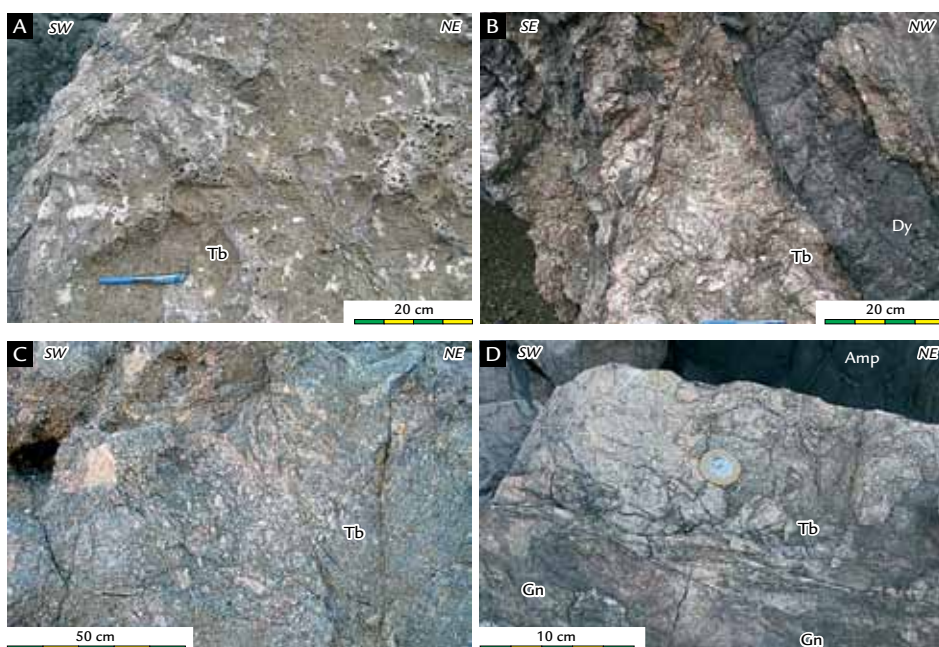
The central part of the breccia shows highly advanced cataclastic texture. The field aspects seem to be those of fault gouge (e.g. Cladouhos, 1999; Zwingmann & Mancktelow, 2004; Billi, 2005) consolidated by silicification. However, on the saw-cutting surface the rock shows light colour clasts of 2 to 4cm in size and dark matrix. The clasts are 50 to 60% in mode and the texture is classified to be clast-matrix supported (Figure 4A). The microscopic observations reveal that the clasts are not made up simply of gneiss fragments, but of cataclastic rocks with gneiss fragments (Figure 4C). That is, the

clasts themselves are fragments of tectonic breccia.

The hydrothermal alteration is quite intense and the matrix is completely consolidated by percolation of hematite, carbonates, sericite, and silica. On the natural rock surface, there are cavities up to 3 cm in diameter (Figure 3A) showing case-hardening fabric (Dorn, 2004). This structure is formed by the mobilization of Fe, Si, Mn, and Ca of the rock surface by chemical alteration (McAlister et al., 2003), and observed frequently on the surface of sandstone (e.g. Campbell, 1999; Farmer, 2005; Turkington & Paradiseb, 2005), semi-porous pyroclastic rocks (Motoki et al., 2007a; Sichel, 2008), and

Figure 3
Tectonic breccia of the Ilha do Japonês,
Cabo Frio, State of Rio de Janeiro:

- A) Central zone with strong hydrothermal effects.
B) Border zone with the mafic dyke intrusion.
C) Angular clasts of the border zone.
D) Contact zone grading into the host gneiss. Gn - felsic granitic orthogneiss;
Amp - mafic amphibolitic gneiss;
Tb - tectonic breccia; Dy - mafic dyke.



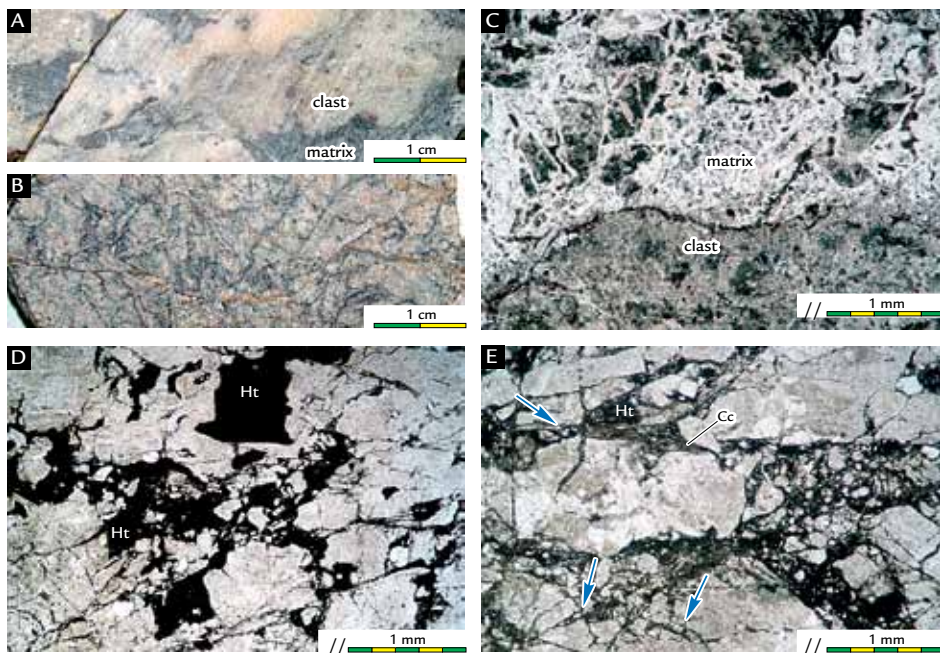


Figure 4
 Texture of the tectonic breccia close to the Ilha do Japonês, Cabo Frio, State of Rio de Janeiro:
 A) Strong hydrothermal effects at the central zone.
 B) Cataclastic texture of at border zone.
 C) Photomicrography in parallel nicols for the clast and matrix of the sample A.
 D) Cataclastic texture with the matrix filled by iron oxide.
 E) Cataclastic texture with the space filled by iron oxide and carbonate of the sample B. The arrows on the photomicrography E indicate auto-brecciation texture. Ht - iron oxide; Cc - carbonates.

on mafic and ultramafic rocks (Motoki et al., 2009a; b). The existence of this fabric suggests the abundance of disseminated carbonates.

Most of the tectonic breccia show moderately developed cataclastic texture. The clasts are composed mainly of the above-mentioned cataclastic rock with little amount of host gneiss (Figure 3B). Their modal amount is 80 to 90% (Figure 4B), so the texture is classified as clast-supported. The clasts are highly angular and 1cm to 3cm in size and the large clasts tend to be angular (Figure 3C, 4D, 4E). They show in-situ fragmentation texture without notable displacement, deformation and rotation (Figure 4E, arrows), so-called auto-brecciation texture. The contact of the breccia with the host rock is

gradual and the low-grade cataclastic rock grades into the host rock within a distance of 10cm (Figure 3D). These aspects are characteristically found in tectonic breccias, such as that of Carapebus (Zimbres et al., 1989), showing remarkable textural contrasts with the subvolcanic breccia of this region, for example of Mendanha (Motoki et al., 2007b, c; 2008a; Petrakis et al., 2010), Itaúna (Motoki et al., 2008b; c), and Cabo Frio Island (Motoki & Sichel, 2008; Sichel et al., 2008).

The matrix of the tectonic breccia is well-consolidated because of strong hydrothermalism. However no case hardening fabrics are observed on the natural rock surface (Figure 3C). Under the microscope, it is observed that the cataclastic matrix is filled by iron oxide (Figure 4D),

carbonates (Figure 4E), and sericite. The macroscopic colour of the iron oxide suggests that the mineral is hematite. Percolation of chalcedony is not very expressive. The alkaline feldspar and plagioclase are partially altered into sericite. Some crystals of plagioclase show dislocation along the cataclastic fractures. It is considered that the consolidation of the matrix is due to hydrothermal percolation by iron oxide and carbonates rather than of chalcedony.

The fault breccia cuts either the felsic gneiss or the mafic one. The total displacement is not clear. However some branches of the tectonic breccia show partial displacement with vertical components of about 1m (Figure 5A, B). They show normal fault sense on the outcrops.

The clasts of this tectonic breccia

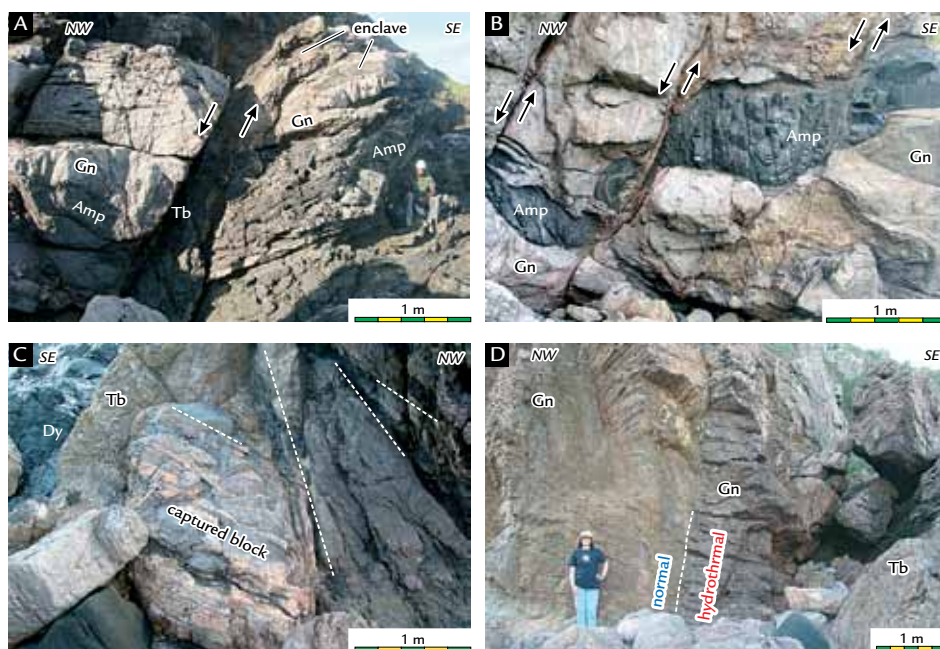


Figure 5
 Fault displacement observed at the outcrop close to the Ilha do Japonês:
 A) Apparent displacement of 1.5m with tectonic breccia intercalation of 40cm to 1m in width.
 B) Apparent displacement of 80 cm almost without tectonic breccia intercalation.
 C) Captured block.
 D) Hydrothermal consolidation extending to the non-cataclastic host gneiss. Tb - tectonic breccia; Gn - granitic orthogneiss; Amp - mafic gneiss; Dy - mafic dyke.

sometimes show different orientations, suggesting right-lateral displacement (Figure 5C). The displacement sense is according to the last stage of the Pan-African Orogeny of this region (Campos Neto, 2000). A gneiss block without cataclastic structure of 2.5m in size is found in the

central part of the breccia zone. This block would be constituent of the wall rock body and probably was captured into the tectonic breccia.

Hydrothermalism is intense and affects not only the tectonic breccia but also the non-cataclastic host gneiss. The

mechanical contrast between the hydrothermally consolidated host gneiss and the gneiss without hydrothermal consolidation formed the parallel fractures system along the border zone that are perpendicular to the contact between the hydrothermal and the non-hydrothermal zone (Figure 5D).

4. Mafic dyke close to the Ilha do Japonês

The mafic dyke exposed at the above-mentioned outcrop is sub-vertical and 7m to 10m wide. It is characterised by horizontal columnar joint of 1m in diameter (Figure 6A). This dyke has strike of N45°E (Figure 1), varying up to N20°E, and dip of 70 to 80° to the northwest. There are two branches parallel to the main dyke, 20cm and 50cm wide respectively. They demonstrate clear intrusive contact into the host tectonic breccia (Figure 3B). The branches are of en-echelon layout of left-handed strike-slip sense (Figure 6B). The cooling joints oblique to the dyke indicate left-lateral displacement during the magma cooling. Such structure is common in the dykes of this region, pointing out that the intrusion occurred by hydraulic shear fracturing

(Motoki et al., 2009b). This dyke is correlated to the Early Cretaceous tholeiitic magmatism of the Paraná Flood Basalt (Peate et al., 1992).

The central zone of the dyke has main columnar joints of 50cm to 1m in diameter with secondary short parallel joints with an interval of 10cm to 20cm. The rock is gross-grained (Figure 6C) and the minerals are easily identified by naked-eye. Microscopic observations show idiomorphic plagioclase crystals of 1.2 x 0.2mm frameworks with interstitial spaces filled by xenomorphic augite of 0.6 x 0.4mm in size and small magnetite crystals of 0.5 x 0.3mm, demonstrating ophitic texture (Figure 7A). This rock is classified as gabbro.

The dyke is in sharp contact with

felsic gneiss, mafic gneiss, and the tectonic breccia. In all cases, well-defined chilled margin is observed. The interval of cooling joints is wide in the central part and close at the border (Figure 6A). On the contact zone, prismatic joints are observed (Figure 6C, D). Microscopic observations show that this rock is of porphyritic texture with plagioclase phenocrysts of 1 x 0.4mm, and augite phenocrysts of 0.4 x 0.3 mm. The plagioclase phenocrysts are altered into sericite. The groundmass is of fine-grained microcrystalline interstitial texture with plagioclase of 0.2mm x 0.05mm, small grains of augite and magnetite (Figure 7B). This rock is classified as basalt.

Such gradual grain-size variation within the dyke is common in the Early

Figure 6
Early Cretaceous mafic dyke of the outcrop of the Ilha do Japonês:
A) General view showing horizontal columnar joints.
B) Linkage of en-echelon dykes intruding into the border zone of the tectonic breccia.
C) Intrusion contact into the tectonic breccia.
D) Dyke chilled margin with prismatic joints. Gn - felsic granitic orthogneiss; Tb - tectonic breccia; Dy - mafic dyke.

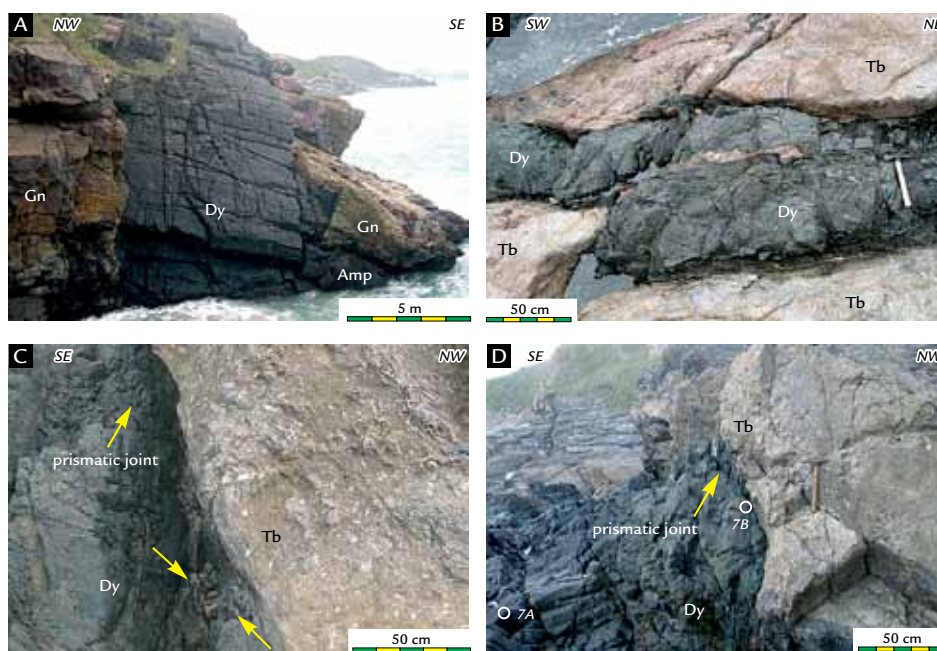
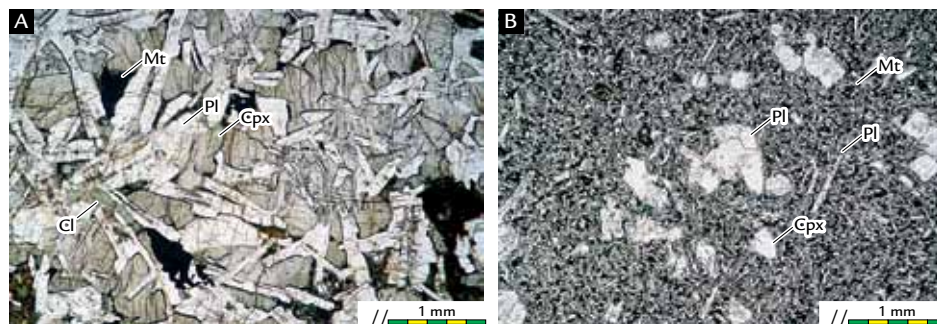


Figure 7
Photomicrography in parallel nicol for the mafic dyke close to the Ilha do Japonês, Cabo Frio:
A) Gabbro of the central part.
B) Basalt of the contact zone.
Their sampling positions are indicated on the Figure 6D. Pl - plagioclase; Cpx - clinopyroxene, augite; Mt - magnetite; Cl - clorite.



Cetaceous mafic dyke in this region (Motoki & Sichel, 2006). In spite of the quite strong hydrothermal effects in the host

cataclastic gneiss, the hydrothermalism of mafic dyke is small, only deuteric one. The above-mentioned observations show

clear evidences of dyke chilled margin, affirming that the mafic dyke is intrusive into the tectonic breccia.

5. Other contact outcrops

The outcrops of the tectonic breccia, especially of silicified ones, are abundant in the State of Rio de Janeiro (Ferrari & Riccomini, 2003; Trotta, 2004), but the contact outcrops with mafic dyke are scarce. Recently the authors found another four contact outcrops in the areas of Cabo Frio and Arraial do Cabo, State of Rio de Janeiro (e.g. Motoki et al., 2008d; 2009b).

One of these contact outcrops is exposed on the island between Conchas Beach and Però Beach in Cabo Frio (S22°51.85', W41°58.36'). The breccia zone is 40cm to 60cm wide and strikes

N20°E to N30°E. The clasts are angular, 5cm to 10cm in size. Auto-brecciation texture is commonly observed. The matrix is strongly consolidated. This breccia is cut obliquely by a mafic dyke of 30cm in width of NE-SW. The hydrothermal zone also extends out of the breccia into the host rock along the fractures (Figure 8A, arrows). In spite of the intense hydrothermal consolidation of the tectonic breccia, no hydrothermalism of the mafic dykes is observed.

The same island exposes another contact outcrop (S22°51.95', W41°58.70').

The tectonic breccia zones are 20 to 50cm wide and the strike is almost E-W. The clasts are angular and 3 to 5cm in size. The matrix is well consolidated. The breccia zones are intruded by a mafic dyke of NE-SW direction (Figure 8B). The mafic dyke of this outcrop also has no hydrothermal alteration.

At the peninsula situated to the east of Prainha (S22°57.16', W42°00.66'), Arraial do Cabo, a mafic dyke of 4m in width intrudes into well-consolidated tectonic breccia. The clasts are angular and 1 to 3cm in size. The auto-brecciation texture

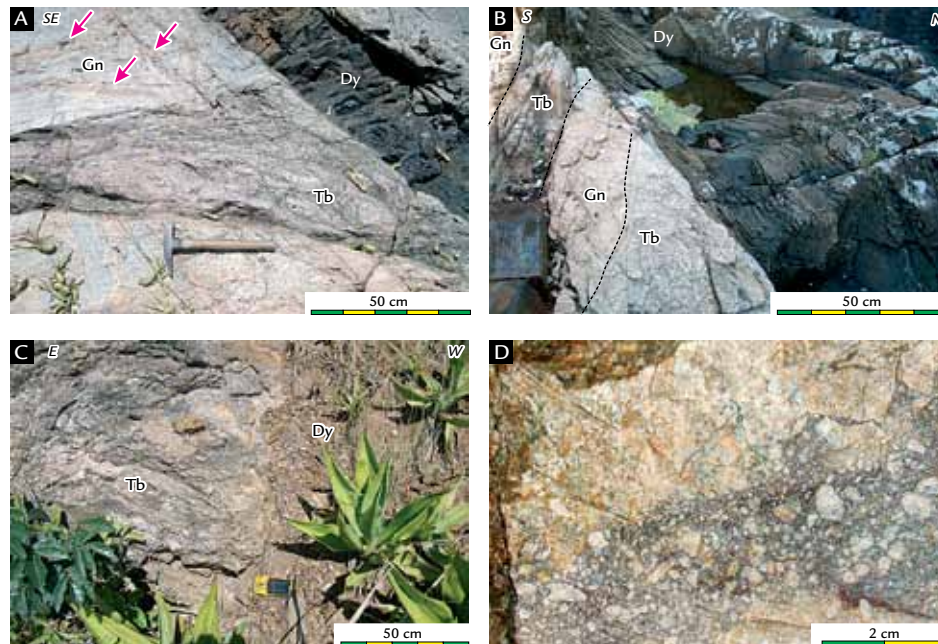


Figure 8

Outcrops showing the mafic dyke intruding into the tectonic breccia: A) At the island between the Conchas Beach and the Però Beach, Cabo Frio (S22°51.85', W41°58.36'). B) Another outcrop at the same island (S22°51.95', W41°58.70'). C) At the Ponta da Atalaia peninsula, Arraial do Cabo (S22°58.78'S, W42°01.67'). D) Tectonic breccia with angular clasts and hematite, muscovite, and calcite-rich matrix of the same outcrop. Gn - felsic granitic orthogneiss; Tb - tectonic breccia; Dy - mafic dyke; Ht - hematite, muscovite, and calcite-rich matrix.

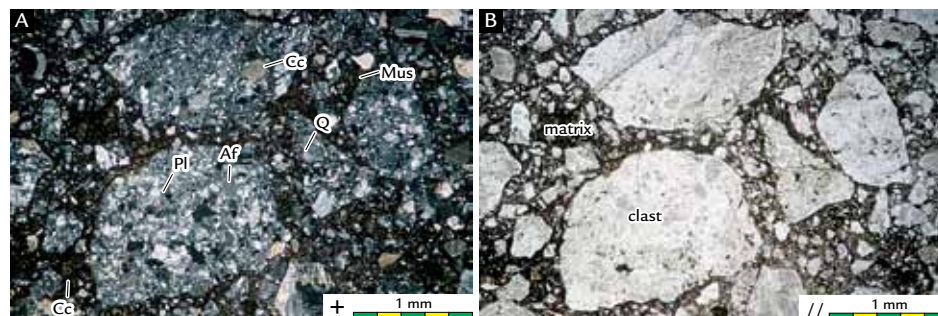


Figure 9

Photomicrography of the tectonic breccia at the Ponta da Atalaia peninsula, Arraial do Cabo (S22°58.78'S, W42°01.67'), belonging to the outcrop shown on Figure 8D. Note that the clasts themselves are fragments of tectonic breccia. Q - quartz; Af - alkaline feldspar; Pl - plagioclase; Mus - muscovite; Cc - carbonate.

is commonly found. The breccia zone is 2m wide and grades into the host gneiss. The mafic dyke is free from hydrothermal alteration.

At the Ponta da Atalaia peninsula of Arraial do Cabo (S22°58.78'S, W42°01.67'), a dyke of 3m in width cuts

a tectonic breccia of 1m in width (Figure 8C). At the border of the breccia there are intensely brecciated layers with the matrix of hematite, muscovite, and calcite, which are 2cm to 3cm thick. The clasts are angular of up to 1cm in size (Figure 8D). Microscopic observations show that

there are many clasts of 1 to 2mm in size made up of breccia with similar aspects of the host breccia, composed of crystal fragments cemented by hydrothermal carbonates (Figure 9).

These outcrops also confirm that the tectonic breccia is intruded by the Early

Cretaceous mafic dyke. The relative age (Figure 3B, 8B, 8C, 8D) and right-lateral

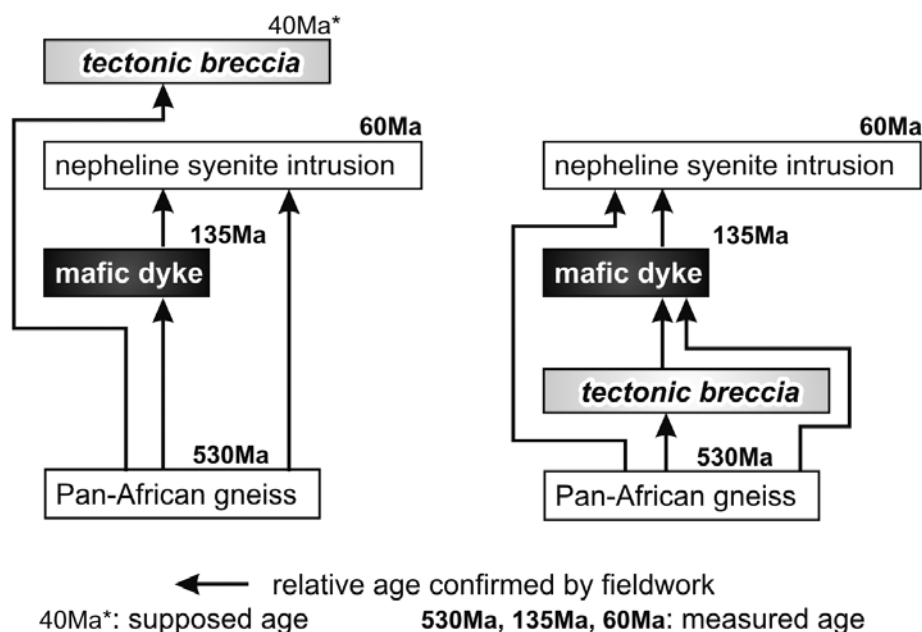
displacement (Figure 5C) suggest that the tectonic breccias are originated from the

brittle deformation phase of the latest stage of the Pan-African Orogeny (Figure 10).

A. Previous ideas

B. Present article

Figure 10 Comparative diagram representing the relative age of mafic dikes and tectonic breccias based on contact observations of fieldworks as presented by previous interpretations (e.g. Ferrari, 2001; Ferrari & Riccomini, 2003; Trotta, 2004) and the present article.



6. Discussion

The previous paper presented the conclusion that the silicified tectonic breccias of the State of Rio de Janeiro were formed by the hydrothermal event of the last stage of Early Cenozoic felsic alkaline magmatism at about 40Ma, in which a supposed regional heating event would have taken place all over the state of Rio de Janeiro (e.g. Ferrari, 2001; Ferrari & Riccomini, 2003; Trotta, 2004; Figure 10A). These authors pointed out that the

silicified tectonic breccias occur in the localities close to the alkaline intrusive bodies.

However, the tectonic breccias take place at the sites either close to or far from the felsic alkaline intrusions (Figure 11). The largest tectonic breccia of this region is present at Carapebus, which is situated almost 100 km to the north-northeast of the closest alkaline body, Morro de São João. In fact, there is no notable relation-

ship in spatial distribution between the tectonic breccias and the felsic alkaline intrusions. In addition, the preferred direction of the tectonic breccia is about N50°E to N60°E, which is according to the strike of the gneiss and shear zones the Ribeira metamorphic belt, which were formed during the Pan-African Orogeny, and not, to the lineament direction of the felsic alkaline intrusive rock bodies, N80°W.

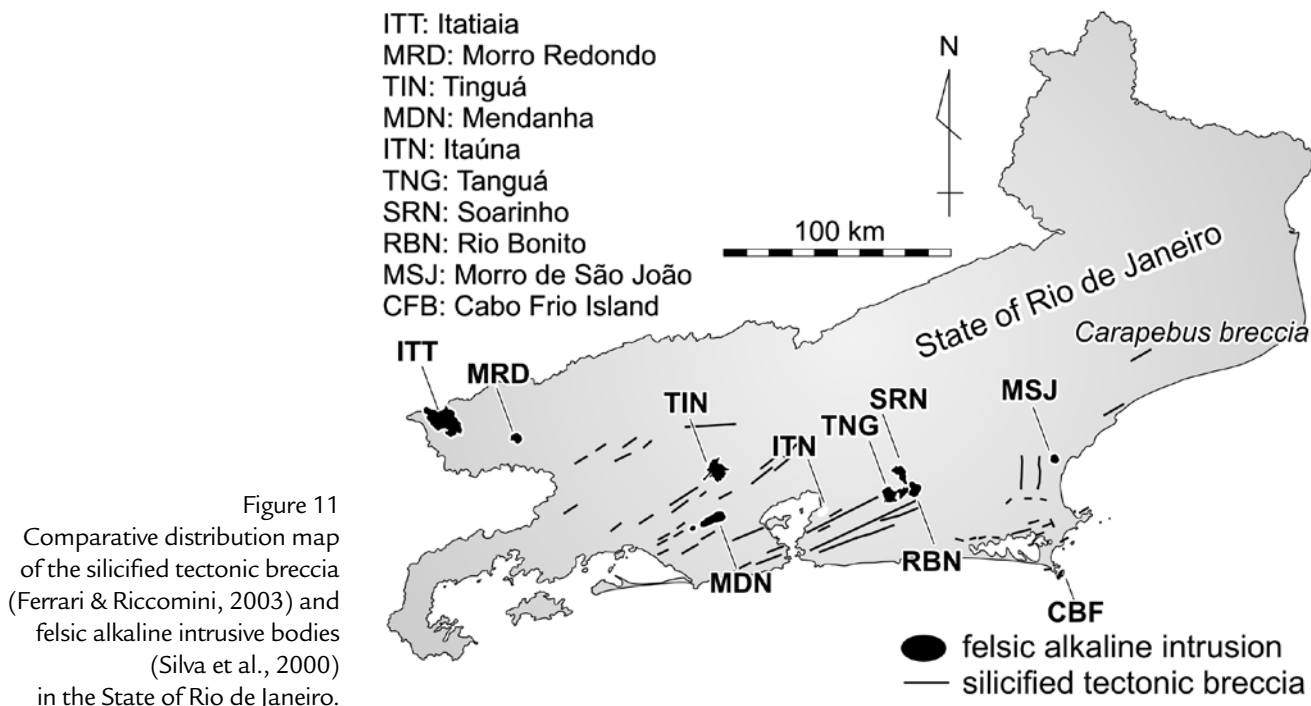


Figure 11 Comparative distribution map of the silicified tectonic breccia (Ferrari & Riccomini, 2003) and felsic alkaline intrusive bodies (Silva et al., 2000) in the State of Rio de Janeiro.

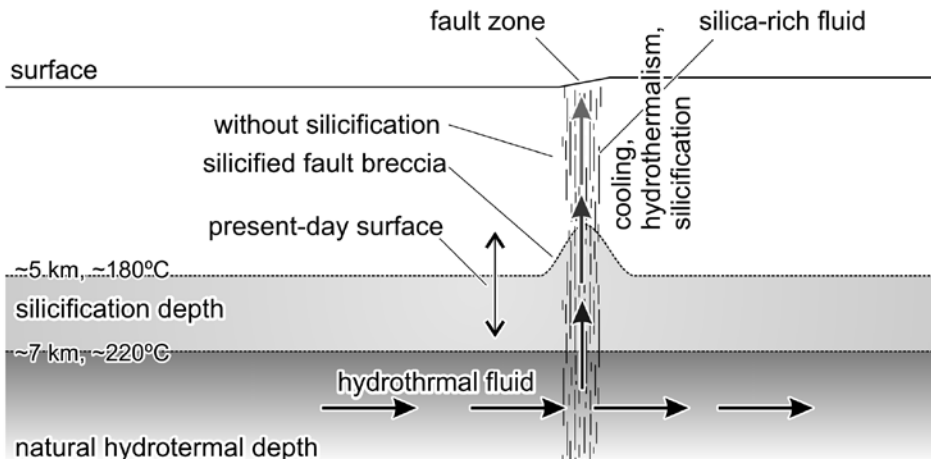


Figure 12
Process for the silicification and hydrothermalism of the Carapebus tectonic breccia during earthquake in the geologic time, proposed by Zimbres et al. (1989).

Some of the alkaline intrusive bodies are accompanied by breccias with hydrothermal evidences, such as Itatiaia (Brotsu et al., 1997), Mendanha (Motoki et al., 2007a; b), Itaúna (Motoki et al., 2008b; c), Tanguá (Valença, 1980; Motoki et al., 2010), and Cabo Frio Island (Sichel et al., 2008; Motoki et al., 2008d). However, according to the field descriptions and petrographic observations, they are not tectonic breccia but vent-filling subvolcanic pyroclastic rocks (e.g. Motoki & Sichel, 2006; Motoki et al., 2007c).

Zimbres et al. (1989) proposed a unique model for the origin of the Carapebus breccia. This silicified tectonic breccia is supposed to have been formed during the brittle deformation phase in the last stage of the Pan-African Orogeny. The direction of the tectonic breccia zone, N40°E, is favourable to this idea. They considered that the hydrothermal

silicification is of tectonic origin, without participation of magmatism. The geothermal gradient of continental regions is generally 2.5° to 3.0°/km. In this condition, the localities deeper than 7 km are hotter than 200°C and any H₂O present there is in hydrothermal condition. While the hydrothermal fluid stays in this depth, no hydrothermal activities take place in shallower places.

When earthquake and consequent fault movement take place, an abrupt stress change occurs, causing hydrothermal liquid movement. As soon as the hydrothermal flow crosses the fault zone, a part of the hydrothermal fluid rises up along the fault. During the ascension, the hydrothermal liquid cools down and the tectonic breccia is submitted to hydrothermalism (Figure 12). The fault zone is consolidated and transforms from weak zone into firm zone. According to the

progress of this process, the aftershocks reduce either in frequency or in intensity. When the fault zone is completely frozen, the aftershocks become null.

The fault breccia is consolidated by hydrothermal activities. So, not all the spans of the fault are weak zone but some of them work as firm zones. Therefore, the crust stress accumulates at the firm zones. When the stress increases to the limit of the rock resistance, the frozen fault breccia breaks down and a new earthquake occurs. The new fault movement crushes the entire fault zone and newly formed breccia is consolidated again by the tectonic hydrothermalism and consequent silicification. The repeated earthquakes result and the consequent stick-slip fault displacements result the multiple cycles of brecciation, hydrothermalism, and silicification of the fault breccia. This phenomenon would occur at a depth a

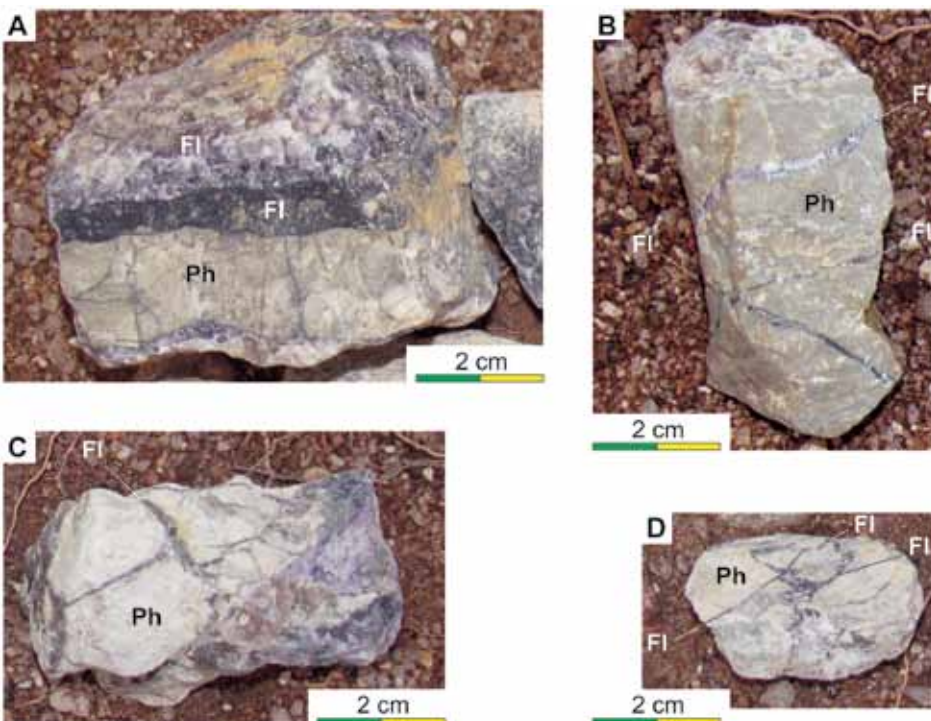


Figure 13
Fluorite veins present in strongly hydrothermalised phonolite of the Tanguá intrusive complex, State of Rio de Janeiro:
A) Vein with more than 3 cm in width.
B), C), D) Veins narrower than 5 mm.
The samples are obtained from the quarry situated at 22°43.59' 42°44.75'.
FI - fluorite vein,
Ph - hydrothermal phonolite.

little shallower than 7km.

This idea is supported by the clasts made up of breccia fragments with similar aspects of the host tectonic breccia, the textures of recrystallisation, and resorption of quartz, which are observed in the Carapebus breccia. As mentioned before, the fault breccias of the Cabo Frio and Arraial do Cabo area also have similar breccia clasts. The above-mentioned model provides an additional explanation for the stick-slip movements (e.g. Byerlee & Brace, 1968; Byerlee, 1970; Byerlee & Summers, 1975; Byerlee et al., 1978) of faults which are present in continental regions.

The tectonic breccias of the State of Rio de Janeiro have a wide variation in rock body size, clast form, clast-matrix ratio, texture, hydrothermal type, and silicification grade. The Carapebus breccia zone is long and wide and its silicification

grade is quite strong. The Canaã breccia (about S22°37', W43°17') is smaller in size but the silicification grade is very high. The Ilha do Japonês breccia is much smaller and hydrothermalism is much more expressive in hematite, muscovite, and calcite dissemination than silicification. The breccia zones at Arraial do Cabo are small, from 0.5 to 2 m wide and hematite, muscovite, and calcite are relevant.

Considering this variety, it is possible to exist more than one origin for the silicified tectonic breccia. For example, the hydrothermalism of the tectonic breccias of the Cabo Frio and Arraial do Cabo took place before the mafic dyke intrusion and they are originated probably from the brittle deformation phase of the last stage of the Pan-African Orogeny of the Cambrian to the Ordovician.

On the other hand, the breccia of

Tanguá is characterised by the clast made up of the host phonolite of very strong hydrothermal alteration (Figure 13). The original texture of the host phonolite is no longer preserved. No clasts are made up entirely of hydrothermally altered phonolite. No clasts composed of breccia, such as that of Figure 9, are recognised. This observation indicates that the brecciation took place only once and not repeatedly. All of the fractures are filled completely by fluorite suggesting that the fractures were formed by flour-rich fluid injection and consequent expansion of the veins. Therefore, this breccia could be related to the heating event by the intrusion of felsic alkaline magma at the Early Cenozoic, about 66.8Ma (Motoki et al., 2010), and different from the above-mentioned tectonic breccias either in the origin and/or the formation age.

7. Conclusion

The study of contact outcrops between the tectonic breccia and the early Cretaceous mafic dyke of the Cabo Frio and Arraial do Cabo areas, State of Rio de Janeiro, Brazil, lead to the following conclusions:

1. On the outcrop close to Ilha do Japonês, the tectonic breccia is 10m to 20m wide and strikes to N30°E. The clasts are angular and auto-brecciation texture is common. The matrix is firmly consolidated by hydrothermalism evidenced by the dissemination of hematite, muscovite, and calcite. The silicification by chalcedony is not very expressive. The

clasts are angular with auto-brecciation texture and composed of breccia fragments similar to the host tectonic breccia.

2. The mafic dyke is 7m to 10m wide, strikes to N45°E and is correlated to the Early Cretaceous tholeiitic magmatism. Along the contact with the tectonic breccia, there is well-defined chilled margin characterised by basalt and prismatic joints. No notable hydrothermalism is observed in the mafic dyke.

3. At the Conchas Beach, Cabo Frio, and the Pontal da Atalaia, Arraial do Cabo, there are four additional contact outcrops that demonstrate the same

intrusive relationship. The clasts of these breccias are also formed by breccia of aspects similar to the host tectonic breccia.

4. Unlike previous opinions, the mafic dyke is intrusive into the tectonic breccia, that is, the breccia is older than the Early Cretaceous. It is possible that the breccias are originated from the brittle deformation phase during the last stage of the Pan-African Orogeny.

5. The clasts composed of the breccia suggest that the fault movement, tectonic breccia formation, and hydrothermalism consolidation of the fault zone occurred repeatedly.

8. Acknowledgement

A part of the instruments for the fieldworks and the resources for the office work were supported by FAPERJ (Fundação de Amparo à Pesquisa do Estado do

Rio de Janeiro, Carlos Chagas Filho) according to project E26/110.279/2008 and E26/110.928/2008. MSc. Samuel Martins da Silva of the Federal Fluminense Uni-

versity (Universidade Federal Fluminense) had helpful field assistance. The authors are grateful to the above-mentioned institutions and scientist.

9. Referências bibliográficas

- AL-MISHWAT, A.T. A Field Trip to the Rio Paraíba do Sul Transpressive Shear Zone, Rio de Janeiro, SE Brazil. *Gondwana Research*, v. 4, n. 2, p. 260-261, 2001.
- BILLI, A. Grain size distribution and thickness of breccia and gouge zones from thin (<1 m) strike-slip fault cores in limestone. *Journal of Structural Geology*, v. 27, n. 10, p. 1823-1837, 2005.
- BROTZU, P., GOMES, C. B., MELLUSO, L., MORBIDELLI, L., MORRA, V., RUBERTI, E. Petrogenesis of coexisting SiO₂-undersaturated to SiO₂-oversaturated felsic igneous rocks: the alkaline complex of Itatiaia, southern eastern Brazil. *Lithos*, v. 40, p. 133-156, 1997.
- BYERLEE, J.D. The mechanics of stick-slip. *Tectonophysics*, v. 9, n. 5, p. 475-486, 1970.
- BYERLEE, J.D., BRACE, W.F. Stick slip, stable sliding, and earthquakes - effect of rock type, pressure, strain rate, and stiffness. *Journal of Geophysical Research*, v.

- 73, n. 18, p. 6031-6037, 1968.
- BYERLEE, J.D., MJACHKIN, V., SUMMERS, R., VOEVODA, O. Structures developed in fault gouge during stable sliding and stick-slip. *Tectonophysics*, v. 44, n. 1-4, p. 161-171, 1978.
- BYERLEE, J.D., SUMMERS, R. Stable sliding preceding stick-slip on fault surfaces in granite at high pressure. *Pure and Applied Geophysics*, v. 113, p. 63-68, 1975.
- CAMPBELL, S.W. Chemical weathering associated with tafoni at Papago Park, Central Arizona. *Earth Surface Process and Landforms*, v. 24, p. 271-278, 1999.
- CAMPOS NETO, M.O. Orogenic systems from Southwestern Gondwana: An approach to Brasiliano-Pan Africa cycle and orogenic collage in southeastern Brazil. In: CORDANI, U.G., MILANI, E.J., THOMÁZ FILHO, A., CAMPOS, D.A. (eds.). *Tectonic Evolution of South America*, Rio de Janeiro, Sociedade Brasileira de Geologia, p. 255-265, 2000.
- CLADOUHOS, T.T. Shape preferred orientations of survivor grains in fault gouge. *Journal of Structural Geology*, v. 21, n. 4, p. 419-436, 1999.
- DORN, R.L. 2004. Case hardening. In: GOUDIE, A.S. (Ed.). *Encyclopedia of Geomorphology*, Loutledge, London, 118-119.
- EGYDIO-SILVA, M., MAINPRICE D. Determination of stress directions from plagioclase fabrics in high grade deformed rocks (Além Paraíba shear zone, Ribeira fold belt, southeastern Brazil). *Journal of Structural Geology*, v. 21, n. 12, p. 1751-1771, 1999.
- FARMER, J.D. Case-hardening of rocks on Mars: evidence for water-mediated weathering processes. *Abstracts of annual meeting of the Geological Society of America*, Salt Lake City, paper 223-5, CD, 2005.
- FERRARI, A.L. *Evolução Tectônica do Graben da Guanabara. São Paulo*. São Paulo: Instituto de Geociências, Universidade São Paulo (IG/USP), 2001. 412 p. (Doctor Theses).
- FERRARI, A.L., RICCOMINI, C. Análise estrutural das brechas tectônicas silicificadas do Gráben da Guanabara - RJ. *Boletim de Resumos do 9º Simpósio Nacional de Estudos Tectônicos*, Búzios-RJ. Rio de Janeiro, SBG, p. 137-139, 2003.
- HEILBRON, M., MACHADO, N. Timing of terrane accretion in the Neoproterozoic-Eopaleozoic Ribeira orogen (se Brazil). *Precambrian Research*, v. 125, p. 87-112, 2003.
- HEILBRON, M., MOHRIAK, W., VALERIANO, C.M., MILANI, E., ALMEIDA, J.C.A., TUPINAMBÁ, M. From collision to extension: the roots of the southeastern continental margin of Brazil. *Geophysical Monograph*, American Geophysical Union, v. 115, p. 1-32, 2000.
- MCALISTER, J.J., SMITH, B.J., CURRAN, J.A. The use of sequential extraction to examine iron and trace metal mobilisation and the case-hardening of building sandstone: A preliminary investigation. *Microchemical Journal*, v. 74, p. 5-18, 2003.
- MOTOKI, A., SICHEL, S.E. Avaliação de aspectos texturais e estruturais de corpos vulcânicos e subvulcânicos e sua relação com o ambiente de cristalização, com base em exemplos do Brasil, Argentina e Chile. *REM - Revista Escola de Minas*, v. 59, n. 1, p. 13-23, 2006.
- MOTOKI, A., SICHEL, S.E. Hydraulic fracturing as a possible mechanism of dyke-sill transitions and horizontal discordant intrusions in trachytic tabular bodies of Arraial do Cabo, State of Rio de Janeiro, Brazil. *Geofísica Internacional*, Mexico City, v. 47, n. 1, p. 13-25, 2008.
- MOTOKI, A., SOARES, R.S., LOBATO, M., SICHEL, S.E., AIRES, J.R. Weathering fabrics in felsic alkaline rocks of Nova Iguaçu, State of Rio de Janeiro, Brazil. *REM-Revista Escola de Minas*, Ouro Preto, v. 60, n. 3, p. 451-458, 2007a.
- MOTOKI, A., SOARES, R., NETTO, A.M., SICHEL, S.E., AIRES, J.R., LOBATO, M. Geologic occurrence shape of pyroclastic rock dykes in the Dona Eugênia River Valley, Municipal Park of Nova Iguaçu, Rio de Janeiro. *Geociências*, Rio Claro, v. 26, n. 1, p. 67-82. 2007b.
- MOTOKI, A., SOARES, R.S., NETTO, A.M., SICHEL, S.E., AIRES, J.R., LOBATO, M. Genetic reconsideration of the Nova Iguaçu Volcano model, State of Rio de Janeiro, Brazil: eruptive origin or subvolcanic intrusion? *REM- Revista Escola de Minas*, Ouro Preto, v. 60, n. 4, p. 583-592. 2007c.
- MOTOKI, A., SICHEL, S.E., SOARES, R.S., NEVES, J.L.P., AIRES, J.R. Geological, lithological, and petrographical characteristics of the Itaúna Alkaline Intrusive

- Complex, São Gonçalo, State of Rio de Janeiro, Brazil, with special attention of its emplacement mode. *Geociências*, Rio Claro, v. 27, n. 1, p. 33-44, 2008a.
- MOTOKI, A., SICHEL, S.E., SOARES, R.S., AIRES, J.R., SAVI, D.C., PETRAKIS, G.H., MOTOKI, K.F. Vent-filling pyroclastic rocks of the Mendanha, the Itaúna, and the Cabo Frio Island, State of Rio de Janeiro, Brazil, and their formation process based of the conduit implosion model. *Geociências*, Rio Claro. v. 27, n. 3, p. 451-467, 2008b.
- MOTOKI, A., PETRAKIS, G.H., SICHEL, S.E., CARDOSO, C.E., MELO, R.C., SOARES, R.S., MOTOKI, K.F. Landform origin of the Mendanha Massif, State of Rio de Janeiro, Brazil, based on the geomorphological analyses by summit level map technique. *Geociências*, Rio Claro, v. 27, n. 1, p. 99-115, 2008c.
- MOTOKI, A., SICHEL, S.E., SAVI, D.C., AIRES, J.R. Intrusion mechanism of tabular intrusive bodies of subhorizontal discordant emplacement of the Cabo Frio island and neighbour areas, State of Rio de Janeiro, Brazil. *Geociências*, Rio Claro, v. 27, n. 2, p. 207-218, 2008d.
- MOTOKI, A., SICHEL, S.E., CAMPOS, T.F.C., SRIVASTAVA, N.K., SOARES, R.S. Present-day uplift rate of the Saint Peter and Saint Paul Islets, Equatorial Atlantic Ocean. *REM- Revista Escola de Minas*, Ouro Preto, v. 62, n. 3. p. 331-342, 2009a.
- MOTOKI, A., SICHEL, S.E., PETRAKIS, G.H. Genesis of the tabular xenoliths along contact plane of the mafic dykes of Cabo Frio area, state of Rio de Janeiro, Brazil: Thermal delamination or hydraulic shear fracturing? *Geociências*, Rio Claro, v. 28, n. 1, p. 15-26, 2009b.
- MOTOKI, A., SICHEL, S.E., VARGAS, T., AIRES, J.R., IWANUCH, W., MELLO, S.L.M., MOTOKI, K.F.; SILVA, S., BALMANT, A., GONÇALVES, J. Geochemical evolution of the felsic alkaline rocks of Tanguá, Rio Bonito, and Itaúna intrusive bodies, State of Rio de Janeiro, Brazil. *Geociências*, Rio Claro, v. 29, n. 3, p. 291-310, 2010.
- PEATE, D.W., HAWKESORTH, C.J., MANTOVANI, M.S.M. Chemical stratigraphy of the Paraná lavas (South America): classification of magma types and their spatial distribution. *Bulletin of Volcanology*, v. 55, p. 119-139, 1992.
- PETRAKIS, G.H., MOTOKI, A., SICHEL, S.E., ZUCCO, L.L., AIRES, J.R., MELLO S.L.M. Geologia de jazidas de brita e areia artificial de qualidade especial: exemplos do álcali sienito de Nova Iguaçu, RJ, e riolito de Nova Prata, RS. *Geociências*, Rio Claro, v. 29, n. 1, p. 21-32, 2010.
- RICCOMINI, C., ASSUMPÇÃO, M. Quaternary tectonics in Brazil. *Episodes*, v. 22, n. 3, p. 221-225, 1999.
- SCHMITT, R.S., TROUW, R.F.J., MEDEIROS, R.S., DANTAS, E.L. Age and geotectonic setting of Late Neoproterozoic juvenile mafic gneisses and associated paragneisses from the Ribeira belt (SE Brazil) based on geochemistry and Sm-Nd data - Implications on Gondwana assembly. *Gondwana Research*, v. 13, n. 4, p. 502-515, 2008b.
- SCHMITT, R.W., TROUW, R.A.J., VAN SCHMUS, R., PASSCHIER, C.W. Cambrian orogeny in the Ribeira Belt (SE Brazil) and correlations within West Gondwana: ties that bind underwater. Pankhurst, R.J., Trouw, R.A., Brito Neves, B.B., De Wit, J.J. Eds. West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. Geological Society of London, Special Publications, v. 294, p. 279-296, 2008a.
- SICHEL, S.E., MOTOKI, A., SAVI, D.C., SOARES, R.S. 2008. Subvolcanic vent-filling welded tuff breccia of the Cabo Frio Island, State of Rio de Janeiro, Brazil. *REM - Revista Escola de Minas*, Ouro Preto, v. 61, n. 4, p. 423-432, 2008.
- SILVA, L.C., SANTOS, R.A., DELGADO, I.M., CUHA, H.C.S. *Mapa Geológico do Estado do Rio de Janeiro, escala 1:250.000*. Serviço Geológico do Brasil, CPRM, Rio de Janeiro, 2000.
- TROTTA, M.C. *Análise estrutural dos diques e brechas tectônicas da região leste do Gráben da Guanabara, Estado do Rio de Janeiro*. Niterói: Department of Geology, Federal Fluminense University (LAGEMAR/UFF), 2004. 62p. (Master Theses, unpublished)
- TURKINGTONA, A.V., PARADISEB, T.R. Sandstone weathering: a century of research and innovation. *Geomorphology*, v. 67, p. 229-253, 2005.
- VALENÇA J.G. *Geology, petrography and petrogenesis of some alkaline igneous complexes of Rio de Janeiro State, Brazil*. Canada: West Ontario University, 1980. 247p. (Doctor Thesis, unpublished).

- ZIMBRES, E., KAWASHITA, K., VAN SCHMUS, W.R. Evidências de um núcleo transamazônico na região de Cabo Frio, RJ e sua correlação com o Cráton de Angola, África. In: CONGRESSO BRASILEIRO DE GEOLOGIA, 36. *Anais...* Natal, SGB, v. 6, p. 2735-2743, 1990.
- ZIMBRES, E., MOTOKI, A., SANTOS, R.A. Brecha de Carapebus, Macaé-RJ: Evidências de origem tectônica. *Boletim de Resumos do 1º Simpósio de Geologia do Sudeste*, Rio de Janeiro, SBG, p. 122-123, 1989.
- ZWINGMANN, H., MANCKTELOW, N. Timing of Alpine fault gouges. *Earth and Planetary Science Letters*, v. 223, n. 3-4, p. 415-425, 2004.

Artigo recebido em 13 de junho de 2010. Aprovado em 18 de novembro de 2010.