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 ?

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ABSTRACT – This article presents field descriptions and genetic considerations for the tabular xenoliths observed along contact plane of the mafic dykes of Cabo Frio and Arraial do Cabo area, State of Rio de Janeiro, Brazil. They are 10 cm to 1 m wide, commonly 30 to 50 cm, with horizontal extension up to 100 m and vertical extension at least 20 m. The aspect ratio measured on the outcrop surface is more than 100. The xenolith terminals are generally sub-rectangular, but they sometimes show acute edges. The fractures parallel to the xenolith extension are often observed. These fractures and the high aspect ratio suggest a strong tendency of fracture formation in parallel to the dyke contact plane. For the tabular xenolith genesis, the thermal delamination model is a possible opinion. However, considering the very high-aspect ratio of the tabular xenoliths and their occurrence with the leftward branching of the mafic dykes, the model based on combined effects of the dyke branching by the hydraulic shear fracturing and xenolith detachment by the thermal delamination is more plausible.
Keywords: tabular xenolith, mafic dyke, thermal delamination, hydraulic shear fracturing, Cabo Frio, Arraial do Cabo.

RESUMO – *A. Motoki, S.E. Sichel, G.H. Petrakis - Xenólitos tabulares ao longo do plano de contato dos diques máficos da área de Cabo Frio, RJ: Delaminação térmica ou fraturamento hidráulico de cizalhamento ?* Este artigo apresenta descrições de campo e consideração genéticas para os xenólitos tabulares observados ao longo do plano de contato dos diques máficos da área de Cabo Frio e Arraial do Cabo, RJ. Esses têm 10 cm a 1 m de largura, comumente 30 a 50 cm, com extensão horizontal de até 100 m e extensão vertical de pelo menos 20 m. A razão entre comprimento e largura medida na superfície dos afloramentos é maior do que 100. As extremidades dos xenólitos são geralmente sub-retangulares, porém encontram-se às vezes extremidades agudas. As fraturas paralelas à extensão dos xenólitos são comumente observadas. Essas fraturas e a alta razão entre comprimento e largura sugerem uma forte tendência de fraturamento em paralela ao plano de contato dos diques. Para a gênese dos xenólitos tabulares, o modelo de delaminação térmica é uma possível opinião. Entretanto, considerando a alta razão entre comprimento e largura muito alta dos xenólitos tabulares e sua ocorrência junto com a ramificação sinistral dos diques máficos, o modelo com base nos efeitos conjuntos da ramificação dos diques pelo fraturamento hidráulico de cizalhamento e descolamento dos xenólitos pela delaminação térmica é mais aplausível.
Palavras-chave: xenólito tabular, dique máfico, delaminação térmica, fraturamento hidráulico de cizalhamento, Cabo Frio, Arraial do Cabo.

INTRODUCTION

In Brazilian southeast region, a great number of early Cretaceous large tholeiitic dykes are found (Figure 1). They are generally 8 to 10 m wide and considered to be feeder dykes of the Paraná Continental Flood Basalt (Peate et al., 1992). The dyke swarms develop along three main axes configured in radial directions: 1) the South Branch, along the Atlantic coast of the State of Santa Catarina and Rio Grande do Sul (Deckart

et al., 1998); 2) the West-Northwest Branch, Ponta Grossa area of the State of Paraná (Renne et al., 1996); 3) the Northeast Branch, along the Atlantic coast of the State of São Paulo and Rio de Janeiro. The dykes of the South Branch and the West-Northwest Branch are confirmed to be feeder of the lava flows of the Paraná Basalt. However, in the Northeast Branch, the continental lava flows have been completely

eliminated by large-scale regional uplift and deep denudation.

The dyke swarms of the Northeast Branch are observed in many localities along the coast (Figure 2), such as Ubatuba, Ilha de São Sebastião, Ilha dos Búzios, Maciço Tijuca, Ponta Negra, Cabo Frio, Arraial do Cabo, and Armação de Búzios. Some of them are well exposed on sea-cliffs permitting detailed field observations, such as branching mode, dyke terminals, and en-echelon dyke linkage (e.g. Motoki, 1994).
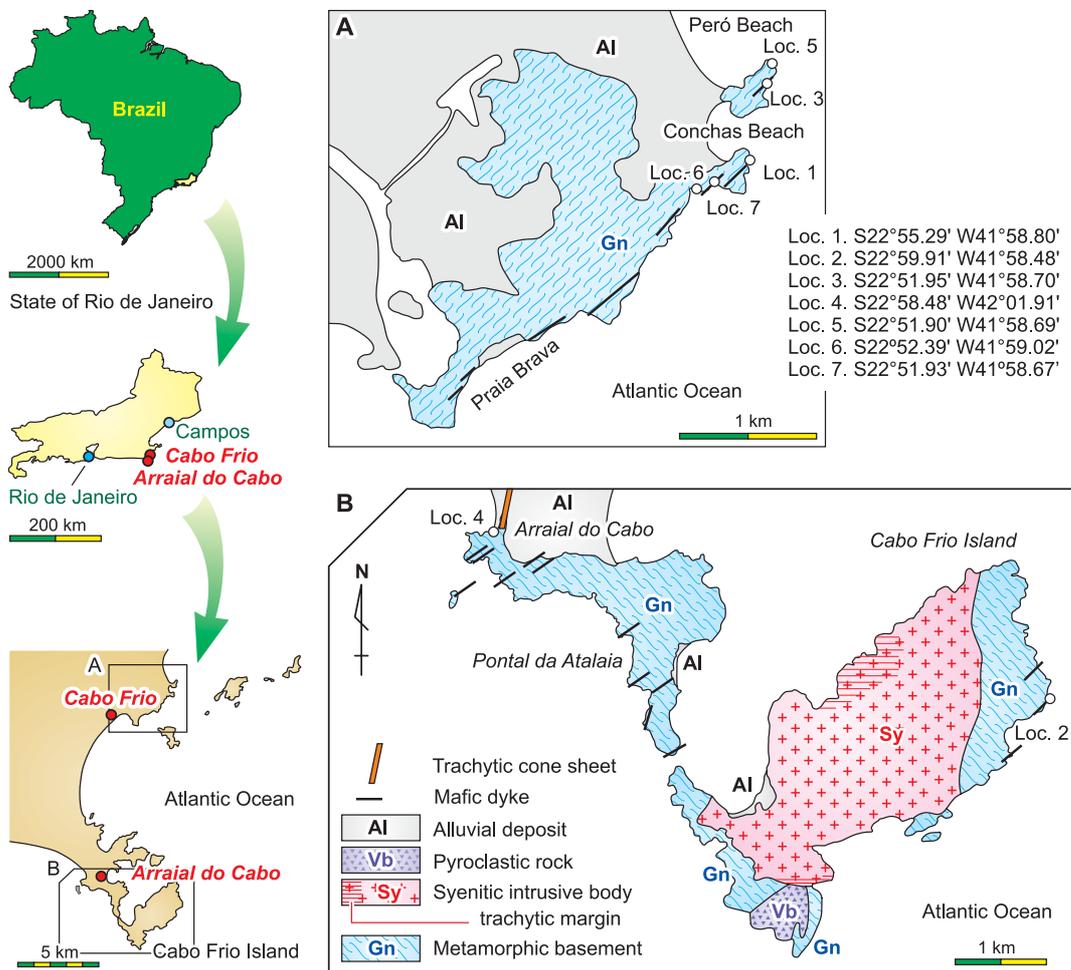

FIGURE 1. Geologic maps of the studied areas: A) Conchas Beach, Cabo Frio; B) Cabo Frio Island, Arraial do Cabo, modified from Motoki etal. (2009). Both of the areas are situated in State of Rio de Janeiro, Brazil.
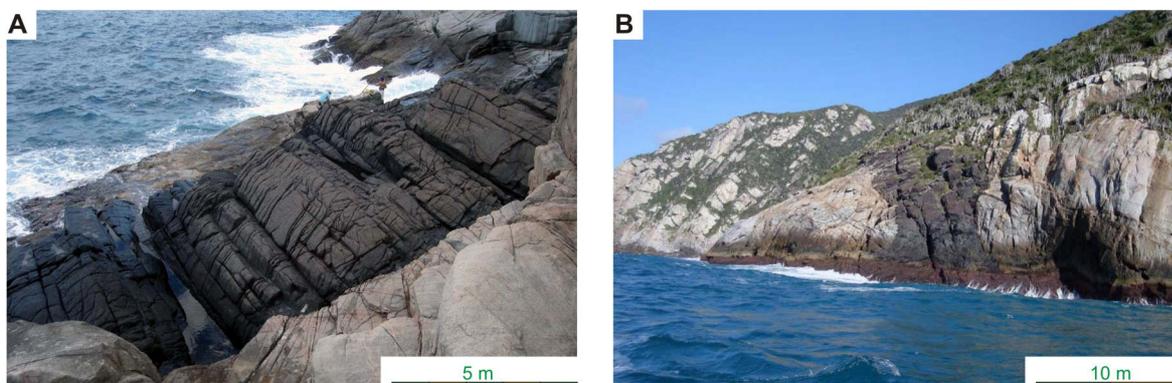
FIGURE 2. Large basaltic dykes with horizontal columnar joints of the studied area: A) Dyke of west side at the Conchas Beach, Cabo Frio (Loc. 1); B) Dyke at east cliff the Cabo Frio Island, Arraial do Cabo (Loc. 2). The host rock is orthogneiss of the Congo Craton.

Some of the dykes, especially large and wide ones, contain narrow and long tabular xenoliths along the contact plane (Figure 3). Up to the present, they have been little interested, and therefore, almost no papers are available.

The present article reports the field descriptions of these xenoliths exposed at Cabo Frio and Arraial do Cabo areas, and considers their origin based on the models of thermal delamination and hydraulic shear fracturing.
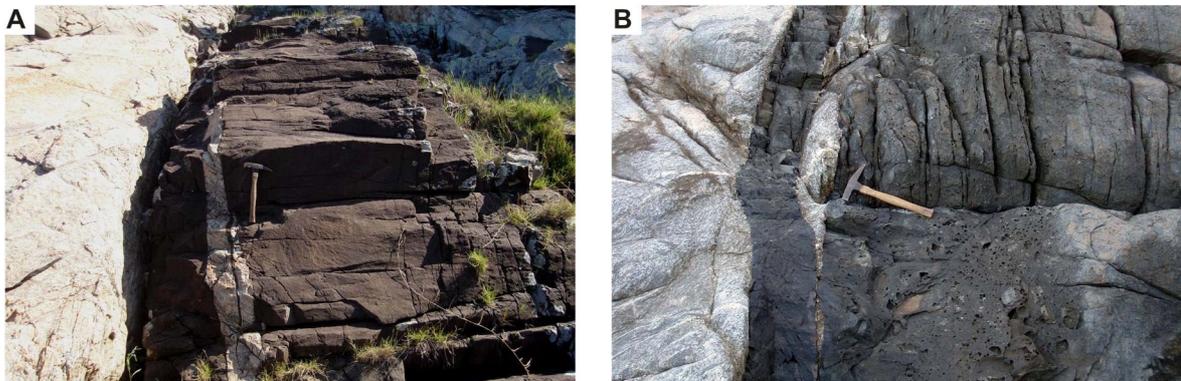
FIGURE 3. High-aspect ratio tabular xenoliths along the contact of early Cretaceous mafic dyke: A) East side Conchas Beach, Cabo Frio, State of Rio de Janeiro (Loc. 3); B) West side of the same beach (Loc. 2).

REGIONAL GEOLOGY

The Cabo Frio and Arraial do Cabo areas are underlain by the orthogneiss basement. Two U-Pb discordia datings by ID-TIMS show Hudsonian upper interception, 1975±6.5 Ma, interpreted to be of the granitic magma intrusion, and Pan-African lower interception, 501±6.0 Ma, attributed to the metamorphic age of the late stage of the continental collision event (Zimbres et al., 1990; Schmitt et al., 2008).

The strike of the above-mentioned gneiss ranges N10ºW to N30ºW being quite different from the general strike of the Pan-African gneiss of the adjacent area, N45ºE to 55ºE. Because of the difference, this area is considered to be an independent block, called Cabo Frio Terrane, composing a part of western margin of the Congo Craton (e.g. Schmitt et al., 2004; 2008). The metamorphic basement is cut by tectonic breccia with well-cemented matrix. The breccia is interpreted to be of the remnant brittle stage of the Pan-African tectonism (Motoki et al., 2008a).

The early Cretaceous mafic dykes take place forming dyke swarms. Some of them are more than 8 m wide and 3 km long. The centre of the dykes is constituted by gabbro with millimetric grain-size and the contact zone, by hialocrystalline to vitric basalt (Motoki & Sichel, 2006). The postulate is subvertical with preferred direction of N55ºE. This orientation is discordant with the host rock structure (Motoki & Sichel, 2008). Most of the mafic dykes are classified geochemically to be of low-Ti type. The whole-rock Ar-Ar datings for three dykes of Arraial do Cabo Peninsula indicate early Cenozoic ages, however the

age plateaus are highly disturbing (Bennio et al., 2003). Therefore, in this moment the intrusive ages are strongly believed to be about 135 Ma, based on the well-defined Ar-Ar ages of the correlated lava flows of southern Brazil (Stewart et al., 1996),

The fission track datings for apatite extracted from the basement rocks (e.g. Hackspachel et al., 2004; Motoki et al., 2007a) indicated that in Rio de Janeiro coast region there were a regional uplift and denudation of kilometric depth during the early Cenozoic. The emplacement depth of these mafic dykes is estimated to be 4 to 5 km (e.g. Motoki & Sichel, 2008). They should be feeder dykes of the early Cretaceous lava flows that might be present also in this area (Motoki, 1994).

The basement and the mafic dykes are cut by lamprophyre dykes, syenitic intrusive body of the same island, trachyte dykes contemporaneous to the syenite and newest phonolite dykes (Sichel et al., 2008). Similar syenitic intrusive bodies occur at Itatiaia (Brotsu et al., 1997), Morro Redondo (Brotsu et al., 1989), Tinguá, Mendanha (Motoki et al., 2007b), Tanguá, Rio Bonito, Soarinho, and Morro de São João (Brotsu et al., 2007). At the southwest corner of the Cabo Frio Island, pyroclastic rocks are present forming a subvolcanic conduit (Sichel et al., 2008), which is correlated to the vent breccia of Mendanha (Motoki et al., 2007c; 2008b), Itaúna (Motoki et al., 2008a), and Tanguá subvolcanic bodies (Motoki et al., 2008d). The subvolcanic conduits of the Cabo Frio Island cuts mafic dykes and lamprophyre dykes, but intruded by the syenitic body and felsic alkaline dykes.

DESCRIPTION OF THE TABULAR XENOLITHS

Some of the dyke outcrops expose tabular xenoliths emplaced in parallel to the contact plane (Figure 3). They are from 10 cm to 1 m wide, commonly from 30 to 50 cm, with horizontal extension up to 100 m and confirmed minimum vertical extension of 20 m. The aspect ratio measured on the outcrop surface is very high, more than 100 (Figure 3B; 4).

The contact planes of the tabular xenoliths are generally flat (Figure 4A). However, step contacts with unevenness of 10 to 30 cm are also observed (Figure 5B; 6A, Arrow 1). In some cases, curved contacts are found dykes show curved contact (Figure 5C).

In the tabular xenoliths, some fractures filled by mafic magma are observed. Most of them are parallel to xenolith extension. Many parallel fractures are associated with the step contacts (Figure 5D), but they can occur also without step contact (Figure 6A, Arrow 2). There are an oblique fractures (Figure 6A, Arrow 3; 6B, arrow 4) truncated by a parallel fracture (Figure 6C, Arrow 5). This observation indicates that this parallel fracture opened after the oblique fracture. On the outcrop, the fractures filled by the magma are exposed, but the blocks of the both sides might be linked in three-dimensional structure.

The large aspect ratio of these tabular xenoliths and the parallel fractures in the xenoliths formed at the last stage of the dyke intrusion suggest that a strong tendency of fracture formation parallel to the dyke contact was present at the intrusion process.

The terminals of the tabular xenoliths are generally rectangular (Figure 7A) but some of them have their tail-ends of acute edge (Figure 7B). Acute terminals are observed generally in the xenoliths with curved contact plane (Figure 3B). There are few outcrops showing that one terminal of the tabular xenolith is still linked to the country gneiss through a fractured zone (Figure 7C). In these cases, the xenolith detachment process is not complete.

The tabular xenoliths are observed generally along the contact of mafic dykes, but rarely in newer dykes of phonolite and trachyte. In these cases, the aspect ratio is lower, being less than 10. This observation suggests that low magma viscosity is an important factor for the formation of high-aspect ratio xenolith.
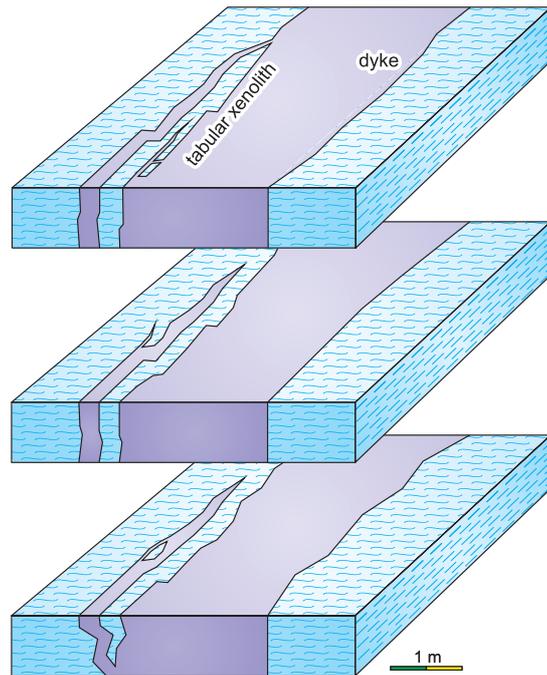

FIGURE 4. Schematic illustration of three-dimensional form of the tabular xenoliths along mafic dyke margin of Cabo Frio region, compiled from the field observations. The scale is not so exact and shows only approximate size of the dyke.
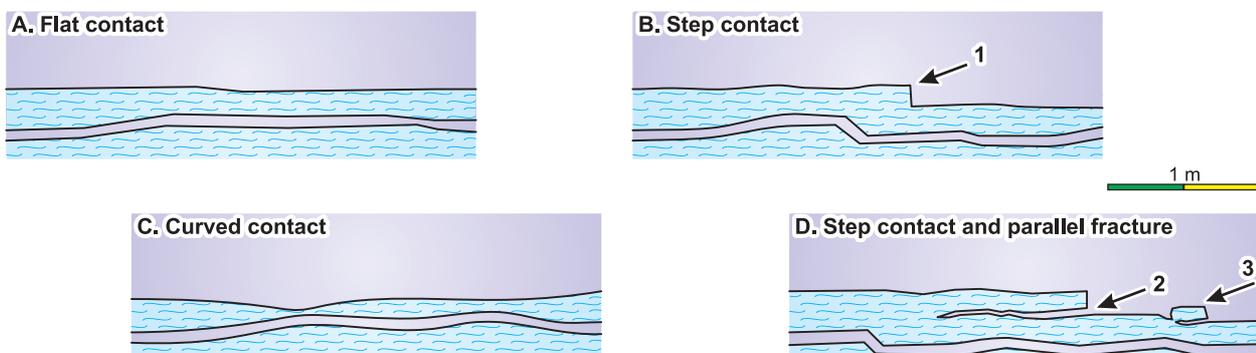
FIGURE 5. Contact plane types of the long tabular xenoliths according to the fields observations: A) Flat contact; B) Step contact; C) Curved contact; D) Step contact associated with a fracture parallel to the xenolith extension.
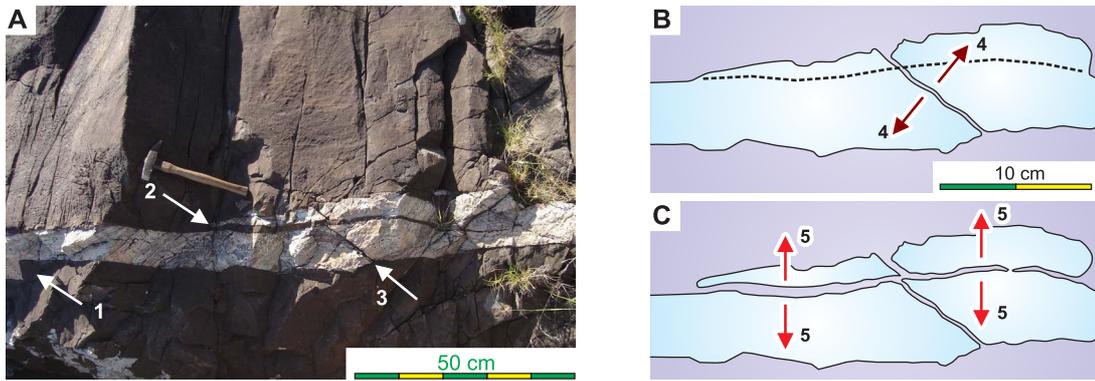
FIGURE 6. Fracture parallel to the xenolith extension observed at east side of the Conchas Beach (Loc. 3): A) Outcrop photo-mage; B) Formation of the oblique fracture, arrow 4; C) Formation of the parallel fracture (Arrow 5) after the oblique fracture.
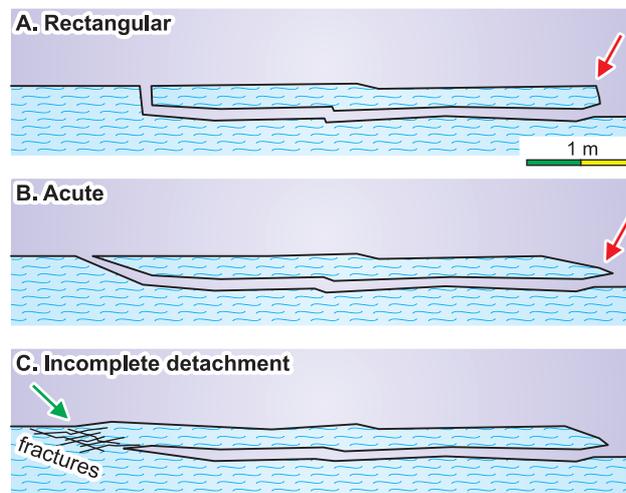
FIGURE 7. Schematic illustrations for the observed terminal types of the high-aspect ratio tabular xenoliths, compiled from the field observations: A) Rectangular terminal; B) Acute edge; C) Incomplete detachment. The scale is not so exact.

THERMAL DELAMINATION

As far as the authors are aware, no previous papers have discussed about the geneses of the above-mentioned high-aspect ration tabular xenoliths. Based on the field observations, the authors propose two possible mechanisms that can take place during the mafic dyke intrusion: 1) Thermal delamination; 2) Hydraulic shear fracturing.

The thermal delamination model was recently proposed by Motoki et al. (2005) in order to explain the geneses of the tabular xenoliths that are found in the contact zone of Pan-African granitic intrusion of the Gávea Rock (*Pedra da Gávea*; 22°59.89'S, 43°17.10'W), Rio de Janeiro city. When hot magma intrusion takes place into cold and brittle host rock, the thermal expansion by the magma is strong at the contact zone but less intense at distant portions. The differential

thermal expansion causes a fracture parallel to the contact plane and consequent detachment of wall rock plate (Figure 8). The similar field examples are observed also at Suruí Quarry, Magé (22°39.65'S, 43°06.83'W), State of Rio de Janeiro, and Ibrata Quarry (22°59.12'S, 43°26.78'W), Jacarepagua, Rio de Janeiro city.

In the case of early Cretaceous mafic dyke intrusion of the studied area, the differential thermal expansion must be much larger than the cases of granitic intrusions because of the high magma temperature, more than 1200 °C, and relatively shallow intrusion depth, 4 to 5 km from the surface (Motoki et al., 2008a; d).

In the mafic dykes there also are small tabular xenoliths, up to 15 x 4 cm in size, made up of host gneiss, configured in parallel to the contact plane

(Figure 9). There aspect ratio is not so high as the long tabular xenoliths of the Figure 3 and 6, ranging from 5 to 12, being close to that of the thermal delamination xenoliths of the Gávea Rock, 6 to 15 (Motoki et al., 2009).

The gneiss structure of these small xenoliths is usually discordant with the xenolith extension, sometimes sub-perpendicular. This fact indicates that the tabular shape is not originated from the gneiss banding, that is, pre-existing weak zone of the host gneiss, suggesting that they were possibly formed by the thermal delamination.

The thermal delamination model is a possible and consistent mechanism for the tabular xenolith genesis. The strong tendency of fracture formation parallel to the dyke contact corroborates this model (Figure 6). It is considered that the small tabular xenoliths of the Figure 9 are probably originated from this mechanism.

However, the aspect ratio of the large tabular xenoliths, more than 100, is much larger than the small xenoliths in the mafic dykes, less than 12, and the tabular xenoliths found in the granite bodies, less than 15. Therefore, so high aspect ratio is difficult to be justified only by the thermal delamination.

Most of the large tabular xenoliths take place on the right side of step contact of the mafic dykes (Figure 10A, Arrow). The opposite cases are rare (Figure 10B). If they were originated purely from thermal delamination process, both of the cases must be observed in evenness. In addition, the xenoliths between the two step contacts (Figure 10C) must be present, however no such an example has been observed. Some outcrops show that the tabular xenoliths are present between two parallel dykes that intruded within a close interval (Figure 3B; 11).

These observations suggest that the thermal delamination can be an important mechanism, but may not the most important one for the xenolith genesis. In order to explain the above-mentioned field observations, the authors propose another model: Dyke branching by the hydraulic shear fracturing and xenolith detachment by the thermal delamination.
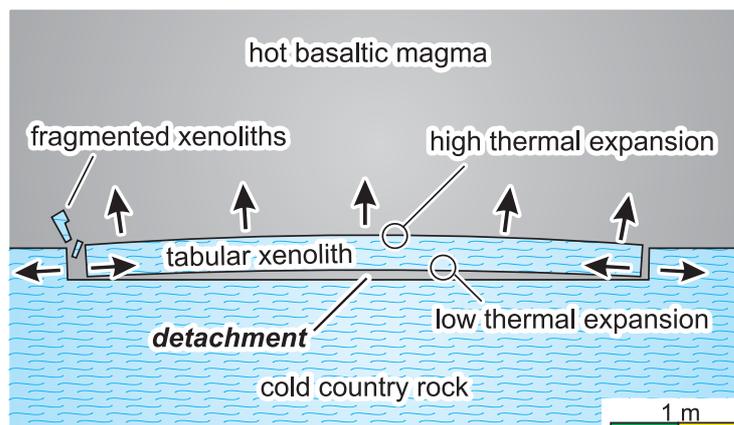

FIGURE 8. Detachment process of a rock plate by differential thermal expansion, the phenomenon called the thermal delamination, resulting a tabular xenoliths along the dyke contact, after Motoki et al. (2005). The scale is not so exact.
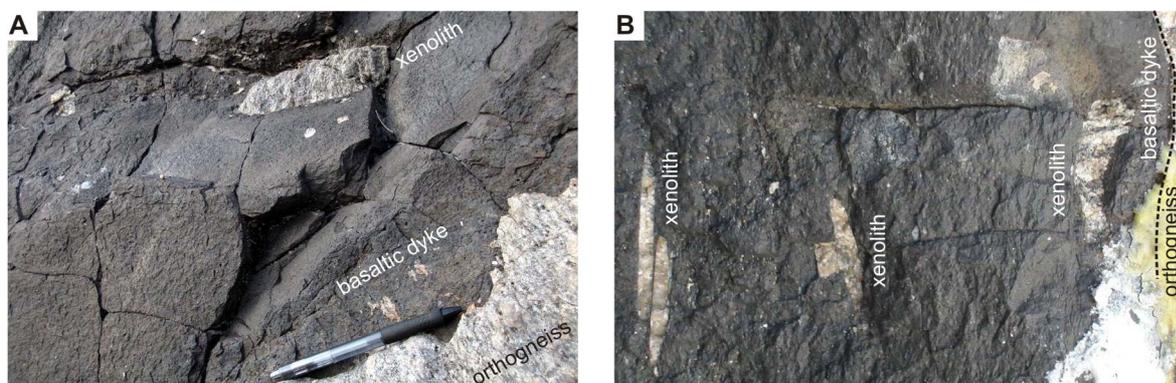
FIGURE 9. Small tabular xenoliths of orthogneiss emplaced close to the mafic dyke contact, Praia Grande, Arraial do Cabo, State of Rio de Janeiro, Brazil (Loc. 4).
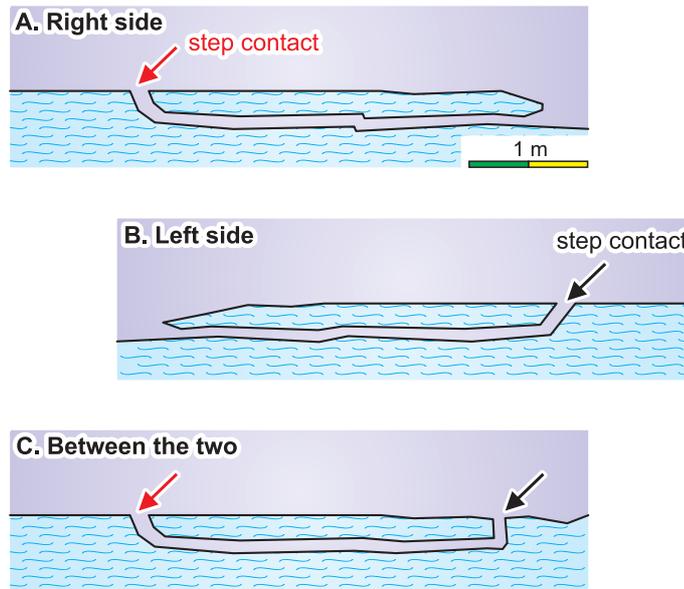
FIGURE 10. Positions of the tabular xenolith relative to step contact of the mafic dyke: A) Right side of the step contact, common case; B) Left side of the step, rare case; C) Between two steps, no case has been observed.
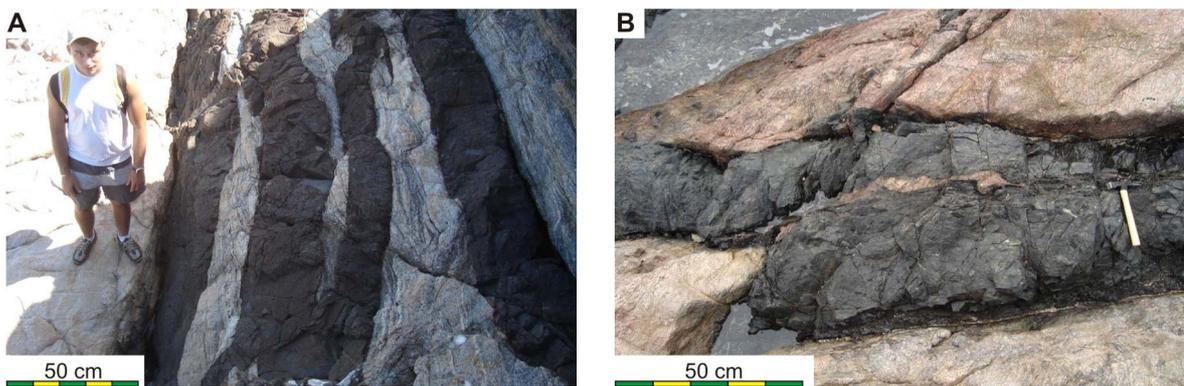
FIGURE 11. Dyke branching and tabular xenolith formation: A) East side of the Conchas Beach, Cabo Frio (Loc. 5); B) West side of the same beach (Loc. 6).
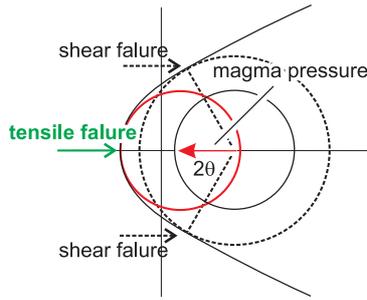
HYDRAULIC SHEAR FRACTURING

Dyke intrusion mechanism was attributed traditionally to the magma filling along pre-existing fracture of the host rock (e.g. Delaney et al., 1986; Bear et al., 1994; Delaney & Gartner, 1997). This idea, called fracture-fill model, is based on the daily experience: the magma permeation along pre-existent fractures might be easier than new fracture creation in non-fractured host rock.

However, the rock behaviour in Earth's crust is, in fact, different from that of the Earth's surface. Recent studeis revealed that the dykes intrudes opening a new tensile fracture by magma pressure in direction perpendicular to the σ_3 (Figure 12A) according to hydraulic tensile fracturing model (Rubin, 1993; Valentine & Krogh, 2006). The tensile fracture for dyke intrusion is dilatational, without displacement of

the host rock, and the direction is parallel to the σ_1 and σ_2. The pre-existing weak zones are generally not filled by the magma and dyke intrusion is discordant with the host rock structure. The fracture-fill can take place only in exceptional cases, such as intrusion in very shallow depth (Motoki & Sichel, 2008).

The hydraulic tensile fracturing model is not a new idea and firstly used to explain the genesis of the radial dyke system around the Shiprock, New Mexico, USA (Hubbert & Willis, 1957). Today, numerous field examples of the dykes intruded by hydraulic tensile fracturing are known in the magmatism of compressive tectonic fields, such as subduction zones (e.g. Haimson, 1975; Hori & Kobayashi, 1980; Nicolas & Jacson, 1982; Chevallier & Verwoerd, 1987). Nevertheless, this idea has been little diffused in geologists, except for
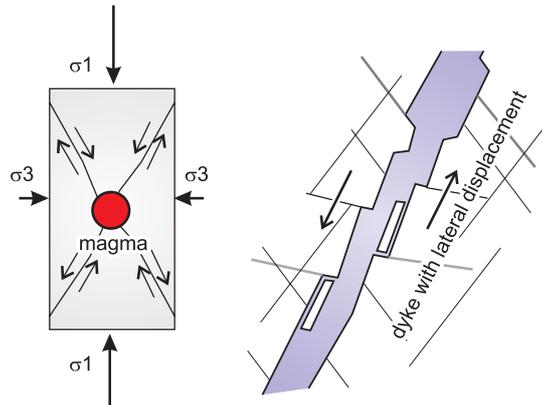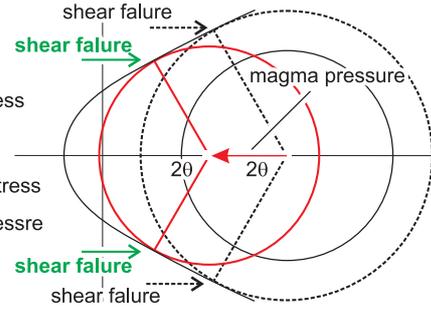
A. Hydraulic tensile fracturing

B. hydraulic shear fracturing

○ circle under original tectonic stress
◎ circle under magma pressure
◌ circle under adittional tectonic stress
← circle deslocation by magma pressre
→ rock falure for dyke intrusion
--→ rock falure for fault formation
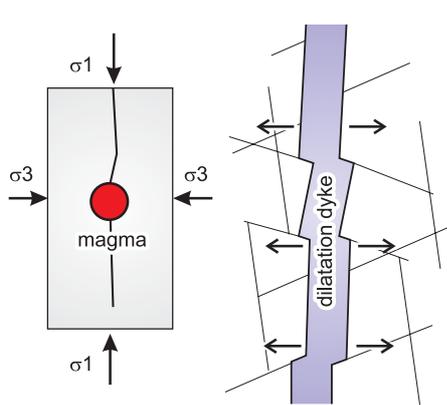
FIGURE 12. Dyke intrusion mechanism according to hydraulic fracturing after Motoki & Sichel (2008): A) hydraulic tensile fracturing under relatively low deviatory stress, forming a dilatation dyke; B) hydraulic sheer fracturing under relatively high deviatory stress, resulting a dyke with offset.

the structural geologists specialised in dyke intrusion and the engineers of petroleum extractions. This theory was introduced to Brazil only in a short time ago (Motoki & Sichel, 2008; Motoki et al., 2008a).

The hydraulic tensile fracturing takes place under relatively low deviatory stress, minor than four times of the tensile strength of the host rock. This theory is confirmed by experimental studies for low-permeability rocks (Solberg et al., 2005). On the other hand, when the deviatory stress is enough high, the host body fails forming shear fractures oblique to the σ_1 and σ_3 (Figure 12B). This model, called hydraulic shear fracturing, predicts that the dyke orientation is oblique to the σ_1, and they can have en-echelon emplacement with wall body's displacement.

However, field examples of vertical parallel dykes by hydraulic shear fracturing are still unknown. This mechanism is theoretically expected for the horizontal intrusion at initial stage of the dynamic emplacement of cone-sheets (Phillips, 1974).

In the State of Rio de Janeiro, Brazil, a strong extension tectonism took place in the Cretaceous during the continental rifting and Atlantic Ocean opening. In this condition, very strong deviatory stress could have occurred that could make possible the mafic dyke intrusion by hydraulic shear fracturing.

Most of the mafic dykes of the studied area shows leftward branching (Figure 13A) and the rightward branching (Figure 13B) is rare. This observation suggests that the dyke intrusion could have occurred by hydraulic shear fracturing under counterclockwise shear stress. If so, the mafic dykes

A. CCW shear   B. CW shear
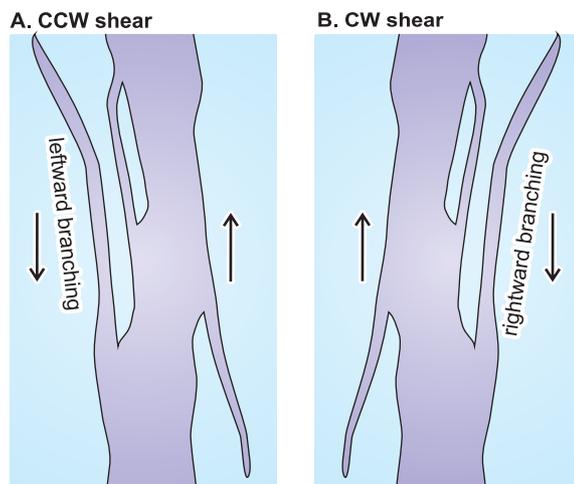
FIGURE 13. Illustration of dyke branching modes: A) leftward branching under counterclockwise shear stress; B) rightward branching under clockwise sense shear stress.

of the studied area correspond to the first field description of the hydraulic shear fracturing dykes, of left strike slip sense, that is, of sinistral sense.

According to this model, the tabular xenoliths would be formed based on the leftward dyke branching with the help of the thermal delamination. Under the high deviatory stress of continental rifting, en-echelon intrusion of mafic dykes took place as the "narrow dykes" (Figure 14A). Additional magma injection and consequent dyke growth linked the two dykes, forming a dyke with leftward branching, namely "wide dyke" (Figure 14B). Where the thermal delamination effect worked efficiently, the country rock plate between the two dykes detaches forming a tabular xenolith (Figure 14C, E). On the other hand, where the thermal delamination was less expressive, the dyke branches would develop without tabular xenolith formation (Figure 14D, F). The authors have observed the both cases in the field. The dyke intrusion occurred not instantaneously but in step-by-step in a relatively short time without complete cooling interval. The hydraulic shear fracturing and consequent dyke branching is the factor of the primary importance and the thermal delamination is the secondary one.
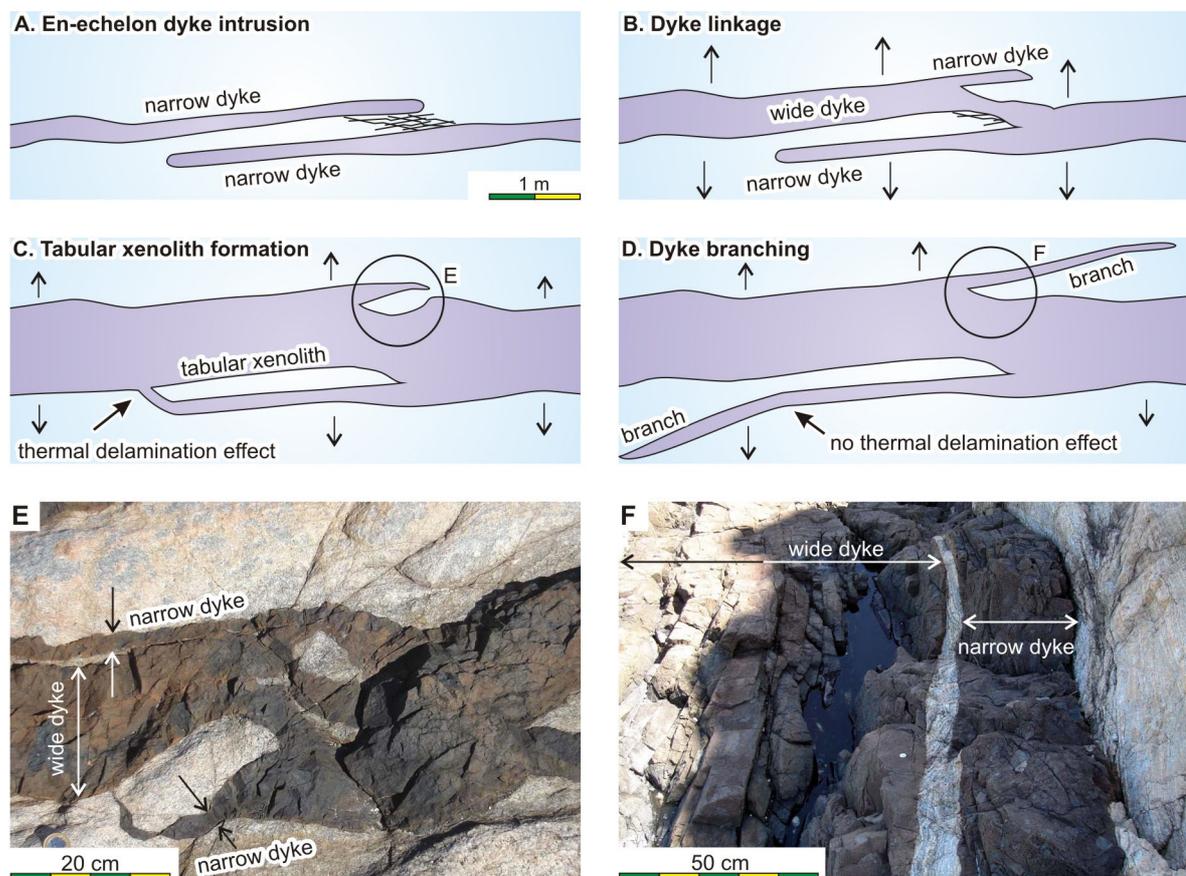
FIGURE 14. Formation process of the high-aspect ratio tabular xenoliths proposed by the present article: A) En-echelon dyke intrusion by the hydraulic shear fracturing (narrow dykes); B) Dyke growth by magma injection and formation of leftward branched dyke (wide dyke); C) Tabular xenolith formation where the thermal delamination effect is remarkable; D) Dyke branch extension where the thermal delamination effect is less expressive (Loc. 7); E) Field example of the case C, east side of the Conchas Beach, Cabo Frio; F) Field example of the case D, west side of the same beach (Loc. 2).

DISCUSSION

At an initial stage of the continental rifting, a parallel dyke system would intrude by the hydraulic tensile fracturing under the moderate extension tectonism along the spreading axis zone (Figure 15A). The dyke swarm of Ponta Grossa Arc, State of Paraná, Brazil, can correspond to an example. The dyke orientation is WNE-ESE ant it is parallel to the aborted spreading axis, that is, to the regional σ_1 of the intrusion time. This direction concordance is favorable to the hydraulic tensile fracturing model (Figure 12A).

Because of relatively low deviatory stress, the long tabular xenoliths may not take place under this condition. For the same reason, the tabular xenoliths are improbable in compression fields of subduction zones and continental collision zones.

A large deviatory stress by strong extension tectonism can be formed at an advanced stage of the continental rifting in lateral zones of the spreading axis (Figure 15B). In the Cretaceous, the studied area corresponded to western lateral zone of the continental rift axis, that is, off-ridge zone. The spreading axis of that time should be present at the continental slope of the Atlantic Ocean. The mafic dykes are oriented approximate to N50ºE and this direction is oblique to the continental rifting axis, about N-S, which corresponds to the regional σ_1. The oblique relation between the regional σ_1 and the dyke orientation corroborates the model of the hydraulic shear fracturing (Figure 12B).

As far as the authors concern, the very high aspect ratio interested long tabular xenoliths have been reported only in early Cretaceous mafic dykes of the State of Rio de Janeiro and São Paulo. Of course, other occurrence can be discovered in near future. According to the above-mentioned consideration, they will be found in the Cretaceous mafic dykes in the coast region of the State of Santa Catarina and Rio Grande do Sul. On the other hand, along the axis zone of the Ponta Grossa Arc, State of Paraná, it is improbable, but it can be found in the dykes of the lateral zones. The regional occurrence of the long tabular xenoliths is intimately related to their geneses, and therefore, further field investigations are desired.
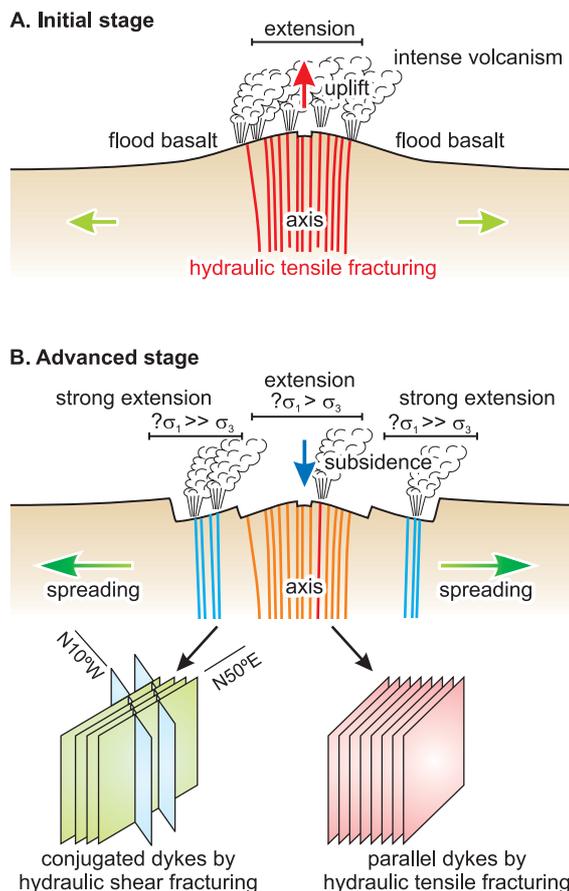
FIGURE 15. Schematic diagram for parallel dyke swarm formation by: A) Hydraulic tensile fracturing in a initial stage of continental rifting on the central axis zone under moderate spreading tectonism and deviatory stress; B) Hydraulic shear fracturing at an advanced stage on lateral zones under strong extension tectonism and high deviatory stress.

CONCLUSIONS

The field observations of the tabular xenoliths emplaced along contact planes of the mafic dykes of Cabo Frio and Arraial do Cabo areas present the following results:

1. The tabular xenoliths are present close to the contact plane of the mafic dykes. They are commonly from 30 to 50 cm wide with horizontal extension up to 100 m and confirmed minimum vertical extension of 20 m.

2. The aspect ratio on the xenoliths is very high, sometimes more than 100.

3. The contact planes of the xenoliths are generally flat, but sometimes curved.

4. The xenolith terminals are generally sub-rectangular, but some of them with curved contact have acute tail-ends.

5. In the tabular xenoliths, fractures parallel to the contact are often observed.

6. The high aspect ratio and the fractures parallel to the xenolith extension suggest a strong tendency of fracture formation parallel to the dyke contact.

7. The thermal delamination model can explain the geneses of the tabular xenoliths. This model is efficient for the small tabular xenoliths of relatively low aspect ratio, however it would not be the main factor for the interested high-aspect ratio xenoliths.

8. It is suggested that the dyke branching by the hydraulic shear fracturing is the most important factor and the thermal delamination is secondary factor. If so, the high-aspect ratio xenoliths can take place only in large deviatory stress field, that is $\sigma_1 > 4\sigma_3$.

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