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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

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Resumen

Este artículo presenta descripciones de campo y consideraciones genéticas acerca de la transición dique-sill y la intrusión subhorizontal discordante en un enjambre de diques alcalinos félsicos del Terciário inferior en el área de Arraial do Cabo, Estado de Río de Janeiro, Brasil. Dos ejemplos muestran el proceso íntegro de la transición de dique a sill: cerca del nivel del mar son verticales-discordantes y a media altura, oblicuos-concordantes; en la cima del barranco, horizontales-discordantes. Este último proceso no concuerda con el modelo tradicional de intrusión en fracturas preexistentes. Puede explicarse con un modelo de fracturamiento hidráulico: la presión magmática crea una nueva fractura normal a σ3, independientemente de la existencia de sistemas anteriores de fracturas. La transición de dique a sill ocurre a una profundidad tal que la dirección de σ3 cambia de horizontal a vertical. En el caso específico del área investigada, el cambio podría deberse a la intrusión y expansión del volumen del cuerpo sienítico de la Isla de Cabo Frío.

Palabras clave: Dique, sill, fracturamiento hidráulico, intrusión horizontal, Arraial do Cabo.

Abstract

This paper presents some field descriptions and genetic considerations about dyke-sill transitions and horizontal-discordant intrusions of the early Tertiary felsic alkaline dyke swarm at Arraial do Cabo, State of Rio de Janeiro, Brazil. Two examples show the entire process of dyke-sill transition. Near sea level they are vertical-discordant; at middle height, oblique-concordant; at the top of the cliff, horizontal-discordant. The latter process cannot be explained by a traditional model of magma intrusion along weaknesses in the host body. It can be accounted for by hydraulic fracturing: magma pressure creates a new fracture normal to σ_3, regardless of whether old fracture systems exist. The dyke-sill transition takes place at a depth such that σ_3 changes direction from horizontal to vertical. In the specific case described here, the stress change could be caused by intrusion and volume expansion of the Cabo Frio Island syenitic body.

Key words: Dyke, sill, hydraulic fracturing, horizontal intrusion, Arraial do Cabo

Introduction

Dykes and sills are common tabular intrusives. Most textbooks (e.g., Billings, 1972; Best, 1982; Bates and Jackson, 1987; Hall, 1987) employ the term “dyke” to denote a tabular body that intrudes normally or obliquely to the bedding plane, the schistosity or the gneiss banding of the country rock, to be called “discordant intrusion”, while “sill” indicates a sub-parallel or “concordant” intrusion.

Some other definitions exist. Bates and Jackson (1987) adopted the term “dyke” as meaning a vertical tabular intrusion and “sill”, a horizontal one. Hatayama *et al.* (1980) define a “dyke” as a vertical intrusion, “sheet” as a horizontal one, and “sill” as a horizontal and concordant one. However, Billings (1972) commented that such definitions are “quite erroneous”.

The traditional definition (Billings, 1972) appears to be based on the idea that magma intrusion is easier along pre-existent fractures systems or weaknesses, rather than by new fracture creation. The model of magma permeation along pre-existing fractures is widely accepted in Brazil, as old fracture systems in the Precambrian basement were considered to be an essential factor in Phanerozoic magmatic events (e.g., Almeida, 1986; Ricommini, 1997; Ricommini *et al*., 2004; Schmidt & Stanton, 2007). These authors assumed that the upper crust is highly fractured, and that the magma pressure is not sufficient to fracture the host rock. Some authors considered the fracture-fill model as an important dyke intrusion mechanism (e.g. Delaney et al., 1986; Bear *et al.,* 1994; Delaney & Gartner, 1997; Valentine & Krogh, 2006).

It is widely known that most dykes of traditional definition crop out sub-vertically and that most sills crop out sub-horizontally. Dykes are more widely observed than sills even in a sub-horizontal sedimentary country rock. Sills are found mainly in sub-horizontal young sedimentary formations and rarely in steeply dipping Precambrian gneiss. The traditional fracture-fill model is unable to explain this tendency. Field observations of dyke-sill transitions and dyke fadeout could be important, though rarely described (Motoki, 1986; Motoki *et al.,* 1988).

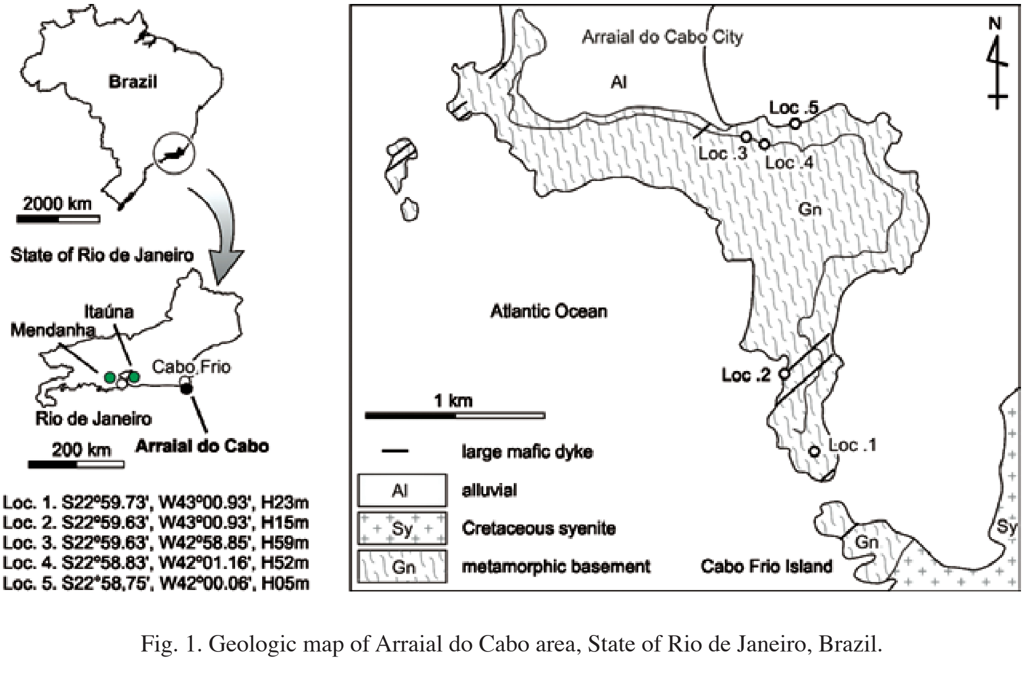
The magma intrusion mechanism in the upper crust and the process of dyke and sill formation represent an interesting geophysical subject. However, it has not interested many South American geologists. The present paper describes field observations of some peculiar forms of dyke-sill transition, discordant horizontal intrusions, and the fadeout of trachytic tabular rock bodies of Arraial do Cabo, State of Rio de Janeiro, Brazil. We propose a mechanism of formation of these features based on a hydraulic fracturing model involving magma pressure.

Geology of the studied area

The studied area covers the Atalaia Peninsula (*Pontal da Atalaia*) located about 22°58'S, 42°01'W, south of the town of do Cabo, about 120 km east of Rio de Janeiro city (Fig. 1). The area is underlain by a Pan-African metamorphic basement of orthogneiss, migmatites and amphibolites. The orthogneiss contains up to 10 m thick xenolith-like, sometimes dyke-like, anphibolitic enclaves. The metamorphic basement features a strike of N15ºE to N15ºW, dipping 20º to 40º to the east, with some local disturbances (Fig. 2A; Motoki *et al*., 1988). These rocks were metamorphosed during the continental collision between the São Francisco and Congo cratons in the Ribeira Belt (Campos Neto, 2000; Campos Neto & Caby, 2000; Trouw *et al*., 2000; Heilbron *et al.,* 2000; Schmitt *et al*., 2004).

The basement is intruded by so-called "Jurassic diabase" dykes (Helmbold, 1967; 1978; Helmbold *et al.,* 1965; Lima, 1974; 1976; Valença, 1976), that are actually early Cretaceous micro-gabbroes (Motoki *et al*., 1988; Motoki, 1994). Recent studies, such as Heilbron et al. (2007), showed that the mafic dyke swarms of the State of Rio de Janeiro are of high Ti type, and that the intrusion is 140 to 120 Ma old. They trend mainly NNE-SSW to NE-SW, with minor occurrences of NNW-SSE dykes. These dykes are usually very thick: they are 5 m to 15 m thick, straight and of vertical configuration. A horizontal columnar joint system is commonly observed. Grain-size variations are significant in the dykes. The 30 mafic dykes measured here trend N55ºE, confirming earlier descriptions (Motoki *et al.,* 1988; 1990; Valente *et al*., 2005). This dike orientation is completely discordant with the host gneiss structure (Fig. 2).

These dykes are believed to be feeders of a part of the Paraná Continental Flood Basalt (Bellieni *et al*., 1984; Hergt *et al.,* 1991; Peate *et al.,* 1992; Turner *et al*., 1994), aged 129 to 134 Ma (Peate, 1997; Deckart *et al*., 1998). However, recent ^{39}Ar-^{40}Ar dates for three tholeiitic dyke samples from the Arraial do Cabo area (Bennio *et al*., 2003) featured disturbed age spectra with some unexpectedly young ages, about 55 Ma. This means that some types of dykes are difficult to date even by the ^{39}Ar-^{40}Ar method.



Loc. 1. S22°59.73', W43°00.93', H23m
Loc. 2. S22°59.63', W43°00.93', H15m
Loc. 3. S22°59.63', W42°58.85', H59m
Loc. 4. S22°58.83', W42°01.16', H52m
Loc. 5. S22*58,75', W42°00.06', H05m

Fig. 1. Geologic map of Arraial do Cabo area, State of Rio de Janeiro, Brazil.

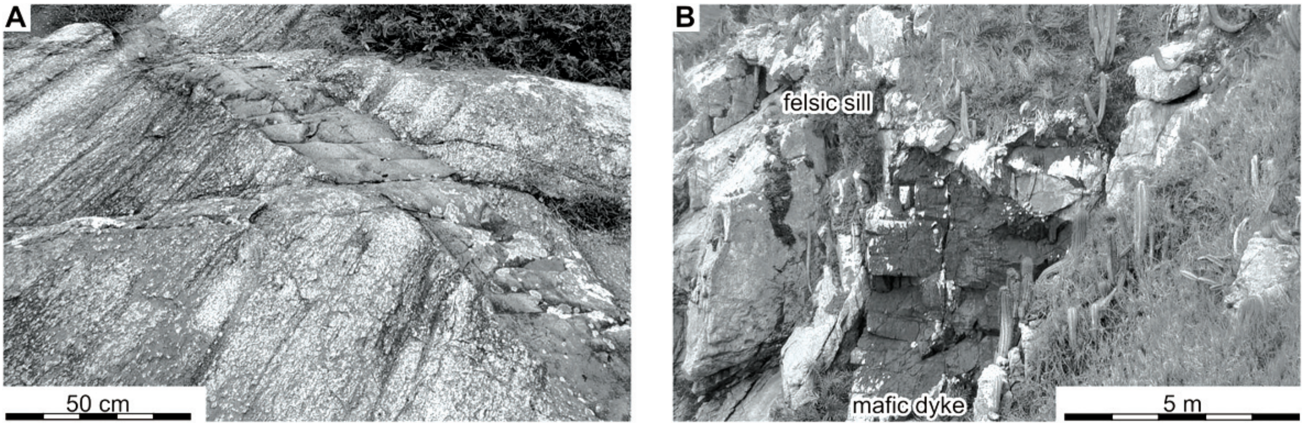


Fig. 2. The rock bodies older than the felsic alkaline dyke swarm of Boqueirão sea-cliff, Arraial do Cabo: a) orthogneissic metamorphic basement at Loc. 1; b) early cretaceous mafic dyke observed at Loc. 2.

The metamorphic basement and the mafic dykes are cut by late Cretaceous to early Tertiary alkaline felsic intrusives. About 2 km south-east of Arraial do Cabo, the Cabo Frio Island syenitic rock body occurs (Fig. 1). Around this body, there are many alkaline felsic dykes and some lamprophyre dykes, generally less than 2 m thick (Lima 1974; 1976; Valença, 1976; Motoki *et al.,* 1988).

Motoki et al. (1988) observed 92 felsic alkaline tabular intrusives of which 61 were sub-vertical and 31 oblique or sub-horizontal. The outcrops suggest three different intrusive episodes for these tabular bodies. The youngest one corresponds to the N40ºW group, which appears to belong to the radial dyke system originating from the Cabo Frio Island syenitic rock body. The second episode features intense deuteric alteration and related phenitization which affected the country rock along the contacts and pre-existing fractures.

Intrusion direction change

Some outcrops show a transition of felsic alkaline dykes of the second episode from sub-vertical to sub-horizontal. At the Boqueirão sea-cliff, near the south-west edge of the studied area (Loc. 1, 2; Fig. 1), we found two examples of complete transition (Fig. 2). Near sea level, these bodies strike NE-SW and dip steeply to the east, in discordance with the country gneiss (sub-vertical discordant stage). At mid-height, about 20 m above sea level, the dip and strike change to sub-parallel to the gneiss structure which trends N15E to 40E. They tend to show zigzag patterns and complex branching (oblique concordant stage). At the top of the cliff, about 40 m above sea-level, they become sub-horizontal and discordant to the host body (sub-horizontal discordant stage). The sub-horizontal part is generally thicker than the oblique one. Most transitions take place from 20 to 50 m above sea level, but they occur also at all elevations. In three dimensions these intrusive bodies show helical patterns. Outcrops that show transitions from oblique to sub-horizontal intrusion are more frequent (e.g. Loc. 3, 4; Fig. 1, 3, 4).

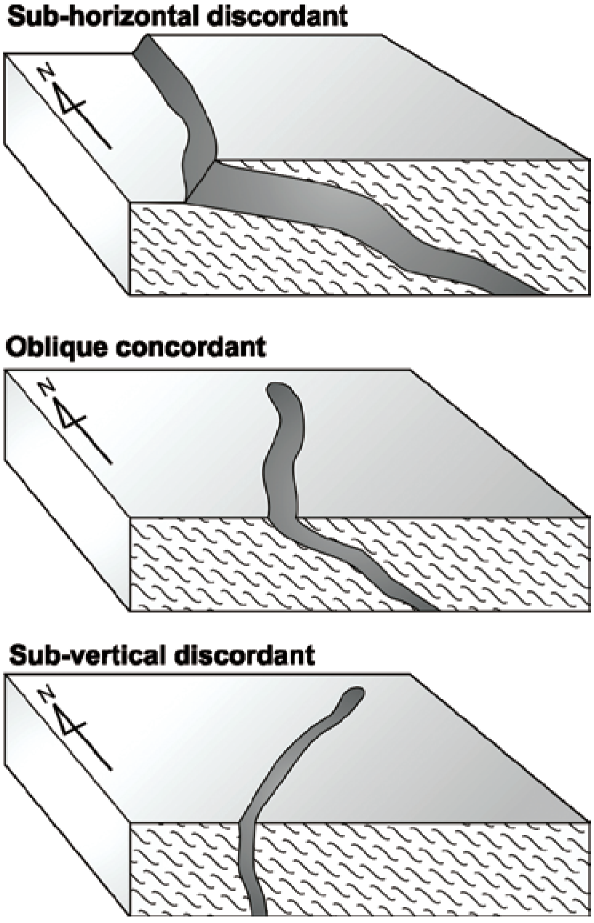


Fig. 3. Schematic block diagrams illustrating helical intrusion of felsic alkaline tabular rock bodies showing transition from sub-vertical to sub-horizontal intrusion observed at Boqueirão sea-cliff, Loc. 2.

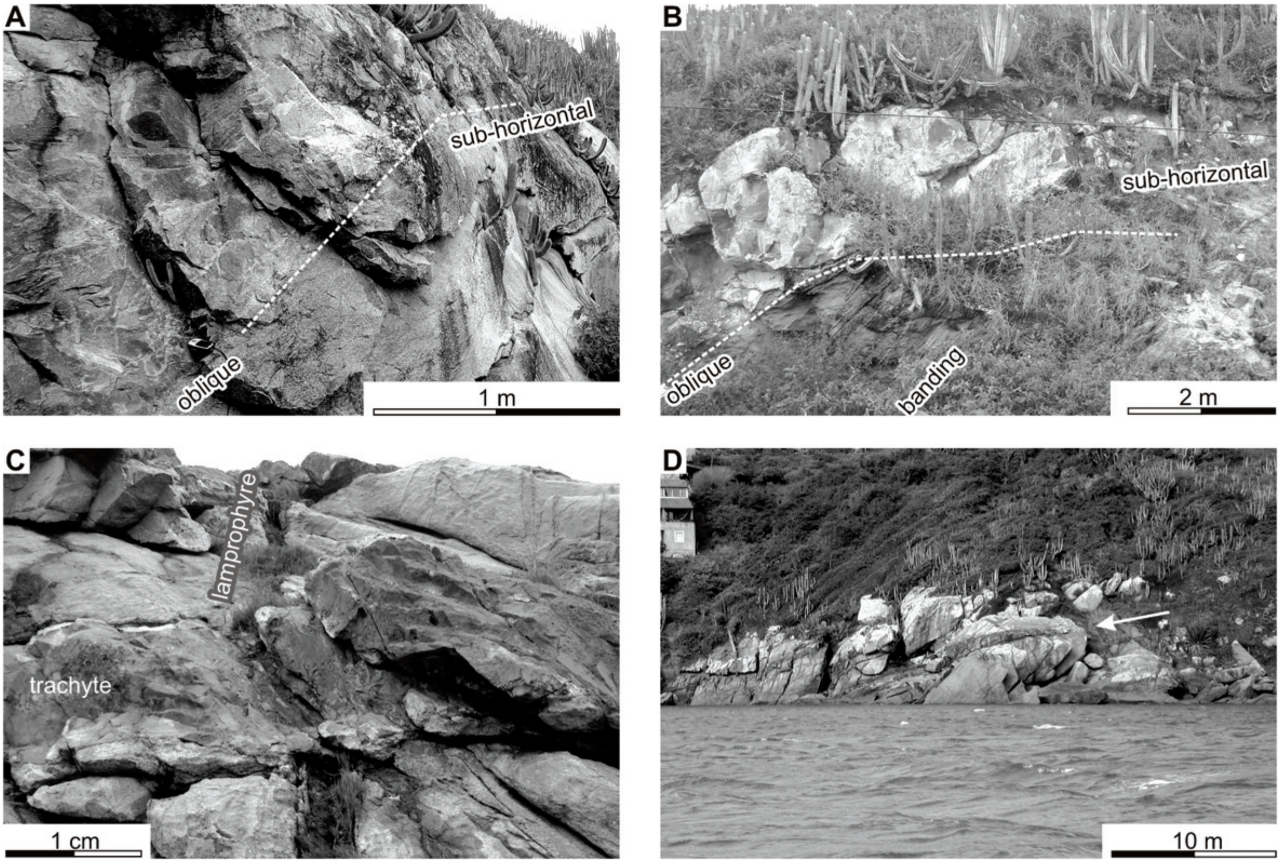


Fig. 4. The outcrops showing the transition from oblique concordant intrusive body to sub-horizontal discordant one at northern slope of the Atalaia Peninsula: a) Loc 3, b) Loc. 4. Typical sub-horizontal discordant bodies are exposed at: c) Boqueirão sea cliff, Loc. 1; d) Alalaia Peninsula, Loc. 5.

Tabular bodies of the sub-horizontal discordant stage are 0.5 to 5 m thick and dip 5º to 20º to the east: they feature a leukocratic fine-grained alkaline composition. Contacts with the surrounding rock feature sharply defined chilled margins, not straight, but wavy (Fig. 5). Strikes and dips of these bodies are highly variable, and show frequent zigzag or irregular patterns (Fig. 5B). Some intrusions may be locally concordant with the country gneiss banding (Fig. 4B). The sub-horizontal sections show no displacements of the host rock along the intrusion. These examples are rarely found in the literature.

Tail-end of the tabular bodies

Field observations of fadeouts of dykes and sills are important for their interpretation and the problem of mechanism of intrusion. The traditional fracture-fill model assumes that a linear weakness such as a fault or joint is continuous along the dyke (Fig. 6A). However, few papers present field descriptions of dyke fadeouts. Motoki (1986) shows some examples of late Cretaceous trachytic and phonolithic dykes intruding the Vitória Island syenitic body, State of São Paulo, Brazil. They show a rounded fadeout and there is no continuous fracture in the host syenite as far as the extension of the dyke. In Arraial do Cabo there are also some examples (Fig. 6B, C). These outcrops show complex curved fadeouts where the host rock is deformed plastically without fractures. No faults or joints are found along the extension of the dykes. The examples suggest that intrusion took place by magma pressure, without any influence of pre-existing weaknesses in the host body.

Hydraulic fractiring

The transitions from oblique concordant bodies to sub-horizontal discordant ones and the rounded fadeouts in the studied area cannot be explained by a traditional dyke intrusion model. According to this model, magma should intrude along pre-existing weaknesses in the host body, such as faults, shear zones, tectonic lines, layered structures or parallel fractures (e.g. Almeida, 1986; Riccommini *et al.,* 2004).

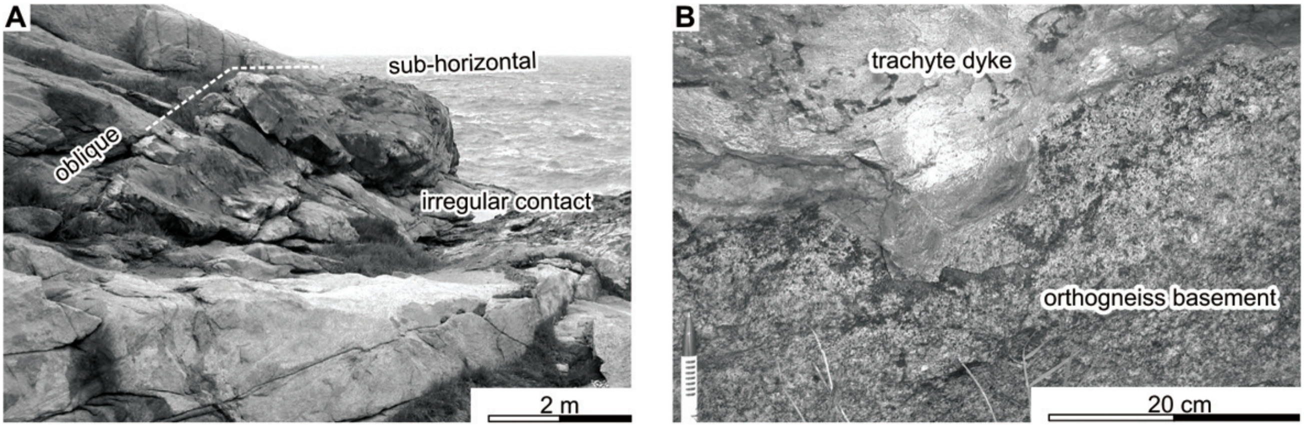


Fig. 5. Contact of the oblique and sub-horizontal parts of with the felsic alkaline intrusive rock body at: A) Loc. 1; B) Loc. 3

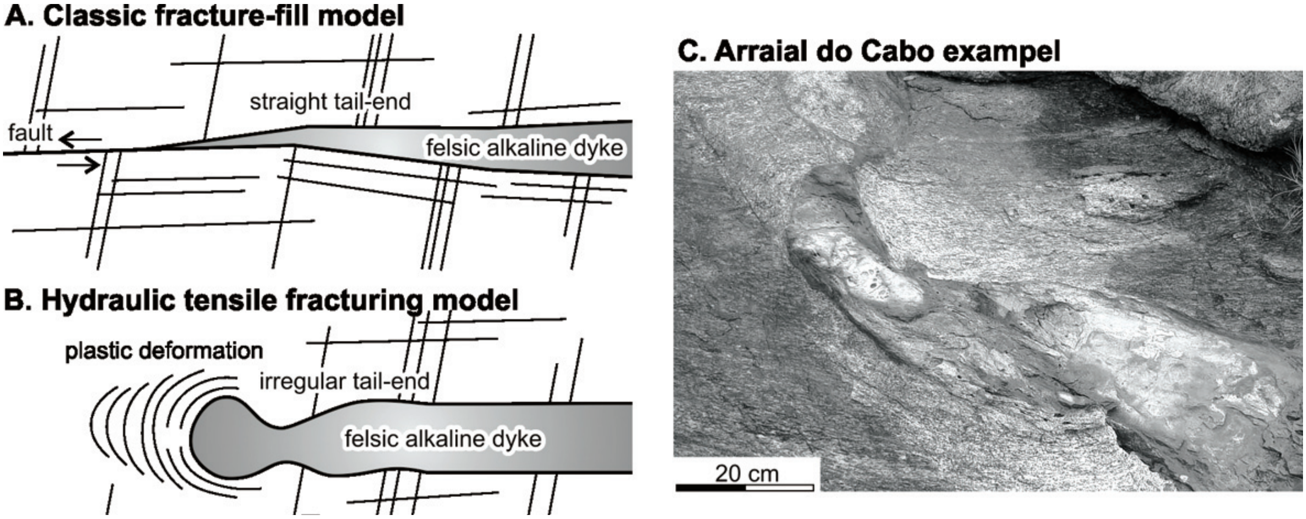


Fig. 6. Models for tail-end of tabular intrusive rock bodies according to: a) classic fracture-fill model; b) hydraulic tensile fracturing model. An example is exposed at Boqueirão sea-cliff (c), Arraial do Cabo, Loc. 1.

A model of fracture formation involving magma pressure in the brittle upper crust and a hydraulic fracturing mechanism is an attractive alternative. The idea of self-propagating fractures being referred to as dykes (Rubin, 1993; 1995) is little known in Brazil, yet it is assumed to be the most common mechanism for dyke intrusion (Valentine & Krogh, 2006).

This model originated in petroleum engineering. The actual water pressure for secondary oil recovery is known to be generally less than estimated from the overburden. Hubbert and Willis (1957) concluded that water is not intruding horizontally into the sedimentary formation, as in sills, but vertically as in a radial dyke system. If the deviator stress σ_1-σ_3 at the intrusion is higher than the stress needed for extensional fracture of the country rock, the water under pressure does not intrude along the stratification. Instead water pressure creates vertical tensile fractures normally to the minimum principal stress axis σ3. Hubbert and Willis suggested that dykes may intrude by hydraulic fracturing. An example is the Spanish Peak, Colorado radial dyke system (Ode, H., 1957). This idea was developed by Nakamura (1977), Nakamura *et al*. (1977), Phillips (1974), Hills (1975) and Haimson (1975) and was introduced to South America by Llambías (2003).

Under relatively low deviator stresses, less than four times the tensile strength of the host rock, hydraulic tensile fractures are formed normally to σ_3, that is, parallel to the σ_1-σ_2 plane, when the magma pressure exceeds σ_3 plus the host rock tensile strength (Fig. 7A).

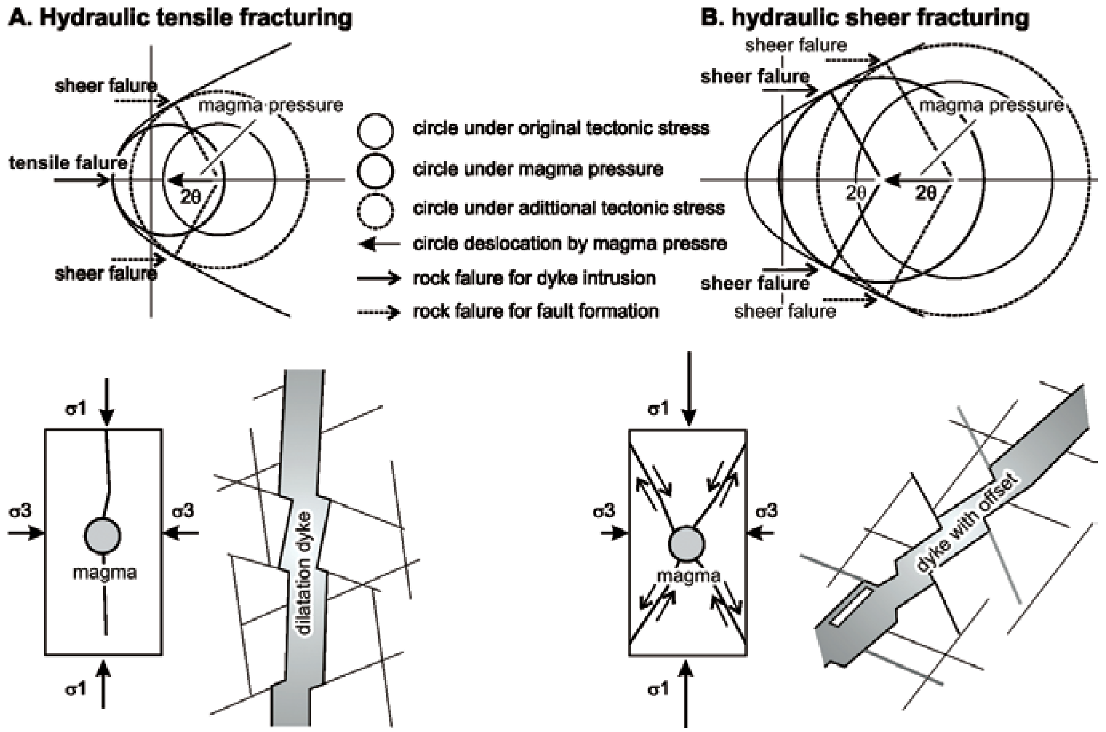


Fig. 7. Physical mechanism of dyke intrusion according to: a) hydraulic tensile fracturing under relatively low deviatory stress, forming a dilatation dyke; b) hydraulic shear fracturing under relatively high deviatory stress, resulting a dyke with offset

This is called “hydraulic tensile fracturing”, and the fractures are filled immediately by magma, with the result that tabular intrusives such as dykes and sills are formed. Because of magma pressure, tensile fracture formation for dyke intrusion takes place more easily than does shear fracturing in fault formation. It is worth noting that the tensile fracture crosses obliquely the shear fracture. Unless the pre-existent fracture system in the host body is sub-parallel to the σ_1-σ_2 plane, the magma does not intrude along it. In the upper crust, the σ_1 axis is usually vertical. Therefore, vertical tabular intrusive bodies or dykes are easily formed even in a massive host body, such as a granitic batholith. The present model explains the dominance of dykes over sills even in highly stratified sedimentary host rock.

Nakamura (1977) and Nakamura *et al.* (1977) estimated the direction of the horizontal compression stress axis from the alignment of parasitic cones of stratovolcanoes, a surface indication of the presence of underground radial dykes. Bacon *et al.,* (1983) performed a similar estimation based on the distribution of monogenetic volcanoes. Haimson (1975), Kobayashi (1979a, b), Hori and Kobayashi (1980), Takeuchi (1980), Nicolas and Jackson (1982), Laughlin *et al.* (1983), Feraud and Campredon (1983), Southwick and Day (1983), Ui *et al.* (1984), Chevallier & Verwoerd (1987), and others applied the same theory to the problem of reconstructing palaeo stress-fields.

On the other hand, when the deviator stress is very high and the magma pressure is relatively low, the host body will fail with displacement along shear fractures. This is called “hydraulic shear fracturing”, resulting in tabular intrusive rock bodies accompanied by wall displacement (Fig. 7B). Dykes are formed more easily than faults because of magma pressure. However, unlike in hydraulic tensile fracturing, dykes and faults become sub-parallel. In addition, the dykes are associated with fault-like displacements. Such types of dykes do occur, but examples are rarely described. Phillips (1974) proposed that cone sheets are formed at shallow depths by a dynamic process based on a combination of hydraulic tensile fracturing with hydraulic shear fracturing.

Preferred directions of dykes and faults

Based on observations of volcanoes, dyke swarms and fault systems, Nakamura (1977) and Nakamura *et al.* (1977) proposed a model relating volcanic eruption modes, preferred directions of dykes and faults, and regional stress field conditions, on the basis of the hydraulic tensile fracturing theory.

In a compressive stress field, rock is harder to fracture by magma pressure than in the case of an extensional stress field. Once a conduit is formed, the magma rises in it by many small pulses. Therefore, if a small volume erupts over a short time interval in a polygenetic eruption it form a large stratovolcano on the surface. The distance between stratovolcanoes is large. At deeper sites, σ_1 is vertical and σ_2 is parallel to the compression axis of the regional tectonic stress. Therefore, the volcano develops a radial dyke system with preferred direction parallel to the regional tectonic compression, that is, the main horizontal stress axis (Fig. 8A). Flank volcanoes, called parasitic cones, arise along a dyke, and the base of the main stratovolcano is elliptical. Contemporaneous fault systems are reverse and conjugated strike-slip systems. On a geologic map, reverse faults are normal to the preferred direction of the dyke swarm and strike-slip faults are oblique to it. Neither is parallel to the general dyke direction. The discordance between preferred directions of dykes and faults are attributed to different fracturing mechanisms. Dykes are formed by tensile fracturing by magma pressure and faults by shear fracturing. Because of tensile fracturing, dykes do not feature any host rock displacement. This case is mainly observed in active arcs. The active Chilean stratovolcanoes in the Southern Volcanic Zone, such as Villarica (Clavero & Moreno, 2004) and Osorno (Lara *et al.,* 2001), are good examples. Some Pliocene volcanoes of the back-arc region, such as Cerro Nevado (Holmberg, 1973; Bermudez *et al.,* 1993) in southern Mendoza, Argentina, also show these characteristics.

On the other hand, in an extensional stress field, new fractures open relatively easily and the magma in the chamber rises in a single pulse through a dyke. The eruptions are voluminous and occur at long time intervals. The rise of voluminous magma causes a large fissure eruption on the surface, while less voluminous ones generate many monogenetic cones along the dyke. The distance between cones is small. At deeper sites, $\sigma 1$ is vertical and σ_2 is normal to the regional extension axis. Therefore, a parallel dyke system normal to the extension axis develops. The contemporary fault system is normal, and its trend is parallel to the dyke direction. Actually, however, the dykes and faults are not parallel, as dykes are vertical and faults show a high to low-angle dip (Fig. 8B). Also, dykes are formed by tensile fracturing and faults by shear fracturing. Thus a normal fault system forms a conjugate shear fault system with a vertical maximum compression axis. Because of magma pressure, hydraulic tensile fractures for dyke intrusion are formed more easily than normal faults. Therefore, the dykes intrude by means of this mechanism before the fault system is formed. In other words, magma does not fill the parallel normal faults in a given region. This case is mostly observed in active back-arc volcanoes and flood basalt eruptions in the initial stage of continental rifting. The Cretaceous parallel dyke system of the Ponta Grossa Arc, State of Paraná, Brazil, is a good example. Some very young back-arc monogenetic cones, such as Cerro Amarillo, Cerro Las Niñas, and Cerro Mancha Jarilla of the Mancha Jarilla Formation in southern Mendoza, Argentina (Bermudez *et al.,* 1993), are other examples.

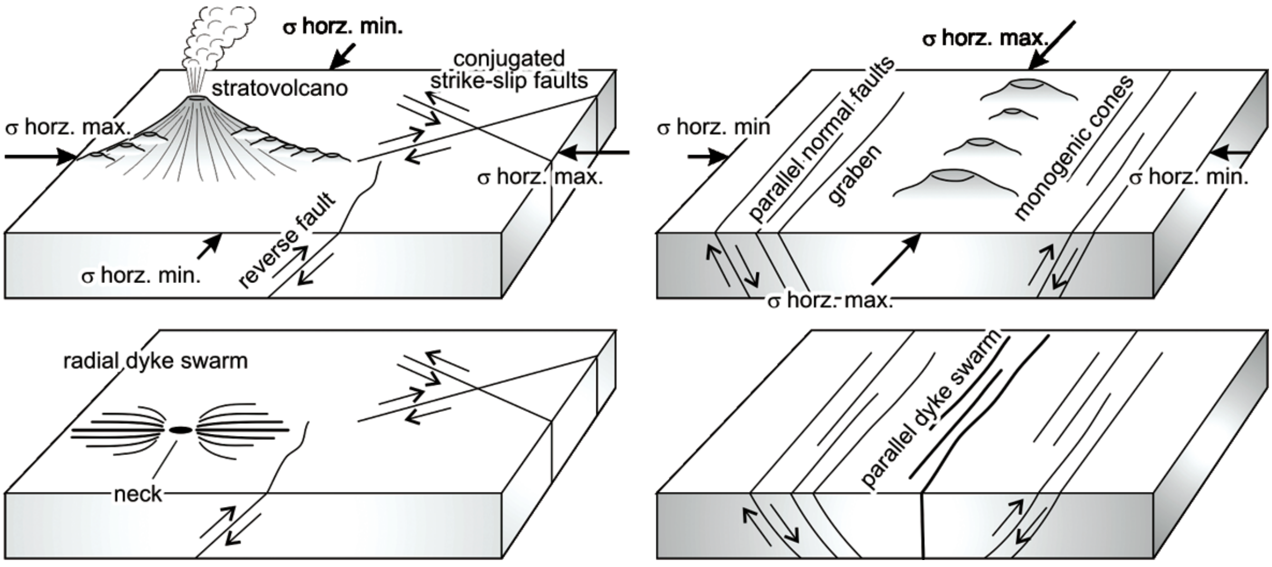


Fig. 8. Mode of occurrence of volcanoes, dykes, and fault systems according to hydraulic fracturing theory proposed by Nakamura (1977) and Nakamura et al. (1977): a) compressive tectonic stress field; b) extensional tectonic field.

Dyke-sill transition mechanism

Most sills intrude into sub-horizontal sedimentary host rock bodies at shallow depths. Sub-vertical concordant intrusive bodies exist but are rarely observed in the field. Usually they were originally sub-horizontal intrusions tilted by some later tectonic event. Sill occurrence in a limited geologic environment does not agree with the traditional model of fracture-fill.

Valentine and Krogh (2006) proposed the following mechanisms of dyke-sill transitions in brittle host rock: (1) magma rising by buoyancy at deeper sites would accumulate at a level of neutral buoyancy (LNB) (e.g. Lister & Keer, 1991); (2) a change of orientation of σ_3 from vertical at deeper sites to horizontal at shallower sites (e.g. Parsons & Thompson, 1992).

The first mechanism is based on the traditional fracture-fill theory, as it assumes that heavy basaltic magma intrudes light sedimentary formations. In this case, the host rock must be less dense than the magma when the sites are shallower than the sill. At Arraial do Cabo, the trachytic magma intrudes gneissic host rock: thus the model is not applicable (Motoki, *et al.,* 1988).

The second mechanism is based on the hydraulic tensile fracturing theory. Phillips (1974) and Hills (1975) explained the intrusion mechanism of sills (Fig. 9), and they stressed the importance of lateral compressive stress and shallow emplacement of the rock body. At deep sites, the vertical stress is large because of high overburden and because of the vertical stress σ_1. In such conditions, magma pressure can open a sub-vertical tensile fracture. At shallow sites, vertical stress is small. When the horizontal stress is high enough, the σ_3 becomes vertical, and horizontal tabular intrusion takes place. The horizontal stress is mainly due to magma pressure on dyke walls. At this level, the intrusion changes direction from vertical to horizontal, causing the dyke-sill transition (e.g. Parsons & Thompson, 1992). This transition can also occur in homogeneous country rock such as granite. Fracture analyses in the Arraial do Cabo area suggest that σ_3 was vertical at the time of fracture formation (Ferrari, 2001).

Hall (1987) pointed out that large sills can transgress the stratification of the host rock when mapped over a large area, showing abrupt steps rather than angular discordances. The author cited the example of Stirling coalfield (Dinham and Haldane, 1932), which shows that the general direction of sills over a large area may not be parallel to the sedimentary bedding planes, but to the surface of the ground. Thus the sill was not intruded according to the sedimentary stratification, but at a certain depth below the surface.

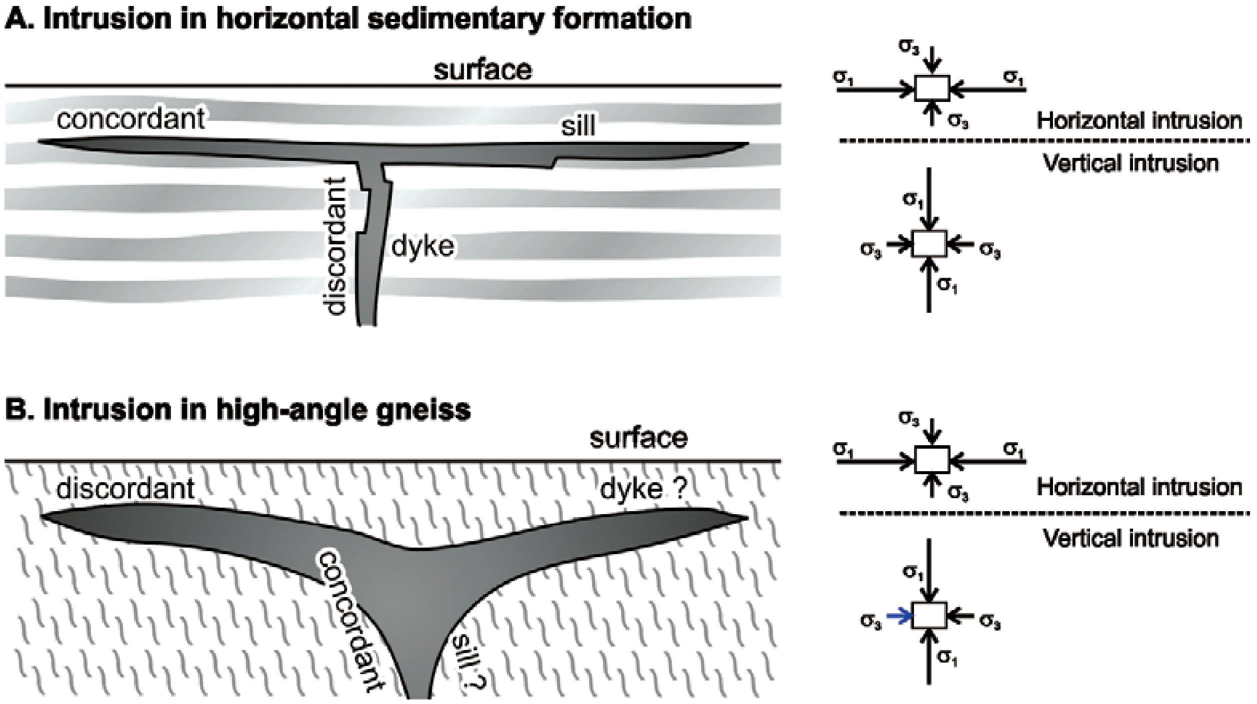


Fig. 9. Schematic diagrams for dyke-sill transition by mean of direction change of the σ1 and σ3 according to depth based on Hills (1975), in case of intrusion in: A) horizontal sedimentary formation; B) steeply dipped gneissic body.

A specific case of Arraial do Cabo dykes

Fig. 3 may seem similar to Fig. 9. However, the dyke-sill transition at Arraial do Cabo is not easily explained by this model. The regional history of uplift and denudation may be reconstructed from a combination of fission track datings for apatite in the host gneiss. and of cooling ages of the intrusive rock bodies (e.g. Hackspacher, 2003; Motoki *et al.,* 2007a). Thus the tabular intrusives are estimated to having been emplaced at a depth of 3 km. As compared to this intrusion depth, the vertical variation of outcrops is less than 100 m, which fails to account for the change in direction of the maximum stress axes $\sigma 1$ and σ_3.

About 1 km to the south-east of the studied area is the syenitic intrusive body of Cabo Frio Island belonging to the same magmatic event. Earlier papers failed to define the precise mode of emplacement of this body. The lithology around Cabo Frio Island syenite suggests that the emplacement mode was similar to that of the Mendanha body in Nova Iguaçu (Motoki *et al.,* 2007a), and of the Itaúna body in São Gonçalo (Motoki *et al.,* 2007b; Fig. 1), both in the State of Rio de Janeiro. They correspond to the root of an upward mushrooming pluton. They could be stereotypes of the Cabo Frio Island syenitic intrusive.

The Cabo Frio Island intrusion and its horizontal ballooning expansion could have produced a transient but strong horizontal stress in radial directions, that might have included the study area situated on the same level. This horizontal stress could partly account for the change in σ_3 direction from horizontal to vertical (Fig. 10).

When the lateral pressure of the syenitic intrusion was large enough, a dynamic process of combined hydraulic tensile and shear fracturing (Phillips, 1974) could have taken place, forming conic sheets. A conic sheet-like trachytic intrusive may be observed crossing the peninsula west of Arraial do Cabo town (Fig. 1). This continuous tabular body has an extension of 3 km and a thickness of 5 to 10 m. Its composition is trachyte with intense deuteric alteration. The general trend is N5ºE40ºE and it dips toward the Cabo Frio Island syenitic body.

Fracture-fill and hydraulic fracturing

Field observations of tabular intrusives in the Arraial do Cabo area indicate that the self-propagating cracks originated from hydraulic fracturing by magma pressure. It is the main intrusion mechanism of the tabular rock bodies. Hydraulic fracturing occurs when σ_1, σ_2, and σ_3 are large enough, magma pressure is high enough in terms of the tensile strength of the host rock, and the deviator stress is adequate. If these conditions are not all fulfilled, magma intrusion may take place along pre-existing fractures. Motoki (1986) showed that small branches of phonolithic dykes, less than 5 cm wide, show intrusion along pre-existing fractures. This phenomenon might be due to insufficient magma pressure. Valentine and Krogh (2006) described dyke intrusions along host rock structures in very shallow subvolcanic sites. This may be due to insufficient lithostatic stress. At Arraial do Cabo, the intrusions along pre-existing host rock structure take place at the dyke-sill transition level (Fig. 3, 4).

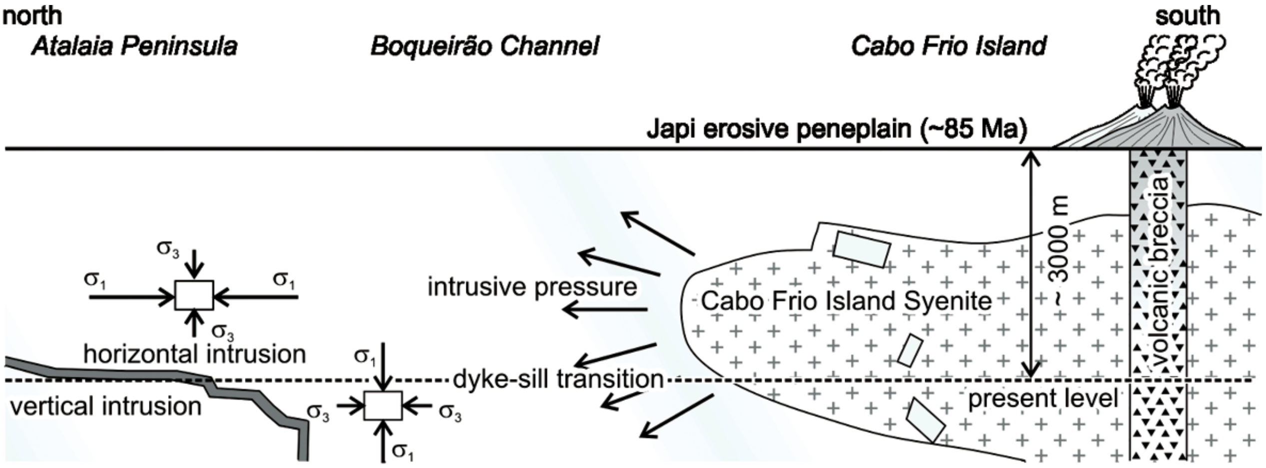


Fig. 10. Proposed dyke-sill transition mechanism for the felsic alkaline intrusive rock bodies of Arraial do Cabo area, because of the stress change caused by intrusion and volume expansion of the Cabo Frio Island Syenitic Body.

Conclusion

The intrusion mode of alkaline felsic tabular bodies in the Arraial do Cabo area, State of Rio de Janeiro, Brazil, and especially the dyke-sill transitions, cannot be explained by a traditional intrusion model involving the filling of pre-existing fractures. The field observations fit a hydraulic fracturing model powered by magma pressure. According to this model, vertical intrusion takes place where σ_1 is vertical and σ_3 is horizontal, which happens ordinarily at deep sites. Horizontal intrusion occurs where σ_1 is horizontal and σ_3 is vertical, usually at shallow depth. Local plastic deformation of the host rock by hot magma is important in order to define the tapered shape of tabular intrusive bodies. Dyke-sill transitions occur at a depth where the vertical maximum stress axis changes from σ_1 to σ_3. In some cases within the studied area, the dyke-sill transition may not be related to intrusion depth variations. The horizontal stress needed for a transition could originate from the intrusion itself, and from horizontal ballooning of the Cabo Frio Island syenitic body. Magma intrusions along pre-existing fractures do also take place under certain conditions, such as insufficient magma pressure, very shallow depth, and the dyke-sill transition process.

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