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Subvolcanic neck of Cabugi Peak, State of Rio Grande do Norte, Brazil, and origin of its landform

Neck subvulcânico de Pico do Cabugi, RN, e origem do seu relevo

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Resumo

Esse artigo apresenta as observações geológicas, petrográficas e geomorfológicas do neck subvulcânico de rocha alcalina máfica do Pico do Cabugi, RN. Esse maciço tem 370 m de altura relativa e cerca de 0.4 km³ de volume total. É constituído, principalmente, pelo Ortognaiss Caicó. O neck está exposto no topo do maciço formando uma saliência cônica de 160 m de altura relativa e 500 m de diâmetro. O volume da rocha alcalina máfica é 0,056 km³, ocupando 14% do maciço. A forma geral do maciço é fortemente convexa com o MCI (Índice de Macro Concavidade) de -2.3. O neck é constituído por álcali microgabro rico em olivina no centro e por álcali dolerito na zona de contato. Observam-se disjunções colunares bem desenvolvidas com diâmetro típico de 60 cm. As disjunções colunares são de alto ângulo no centro do neck e sub-horizontais na zona de contato. Na Planície Sertaneja, não foram observados afloramentos de vala de rochas alcalinas máficas, outros depósitos eruptivos ou debrís de rochas vulcânicas. Essas observações permitem concluir que o edifício vulcânico e os depósitos eruptivos do final do Oligoceno foram removidos completamente pelo soerguimento posterior e consequente denudação regional e que a superfície atual é, significativamente, mais baixa do que aquela da época da erupção. Os afloramentos do Pico do Cabugi exibem a estrutura geológica subterrânea do vulcão do Oligoceno. A morfologia original do vulcão não é mais preservada e a saliência morfológica atual é atribuída à erosão diferencial do neck subvulcânico. Conforme a definição vulcanológica, a morfologia atual do Pico do Cabugi não é classificada como um vulcão extinto.

Palavras-chave: Pico do Cabugi, Rio Grande do Norte, olivina microgabro, neck subvulcânico, magmatismo alcalino de Macau, erosão diferencial.

Abstract

This article reports geologic, petrographic, and geomorphological observations of the mafic alkaline subvolcanic neck of the Cabugi Peak, located in the State of Rio Grande do Norte, Brazil. The massif is 370 m high and has 0.4 km³ of total volume. It is constituted mainly by Caicó orthogneiss. The neck is exposed on the top of the massif forming a conical morphologic protrusion with relative height of 160 m and diameter of 500 m. The volume of the mafic alkaline rock is 0.056 km³ occupying 14% of the whole massif. The general form of the massif is strongly convex with the MCI (Macro Concavity Index) of -2.3. The neck is constituted by olivine-rich alkaline micro-gabbro in the centre and alkaline dolerite at the contact zone. There are well-developed cooling columnar joints with typical diameter of 60 cm. They

are steep at the centre of the neck and sub-horizontal at the contact zone. On the foothill surface, called *Sertaneja surface*, no outcrops of mafic alkaline lava, other eruptive deposits, or volcanic rock debris have been observed. These observations allow a conclusion that the volcanic edifice and eruptive deposits of the late Oligocene were completely removed by later uplift and consequent regional denudation and that the present-day surface is significantly lower than that of the eruption time. The outcrops of the Cabugi Peak exhibit the underground geologic structure of the late Oligocene volcano. The original volcano form is not preserved anymore and the present morphologic elevation is attributed to differential erosion of the subvolcanic neck. According to the volcanological definition, the present-day morphology of the Cabugi Peak is not classified as an extinct volcano.

Keywords: Cabugi Peak, Rio Grande do Norte, olivine micro-gabbro, subvolcanic neck, Macau alkaline magmatism, differential erosion.

1. Introduction

The Cabugi Peak (*Pico do Cabugi*) is located in the central region of the State of Rio Grande do Norte, Brazil, at the coordinates of N05°42.3', W36°19.3', about 7 km to the west of Lages city and 120 km to the west of Natal city (Figure 1). This massif has 370 m of relative height and its top exposes a neck of mafic alkaline rocks (Sial, 1978; Silveira et al., 2002). It is a member of the Cenozoic Macau mafic alkaline magma province (Mizusaki, 1989; Souza et al., 2007), which is attributed to a hot-spot track (Sial, 1978). These mafic rocks were studied either in terms of geochemistry or geochronology (e.g. Sial, 1976; 1978; Silveira et al., 2002), having a K-Ar age of 19.7 Ma, whole-rock Ar-Ar age of 23.7 ± 1.2 Ma (Archanjo & Brito Neves, 2001),

and high accuracy whole-rock Ar-Ar age of 24.6 ± 0.8 Ma (Souza et al., 2003). Recent Ar-Ar datings show late Oligocene ages, 24.6 ± 0.8 , 24.8 ± 0.3 , 25.5 ± 0.4 Ma, and 25.5 ± 0.6 (Silveira, 2006). The rocks of the Cabugi Peak have normative nepheline, SiO₂ varying from 39% to 45%, and are characterised by enrichment of Ti, K, Sr, and Ba (Souza et al., 2003). The Sr isotope ratio varies from 0.7039 to 0.7044 (Sial et al., 1981), which indicates their origin from enriched mantle.

The peculiar landform of the Cabugi Peak (Figure 2) seems to be of an extinct volcano. This idea was transmitted mainly by non-academic sources. However, no revised scientific article with volcanological discussions has been published, and therefore, its geologic mode of occurrence

is still unclear. There are two possible hypotheses: 1) The present morphological elevation is attributed directly to the volcanic edifice; 2) The original volcanic edifice was completely removed by later regional uplift and consequent deep denudation and the present-day morphology is originated from differential erosion of subvolcanic neck, that is, underground geologic structure beneath the late Oligocene volcano.

This article presents geologic, lithologic, and geomorphological observations of the Cabugi Peak, State of Rio Grande do Norte, Brazil, and petrographic description of its constituent mafic alkaline rocks. Based on the data, the authors discuss its geologic emplacement mode and the origin of the present landform.

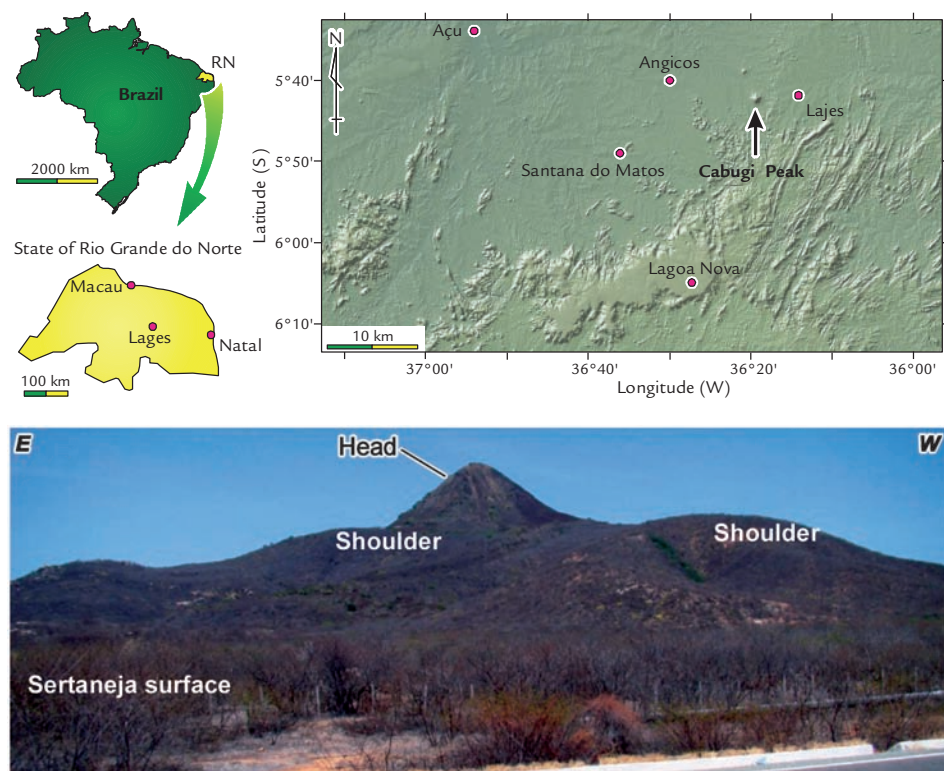


Figure 1
Locality map of the Cabugi Peak, State of Rio Grande do Norte, Brazil, based on Shuttle Radar Topographic Map (SRTM) processed by GeoMapApp™.

Figure 2
General view of the Cabugi Peak from the BR-304 national freeway. The relative height is about 370 m.

2. Geomorphological analyses

For the geomorphological analyses, the authors have adopted digital elevation model of ASTER sensor component of the TERRA satellite, called GDEM (*Global Digital Elevation Map*), with horizontal resolution of 30 m. In order to express the morphology in a better manner, the drainages narrower than 60 m wide are virtually filled using summit level technique (Motoki et al., 2008a; 2009a; Fortes et al., 2010). The above-mentioned operations have been

performed by the original software system BAZ (Basic Applications of Zenith geomorphological tools) ver. 1.0, build 72 (Motoki & Motoki, 2011).

The ASTER GDEM shows that the Cabugi Peak is a small mountain, about 370 m high, standing up on the regional peneplane-like surface with altitude of 180 m, called locally Sertaneja surface (*Planície Sertaneja*). The highest point is 551 m above sea level (Figure 3). The Sertaneja surface exposes Archaean to Palaeoproterozo-

ic high-grade migmatitic orthogneiss of the basement, called Caicó Complex (Souza et al., 1996; Jardim de Sá et al., 1995).

The Cabugi Peak has a circular truncated cone-like general form, so-called “Shoulder” (Figure 4). The diameter of the base circle is 2.0 km and that of the top circle is 1.0 km. The Shoulder is constituted by migmatitic orthogneiss of the Caicó Complex. On the top of the Shoulder with altitude of 400 m, a conical morphologic pro-

Figure 3
Landform of the Cabugi Peak and adjacent area based on the ASTER GDEM:
A) Topographic map.
B) Simplified morphologic model.
The drainages narrower than 60 m are filled virtually by the summit level technique.

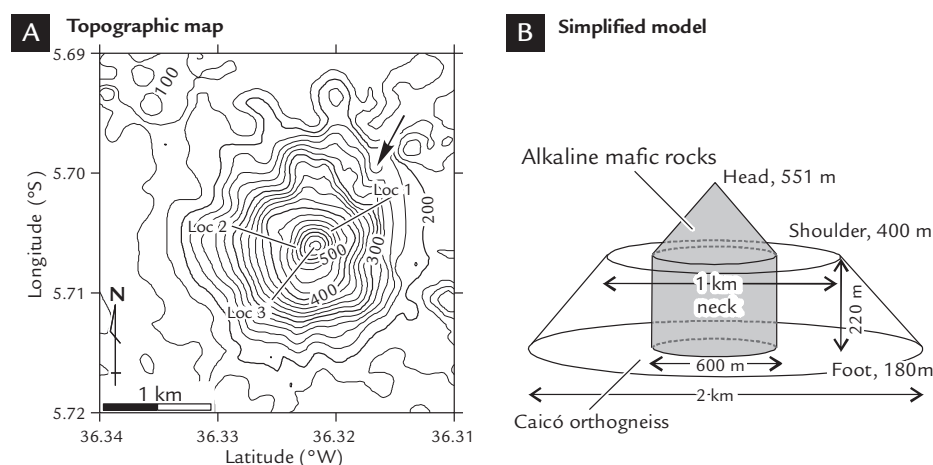


Figure 4
Orthogneiss of the Caicó Metamorphic Complex, the basement of the Cabugi Peak mafic alkaline subvolcanic neck:
A) Field occurrence.
B) Photomicrography.



trusion occurs, called “Head”. The Head is 500 m in diameter and 160 m in relative height, and is made up of mafic alkaline rocks.

According to the pixel counting method (Motoki et al., 2007a), using the original software Wilbur (Motoki et al., 2006), the volume of the Shoulder above the Sertaneja surface is about 0.40 km³ and that of the Head is 0.012 km³. The distribution area for the mafic alkaline rocks is 0.20 km². The mafic alkaline neck has approximately cylindrical form and it is intrusive into the basement gneiss. The neck volume is 0.056 km³, corresponding to only 14% of the whole massif (Figure 3B). In case the neck is of

slightly funnel-shaped form, the volume would be smaller. The small distribution area of mafic alkaline rocks is comparable with the other intrusive rock bodies of the Macau magmatic province.

The geomorphological analyses show that the erosion effects of the drainages are small, either on the Shoulder or on the Head. On the Shoulder, the largest drainage is 30 m deep (Figure 3, arrow). On the Head, no drainage is recognised.

The Macro Concavity Index (MCI; Motoki & Motoki, 2011) for the Cabugi Peak is strongly negative, being -2.3, indicating that the massif is remarkably convex in three-dimensional form (Figure 5A).

According to the Figure 5B, the active and young volcanoes have slightly positive MCI because of the original stratovolcano landform. When they are eroded, the mountain slope will be more concave and the MCI will be higher.

On the other hand, felsic alkaline rocks are mechanically very firm (Petrakis et al., 2009) and form convex-form massifs with remarkably negative MCI. The MCI value of the Cabugi Peak, -2.3, is minor than that of the alkaline massifs, suggesting that the massif is of high erosive resistance. This strongly negative MCI is favourable to differential erosion hypothesis, but unsuitable to an eroded extinct volcano.

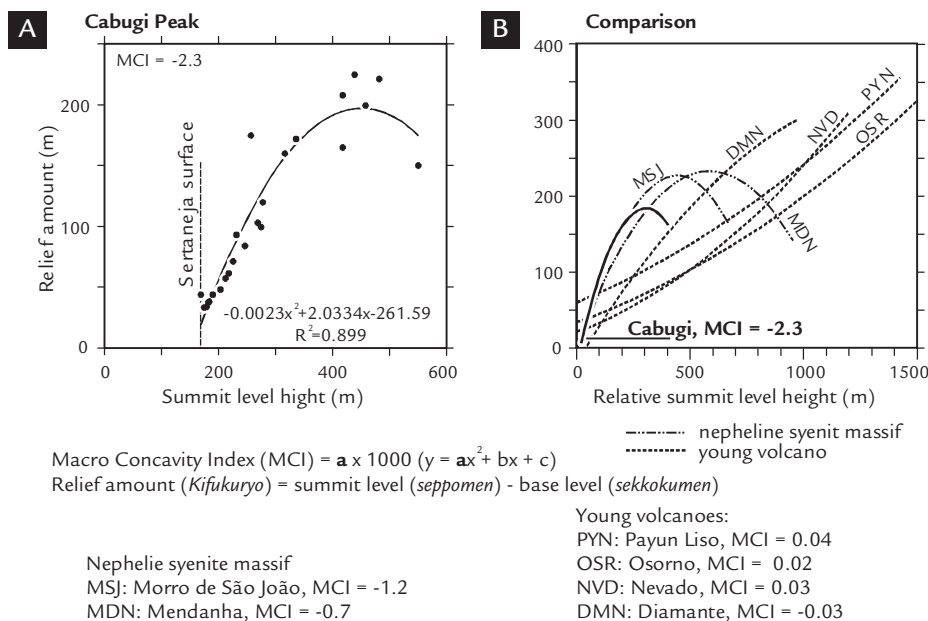


Figure 5

The MCI diagram for the Cabugi Peak according to the method of Motoki & Motoki (2011): A) Projection of summit level vs. the difference between summit level and base level of grid interval of 480 m; B) MCI for the Cabugi Peak compared with young volcanoes and nepheline syenite intrusive massifs. OSR - Osorno Volcano, Chile; PYN - Payún Liso Volcano, Argentina; DMN - Cerro de Diamante Volcano, Argentina; NVD - Nevado Volcano, Argentina; MDN - Mendanha nepheline syenite massif, Brazil; MSJ - Morro de São João nepheline syenite massif, Brazil.

3. Field observations

The Head is constituted by mafic alkaline rocks and covered by its blocks with representative size of 60 cm. The slope of the Head is of high angle, about 30°, corresponding to the maximum stability angle for dry solid objects. At some localities, there are outcrops, which are characterised by hexagonal columnar joints, because of removal of the blocks by surface collapse. The largest outcrop, about 60 m long and 30 m wide, is located at the northwest slope (Loc. 1, Figure 3A). The columnar joints of the central part of the neck are of high-angle (Figure 6A, arrow H), and these of the border zone are of low-angle (Figure 6A, arrow L). The columnar joints close to the contact are sub-horizontal (Loc. 2, Figure 3; 6B).

Lava flows and shallow subsurface intrusive bodies, such as sill, generally have sub-vertical columnar joints, for example: Columbia River Basalt (e.g. Spry, 1962; Long & Wood, 1986); Devil's Tower, Wyoming (Robinson, 1956); *Sheepeater* Cliff, Yellowstone National Park (Harris & Kiver, 1985); Palisades Sill, New Jersey (Spry, 1962); Shiprock, New Mexico, USA (Delaney & Pollard, 1981); Cerro Re-

dondo, Santa Cruz, Argentina (Schilling et al., 2005). Vertical columnar joints of lava flows indicate that the magma cooled by surface thermal irradiation.

On the other hand, early Cretaceous tholeiitic dykes of the State of Rio de Janeiro, Brazil, related to the magmatism of the Paraná basaltic province, have well-developed horizontal columnar joints (Motoki et al., 2009b). They were emplaced at a depth of about 5 km (Motoki & Sichel, 2008; Motoki et al., 2008b) and cooled by thermal conduction to the dyke wall. Similar Cretaceous tholeiite dykes are exposed on the Sertaneja surface (Angelim et al., 2006), also showing horizontal columnar joints.

The Devil's Tower is an intrusive body of cylindrical form with highly developed vertical columnar joints. On the other hand, the Cabugi Peak has oblique to sub-horizontal columnar joints (Figure 6; 8A). The angle of the columnar joints indicates thermal flow direction during the magma cooling (Jiang & Chen, 2004; Figure 7B). The columnar joint direction indicates that the cooling effect of the Earth's surface is strong for Devil's

Tower but that for the Cabugi Peak is less expressive. In this sense, the Cabugi Peak subvolcanic neck could have been emplaced at a site deeper than the Devil's Tower, but not as deep as tholeiite dykes with horizontal columnar joints.

The block layer on the Head is 5 to 10 m thick and it is composed of angular mafic alkaline rocks. They are originated from the columnar joints and have hexagonal column form (Figure 8A). Many blocks have fresh fragmentation surfaces. The Shoulder top generally exposes orthogneiss of the Caicó Complex, but is covered by mafic alkaline blocks at few localities (Figure 8B). The blocks on the Shoulder tend to be slightly rounded (Figure 8C), showing node rounding. However, hexagonal edges are often preserved. These observations indicate that the block tumbling is still very active and the Head is in on-going surface collapse process. The neck was exposed at the surface in a recent geologic time.

On the other hand, no outcrops of mafic alkaline lava, pyroclastic eruptive deposits or volcanic rock debris have been observed. The foothill of the Sertaneja

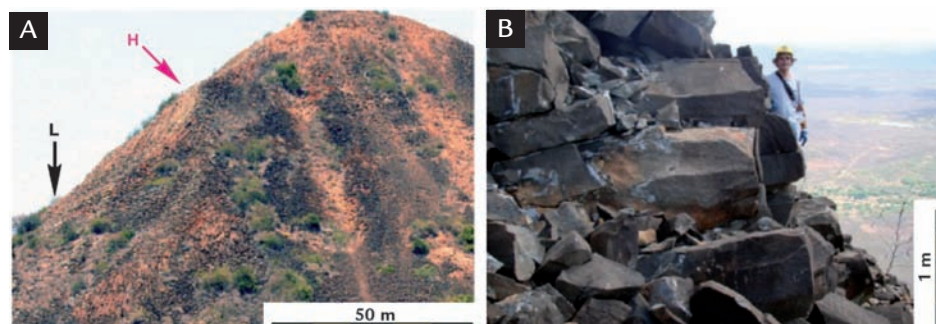


Figure 6

Columnar joints of the mafic alkaline rock at the Head of the Cabugi Peak, State of Rio Grande do Norte, Brazil: A) Transition from high-angle joint at the central part of the neck (arrow H) to low angle ones at the border (arrow L). B) Horizontal columnar joints close to the contact.

Figure 7
Direction change of columnar joints:
A) The Cabugi Peak neck, State of Rio Grande do Norte, Brazil, schematic illustration of the authors.
B) Lütao dyke-lava system, Pengfu Islands, Taiwan (Jiang & Chen, 2004).
Note the similarity between the columnar joint of the Cabugi Peak and dyke part of the Lütao intrusive body.

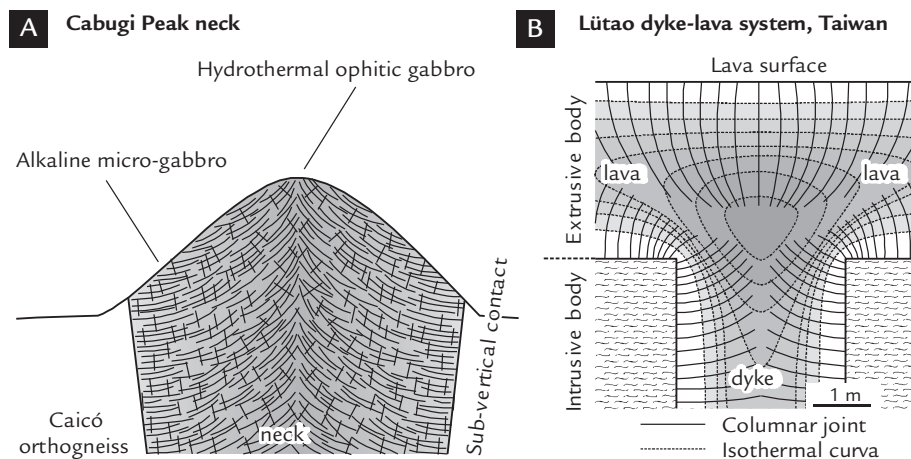
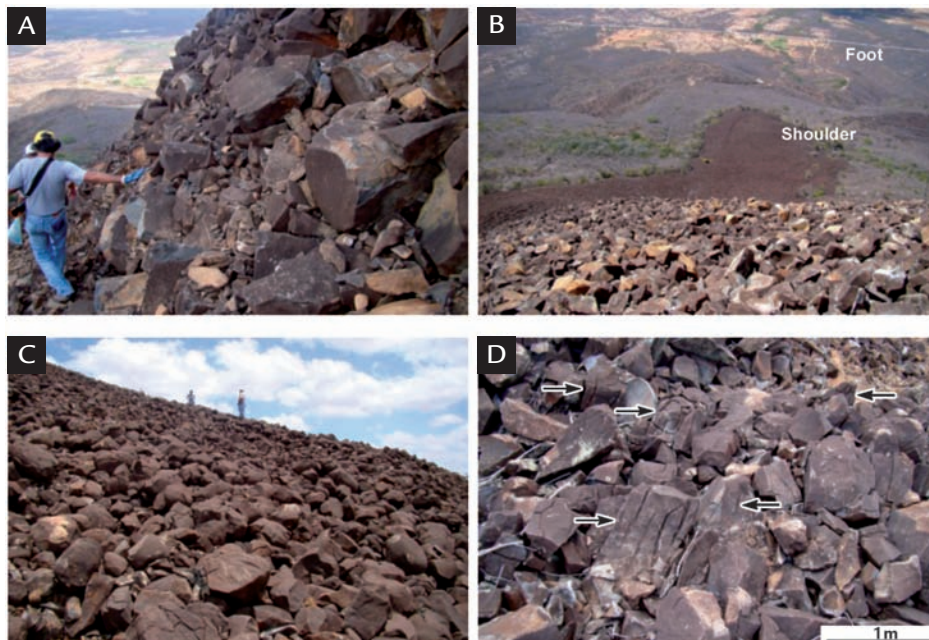


Figure 8
Mafic alkaline rock blocks covering the Head:
A) High-angle slope of the Head covered by hexagonal and fragmented angular blocks.
B) View from the top of the Head showing the surface of the Shoulder covered partially by the blocks.
C) Slightly rounded blocks on the Shoulder.
D) Linear and polygonal cooling cracks (black arrows).



surface exposes the Caicó Complex orthogneiss and tholeiitic dykes intruded in a deep site. If the Cabugi Peak were an extinct volcano, the above-mentioned volcanic materials must be abundantly present on the Sertaneja surface, especially at the localities close to the Cabugi Peak.

The contact plane between the neck and its country body is a most important subject to be observed, but during the fieldwork no adequate outcrop has been found. Sub-horizontal columnar joints at the contact zone suggest that the contact is sub-vertical. All of the columnar joints

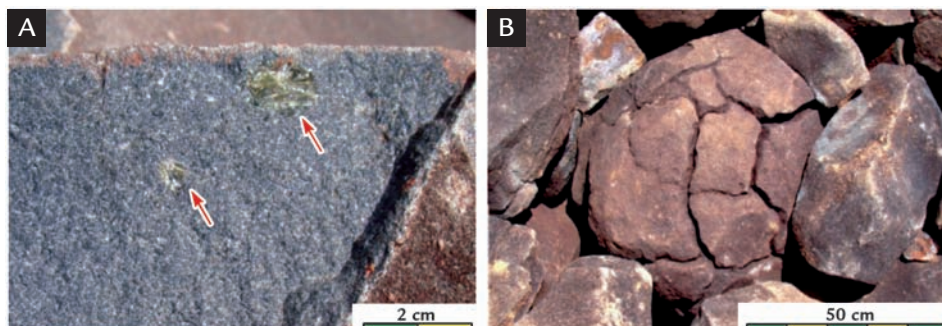
are tilted largely or slightly to the centre of the neck. This observation suggests that the contact plane is of slightly funnel-shaped three-dimensional form, that is, the neck could be open upward. If so, the abundance of the mafic alkaline blocks on the Head is easily explained.

Macroscopically, the mafic alkaline rocks are relatively coarse-grained, with grain-size of about 1 mm, and contain olivine-rich mantle xenoliths less than 2 cm in size (Figure 9A). There are blocks with linear cracks and curved polygonal crack like turtle's carapace (Figure 8D,

arrows). Some of them are apparently similar to bread-crust bomb (Figure 9B). These fractures occur only on lateral surfaces of the columnar joints and originated from surface volume contraction by rapid cooling along columnar joint planes (Figure 10).

Bread-crust bombs are characterised by: 1) Volume expansion; 2) Porous texture by vesicular formation; 3) Elliptic form (e.g. MacDonald, 1972); 4) Vitric; 5) Andesite to dacite composition. The blocs of the Cabugi Peak are featured by: 1) Volume contraction; 2) Massive texture

Figure 9
Peculiar fabrics of the mafic alkaline rock blocks:
A) Olivine-rich xenoliths (red arrows).
B) Polygonal cooling crack on the lateral surfaces of a hexagonal columnar joint.



without vesicles (Figure 9A); 3) Hexagonal column form; 4) Holocrystalline; 5) Mafic

to ultramafic composition. Therefore, the above-mentioned mafic rock blocks

(Figure 9B) are not considered to be bread-crust bombs.

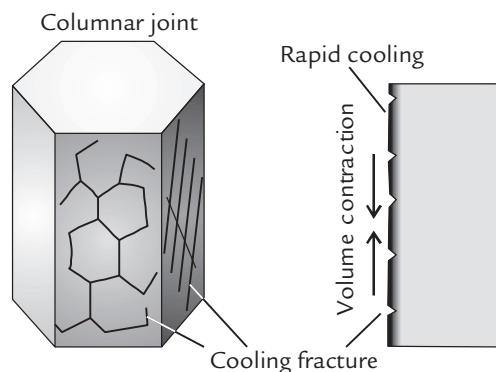


Figure 10
Schematic illustration for the polygonal cooling crack of columnar joint of the Head of the Cabugi Peak.

4. Petrographic observations

The mafic alkaline rocks of the Head are made up of olivine, clinopyroxene, plagioclase, opaque minerals, and apatite (Figure 11). According to Sial et al. (1981), the SiO_2 contents are 39~45wt%, which correspond to picritic alkaline gabbro of ultrabasic category. In spite of ultrabasic composition, these rocks are not ultramafic.

Olivine occurs either as phenocrysts of 1.0 mm in diameter, or in the ground-mass. Some large olivine crystals show resorption texture (Figure 11D). The clinopyroxene is titanaugite and 0.2 mm to 0.4 mm in size (Figure 11B). Plagioclase takes place as large tabular crystals (Figure 11A) and microliths (Figure 11B, C).

There is a notable textural contrast between the central part of the neck and

the contact zone. The sample of the centre is relatively coarse-grained (Figure 11A). The plagioclase crystals are 1.5 mm x 0.4 mm in size, and the rock is classified to be olivine-rich micro-gabbro. Alteration of large plagioclase crystals and partial decomposition of the mafic minerals into opaque ones are notable. These features suggest metasomatic or hydrothermal alteration, which is commonly observed in the central part of alkaline rock dykes (Motoki et al., 2008b).

The sample of the contact zone is holocrystalline and relatively fine-grained (Figure 11B). According to the crystallinity and grain size, it is classified to be olivine-rich dolerite. In contrast to the central part of the neck, the rock is fresh without signs

of alteration. The texture is sometimes not typically porphyritic. It is characterised by intermediate-sized olivine and clinopyroxene crystals. The plagioclase microliths are 0.08 mm x 0.4 mm (Figure 11C).

Some of the olivine crystals show sign of remelting (Figure 11D) but most of them are idiomorphic without remelting. This observation suggests two different origins. Considering the existence of olivine-rich mantle xenoliths (Figure 9A), the re-melted olivine could be originated from the xenolith. On the other hand, the idiomorphic ones are phenocrysts.

These observations confirm basically the previous description (e.g. Sial et al., 1981; Ferreira & Sial, 1999), but no volcanic glass is recognised.

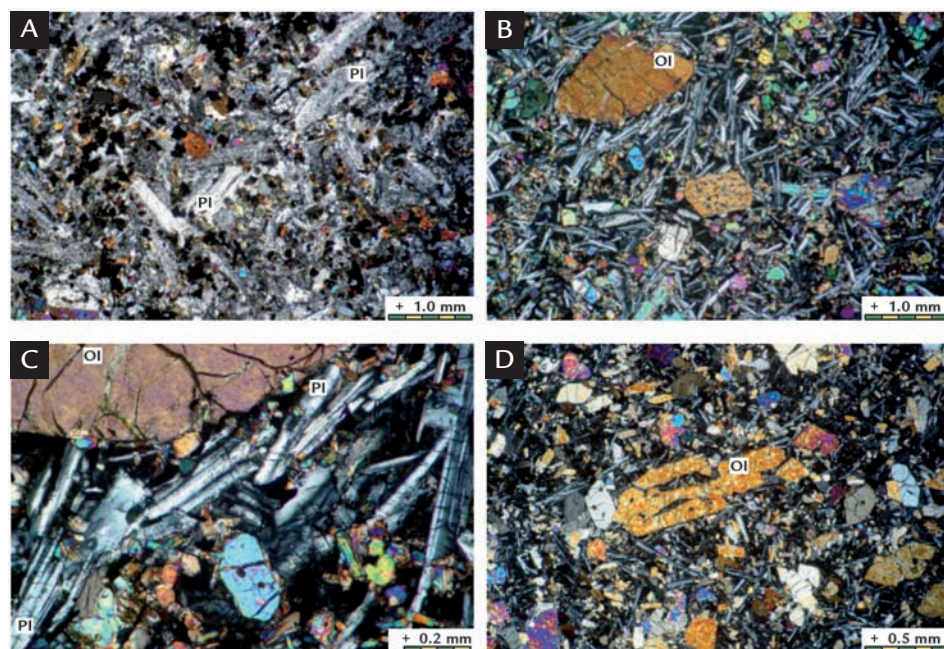


Figure 11
Photomicrography of the Cabugi Peak mafic alkaline rocks:
A) Central part of the neck.
B) Contact zone of the neck.
C) Tabular plagioclase of the sample B.
D) Olivine with resorption texture.
Ol – olivine; Pl – plagioclase.

5. Extinct volcano or shallow intrusive body?

The idea of the Cabugi Peak as an extinct volcano was proposed by Moraes

(1924). He considered that the present morphology is originated directly from

the volcanic edifice without notable erosive effects (Figure 12A). That is, the late

Oligocene volcanic landform is almost perfectly preserved up to the present. Most of the non-academic sources (e.g. Rocha & Nascimento, 2007; Barros, 2009; Jornal do Turismo, 2011) adopted this opinion and call it as “the only one Brazilian extinct volcano with preserved original form”.

Souza et al. (2002), Paiva et al. (2004), and Nascimento et al. (2006) accepted the volcano model, but with some modifications. There was a volcanic edifice larger than present morphology of the Cabugi Peak and its lateral slope

was deeply eroded remaining the central conduit filled by magma, that is, neck (Figure 12B). The original volcanic landform is no more preserved. These authors used the term “neck” as the conduit filled by consolidated magma at the centre of the volcanic edifice, that is, cylindrical magma feeder above the surface level of the eruption time. However, the geologic term “neck” corresponds to the cylindrical magma feeder either above or under the original surface (MacDonald, 1972). In order to distinguish the both types, the authors adopt the expression “neck in the

volcanic edifice” for the former (Figure 12B) and “subvolcanic neck” for the latter (Figure 12C).

The models A and B of Figure 12 consider that the Cabugi Peak is an extrusive volcanic rock body. In addition, the surface of the Oligocene was the same of the present, without regional denudation. Therefore, the present position of the Cabugi Peak is above the surface of the eruption time. Rolff (1965) and Sial (1978) described it as a neck or plug. But no clear model for the geologic emplacement was expressed.

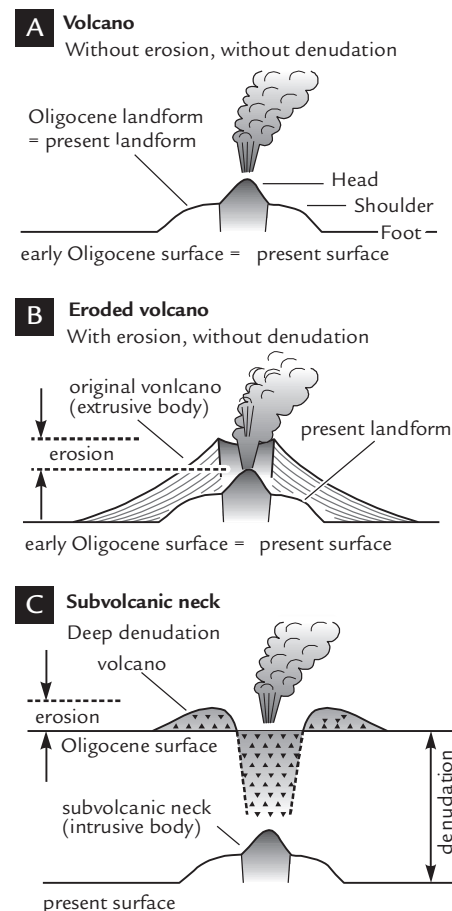


Figure 12
Comparative illustration of the models
for geologic emplacement mode of the
Cabugi Peak mafic alkaline rock body:
A) Preserved extinct volcano (Moraes, 1924).
B) Eroded volcanic edifice (e.g. Souza et al., 2002;
Paiva et al., 2004; Nascimento et al., 2006).
C) Subvolcanic neck, proposal of the present paper.

The present study has clarified that the Cabugi Peak neck is characterised by: 1) Cylindrical or slightly funnel-shaped three-dimensional rock body form; 2) High-angle columnar joints at the centre of the neck and sub-horizontal ones, at the contact zone; 3) Centre of the neck constituted by olivine-rich micro-gabbro and the border, by olivine-rich dolerite; 4) Distribution of the mafic alkaline rock in very restrict, in an area of 0.20 km²; 5) Absence of mafic alkaline lava, eruptive deposits, and volcanic rock debris on the Foot plane of the Sertaneja surface; 6) The three-dimensional form of the massif is strongly convex, with strongly negative MCI of -2.3.

The models of volcano and eroded volcano (Figure 12A, B) have incompatibilities with the present observations. The magma of the Cabugi Peak is of ultrabasic composition and has low viscosity and high fluidity. If the Cabugi Peak were an extinct volcano, the eruptive materials, such as lava flow and pyroclastic deposits, should be present extendedly on the Sertaneja surface. In addition, the blocks originated from the eroded part of the volcanic edifice should be present abundantly. However, in fact, no such materials have been observed. The strictly limited distribution area is unfavourable to an extinct volcano hypothesis.

If the Head were the central conduit

in the volcano, that is, the neck in the volcanic edifice, the Shoulder must be a part of the volcanic edifice (Figure 12B). However, the Shoulder is made up of the Caicó orthogneiss. If the mafic alkaline rocks were constituent of an extrusive body, the rocks should be vitric or very fine-grained and porous, and the columnar joints should be vertical. However, the rocks are holocrystalline massive micro-gabbro or dolerite and the joints are sub-horizontal at the contact zone.

If the Cabugi Peak were eroded volcanic edifice and not a morphological elevation originated from differential erosion of a subvolcanic intrusive body, the general massive form should be concave

and the MCI should be positive. However, its three-dimensional form is convex, with a strongly negative MCI, of -2.3. These facts indicate that the Cabugi Peak neck is not an extrusive body at the surface, but an intrusive one emplaced at an underground site.

Ferreira & Sial (1999) interpreted the blocks with polygonal cooling fractures on the lateral surfaces of the columnar joint (Figure 8D, 10B) as bread-crust bombs. Such bombs are formed by volume expansion by vesiculation of vitric essential fragments, that is, the magma drops ejected from the crater in consolidation process. However, the blocks in question are holocrystalline and massive, and not, vitric and porous. Bread-crust bomb occurs in the eruption of high viscosity magmas, such as andesitic, dacitic, and trachytic ones, represented by Vulcanian eruption (MacDonald, 1972). However, the blocks of the Cabugi peak are constituted by holocrystalline olivine-rich alkaline micro-gabbro or dolerite of ultrabasic composition, and therefore, such magma cannot generate bread-crust bomb.

Considering the previous discussions, the authors propose a subvolcanic

neck model for the Cabugi Peak. The Earth's surface of eruption time of the late Oligocene was not the same height of the present regional level of the Sertaneja surface, but it was much higher. The volcanic edifice was emplaced on this previous surface. However, later regional uplift and consequent deep denudation removed completely the volcanic edifice and eruptive deposits. At the present, only the underground conduit is left as a subvolcanic neck (Figure 12C).

The Sertaneja surface has wide and shallow morphologic depressions originated from lateral river erosion. The surface is close to be an elevated peneplane but it is not completely in erosive equilibrium. In this sense, the regional denudation is still active in spite that it is not so strong.

The model of the Figure 12C is similar to that of the alkaline intrusive complexes with pyroclastic bodies of the State of Rio de Janeiro, such as Mendanha (Motoki et al., 2007b), Itaúna (Motoki et al., 2008c), Tanguá, Rio Bonito, Soarinho (Motoki et al., 2010), Morro dos Gatos (Motoki et al., 2011), and Cabo Frio Island (Sichel et al., 2008). The original surface

has been removed by later uplift and consequent regional denudation. The magma chambers and subvolcanic conduits 3 km below the prior surface are exposed at the present-day surface (e.g. Motoki & Sichel, 2006; Motoki et al., 2008d).

The geologic expressions “volcano” and “volcanic edifice” are defined as a morphologic elevation formed directly by eruptions and consequent accumulation of eruptive materials on the Earth's surface (e.g. MacDonald, 1972; Bates & Jackson, 1987). The positive relieves originated from differential erosion of intrusive bodies, such as dyke and subvolcanic neck, are not classified to be extinct volcanoes.

For example, the Chachahuén Volcano and the Plateado Volcano, Mendoza Province, Argentina are deeply eroded stratovolcanoes (Bermudez et al., 1993). In spite of the strong erosion effects, the denudation is null. The surface of the eruption time is the same of the present. The present-day topographic elevations are directly delivered from volcanic edifices and not because of differential erosion. Therefore, they are classified to be eroded extinct volcanoes.

6. Interpretation of eruption mode

Low viscosity magmas, such as of alkaline olivine gabbro, rise up in the upper crust by means of dyke intrusion. When the magmas arrive at the surface, a fissure eruption takes place. In this case, large cylindrical conduits, such as the Cabugi subvolcanic neck, are unnecessary.

Cylindrical or slightly funnel-shaped subvolcanic conduits are formed by explosive eruptions. Some mafic to ultramafic alkaline magmas have high fluid contents

and it causes explosive eruption forming tuff volcano and upward opened funnel-shaped conduits called diatreme (Figure 13A). When a large amount of magma is provided just after the explosive eruption, the diatreme vent space is filled by magma (Figure 13B).

After the eruption, deep regional denudation occurred. The volcanic edifice, eruptive deposits, and the surface of eruption time have been removed, remaining only the subvolcanic neck. The

present erosion base level is situated at the Sertaneja surface and it is much lower than the old surface. The outcrops of the Cabugi Peak correspond to the subvolcanic structure of the eruption time and the subvolcanic neck is an intrusive body. The morphological relief of the Head is formed by differential erosion of the subvolcanic neck (Figure 13C). This is a possible interpretation without contradiction with the field evidences.

7. Conclusion

The Cabugi Peak was reported as the only one Brazilian extinct volcano with preserved original form. However, the present study leads to a different conclusion. Field observations, geomorphological analyses, petrographic descriptions, and volcanological consideration of the Pico do Cabugi indicate the following conclusions:

1. The Cabugi Peak is 370 m high, has a volume of 0.4 m³, and is made up mainly of basement orthogneiss of the Caicó Complex. The neck is exposed on its top forming a conical morphologic protrusion of 160

m of relative height and 500 m of diameter. The volume of the mafic alkaline rock is 0.056 km³ occupying 14% of the whole massif. The massif has remarkably convex general form and the MIC is -2.3. This strongly negative MCI is favourable to differential erosion hypothesis, but unfavourable to eroded extinct volcano one.

2. The neck is characterised by well-developed columnar joints with typical diameter of 60 cm. They are steep at the centre of the neck and sub-horizontal at the contact zone.

The sub-horizontal columnar joints suggest that this neck is not an extrusive body, but a shallow intrusive one. The fragments originated from the columnar joints cover the surface of the neck. The fractures similar to those of bread-crust bomb are formed by rapid cooling on the hexagonal planes of columnar joints.

3. The neck is constituted by olivine-rich micro-gabbro of 1.5 mm in grain size at the central part and olivine-rich dolerite of 0.4 mm at the border. The rock is holocrystalline and massive, without porous structure.

4. No outcrop of lava flow of the mafic alkaline rocks, eruptive deposits, or volcanic debris is observed on the Foot plane of the Sertaneja surface. The mafic alkaline rock occurs only on the Head in an area of 0.2 km². This limited distribution is favourable to subvolcanic neck model. The volcanic edifice and eruptive deposits of the late Oligocene were completely removed by later denudation caused by regional uplift and the original

landform of volcanic edifice is not preserved any more.

5. The present-day exposure of the Cabugi Peak corresponds to a subvolcanic neck, being a shallow intrusive body, and not a neck in the volcanic edifice. The topographic high is attributed to differential erosion. According to the geologic definition, the Cabugi Peak is not classified to be an extinct volcano because of the total elimination of the original volcanic

edifice and eruptive deposits.

6. Geologic setting of the Cabugi Peak suggests the following eruption history; 1) Explosive eruption took place forming tuff-ring and diatreme; B) Diatreme vent was filled by mafic alkaline magma forming a cylindrical intrusive body; C) Regional denudation exposed the underground structure and differential erosion made the morphologic elevation of the subvolcanic neck.

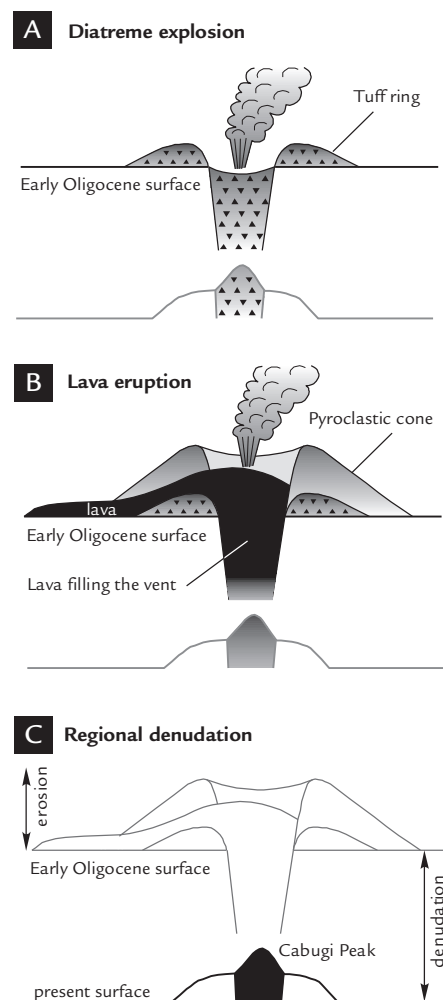


Figure 13
Schematic illustration of the model for the formation process of the Cabugi Peak:
A) Explosive eruption and formation of tuff-ring and diatreme.
B) Diatreme vent filled by magma.
C) Regional denudation exposing the subvolcanic structure.

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