THE SOUTH ATLANTIC OCEAN OPENING AND ITS RELATIONSHIP WITH THE DIKE SWARMS EMPLACEMENT OF THE NE SÃO PAULO STATE (BRAZIL).

M. Irene B. Raposo

Instituto de Geociências da Universidade de São Paulo, São Paulo, Brasil

e-mail: irene@usp.br

RESUMO

Foram estudados 91 diques Cretáceos pertencentes a dois enxames; um deles de composição toleítica e o outro de composição lamprofírica. Os diques intrudem rochas metamórficas do Complexo costeiro, apresentam espessuras que variam de poucos centímetros até 2 m para os lamprófiros e até > 10 m para os diabásios, possuem direção predominante N30º-60ºE com mergulho vertical e afloram lado a lado nas praias do litoral Norte do Estado de São Paulo. As tramas magnéticas foram determinadas através da anisotropia de suscetibilidade magnética (AMS) e da anisotropia da magnetização remanente anisterética (AARM). As propriedades magnéticas, obtidas através de vários experimentos, indicam que o mineral magnético presente nos dois enxames é a magnetita. Para a maioria dos diques a magnetita é responsável pela suscetibilidade magnética, mas surpreendentemente, os minerais paramagnéticos são os responsáveis pela AMS como mostrado pela AARM. A principal trama de AMS é devido ao fluxo magmático, onde a inclinação de K_{max} sugere que os diques foram alimentados por fluxos horizontal a vertical. Entretanto para a maioria dos diques as tramas de AMS e de AARM não são coaxiais. A lineação da AARM é orientada a N30-60W, aproximadamente perpendicular a lineação da AMS e é similar a direção do sistema de falhas das bacias marginais Brasileiras, principalmente, Santos e Campos que tiveram origem durante a abertura do oceano Atlântico. A comparação das tramas de ASM e AARM permite inferir que os diques dos dois enxames foram colocados em três eventos tectônicos distintos nas fases iniciais da abertura do Atlântico Sul.

Palavras Chaves: AMS, AARM, Oceano Atlântico, Enxame de Diques

ABSTRACT

A total of 91 Cretaceous dikes from two swarms was studied; one of them having a toleiitic and the other a lamprophyric composition. The dikes intrude metamorphic rocks of the Coastal Complex, their thicknesses ranging from a few centimeters up to 2 m for the lamprophyres and up to> 10 m for the diabase. They have a predominant direction N30-60E with vertical dip, and outcrop side by side in the beaches of the North São Paulo State coastline. Magnetic fabrics were determined by the anisotropy of magnetic susceptibility (AMS) and anisotropy of the anhysteretic remanent magnetization (AARM). The magnetic properties, obtained through several experiments, indicate that magnetite is the magnetic mineral in both swarms. For most dikes magnetite is responsible for the magnetic susceptibility, but surprisingly, the AMS is carried by Fe-bearing minerals, as shown by AARM. The main AMS fabric is due to the magmatic flow, where the inclination of K_{max} suggests that the dikes were fed by horizontal up to vertical flows. However, for most dikes AMS and AARM fabrics are not coaxial. The AARM lineation is oriented to N30-60W, approximately perpendicular to the AMS lineation and is similar to the direction of the fault system from Brazilian marginal basins, mainly Santos and Campos, which were formed in the Cretaceous rifting during the South Atlantic opening. The comparison of the ASM and AARM fabrics allows inferring that the dikes from both swarms were emplaced in three different tectonic events in the earliest stages of the South Atlantic opening.

Keywords: AMS, AARM, Atlantic Ocean, Dike Swarms.

1. Introduction

There is consensus that the break up of Western Gondwana and the opening of the South Atlantic Ocean started in the Late Jurassic/Early Cretaceous in the southernmost parts of the South American continent,

and it advanced towards the northeastern Brazilian margin (Almeida, 1986; Mohriak *et al*., 2008, among many others). This break up was accompanied and followed by an intense magmatism that occurred in distinct phases on both continental margin basins and on the adjacent continent. Therefore the Mesozoic magmatism in southern Brazil is represented mainly by the basaltic flows of the Serra Geral Formation (Paraná flood basalts), the tholeiitic dike swarms from the Ponta Grossa Arch, Florianópolis, and along the coast between São Paulo and Rio de Janeiro, and several alkaline complexes (stocks) that lie along tectonic features associated with the evolution of the Paraná Basin. The emplacement of the dike swarms and the alkaline complexes is related to the processes of the breakup of Gondwana Continent and with the opening of Atlantic Ocean which originated the marginal basins in the coast of Brazil such as Santos and Campos basins (among others) that are close to the studied swarms. In general, continental flood basalts are associated with the early phase of continental break up, and dike swarms which reflect the initial geometry of tectonic features affecting the lithosphere at the very beginning of rifting are most often well developed, but in the case of the studied swarms in this paper, their relationship in time and space with Paraná flood basalt are poorly known. This paper focus on dike swarms which out crop along the northern coast São Paulo state between São Sebastião and Ubatuba cities (Fig. 1), in which a detailed magnetic study was performed. The principal purpose of this study is: to investigate the magma flow in the dikes, to provide information on its mode of emplacement, to investigate the relative position of magma sources and fractures through out magnetic fabrics determinations (anisotropy of magnetic susceptibility, AMS), to investigate the relationship between dikes with different composition, to determine the magnetic mineral fabric through out anisotropy of magnetic remanence in order to verify the overlap of tectonic events that could affected the dikes (as will be shown further), and to contribute to better understanding of the tectonic processes during the Atlantic Ocean opening. To better define the magnetic carriers and their relative contribution to both the mean magnetic susceptibility and the remanence it was also performed an extensive rock magnetism study.

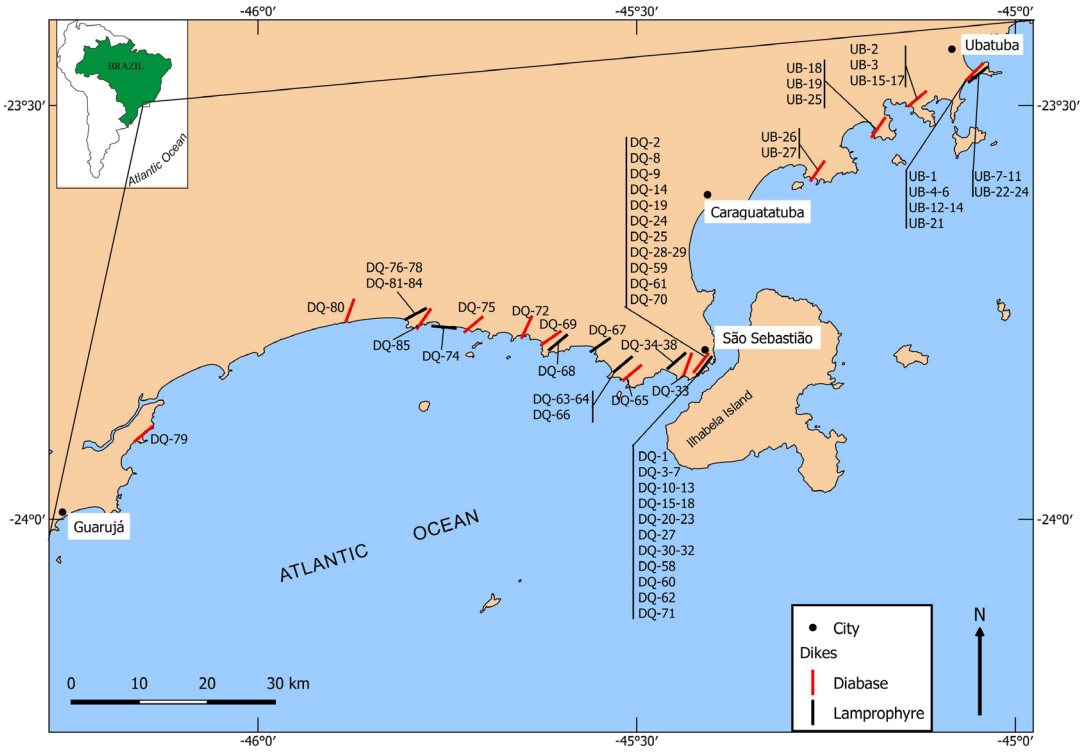

Figure 1. Map of localization of the sampled dikes. It has been plotted a mean direction representing the dikes and identified them with the numbers in order to clarify the figure.

2. Magnetic Measurements

Oriented samples from 52 lamprophyre and 39 tholeiitic diabase dikes, widely distributed throughout the beaches between São Sebastião and Ubatuba region (Fig. 1) were collected for magnetic measurements. Sample orientations were determined using both magnetic and sun compasses, whenever possible. At least 15 (6 from each border and 3 from the center) and up to 20 cores, using a gasoline-powered rock drill, were collected from each site (dike) for which the strike and thickness could be determined. Both margins of the dikes were symmetrically (whenever possible) sampled, together with the center in order to verify whether there is an imbrication of the AMS axes.

3. AMS Fabric

AMS measurements were performed on 2.5 cm x 2.2 cm cylindrical specimens that were cut from the cores collected all sites of the lamprophyre and diabase dikes, using a Kappabridge instrument (KLY-4S, Agico, Czech Republic). The dominant AMS fabric in both swarms is that one which is expected for dikes, and is called as *Normal* fabric. It is characterized by having the AMS foliation (K_{max}- K_{int} plane) nearly parallel to the dike plane whereas the AMS foliation pole (K_{min}) is nearly perpendicular to it, however, *Intermediate* and *Inverse* fabric were found in some dikes (Fig. 2). The *Intermediate* is defined by K_{max} and K_{min} axes clustering close to dike plane while K_{int} axes are nearly perpendicular to this plane whereas *Inverse* fabric is defined by K_{int} and K_{min} axes clustering close to dike plane and K_{max} axes nearly perpendicular to this plane.

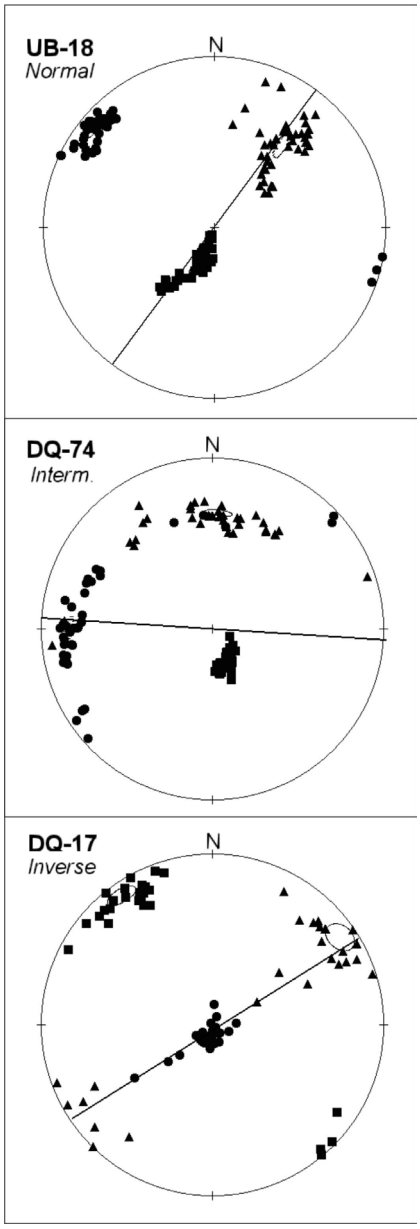

Figure 2. Examples of AMS fabrics found in the studied dikes. *Interm.* = *intermediate* fabric. Squares are maximum susceptibility (K_{max}) triangles are intermediate susceptibility (K_{int}) and circles are minimum susceptibility (K_{min}). *Dashed line ellipses = 95% confidence ellipses. The full line represents* the dike plane with vertical dip. Data plotted in the lower hemisphere stereonets.

4. Rock Magnetic Properties

Rock magnetism properties obtained by many experiments indicate that pseudo-single-domain with a single-multi-domain mixture grains of almost pure magnetite carry the magnetic susceptibility and the AARM fabric for both swarms.

5. AARM Fabric

For the majority of the dikes from both swarms the AARM and AMS tensors are not coaxial. For dikes with *normal* and *intermediate* AMS fabrics the AARM fabric becomes either "inverse" or "intermediate" or even "normal" (*i.e.* coaxial). The SD effect cannot explain the *inverse* and *intermediate* AMS fabric for the studied dike swarms. Because if the *inverse* and *intermediate* AMS fabrics in both warms were due to SD effect, the AARM fabric would be "*normal*", *i.e* the $AARM_{max}$ would be oriented in the dike plane and the $AARM_{min}$ would be perpendicular to it (a flow fabric). However, it does not occur since, in studied dikes, both AMS and AARM fabrics are coaxial (*i.e.* both are *inverse*). All dikes with *inverse*

AMS fabric have a AARM fabric coaxial.

6. Discussion

In the studied dike swarms the *normal* AMS seems to be primary in origin as it is supported by the presence of bayonets in some dikes, which indicate magma flow. On the other hand, for the majority of dikes AARM fabric is not coaxial with *normal* AMS fabric suggesting a tectonic origin for it. It seems that magnetite has a very low intrinsic anisotropy, or it has a nearly random orientation distribution, then magnetite may not have a strong influence on the orientations of the AMS axes. Even though the magnetite grains in the studied dike swarm dominate the bulk susceptibility, more anisotropic mafic silicates may still express their preferred-orientation through AMS fabric, and magnetite grains are weakly orientated, and their contribution to low field susceptibility is not sufficiently anisotropic to deflect the AMS fabric (*i.e.* to become AMS parallel to AARM). On the other hand, the orientation of AARM lineation ($AARM_{max}$) for dikes with *normal* AMS fabric is similar to the orientation of a system fractures zones found in the Santos and Campos marginal basins located on the eastern Brazilian margins which were formed after the Gondwana break-up and South Atlantic opening (*e.g.* Chang *et al*., 1992; Mohriak *et al*., 2008), and is also similar to the direction of the stretching between South America and Africa. Therefore the AARM fabric found for these dikes is probably tectonic in origin and suggests that the earliest tectonic processes, which were responsible for the South Atlantic opening, affected the dike swarms.

The comparison of both AMS and AARM tensors allow to infer that the lamprophyre and diabase dikes were emplaced in three distinct events. They are: (1) the increased lithospheric stretching (after or during the earliest beginning of the separation of South America and Africa was responsible by the intra-continental rifting in the South Atlantic, which probably reactivated the old fractures of the country rocks, associated with this process some dikes were NE emplaced almost parallel to coastline. These dikes show a *normal* and *intermediate* AMS fabric; (2) immediately after the emplacement of these dikes (first event) there was probably a field extensional stress which was responsible for the magnetite counterclockwise rotation as registered by the AARM fabric (*i.e.* $AARM_{max}$ is approximately perpendicular to K_{max}), and the dikes with *inverse* AMS fabric (second event, which is coaxial with AARM fabric) were emplaced: (3) The last intrusive event (third) is given by dikes in which *normal* AMS is coaxial with AARM tensor, and probably they were emplaced after the dikes from the second intrusive event since they have the same AMS and AARM fabrics.

The *intermediate* AMS fabric is interpreted as primary in origin in which the dikes acted as stress conduits, with continuing compression tending to force material along the dike direction. Only in two dikes the AMS and AARM fabric are coaxial, suggesting that they were emplaced in the third intrusive event. The other dikes (6) were emplaced in the first event and were affected by the tectonic processes responsible by the second event.

Normal AMS fabric for dikes emplaced in the first and third events is interpreted as due to magma flow. The analysis of K_{max} inclination permitted to infer that dikes were fed by gently plunging fluxes, inclined up to vertical fluxes. Such K_{max} plunge values allow inferring that the mantle sources were underlain the São Sebastião area and another diabase magma chamber would be in the Ubatuba region. In São Sebastião area the dikes from both swarms were fed also by horizontal or sub-horizontal flow suggesting either a displacement of South American plate or the existence of more than one magma chamber in the region.

Therefore *normal* and *intermediate* AMS fabrics of the São Paulo coastline swarms are primary in origin while the *inverse* AMS and AARM fabrics are tectonic, and they were acquired during the earliest process of the Atlantic Ocean opening. Based on magnetic fabrics (AMS and AARM) was possible to infer that the dikes were emplaced in three intrusive events in a short period of time during the earliest process of Gond-

wana break-up.

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References

Almeida, 1986. Rev. Bras. Distribuição regional e relações tectônicas do magmatismo pós–paleozoico no Brasil. *Revista Brasileira de Geociências 16 (4)*, 325-349

Chang, H.K., Kowsmann R.O., Figueiredo, A.M.F, Bender A.A., 1992. Tectonics and stratigraphy of the East Brazil Rift system: an overview. *Teconophysics 213*, 97-138

Mohriak W.U., Nemcok, M., Enciso G., 2008. South Atlantic divergent margin evolution: rift border uplift and salt tectonics in the basin of SE Brazil. In Pankhurst, R.J., Trouw, R.A., Brito Neves, B.B., De Wit, M.J. (eds). West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. *Geological Society, London, Sepecial Publications 294*, 365-398.