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MAGMA FLOW PATTERN IN DYKES OF THE AZORES REVEALED BY ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2014JB010982

2. ABSTRACT

The localization of magma melting areas at the lithosphere bottom in extensional volcanic domains is poorly understood. Large polygenetic volcanoes of long duration and their associated magma chambers suggest that melting at depth may be focused at specific points within the mantle. To validate the hypothesis that the magma feeding a mafic crust, comes from permanent localized crustal reservoirs, it is necessary to map the fossilized magma flow within the crustal planar intrusions. Using the AMS, we obtain magmatic flow vectors from 34 alkaline basaltic dykes from São Jorge, São Miguel and Santa Maria islands in the Azores Archipelago, a hot-spot related triple junction. The dykes contain titanomagnetite showing a wide spectrum of solid solution ranging from Ti-rich to Ti-poor compositions with vestiges of maghemitization. Most of the dykes exhibit a normal magnetic fabric. The orientation of the magnetic lineation k1 axis is more variable than that of the k3 axis, which is generally well grouped. The dykes of Sao Jorge and Sao Miguel show a predominance of sub-horizontal magmatic flows. In Santa Maria the deduced flow pattern is less systematic changing from sub-horizontal in the southern part of the island to oblique in north. These results suggest that the ascent of magma beneath the islands of Azores is predominantly over localized melting sources and then collected within shallow magma chambers. According to this concept, dykes in the upper levels of the crust propagate laterally away from these magma chambers thus feeding the lava flows observed at the surface.

3. KEY POINTS

The ascent of magma beneath the Azores is mainly focused over localised melting sources.

Dykes propagate laterally away in the upper levels of the crust from these magma chambers.

AMS data allow the calculation of magmatic flow vectors in basaltic dykes from the Azores.

4. Keywords

AMS

Azores

dykes

lithosphere

magma flow

volcanism

5. Text

1. Introduction

1.1. Magmatism at divergent plate boundaries

While oceanic spreading ridges are fundamentally segmented along-strike, the wavelength and nature of this segmentation differs depending upon the ridge spreading rate [e.g. *Macdonald et al*., 1988]. At slow-spreading ridges, accretion segments define the first-order segmentation [*Durand et al*., 1995; *Gente et al*., 1995; *Lin et al.*, 1990]. The center of these segments is associated with a central volcanic area where most of the volcanic and hydrothermal activities are observed, bounded on either side by fault-controlled deeper basins. As *Tolstoy et al*. [1993] clearly outlined, the crust thickness is higher at the segment center where most of the volcanic activity is observed and where tectonic extension dominates over magma accretion/dilatation. Analogous volcano-tectonic segments are found in other geodynamical contexts such as volcanic rifts in continental Large Igneous Provinces (LIP) [*Geoffroy et al*., 2007] where a hot-spot is interacting dynamically and magmatically with a nascent ridge e.g. Djibouti, see *De Chabalier and Avouac* [1994] or a established slow-spreading ridge (e.g. Iceland). In these latter cases, the central magmatic activity is expressed by a large polygenetic volcano, underlain by one or several large magma chambers located at shallow levels (3 - 5 km) e.g.*Bjornsson et al.* [1979], *Paquet et al*. [2007]. A very common observation in fossilized or active volcano-tectonic segments is that the magma chambers, underlying the central volcanic system, feeds lava fields through lateral and radial propagated dykes at the extremities of the segment (Fig. 1). Following from the model of *Chevalier and Verwoerd* [1988], *Geoffroy* [1998] and *Doubre and Geoffroy* [2003] argued that this mechanism is potentially viable because magma chambers act as stress concentrators within the upper-crust. According to these authors, dykes develop preferentially from the edges of magma chambers along the horizontal maximum stress σ_H. Only high magma pressures or/and small stress differential in the horizontal plane could promote a more radial pattern of dykes injection. From a review of previous studies of magma flow in dykes including eroded and active extensional systems, *Geoffroy et al*. [2007] suggest that magma is injected laterally in dykes within the upper crust (for a review of more recent data see *Wright et al*., [2012]).

These views conflict with old conceptual models suggesting that the dynamics of magma could be dominantly bottom to top from “deep magma layers” (e.g. *Gudmundsson*, [1986, 1990]). *Geoffroy* [2005] and *Geoffroy et al*. [2007] indicate the geodynamical importance of this result: if most of the lavas at spreading ridges and in LIP s are fed from dykes issued from long-lived magma centers and cross-cutting the topographic surface, this gives some insights into the distribution of melting at the asthenosphere-lithosphere boundary (see *Geoffroy et al.*, [2007] and references therein). **Fig. 1** summarizes the generalized LIP accretion segment concept developed by *Geoffroy et al*. [2007]: the upper crustal magma reservoir underlying each volcano segment center is directly or indirectly fed by the development of either a mantle diapir [*Geoffroy*, 1998] or a small-scale convection cell [*Geoffroy et al*., 2007]. This mantle upwelling thermally weakens the lithosphere, creating a so-called lithospheric (rheological) soft-point [e.g. *Callot et al*., 2004; *Gac and Geoffroy*, 2009]. In addition, this lithosphere-scale weakening leads to a lithosphere stretching and thinning that is orthogonal to the regional minimum principal stress $\sigma3$ and in the trend of the maximum horizontal stress σH (intersection of the $\sigma1$-$\sigma2$ plane with the topographic surface). Moreover, the upper-crustal magma chambers act as local stress concentrators, promoting dykes injection orthogonal to $\sigma3$ and in the trend of σH. As a result, within the upper crust, the active normal faults are focused away from the magma centre and control the subsidence and topography of basins in which the magma flows from the intersection of dikes with the topographic surface.

Such views, which have important consequences on the way we understand mantle melting processes, remain to be validated. Therefore it is important to have additional constraints on the pattern of magma flow and crustal growth in divergent magmatic systems, especially in contexts where the dynamics of the mantle is thought to be complex (e.g. oceanic ridge/hot spot interaction).

Our study is focused on the determination of magma flow vectors in the upper crust of a particular complex volcano-tectonic setting, the Azores hotspot.

1.2. The Azores area: a combination between a hot-spot and a triple junction

The Azores region consists broadly of a triangular anomalous shallow volcanic plateau centered to the east of the Mid-Atlantic Ridge (**Fig. 2**). To the North-East of this plateau, the en-echelon Terceira and Faial-Pico rift system (here designated as the Terceira Rift System, TRS) form a seismically active 125^{o} azimuth trending divergent plate boundary between Africa and Eurasia with a present-day half-spreading rate of ~2.5 mm/yr along 063^{o} trend [*DeMets et al*., 1990; *Luis et al*., 1998]. Together with the Middle Atlantic Ridge (MAR) north and south of latitude ~39°N, the TRS would be the third rift arm of a Ridge-Ridge-Ridge (RRR) or Ridge-transform Fault-transform Fault (RFF) triple junction between the North American, Eurasia and Africa plates [e.g. *Searle*, 1980]. A curious set of en-echelon abandoned volcanic ridges trending parallel to the TRS extends from the extinct East-Azores Fault Zone to the south of the Plateau to the active TRS, from south to north: Princess Alice Bank, Azores Bank, Terra-San Mateus Bank (**Fig. 2**). This could suggest a progressive northward migration of the triple junction, as formerly suggested by *McKenzie and Morgan* [1969], a view contradicted by *Searle* [1980] but rejuvenated by *Luis et al*. [1994].

Alternatively, this pattern could suggest a southwestward absolute migration of the Africa-Eurasia plates over a fixed hot-spot now located close to the Terceira Island [e.g. *Yang et al*., 2006].

Recent studies involving elastic plate modelling [*Luís, et al*., 1998, *Luís and Neves*, 2006] point to a mean crust thickness of about 9-12 km for the Azores plateau. This excess in oceanic crustal thickness suggests that the Azores plateau is located above a sub-solidus mantle. Trace elements and helium and lead isotope geochemistry suggest that the extreme variability in composition of the mantle source beneath the Azores Archipelago [e.g. *Bonatti*, 1990, *Moreira et al*., 1999a; *Dosso et al*., 1999; *Schaefer et al*., 2002; *Widom*,2003; *Asimov and Langmuir*, 2003]. These data indicate that the mantle is fertile, rich in radiogenic elements, but evidences are lacking from the geochemistry for a deep mantle plume. A seismic study of the mantle beneath Azores led *Yang et al*. [2006] to a model of a plume-ridge interaction, in which the plume conduit is deflected to the southwest in the shallow mantle by asthenospheric flow and plate motion. Anisotropic surface waves tomographic studies [*Silveira et al*., 2006] revealed a S-wave velocity negative anomaly beneath Azores, confined within the upper 250-300 km, pointing to the hypothesis that Azores could be a present-day dying plume.

The origin of the Azores plateau remains unclear. Continental mantle lithosphere contributions have been invoked [*Dosso et al*., 1999; *Moreira et al*., 1999a] and the imaging of a deep mantle plume is still a matter of debate. It is clear, however, that a large mantle compositional anomaly is present beneath the plateau [see also *Vlastelic et al*., 2002]. Whatever its origin, it must be kept in mind that the tectonic expression and the regional tensional regime of the Azores dynamics, controls the magmatic feeding and forms a diffuse plate boundary that weakly overprint the MAR's spreading seafloor. This is particularly evident from magnetic and gravity data [*Lourenço et al*., 1998].

1.3. Volcano-tectonic features of the TRS and aim of the study

The TRS (including Faial and Pico alignments) is a seismically and volcanically active ~120° trending structure. It shows an alternating morphology between the islands represented by bathymetric highs and the offshore deep basins (**Fig. 2**). Most islands and deeps present a non-circular outer shape with a long axis generally parallel to the overall ~110° to 125° azimuth trend. Each TRS island is associated with one or several large polygenic volcanoes and subordinated alignments of fissure-born monogenic cones. No TRS alkaline volcanism, is older than 4 Ma (at the eastern edge of San Miguel Island), and the bulk of it is younger than 1.3 Ma [*Féraud et al*., 1980; *Luis et al*., 1994; *Hildenbrand et al*., 2008].

The overall organization of the TRS could suggest that this rift is a very recent oceanic ultra-slow-spreading axis consisting of distinct volcano-tectonic segments (**Fig. 1**). The narrowness of the spreading axis is outlined by the pattern of the pre-hotspot MAR-related linear magnetic anomalies, which are still recognizable very close to the islands [*Luis et al*., 1998] and by the distribution of the seismicity. The islands broadly correspond to the volcanic centers, whereas lateral deeps could be areas from apart the magma centers where divergence takes place predominantly by tectonic extension rather than magmatic accretion. This overall structure is suggested by the pattern of volcanism and deformation. Point-source volcanism is suggested by the associated occurrence of large polygenic volcanoes and the important role of fissural volcanism. Fissural volcanism is characterized by alignements of monogenetic cones and the exposure of dyke swarms in eroded cliffs, being generally centered on the polygenetic volcanoes. Significantly, the eruptive fissures are roughly parallel to the general alignments of the segments forming the TRS, except notably on Santa Maria (**Fig. 3**). In addition, while normal faults are the dominant pattern of faulting on the islands [*Hildenbrand et al*., 2012] there is nevertheless, a clear component of dextral shear [*Searle, 1980*]. The normal faults are best developed at the NW and SE edges of the islands, with throws increasing towards the offshore basins. This is consistent with the distribution of seismicity, which is preferentially located between the volcanic centres [*Miranda et al*., 1998]. These rift-type trend dominantly parallel to the dyke swarms with fissural volcanism at the ground surface.

However, this general volcano-tectonic segmentation proposed for the structure of the TRS is challenged by a number of additional facts and observations which must be taken into account. Although rather few focal mechanisms are published for seismic events in the Azores, extensional double-couple is expressed along the TRS [*Grimison and Chen*, 1986] with P axes generally plunging with a significant dip [*Buforn et al*., 1988; *Hirn et al*., 1980]. It is noteworthy that the solution for the last major earthquake (January 1980, M~7) and its aftershocks indicates a sinistral strike-slip displacement along a 154^{o} azimuth fault between Sao Jorge and Terceira islands [*Hirn et al*., 1980]. Therefore in the tectonic setting of the TRS, we must consider the consequence of the obliquity of the volcano-tectonic rift system in relation to the present-day kinematic vector between the Eurasia and Africa plates. This obliquity would generate a component of dextral shear along the plate boundary that probably promotes some book-shelf faulting and vertical axis rotation between the islands [*Hirn et al*., 1993; *Miranda et al*., 1998].

Another important point is the geodynamical setting of the Sao Jorge and Santa Maria islands. Sao Jorge is located between the overlapping axis of Faial-Pico and the Terceira rift and consists of a linear volcanic ridge whose topography is dominated by a chain of monogenetic volcanic cones trending ~120^{o}. This direction is also apparent in the dykes from the oldest part of the island [*Moreira et al*., 1999b; *Hildenbrand*, 2008]. No igneous center are observed on Sao Jorge in contrast with the other TRS islands. Santa Maria occupies a southerly position in relation to the TRS and EUR/AFR plate boundary (**Fig. 2**). The lava flows are older than elsewhere with maximum ages of 8.12 Ma [*Féraud et al*., 1980] and this seismically inactive island lies at the eastern edge of the inactive East Azores Fracture Zone. The island is associated with a particular configuration of dykes with an apparent radial pattern at the scale of the island.

In this study, we present the deduced orientation of the fossilized magma flow vectors derived from dykes sampled from the islands of Sao Jorge, Sao Miguel and Santa Maria. In addition to observing the geometry of the recent fissural volcanism, the purpose of this study is to test the hypothesis that the TRS corresponds to an accretionary axis while also elucidating the feeding mechanism of the Sao Jorge Sao Miguel and Santa Maria islands. This hypothesis would imply dominat lateral and centrifugal (radial) flows in dykes fed by the known central volcanoes. A summary of results from Sao Jorge has already been published [*Moreira et al*., 1999b] and their interpretation is developed further below.

2. GEOLOGICAL DESCRIPTION

Rock samples were extracted from a total of 34 basaltic dykes, outcropping along the coast of the islands of Sao Jorge, Sao Miguel and Santa Maria (**Fig. 3**; **Table 1**). Most of the sampled rocks show a trachytic texture. Frequently, the plagioclase microphenocrysts show strong alignment indicating a flow lineation (**Fig. 4**)

2.1 São Jorge – São Jorge Island (**Fig. 3 top**) belongs to the Central Group of the Azores islands. It is a WNW-ESE elongated island approximately 55 km long and a maximum width of 7 km. This linear volcano island is characterized by fissural volcanic activity that has led to the formation of approximately 200 monogenetic cones and associated *aa* lava flows.

As the other islands of the Central Group such as Faial and Pico islands, São Jorge is dominated by an active WNW-ESE tectonic direction. The alkali-basalts of São Jorge were, dated earlier than 0.5 Myr [*Féraud et.al*., 1984] but are now shown to be nearly 1.3 Ma

[*Hildenbrand et al*., 2008]. The island is made up of two main areas: i) the younger western half, with numerous volcanic cones included in the two main volcanic complexes of Manadas (Pleistocene) and Rosais dated from ~0.750 Ma [*Hildenbrand et al*., 2008] and ii) the older eastern half of the island formed by the Topo Volcanic Complex composed mainly by the stacking of basaltic lava flows and a few dismantled cones, cut by numerous dykes [*Madeira et. al*., 1998] and dated at 1.32 Ma to 1.21 Ma [*Hildenbrand et al*., 2008]. The main tectonic features of this island are represented by alignments of monogenetic cones along NW-SE trending eruptive fissures, WNW-ESE trending faults/volcanic rifts, and discrete normal faults. Historic volcanic activity on the island developed mainly in the Manadas Complex with two recent eruptive events recognized: Queimada in 1580 and Urzelina in 1808 [*Forjaz,* 1980; *Madeira et. al*., 1998]. Neotectonic activity along NNW-SSE to NW-SE trending normal-dextral faults is expressed by recent surface ruptures forming fault scarps [*Madeira and Brum da Silveira*, 2003].

Three sites were chosen for dyke sampling all from the Topo Volcanic Complex. Site 1 at Fajã de Sao João located on the south shore with 7 dykes sampled. Five dykes were located close to sea level and 2 dykes (#7 and #11) were located at 20 to 30 above sea level. The dykes trend on average NW-SE with an average dip of 80^{o}E. Site 2 in Fajã dos Cúberes located on the north shore with two dykes sampled. Site 3 located in Ponta do Topo the eastern extremity of the island with two dykes sampled, all at sea level. At sites 2 and 3 the dykes trend roughly E-W and are subvertical**.**

2.2 São Miguel – Located in the eastern segment of the Terceira Rift, São Miguel (**Fig. 3 middle**) is the largest island of the Azores Archipelago. From west to east, the island is made up of four main composite active volcanoes and associated fissural systems: (1) the strato-volcano of Sete-Cidades, (2) the strato-volcano of Fogo – Água de Pau, (3) the strato-volcano of Furnas, and (4) the inactive Nordeste basaltic shield, the oldest and extensively eroded unit which includes the Povoação Caldera.

Along with the Picos Region, the Sete Cidades strato - volcano in the western part of the island is aligned NW-SE parallel with the Terceira Rift axis. In the central and eastern part of the island, the remaining volcano–tectonic structures are offset along an E-W direction parallel to the East Azores Fracture zone. The formations are Quaternary, with the exception of the Nordeste shield, which is partly Pliocene [*Abdel Monem et al*., 1975; *Feraud et al*., 1980]. Moreover, according to *Johnson et. al.* [1998] using both bulk fusion and laser incremental heating techniques the alkali-basalt flow of Lombo Gordo yields a younger radiometric ^{40}Ar / ^{39}Ar age of 0.820 to 0.852 Ma. The Lombo Gordo flow yield a reverse polarity magnetization which places this formation within the Late Matuyama polarity chron. The intruding dyke swarm yields normal polarity magnetization and was likely emplaced during the Brunhes chron. The dykes belonging to this dyke swarm sampled on Sao Miguel were studied at two sites: Site 4 on Lombo Gordo beach, located on the east shore of the island and Site 5, located on the south coast, in the cliffs, close to Faial da Terra. The Lombo Gordo section is extensively cut by several dykes. In most of the dykes (22 out of 34 measured dykes representing 61%) the strike ranges between 075^{o} to 105^{o} azimuth. The dip is more variable ranging from 50^{o}N to 80^{o}S. From this site, 10 dykes were sampled. At Site 5, located 500 m east of Faial da Terra, the strike of 22 measured dykes ranges from 130^{o} to 180^{o} with sub-vertical dips. At this site 3 dykes were sampled close to sea level.

2.3 Santa Maria - The island of Santa Maria (**Fig. 3 bottom**), in the Oriental Group, is the southeasternmost and the oldest of the Azores Archipelago. The island emerged in the Miocene [~8Ma *Abdel-Monem et al., 1975*] and the volcanic activity continued through the Pliocene. This is the only island of Azores Archipelago with marine fossiliferous sediments. It comprises two morphologically distinct domains. The western half is flat, forming a plateau with maximum elevations of 250m above sea level. This area is composed of basaltic eruptive products from several volcanic phases as well as their associated sediments: the submarine Cabrestantes Formatiom, the strombolian Porto Formation, the subaerial basaltic shield comprising the Anjos Volcanic Complex and the Touril Formation made up of marine and terrestrial sediments with minor volumes of volcanic clasts. The volcanism of the Complexo dos Anjos is essentially fissural and the flows and dykes have an alkali basalt composition [*Serralheiro, et al*., 1987, *Serralheiro and Madeira*, 1993]. The eastern half of the island is rugged reaching an elevation of 450 m. It is mostly built up from products of the Pliocene Facho – Pico Alto Volcanic Complex, an initially submarine volcanic ridge which progressively evolved into subaerial as the island grew eastward. The passage from submarine to subaerial volcanism in the Facho-Pico Alto Volcanic Complex is diachronic with the youngest published age for submarine lavas established at 3.2 Ma [*Féraud et al.,* 1981; *Serralheiro and Madeira*, 1993].

Dykes from Santa Maria were sampled in three localities all at sea level. Site 6 in Vila do Porto, close to the harbour (4 dykes) and site 7 at Praia Formosa (3 dykes), are both located along the southern coast. These intrusions trending 050^{o} to 070^{o} azimuth in site 6 and 020^{o} to 040^{o} azimuth at site 7, cut the Complexo dos Anjos lava pile, but not the conglomerates and fossiliferous marine limestones of the Late Miocene – Early Pliocene Complexo do Touril. Site 8 (3 dykes) is located in the north coast, in front of the Lagoínhas islet. The dykes show the same stratigraphic relations as observed at sites 6 and 7 with strikes trending N-S and dipping 60^{o}E to 75^{o}E.

A synthesis of the localization of sampled sites and number of dykes in the three islands is presented in Table 1.

3. MINERAL MAGNETIC PROPERTIES

3.1 High field magnetic properties: IRM and hysteresis

The acquisition of isothermal remanent magnetization (IRM) was studied on 5 specimens from 4 dykes on Sao Jorge Island. The IRM acquisition curve and the associated back field IRM provide information on both the dominant domain state of the magnetic fraction and composition of the material. Low coercivity phases such as multidomain (MD) magnetite grains are characterized by steep acquisition with saturation at low applied fields. The measured saturation field is in most of the MD samples, between 600 and 1200 ($\times 10^{-3}$ Am^2 /kg). Single domain (SD) grains require a higher peak-field to reach saturation with complete saturation around 300 mT. High coercivity phases such as hematite (Fe_2O_3), pyrrhotite (Fe_7S_8) or gregite (Fe_3S_4) do not reach saturation until well above field-strenght of 1.0 T fields. The results in **Fig.5** show that 90% of the magnetic saturation is achieved at around 100 mT, while complete saturation is obtained at 200 mT. Backfield IRM experiments show that coercivity of remanence is achieved for fields between 10 mT and 30 mT.

The hysteresis properties were determined for a total of 30 specimens chosen from different dykes on the 3 islands (25 specimens from dyke margins and 5 in the inner zone). The measurements were performed at the “Observatoire de Magnétisme” at the IPGP (Saint Maur, Paris) using a translation inductometer within an electromagnet. The domain state of the magnetic fraction can be determined by the ratio of hysteresis parameters H_{cr} / H_{cf}, while the relative magnetic grain size can be estimated from the magnetization ratio J_{rs}/J_s [*Day et.al.*, 1977; *Dunlop and Özdemir*, 1997]. These relations are represented in a Day diagram [*Day at.al.*, 1977]**,** Figure 6 (left), while two representative hysteresis curves are shown in Fig.6 (right**)**. The results show that the paramagnetic component is very weak. Most of the population display low coercivity ratios with H_{cr} / H_{cf} < 2.2 thus, falling in the region of pseudo-single–domain (PSD) behaviour [see *Dunlop*, 2002]. There is an almost linear correlation between the decrease of coercivity ratio H_{cr} / H_{cf} and the increase of the magnetization ratio J_{rs}/J_s. Nevertheless, there are specimens with high magnetization ratio that fall in the single-domain (SD) region.

Frequently, specimens with both PSD and SD magnetic state occur in the same dyke or site suggesting that mixtures of grains with different dimensions and magnetic behaviour are common. High field measurements of samples from the central parts of 3 dykes (dykes 1 and 5 from Sao Miguel and dyke 4 from Santa Maria) show clear differences with samples from the margins yielding higher coercivity ratios (H_{cr} / H_{cf} > 2.5). This result is expected since the natural slow cooling rate of the central parts of the dykes should favour larger grain size. The results indicate that the magnetic properties are mostly dominated by titano-magnetite bearing rocks, with a prevalence of PSD character, especially in Sao Miguel dykes. However, there is an influence of SD particles, indicating that magnetic grains with an inverse magnetic fabric may contribute to the properties of some samples [*Rochette and Aubourg*, 1999].

3.2 Thermomagnetic measurements

The temperature dependence of low field magnetic susceptibility, k - T curves, were performed on 20 samples from 15 dykes. Experiments were run in a CS2 furnace coupled to a KLY-2 Kappabridge with heating from 50^o C up to a maximum of 700^o C in an argon atmosphere with a steady heating and cooling rate of 9^o C/min. Cycles of heating-cooling with stepwise heated curves were performed for 5 selected samples in a CS4 furnace coupled to a MFK1-A Kappabridge also in argon atmosphere. The Curie temperatures were estimated using the method of *Grommé et al.*, [1969].

The thermomagnetic cycles show no reversibility and in general the occurrence of two magnetic phases (e.g. Jr11-11a, Mi6-9 in Fig. 7). There is a variation of behaviour of the curves according to the relative importance of the low and high temperature magnetic phase.

The low T_C magnetic phase yields Curie temperatures in a relatively large range of $200^o < T_C < 350^o$ C. With further heating, the susceptibility increases steeply until a very sharp decrease is again observed, defining a second magnetic phase. The obtained Curie temperatures T_C of this second phase lies between 560^o and 590^o C. In some samples this high T_C phase yields high values of susceptibility (e.g. Ma8-9 in Fig 7) while in other samples the increase in the susceptibility is much lower (e.g. Mi1-14, Fig. 7).

The cooling curve, shows usually higher susceptibility values than the heating curve, and does not reproduce the heating behaviour, especially in the high temperatures range. Approaching low temperatures ~ 200^o - 250^o C the cooling curve tends to approach the shape of the heating curve. The final magnetic susceptibility at room temperature, at the end of the cooling phase, is usually higher than the initial magnetic susceptibility (Fig. 7).

Cycles of heating-cooling with stepwise heated curves show (Fig. 8) that the k-T curves are practically reversible for cycles reaching 200^o - 225^o C revealing again the low T_C magnetic phase. After an heat phase up to 300^o C the cooling curve begins to diverge from the corresponding heating curve. From a temperature of 300^o C and higher the behaviour of the heating and cooling susceptibility curves is clearly different, showing the formation and growth of a magnetic phase with high T_C. The T_C of this new phase falls in the range 560^o - 590^o C indicating the formation of magnetite which is agreement with the fact that in the end of the cycles the final magnetic susceptibility at room temperature is usually higher than the initial susceptibility.

The progressive increase of the susceptibility that occurs around 300^o – 400^o C, that is not observable in the cooling curve, indicates the formation in the heating process of a magnetic phase, most probably of a titanomaghemite solid solution. The formation of that phase at

250^o - 300^o C with a Curie temperature around 560^o - 590^o C is indicative of magnetite formed during heating by the inversion of the maghemite [*Dunlop and Özdemir,* 1997].

Concluding, these results define a magnetic composition characteristic of a solid solution of Ti-rich titanomagnetite with large range of percentages of titanomaghemite. As a result of the heating above 250^o – 300^o C mineral alterations begin to occur. The temperature were these transformations occur and the obtained magnetic mineral is compatible with the process of transformation of titanomaghemite, which is metastable, being converted through a process of inversion. The new magnetic phase is a solid solution with a composition between titanomagnetite and magnetite, including as well other minor phases such as ilmenite or hematite [*Özdemir*, 1987; *Dunlop and Özdemir*, 1997].

The observed range of T_C of the low temperature phase, reveals a solid solution of titanomagnetite Ti-rich with different degrees of low temperature oxidation. The variation of the relative susceptibility of the secondary magnetic phase, due to mineral alteration induced by temperature, is an indicator of the occurrence of different percentages of the titanomaghemite.

slightly oxidised.

3.3 Chemical analyses

To supplement the study of the magnetic properties of the matrix and microcrystalline oxide phases, chemical analyses were conducted on 6 specimens from dykes of Santa Maria and Sao Miguel using an Electron Probe Microanalyser JEOL–JCXA 733 at the Geologic Department of the Faculty of Sciences of the University of Lisbon. Data are summarized in **Tables 5** and **Table 6**.

The dominant minerals, include plagioclase (≈ 20% to 26 % in Santa Maria samples and ≈ 40% in Sao Miguel samples), pyroxene (≈13% to 23 % in Santa Maria samples, < 10% in

Sao Miguel samples) and Fe-Ti oxides (ususlly ≈10% to 15 %, with the exception of one sample from Santa Maria with a low content of ≈3%).

The oxides are normally distributed in two groups: Ti-rich spinels, sometimes occurring in the skeletal form and ilmenites. Magnetite is scarce. Only sample Ma8-6 displays a distinctive composition with micrometric grains of magnetite with a calculated chemical formula of $Fe^{3+}_{1,98}$ $Fe^{2+}_{1,04}$ O_4 and a large percentage of plagioclases (49.3%) and oxides (14.6%).

The composition of the oxides plotted on the ternary diagram of **Fig.9,** is defined by the chemical formula Ti_x $Fe_{(3-x)}$ $O_{4,}$ with x = 0.65 ± 0.12. These values indicate that the oxide phase contained in the basalts corresponds to a titanomagnetite solid solution, mainly Ti-rich in composition which is in agreement with the conclusions from the thermo-magnetic measurements. Nevertheless there exist a large spectrum of variation in the compositions. The deviations from the theoretical line of the titanomagnetite solid solution and the departure of the ilmenites composition from the theoretical FeTiO reflects an oxidation process or maghemitization (low temperature oxidation of the titanomagnetite). Despite the mainly Ti-rich composition of the solid solution, chemical analysis show that "pure" magnetite grains are present in samples. This results agrees with the high field measurements which indicate a SD character for some samples of Sao Jorge and Santa Maria .

In conclusion, the results indicate a large range of composition of the titanomagnetites Ti-rich, slightly oxidised with different percentages of the titanomaghemite.

4. AMS sampling and results

4.1 Magnetic susceptibility and anisotropy

The origin and geophysical applications of the anisotropy of magnetic susceptibility are extensively explained in several text books and specialized articles [e.g. *Tarling and Hrouda*, 1993; *Rochette et al*.,1992; *Butler*, 2004; *Tauxe*, 2005].

In an isotropic medium, the magnetic volume susceptibility k is a scalar parameter defined by the ratio between the induced magnetization J and the applied magnetic field H, according to the expression: $J = k / H$. If the medium is anisotropic the above relation can be rewritten as $J_i = k_{ij} H_j \quad (i, j = 1,2,3)$ where J_i is the magnetization in the direction i and H_j the applied magnetic field in the direction j. As J and H are expressed in Am^{-1} (SI), the volume susceptibility k is dimensionless. The coefficients of the magnetic susceptibility k_{ij} are the elements of a 2nd order symmetric tensor called Anisotropy of Magnetic Susceptibility (AMS).

For a weak inducing field (the induction bridges Kappabridge KLY-2 and KLY-3 uses 300 Am^{-1}, at 920 Hz and 875 Hz respectively, *Hrouda*, [2002]) the magnetization is linear and reversible which means that k_{ij} is also symmetric. The diagonal and symmetric terms of this tensor measure the induced magnetization in three orthogonal directions. These three diagonal terms with magnitudes $k_1 \geq k_2 \geq k_3$, are the maximum, intermediate and minimum susceptibility axes of the anisotropy of magnetic susceptibility ellipsoid. The mean susceptibility k_m is determined by $(k_1 + k_2 + k_3)/3$. The AMS is conventionally represented as a triaxial ellipsoid whose major, intermediate and minor axes correspond to the respective directions and magnitudes of the magnetic susceptibility. If $k_1 = k_2 = k_3$, the ellipsoid is spherical. When $k_1 \approx k_2 > k_3$ the ellipsoid is oblate (flattened or disk shaped) and when $k_1 > k_2 \approx k_3$ the ellipsoid is prolate (acute or needle shaped).

The AMS ellipsoid may be characterized by several parameters among which the most used being the directional parameters i.e.: the magnetic lineation *L*, defined as the direction of the k_1 axis and the magnetic foliation *F*, defined by the plane containing the k_1 and k_2 axes, which is perpendicular to the k_3 axis. Anisotropy is quantified by the corrected degree of anisotropy P' where $P' = \exp\sqrt{2\left((\ln(k_1/k_m))^2 + (\ln(k_2/k_m))^2 + (\ln(k_3/k_m))^2\right)}$ and also by the magnetic lineation $L = k_1/k_2$, the magnetic foliation $F = k_2/k_3$ and the shape of the AMS ellipsoid (or shape parameter) defined as $T = (2(\ln k_2 - \ln k_3)/(\ln k_1 - \ln k_3)) - 1$. The shape parameter *T* may be visualized on a k/T diagram were the oblate shapes fall in the positive T region ($0 \le T \le 1$) and prolate shapes in the negative T region ($-1 \le T \le 0$). The definition of many others shape parameters are given in *Jelinek*, [1981], *Tarling and Hrouda*, [1993], *Hrouda*, [1982], *Borradaile*, [1988] and *Rochette et.al*. [1992].

In mafic igneous rocks, the minerals responsible by the magnetic fabric are the Fe-Ti oxide solid solutions, titanomagnetites and titanohematites. The main contributions to the AMS at the microscopic scale are due to: (1) the anisotropic shape of grains or shape anisotropy and (2) the crystallographic anisotropy of the grains or magnetocrystalline anisotropy (e.g. *Stacey* [1960]; Ellwood, [1978]; *Rochette et al*., [1992]). Furthermore, in ferromagnetic igneous rocks (e.g. basalts) were titanomagnetite is the main contributor to the magnetic signal, the observed anisotropy is a result of both the intrinsic anisotropy or grain shape of magnetite (the magnetocrystalline anisotropy is very weak as the mineral has a cubic crystal structure) and of the distribution of magnetic particles between the silicate phases [*Hargraves et al*., 1991].

4.2 Sampling

The sampled dykes have a mean thickness of 1.8 ± 1.1 m (0.45 m to 4.40 m) (**Fig. 3 and Fig. 4 top**). The sampling was carried out along the chilled margins of the dyke, usually no more than 10 cm from the contact with the host rock. Dykes were not sampled if they showed weathered margins, ambiguous or imprecise contact with the country rock or if they exhibited closely-spaced columnar joints. The orientations of cored samples and local dyke margins were measured with a magnetic compass. To check the local variations of magnetic declination or abnormal dyke remanence, solar determinations of strike azimuth were carried out at each site. We sampled a total of 34 dykes on the three islands, representing 66 sampled margins. From this set we obtained a total of 413 core samples, from which 559 cylindrical specimens were cut with the usual dimensions of 2.5 cm diameter and 2.2 cm long.

4. 3 Magnetic susceptibility and shape parameters

The specimens were measured to obtain the principal axes k_1 (maximum), k_2 (intermediate) and k_3 (minimum), using low alternating inductive field bridges KLY-2 and KLY-3 Kappabridge. The magnitude and orientation of the magnetic ellipsoid of each specimen was calculated using the *Jelinek* [1978] statistics and the mean directions and confidence zones were calculated using the statistical method of *Henry and Le Goff* [1995].

To systematize the directional information of the AMS at the scale of the dyke, the AMS of the specimens for each margin was plotted according to a common reference, related to the average orientation of that margin. Because the margins may show local undulations which significantly change the local strike and dip values we measured the orientation of the margins in the vicinity of each sampled point. Then by rotating the magnetic axis of each sample to a common direction defined by two axes (i.e. the strike and dip directions) we are able to integrate the AMS axes of all samples with respect to a common reference frame. In this way the orientation of the magnetic anisotropy axes of each sample is related to a common plane corresponding to the mean strike and dip orientation of the margin. The mean directions and confidence limits of the AMS of each margin are then calculated using all the specimens of that margin based on the statistical method of *Henry and Le Goff* [1995]. Tables 2, 3 and 4 reports the results obtained for the following AMS parameters: mean magnetic susceptibility (k), the corrected degree of anisotropy (P'), shape parameter (T), magnetic lineation (L) and foliation (F) .

The magnetic susceptibility of the dykes ranges from $k = 2.0\times10^{-3}$ to 50×10^{-3} SI, with a mean susceptibility $k = 16.3 \pm 11.8 \times 10^{-3}$ SI units (**Fig. 10**). The dykes of Sao Jorge island yield a magnetic susceptibility k usually lower than 35×10^{-3} SI - analogous to the results obtained by *Silva et al* [2012] - while the values obtained for Santa Maria are lower than $k = 25\times10^{-3}$ SI. In the case of Sao Miguel, the dykes show not only a wider range of magnetic susceptibility but also higher values in the range $k = 35 \times10^{-3}$ to 45×10^{-3} SI.

The average corrected degree of anisotropy in the studied dykes is low, with $P' = 1.039 \pm 0.028$. Nevertheless, some specimens may reach values as high as $P' = 1.115$ in dyke 3 or $P' = 1.187$ in dyke 10, both from Santa Maria. The P’ - T diagram (degree of anisotropy versus shape parameter in **Fig.** 11) show that, on average, the specimens from Sao Jorge yield both oblate and prolate shaped ellipsoids whereas for Sao Miguel and Santa Maria, oblate shapes are predominant. However some exceptions exist, such as dykes from site 1 of Sao Jorge and dykes from site 5 on Sao Miguel, where most of the margins show specimens with a dominance of lineation.

4. 4 - Magnetic fabric: shape and orientation

The AMS data was plotted on equal area (lower hemisphere) stereographic projections with AMS axes k_1 (squares), k_2 (triangles) and k_3 (circles). Filled symbols represent the mean tensor with the associated confidence ellipses.

At the scale of the dyke “normal fabrics”, according to the definition of *Rochette et al*. [1991] are largely dominant. In 52 out of 66 (~78%) of the sampled margins, labelled in **Tables 2, 3**

and 4 by “N” (normal), the magnetic fabric shows that the k_3 axis close to the normal of the dyke and the magnetic foliation plane is subparallel to the dyke margin (e.g. **Fig. 12a and b**). Moreover in most of the dykes with normal fabrics at both margins the imbrication angle between of the magnetic foliation plane (MFP) and the margin is broadly symmetrical relatively to the dyke axis. The measured MFP-dyke wall angles, range between 10^o and 30^o in 37 margins (56%) with a mean value of 18^o.

Out of the remaining 14 margins, 9 margins (i.e. ~14%) yield a magnetic foliation plane that is roughly perpendicular to the dyke plane (**Fig. 12c**), with the k_3 axis close to the plane of the dyke, indicating an inverse magnetic fabric (Mi3, Mi4, Mi5-south margin, Jr9-north margin) and labelled as “I”. These dykes yield a shape of ellipsoid similar to the normal fabric dykes, but their magnetic susceptibility is usually lower than the average value measured in the normal fabric dykes. For example, the Lombo Gordo dykes with an inverse magnetic fabric (Mi-04, Mi-05 south or Mi-07 north) yield k = 17.5×10^{-3} SI ($\pm$ 3.3×10^{-3} SI), while the dykes with normal fabric show k = 28.4×10^{-3} SI ($\pm 10.5 \times 10^{-3}$ SI). The remaining 5 margins (ie ~8%) yield an abnormal magnetic fabric labelled here as “A”, which is characterized by a more dispersed clustering of axes or with the mean k_3 parallel or very close to the margin orientation (**Fig. 12d**).

The dispersion of the magnetic lineation k_1, is greater than the k_3 axis. Therefore, the mean magnetic foliation plane is more constrained then the magnetic lineation. In 43 of the 66 of sampled margins (representing 65%) the average radius of confidence of k_3 mean direction is less than 10^o. In fact, the k_3 axes clusters are tightly constrained with 95% confidence ellipses of (e_{23} = 11.1 ± 5.9) having smaller areas than for the k_1 axes clusters (e_{12} = 15.3 ± 7.7).

5. Magma flow vectors estimated by AMS

5.1 - The use of AMS to infer fossilized magma flow vectors in dykes

The magmatic flow fabric in a dyke is represented by the fabric of the early crystallized phenocrysts, usually with high aspect ratios, that act as rigid particles. The mechanism that promotes the preferred orientation of phenocrystals in a conduit, assuming a Newtonian laminar flow, is due to the mechanical drag and force moment produced close to the interface between the magma and the solid wall. In the vicinity of a dyke's wall, the flow induces a strain gradient regime characterized by simple shear that changes to pure shear in the central part of the dyke. According to *Ildefonse et al.*, [1992] or *Arbaret et al.*, [1996], even low concentrations of phenocrysts particles should interact and become aligned with their long axis at a low angle to the flow direction. This spatial arrangement is expressed by a tiling pattern which determines an imbrication angle for the phenocrysts relative to the margin where the shear gradient is higher.

The imbrication of the phenocrysts provides information on the sense of shear and, in some cases, the shape of the strain ellipsoid can be connected to the fabric. In a simple model without along-plane displacement of the walls, the imbrication would be symmetric relative to the dyke axis producing a theoretical symmetrical fabric [*Knight and Walker,* 1988]. In such cases, the magnetic fabric is linked to the preferred orientation (shape or alignment) of magnetic minerals that are developed between the phenocrystals, and thus becomes a proxy of the magmatic flow fabric.

Such a relationship between the magmatic flow and the AMS in dykes was proposed by *Knight and Walker* [1988], based on the relation between orientation of magnetic axes and orientation of the elongated vesicles at the margins of the dykes. They concluded that the orientations of k_1 axes and the observed imbrication angle between k_1 axes at each margin could be interpreted to determine the orientation of the flow vector.

However in some circumstances, the magnetic lineation may not be directly related to the flow direction. *Jeffrey* [1922] demonstrated that non-interacting prolate rigid particles immersed in a fluid with laminar flow are aligned with the long axis normal to both the velocity of flow and the direction of its maximum gradient. For high shear strains, particles should interact and tend to align their long axes at low angle to the flow direction. Both *Khan* [1962] and *Elwood* [1978] pointed out that, in dykes, k_2 could also be aligned with the flow line. *Elwood* [1978, p. 263] stated that "In dykes, emplacement direction is represented by either an azimuth normal to a non-random k_a (i.e. k_1) axial mean.or by a direction parallel with the azimuth of a non-random k_b (i.e. k_2) mean".

Magnetic lineations perpendicular to the flow direction were also subsequently reported by *Knight and Walker* [1988], *Dragoni et al*., [1997] and *Philpotts and Philpotts*, [2007].

The size of magnetic grains also affects the magnetic fabric behavior. Indeed, in magnetite-bearing rocks, multi-domain magnetite show a normal magnetic anisotropy meaning that the maximum susceptibility is oriented parallel to the long axis of the grain, while single-domain magnetite (broadly with grain lengths < 0.1 μm) yield an inverse magnetic fabric, where the easy axis of magnetization is perpendicular to the long axis of the grain [*Tarling and Hrouda*, 1993; *Potter and Stephenson*, 1988, *Ferré*, 2002]. Thus, mixtures of different grain sizes or strong interaction between ferromagnetic grains [*Hargraves et al.*, 1991; *Canon-Tapia*, 1996; *Gaillot et al*., 2006] may imply an intermediate magnetic fabric [Rochette et al., 1999] which can complicate the interpretation. Ambiguities that may arise from an interpretation based on the magnetic lineation were also pointed out by *Aubourg et al*. [2002, 2008] and *Geoffroy et al*. [2002, 2007]. Using a comparison between the AMS axes and preferred orientation of plagioclases in oriented thin-sections of mafic dykes from the East-Greenland volcanic margin led *Geoffroy et al*. [2002] to show that the angular deviation between the magnetic lineation and plagioclases orientation display a bimodal distribution, meaning that either k1 or k2 is parallel or close to the alignment of phenocrysts. As pointed out by *Callot and Guichet* [2003], another ambiguity stems from the possible combination of highly planar or composite rock textures, very common in magmatic rocks, which may lead to an apparent magnetic lineation, or "zone axis" due to the intersection direction of different magnetic foliation planes. A new problem arises also when a composite fabric is developed during dyke emplacement in which the ferrimagnetic and paramagnetic fabrics may not be coaxial. *Silva et al* [2014] analysed this problem in the doleritic dyke Foum Zguid. They concluded that is most probably the paramagnetic fabric that is associated with the magma flow direction, while the ferrimagnetic and AMS (which yield similar fabrics) are associated to late stage cooling stress and as a consequence not directly related to the flow fabric. Despite de fact that these results were obtained from a thick dyke, the different behaviour of individual fabrics in a composite fabric rock, justify all the prudence in the interpretation of the relationship of the AMS axis with the magmatic flow direction.

As a consequence, it is incorrect to assume as a rule that the magnetic principal axis k_1 represents the flow direction everywhere along a dyke; this hypothesis is not corroborated and detailed rock experiments must be performed to establish the magnetic mineral grain size as well the magnetic and the mineral flow fabrics relationship.

5.2 - Petrofabric analysis of preferred orientations of mineral phases

We performed a petrofabric analysis to asses the uncertainty discussed above concerning the interpretation of the magnetic lineation as the preferred orientation of the longer axis of opaque ferromagnetic grains, (broadly the whole set of Fe and Ti oxides minerals) and its relation to the orientation of phenocrysts (mainly plagioclases). Our aim was to quantify the angular difference between the directions of the principal magnetic axes, obtained from the AMS measurements and to correlate these results with the alignment of phenocrystals and opaques in 2D space as observed on microscopic images.

Forty thin sections cut parallel to the magnetic foliation plane were prepared from 25 cores representing 18 different dykes using the cylindrical specimens selected for the AMS study. From each thin section several high-resolution images were digitized. After image filtering to separate phenocrysts (mainly plagioclases) from opaque phases we used the "Intercept" software to obtain the statistical directional distribution of the minerals. This alghoritm creates a rose (or polar distribution) of mean intercept lengths that is calculated for the intersection of boundaries of a phase or mineral selected in the image and constructed with a Fourier decomposition up to a choose harmonic. The obtained rose of directions show usually a long axis (first harmonic) a short axis (2^{nd} harmonic) and, depending of the Fourier analysis degree, some minor orientations more or less scattered [*Launeau and Robin*, 1996].

We used the direction of the long axis of the rose of directions, as the maximum of the preferred orientation, here designated as maxPO to study the correlation with the orientation of the k_1 magnetic axis in the plane of the image, parallel with the foliation plane. (**Fig. 13**).

The angular deviation between the maxPO of ferromagnetic opaques and phenocrystals (**Fig. 14a)** shows a monomodal distribution. In most of the observations (75%), the angle between the maxPO of the two minerals is less than 20^o. We may infer that in the magnetic foliation plane k_1-k_2, the preferred orientations of opaques and phenocrysts are mostly coaxial.

However, an analysis of the relationship between maxPO of opaques and k_1 direction yields a bimodal distribution (**Fig. 14b).** At first order the angular differences are around 20^o with second order differences approaching 80^o to 90^o which is close to the k_2 axis. The difference between the orientation of the opaques and the k_1 axis is less than 30^o in 51% of the studied cases but it is greater than 60^o in 24% of the thins sections meaning that the maxPO of the opaques tends here to be close to the orientation of the k_2 axis.

It is interesting to note that the specimens which show a maxPO of opaque grains closer to the k_2 axis (Ma3-21, Ma4-4, Ma7-8, Jr4-8(1), Jr5-4 and Jr10-11b) display a normal rather than an inverse magnetic fabric. This behavior is observed in prolate and oblate specimens, with high or low anisotropy so, it seems not to be dependent of the shape of the ellipsoid of susceptibility or anisotropy. Besides, the k_2 axis is systematically with low inclination. With the exception of the specimen Mi5-1b that presents an inverse magnetic fabric, this low inclination is coincident with the inclination of the deduced magmatic flow vector of that particular margin.

The remaining 15% of images relating maxPO of opaques and k_1 directions shows intermediate angular separations, ranging between 30^o to 60^o.

The angular differences between the magnetic lineation and the maxPO of the phenocrysts is presented in **Fig.14c**. While these data also yield a slight bimodal correlation, it is here superposed on an almost continuous range of values of different angular separations ranging from 0^o (coaxial) to 90^o (perpendicular).

From these results, we conclude that: (1) within the foliation plane the maxPO of oxide grains (opaques) is essentially coaxial with the orientation of the phenocrysts, (2) the maxPO of both opaques and plagioclases is split into two orthogonal directions: one direction being coaxial with the magnetic lineation and other perpendicular.

The angular relationships obtained between maxPO of minerals (opaques and phenocrysts) and the magnetic lineation axis shows that, on average, either k_1 or k_2 may be coaxial with the preferred orientation of the dominant phase, *i.e.* plagioclase, thus giving rise to an ambiguity in the directional relationship.

5.3 Magmatic flow direction inferred by AMS measurement

As previously discussed (section 4.4), the orientation of the k_3 axis is more constrained than the k_1 axis. At the scale of the dykes margin, confidence angles are smaller around k_3 axes than around k_1 axes. Moreover, in the dykes with a normal magnetic fabric the magnetic foliation planes define imbrications angles which open symmetrically with respect to the dyke axis, thus defining a unique magma flow direction **Fig. 12(a and b) and 15.** In 44 out of the 66 sampled margins (≈ 67%), the magnetic foliation planes strike at angles between 10^o to 30^o relative to the respective margins.

The interpretation of the image analysis (section 5.2) show that there is no simple relationship between the magnetic lineation, the PO of phenocrysts, and the assemblage of magnetic mineral phases. To avoid the uncertainty in choosing arbitrarily the k_1 or k_2 axis to describe the flow trend and given the small but overall dominant oblate fabrics (Fig. **11**), the flow vector would be best determined using the "attitude" of the magnetic foliation plane relative to the margin dyke. To define a unique flow direction we consider the imbrication of the magnetic foliation plane relative to the dyke margin, following the model explained in detail by *Geoffroy et al*., [2002] Fig. 2 and *Geoffroy et al.*, [2007] Fig. 6, to define unique flow direction. This proposed method makes use of the imbrication angle of the magnetic foliation plane relative to the margin plane as an indicator of the magmatic flow direction and sense. Assuming, as previously mentioned, a Newtonian rheology and no displacement at the margins of the dyke in the final phases of the intrusion flow, the magnetic fabric at the dyke margin can be used to determine the flow vector geometrically, for each dyke margin. This can be performed on each dyke wall using the perpendicular to the axis of intersection between the magnetic foliation plane and the dyke wall plane. The sense of the flow-vector is obtained by considering the orientation of the imbrication angle between the magnetic foliation and the dyke wall.

Representative examples of this analysis are shown in **Fig 15** for dyke 7 from Santa Maria and dykes 6 and 7 from Sao Jorge. In each case, both margins yield concordant results concerning the sense of the flow, predominantly horizontal in the first two dykes and dominantly vertical in the last one.

5.4 –Flow vectors in the Azores dykes

In the case of 19 dykes it was possible to obtain interpretable data from both margins. However for five of these dykes we obtain opposite flow vectors from each margin. To obtain an overview of the whole data set we plot in **Fig. 16** the flow vectors for all of the 48 interpretable margins observed at each of the studied sites.

For the Sao Jorge dykes, we obtain 21 margins with normal magnetic fabric. For ten of these margins, the flow vector has an inclination of less than 40^o, while nine margins show an inclination greater than 45^o. In the remaining two margins, the principal magnetic axes are scattered. These dykes show a complex flow pattern due to the coexistence of low inclination and subvertical flow vectors. Interestingly, the vertical flow vector in dyke Jr7 (see Fig.15c) yields a “downward” sense of the flow. This is probably an effect of flow convection within the dyke related to the final stages of magma emplacement and subsequent reflux and/or deflation of magma into the dyke. This result is not uncommon, and has been reported at different sites (e.g. East Greenland dykes [*Callot et al*.,2004], including rhyolitic dykes from Ponza island [*Aubourg et al*., 2002], in a tholeitic dyke swarm of the Isle of Skye [*Geoffroy et al. 2007*], in a camptonite dyke of the Higby Mountain in New England [*Philpotts and Philpotts*, 2007], in dykes on Tenerife [*Soriano et al*., 2008], or at the scoria cone of Lemptégy [*Petronis et al*. 2013]).

On Sao Miguel, the flow vectors obtained at both sampled sites are very consistent, indicating a predominantly horizontal or low inclination flow with a sense from west to east (in 10 out of 13 margins with a normal magnetic fabric) at Lombo Gordo site 4 (east shore) and broadly from north-west to south-east (in 4 of 5 margins with normal magnetic fabric) at the Faial da Terra site 5, located on the south shore (**Fig. 16**). To highlight the fact that the majority of the inferred flow vectors from these two sites imply a flow away from a common central source, we grouped all the data together by rotating all margins and their associated fabrics according to a common reference frame. This reference frame correspond to a synthetic dyke with an arbitrary E-W strike and a vertical dip, that is close to the average attitude of the dykes from site 4. **Fig 17** shows the density contours of the k_3 axes along with the mean magnetic foliation plane and the (synthetic) dyke. This representation outlines the coherent imbrications angles indicating an unambiguous direction and sense of the magmatic flow, which is thus lateral and centrifugal apart from the Nordeste basaltic shield.

On Santa Maria Island, the obtained flow vectors are also predominantly horizontal at sites 6 and 7 with a predominant north-to-south sense (Vila do Porto and Praia sites, south shore of the island) and oblique flow with a systematic south–to-north sense of flow at site 8 (Lagoínhas, on the northern shore). This is noteworthy because all the dikes from these sites are contemporaneous. The orientation of the dykes from these three sites, define a converging point, located close to the apex of Pliocene Pico Alto Volcanic Complex. Since these dykes are older than this volcanic centre, they are probably not associated with the subsequent Pico Alto magmatic events, but rather to a former magmatic centre located near the same position. The existence of such magmatic structure is consistent with an important magnetic anomaly of reverse polarity - Fig. 6 in *Storevedt et al*. [1989] - which is broadly centered on this zone. Our data and interpretations indicate a steeper inclination of the magmatic flow in dykes from site 8 (Lagoínhas at north) and a predominant horizontal to sub-horizontal magmatic flow from sites 6 and 7 (in the south). This is in agreement with the presence of a shallow magmatic centre located in the central-northern part of the island, with a centrifugal propagation of dykes away from this centre. Dykes sampled on the north shore are closer to the magmatic center, which implies a steeper magmatic flow, while dykes on the south shore, show predominantly lateral or sub-horizontal flow geometry.

As a resume our data set suggest that the dominant magma flow pattern in dykes is lateral, away from the volcanic centers. In fact, 53 margins (out of the 66 margins from the 34 sampled dykes) show a normal magnetic fabric and 43 out of these margins yield a sub-horizontal magmatic flow. In 12 dykes (5 from Sao Jorge, 5 from Sao Miguel and 2 from Santa Maria) the data for both margins are coincident. For Santa Maria the calculated magmatic flow is sub-horizontal to oblique and no vertical or sub-vertical magmatic flow can be identified in any single dyke or margin.

Only three dykes from São Jorge (both margins of Jr7, plus the NE margin of Jr1 and the SW margin of Jr3) clearly exhibit a vertical magmatic flow, which, in these cases, takes place from top to bottom. We thus have no evidence of a direct feeding of the dykes from a continuous magma layer at depth. Rather we interpret these results as indicating that magma was fed into the upper crust by magma injected in a horizontal or sub-horizontal direction from volcanic centers inside the islands.

5.5 - Indications of an external dextral shear strain?

As previously pointed, at site 4 on the eastern shore of Sao Miguel it was possible to obtain a dense sampling at both margins of 9 dykes trending roughly E-W. The the density contours of the k_3 axes of site 4 **(Fig 17)** show that the imbrications angles at both margins are coherent but systematically display a slight difference in angle amplitude: along the northern margins a mean imbrication angle $\varphi_N = 16^o$, while along the southern margins a mean imbrication angle $\varphi_S = 6^o$ (**Table 7**). It is interesting to note that the degree of anisotropy P’ at both margins is similar, but the shape parameter shows important differences between northern and southern margins of dykes at this site.

This asymmetrical fabric could be interpreted as the result of a shear displacement of the dyke walls during the magma injection [*Rochette,et al., 1991*; *Correa-Gomes et. al*., 2001; *Fémenias et al*.; 2004]. Indeed, a theoretical symmetrical fabric model can be applied when a narrow dyke is injected in an isotropic strain field. However if an anisotropic regional strain field or a horizontal strike slip is applied roughly parallel to the dyke strike during the final phases of dyke injection (with the magma flow arrested while still a viscous fluid), a corresponding shear should occur (that is a late-stage Couette flow superimposed on an overall laminar flow). The observed asymmetry in the fabric could thus result from the application of an external shear strain. In the Lombo Gordo dykes, the northern margins systematically display a higher imbrication angle and an almost neutral shape of the fabric, while the southern margins shows smaller imbrication angles with a slightly oblate shape of the fabric. This asymmetrical magnetic fabric would be compatible with an external dextral shear coeval with the intrusion of the magma [*Correa-Gomes et al*., 2001; *Féménias et al*., 2004].

A similar asymmetrical distribution of imbrications also appears to occur at site 5 (Faial da Terra) where the mean imbrication angle in the eastern margins is $\varphi_E = 34^o$ and the mean imbrication in the western margins is $\varphi_W = 14^o$. Nevertheless, the number of sampled dykes/margins at this site is relatively low and we will not develop such analysis for this site.

6. Conclusions

The detailed study of magnetic properties of dykes from the Azores shows that, in this volcano-tectonic environment, they can be used to infer the fossilized flow pattern within the intrusive complex of this hot-spot related rift-system. These dykes solidify at depth within the crust, or as they cross-cut the ground surface, acting as feeders for the extrusive lavas. They are thus essential in the crustal accretion of the Azores igneous crust.

AMS measurements allow us to conclude that the magmatic flow within these upper-crustal dykes is predominantly horizontal or with a slight inclination, propagating away from the volcanic centres on the islands (Fig. 16). There are some exceptions such as observed in a dyke from São Jorge where vertical (downward direction) flow is inferred and in dykes on the the northern shore of Santa Maria yielding oblique flows of uncertain interpretation.

From these data we conclude that the magma forming the volcanic upper-crust in the Azores is injected from a limited number of igneous centres, feeding dykes in a sub-horizontal pattern which propagates away from these centres in agreement with the model of **Fig.1**.

In the light of these observations it appears unnecessary to invoke the existence of a uniformly melting asthenosphere that would promote, either directly or indirectly, a general upward flow of magma through a deep magma layer as proposed in Iceland [*Bjornsson*,1979]. Instead, these results point towards a model of localised mantle melting with point sources feeding permanent upper-crustal igneous centres with central magma chambers underlying central volcanoes. The magma stored in these chambers is then injected laterally into the crust as dykes by hydraulic-type fracturing of the magma chamber [*Geoffroy*, 1998, *Doubre and Geoffroy*, 2003]. These dykes would be injected parallel to the trend of the local principal horizontal stress, which is a combination of pressure fields around the magma chamber, gravitational and tectonic stresses [*Chevallier and Verwoerd*, 1998]. It is interesting to note that such a mechanism would account for the formation of Sao Jorge island which is made up of an elongated volcanic ridge and without any apparent crustal igneous centre [*Hildenbrand et al.*, 2008]. As mentioned before, in Sao Jorge we obtain for the 120^{o} - 140^{o} azimuth dykes a range of magmatic flows in opposite directions. One of the possibilities that may partly explain this result is an eventual change of the localization of magmatic sources or a migration of the volcanic activity [*Hildenbrand et al*., 2008]. The lack of age determination of the studied dykes does not make possible to correlate the obtained directions with the ages of the dykes. Therefore we tentatively propose that the inferred flow that is coming equally from the SE and from the NW, possibly reflect the existence of two-point source, one at the centre of the island, and the other offshore near its SE extremity.

Although we drilled most of the dykes that could be observed in the studied areas, we are fully aware of the limited amount of data in support of our model. However, our results are consistent with the overall volcano-tectonic pattern of the TRS with suggests that the volcano-tectonic configuration is highly segmented with localized melting zones at depth (see section 1.3). Finally, we suggest that a component of dextral shear with NW - SE trend is expressed in the igneous fabric of suitably-oriented dykes, especially in those from the eastern and south-eastern of São Miguel island (sites 4, Lombo Gordo and 5, Faial da Terra). This hypothesis is in good agreement with present-day tectonics (see section 1.2) which would suggest that dextral shear existed since at least the Brunhes-Matuyama transition at 0.780 Ma (see section 2.2).

6. Acknowledgements

This study forms part of the PhD project of the first author. We greatly acknowledge Bernard Henry and Maxime le Goff for their support in the high field magnetic measurements performed at the “Observatoire de Magnétisme” at Saint-Maur, (IPGP, Paris), Charles Aubourg (Université de Pau) for fruitful discussions concerning composite magnetic fabrics and AARM measurements, Cécile Doubre for her participation in the collection of samples on Sao Miguel and Santa Maria. We also warmly thank José Madeira and António Mateus from the Geological Department of the Faculty of Sciences of Lisbon, respectively, for providing helpful information on particular details of the geology of the Azores and for the use and interpretation of results from the Electron Probe Microanalyser This work was partially supported by REGENA project - PTDC /GEO-FIQ/3648/2012. Dr M.S.N. Carpenter post-edited the English style. We greatly thank M. Walter, W. Hastie,M. Petronis and B. Henry for the useful comments and sugestions.

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Table 1 – Synthesis of the localization of sampled sites and number of dykes

Island	site	Location	Place	Coordinates	N dykes	# dykes
São Jorge	1	South	Fajã de S. João	38^{o} 34' 41" N 27^{o} 55' 05" W	7	1,2,3,4,5,7,11
São Jorge	2	North	Fajã dosCúberes	38^{o} 38' 31" N 27^{o} 58' 16" W	2	8,9
São Jorge	3	East	Ponta doTopo	38^{o} 32' 32" N 27^{o} 45' 39" W	2	6,10
São Miguel	4	East	Lombo Gordo	37^{o} 47' 13" N 25^{o} 08' 33" W	9	1,2,3,4,5,6,7,8,9
São Miguel	5	South	Faial da Terra	37^{o} 44' 35" N 25^{o} 11' 11" W	3	10,11,12
Santa Maria	6	Southwest	Vila do Porto	36^{o} 56' 44" N 25^{o} 08' 43" W	4	1,3,4,5
Santa Maria	7	South	Praia	36^{o} 56' 57" N 25^{o} 05' 26" W	4	6a,6b,7,8
Santa Maria	8	North	Lagoínhas	37^{o} 00' 54" N 25^{o} 05' 15" W	3	9,10,11

Table 2 – AMS results for Sao Jorge dyes

AMS results after tensorial analysis for Sao Jorge dykes. For each dyke both margins are indicated with the respective azimuth and inclination relative to the horizontal, in the direction indicated N: number of specimens measured; k:mean magnetic susceptibility in 10^{-3} SI units; k_1: Direction and azimuth of k_1 axis; e_{12} and e_{13}: half confidence angles at 95% for k_1 axis; k_3: Direction and azimuth of k_3 axis; e_{31} and e_{32}: half confidence angles at 95% for k_3 axis, angles in degrees; Fab: magnetic fabric. N = normal, I = inverse, A = other; L, F, P' and T: respectively lineation, foliation, corrected degree of anisotropy and shape parameter.

Sao Jorge dykes															
site	Dyke margin	margin Orient.	N	k	k_1	e 12	e 13	k_3	e 31	e 32	Fab	L	F	P'	T
1	Jr1/NE	145/82E	6	6.4	320/41	11	23	51/8	7	19	N	1.009	1.013	1.041	0.181
1	Jr1/SW	155/75E	6	7.4	19/73	6	27	236/24	5	18	N	1.017	1.017	1.038	0.000
1	Jr2/NE	157/82E	5	11.9	138/76	3	28	243/3	2	5	N	1.012	1.033	1.052	0.463
1	Jr2/SW	157/82E	7	20.1	250/81	20	21	133/35	6	24	I	1.016	1.019	1.069	0.085
1	Jr3/NE	130/90	7	25.1	347/71	1	2	229/10	1	8	N	1.045	1.010	1.062	-0.631
1	Jr3/SW	132/76E	8	27.6	85/53	5	30	219/29	4	7	N	1.004	1.019	1.031	0.650
1	Jr4/NE	127/78E	7	14.7	53/69	10	27	252/30	15	24	N	1.015	1.002	1.031	-0.763
1	Jr4/SW	142/82E	8	14.3	3/76	7	11	212/15	11	19	N	1.030	1.012	1.052	-0.425
1	Jr5/NE	156/77E	11	9.8	97/53	5	13	213/29	9	21	N	1.026	1.002	1.037	-0.856
1	Jr5/SW	139/81E	11	12.6	178/63	3	11	71/4	3	14	N	1.054	1.020	1.083	-0.453
1	Jr7/NE	125/83E	14	17.9	148/47	8	25	29/24	6	10	N	1.002	1.011	1.021	0.691
1	Jr7/SW	140/90	10	25.8	133/9	3	9	229/37	3	6	N	1.007	1.021	1.030	0.497
1	Jr11/NE	126/86E	9	7.9	147/64	7	16	32/6	5	10	N	1.012	1.010	1.028	-0.090
1	Jr11/SW	317/86W	8	7.8	136/57	2	7	32/9	4	8	N	1.031	1.008	1.044	-0.586
2	Jr8/N	115/90	11	23.1	315/13	7	19	49/3	3	10	N	1.007	1.038	1.054	0.685
2	Jr8/S	118/90	14	22.4	142/55	13	27	232/5	3	13	N	1.003	1.024	1.038	0.776
2	Jr9/N	098/75N	6	6.9	50/51	12	38	193/47	11	23	N	1.008	1.005	1.018	-0.230
2	Jr9/S	094/73N	7	6.3	297/42	7	24	182/20	8	17	N	1.009	1.004	1.017	-0.384
3	Jr6/N	075/78N	7	3.7	322/77	10	19	181/10	5	11	N	1.011	1.017	1.033	0.213
3	Jr6/S	060/77N	11	5.4	35/67	5	24	127/1	3	14	N	1.009	1.049	1.072	0.684
3	Jr10/N	103/76N	12	18.6	285/53	2	16	189/9	1	6	N	1.004	1.017	1.026	0.617
3	Jr10/S	108/86N	10	9.4	192/70	7	21	32/15	5	18	N	1.004	1.023	1.033	0.701

Table 3 - AMS results for Sao Miguel dykes

Same description as Table 2

Sao Miguel dykes															
site	dyke margin	margin orient.	N	k	k_1 D/I	e 12	e 13	k_3 D/I	e 31	e 32	Fab	L	F	P'	T
4	Mi1/N	081/51N	5	42.9	25/64	9	23	199/24	9	19	N	1.021	1.028	1.050	0.141
4	Mi1/S	090/81N	5	35.7	267/63	10	20	168/2	7	13	N	1.009	1.019	1.026	0.355
4	Mi2/N	081/79N	11	21.1	286/51	5	18	184/7	5	8	N	1.017	1.020	1.038	0.080
4	Mi2/S	083/86S	11	23.6	119/69	29	8	346/15	4	12	N	1.020	1.016	1.037	-0.110
4	Mi3/N	095/82N	11	20.4	136/57	13	21	8/28	8	18	N	1.010	1.015	1.025	0.199
4	Mi3/S	104/66N	9	18.5	32/60	5	19	178/28	5	8	N	1.022	1.018	1.040	-0.099
4	Mi4/N	061/71N	7	13.8	140/55	4	33	259/13	4	7	I	1.009	1.014	1.023	0.216
4	Mi4/S	063/84N	8	13.6	135/60	5	24	253/11	5	9	I	1.008	1.013	1.022	0.237
4	Mi5/N	092/59N	8	12.6	343/56	4	11	199/27	5	6	N	1.016	1.012	1.028	-0.142
4	Mi5/S	085/65N	5	16.8	40/76	8	32	257/29	13	27	I	1.014	1.013	1.029	-0.037
4	Mi6/N	081/59N	5	10.5	21/67	7	9	217/19	7	46	A	1.029	1.009	1.011	-0.523
4	Mi6/S	082/62N	6	20.1	30/69	6	6	291/5	5	39	A	1.004	1.007	1.038	0.272
4	Mi7/N	115/80N	13	21.7	13/50	10	21	275/26	12	20	I	1.012	1.009	1.022	-0.142
4	Mi7/S	096/85N	14	28.1	181/16	17	9	1/61	26	11	A	1.016	1.014	1.031	-0.066
4	Mi8a/N	094/79N	11	42.7	312/62	8	12	203/10	8	11	N	1.013	1.017	1.031	0.132
4	Mi8a/S	104/86N	10	44.4	312/66	13	23	194/9	9	12	N	1.012	1.021	1.034	0.271
4	Mi8b/N	086/69N	4	21.8	87/18	5	31	183/18	2	7	N	1.007	1.020	1.028	0.479
4	Mi8b/S	088/77N	9	25.6	65/13	10	23	161/20	6	11	N	1.009	1.019	1.028	0.355
4	Mi9/N	079/79N	6	22.5	12/71	7	20	184/9	11	15	N	1.024	1.019	1.044	-0.115
4	Mi9/S	096/84S	5	20.1	86/22	13	40	357/8	17	25	N	1.014	1.020	1.035	0.175
5	Mi10/E	159/86E	5	20.6	298/77	3	12	119/16	2	24	A	1.038	1.017	1.059	-0.377
5	Mi10/W	125/68W	7	19.1	245/68	10	17	40/18	6	16	N	1.019	1.030	1.047	0.222
5	Mi11/E	155/75E	4	16.4	214/84	6	16	114/5	4	23	A	1.030	1.028	1.059	-0.034
5	Mi11/W	135/74E	8	12.7	138/58	5	15	357/21	7	17	I	1.021	1.009	1.032	-0.398
5	Mi12/E	151/81E	7	8.3	169/84	2	9	247/2	8	12	N	1.048	1.031	1.082	-0.211
5	Mi12/W	147/87E	7	7.7	119/80	3	8	245/6	2	13	N	1.029	1.035	1.065	0.092

Table 4 – AMS results for Santa Maria dykes

Same description as Table 2

Santa Maria dykes															
site	dyke margin	margin orient.	N	k	k_1 D/I	e 12	e 13	k_3 D/I	e 31	e 32	Fab	L	F	P’	T
6	Ma1/N	066;88N	11	17.3	324;76	12	27	186;7	6	10	N	1.009	1.016	1.027	0.278
6	Ma1/S	070;66S	5	17.4	96;45	15	43	321;21	10	13	N	1.011	1.018	1.029	0.240
6	Ma3/N	059;89S	5	10.4	267;55	13	37	166;2	9	12	N	1.012	1.016	1.027	0.142
6	Ma3/S	070;69S	7	15.6	95;21	17	25	351;17	7	21	N	1.027	1.072	1.093	0.446
6	Ma4/N	057;86N	6	14.0	32;81	7	12	135;2	4	10	N	1.016	1.030	1.049	0.301
6	Ma4/S	061;87S	7	17.1	59;77	7	26	330;1	7	10	N	1.009	1.020	1.031	0.377
6	Ma5/N	059;87N	5	16.0	191;72	11	21	305;3	8	18	N	1.003	1.007	1.011	0.399
6	Ma5/S	064;83N	4	15.2	241;47	17	22	158;1	18	24	N	1.005	1.003	1.009	-0.250
7	Ma6a/W	017;67E	9	71.3	51;60	8	27	278;24	4	13	N	1.004	1.011	1.015	0.465
7	Ma6b/E	017;67E	8	2.2	139;81	14	26	265;15	16	20	N	1.005	1.004	1.009	-0.111
7	Ma6b/W	012; 70E	5	2.6	128;29	18	25	290;37	16	45	N	1.003	1.003	1.013	0.000
7	Ma7/SE	036;77E	8	2.8	112;62	9	19	333;19	6	16	N	1.010	1.009	1.019	-0.052
7	Ma7/W	033;88W	4	2.9	124;73	10	19	277;10	13	22	N	1.006	1.006	1.012	0.000
7	Ma8/SE	040;80SE	3	3.7	92;2	3	10	189;63	5	7	I	1.004	1.006	1.010	0.200
7	Ma8/NW	043;61E	6	3.5	90;19	13	29	205;69	11	21	I	1.003	1.014	1.019	0.645
8	Ma9/E	162;60E	4	6.5	139;37	5	10	239;14	4	6	N	1.008	1.019	1.029	0.405
8	Ma9/W	182;84E	4	6.3	171;35	8	47	280;25	3	12	N	1.013	1.022	1.036	0.255
8	Ma10/E	168;58E	8	6.1	92;17	7	39	226;57	4	18	N	1.033	1.081	1.128	0.412
8	Ma10/W	160;72E	5	8.1	14;66	5	32	256;18	3	9	N	1.049	1.057	1.123	0.074
8	Ma11/E	182;90	8	3.4	345;76	25	34	157;22	10	22	I	1.010	1.006	1.016	-0.249

Table 5 - **Main composition of the sampled basalts of Santa Maria and São Miguel dykes**

		Santa Maria - Praia			Sao Miguel – Lombo Gordo		
		Ma7-12b	**Ma7-6**	**Ma8-6**	**Mi1_14**	**Mi3_10**	**MI6_8**
Microphenocrystal Component (%)	Plagioclase	8,4	8,4	23,3	11,9	5,1	
	Amphibole	1,7	5,1				
	Oxides	0,4			2,2	0,6	
	Piroxene					5,3	0,2
	Olivine				1,0	1,1	
Matrix component (%)	Plagioclase	20,6	24,0	26,0	40,5	37,5	37,5
	Piroxene		22,8	13,5	5,0	7,5	9,5
	Oxides	3,1	12,4	14,6	10,5	12,6	13,1
Fine matrix component (%)		64,8	26,6	21,3	15,0	18,8	23,7
Vesicles (%)		1,1	0,4	1,1	13,7	10,6	15,5

Table 6 – Chemical composition of the spinels

Chemical composition of the spinels in sampled basalts of Santa Maria and Sao Miguel dykes. C: percentage in the crystal; M: the percentage in the matrix.

	Santa Maria - Praia				Sao Miguel – Lombo Gordo				
	Ma7_12		Ma7_6	Ma8_6	Mi1_14		Mi3_10		Mi6_8
%	C	M	M	M	C	M	C	M	M
Al_2O_3	5.23	5.27	5.23	3.54	5.53	2.20	5.14	2.62	3.86
MgO	4.74	2.75	4.31	1.28	6.03	1.81	5.39	1.09	2.75
MnO	0.48	0.68	0.53	0.67	0.29	0.65	0.29	0.51	0.41
V_2O_3	1.15	1.49	0.79	1.22	1.13	1.39	0.76	0.82	1.49
TiO_2	20.54	25.77	21.15	29.84	16.76	21.32	17.46	18.85	19.30
ZnO	0.00	0.02	0.00	0.03	0.00	0.02	0.00	0.02	0.04
NiO	0.03	0.00	0.00	0.00	0.08	0.01	0.11	0.01	0.04
FeO	64.13	55.64	63.97	54.44	64.98	67.16	65.94	70.81	67.63
Cr_2O_3	0.05	0.02	0.05	0.09	1.00	0.02	0.93	0.10	0.00
Total	96.03	91.63	96.10	91.12	95.80	94.58	96.02	94.83	95.52
Al	1.78	1.91	1.80	1.32	1.86	0.79	1.73	0.94	1.35
Mg	1.89	1.26	1.86	0.62	2.56	0.82	2.30	0.49	1.21
Mn	0.13	0.18	0.13	0.18	0.07	0.17	0.07	0.13	0.10
V	0.31	0.37	0.18	0.31	0.26	0.34	0.17	0.20	0.35
Ti	4.57	5.84	4.59	7.12	3.59	4.87	3.75	4.30	4.29
Zn	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01
Ni	0.01	0.00	0.00	0.00	0.02	0.01	0.03	0.00	0.01
Fe^{2+}	10.62	12.55	10.69	14.33	9.06	11.93	9.47	11.17	11.06
Fe^{3+}	4.72	1.77	4.76	0.11	6.41	5.28	6.30	6.17	5.66
Cr	0.00	0.00	0.01	0.02	0.22	0.01	0.21	0.02	0.00
O	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00

Table 7 - Imbrication angles and AMS parameters for site 4

Imbrication angles, anisotropy and shape parameters of samples from the dykes of site 4, Lombo Gordo.

Samples from	Mean Imbrication Angle (^{o})	P	T	Shape
North margin	16	1.030 ± 0.011	0.033 ± 0.135	neutral
South margin	6	1.032 ± 0.006	0.274 ± 0.192	slightly oblate

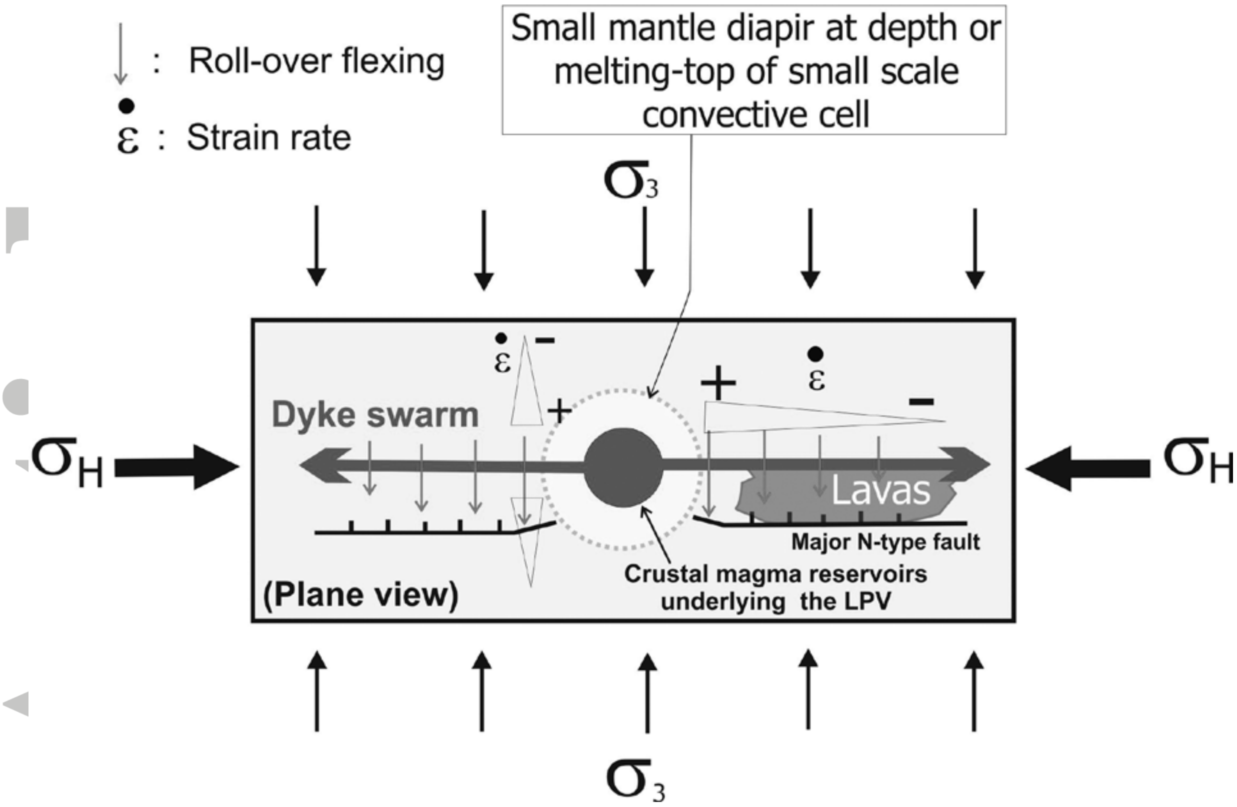

Fig.1 - Conceptual model of volcano-tectonic segment in a horizontal plane view after *Geoffroy*, [2005]. Upper crustal magma reservoirs (magma chambers) are located beneath a large polygenetic volcano (LPV) or a central volcano-tectonic system, not represented in the figure. These crustal reservoirs are fed directly or indirectly by the magma extracted from a localized melting zone at the asthenosphere-lithosphere boundary. This mantle zone may either correspond to the upper-part of a small-scale convection cell [*Geoffroy et al.*, 2007] or a mantle diapir [*Geoffroy*, 1998; *Burg et al.*, 2009]. The upper magma reservoirs are subject to hydraulic-type fracturing due to stress concentration at their edges, thus promoting dyke injection in the trend of the maximum horizontal compressive stress σH. These dykes feed the upper crust producing lava flows and tuffs when cross-cutting the ground surface. In addition, the asthenospheric localized instability generates high thermal gradients at the centre of the volcano-tectonic segment, which favour the development of tectonic extension

in the upper crust (see *Callot et al*., [2001]). Thin triangles along and normal to σ_H represent the relative elongation and shortening direction.

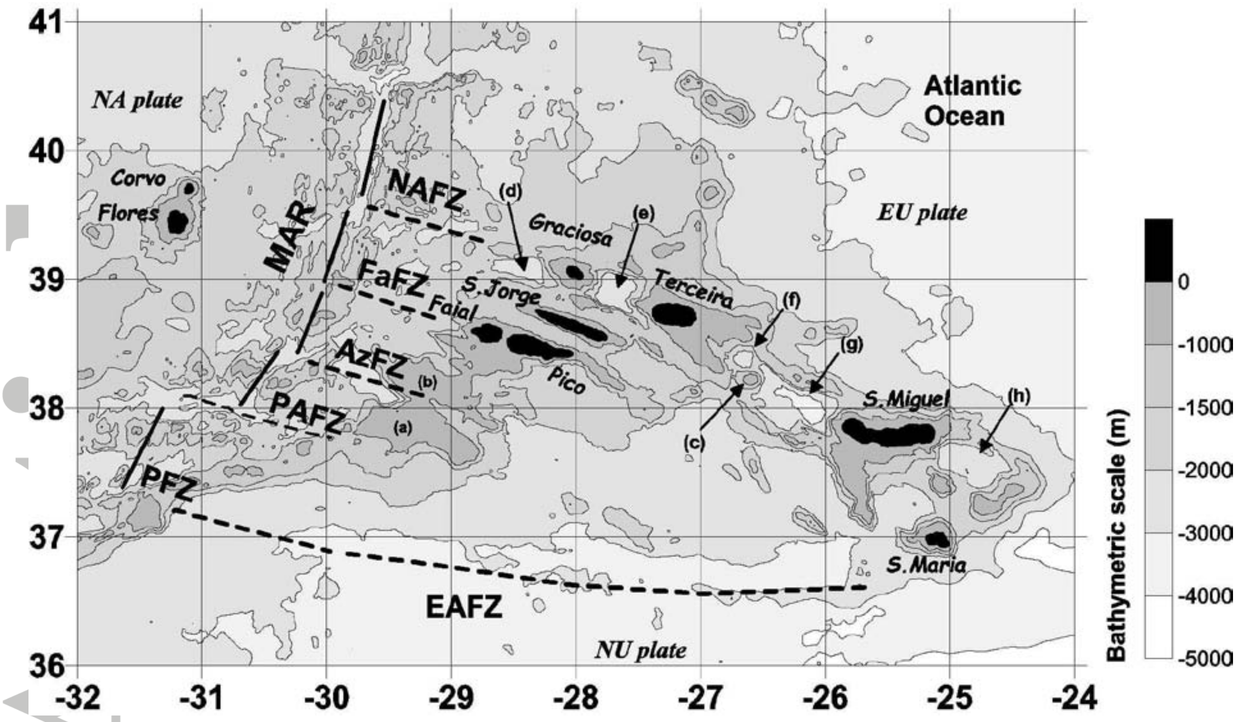

Fig 2 - Simplified bathymetry of Azores Plateau and main tectonic features, contoured at 1000 m interval based on *Luís et al*, [1994]; *Lourenço et.al.*, [1998]. Latitude and longitude in degrees are indicated along the margins.

Legend: NA plate: North Atlantic Plate; EU plate: Eursian Plate; NU plate: Nubian Plate; MAR: Mid Atlantic Ridge; NAFZ: North Azores Fracture Zone; FaFZ: Faial Fracture Zone; AzFZ: Azor Fracture Zone; PAFZ: Princess Alice Fracture Zone; PFZ: Pico Fracture Zone; EAFZ: East Azores Fracture Zone; (a) Princess Alice bank; (b) Azor bank (c) Dom João de Castro bank; (d) West Graciosa basin; (e) East Graciosa basin; (f) North Hirondelle Basin; (g) South Hirondelle basin; (h) Povoação basin.

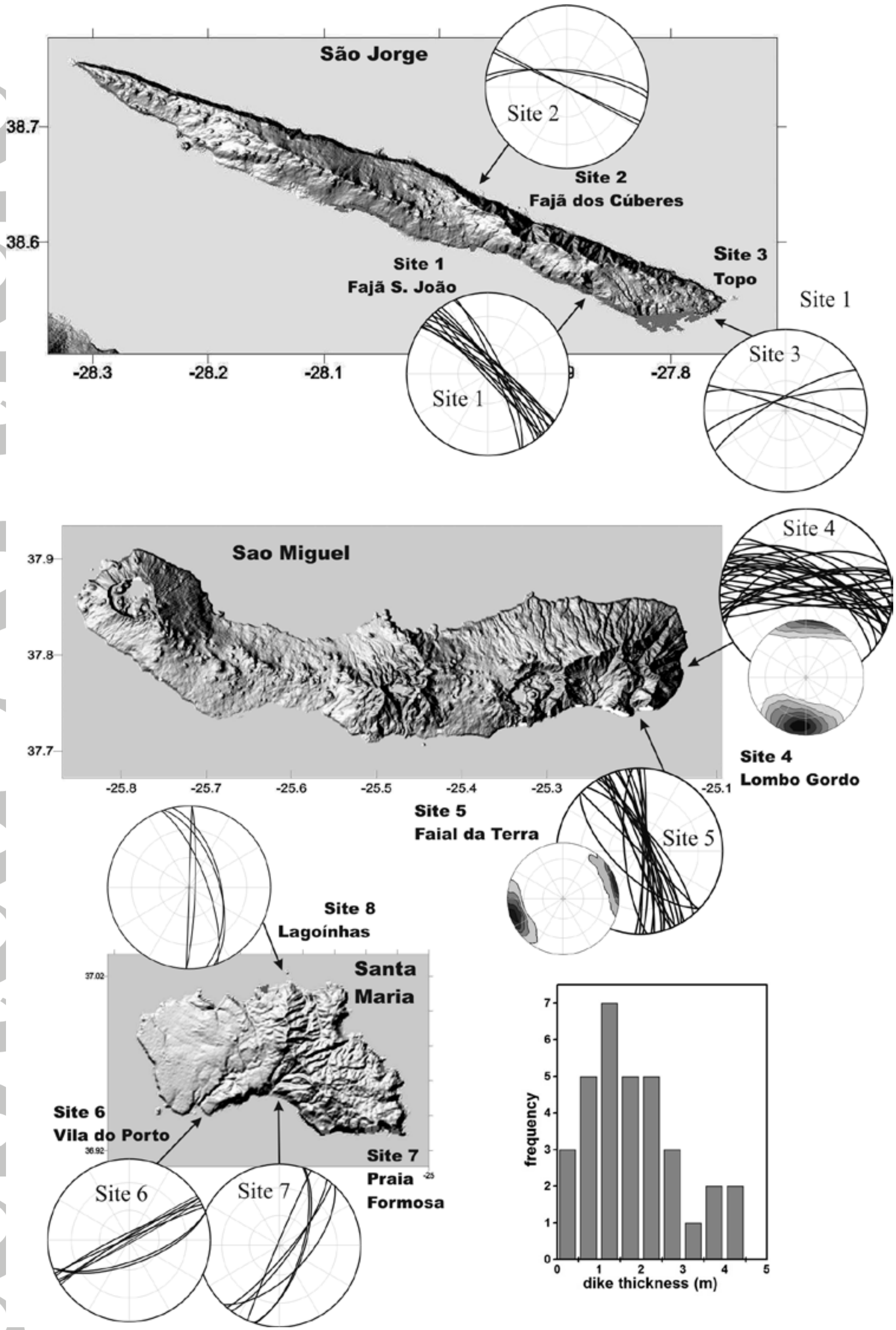

Fig 3 - Location of studied sites in the islands of Sao Jorge (top), Sao Miguel (middle) and Santa Maria (bottom) with stereograph plots of the orientation of the sampled dyke margins. Histogram of the thickness distribution of the sampled dykes (bottom right).

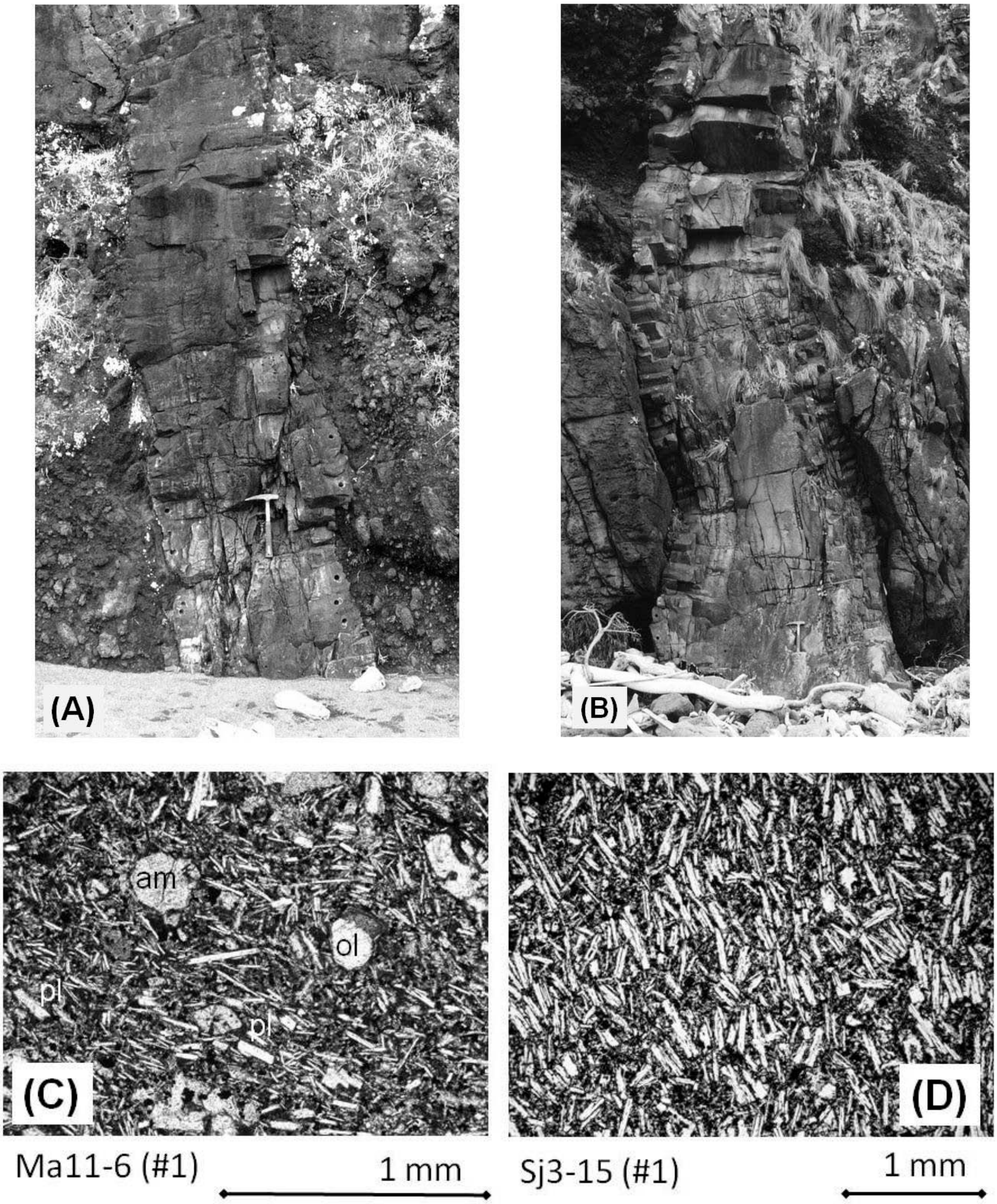

Fig. 4 – (Top) Two typical dikes from Sao Miguel island - site 1(Lombo Gordo). Dike Mi3 (image A, left) and Mi7 (image B, right). Both dikes are narrow (width < 1,5 m), with well defined margins and located around 2m - 3m above sea level.

(Bottom) Two representative micro-photographies of typical rock textures and mineralogy. Trachytic texture with phenocrysts of amphibole and olivine observed in dike 11 of Santa Maria - sample 6 (image C, left) and a typical trachytic texture with a very obvious and dense plagioclase alignment observed in dike 3 of Sao Jorge – sample 15 (image D, right). Main minerals indicated are: (ol) – olivine; (am) – amphibole; (pl) – plagioclase. Opaques (Fe and Ti oxides) are disseminated in ground mass.

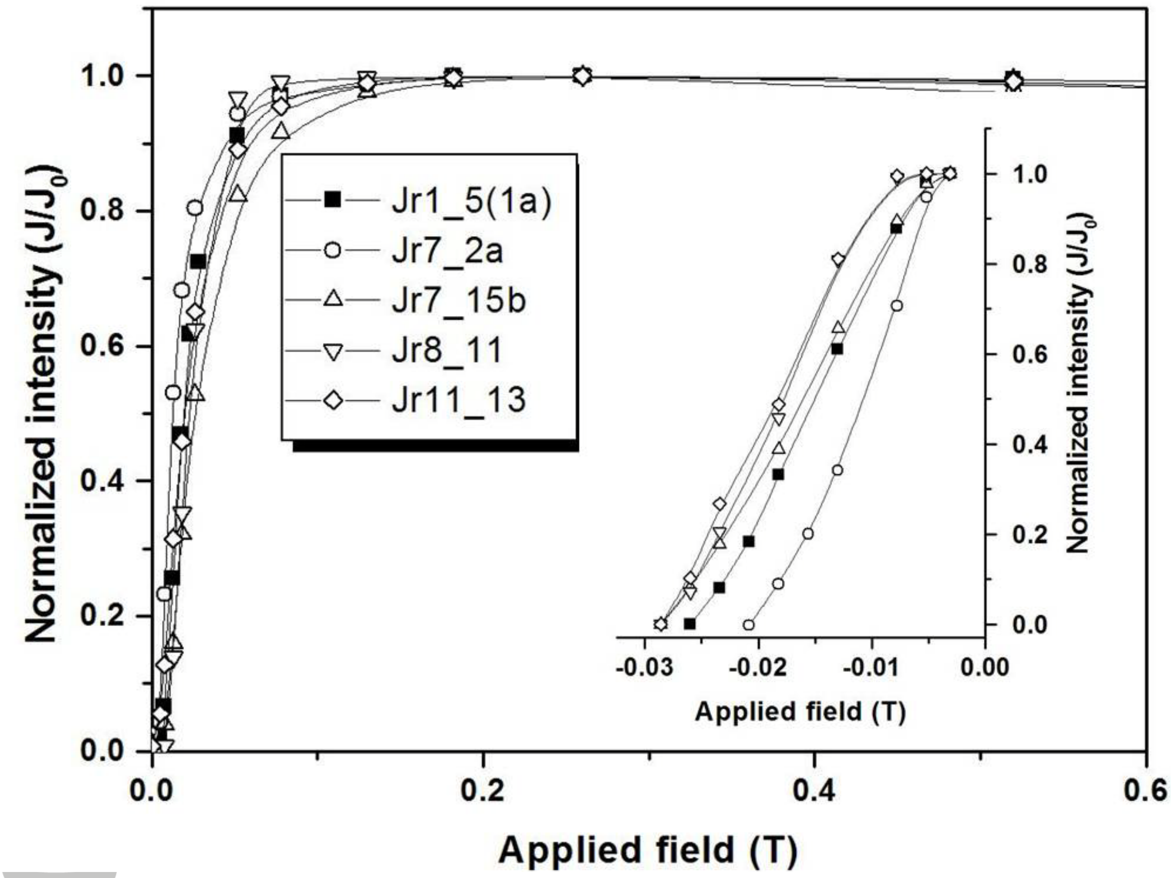

Fig.5 – Representative curves of normalized (a) isothermal remanent magnetization (IRM) acquisition and (b) back-field IRM demagnetization for samples of São Jorge.

Samples show a narrow spectrum of response with steep acquisition and reach saturation by 150 mT - 200 mT, showing no evidence of high coercivity phase. The acquisition and back field curves are characteristic of magnetite or titanomagnetite.

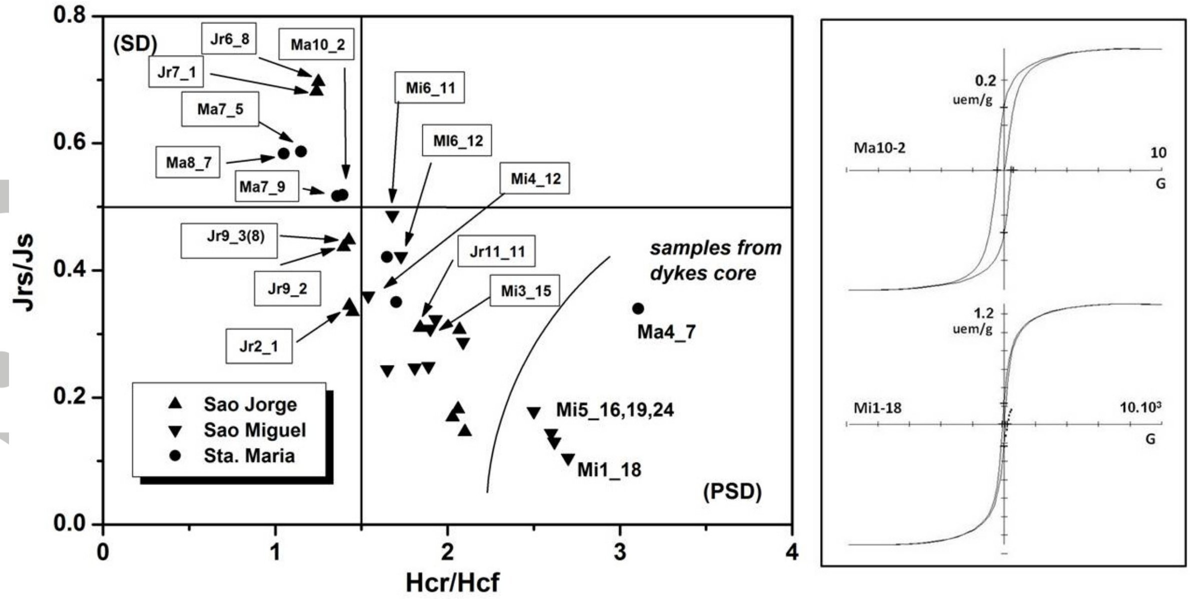

Fig.6 – High field magnetic properties of selected samples from São Jorge, São Miguel and Santa Maria. Left: coercive field versus magnetization plotted on a Day diagram (*Day et al*., [1977]) showing the dominant pseudo single domain (PSD) magnetic character of most of the samples. However samples from Santa Maria and São Jorge exhibit a single domain magnetic character.

Right: hysteresis curves (only the ferromagnetic component) for two selected samples: Mi1-18 (PSD) and Ma10-3 (SD). Applied field H in Gauss versus magnetization J in emu/g.

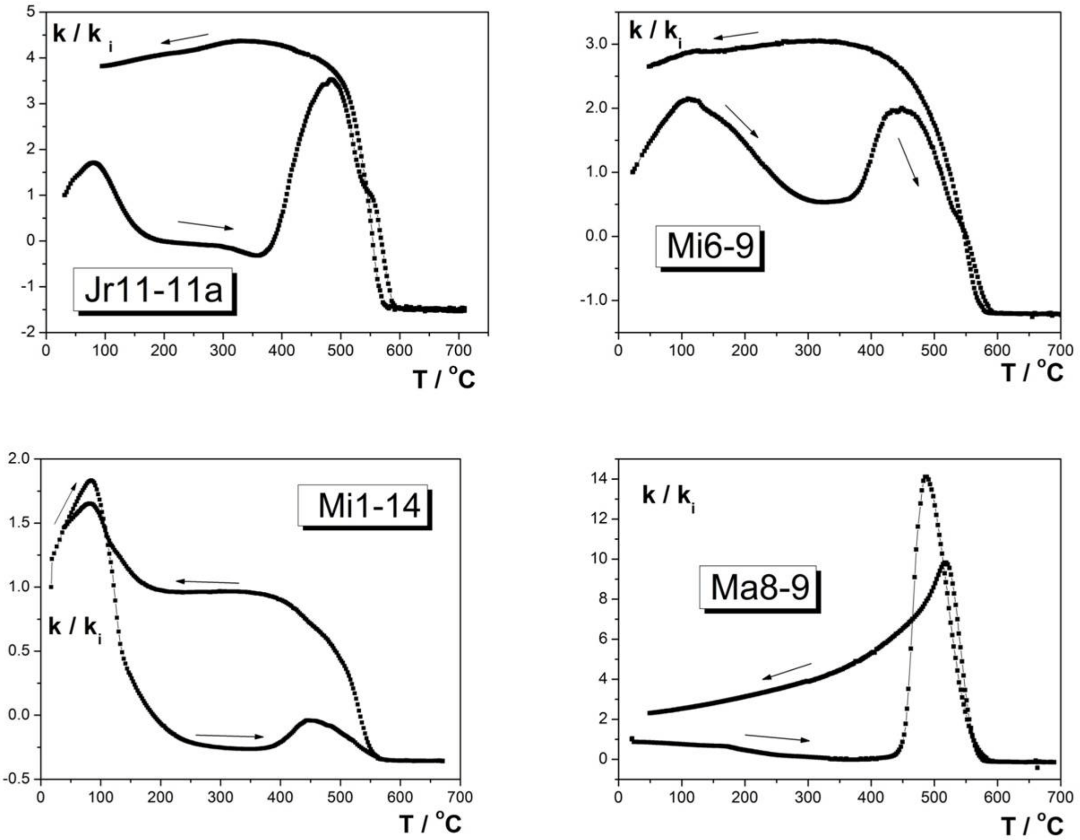

Fig.7– Representative thermomagnetic curves .

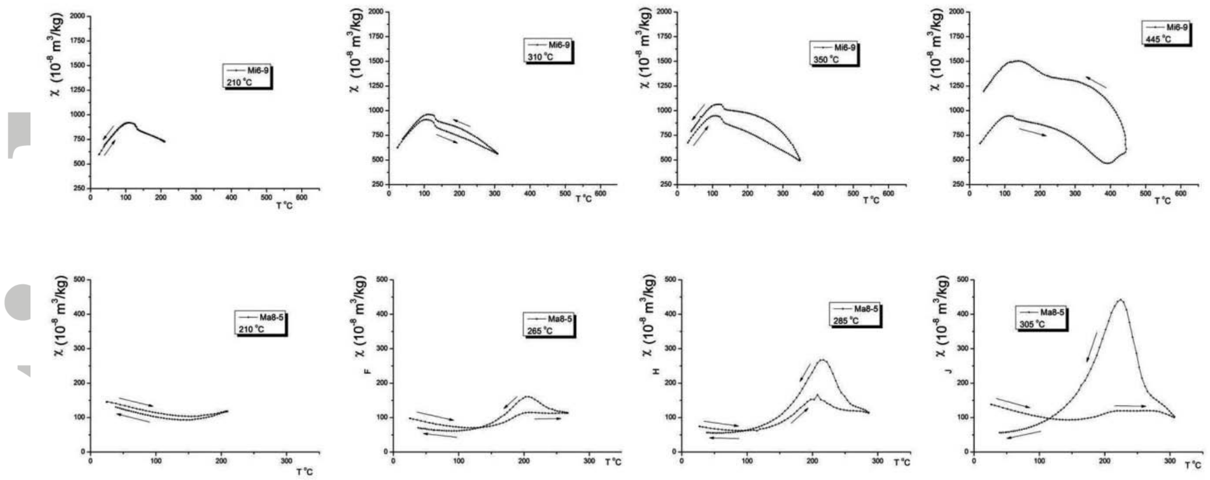

Fig.8– Representative **c**ycles of heating-cooling with stepwise heated curves of two samples. Up to ~ 200^{o} -225^{o} C the process is reversible. but for higher temperatures a new magnetic phase begins to develop.

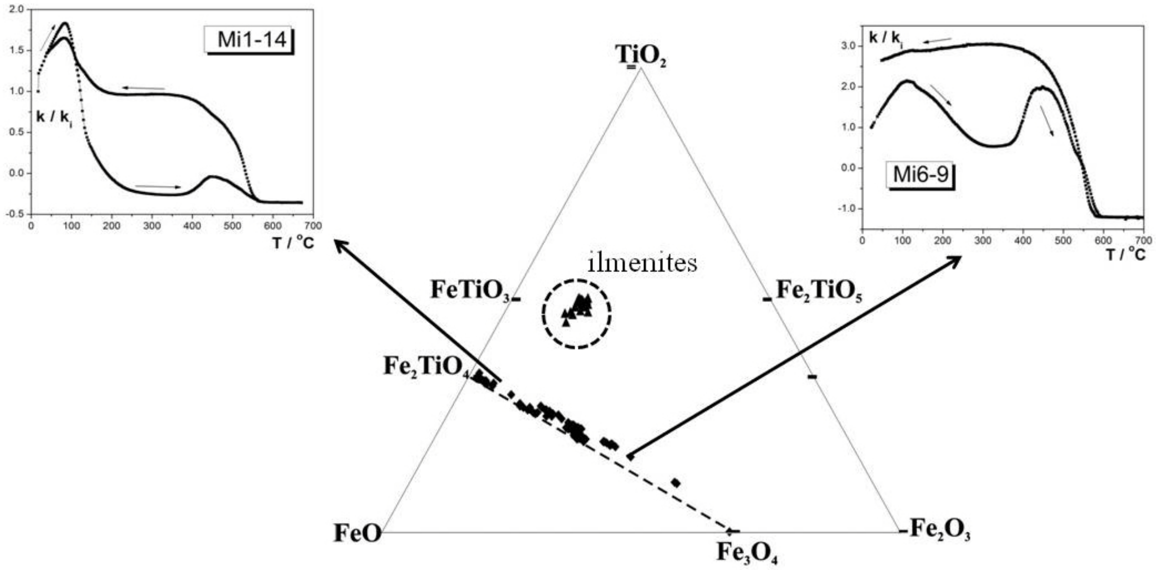

Fig. 9 – Compositional analysis plotted on a ternary diagram with two representative thermomagnetic analysis. This plot shows the range of the composition of the titanomagnetite solid solution and the slight departure from the theoretical titanomagnetite series towards higher *O* contents. The ilmenites plot, away from the theoretical composition, revealing an oxidation effect.

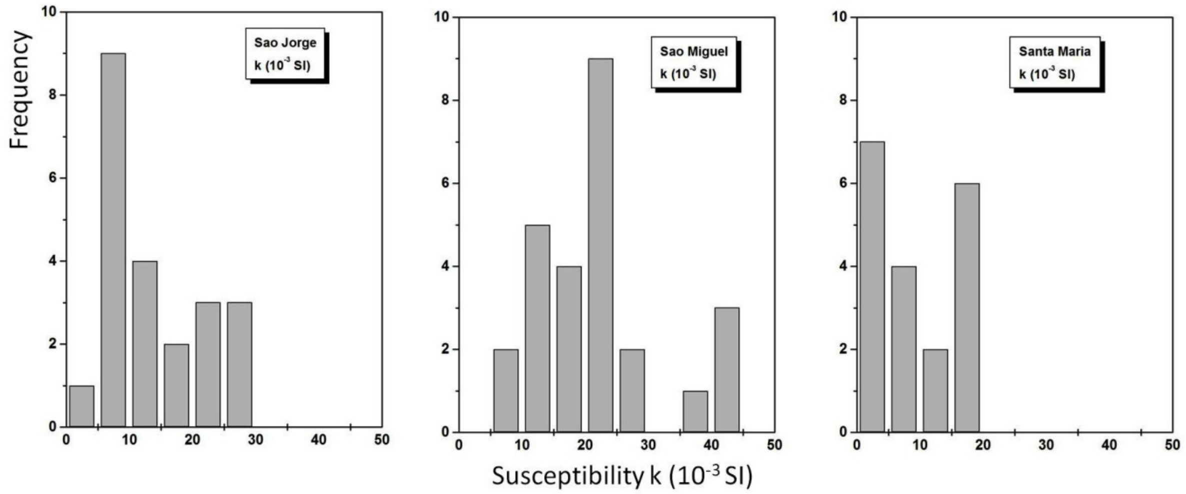

Fig. 10 – Histograms for the magnetic susceptibility of the dykes (average over each margin) from São Jorge, São Miguel and Santa Maria. With the exception of two dykes from São Miguel, the magnetic susceptibility is always below 30×10^{-3} SI.

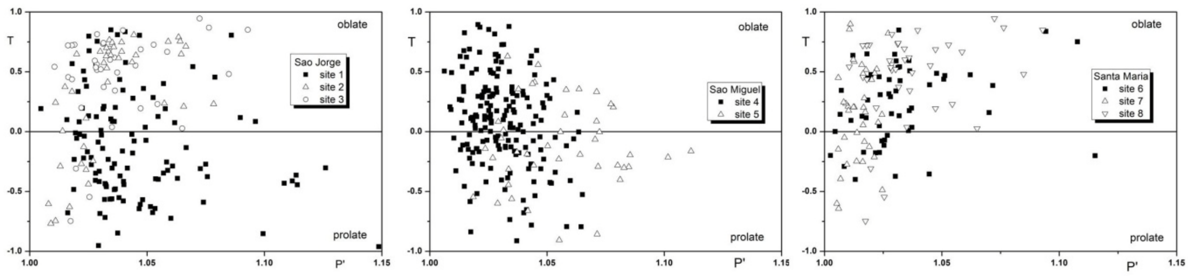

Fig.11 – The P’-T relationship for dykes of São Jorge, São Miguel and Santa Maria.

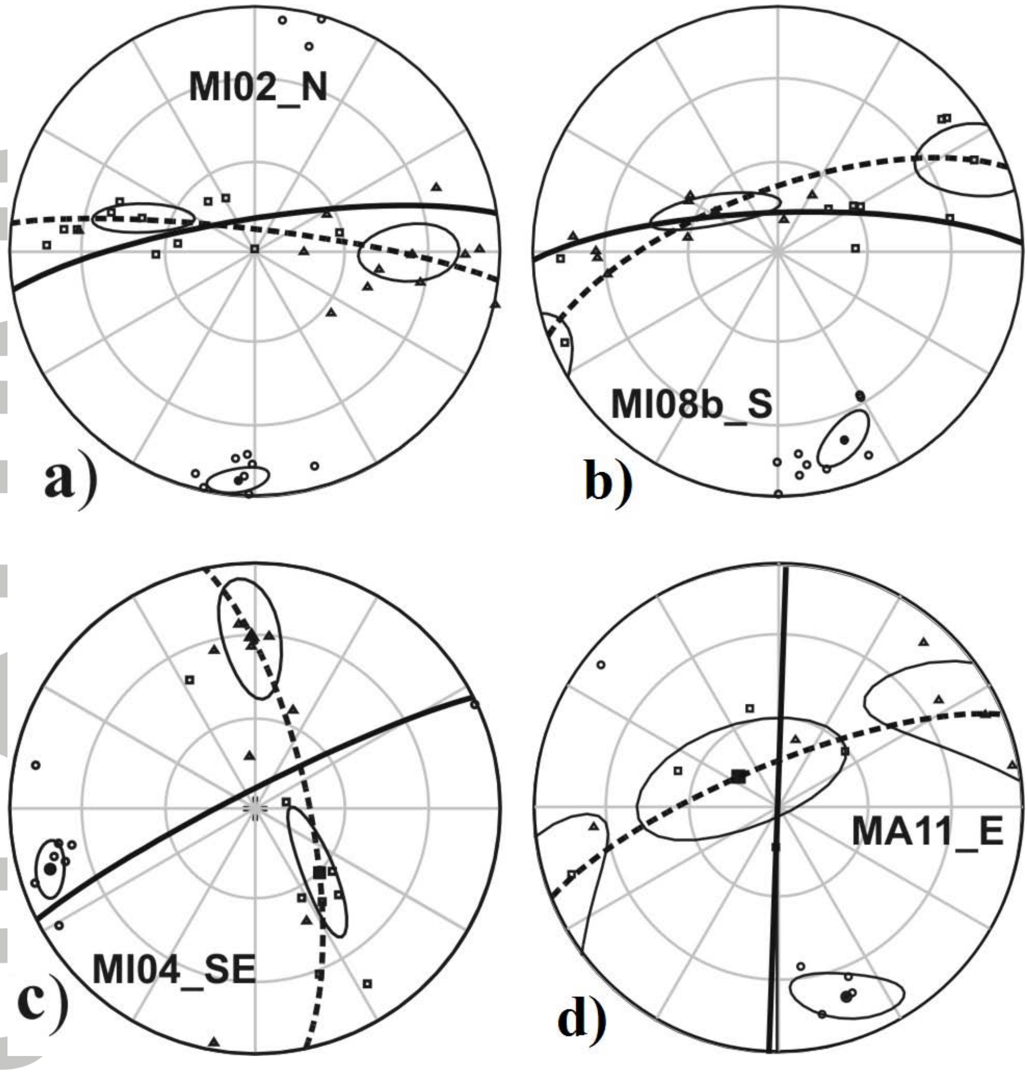

Fig.12 – Representative magnetic fabrics for dykes plotted in geographic coordinates on equal area stereographic projections (lower hemisphere). AMS principal axes are k_1(squares), k_2 (triangles) and k_3 (circles). Filled symbols are the mean tensor within ellipses of statistical confidence. Projection of dyke margin (thick continuous line) and magnetic foliation plane, MFP (dotted line).

a) and b) Two exemples of normal magnetic fabric in dyke 2, north margin and dyke 8b south margin, from site 4, São Miguel; c) One exemple of an inverse magnetic fabric obtained from the south east margin of dyke 4 in São Miguel; d) An high dispersion magnetic fabric from the east margin of dyke 11, site 8 in Santa Maria,.

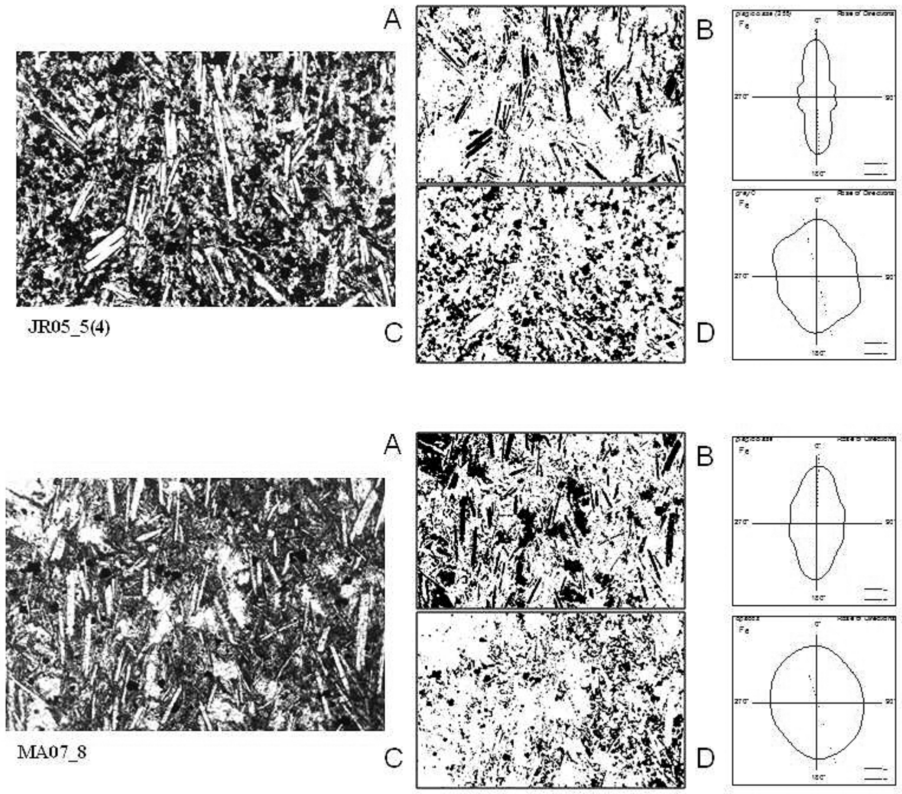

Fig. 13 - Two examples of the microtextural analysis of plagioclases and opaques preferred orientation based on thin section microphotographs, using the Intercepts method [*Launeau and Robin*, 1996]. This algorithm is based on the analyses of boundaries of objects, called phases which may represent a type of individual mineral, discontinuity, border or texture. The counting of the intercepts by Fourier series produces a rose of intercepts from which we can derive a directional rose diagram (alignments or preferred orientations). Results are obtained numerically and graphically in the form of roses diagrams, showing the directions and mean shape of minerals. The directional roses of the minerals boundaries of selected phase, indicate the preferred elongation axis or orientation of the considered phase.

This procedure was applied for the study of phenocrysts – mainly plagioclases - and opaque grains in a total of 49 microphotographs from 40 thin sections cut from 25 cores extracted from 18 different dykes.

Two representative exemples from samples Jr5-5(4) and Ma7-8, with the original image on left; A) the processed image used to analyze the plagioclases (inverted color); B) the obtained directional rose diagrams; C) the processed image used to analyze the opaques and D) the obtained directional rose diagrams.

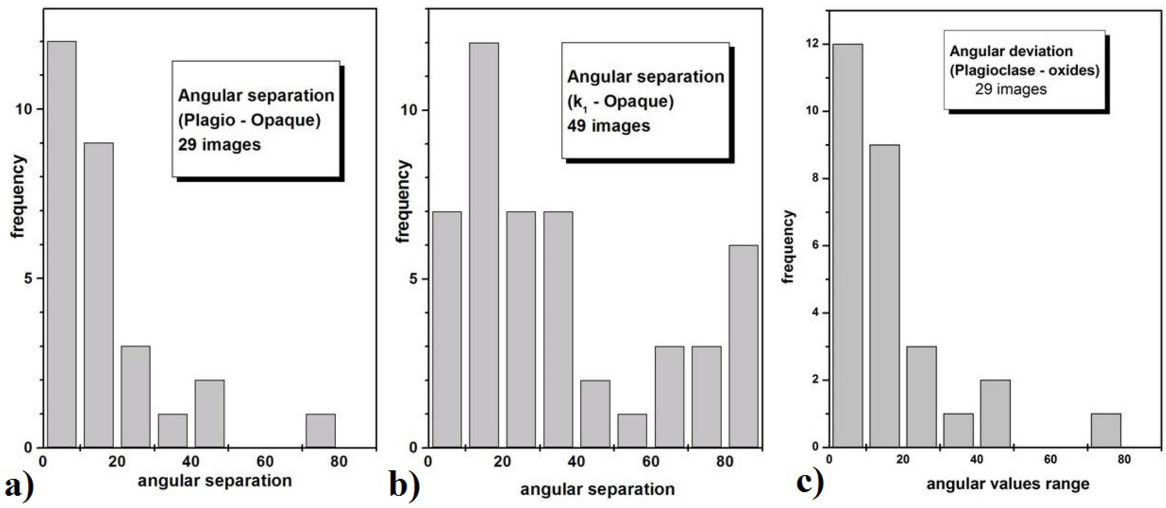

Fig. 14 – Diagrams showing relationship between the maxPO of opaques and phenocrysts as a function of the orientation of the magnetic lineation k_1. Histograms of: a) the angular separation between maxPO of phenocrysts and opaques; b) k_1 and maxPO of opaques and c) k_1 and maxPO of phenocrysts.

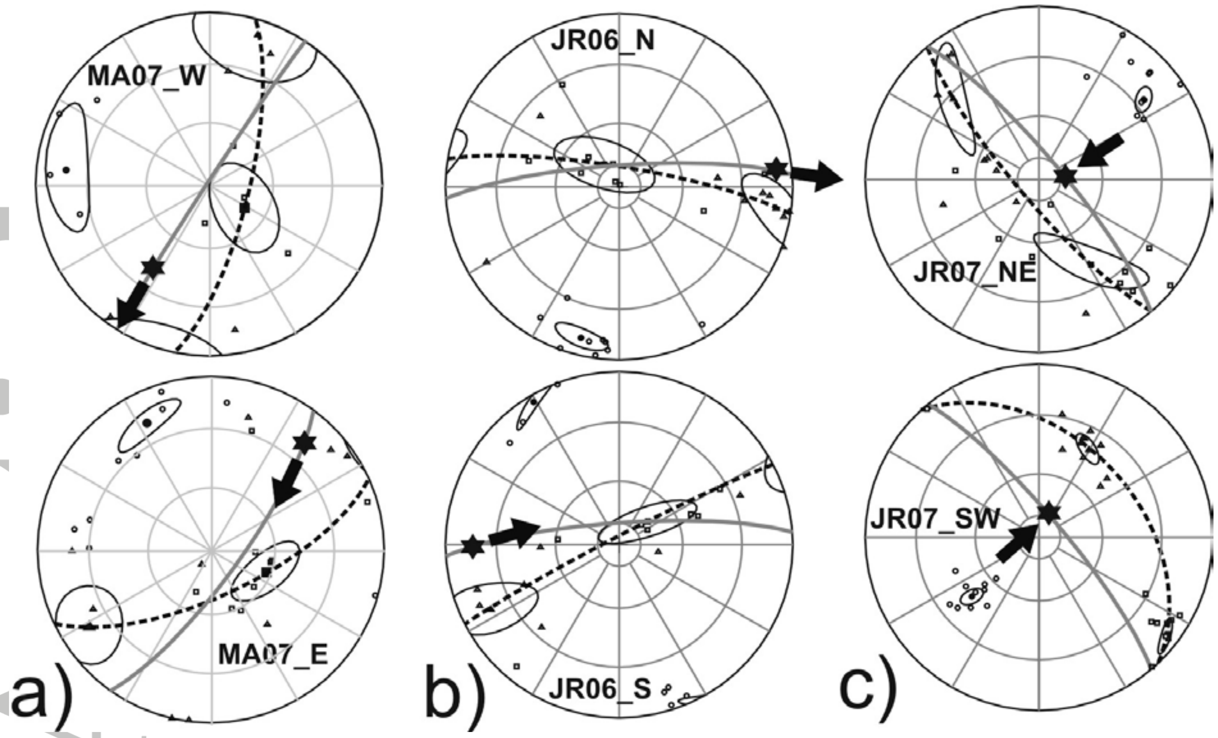

Fig 15 – Representative examples of flow vector determinations for three dykes according to the explanations in text. Legend of the stereonet was explained in fig. 12. Solid arrow represent the direction and sense of the inferred flow vector. a) dyke 7 of Santa Maria, north-west margin (top) and south-east margins (bottom). The imbrication angles are 25^{o} and 29^{o}. respectively. Flow vector points (direction/inclination) 212^{o}/40^{o} (down) in north-west margin and 41^{o}/20^{o} (up) in south-east margin. The sense of the flow is coherent in both margins, i.e. south-west with low inclination. b) dyke 6 of Sao Jorge, margins north (top) and south (bottom). The imbrication angles are 15^{o} and 24^{o} respectively. Flow vector points (direction/inclination) 83^{o}/8^{o} (down) in north margin and 89^{o}/19^{o} (up) in south margin. The sense of the flow is coherent at both margins, i.e. east and sub-horizontal. c) dyke 7 of Sao Jorge, north-east (top) and south-west (bottom) margins. The imbrication angles are of 20^{o} and 38^{o} respectively. Flow vector points (direction/inclination) 45^{o}/80^{o} (down) in the north east margin and 69^{o}/79^{o} (down) in the south margin. The sense of the flow is coherent at both margins, almost vertical and downward. This flow sense is probably associated with a “subsidence” of the magma in the dyke during the final phases of intrusion and not related to the geometry of flow during the intrusion.

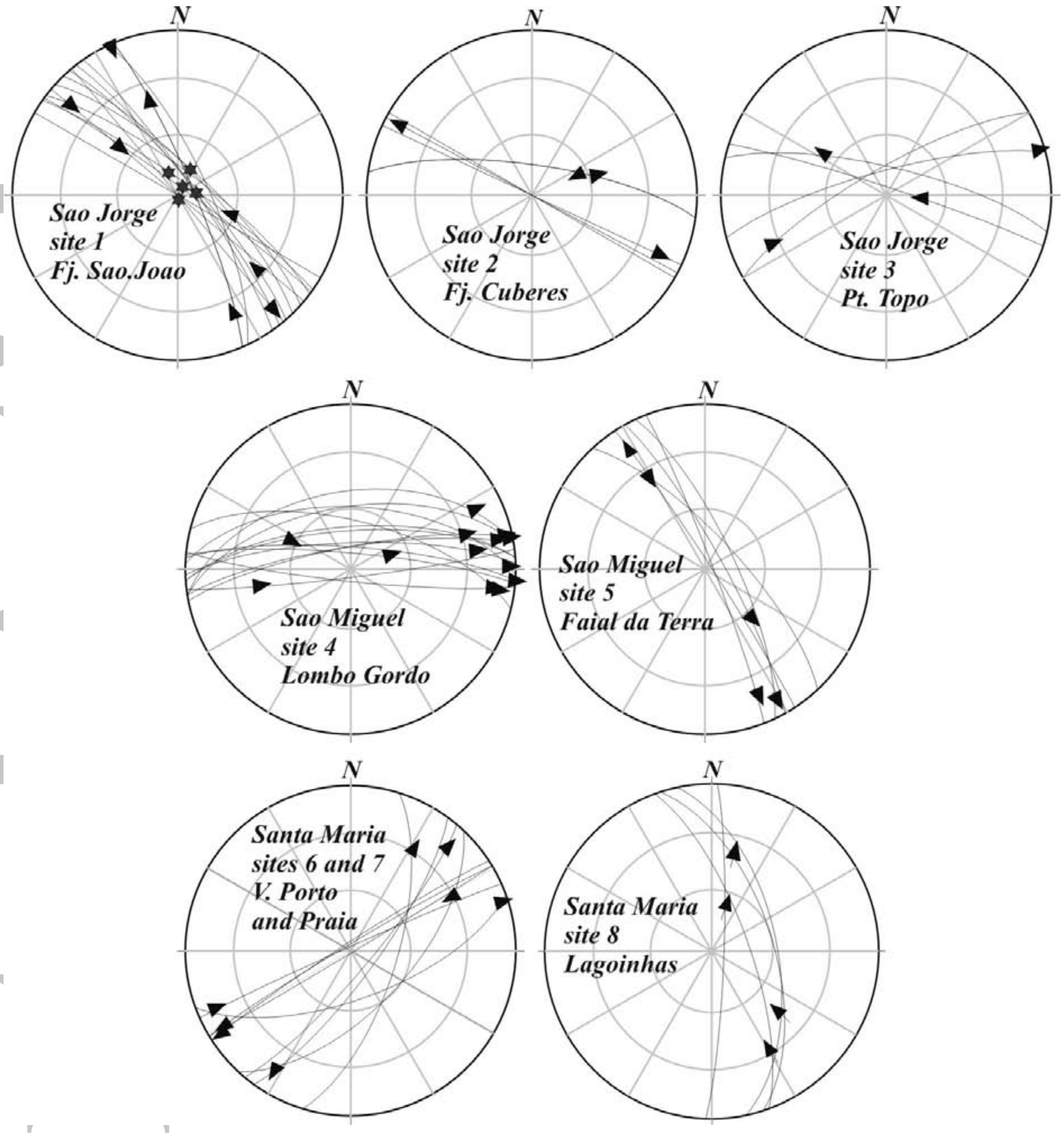

Fig 16 – Inferred flow vectors represented by arrows for all dyke margins. Solid stars for site 1 on Sao Jorge represent the inferred flow vectors of high plunge values observed in dyke 7 (both margins) and in one of the margins of dykes 1, 3 and 11. The dykes margins are represented in their geographic orientations in equal-area stereographic projections (lower hemisphere).

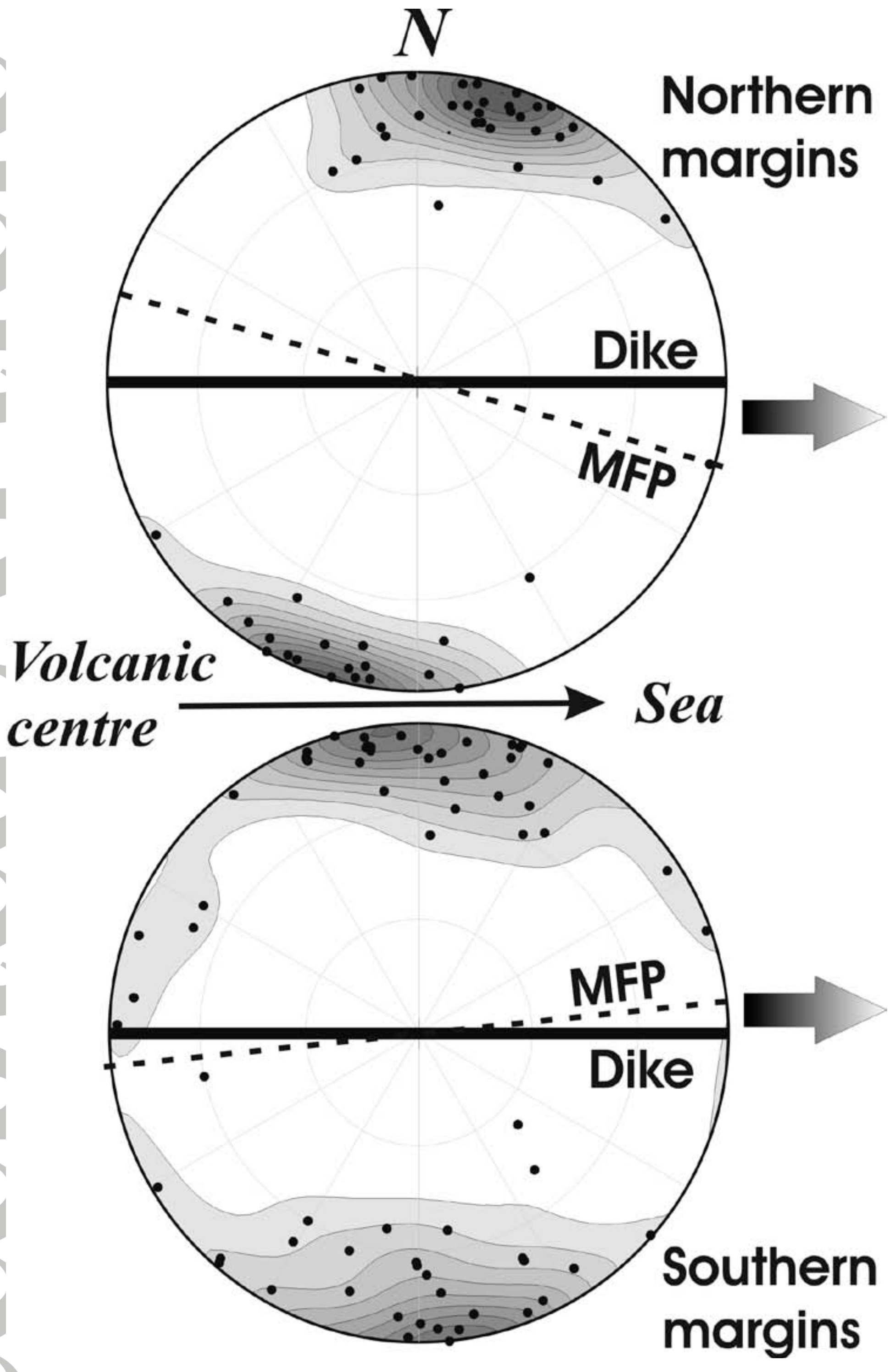

Fig.17 – Contour levels of k3 vectors from the transformed margins of dykes from the site 4 Lombo Gordo on São Miguel. All margins and their respective magnetic fabrics were rotated to a common reference frame, defined as a vertical E-W oriented dyke allowing an overall visualization.