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Dike intrusion under shear stress: Effects on magnetic and vesicle fabrics in dikes from rift zones of Tenerife (Canary Islands)

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Abstract

A theoretical model predicting how anisotropy of magnetic susceptibility (AMS) and vesicle fabrics are modified by shear stress resolved on the dike walls prior to the final cooling of magma is developed for vertical dikes. The resulting fabrics are asymmetric with respect to initial fabrics assumed to be symmetric. Application of this model together with collected data on magma flow direction, dike propagation direction and mechanism, and shear sense, allow us to interpret dike fabrics in terms of shear resolved on the dike walls during intrusion (en echelon arrangement, offsetting, and dike curvature). The interpretation of AMS and vesicle fabrics of the margins of four dikes shows a reasonable agreement with the proposed theoretical models, suggesting that asymmetric fabrics can be used to infer magma flow and may provide valuable information on the shear resolved on the dike walls during intrusion.

Keywords: Dike segmentation; Anisotropy of magnetic susceptibility; Asymmetric distribution; Magma flow

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1. Introduction

The intrusion of dikes is the most efficient mechanism to transport magma from deep reservoirs to shallow crustal levels. Close to the earth's surface and at their tip fronts, dikes can be affected by surface stresses that modify their propagation trajectories and intrusion patterns. As a result dikes may separate into several segments and also curve their trajectories (Delaney and Pollard, 1981; McGuire and Pullen, 1989; Gudmundsson, 2000; Muller et al., 2001; Tibaldi, 2003; Klügel et al., 2005). Ambient stresses resolve as shear stresses on the dike walls (Pollard, 1987) and may influence dike fabrics (Correa-Gomes et al., 2001; Féménias et al., 2004). It is commonly assumed that fabrics of dikes are symmetric (with respect to the symmetry plane of the dike) whereas if an ambient stress is resolved on the dike walls an asymmetric fabric may appear (Correa-Gomes et al., 2001; Aubourg et al., 2002; Féménias et al., 2004; Poland et al., 2004).

The symmetry of a dike can be tentatively assessed in the field by observing the textural distribution across the dike. Dikes may show a symmetric distribution of phenocrysts, vesicles and xenoliths in relation to the symmetry plane of the dike. They may also display a more massive texture in the centre and flow banding at the margins. Crystal segregation in the dike centre has been attributed to the Bagnold effect (Bagnold, 1954; Barrière, 1976; Komar, 1976; Nkono et al., 2006) and an aphyric texture at the margins has been attributed to cooling (Féménias et al., 2004). Aphyric and aphanitic dikes, however, may not be suitable for establishing symmetry or asymmetry in the field. Anisotropy of magnetic susceptibility (AMS) is a useful tool to detect fabric distributions (Féménias et al., 2004) and has been widely used to infer magma flow direction in dikes. The imbrication of the maximum susceptibility axis (K_1) with respect to dike walls provides the mean direction and sense of magma flow in the dike (Knight and Walker,

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1988). However, asymmetric AMS fabrics have received little attention (Féménias et al., 2004) and are seldom used to infer the direction of magma flow (Tauxe et al., 1998; Callot et al., 2001; Aubourg et al., 2002; Poland et al., 2004).

This study concerns dikes showing en echelon segmentation, dike offsetting and curved geometries, pointing to the existence of shear stress resolved on the dike plane during intrusion. Our aim is to investigate how shear stress affects magnetic and vesicle fabrics. We develop models showing how the magnetic fabric is modified by the resolved shear stress. The models, together with field data on the direction of dike propagation and the shear resolved on the dike plane, help us to show that asymmetric fabrics can be used to infer the direction and sense of magma flow. In addition, asymmetric fabrics may help to infer the dike propagation mechanism. The dikes chosen as examples come from rift zones of the Teno and Anaga massifs forming the Upper Miocene basaltic shield of Tenerife, in the Canary Islands. They are nearly vertical, basaltic in composition and, at the site of sampling, they intrude basaltic pyroclastic rocks. Many of those dikes show evidences of have been intruded under shear stress, and strike-slip is a common tectonic regime in the basaltic shield of Tenerife (Marinoni and Gudmundsson, 2000; Walter and Schmincke, 2002).

2. Dike propagation and magma flow

Dikes are planar tensile cracks filled with magma. Their advance is driven by the internal excess pressure of the fluid, which results in the brittle dilation of the surrounding media. The direction of crack propagation is determined by the orientation of stress at the crack tip, and dike walls are assumed to be perpendicular to the least compressive stress (Pollard, 1987; Rubin, 1995). A dike propagating through a homogeneous medium where an ambient stress external to the dike is applied may undergo shear stress on its walls, causing the rotation of the least compressive stress at the crack tip (Pollard, 1987). Three modes of dike propagation, which result in different dike patterns and geometries, have been distinguished depending on the orientation between the shear stress resolved on the dike walls and propagation direction of the dike (Fig. 1). According to these modes, en echelon dikes (Fig. 1: mixed mode I, III) would form when the propagation direction is perpendicular to the resolved shear (Pollard, 1987; Pollard et al., 1975). An alternative mode of propagation for en echelon dikes (Currie and Ferguson, 1970) proposes that segments propagate laterally towards adjacent ones, with eventual merging resulting in an en echelon arrangement (Fig. 2). Field evidence for both "along-dike dip" and "along-dike strike" propagation of segmented dikes is well documented (Currie and Ferguson, 1970; Pollard, 1973; Pollard et al., 1975; Smith, 1987). "Along-dike strike" propagation is also supported by AMS and structural data showing that, in the vicinity of the segment tip, magma flows laterally towards the tip (Baer, 1995), and by fissure eruptions in active volcanoes (McGuire and Pullen, 1989; Acocella and Neri, 2003).

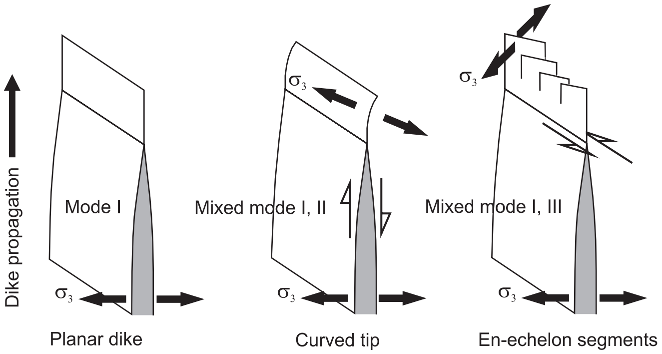

Fig. 1. Modes of dike propagation and dike geometries based on the rotation of the least compressive stress at the dike tip in response to the shear stress resolved on the dike walls (after Pollard, 1987).

Bussel (1989) already noted that propagation directions differing by as much as 90° would depend on the crack dilation process, and that both propagations may coexist at the same time in different parts of the dilating crack. A simple way to reconcile "along-dip" with "along-strike" propagation is to consider a planar dike propagating upwards through a homogeneous medium undergoing shear stress resolved on the dike walls. The dominant propagation direction of both the dike (Rubin, 1995) and the flow of magma is upwards (Fig. 3). However, near steps and tips of segments, in particular at shallow crustal levels, the local propagation direction and magma flow is towards the segment edges (Fig. 3).

Magma flow direction in dikes can be inferred by a number of flow indicators such as flow folds, ropy flow structures, scour marks, groove moulds and fingers, sheared phenocrysts and Riedel shears, magnetic fabrics, crystal alignments and elongated vesicles. When these indicators are well exposed most of them give the direction and sense of flow. Unless imbrications on opposite walls are detected, magnetic fabrics, crystal alignments and elongated vesicles provide the direction of magma flow but not the sense. Flow indicators on the external surfaces of dike walls determine the direction of initial magma injection, which is commonly assumed to be parallel to propagation direction of the dike (Smith, 1987; Rochette et al., 1991; Staudigel et al., 1992; Baer, 1995; Varga et al., 1998).

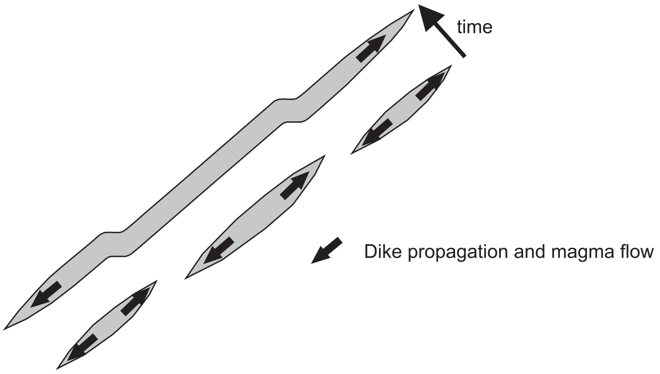

Fig. 2. Plan view showing the lateral propagation of segment dikes towards adjacent segments and yielding an en echelon arrangement (based on Currie and Ferguson, 1970).

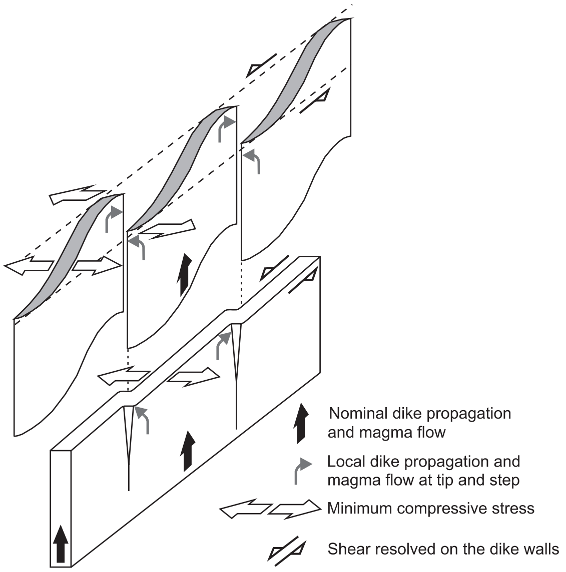

Fig. 3. General mechanism of dike propagation and magma flow under shear stress that combines the lateral propagation and magma flow of dike segments by Currie and Ferguson (1970) and the three modes of dike propagation proposed by Pollard (1987).

3. Theoretical AMS fabrics under shear stress

Correa-Gomes et al. (2001) developed a two dimensional model of fabric ellipses undergoing coeval shear stress in which ellipses are allowed to rotate and change their shape according to the amount of applied shear. In their model particles rotate in the same plane as the applied shear. Here, we use their model to investigate the evolution of magnetic fabrics under increments of shear stress resolved on the dike walls. Three cases are examined: (a) magma flow is parallel to the vector of the applied shear; (b) magma flow is perpendicular to the shear stress vector affecting dike walls; (c) magma flow is oblique to the shear vector (Fig. 4).

Magma is considered a laminar viscous flow which is homogeneous in composition and contains rigid magnetic particles that rotate within the flow until magma solidification. Dike walls are vertical, magma flow in the dike is directed upwards, and the shear is applied dextrally parallel to dike walls. We focus on the rotation of magnetic particles near dike borders, where the shear produced by viscous flow of magma is expected to be higher. Dike borders are also the zones where differences in orientation and stress rate between the applied shear and the shear by magma flow are expected to be best represented. Magnetic fabrics can be represented as ellipses whose axes are the maximum and minimum susceptibility axes (K_1 and K_3 respectively). The ellipses rotate and deform within the plane containing the shear vector and the maximum susceptibility axis (Fig. 4). For simplicity the intermediate susceptibility axis (K_2) is contained on the dike walls. We assume initial mirror imbrication of K_1 and an imbrication angle to the dike walls of 30°. The evolution of K_1 by increasing the applied shear rate is represented in lower hemisphere stereoplots. Once the maximum susceptibility axis becomes parallel to the shear vector on the dike wall (i.e. the imbrication angle is 0°) further rotation is forbidden. In this situation the only possible evolution of fabric ellipses is to modify their shape and degree of anisotropy.

3.1. Magma flow parallel to shear

When flow is parallel to shear the maximum susceptibility axes along opposite margins evolve differently within the planes containing K_1 and the shear vector (maximum circles in lower hemisphere stereoplots) depending on the resultant shear on each margin (Correa-Gomes et al., 2001). On the margin where magma flow and the resolved shear are in opposite senses (Fig. 4a: eastern margin), K_1 will rotate decreasing the imbrication angle to the dike wall (Δ) down to virtually 0° at the maximum shear strain. On such a margin fabric ellipses will tend to deform against the dike wall (Correa-Gomes et al., 2001). Where magma flow and the resolved shear are in the same sense (Fig. 4a: western margin), K_1 will rotate increasing the imbrication angle to the dike wall.

3.2. Magma flow perpendicular to shear

When flow is perpendicular to shear, the maximum susceptibility axes in both margins evolve similarly within the two planes that contain K_1 and the shear vector (Fig. 4b). During rotation of K_1, the imbrication angle decreases down to 0° at the maximum shear strain when K_1 becomes parallel to the shear vector (Fig. 4b).

3.3. Magma flow oblique to shear

In common situations magma flow is oblique to shear, and the rotation of K_1 will result in a combination of the two former cases. Here, we use the example of flow being at 45° to the shear vector to illustrate how complex can be the interpretation of AMS data when magma flow is oblique to shear (Fig. 4c).

4. Methods

The dikes of Tenerife were collected with a portable drill and oriented using both magnetic and sun compass, and sampling sites were positioned by GPS. We obtained 4 to 7 oriented cores, 5–15 cm long and 25 mm in diameter, within a distance of 10 cm from both dike walls. The orientation of dike walls, the mean dike orientation, and any magma flow and dike propagation indicator were collected at the sampling site. All magnetic measurements were corrected according to the magnetic declinations for the different parts of Tenerife provided by the Instituto Geográfico Nacional de España. Specimens were analyzed for their AMS at the Paleomagnetism Laboratory of the University of Barcelona with a KLY-2 magnetic susceptibility bridge. The eigenvectors of the susceptibility tensor representing the maximum, intermediate and minimum susceptibility axes (K_1, K_2 and K_3), mean tensor values under the 95% confidence level, dike orientation, and

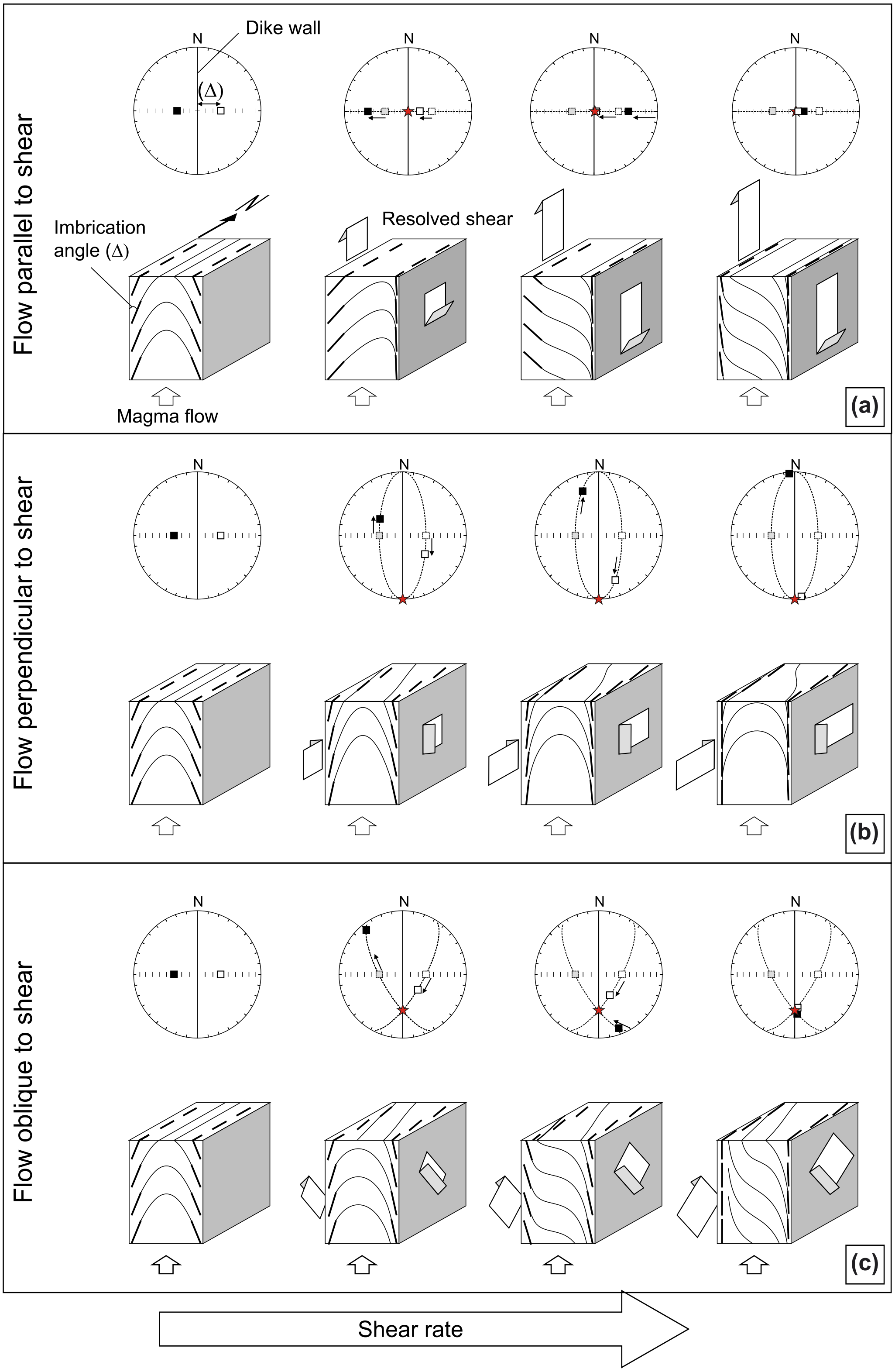

Fig. 4. Rotation of the maximum susceptibility axes of the AMS fabric caused by shear stress resolved on the dike walls during intrusion. Three cases depending on the orientation between magma flow and shear vector are shown (see text for details). Light grey and black squares are the maximum susceptibility axes of the western margin. White squares are the maximum susceptibility axes of the eastern margin. Star is the shear stress vector.

orientation of flow indicators and dike propagation indicators were plotted in lower hemisphere diagrams. Some of the dikes contain phenocrysts of pyroxene of up to 2 cm long and olivine of up to 1 cm in section. Although some contribution to the magnetic susceptibility from paramagnetic minerals is present, mean susceptibilities $(K_1 + K_2 + K_3)/3$ are in the range of $3000–70{,}000 \times 10^{-6}$ SI. These values are well above the 500 to 1000×10^{-6} SI of rocks dominated by paramagnetism

(Rochette, 1987), suggesting a predominance of ferromagnetic minerals. The anisotropy degree P′ and the shape parameter T as defined by Jelinek (1981) were calculated for each sampling site, and the magnetic ellipsoids were classified as prolate ($-1 \leq T < 0$) and oblate ($0 < T \leq 1$) (Hrouda, 1982).

5. Analysis of AMS and vesicle fabrics

Dikes emplaced under shear stress may show en echelon segmentation and curved geometries (Fig. 1: mixed modes I, II and I, III), and dike fabrics may record the shear undergone. When interpreting dike fabrics emplaced under shear stress from natural examples three main uncertainties arise: the orientation and sense of the shear vector, the direction and sense of dike propagation, and magma flow direction and sense. The orientation and sense of the shear resolved on the dike plane is usually unknown and the only constraint concerning this shear is its dextral or sinistral nature observed in exposures. The trend and plunge of segment tips, horns, steps, and cusps have been currently used to infer dike propagation direction (Rickwood, 1990) but unless these structures are well exposed in the three dimensions (e.g. Pollard et al., 1975; Baer and Reches, 1987) uncertainties may arise concerning the sense of dike propagation. Magma flow may change direction and sense along dike and towards the interior of the dike, and opposite senses of flow may coexist in a given dike (Baer and Reches, 1987; Staudigel et al., 1992; Philpotts and Asher, 1994; Baer, 1995; Varga et al., 1998; Féménias et al., 2004; Poland et al., 2004).

In this section we interpret the magnetic and vesicle fabrics of segmented and offset dikes with the support of the theoretical models shown above and of additional data collected in the field concerning sense of shear, dike propagation and magma flow. The distribution of K_1 is assumed to be initially symmetric with respect to the symmetry plane of the dike. K_1 imbricate on both dike margins and rotate into an asymmetric distribution according to the sense of shear within the plane containing the shear vector and K_1. It is also assumed that K_1 tends to be parallel to the shear vector while lowering the imbrication angle during successive shear increments. For simplicity, in the interpretation of AMS stereoplots, shearing is illustrated by the rotation of K_1. Dike segmentation and offsetting take place in host rocks that are homogeneous in strength and where no heterogeneities, such as bedding and faults, affect the observed segmentation pattern.

5.1. Flow parallel to shear: TC-05 (N 28°18.281′, W 16°48.773′)

This dike is segmented and strikes NW–SE, corresponding to the Teno Bajo Rift in the Teno massif (Walter and Schmincke, 2002). It is 40 cm thick, aphyric and aphanitic and shows oblate and prolate vesicles filled with secondary carbonate. The segments are overlapping and curving towards each other, indicating segment interaction (Pollard, 1973; Bussel, 1989). A portion of the segments and the segment tips were exposed on an inclined road-cut at the sampling site (Fig.5a). The shear vector of the stress resolved on the dike plane and magma flow are unknown and, due to exposure restrictions, only the lower segment could be sampled. We obtained 8 cores from opposite dike margins that were studied for their AMS.

The magnetic fabric of TC-05 is asymmetric, with K_1 of the western margin plunging shallowly to the SE and showing an imbrication angle of 5° to the mean dike plane while K_1 of the eastern margin plunges shallowly to the ESE and shows an imbrication angle of 20° to the mean dike plane (Fig. 5b). The anisotropy degree shows similar values on both margins while the shape parameter indicates that the magnetic ellipsoid is more oblate in the western margin than in the eastern one (Fig. 5c). When magma flow is parallel to shear, Correa-Gomes et al. (2001) predicted that fabric ellipses of the margin, where the resolved shear and magma flow are in opposite senses, are less imbricated and more flattened than fabric ellipses of the margin, where flow and shear are in the same sense. In such a scenario, magma flow can be determined by the orientation of the less imbricated and more flattened fabric ellipses (Fig. 5b: K_1 of the western margin) and sense of shear by the rotation of fabric ellipses on both margins (Fig. 5b: sinistral). By comparing the magnetic fabric of TC-05 with the models by Correa-Gomes et al. (2001), we interpret that magma flow was downward to the SE and that the shear was sinistral and parallel to this flow.

5.2. Flow perpendicular to shear

5.2.1. TD-10 (N 28°18.787′, W 16°50.751′)

This dike is 40 cm thick, shows a few pyroxene phenocrysts in a mafic groundmass and trends N–S, corresponding to the Masca Rift in the Teno massif (Walter and Schmincke, 2002). In plan view the dike shows an en echelon arrangement with subvertical steps and visible tips of dike segments (Fig. 6a). Offsetting of steps mainly results from the dike curvature but some steps show a brittle displacement of the dike walls (Fig. 6a). Many steps are attenuated downward (Fig. 6b), indicating that the resolved shear attenuated downward too. Subvertical steps and downward offset attenuation indicate a subvertical and upward directed dike propagation (Pollard, 1987). Although the vector of shear resolved on the dike plane is unknown the en echelon arrangement in plan view suggests that a significant subhorizontal and dextral shear was responsible for the observed segmentation pattern (Fig. 6a). Hence, a mixed mode I, III of propagation is suggested, in which dike propagation is subvertical and upward and the shear on the dike is subhorizontal. The occurrence of ductile and brittle offsets along the dike suggests that shearing persisted up to the cooling of the magma.

Thirty-three cores were drilled on both dike margins and magnetic fabric data on opposite margins at mirror sampling sites were plotted. The maximum susceptibility axes (K_1) are not characterised by a significant asymmetry nor by any imbrication, but instead they show a tendency to cluster in the central part of the diagram indicating subvertical flow (Fig. 6c). The degree of anisotropy shows similar values for

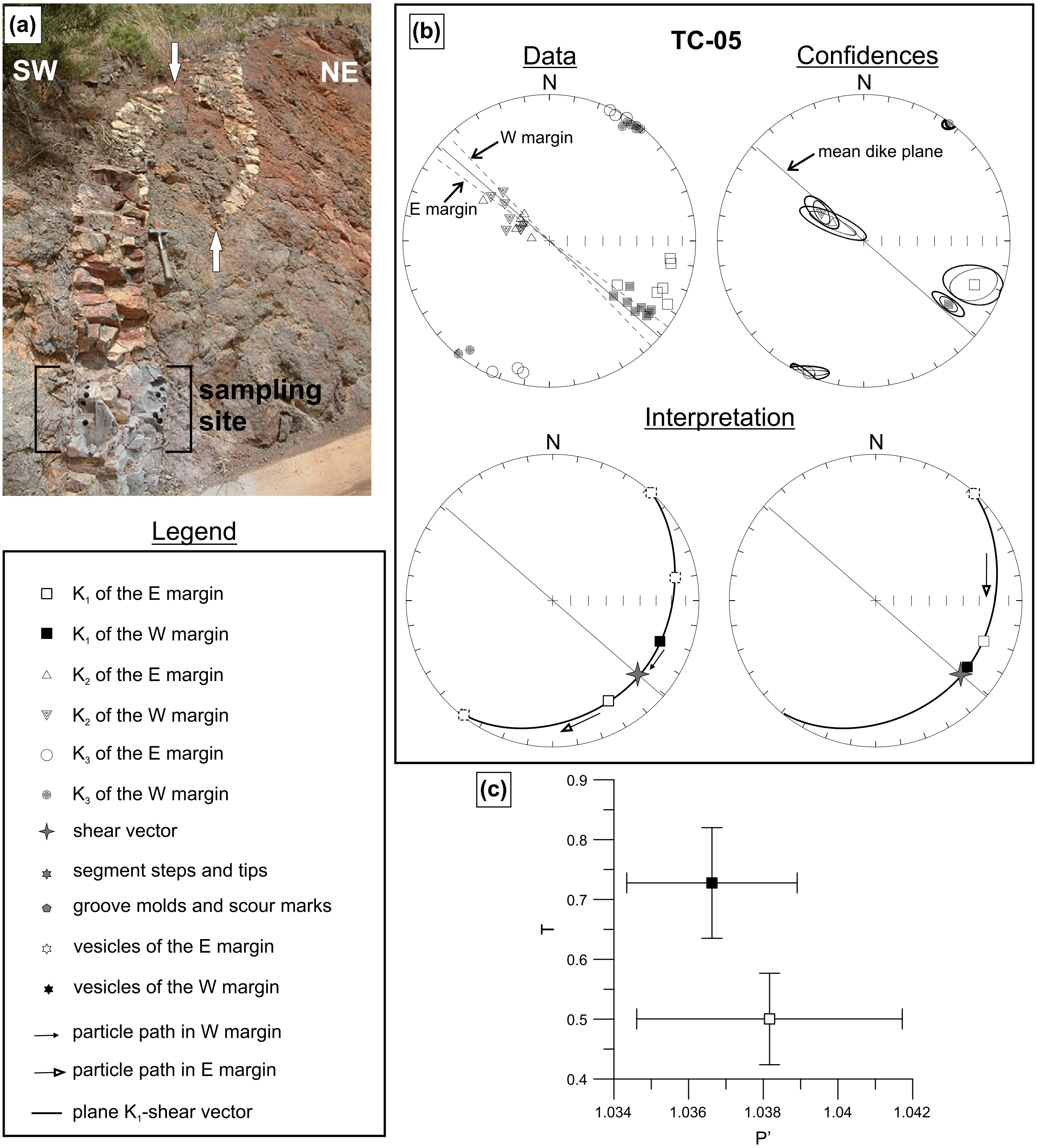

Fig. 5. Dike interpreted to have been intruded under a shear stress that is parallel to magma flow (see text for discussion). (a) Photograph of an inclined outcrop showing two overlapped segments of dike TC-05 and the sampling site. (b) Magnetic susceptibility data and confidences, and interpretation based on the shear stress resolved on the dike walls during intrusion. The interpretation is illustrated in two steps to show the evolution of the maximum susceptibility axes during shearing. (c) P′ vs. T diagram for dike TC-05. Legend is also for the subsequent figures in this paper.

both margins and the shape parameter indicates a triaxial magnetic ellipsoid, slightly oblate for the western margin (Fig. 6d). Dike propagation is upward directed and vertical, and magma flow is subvertical as indicated by magnetic fabrics. Given the agreement between dike propagation and magma flow we accept an upward sense of magma flow. Hence, TD-10 provides an example of a vertical dike within which magma flowed upward and perpendicular to a dextral and subhorizontal shear resolved during intrusion.

5.2.2. TE-04 (N 28°16.496′, W 16°51.104′)

This dike, a part of a multiple intrusion, is segmented and trends N–S parallel to the Masca Rift zone in the Teno massif (Walter and Schmincke, 2002). It is 175 cm thick and contains a few olivine and pyroxene phenocrysts in a mafic groundmass. Along the marine cliffs and deep canyons that dissect the Teno massif most of the dikes of the Masca Rift show an en echelon arrangement, indicating the presence of shear stress resolved on the dike planes at the time of intrusion. TE-04 is well exposed in

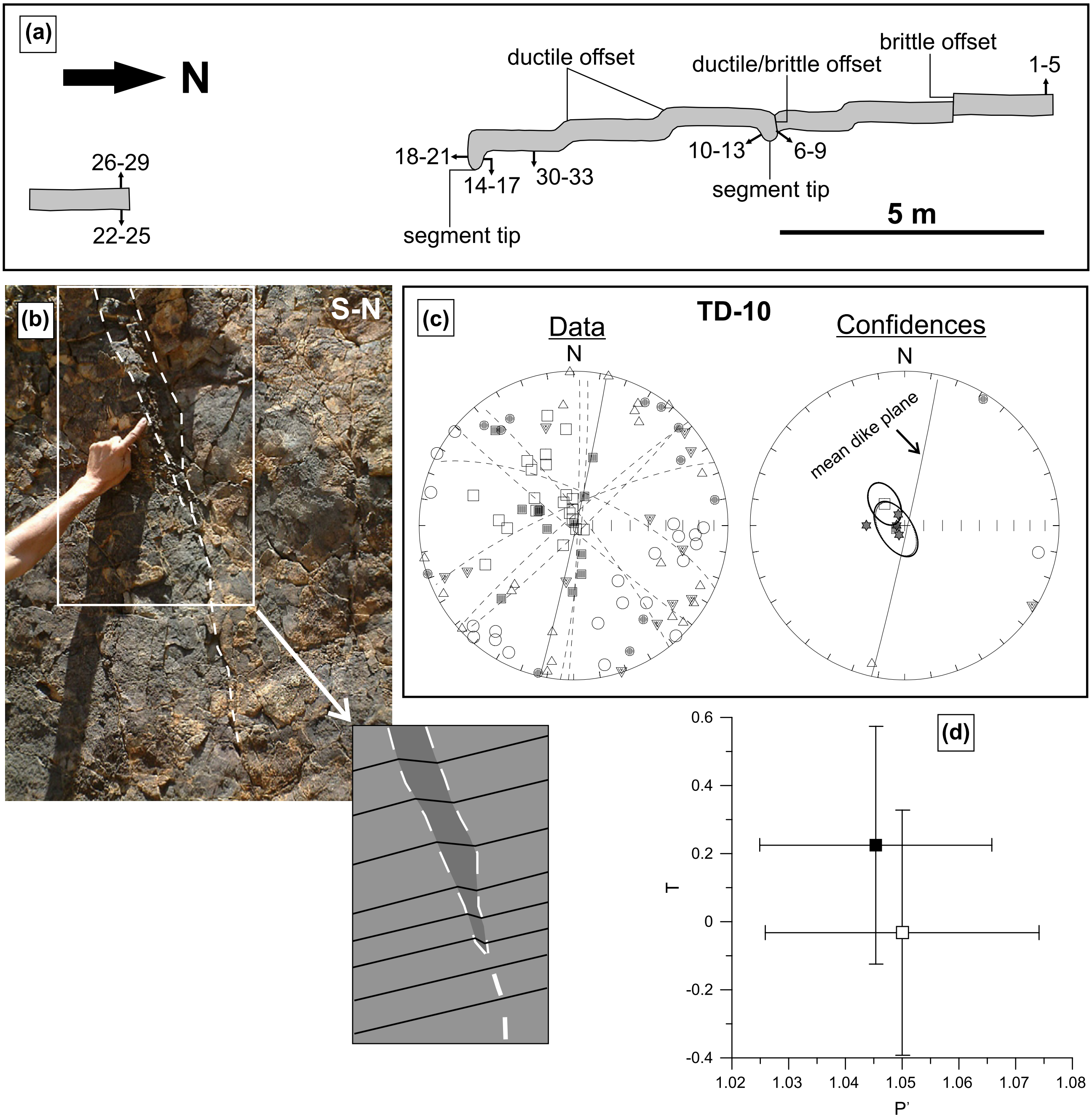

Fig. 6. Example of a dike intruded under a shear stress that is perpendicular to magma flow. (a) Sketch showing the geometry of dike TD-10 in plan view and the sampling procedure. (b) Detail of the eastern wall of TD-10 showing a ductile offset that attenuates downward and indicates that the shear resolved on the dike walls attenuates downward. (c) AMS data, confidences, and segment tips and steps of TD-10. (d) P′ vs. T diagram for dike TD-10. See Fig. 5 for legend.

three dimensions at the sampling site (Fig. 7a), and the apparent shear sense in both nearly vertical and horizontal exposures is dextral and consistent with the shear observed in en echelon dikes of the Masca Rift zone. Thus, the slip vector that acted on the dike walls during intrusion must have plunged to the SSW. The external surfaces of the dike walls show scour marks plunging shallowly to the NNE while groove moulds merge and plunge shallowly to the SSW (Fig. 7a). These flow indicators suggest that the direction of magma flow on the external walls was close to subhorizontal and SSW-directed (e.g. Baer, 1987).

Twelve cores were drilled on the opposite margins of one segment. The anisotropy degree is slightly higher for the eastern margin while the shape parameter is oblate in both margins but with higher values for the western margin (Fig. 7b). The magnetic fabric is asymmetric and ‘‘scissored’’ (Tauxe et al., 1998), with K_1 of the western margin plunging to the N and K_1 of the eastern margin plunging to the S (Fig. 7d). K_1 of individual cores on the western margin are gradually steeper towards the SSW and the difference in inclination of K_1 between the northern and southern cores is about 45°. We assume that

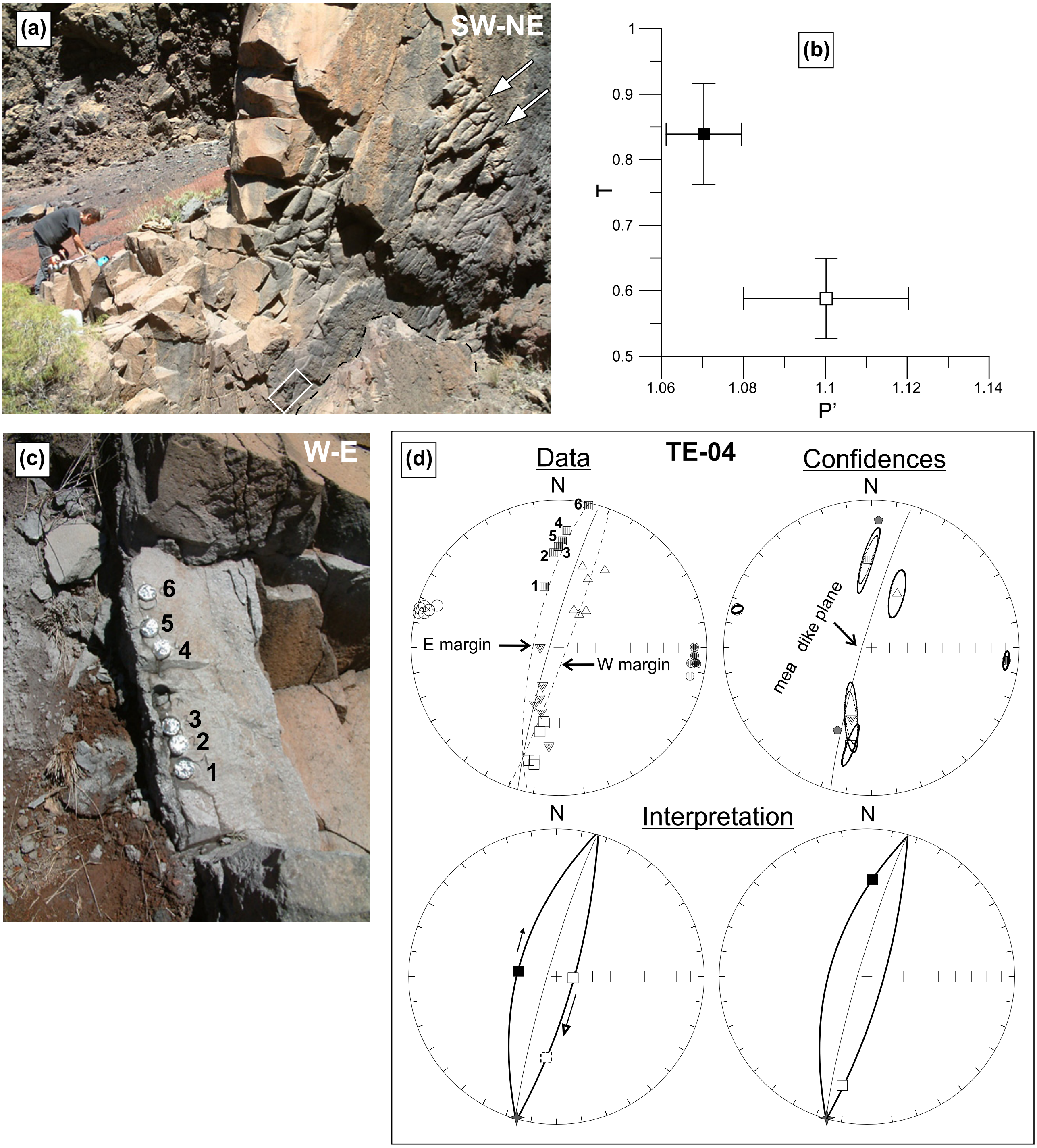

Fig. 7. Dike intruded under a shear stress that is perpendicular to magma flow. (a) Photograph of TE-4 showing the sampling site on both dike margins (geologist stands on the western margin, and white box indicates sampling site on the eastern margin) and groove moulds on the external surface of the eastern dike wall (white arrows). (b) P′ vs. T diagram for dike TE-4. (c) Photograph showing the sampling site on the western margin. Numbers on each sample correspond to the numbers on the stereoplot of AMS data. (d) AMS data and confidences, and two-steps interpretation according the shear stress resolved on the dike walls during intrusion. See text for discussion and Fig. 5 for legend.

the shear resolved on the dike plane has the same orientation and magnitude within the short distance (30 cm) that separates the northern and southern cores of the western margin (Fig. 7c) and that the difference in the plunges of K_1 reflects a different orientation of the magma flow. Bearing in mind a SSW-directed sense of magma flow on the external dike walls as indicated by groove moulds, the orientation of K_1 on the western margin suggests upward-directed and progressively steepening magma flow towards the SSW. Taking into account the orientation of the shear vector and of the magma flow as indicated by K_1, the simplest scenario for the interpretation of a ‘‘scissored’’ fabric like that of TE-04 is a roughly vertical, upward magma flow, the resolved shear being normal to it, dextral and subhorizontal (Fig. 7d).

5.3. Flow oblique to shear: AA-2 (N 28°30.776′, W 16°10.939′)

This dike trends NW–SE, perpendicular to the main rift zone of the Anaga massif that trends NE–SW (Walter et al., 2005). The dike is 150 cm thick and contains minor mafic cumulates and pyroxene phenocrysts in a mafic groundmass. Two overlapped segments of the dike are exposed in a nearly vertical road-cut and on the upper topographic surface that dips shallowly to the SE (Fig. 8a). The upper segment shows a step that is consistent with the apparent dextral shear observed on the road-cut, suggesting that the predominant sense of shear on the dike walls is indeed dextral. Based on the orientation of the exposure surfaces we deduce that the shear vector plunges to the SE. Thirteen cores were collected on opposite margins of the lower segment (AA-2 ''lower'') and 10 cores obtained on opposite margins of the upper one (AA-2 ''upper''). The cores were drilled at a distance of 10 cm from the dike walls, while the orientation of prolate vesicles was directly measured at a distance of 20 cm from the dike walls.

The magnetic and vesicle fabric of AA-2 ''lower'' is asymmetric, the anisotropy degree and shape parameter show similar values on both margins and the ellipsoid is prolate (Fig. 8c). Vesicles on the eastern margin plunge shallowly to the S and show an imbrication angle of 30° with respect to the dike wall, while vesicles on the western margin plunge shallowly to the SE and show an imbrication angle of less than 10° (Fig. 8b). This vesicle asymmetry is consistent with the dextral predominant shear resolved on the dike walls. Magma flow, as deduced from vesicle imbrication, plunges shallowly and is directed to the SE and, based on the theoretical models of Fig. 4, the shear vector would be subparallel to this flow direction. K_1 on the western margin plunges steeply to the SW and lies on the dike plane while K_1 on the eastern

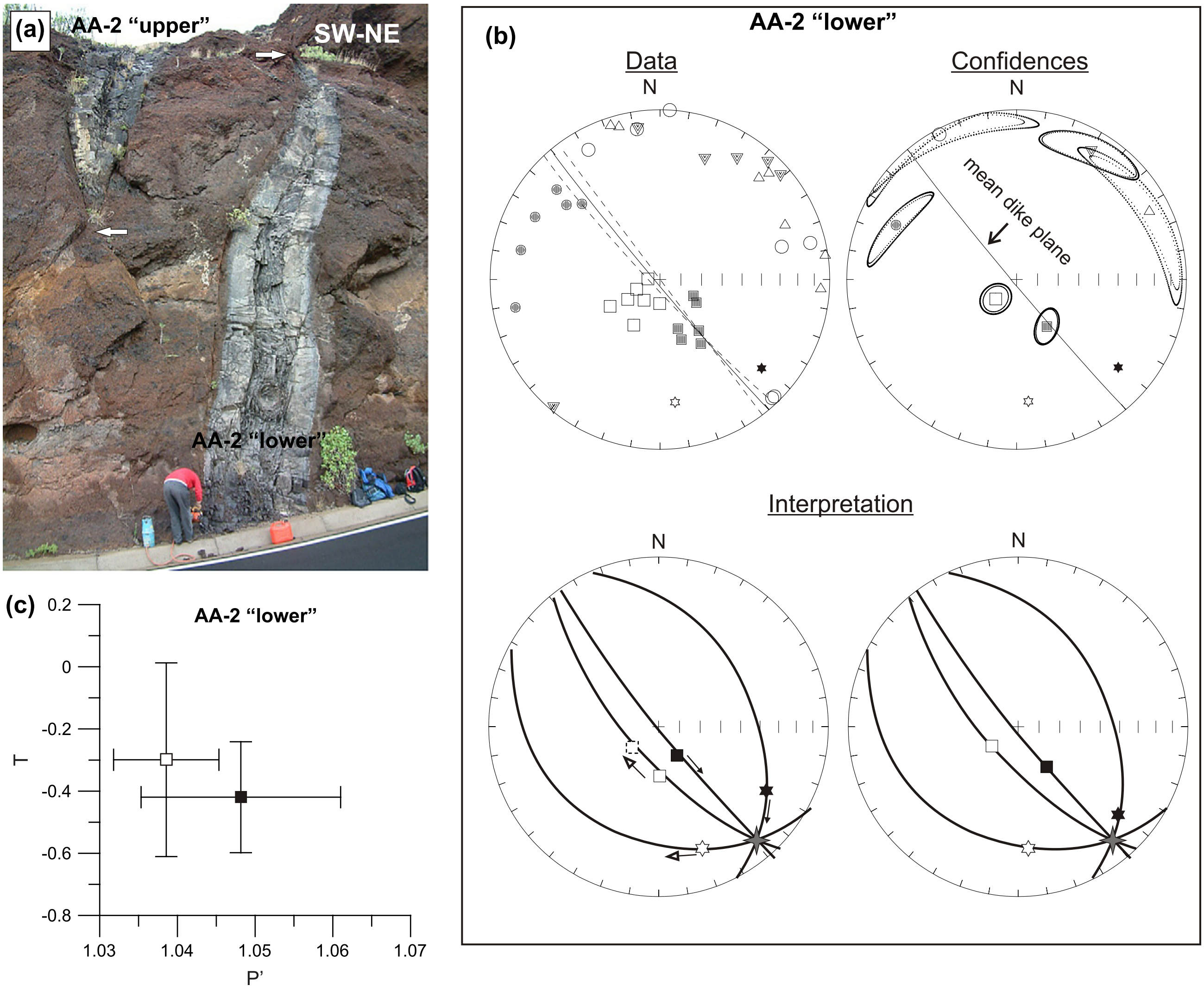

Fig. 8. Example of a dike intruded under a shear stress that is oblique to magma flow. (a) Photograph showing two overlapped segments of dike AA-2 in vertical road-cut and the sampling site at the lower segment (geologist is sampling the western margin). (b) AMS and vesicle data, confidences, and two-steps interpretation (see text for discussion and Fig. 5 for legend). (c) P′ vs. T diagram for the lower segment of dike AA-2 (AA-2 ''lower'').

margin is nearly vertical and shows an imbrication angle of 10° to the dike plane. Regarding imbrication to the dike plane, the asymmetry of the magnetic fabric is consistent with the asymmetry and shear inferred from vesicle distribution, while the magnetic fabric also appears to be somewhat ‘‘scissored’’ (Fig. 8b). The asymmetry of the magnetic fabric can be explained by magma flowing steeply and downwards to the SE, and the vector of dextral shear plunging shallowly to the SE. Such shear vector satisfies the asymmetric distribution shown by both vesicle and magnetic fabrics, and the difference in the inclination of magma flow is probably recording an ‘‘across’’ dike variation in the orientation of magma flow (vesicles were measured at a distance of 20 cm from the dike wall while AMS cores were drilled within 10 cm from the dike wall).

AA-2 ‘‘upper’’ shows prolate vesicles on the western margin plunging shallowly to the W with an imbrication angle of 34°, while those on the eastern margin are horizontal with an imbrication angle of less than 10° (Fig. 9b). The anisotropy degree shows similar values for both margins while the shape parameter indicates a triaxial ellipsoid for the western margin and an oblate ellipsoid for the eastern one (Fig. 9b). K_1 in both margins are subvertical and clustered on the dike plane with no significant asymmetry and imbrication to the dike walls. The imbrication shown by vesicles indicates a subhorizontal flow towards the SE, while their asymmetry suggests a subhorizontal sinistral shear resolved on the dike plane during intrusion (Fig. 9b). This sense of shear is opposite to that deduced for both vesicle and magnetic fabrics at AA-2 ‘‘lower’’ and to the dextral sense of shear inferred from dike segmentation and offsetting.

6. Discussion

6.1. Factors perturbing the expected dike fabrics under shear stress

The initial conditions assumed in the theoretical model of Section 3 and in the interpretation of the studied dikes are mirror imbrication of K_1 with a given imbrication angle to the dike walls (10° to 30°). Shear stress resolved on the dike walls modifies the distribution and imbrication angle of K_1 (Fig. 4). However, such initial conditions (symmetry, imbrication) may not always be satisfied. Dikes may show an initial imbrication

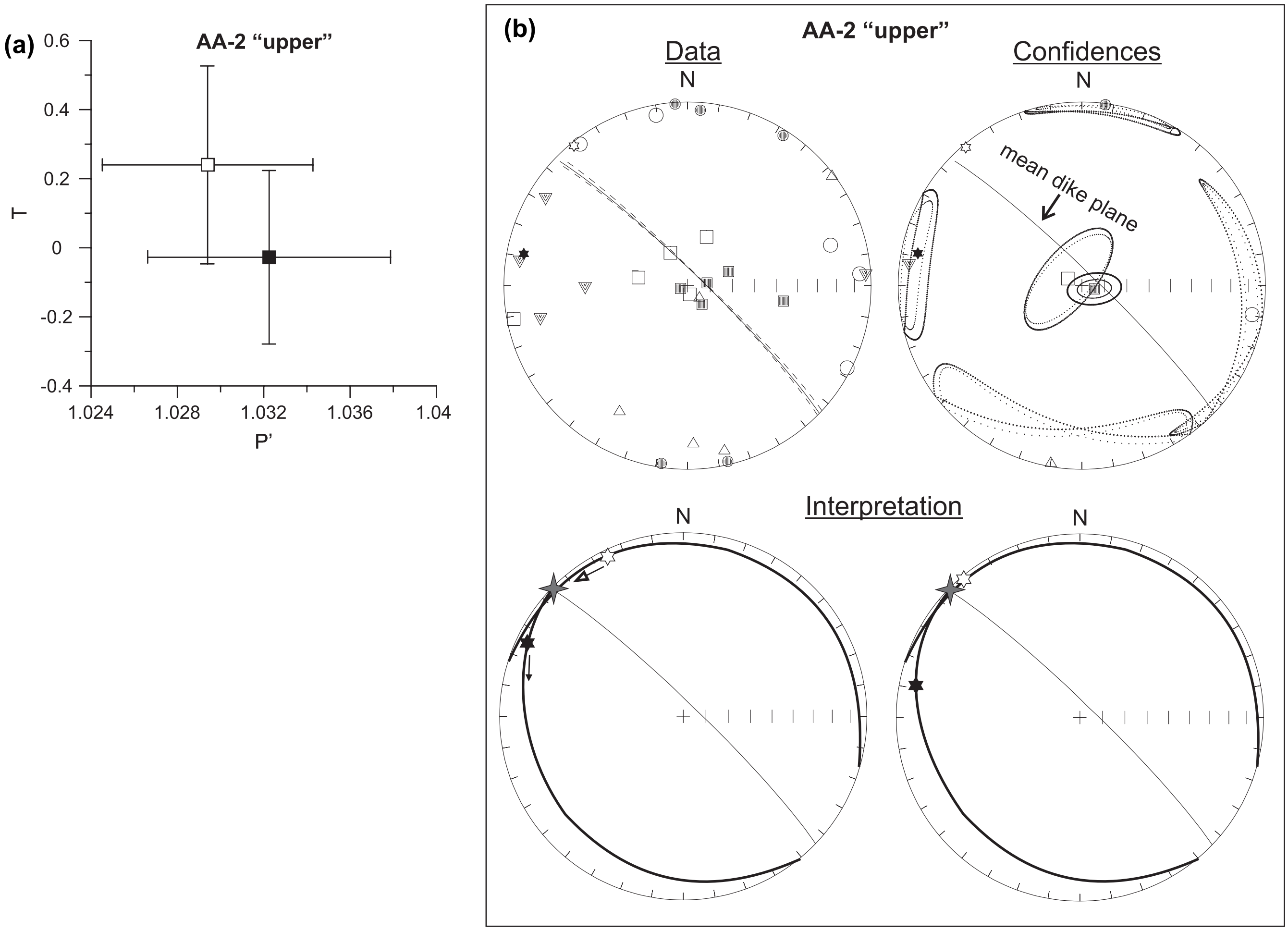

Fig. 9. (a) P′ vs. T diagram for the upper segment of dike AA-2 (AA-2 ‘‘upper’’). (b) AMS and vesicle data, confidences, and two-steps interpretation. See text for discussion and Fig. 5 for legend.

angle close to 0° on one or both margins, and may also show an initial asymmetry related not to an imposed shear but to different orientations of the magma flow (Fig. 7c and d). In addition, dikes may not show any clear AMS asymmetry despite showing clear evidence (offsetting and segmentation) of shear resolved on the dike plane during intrusion (Fig. 6). Such deviations from the initial assumptions and the influence of parameters like magma flow rate, cooling rate, host rock strength and shear rate may affect the final resulting fabrics, complicating their interpretation.

For example, TD-10 and TC-05 are two dikes of similar basaltic composition, thickness (40 cm), and host-rock lithology (basaltic pyroclastic rocks). The magnetic fabric of TD-10 is not asymmetric and K_1 on both margins lie on the dike plane with no significant imbrication. However, there is clear evidence that shear acted on the dike walls causing en echelon segmentation, and that this shear persisted after magma solidification (Fig. 6). On the contrary, the magnetic fabric of TC-05 is asymmetric and K_1 of each margin is imbricated with respect to its dike wall (Fig. 5). Segments of TC-05 show larger offsetting and overlapping than those of TD-10 (Figs. 5 and 6). Given the similar composition, thickness and host-rock lithology, the cooling rates and host rock strength can be assumed to be similar for both dikes. Their relative magma flow rates are unknown and larger offsetting and overlapping of TC-5 suggest that the shear rate undergone by this dyke was higher than that of TD-10. A "weak" shear may not be recorded by the magnetic fabric (Féménias et al., 2004). Hence, we suggest that a low shear rate in combination with a relatively fast cooling rate were responsible for the absence of imbrication and magnetic fabric asymmetry of TD-10.

6.2. Estimation of angular shear by the asymmetry of AMS and vesicle fabrics

We estimate the amount of shear resolved on the dike plane during magma emplacement and before solidification by rotating K_1 and the maximum axis of prolate vesicles back to the position of the initial conditions (symmetry and imbrication). This is a minimum estimate of the total shear since magnetic and vesicle fabrics can continue to develop during deformation, changing their shapes and anisotropy degrees, after the imposed shear has rotated K_1 and the maximum axis of vesicles into parallelism with the shear vector and 0° imbrication angles.

For example, the shear undergone by TC-5 expressed as angular shear is about 160°. This is the rotation undergone by K_1 of the eastern margin from its initial position indicating downward flow directed to the SE to the final position in the AMS stereoplot (Fig. 5b). Similarly, the angular shear for TE-4 is about 55° which is the rotation undergone by K_1 on both margins from their initial position, indicating vertical upward flow to the final position in the AMS stereoplot (Fig. 7d). The angular shear estimated for AA-2 "lower" ranges between 10° and 15° after rotating vesicles and K_1 back to their initial position in the stereoplot (Fig. 8b).

7. Conclusions

Dikes propagating under an ambient stress in a homogeneous medium may undergo en echelon segmentation, offsetting and dike curvature, indicating that shear stress was resolved on the dike walls during intrusion.

Following the work by Correa-Gomes et al. (2001), we have developed theoretical models that allow predicting the rotation of the maximum susceptibility axis (K_1) of AMS fabrics for three different geometric relationships between the resolved shear stress and magma flow: (a) the shear stress vector is parallel to the magma flow direction; (b) shear stress is perpendicular to magma flow; and (c) shear stress is oblique to magma flow. In these models, K_1 rotates according to the resolved shear along the plane containing the shear vector and K_1. Under successive shear increments, K_1 decreases the imbrication angle to the dike walls while rotates into parallelism with the shear vector.

Hence, the asymmetric vesicle and magnetic fabrics of dikes intruded under shear stress can be interpreted in terms of the shear resolved on the dike walls during intrusion. We emphasize that some initial conditions should be satisfied (symmetry, imbrication) and indicators of magma flow, dike propagation, shear direction and sense should be collected in the field. In this way, asymmetric fabrics may be used to infer the direction and sense of the shear vector and magma flow. By rotating asymmetric fabrics back to their "unsheared state", minimum values of the angular shear resolved on the dike walls during intrusion can be estimated. The interpretations of magnetic and vesicle fabrics and estimation of the angular shear for dikes of rift zones in Tenerife show a reasonable agreement with the theoretical models for AMS fabrics.

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