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Magnetic fabric and flow direction in basaltic Pahoehoe lava of Xitle Volcano, Mexico

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Abstract

We sampled five basaltic lava flow-units from Xitle volcano, Mexico City, to study the variation of anisotropy of magnetic susceptibility within their cooling boundaries. We find that the mean maximum susceptibility parallels the geologically-inferred flow direction in the units that were emplaced on a steeper slope, whereas for those on a negligible slope the mean intermediate susceptibility points in the flow direction. We propose, however, that the maximum susceptibility always points in the direction of local movement, and that a change in slope produces a deviation of the local motion from that of the unit as a whole. The axis of susceptibility closest to the geologically-inferred flow direction usually plunges upflow in the basal part of the flow unit, comprising an imbrication which clearly marks the flow azimuth of the lava. Thus, the scenario of emplacement may influence the results in a predictable way. We suggest that the degree of anisotropy could bear a direct relationship to either the viscosity of the lava, the morphology of the flows or both, based on a comparison with lavas from Azufre (Argentina) and Ko'olau (O'ahu) volcanoes. Also, we suggest that the shape of the susceptibility ellipsoid may be related to the degree of internal deformation of the lava flows. We also compare the two methods currently available to calculate regions of confidence around the mean principal susceptibilities.

1. Introduction

Xitle is the youngest (2400 BP; Libby, 1951) and only basaltic volcano in the Chichinautzin monogenetic volcanic field (Gunn and Mooser, 1970; Martin del Pozzo, 1982); it is located on the southern edge of Mexico City and human settlements now cover large parts of the erupted lavas. Extensive quarrying of this rock, however, has produced many excellent outcrops which provide easily accessible cross sections of the lava flows.

The Xitle lava preserved in and near the National University of Mexico (UNAM) campus is a compound pahoehoe flow made of a great number of lava flow units that range in thickness from 0.2 to 13.0 m. We sampled two flow units in 1992 as part of a pilot study of the variation of magnetic properties, including magnetic fabric, and due to the encouraging results (Cañón-Tapia et al., 1993), sampled three more units in 1993.

In this paper we discuss the results of our measurements of anisotropy of magnetic susceptibility (AMS) and its correlation with structural features (e.g., thickness and vesicle-deformation fabric) of the flow units as well as the application of this rock-magnetic technique to determining the flow direction; studies of other magnetic properties will be reported elsewhere.

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2. Field and laboratory techniques

The locations of the sampling sites are shown in Fig. 1. In all cases, we collected samples from the topmost unit so as to avoid possible effects of reheating by overlying lava. Moreover, at site 9 the sampled unit rests on a paleosol and is the only unit present.

Of the five sampled profiles, three (profiles 2, 9 and 6) extend from top to bottom of flow units 8.2 m, 4.7 m and 1.6 m thick, respectively; one (profile 22) includes only the lower 1.1 m of a 6.0-m-thick unit; and one other (profile 1) embraces the top 5.5 m of the flow and consists of the tilted crust of a tumulus on a unit of unknown thickness (Fig. 2). The angle of rotation of different parts of the last profile was inferred from the flat top crust and the vesicle foliation that are clearly observed in the field; the axis of rotation was assumed to coincide with the geologically-inferred flow direction, and in the following only the structurally corrected results are discussed.

All flow units are highly vesicular in their upper third and almost non-vesicular in their lower two thirds apart from a vesicular layer containing pipe vesicles in the basal 0.5 to 1.0 m (Walker, 1995a). The plunge direction of these pipe vesicles, the orientation of ropy structure on the surface crust of the units, the elongation

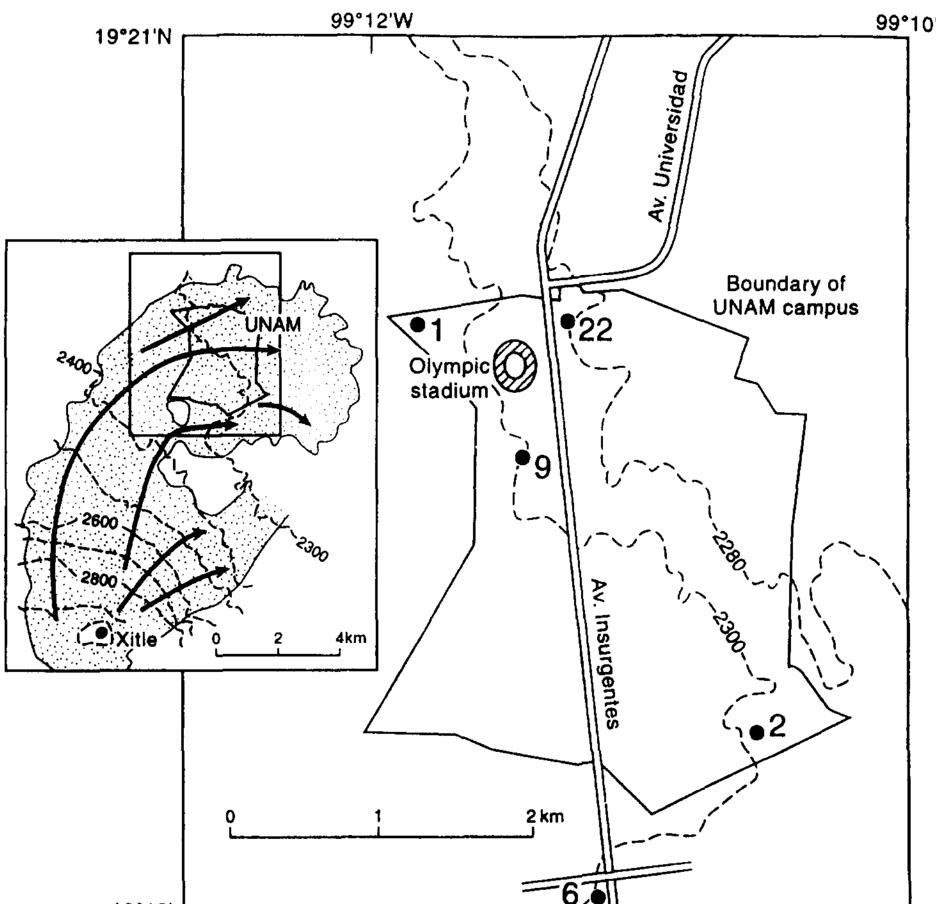

Fig. 1. Location of the sampled profiles in the Universidad Nacional Autonoma de México (UNAM) campus and its vicinity. Dashed lines-contours, elevation in meters. Inset: UNAM campus in relation to Xitle lava flow field. Arrows give the lava flow direction inferred from geological features.

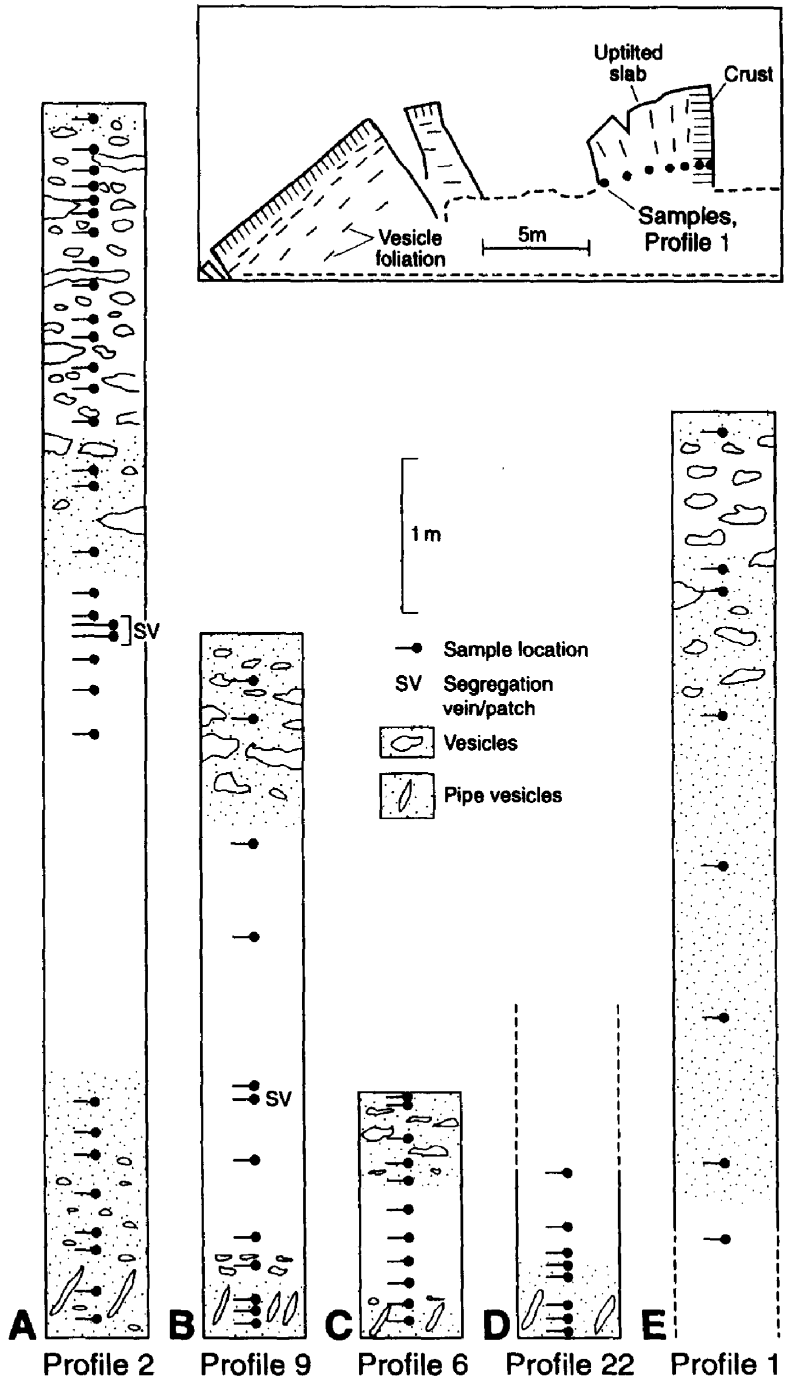

Fig. 2. Profiles of the five lava flow units sampled, showing sample locations in relation to vesicle zonation and other features. Inset: cross section of the tilted block (tumulus) from which the profile 1 samples were collected.

direction of the flow lobes, and the slope of the terrain were combined to infer the overall flow direction of each unit. We refer to this direction as the geologically inferred flow direction. Minor segregation veins up to 5 cm thick, slightly coarser and more vesicular than the lava they cut, occur near the median plane of each unit and some were sampled. The segregation veins indicate lava that remained liquid after solidification of most parts of the unit; the bulk chemical composition of this late liquid may be slightly more differentiated than that of the flow as a whole (c.f. Kuno, 1965).

Cylindrical cores (~25 mm in diameter) were sampled using a gasoline powered drill, and were oriented by magnetic compass and clinometer before their retrieval. Each sample core was subsequently sliced into one to three specimens 25 mm long, and the AMS of all the specimens recovered was measured in the Paleomagnetism Laboratory at the University of Hawaii using a Kappabridge KLY-2 instrument.

3. Results

3.1. Bulk susceptibility

Magnetic susceptibility is the property of matter that determines its internal response to an external magnetic field. The external field interacts with the electrons of the material, deforming their orbits around the atomic nuclei and forcing the spins of the electrons to lie along the field direction if the material is para- or ferro-magnetic. This effect (called induced magnetization) depends on the intensity of the field and usually presents a directional variability (Hrouda, 1982), that is, the induced magnetization will not be the same for different orientations of the magnetic field and, in general, will not be parallel to the magnetic field. Mathematically, it is appropriate to approximate this response by a second order symmetric tensor, the susceptibility

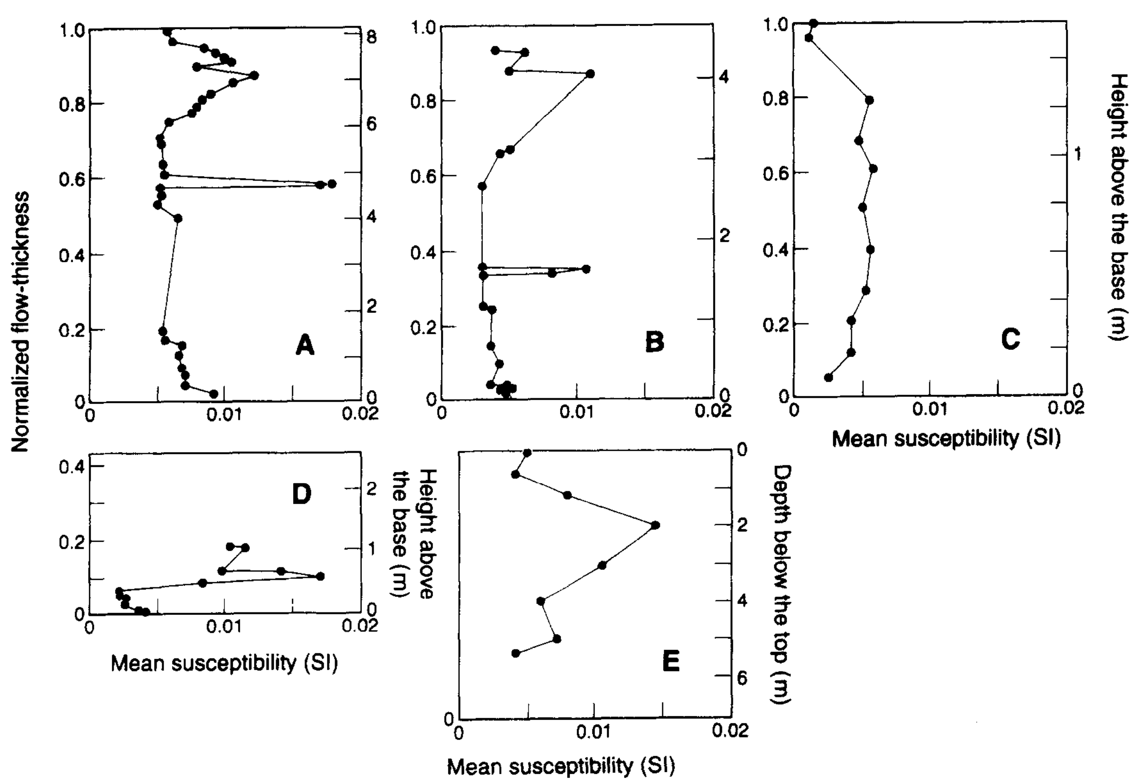

Fig. 3. Variation of bulk susceptibility within the five profiles of Xitle lavas. Total thickness of the flow used to normalize the heights shown (except in profile 1 whose total thickness is not known) is given in the right scale of each profile.

Table 1
(a) Average values of the degree of anisotropy of the five units studied. The two figures listed correspond to the A parameter of Cañón-Tapia (1992) and the P' parameter of Jelinek (1981) where $A = 100\ (1-(k_3+k_2)/2k_1))$ and $P' = (\exp\{2(p_1^2+p_2^2+p_3^2)\}$, $p_i = \ln(k_i/k_m')$ for $i = 1,2,3$ and k_m' = geometric mean of the principal susceptibilities. (b) Average values from different types of lavas, as indicated

(a)

Profile	A(%)	P'	
1	2.4	1.0018	Thick unit on moderate slope
9	1.7	1.0013	Moderate unit on shallow slope
2	1.4	1.0007	Thick unit on shallow slope
22	1.4	1.0006	Moderate unit on shallow slope
6	0.7	1.0002	Thin unit on shallow slope
Mean	1.54	1.0009	

(b)

Site	A(%)	P'	
Azufre	3.0	1.0040	8 aa flows on steep slope
XITLE	2.1	1.0013	1 aa flow on steep slope
Oahu	1.0	1.0003	3 aa flows on steep slope
OAHU	0.3	1.0000	1 pahoehoe on shallow slope

Table 2
(a) Average values of the magnetic fabric of the five units contained in this work. The two parameters used were the B parameter of Cañón-Tapia (1992) and the V parameter of Graham (1966) where $B = 100\ ((k_3-2k_2)/k_1+1))$ and $V = \sin^{-1}\{(k_2-k_3)/(k_1-k_3)\}^{1/2}$. See text for details. (b) Average magnetic fabric of other types of lavas as in Table 1

(a)

Profile	B(%)	V(°)	Flow thickness (m)
2	−1.42	64	8.2
1	−1.39	56	>5.5
9	−1.12	55	4.7
22	−1.10	59	6.0
6	−0.64	58	1.6
Mean	−1.13	58	

(b)

Site	B(%)	V(°)
Xitle (aa)	−1.43	59
Oahu (aa)	−0.41	57
Oahu (ph)	−0.04	48
Azufre (aa)	+1.35	42

tensor (Nye, 1960), which in the SI system is dimensionless.

It is always possible to find three mutually orthogonal directions in which the magnetic field and the induced magnetization are parallel (the eigenvectors of the susceptibility tensor) although the value of the susceptibility along each of these directions (the eigenvalues of the tensor, denoted by k_1, k_2 and k_3) is different; these are called principal susceptibilities and are such that they satisfy the relationship $k_1 > k_2 > k_3$ (Lienert, 1991).

Values for the bulk susceptibility (k_m) calculated as the mean of the three principal susceptibilities from the Xitle lavas average about 6×10^{-3}. This is slightly lower than the value obtained from lava flows of O'ahu ($\sim 2 \times 10^{-2}$, E. Herrero-Bervera, unpubl. data) and from the Azufre volcano in Argentina ($\sim 2 \times 10^{-2}$, Cañón-Tapia et al., 1994). Profiles 2, 1 and 22 give the highest values (between 8×10^{-3} and 7×10^{-3}) and profiles 9 and 6 give the lowest (between 5×10^{-3} and 4×10^{-3}). The difference between the largest and smallest values is very small when compared with the large variations (of several orders of magnitude) found in rocks containing very different amounts of ferromagnetic minerals, as for example some granites or metamorphic rocks (Tarling and Hrouda, 1993).

Variations of k_m within flow units are shown in Fig. 3. The peak values in the middle of profiles 9 and 2 (Figs. 3 a and b) are given by samples collected from segregation veins. Excluding these, k_m tends to increase toward the upper margin from the central parts of these units, although in a narrow zone at the top a sudden decrease takes place. In profile 6 the reverse relationship is observed.

Centeno-García et al. (1986) found similar variations in the magnetic susceptibility across the boundaries of superimposed flow units in the Xitle lavas, suggesting its possible connection with the observed degree of oxidation of the rock. Petersen (1976) pointed out that, in general, the degree of oxidation in thin flows will tend to be higher towards their upper parts, while in flows exceeding 6 m thick preferential escape of hydrogen from their central parts may produce inner zones of high oxidation. In the present case, the observed variations of k_m are compatible with the general picture given by Petersen (1976).

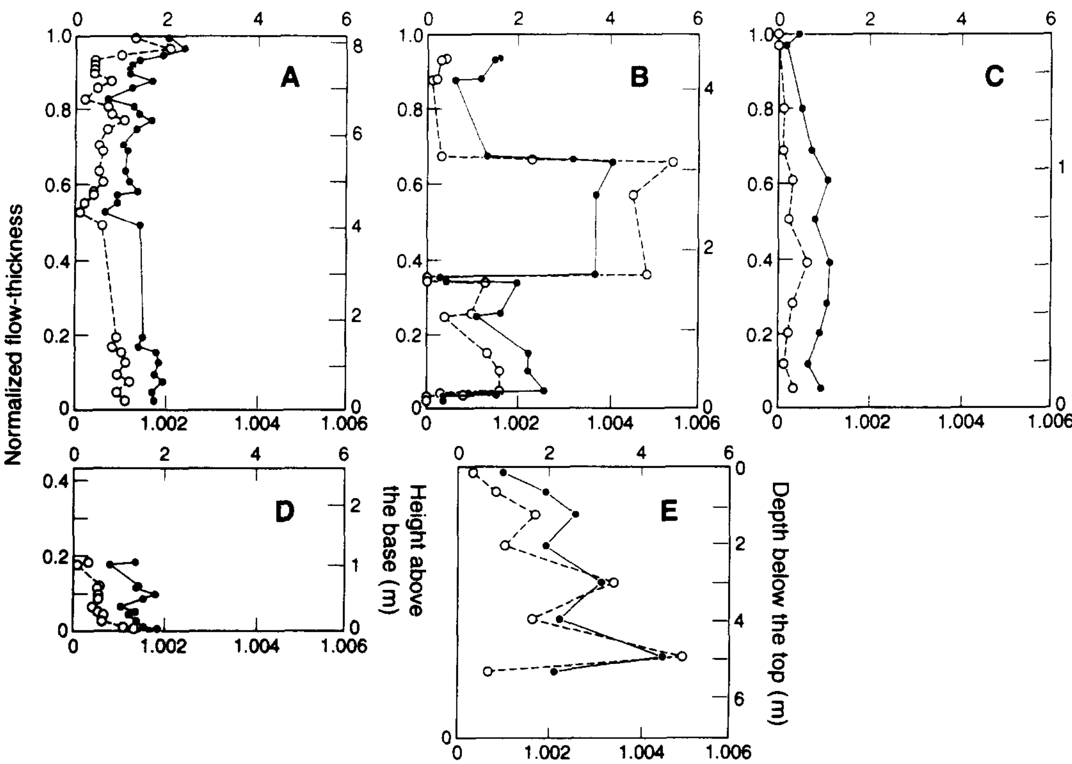

Fig. 4. Variation of the degree of anisotropy within the five profiles of Xitle lavas. See text for details. Dashed lines = P' parameter, solid lines = A parameter.

3.2. Degree of anisotropy

Magnetic susceptibility is said to be isotropic if the three principal susceptibilities are equal in magnitude, and is anisotropic in any other case. Several parameters attempting to give a quantitative estimate of the degree of anisotropy, that is, a number estimating the departure of the measurements from the isotropic case, have been proposed. We used two parameters following Cañón-Tapia (1994). These parameters are defined in Table 1 together with average values calculated for each flow unit.

Internal variations of the degree of anisotropy within single units are shown in Fig. 4. Apparently, the degree of anisotropy increases with depth in the unit, although the differences between top and bottom are rather small and may not be significant. Typical values of anisotropy are between 1% and 2%, except in the middle parts of profile 9 and the lower part of profile 1 (Figs. 4b and e) where values of 5% were obtained.

When we compare the values obtained in these flows with those from different types of lavas (Table 1b) we find that andesite lavas from Azufre give much higher values than those from Xitle or Ko'olau suggesting a possible relationship with the silica content (following MacDonald and Katsura, 1964; Gunn and Mooser, 1970; Verma and Armienta, 1985; Tormey et al., 1989) and therefore the viscosity of the lava. General differences in flow thickness (in decreasing order Azufre-Xitle–Ko'olau) seem consistent with this interpretation.

Also, from the data in Table 1 (a and b) it would appear that aa flows on average tend to yield higher values of the degree of anisotropy than pahoehoe, although further work is needed before it is possible to draw any definitive conclusion.

3.3. Magnetic fabrics

Various parameters have been proposed to quantify magnetic fabrics, or the shape of the susceptibility ten-

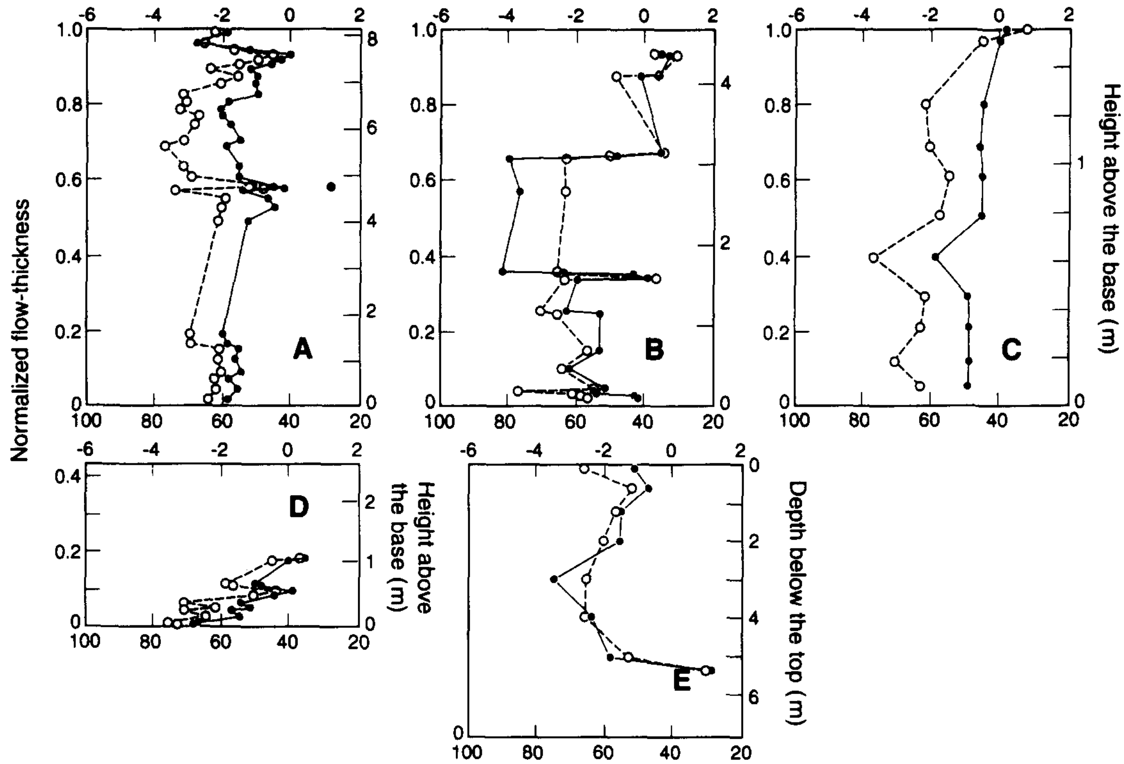

Fig. 5. Variation of the magnetic fabric in the five profiles of Xitle lavas. *B* parameter (solid lines), *V* parameter of Graham (dashed lines). Magnetic foliation increases to the left for both parameters.

sor. As discussed in Cañón-Tapia (1994), these parameters yield an estimate of the relative degree of development of a magnetic foliation and lineation. Following Cañón-Tapia (1994), we used two parameters to quantify the magnetic fabrics, as defined in Table 2. The numerical values for the cases of 'pure magnetic foliation', 'equally developed magnetic foliation and lineation' and 'pure magnetic lineation' of the *V* (*B*) parameter are 100 (−100), 45 (0) and 0 (+100), respectively. There is no one to one equivalence in the way in which each of these parameters 'measures' the magnetic fabrics, nor is there any physical basis to prefer one from the other (Cañón-Tapia, 1994), and therefore it is better to use them both.

The two parameters yield equivalent results for the two partial profiles and for profile 6, but in profiles 2 and 9 some quantitative differences are observed (Fig. 5). In profile 2, the *V* parameter indicates the presence of a unique zone with a slightly higher degree of magnetic foliation at a height fraction of between 0.8 and 0.6, while the *B* parameter indicates a relatively uniform magnetic foliation through the whole thickness of the unit. In profile 9 the *B* parameter identifies a zone of higher foliation between 0.35 and 0.65 height fraction that is not shown by the *V* parameter. The physical relevance of these differences is not clear at present, although by using the *B* parameter it was possible to design a consistent criterion that allowed the size reduction of the regions of confidence around the mean susceptibilities as explained in the next section.

On average, magnetic foliation is a little more developed in profiles 2 and 1 than in profiles 9, 22 and 6 (Table 2a, *B* parameter). Assuming that the exposed section of profile 1 is less than half of the total thickness of the flow (which is a reasonable assumption in view of the mechanism of formation of this type of tumulus as discussed by Walker, 1991, 1995b), the degree of development of the magnetic foliation would be

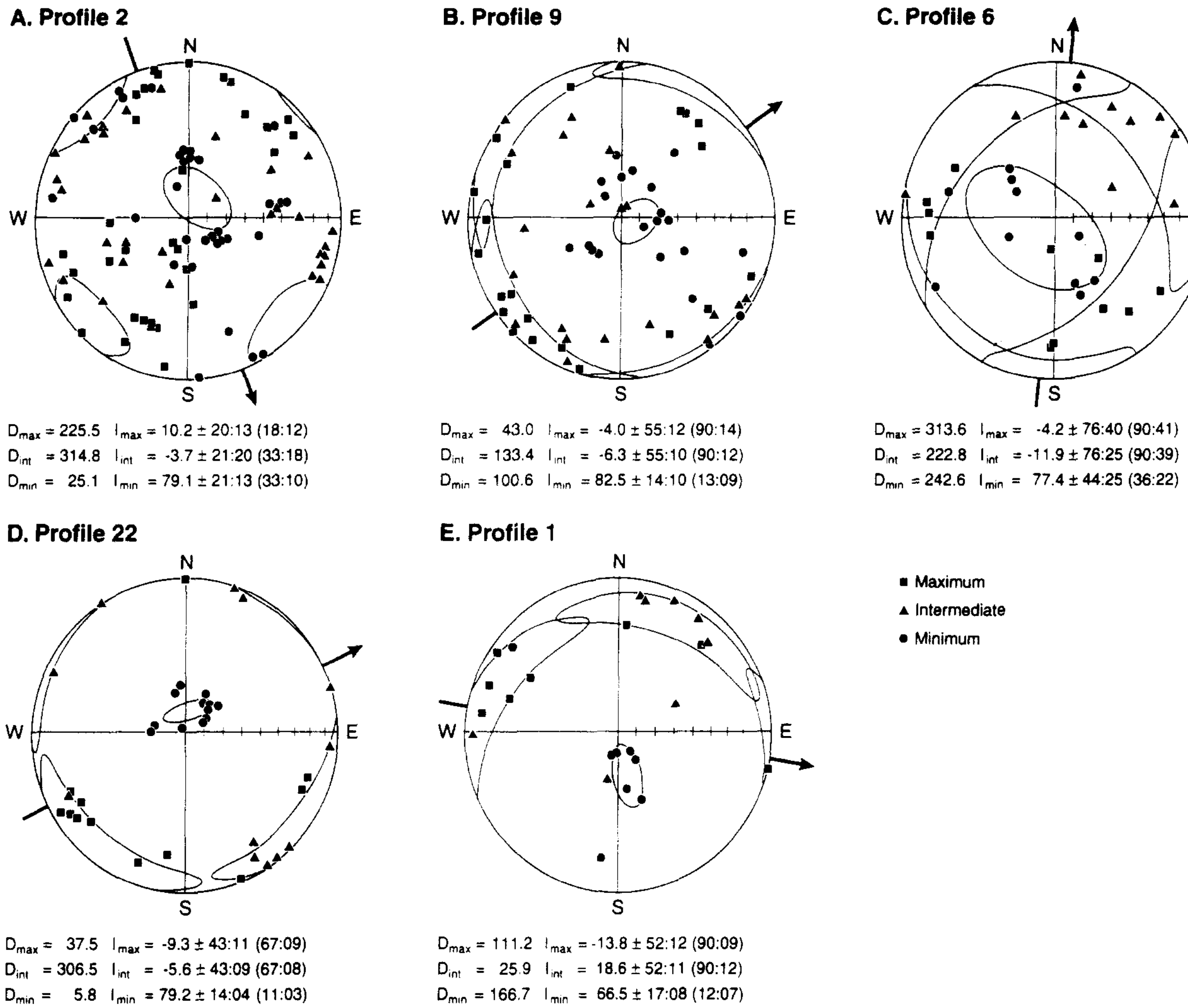

Fig. 6. Equal-area projection (lower hemisphere) of the directions of the principal susceptibilities measured on the five profiles. Geologically-inferred flow direction is given by the arrows. The regions of confidence shown are those calculated with the linear approximation of Jelinek (1978). Numbers in parentheses allow comparison with the regions of confidence obtained with the bootstrap method of Constable and Tauxe (1990).

directly related to the total thickness of the unit, which may be of great importance in the study of the internal emplacement mechanism of lava flows. For instance, it is known from a structural study (Walker, 1995b) that most of the Xitle flow units continued to thicken by endogenous growth by the "lava rise" mechanism of Walker (1991) after they were emplaced, and therefore it would follow that the thicker units are more likely to be subject to larger degrees of internal deformation or shearing. This internal deformation would conceivably affect the development of the magnetic foliation; the larger the amount of internal shearing, the better developed the magnetic foliation.

Clearly, the previous assumption is valid only for the *B* parameter and not for the *V* parameter and therefore, as there is yet no physical basis to prefer any one parameter, the conclusions drawn should be taken as a reasonable inference deserving further investigation.

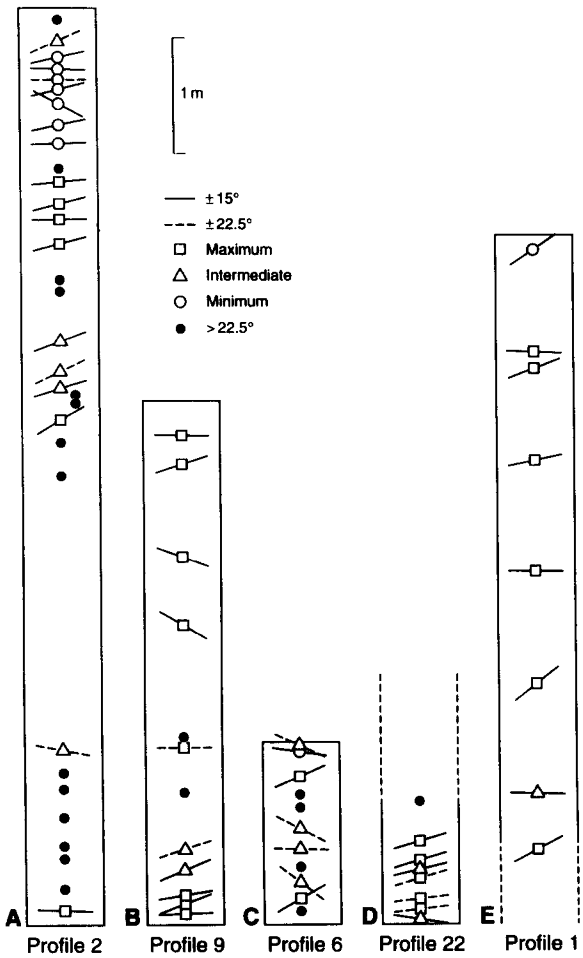

Fig. 7. Plunges of the mean principal susceptibility lying within ±22.5° of the geollogically-inferred flow direction (dashed line) or ±15° of it (solid line). The central symbol indicates whether it is the maximum (square), intermediate (triangle) or minimum (circle) mean. Solid circles are samples for which no principal susceptibility lies within 22.5° of the flow direction.

Comparison of the magnetic fabric of the pahoehoe Xitle lavas with that of lavas from other settings (Table 2b, parameter *B*; data sources as in Table 1b) would seem to indicate that larger degrees of internal deformation occur, on average, in aa than in pahoehoe units of similar composition. The average magnetic fabric of the Azufre lavas (8 flow units), markedly defines a magnetic lineation, which may be the consequence of their higher viscosity as indicated in the preceding section, for such lavas would move more like a plug presenting limited internal deformation therefore preserving a strong vesicle lineation. The data base is, however, meagre.

3.4. Directions of the principal susceptibilities

Fig. 6 consists of lower-hemisphere equal-area plots of the principal susceptibility axes for the five Xitle profiles. The apparent large scatter is similar to that found by previous studies of AMS in lava flows (Khan, 1962; Symons, 1975). By using the statistical tools provided by Hext (1963), however, and criteria proposed by Cañón-Tapia et al. (1994; see also the Appendix) to classify the size of the regions of confidence, the groupings of the principal directions (Fig. 6) range from moderate to very good in most cases. An exception is profile 6 where all the three principal susceptibilities are poorly clustered around their mean. In the other four profiles, the minimum susceptibilities are much better grouped than either maximum or intermediate susceptibilities, which usually define a girdle-like arrangement around the mean minimum. The mean direction of the minimum susceptibilities lies within 10° to 20° of the vertical. The direction of the mean maximum susceptibility of profiles 9, 22 and 1 agrees quite well with the geologically-inferred flow direction, but in profiles 2 and 6 it is the mean intermediate instead. In the former cases (Figs. 7b, 7d and 7e), most of the maximum susceptibility axes are contained within ±22.5° of the flow direction, and have an upflow plunge in the basal parts of the unit. In profiles 2 and 6, on the contrary, all the three principal susceptibilities are within 22.5° of the flow direction (Figs. 7a and 7c) almost irrespective of the position of the sample in the unit, although in profile 2 (Fig. 7a) four distinctive groupings of samples can be identified (see discussion below).

The plunge of the principal susceptibilities in profile 6 (Fig. 7c) seems to be rather random, whereas on profile 2 (Fig. 7a) an upflow plunge is clear in the upper parts of that flow-unit.

4. Discussion

4.1. AMS and flow direction

AMS measurements have proved to be reliable indicators of flow directions in pyroclastic flows (e.g., Ell-

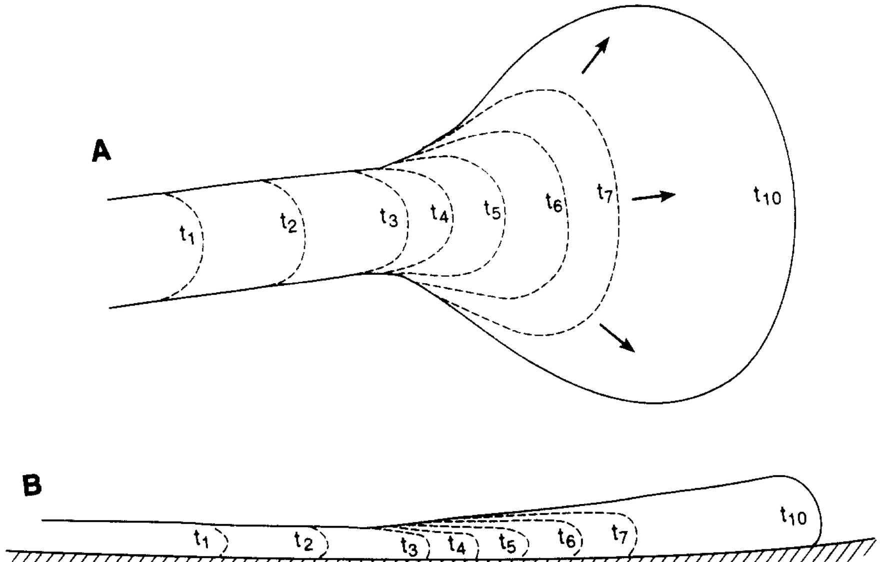

Fig. 8. Flow of lava that passes from a steeper to a shallower slope: (a) in plan view and (b) in cross section. $t_1 ... t_{10}$ indicate the position of the front at approximatly equal time intervals. Note that lava reaching the shallower slope will have significant vertical and lateral components of flow as widening and thickening occur.

wood, 1982; Knight et al., 1986) and dikes (e.g., Knight and Walker, 1988; Ernst and Baragar, 1992; Staudigel et al., 1992, Puranen et al., 1992) but some doubt has existed about their utility in lava flows. For example, Symons (1975) could not find any significant relationship between the geologically inferred flow direction of the Aiyansh flow and the mean direction of the principal susceptibilities. This may be because samples were collected only from the surface of the flow where rotation of blocks during emplacement may occur, or cooling effects could modify to some extent the original directions of AMS. Moreover, the statistical methods available at that time to calculate the mean directions of the principal susceptibilities were largely inappropriate.

More positive results were obtained by Khan (1962), who found that the mean intermediate susceptibility was roughly parallel to the flow direction of lava flows although the scatter of the main susceptibilities was large, and by Kolofikova (1976; reported by Hrouda, 1982) who found a good agreement between the direction of the maximum axis of susceptibility and the flow direction, but only in the intermediate and not in the frontal parts of the flow. MacDonald et al. (1992) also found a parallelism between the principal maximum susceptibility and lineations assumed to be produced by laminar flow of lava.

In the case of the Xitle lavas, we found that either the mean maximum or the mean intermediate susceptibilities point in the same direction as the geologically-inferred flow direction. These apparently contradictory results can be reconciled, however, by considering the way lava flows move.

The dimensions, especially the width and thickness, of lava flows are strongly controlled by the rheological properties and the slope of the preexisting terrain (e.g., Gauthier, 1973; Hulme, 1974; Baloga and Pieri, 1986; Naranjo et al., 1992). Assuming constant rheological properties along a flow, a decrease in slope results in both a widening and a thickening of the lava, to reach the new equilibrium configuration. In widening, the lava will thus be forced to change its direction of movement locally except, perhaps, close to the axis of the flow, as schematically shown in Fig. 8. Thus, in those regions away from the flow axis, the local flow direction may be nearly perpendicular to the direction of advance of the front of the lava lobe. Moreover, small variations in direction and amount of the groundslope, as well as the resistance that may be encountered by the flow at the front of the lobe due to the formation of

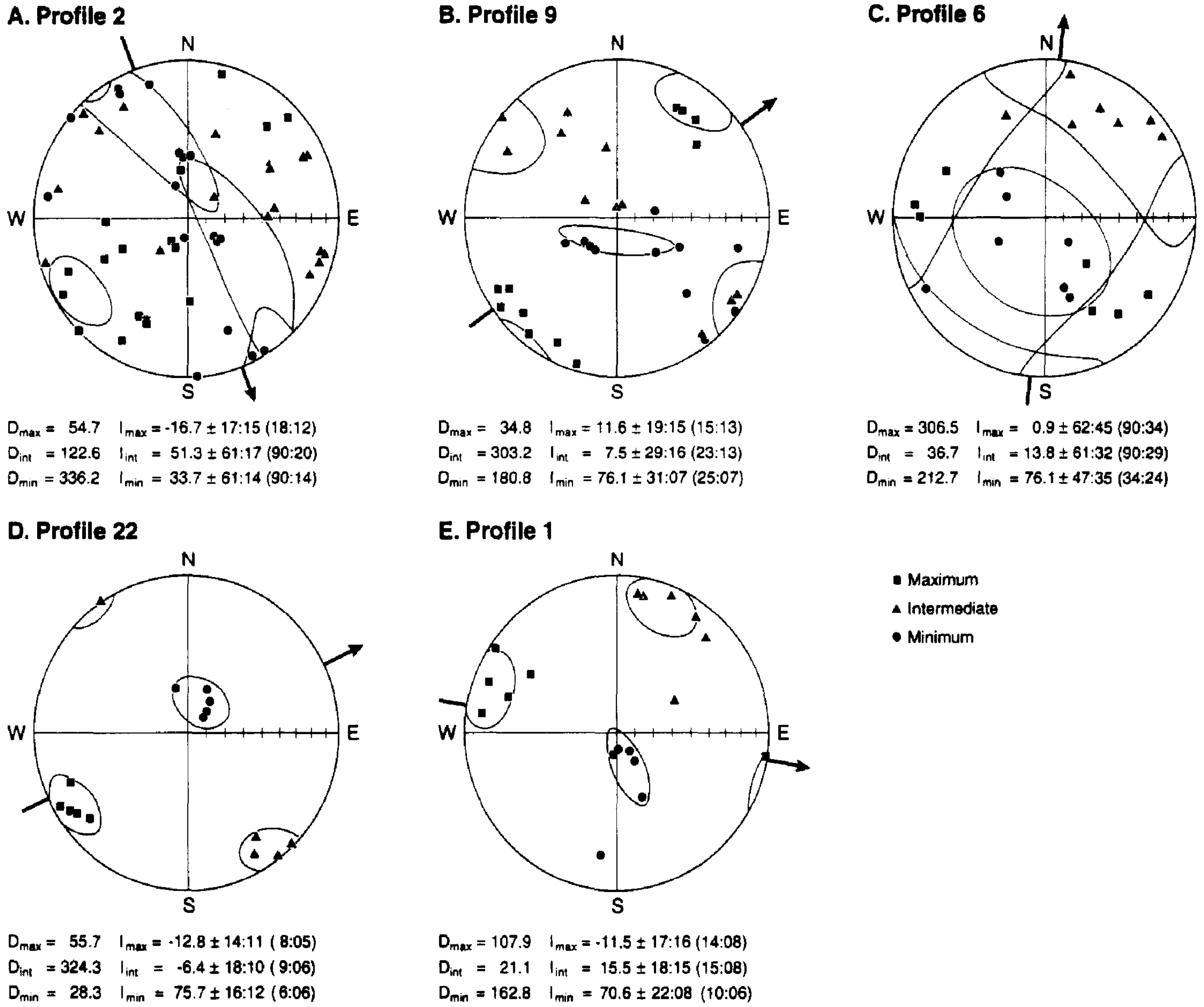

Fig. 9. Equal-area projection of the directions of the principal susceptibilities of selected samples of the five units. Symbols as in Fig. 6.

a rigid crust or the accumulation of debris, may cause subsidiary lobes to form in directions at an angle of up to 90° with the main lobe.

In our case, the present day slope of the terrain in the locations of profiles 9, 1 and 22, where the mean maximum susceptibility and the geological information were in agreement, is steeper (~4°) than that of profiles 2 and 6 (< 1°). The first three units form rather narrow lobes, and this can be interpreted as resulting from flow down a moderate paleoslope. Also, profile 9 unit rests on a paleosol, which eliminates the possible effects of the underlying flows on the topography.

We conclude that the mean maximum susceptibility points in the direction of the local movement in every case; the local movement coincides with the direction of advance of the unit as a whole only in the cases where the slope is steeper.

4.2. *Internal variation within single units*

As described above, the axes of minimum susceptibility are usually better clustered than the other two principal susceptibilities. The degree of clustering of the maximum susceptibilities was improved, however, by filtering out selected specimens from the profile. The criteria that proved to be the most useful to reduce the confidence regions around the mean maximum susceptibility were 1) to eliminate specimens having a degree of anisotropy lower than an arbitrary threshold value (different for each unit) and 2) to take out from the calculations those specimens with a particularly large degree of foliation. These criteria resulted in the removal of 25%–58% of the specimens in each profile. The remaining specimens yield the distributions shown in Fig. 9. The regions of confidence around the mean maximum and intermediate susceptibilities were most clearly reduced after filtering on profiles 9, 22, and 1 (compare Figs. 6b, 6d, and 6e with 9b, 9d and 9e).

Groups of specimens at very specific positions within the flow units defining well clustered axes of maximum susceptibility were delineated through filtering. For example, in profile 6 specimens from the upper and lower parts of the unit define two clusters that reflect a 15°–20° imbrication in opposite directions of k_1; the effects of a rotation around an axis trending in a NW–SE direction are also indicated by these two clusters, and seem to be responsible for the large dimensions of the regions of confidence around the mean values. The opposite imbrication of the k_1 axis of specimens from the upper and lower parts of the unit is most clearly observed in profile 9. Additionally, in unit 9 a third group of specimens, in which the directions of maximum susceptibilities are nearly normal to these found near the top and bottom, is defined by specimens from its central parts, namely those showing the higher degrees of development of the magnetic foliation as indicated in a previous section.

In the profile of unit 2, three groups of specimens, roughly corresponding to the upper, middle and basal parts of the unit, were identified. The k_1 directions in the upper and lower parts of the unit do not show the imbrication relationship found in the other two complete profiles, although this could be due to the high vesicularity observed in the upper section. All of the specimens from the upper part of this unit have the k_3 axis parallel to the geologically inferred flow direction. It is not clear why this should occur, although possible explanations may include 1) the exclusive presence of single domain magnetite in this region of the flow leading to an inverse magnetic fabric (Rochette, 1988), 2) distortion of the flow patterns due to turbulence or to the effect of rising bubbles, 3) deviation of flow direction in late-injected lava from the original flow direction during endogenous growth and, 4) the rotation of a rigid crustal block of lava during movement of the flow. The last possibility was suggested by the resemblance of the distribution of the AMS measurements of this group (Fig. 9b) to the results for profile 1 before introducing the structural correction (not shown). Detailed study of other magnetic properties is needed to validate the first possibility, while the other three are more difficult to evaluate.

Yet a fourth group of only four specimens located between the upper and middle parts of the flow can be identified in this unit. These specimens have a better degree of definition of the magnetic foliation than the rest of the specimens from the unit. For this reason, they are not included in Fig. 9a, although their k_1 directions are nearly parallel to the geologically inferred flow direction. Usually, a better development of a magnetic foliation may be associated with a stronger influence of shearing stresses of some sort, and therefore the presence of this fourth group of specimens may be indicating the location of a region within the unit in which internal shearing was stronger during emplacement. The possible rotation of the upper block of the unit is compatible with this interpretation.

5. Summary

Our main conclusions are:

(1) It is possible to infer the flow direction of lava flows from AMS measurements.

(2) An imbrication of the maximum axis of susceptibility in opposed directions at top and bottom may be observed very clearly in some profiles, which may constrain the azimuth of motion of lava flows, although certainly some complications may distort this behavior.

(3) Among the possible complications that may exist in the interpretation of AMS measurements the most important are: (a) the principal maximum susceptibility is more likely to be directed parallel to the direction of the local movement, which may be different from the direction of advance of a lava flow; (b) the presence of large vesicles and the possibility of significant crustal rotations may disturb the AMS initially related with the flow of lava; and (c) in very thick units it may be possible to obtain different directions of movement from different parts of the unit, especially from its central parts, which may be reflecting a change in the direction of movement of lava with time. In particular, the endogenous growth of lava flow units, by continued injection of lava under a surface crust,

and jacking up of that crust, may produce significant deviations from the initial flow direction. Xitle flow units show particularly clear evidence for this type of endogenous growth.

(4) In order to obtain significant results from lava flows, it seems necessary to collect as many samples as possible from the same unit and these should be uniformly distributed along a vertical profile that must include the base of the unit, especially in the case of thick lava flows. It also may be necessary to filter the resulting measurements.

Finally, relationships suggested by this study that require further research include:

(1) The degree of anisotropy is directly related to either the viscosity of the lava, the morphology of the flow, or both, and

(2) The magnetic fabric indicated by the susceptibility ellipsoid is directly related to the state of internal deformation suffered by lava flows during movement.

Clearly, should this relationships be confirmed, AMS would offer a unique opportunity to study the details of the formation of flow fields.

Acknowledgements

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Appendix 1

Currently, two main methods are available to characterize the statistical variability of AMS data. Jelinek (1978), used the statistics of the second order tensor (Hext, 1963), to propose a multivariate analysis technique in which the uncertainties in the determination of the mean tensor are assumed to be sufficiently small to allow their effects to be linearly superimposed. The second approach, proposed by Constable and Tauxe (1990), uses a bootstrap method to estimate the variability in the distribution of AMS measurements in which the uncertainties can not be assumed to be small. Both methods yield elliptical regions of confidence for each of the three principal susceptibilities, although their interpretation is slightly different. The regions of confidence obtained with the multivariate analysis technique delimit the area in which 95% of the most probable means are included, while those calculated by the resampling method indicate the area necessary to include 95% of all the observations. Clearly, a population of well clustered susceptibility axes will yield small regions of confidence irrespective of which method is used, but apparently scattered data (therefore having a large region of confidence according to the resampling method) may still yield statistically significant mean directions (with small regions of confidence from the multivariate method).

During the study of the AMS of Xitle lavas, we used both methods to calculate the regions of confidence around the mean susceptibilities and it was found that, in general, when all the specimens from a single unit were included in the calculation of the mean, the linear perturbation analysis produced smaller regions of confidence than the bootstrap method. However, after filtering out some specimens, the regions of confidence calculated with the resampling method became slightly smaller than those calculated using the linear approximation technique. This was especially clear in the case of very small populations. Similar results where found during the study of AMS of the Azufre volcano lavas (Cañón-Tapia et al., 1994).

The practical consequences of this are important because in populations showing an apparent large scatter it is very difficult to identify specific specimens that may be considered outliers (for example those specimens inadvertently collected near vesicles that may have distorted the flow direction very locally), and a limited number of such specimens may result in an apparently poor grouping of directions of susceptibility (and therefore a non-significant mean direction) if the regions of confidence are calculated solely by using the bootstrap method.

We suggest that both statistical methods should be used in combination whenever possible. The linear perturbation analysis seems to be more robust than the resampling method, provided the number of samples used is not very small, and it is, therefore, more advantageous to use it when the sample population is large and apparently scattered and consequently, outliers can not be easily identified. After removal of outliers, and whenever the number of samples used is very small, the resampling method seems to yield the most accurate regions of confidence.

The size of these regions of confidence can be easily quantified (Cañón-Tapia et al., 1994) by calculating their 'area' given by the product $\sin(a_1)\cdot\sin(a_2)$ where a_1 and a_2 are the angles of the ellipses of confidence. Depending on this product, the grouping of the axes (or the significance of the mean, depending on the method used as explained above) will then be considered to be excellent (<0.03), very good (<0.07), good (<0.12), moderate (<0.18), fair (<0.25) or poor (>0.25).

References

Baloga, S. and Pieri, D., 1986. Time dependent profiles of lava flows. J. Geophys. Res., 91: 9543–9552.

Cañón-Tapia, E., 1992. Applications to volcanology of palaeomagnetic and rock-magnetic techniques. MS thesis, Univ. of Hawaii, 146 pp.

Cañón-Tapia, E., 1994. AMS parameters: guidelines for their rational selection. Pure Appl. Geophys., in press.

Cañón-Tapia, E., Walker, G.P.L. and Herrero-Bervera, E., 1993. Magnetic properties of two flow units of Xitle volcano, Mexico: structural correlations and flow direction. EOS, 74 (spring meeting suppl.): 115.

Cañón-Tapia, E., Herrero-Bervera, E. and Walker, G.P.L., 1994. Flow directions and paleomagnetic study of rocks from the Azufre volcano, Argentina. J. Geomag. Geoelec., 46: 143–159.

Centeno-García, E., Urrutia-Fucugauchi, J. and Herrero-Bervera, E., 1986. Diferenciación y caracterización de flujos de lava por medio de sus propiedades magnéticas: Pedregal de San Angel, México. Mem. Reunión Anual de la Unión Geofísica Mexicana, pp. 464–471.

Constable, C. and Tauxe, L., 1990. The bootstrap for magnetic susceptibility tensors. J. Geophys. Res., 95: 8383–8395.

Ellwood, B.B., 1982. Estimation of flow directions for calk-alkaline welded tuffs and paleomagnetic data reliability from anisotropy of magnetic susceptibility measurements: central San Juan mountains, southwest Colorado. Earth Planet. Sci. Lett., 35: 116–122.

Ernst, R.E. and Baragar, W.R.A., 1992. Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature, 365: 511–513.

Gauthier, F., 1973. Field and laboratory studies of the rheology of Mount Etna lava. Philos. Trans. R. Soc. London, Ser. A, 274: 83–98.

Graham, J.W., 1966. Significance of magnetic anisotropy in Appalachian sedimentary rocks. In: J.S. Steinhart and T.J. Smith (Editors), The Earth beneath the Continents. Am. Geophys. Union, Geophys. Monogr., 10: 627–648.

Gunn, B.M. and Mooser, F., 1970. Geochemistry of the volcanics of central Mexico. Bull. Volcanol., 34: 577–616.

Hext, G.R., 1963. The estimation of second-order tensors, with related tests and designs. Biometrika, 50: 353–373.

Hrouda, F., 1982. Magnetic anisotropy of rocks and its applications in geology and geophysics. Geophys. Surv., 5: 37–82.

Hulme, G., 1974 The interpretation of lava flow morphology. Geophys. J. R. Astron. Soc., 39: 361–383.

Jelinek, V., 1978. Statistical processing of AMS measured on groups of specimens. Stud. Geophys. Geod., 22: 50–62.

Jelinek, V., 1981. Characterization of the magnetic fabric of rocks. Tectonophysics, 79: T63–T67.

Khan, M.A., 1962. The anisotropy of magnetic susceptibility of some igneous and metamorphic rocks. J. Geophys. Res., 67: 2873–2885.

Knight, M.D. and Walker, G.P.L., 1988. Magma flow directions in dikes of the Koolau complex, Oahu, determined from magnetic fabric studies. J. Geophys. Res., 93: 4301–4319.

Knight, M.D., Walker, G.P.L., Ellwood, B.B. and Diehl, J., 1986. Stratigraphy, paleomagnetism, and magnetic fabric of the Toba tuffs: constraints on the sources and eruptive styles. J. Geophys. Res., 91: 10,355–10,382.

Kolofikova, O., 1976. Geological interpretations of magnetic properties of basalts: examples of the Chibsky Les lava flow of the Velky Roudny volcano (Nizky Jesenik). Cas. Min. Geol., 21: 387–396 (In Czech).

Kuno, H., 1965. Fractionation trends of basalt magmas in lava flows. J. Petrol., 6: 302–321.

Libby, W.F., 1951. Radio Carbon Dating. Chicago, IL, 124 pp.

Lienert, B.R., 1991. Monte Carlo simulation of errors in the anisotropy of magnetic susceptibility: a second-rank symmetric tensor. J. Geophys. Res., 96: 19,539–19,544.

MacDonald, G.A. and Katsura, T., 1964. Chemical composition of Hawaiian lavas. J. Petrol., 5: 82–133.

MacDonald, W.D., Palmer, H.C. and Hayatsu, A., 1992. Egan range volcanic complex, Nevada: geochronology, paleomagnetism and magnetic fabrics. Phys. Earth Planet. Inter., 74: 109–126.

Martin del Pozzo, A.L., 1982. Monogenetic Vulcanism in Sierra Chichinautzin, México. Bull. Volcanol., 45: 9–24.

Naranjo, J.A., Sparks, R.S.J., Stasiuk, M.V., Moreno, H. and Ablay, G.J., 1992. Morphological, structural and textural variations in the 1988–1990 andesite lava of Lonquimay volcano, Chile. Geol. Mag., 129: 657–678.

Nye, J.F., 1960. Physical Psical Properties of Crystals: their Representation by Tensors and Matrices. Clarendon Press, Oxford, 323 pp.

Petersen, N., 1976. Notes in the variation of magnetization within basalt lava flows and dikes. Pure Appl Geophys., 14: 177–193.

Puranen, R., Pekkarinen, L.J. and Pesonen, L.J., 1992. Interpretation of magnetic fabrics in the early Proterozoic diabase dykes of Keuruu, central Finland. Phys. Earth Planet. Inter., 72: 68–82.

Rochette, P., 1988. Inverse magnetic fabric in carbonate-bearing rocks. Earth Planet. Sci. Lett., 90: 229–237.

Staudigel, H., Gee, J., Tauxe, L. and Varga, R.J., 1992. Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: anisotropy of magnetic susceptibility and structural data. Geology, 20: 841–844.

Symons, D.T.A., 1975. Age and flow direction from magnetic measurements on the historic Aiyansh flow, British Columbia. J. Geophys. Res., 80: 2622–2626.

Tarling, D.H. and Hrouda, F., 1993. The Magnetic Anisotropy of Rocks. Chapman and Hall, London, 217 pp.

Tormey, D.R., Frey, F.A. and López-Escobar, L., 1989. Geologic history of the active Azufre–Planchon–Peteroa volcanic center (35°15′S, southern Andes), with implications for the development of compositional gaps. Asoc. Geol. Argentina, Rev., 44: 420–430.

Verma, S.P. and Armienta, M.A., 1985. $^{87}Sr/^{86}Sr$, alkali and alkaline earth element geochemistry of Chichinautzin Sierra, Mexico. Geofis. Int. 24: 665–678.

Walker, G.P.L., 1991. Structure, and origin by injection of lava under surface crust, of tumuli, 'lava rises', 'lava-rise pits', and 'lava-inflation clefts' in Hawaii. Bull. Volcanol., 53: 546–558.

Walker, G.P.L., 1995a. Origin of vesicle types and distribution patterns in the Xitle Pahoehoe basalt in Mexico City. Bull. Volcanol., in press.

Walker, G.P.L., 1995b. Recognition of lava rises: an alternative mode of lava flow growth. (in prep.)